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The Contribution of the CSIRO Division of Radiophysics Penrith and Dapto Field Stations to International Radio Astronomy

Thesis submitted by
Ronald Thomas STEWART BSc (Hons) Qld, M Teach UT
December 2009

for the degree of Doctor of Philosophy
in the School of Engineering and Physical Sciences
James Cook University.

R.T. Stewart – The Contribution of the CSIRO Division of Radiophysics Penrith and Dapto Field Stations to International Radio Astronomy

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I certify that this thesis is entirely my own work apart from assistance offered by Harry Wendt in obtaining archival material from the National Archives of Australia, discussions with John Murray and Jim Roberts about the early days at Penrith and Dapto Field Stations, and email correspondence with Kevin Sheridan and Donald Mclean. I also made use of the library services provided by the Australian Telescope National Facility (ATNF) , the Anglo Australian Telescope (AAT), the University of Sydney and Macquarie University.

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I would also like to thank Dr. Harry Wendt for assistance in digging into the National Archives of Australia for relevant letters and minutes of meetings before my arrival at the CSIRO Division of Radiophysics, as well as help on other IT matters.

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Finally I would like to thank my family for their encouragement and wish to dedicate this thesis to the memory of three giants in the history of Australian solar radio astronomy, Paul Wild, Steve Smerd and Kevin Sheridan who were my mentors and a continuing source of inspiration throughout my career.

ABSTRACT

This thesis presents a detailed study of the research activities of the CSIRO Division of Radiophysics Penrith and Dapto Solar Group, who, it will be demonstrated, achieved an international reputation in solar radiophysics during the period 1949 to 1964, by innovative design of observing equipment and by ground breaking investigations into the nature of metre wavelength solar radio bursts and the disturbances which give rise to them.

An account of the planning, development and implementation of the world's first radiospectrograph at the Penrith field station in 1949 and its extensions to increasingly lower frequencies at the Dapto field station from 1952 to 1963, as well as the first swept-frequency interferometer, is presented using archival material, personal reminiscences and published literature.

The Penrith observations led to the first classification of Spectral Type I, II and III bursts. The observed frequencies of the leading edges of the slowly drifting Type II bursts and the rapidly drifting Type III bursts were converted to radial heights by using a standard coronal density model and by assuming that the radio emission occurs at the fundamental plasma frequency. This was referred as the *plasma hypothesis*.

The resulting height-time plots suggested that the disturbances exciting the radio emissions moved outwards through the corona with velocities of the order of 1000 km/sec for Type II bursts and 100,000 km/sec for Type III bursts. This was the first evidence for the ejection of corpuscular material to such great heights in the corona and it was suggested that the Type II disturbance upon reaching the Earth might be responsible for initiating geomagnetic storms which disrupt radio communication. Likewise the fast moving Type III disturbance was considered to be a possible candidate for solar cosmic rays, although the exact nature of the particles involved in the emission of Type II and III bursts was not known at that time.

The development of an improved radiospectrograph at Dapto led to the discovery in 1954 of fundamental and second harmonic components in both Type II and III bursts. This discovery gave support to the plasma hypothesis and allowed the height-time plots to be extended to greater heights in the corona. Further low frequency extensions to the spectrograph from 1956 to 1961

pushed the investigations to even greater coronal heights until it was established that the fast moving electron streams responsible for the Type III burst moved virtually unimpeded out to heights of at least 3 solar radii above the photosphere. This height was the limit that could be observed by ground based radio observations because of absorption effects in the Earth's ionosphere at frequencies below 7 MHz. Also, the Type II disturbance was traced to similar heights indicating that the shock wave responsible also escaped into interplanetary space.

Final confirmation of the *plasma hypothesis* was obtained with the development of the swept-frequency interferometer at Dapto in 1957. The radial heights found subsequently for Type II and III sources were in good agreement with coronal density models assuming, as before, that the emission occurs at the fundamental and second harmonic plasma level. An earlier experimental model of the interferometer, the first of its kind, had been installed at Dapto in 1954 for the study of radio scintillations from the source Cygnus A.

Later, spacecraft observations confirmed that the Type III bursts were associated with electron streams travelling outwards towards the earth along Archimedes spiral paths, at speeds of the order of c/3 in agreement with the earlier Dapto results. Similarly, the Type II burst was found sometimes to be associated with interplanetary shock waves and ejected plasma clouds known as coronal mass ejections (CME's). The latter are considered now to be the initiating cause of the Geomagnetic disturbance. The close association of Type II-IV bursts with CME's is why ground based radiospectrographs are still used today to monitor space weather.

The Dapto observations also led to the classification of a new type of burst called the Type V which sometimes followed Type III bursts. A model was proposed for this event in which some of the Type III electrons became trapped in coronal magnetic fields to produce the longer duration and broader bandwidth Type V burst. Other phenomena discovered at Dapto included the reverse drift pairs (RDPs) which were closely associated with Type I storms and the split-band and *herring-bone* structure in Type II bursts. The RDPs were thought to be evidence for radio echoes in the corona while several magnetic theories were proposed for the split-band structure in Type II bursts. The *herringbone* features were found to be highly polarized suggesting that the Type II shock wave excited streams of fast electrons as it moved across magnetic field lines in the corona.

The only metre wavelength burst not discovered by the Australian group was the Type IV, first classified by the French in 1957, who attributed the emission to synchrotron radiation from electrons spiralling along magnetic field lines in the corona. Dapto interferometer observations revealed that the Type IV had two components, an early moving source, called the *moving Type IV burst*, followed by a stationary source called the *stationary Type IV burst*. A model was proposed to account for the observed characteristics of the moving Type IV burst, which involved an ejected plasmoid, containing relativistic electrons generating synchrotron radiation, behind a Type II shock wave. The second stationary component lasted several hours before degenerating into a Type I storm. It was assumed that the fast electrons generating plasma emission in these stationary sources were trapped in magnetic fields above the flare region. Spectral observations of slowly drifting chains of Type I bursts were taken as evidence that the emitting electrons were excited by Alfven waves in the corona.

Although the Solar Group concentrated mainly on the collection and interpretation of the observed properties of solar radio bursts at metre wavelengths, several important contributions of a theoretical nature also were produced and theories reviewed. These concerned the propagation of electron streams and shock waves in the corona, as well as the conditions required for coherent plasma wave emission which occurs in Type II and Type III bursts. Also a two phase acceleration process for flare particles was propose based mainly on metre wavelength observations of solar bursts.

By the early 1960s the Division of Radiophysics had been granted funding to build a radioheliograph at Culgoora, NSW. As a result the Dapto Field Station was closed down in 1964. Solar radio observations continued at Culgoora from 1967 until 1984.

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1. INTRODUCTION

1.1 Thesis Topic

The aim of this thesis is to present, for the first time, a detailed account of the research activities of members of the CSIRO Division of Radiophysics Solar Group using facilities at the Penrith and Dapto field stations during the period 1949-1964. Through their original contributions to radioastronomy the Solar Group attained an international reputation of excellence during this period and were, in my opinion and others, to be the leading research group in the study of metre wavelength solar radio bursts. The thesis includes descriptions of the unique instruments which were developed for observations of solar radio bursts, data analysis and interpretations, supplemented by notes from archival material and discussions with surviving members.

1.2 Explanation of Terms

1.2.1 Radio Waves

Radio emission is propagated as an *electromagnetic wave*, where the electric and magnetic vectors oscillate in planes mutually perpendicular to the direction of propagation.

Radio waves today are often defined as only occupying that part of the ***electromagnetic spectrum*** over the wavelength range from about 10 m down to 30 cm with frequencies ranging from 30 MHz up to 1000MHz. This modern definition includes the VHF and UHF bands but excludes long radio waves in the decimetre, hectometre and kilometre wavelength bands and short radio waves in the microwave and millimetre bands. Traditionally, all of these spectral bands have been considered to be radio emission. Also, radio astronomers, unlike their optical counterparts, speak in frequencies rather than wavelengths, reflecting the origins of radio astronomy in radio engineering and communications.

The frequency (f) and wavelength (λ) of electromagnetic waves are related by the formula

$$f = c / \lambda \qquad (1)$$

where f is in units of Hertz (Hz) or in the past in units of cycles per second (c/s), λ is given in metres (m), and c is the velocity of light in a vacuum where $c = 3 \times 10^8$ m/s.

For example, if $\lambda = 1$ (m) then $f = 3 \times 10^8$ Hz = 300 MHz

The thesis deals mainly with metre wavelength radio band that is with frequencies from 30 MHz to 300 MHz, but some radio bursts have been recorded with the Dapto spectrograph down to frequencies as low as 5 MHz, the limit imposed by ionospheric absorption in the F layer. It includes TV and FM radio frequencies which often become a source of interference for solar radio observations.

1.2.2 Radiospectrograph

A radiospectrograph measures the intensity versus frequency of radio emission. The incoming radio waves are collected by a broadband aerial connected to a *super-heterodyne* receiver. In this Type of analogue receiver the incoming radio spectrum is swept by tuning a local oscillator connected to the mixer. The difference signal between the radio frequency (RF) and local oscillator (LO) frequencies is passed to an intermediate frequency (IF) amplifier for detection and display. Radiospectrographs are described in Chapter 2.

1.2.3 Radio Interferometer

A radio interferometer consists of two or more aerials whose signals are combined together (by addition or multiplication) to form an *interference pattern*. When the path-lengths from the source to each antenna are equal or differ by one or more wavelengths ($n\lambda$) the signals combine in phase to produce maximum amplitudes. At other times when the path difference is a multiple of half a wavelength ($n\lambda/2$) the combined signal pattern shows minima.

For an interferometer on an east-west baseline maxima occur when

$$d \sin\theta = n \lambda \qquad (2)$$

and minima occur when

$$d \sin\theta = n \lambda / 2 \qquad (3)$$

Knowing d, n and λ one can measure the position θ of the source in the sky. This is the principle use of a radio interferometer. Figure 1 shows a typical interference pattern for a two-element interferometer on an east-west baseline. Note the interference fringes are always modified by the antenna main lobe. Most interferometers operate at one frequency. The Dapto swept –frequency interferometer described in Chapter 2 was the first to operate over a continuous range of frequencies.

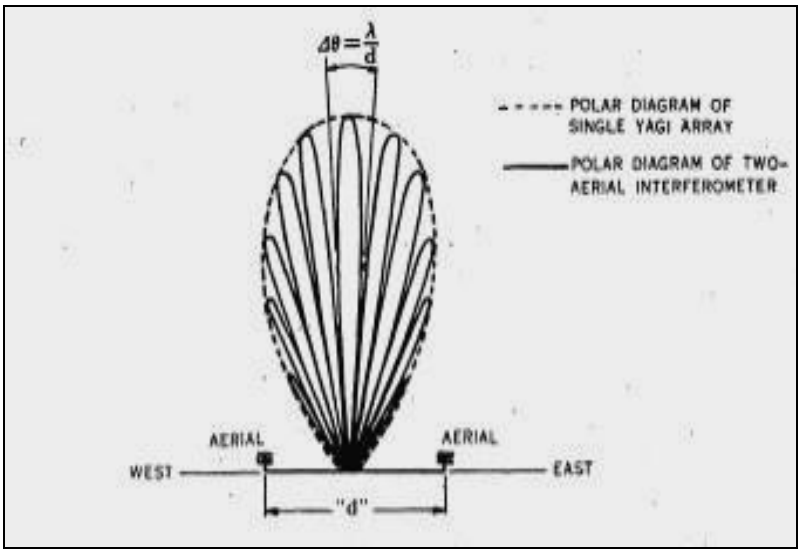


Figure 1 A typical interferometer pattern where "d" is the spacing between the two aerials (after Little and Payne-Scott, 1951: Fig. 2).

1.2.4 Refraction

Radio waves passing through an ionized medium with density gradients such as the solar corona or the ionosphere suffer bending or refraction. This disperses the spectrum just as a prism refracts white light into its separate colours. The amount of bending or dispersion is specified by the refractive index of the medium.

The degree of "bending" of the ray is given by Snell's Law

$$\sin\theta_2 / \sin\theta_1 = \mu_1 / \mu_2 = v_2 / v_1 \qquad (4)$$

where θ_2 is the refracted angle to the normal, θ_1 the incident angle to the normal, μ_2 the refractive index of the second medium, μ_1 the refractive index of the first medium, v_2 the wave

velocity in the second medium and v_1 the wave velocity in the first medium. Note that in a denser medium where $\mu_2 > \mu_1$ the wave is slowed down and refracted into separate colours because the refractive index is a function of frequency (except in vacuo or air where μ (f) = 1).

The refractive index of the solar corona, in the absence of a magnetic field, is given by the Lorentz formula

$$\mu^2 = 1 - Ne^2 / \pi m f^2 \qquad (5)$$

where N is the electron density and m is the electron mass.

1.2.5 Ionospheric Scintillations

Intensity and phase fluctuations of electromagnetic waves are called *scintillations* and are the result of variations in the refractive index of the medium. Scintillations of radio signals passing through the ionosphere are the result of irregularly structured regions producing horizontal density gradients in the F and E layers of the ionosphere causing the waves to be diffracted and scattered. An early study of the spectrum of ionospheric scintillations from the radio source Cygnus A is discussed in Chapters 2 and 3.

1.2.6 Polarization

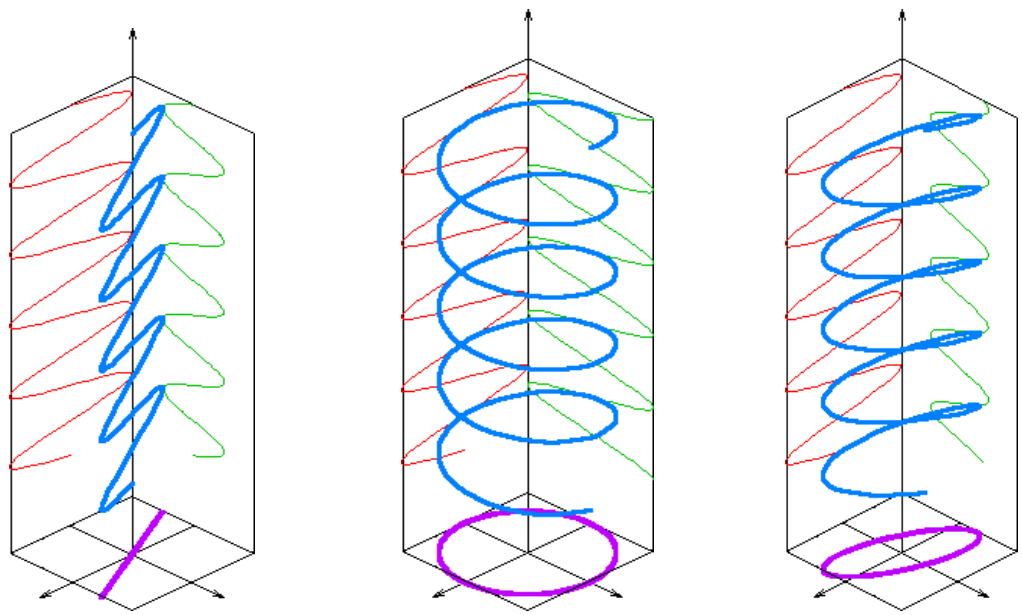
A polarimeter measures the degree of linear, elliptical or circular polarization of an electromagnetic wave. Figure 2 illustrates the three states of polarization.

In (a) the two orthogonal (perpendicular) components of the electric field E_x and E_y (shown in red and green) are in phase so the direction of the electric vector (the sum of E_x and E_y shown by the heavy blue trace) is constant and traces out a single line (purple) in the XY plane so the wave is said to be *linearly polarized*.

In (b) the two components are equal in amplitude but 90 or 270 degrees out of phase and the resultant vector traces out a circle in the XY plane and the wave is said to be either right-hand or left-hand *circularly polarized*.

In (c) the two components have different phase and amplitude and the wave is said to be *elliptically polarized*.

If the wave is only partially polarized the *degree of polarization* is needed also to fully describe the polarization. Measurements of polarization of solar radio bursts are described in Chapters 2, 3 and 4.



(a) (b) (c)

Figure 2 (a) Linearly polarized (b) circularly polarized (c) elliptically polarized wave (from Wikipedia, the free encyclopaedia website).

1.2.7 Radio Emission Mechanisms

In this thesis two emission processes for solar radio bursts are discussed.

The first is called *plasma emission* and results from the scattering of longitudinal plasma or Langmuir waves into transverse electromagnetic radiation. Emission at the fundamental plasma frequency f_0 occurs when the refractive index is zero. Substituting $\mu = 0$ into equation (1.5) gives

$$f_0 = (e^2 N / \pi m)^{1/2} = 9 \times 10^{-2} N_{(\mathrm{cm}^{-3})}^{1/2} \text{ MHz} \qquad (6)$$

where e and m are the electronic charge and mass (*e.s.u.*) (Wild et al., 1963).

In a magnetic field the fundamental frequency of emission of the spiralling electrons is known as the "gyro frequency" and is given by

$$f_H = e H / 2 \pi m c = 2.8 H_{(gauss)} \text{ MHz} \quad (7)$$

where H is the magnetic induction or field strength (Wild et al., 1963).

For relativistic (MeV) electrons many harmonics (n>100) of the gyro frequency produce a continuum known as *"synchrotron emission"* where

$$f = n f_H \quad (8)$$

At lower electron energies the emission is called *"gyro or gyro-synchrotron emission"* and is restricted to low harmonics of the gyro frequency (n< 100) the number depending on the electron energy). This is the second emission mechanism to be discussed for solar radio bursts.

1.2.8 **Electron Density Models**

Two electron density models for the solar corona are considered. The first model applies to a spherically symmetric corona near solar minimum and has been derived from optical observations by Baumbach and modified by Allen (1947a) where the electron density N is given by the formula

$$N_{(cm-3)} = 1.42 \text{ X } 10^{8} R^{-6} (1 + 1.68 R^{-10}) \quad (9)$$

where R is the radial height in solar radii ($R_0 = 6.95 \text{ x } 10^{5}$ Km)

The second model is due to Newkirk (1961) and applies to electron densities in a coronal streamer where N is given by

$$N_{(cm-3)} = 8.3 \text{ x } 10^{4} \text{ x } 10^{4.32/R} \quad (10)$$

The Newkirk densities are about 10 times greater than the Baumbach-Allen densities and, as it will be shown in Chapter 4, are more applicable to solar radio bursts.

1.3 Methodology

The methodology used in this thesis includes an exhaustive literature review of all articles and research papers by members of the Dapto Solar Group, invited talks and reviews at international conferences, newspaper articles, historical documents and interviews with surviving members and their associates.

Discussions were held with Bruce Slee, John Murray and Jim Roberts on several occasions in 2007 and 2008. Jim also gave me notes on his early days at Dapto, some of which are included in Appendix II. Email and telephone conversations were recorded with Kevin Sheridan and Donald McLean. Also, I have included some of my recollections as a summer student at Dapto in December 1960 and at the Radiophysics Laboratory from time to time during 1961-62, then as a full time member of the solar group from January 1963 until 1985. Historical documents including minutes of meetings and letters were obtained from the National Archives of Australia, some of which are reproduced in Appendix I.

Visits to field sites, archival material and photographs are used to enhance the historical context of this topic. Publications are treated in chronological order, wherever possible, to show the development and flow of ideas in the design of equipment, in observing techniques, in analysis of data and interpretation of results.

Each published paper is described in enough detail to show the relative importance it played in the progress of ideas and interpretation in this international research area. As much as possible I have tried to follow the style of the authors in the presentation of their ideas.

Copies of articles and research publications have been obtained from the world- wide-web or from the libraries at the CSIRO Australia Telescope (formerly the Division of Radiophysics), the Anglo-Australian Telescope, the James Cook University and from individual contributors. All original material is referenced or acknowledge in the text. Archival material has been obtained from the National Archives of Australia and referenced accordingly. Important original letters and reports are reproduced in Appendix I.

1.4 Justification of Chosen Topic

1.4.1 Originality

Although other researchers have published individual papers on certain aspects of this thesis topic no one has made a definitive study of the research activities as a whole, putting them into historical content and showing the development of innovative observing techniques and interpretation.

Earlier observations of solar radio emission by various members of the Division of Radiophysics were all made at discrete frequencies and have been described by Orchiston, Slee and Burman (2006) and others. Later observations from 1967 to 1985 involving the Culgoora radioheliograph have been adequately covered by review articles in the book "Solar Radiophysics" eds. D.J. McLean and N.R. Labrum (1985).

However, to-date no one has reviewed in any detail the significant observations conducted at the Penrith and Dapto field stations by members of the Dapto solar group, as it became known. My thesis covers the formative years from 1948 to 1964 when this group achieved an international reputation for excellence in the research. This was a period of *small science* where modest budgets and small groups of scientists and engineers, based at a number of different field stations in and near Sydney, used a "string and ceiling wax" approach and lots of ingenuity to help develop the emerging branch of radio astronomy (Orchiston and Slee, 2005). By 1964 when the Dapto field station closed down to make way for the construction of the radioheliograph at Culgoora, following the completion of the 64m radio telescope at Parkes, the Division of Radiophysics had become involved in *big science* (see Sullivan, 2005).

1.4.2 Relevance and Importance of this Study

The CSIRO Division of Radiophysics was established in 1939 to bring radar to the Pacific region. The first Chief was D.F. Martyn, a well known ionospheric physicist and close friend of Appleton (Piddington and Oliphant, 1971). The Division's research and development of radar and navigational aids was placed in the capable hands of two physicists J. L. Pawsey (Lovell, 1964) and J. H. Piddington (Melrose and Minnett, 1998) The Division advised the Australian military in the setting up of an air warning radar system at various sites along the coastline, as well as

undertaking fundamental research on problems associated with the propagation of radio waves through the Earth's atmosphere and ionosphere. In 1945 F. W. G. White, who had replaced Martyn as chief in 1942, became the Head of CSIRO (Minnett and Robertson, 1996) and encouraged the new Chief E. G. Bowen, a distinguished British radar pioneer (Hanbury Brown et al., 1992), to look for new research projects in both pure and applied science (Bowen, 1984).

Following the release of secret wartime documents from Britain and reports of radio detections from New Zealand (Orchiston, 2005), observations of solar noise at a frequency of 200 MHz were undertaken by a team led by J. L. Pawsey, using the wartime military radar sites at Dover Heights and Collaroy Plateau. These initial observations led to the discovery of the million degree corona and the association of solar bursts with sunspots. Solar observations were extended to both higher and lower frequencies using various sites around Sydney (Orchiston and Slee, 2005).

In 1949 the world's first radiospectrograph was installed at Penrith, N.S.W. and recorded solar bursts over a continuous frequency band from 70 -130 MHz. This led to the spectral classification of Type I, II and III solar radio bursts by Wild and McCready (1950). An improved spectrograph, installed at Dapto, N.S.W. in 1952, extended the frequency from 40-240 MHz. Further extensions were installed in 1958, 1960, 1961 and 1963 giving a final frequency coverage from 5-2000 MHz. Apart from the 1963 extension to decimetric wavelengths, the earlier developments were unique to radio astronomy and each one provided new information on the nature of solar radio bursts. To complement the spectral observations, a swept-frequency interferometer, again the fist of its kind, was installed at Dapto in 1957 to measure radio burst positions over the 40–70 MHz frequency range. Also, the first spectral observations of ionospheric scintillations were conducted during the solar minimum years of 1955-56.

The Dapto spectrograph discovered fundamental and second harmonic structure in Type II and III bursts, "herringbone" and split-band structure in Type II bursts, "reverse drift pairs" and "drifting chains" in Type I noise storms, as well as the Type V burst. (The only spectral Type not discovered by the Dapto group was the moving Type IV burst, which was discovered by the French using the 169 MHz grating interferometer at Nancay.)

Dapto interferometer measurements of the heights of Type II and III bursts firmly established the *'plasma hypothesis'* first postulated by Wild in 1950 to convert frequency-time

records of Type II and Type III bursts into height-time plots from which radial velocities could be determined. Low frequency observations from Dapto, extending down to the limit imposed by the ionosphere (~ 5 MHz), showed that the shock waves and the electron streams generating Type II and III bursts escaped with negligible loss of energy to heights beyond 3 solar radii in the solar corona and probably travelled all the way to the Earth, producing disturbances in the geomagnetic field.

As I said in an introductory talk at the 'History of Astronomy Conference held at JCU in October 2007:

> The great significance of invention of the radiospectrograph was that for almost twenty years before the advent of observations from space, radiospectrograph records provided the only real-time pictures of the active corona out to heights of several solar radii (apart from short and infrequent optical observations at the times of solar eclipse).

Since 1956 a number of observatories around the world have built instruments similar to the Dapto radiospectrograph or interferometer to provide wider coverage of solar activity (see Table 8). These observations have been collated and published in the Quarterly Bulletin of Solar Activity. One of the early collecting centres was supervised by Steve Smerd, a member of the Dapto solar group. I know this journal very well because I was given the job when I joined the solar group in 1963 of scanning the Dapto spectral records and later the Culgoora records for burst activity to be reported in the Bulletin.

Today, almost sixty years since the first detection by Wild and his colleagues, Type II bursts are being recorded from metric to kilometric wavelengths by ground- based and satellite spectrographs (Gopalswamy et al., 2005; Cairns et al., 2008). Along with interplanetary shock waves and coronal mass ejections they are monitored for *"space weather"* reports because of their known disruptive effects on the geomagnetic field and ionosphere, which can cause blackouts to radio communication, navigational and other satellite systems. As recent as December 2006 all GPS receivers on the sunlit side of the earth were reported to be disrupted for hours by the arrival of ejecta from two large solar flares.

1.5 Penrith and Dapto Field Station Team Members

Members of this group at various times during 1948 to 1964 included the following:

J.P. Wild (deceased), L. L. McCready (deceased), J.D. Murray (retired), W.C. Rowe (deceased), S.F. Smerd (deceased), J.A. Roberts (retired), M. Komasaroff (deceased), J.J. Joisce (retired) , K.V. Sheridan (retired), G.H. Trent (deceased), A.A. Neylan (retired), C.F. Attwood (retired), D.J. McLean (retired), R.T. Stewart (retired), S. Suzuki (retired), and W. Orchiston (JCU).

1.5.1 John Paul Wild CBE AC

Paul Wild was born in Sheffield, England in 1923 and undertook a degree in mathematics at Cambridge University in 1943 before joining the British Navy where he served as a gunnery officer from 1943-47. He then joined the Division of Radiophysics and worked with Lindsay McCready on the design of the Penrith radiospectrograph. Later he designed and supervised the construction of the Dapto spectrograph, the swept-frequency interferometer and the Culgoora radioheliograph. In 1971 he became Chief of Radiophysics and then Chairman of CSIRO in 1978. He died in May 2008 (Stewart et al., 2008a).

1.5.2 Lindsay McCready

Lindsay McCready had worked at AWA during the war and was Joe Pawsey's right-hand man in solar studies and helped set up the solar noise group in January1946. McCready supervised the design and construction of two unique instruments in radio astronomy:

(1) The Cliff Top Interferometer at Dover Height, which was the first instrument in radio astronomy to successfully locate source positions using interferometer techniques (It preceded Ryle and Vonberg's variable baseline interferometer solar observations by one month in July, 1946.)
(2) The Penrith radiospectrograph.

1.5.3 John Murray

John Murray joined Radiophysics in January 1948 after graduating in engineering at the University of Tasmania. His first job was to build a display for the Penrith spectrograph. He then helped Paul Wild with the observations before joining Bill Rowe on the development of the Dapto spectrograph receivers and display as well as the Cygnus scintillation equipment. At Dapto he shared observational shifts with Wild and Rowe and was on duty when the first Type II burst with harmonic structure was recorded. In August 1953 he was transferred to the newly formed hydrogen line group where he designed filters for the multi-channel system at Murray Bank. Later he spent time in Leiden before returning to Sydney to join the Parkes radio telescope receiver group.

1.5.4 John Rowe

John Rowe worked with Bernie Mills during the war in the Radiophysics high voltage laboratory (Murray, 2007). In 1948 he was assigned by McCready to help the construct the 70-130 MHz receiver for the Penrith spectrograph and later helped with observations. He then worked on the construction of the 40-240 MHz receiver system for the Dapto spectrograph with John Murray and assisted with the maintenance of equipment and observations. In 1953 he developed leukaemia and died in 1954.

1.5.5 Stefan Smerd

Steve Smerd joined the Division of Radiophysics in 1946 after working in England during the war at the University of Birmingham and the Admiralty Signals Establishment at Whitley. He was transferred to Pawsey's solar noise group in 1949 where he worked on theoretical aspects of the radio emission from the quiet sun and from solar bursts. He became leader of the Culgoora Solar Group in 1971 and died in 1978 (Wild, 1980; Robertson, 2002).

1.5.6 Jim Roberts

Jim Roberts joined the Division in November 1952 after completing a PhD at Cambridge under Fred Hoyle. Six months later he transferred to Wild's Dapto solar group and assisted with the Dapto observations, analysis and interpretation of the spectral characteristics of solar bursts and

ionospheric scintillations. In mid 1958 he left the solar group to visit CALTECH before returning to Sydney to join the Parkes Radio Telescope Group, under the directorship of John Bolton. Jim had very wide interests and knowledge in radio astronomy which he put to good use as editor of Radiophysics publications. He retired from CSIRO in 1983.

1.5.7 Max Komesaroff

Max Komesaroff joined the Dapto team in mid 1953 when John Murray left. He had worked previously on aerial surveys for the Department of for Mineral Resources. At Dapto he helped with daily observations as well as undertaking a study of the polarization properties of solar bursts. He later joined the Parkes Radio Telescope Group.

1.5.8 Jack Joisce

Jack Joisce was appointed in 1953 as the Dapto field station caretaker and was responsible for the daily running of equipment. His Navy training came in handy and Paul Wild used to joke that Jack's naval background made him one hundred percent reliable when it came to following a sequence of instructions. Jack remained with the solar group until he retired in 1981.

1.5.9 Kevin Sheridan OA

Kevin Sheridan was born in Brisbane in 1918. He joined the CSIRO Division of Radiophysics in 1945 and in 1956, after working with Bernie Mills and Alec Little on the Mills Cross, transferred to the Dapto Solar Group. At Dapto he helped develop the radiospectrograph and swept-frequency interferometer before becoming involved in the construction of the Culgoora radioheliograph. In 1975 he became leader of the Solar Group until he retired in 1984.

1.5.10 Gill Trent

Gil Trent was a radar technician on the Australia and narrowly escaped death when the ship was hit by a kamikaze dive bomber off the Philippines. He was a capable technician (Murray, pers. comm., 2007). After the war he joined the Radiophysics Division and was transferred to the Dapto group in 1956 to work on the development of the swept-frequency interferometer and

extensions to the spectrograph. He had a reputation as a good cook and I was fortunate to share some of his meals at Dapto. In 1963 he transferred to the Parkes receiver group.

1.5.11 Tony Neylan

Tony Neylan while a PhD student at Mt. Stromlo spent about one year at Dapto in 1958 helping with interferometer observations and data analysis. He later entered the church much to Paul Wild's amusement.

1.5.12 Charles Atwood

Charlie Attwood replaced Gill Trent around 1960 and worked on radiospectrograph development with Sheridan and Suzuki at Dapto and then later at Culgoora. Along with Kev Sheridan, Gil Trent and Paul Wild he was part of the Radiophysics cricket team (Figure 3).

Figure 3 The Radiophysics cricket team in the late 1950s with Paul Wild holding the bat, Kevin Sheridan seated second from right, John Bolton top left and Charlie Attwood top right (Courtesy of the ATNF photographic archive).

1.5.13 Donald McLean

Don McLean was born in Australia in 1938 and educated at the University of Sydney and the Universite de Paris. As a student in 1959 he worked with the Dapto Solar Group and published a model for moving Type IV bursts. Upon returning from Paris he helped Wild develop the Culgoora radioheliograph and remained a member of the group until the instrument was de-commissioned in 1985. With Norman Labrum he edited the book “Solar Radiophysics”.

1.5.14 Alan Weiss

Alan Weiss transferred from Adelaide to Sydney in 1959 to supervise the analysis of Dapto observational data. One of his assistants was a young Wayne Orchiston. He wrote several important papers on solar radio bursts before dying from leukaemia in early 1965.

1.5.15 Ronald Stewart

I was born in 1939 and attended the University of Queensland from 1958-62 visiting the Division of Radiophysics on a number of occasions as a summer student working with the Dapto group. In January 1963 I became a full-time member of the Solar Group working on data analysis and building the 158 MHz three-element interferometer at Culgoora before working on the interpretation of radioheliograph observations. I was a Visiting Astronomer at the University of Hawaii in 1971-2 and at the University of Colorado in 1981 and remained a member of the Culgoora solar group until the closure of the radioheliograph in 1985. I then transferred to the Australia Telescope and retired from CSIRO in 1996.

1.5.16 Shigemasa Suzuki

Marchan Suzuki, as he preferred to be called, joined the Dapto group in 1962 having built the 201 MHz four-element interferometer at Mitaka, Japan in 1958. In 1963 he extended the Dapto spectrograph from 200-2000 MHz. Later he developed the spectro-polarimeter at Culgoora before retiring from CSIRO in 1984.

1.5.17 Wayne Orchiston

Wayne Orchiston worked with the Dapto solar group during 1965-66 when he was a part-time student at the University of Sydney. He now holds a position as Associate Professor at James Cook University and is my thesis supervisor.

The size of the solar group had grown by 1965 with the construction of the Culgoora radioheliograph as the photograph in Figure 4 shows.

List of participants in Figure 4 clockwise from top: (inner circle) Paul Wild, Masaki Morimoto, Charlie Atwood, John Sparks, Jack Palmer, Bill Bowie, Les Clague, Geoff Chandler, Kevin Sheridan; (outer circle) Steve Smerd, Shigemasa Suzuki, Ron Stewart, Gopala Rao, Len Binskin, Joe Mack, Wayne Orchiston, Nick Fourikis, Warren Payten, Norman Labrum, Alan Weiss. Missing is Donald Mclean who was overseas at that time.

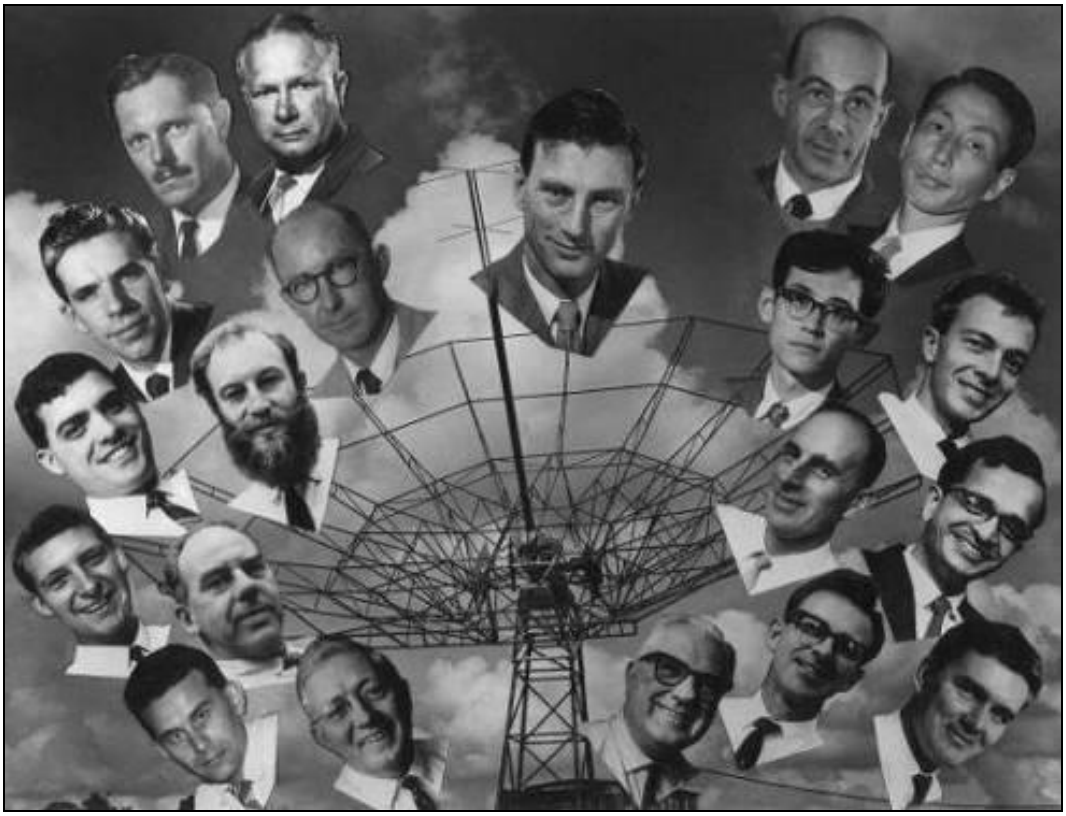


Figure 4 Collage of the solar group members circa 1965 (courtesy of the ATNF Photographic archive).

1.6 Outline of Thesis

Rather than treat each spectral type separately, the research activities are discussed under three main headings:

Ch.2 Instrumental developments 1949-63

Ch.3 Radiospectrograph results 1949-64

Ch.4 Interpretation of interferometer observations 1957-65

Ch.5 Significant contributions to metre wavelength solar astronomy 1942-1963

The contributions are presented in chronological order to give a correct historical perspective to the flow of ideas and developments in our knowledge of the nature of solar radio bursts. Table 1.1 can be used to follow the development for each spectral Type. Quotations are used frequently throughout this thesis to give authenticity to authors' contributions. All references to external researchers in the text have been included to place the solar group's contributions in the context of concurrent international research. From Table 1 it is clear that the majority of the research effort of the Solar Group was in three areas; instrumental development, the study of Type II and Type III bursts and in the interpretation of burst characteristics. The spectacular nature of the moving Type IV burst (Stewart, 1984) was not fully realised until the advent of the Culgoora Radioheliograph during the late 1960s.

TABLE 1

LIST OF LOCATIONS IN THESIS FOR EACH SPECTRAL TYPE AND INSTRUMENTAL DEVELOPMENT

Topic	Sections
Penrith radiospectrograph	2.1, 2.2
Dapto radiospectrograph	2.4
Extensions to Dapto radiospectrograph	2.8
Scintillation studies and equipment	2.5, 3.8
Polarization studies	2.6, 3.12, 4.9
Swept-frequency interferometer	2.7
Type I bursts	2.3, 3.3, 3.12, 3.19, 4.1
Type II bursts	2.3, 3.1, 3.5, 3.7, 3.15, 3.16, 4.1, 4.2, 4.4, 4.5, 4.9, 4.10, 5.4, 5.5

Type III bursts	2.3, 3.2, 3.6, 3.7, 3.13, 3.20, 4.2, 4.3, 4.4, 5.4,5.5
Type IV bursts	3.9, 3.17, 4.1, 4.2, 4.6, 5.4
Type V bursts	3.18, 3.20, 4.3, 4.7, 4.8, 5.4.
Reverse Drift Pairs	3.14,
Herringbone structure	3.16, 4.9. 5.4

The topics to be discussed in this thesis (not necessarily in the order given below) include:

- Early radio observations recorded at one or more frequency
- Penrith Radiospectrograph
- Initial classification of spectral Type I, II and III solar bursts
- Dapto Radiospectrograph and its extensions
- Discovery of harmonic structure in Type II and Type III bursts
- Height-time plots of Type II and Type III bursts
- Coronal electron density models
- Dapto Swept-frequency Interferometer
- Observations of source positions and movement
- Confirmation of the Plasma Hypothesis
- Classification of Type IV and Type V bursts
- Radio emission mechanisms
- Discovery of drifting pairs, split-band and herringbone structure
- Polarization studies of metre wavelength solar bursts
- Correlation studies with optical flares, short wave fadeouts and geomagnetic storms
- Interpretation of burst phenomenon including emission processes and exciting agencies
- Ionospheric and coronal refraction effects on source position
- Ionospheric scintillations from Cygnus A.
- Significant contributions to solar radio astronomy

1.7 Publications Arising from this Thesis

Several research articles have arisen so far from my thesis work and are in the process of being prepared for publication. These include the following papers presented at conferences on the History of Astronomy:

(1) "The Sun has set on a brilliant mind- John Paul Wild (1923-2008)" (Stewart et al., 2008a). Presented at the JCU Meeting in July 2008 (in press)

(2) "A Retrospective View of Australian Solar Radio Astronomy 1945 to 1960" (Stewart et al., 2008b); Presented at the JCU Meeting in July 2008 (in press)

(3) "The World's First Radiospectrograph – Penrith 1949" (Stewart et al., 2008c); Presented at the JCU Meeting March 2008 (in press)

(4) "Contributions of the Dapto Field Station to Solar Astronomy – 1957-1964" (Stewart et al., 2009) presented at the JCU Meeting March 2009.

2. INSTRUMENTAL DEVELOPMENTS 1947-1963

In this chapter instrumental developments by the solar group are reviewed in detail. These innovative instruments were designed and built within the CSIRO Division of Radiophysics.

2.1 Planning the World's First Radiospectrograph 1945-48

2.1.1 Introduction

From 1945 to 1948 a number of important observations of solar radio emissions were conducted by members of the CSIRO Divisions of Radiophysics under the team leadership of Joe Pawsey (for a more comprehensive account see Orchiston, 2005: Orchiston et al., 2006). Sudden increases in the intensity of the radiation received or *bursts* as they were called, were recorded mainly at a single frequency, but sometimes simultaneously at two or more frequencies. The chart recordings of these solar bursts at metric wavelengths showed that the burst emission included both circularly- polarized *noise storms,* and also unpolarized *isolated bursts* and occasional longer duration *outbursts,* which were associated with solar flares.

On 8 March 1947 Payne-Scott, Yabsley and Bolton observed a systematic delay of a few minutes between the commencement of an *outburst* at 200, 100 and 60 MHz (Figure 5) suggesting the possibility that the source moved outwards through the corona with a velocity ~ 1000 km/s (Payne-Scott et al., 1947). They speculated that the outburst might be caused by ionized particles travelling outwards through the corona with sufficient speed to arrive at the Earth several days later and initiate the geomagnetic storms which disrupt long distance radio communication.

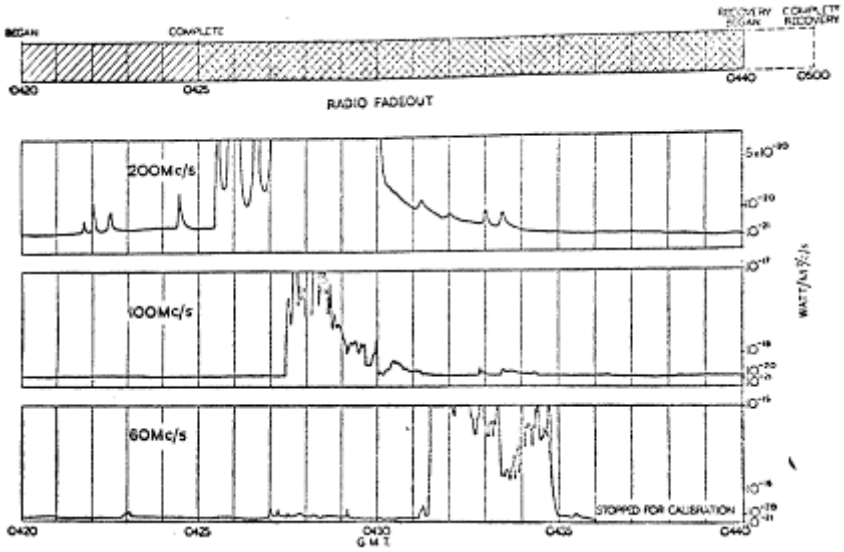


Figure 5 An outburst recorded simultaneously at three frequencies on 8 March 1947 showing time delays between different frequencies (after Payne-Scott et al.1947: Fig 1).

The importance of this observation was recognized by Pawsey (1949: 9-10) who wrote about such an event:

> One of the interesting speculations concerning the origin of some of the largest radio disturbances, which are called *outbursts*, is that these may be due to explosions on the Sun which hurl great masses of gas upwards, some with so great a velocity as to escape from the Sun. Incidentally, terrestrial magnetic storms and auroras are supposed to be caused by the arrival at the Earth of such masses of gas. In the Sun, these gases would move upwards and if, as is suspected, a particular wavelength of radiation is associated with each level in the solar atmosphere, we should expect to observe different wavelengths excited in succession. Some of the greatest outbursts have shown just such delays between the onsets at different wavelengths.

In a later article entitled "The *Origins of Radio Astronomy in Australia*" Bowen, who was the Chief of the Division of Radiophysics from 1946 until 1967 wrote (Bowen, 1984: 93):

> It happened that during the war the Division – as part of a secret within a secret – had been involved in the construction of receivers for surveillance of enemy

> radio and radar transmissions. The basic method of carrying this out was to scan rapidly over a 2:1 frequency range and to cover the whole band of usable frequencies in a series of 2:1 steps. Within the Division there was a substantial store of such receivers. These were ready made for spectral analysis of the noise from the Sun and they were quickly pressed into service. In the inventive hands of Lindsay McCready and Paul Wild, a "radio spectrometer" evolved which was to dominate the field of solar studies for the next twenty years.

However, it is very clear from my research that Bowen's comments that a *spectrum analyser* was quickly pressed into service from surplus wartime radar equipment was an understatement of actually what took place, as the following archival data shows (see also Stewart et al., 2008).

The first reference to using a spectrum analyser approach for solar radio studies was found in the Minutes of the Propagation Committee Meeting (National Archives, 2007) held at Radiophysics on 8th July, 1946 where McCready (1946), discussing the possibility of extending solar observations to 200 MHz at Brisbane, reported: "General opinion however favoured a spectrum analyser style of approach, with all frequencies being studied at the same place."

From the records of Minutes of the Solar Noise Group during 1948-49, (National Archives, 2007) the following notes on the development of a spectrum analyser for the study of solar radio bursts were found:

1. First mention in the minutes of the Solar Noise Group (which had been set up by Pawsey and McCready on 15 Jan 1946) of work on a *spectrum analyser* is the second meeting of the Group on 6th June 1947. Bolton was looking at further simultaneous multi-frequency solar observations at Dover Heights. This was basically an extension of the work Payne-Scott was doing (also at Dover Heights), but she was writing up her initial findings. Bolton was looking at measurements at 60, 85, 100 & 200 MHz. In the minutes it notes that Bolton mentions underdevelopment a spectrum analyser for looking at the 60-100 MHz band for intensity and polarisation changes. At the same time the minutes also show that McCready was doing work on instruments and techniques, part of which was looking at the use of *rhombic* aerials.

2. In the next meeting held on 23rd September 1947 the minutes note that Ruby Payne-Scott and Miss M. Clark are working at Dover Valley. Ruby mentioned that: "Mr. McCready is planning the more elaborate follow-up experiment of a spectrum analyser."

McCready then reported on the Proposed Technique:

> Spectrum analyser – arrangement with alternative displays. (1) Similar to Class A with visual observation = cine photography. (2) Intensity modulation with f and t as axes).
> Plans: Begin on 100 Mc/s using rhombic aerial. Personnel: McCready + Medhurst (part time) until he leaves then new man.
>
> [The new man referred to was either Paul Wild or John Murray.]

In the minutes of the meeting of 16th October 1947 McCready and Wild report that:

> A P58 English search receiver covering the range 280-600 MHz has been borrowed from Electrotech. It is proposed to modify this and to obtain (via Eagles) another model if possible. Wild is looking into the theory of Rhombics for U.H.F. [ultra high frequency] operation.

In the minutes of the 14th November 1947 meeting the following report is listed under McCready, Wild and Medhurst:

> The P58 search receiver (280-610Mc/s) has been tested. Its noise factor is 20 db. While it may still be useful, it is considered advisable to proceed with another RF unit designed for a noise factor of 10 db, to avoid delays in waiting for large magnitude bursts. In the meantime a 200 to 600 Mc/s Rhombic is being constructed for use with the P58 receiver during periods of intense bursts at 200 Mc/s, when it is hoped to find the region where they disappear. An additional P58 receiver has now been obtained and it is proposed to modify this to cover the 70-140 Mc/s range pending the completion of a better receiver.

In the minutes of 6th January 1948 meeting, McCready and Wild report on the Spectrum Analyser:

> The 200-600 Mc/s Rhombic has been completed. MacAlister has commenced design of polar axis mount for 70-140 Mc/s Rhombic. P58 search receivers are not sufficiently sensitive for average bursts. Wild will commence design of a 70-140 Mc/s RF unit shortly.

In minutes of 20th February 1948 meeting, Murray has now joined McCready and Wild. The following is reported:

> Design of rhombic aerial mount completed and orders placed for timber etc. Exp. Tuneable RF unit (70-140Mc/s) has been completed. Good sensitivity has been obtained and consideration now being given to the design of a high speed mechanical drive for this unit. Tentative breadboard models of oscillograph amplifiers, slow speed time bases etc. were completed by Medhurst before he left.

In minutes of 30th April 1948 meeting the spectrum analyser report is listed by McCready, Wild and Rowe:

> The experimental r.f. unit (motor-tuned) is in the process of assembly. It is hoped to commence tests of this unit within a week or two. A complete overall sensitivity test will then be made on the aerial-receiver combination (without the C.R.O. displays) followed by development of calibration procedures in regard to the intensity of the radiation received. The C.R.O. [cathode ray oscillograph, my words] display panel and photographic recording devices are still under development but progressing favourably.

Also, in a letter dated 5th May 1948 Bowen had written to Pawsey who was visiting England at that time:

> McCready is carrying on slowly but surely with his spectral analyser and should be getting results before you come back. He is concentrating on the 70-140 Mc/s range but is ready to extend this if the results are sufficiently promising. We anticipate that when the spectrum analyser is running it will make Ruby's work on delays redundant, so she is aiming to complete her investigations [at Hornsby Valley] and have it written up before long.

Further extracts from letters between Pawsey and McCready during the period October 1947 to June 1948 discussing the progress on the construction of the spectrum analyser and a search for a suitable site are reproduced in Appendix I.

It is clear from the above mentioned archival notes and letters that the design of a spectrum analyser for solar studies had been in progress for some time before Wild joined the group as a Research Scientist in October 1947 (see letter from Lehany to Pawsey in Appendix 1) after serving as a gunnery officer in the Royal Navy. Under the guidance of L. L. McCready, Wild was given the task of designing the 70-130 MHz receiver and rhombic aerial for the world's first *radiospectrograph* as it became known.

Murray recalls that soon after he joined Radiophysics in January 1948 he was given the job of building the display system by Lindsay McCready, who then introduced him to Paul Wild working in the Radiophysics Test Room. He recollects that Paul did not do much of the technical work apart from "fiddling around" with aerial cables and connectors. The job of assembling, testing and maintaining the receiver and display system fell to Bill Rowe and himself. They also helped Paul with the daily observations at Penrith (Murray, pers. comm., 2007). Jim Roberts told me that Paul used to joke that whenever he wanted John Murray to do any work he had only to pick up a soldering iron and John would quickly take over the task (Jim Roberts, pers. comm., 2007).

Years later, when Chief of CSIRO, Wild (1985: 8) wrote in the book *Solar Radiophysics* (eds. Mclean and Labrum) about his recollections of his early days at Radiophysics:

> The situation around 1948, when I joined the Sydney group of investigators led by Joe Pawsey, was one characterized by mystery, incredulity and intense interest. A whole new field of research lay ahead with obvious objectives: to

disentangle the conglomeration of phenomena; to interpret and understand them; and to put the results to use in the mainstream of research for solar physics, astronomy and physics.

Before the 'origin of species' could be identified there had to be an exercise in taxonomy. Already Pawsey and his colleagues at Sydney had found that, in addition to the polarized storm radiation, there were different kinds of unpolarized bursts: there were large outbursts lasting 10 or 20 min which accompanied large flares, and there were short, sharp 'isolated' bursts lasting a few seconds....

A new clue was discovered when Payne-Scott et al. (1947) noted systematic time delays in the starting time of bursts, high frequency preceding low. In the case of the isolated bursts these delays were typically a few seconds and were thought to be due to the difference in travel time.

In the case of outbursts, one event was recorded with long delays (a few minutes) between frequencies, and the possibility was suggested that the delay was due to the outward movement of the source.

However, in a subsequent extended series of observations [from January to September 1948, my words] Payne-Scott (1949) found no further evidence of similar delays and was inclined to believe that the long delays of that one event was fortuitous. She stressed the difficulty of identifying corresponding features of a complex burst at different frequencies.

An obvious next step, therefore, was to develop a radiospectrograph to record the intensity of the solar emission as a continuous function of frequency and time.

2.2 The Penrith Radiospectrograph 1949

Observations with the first radiospectrograph were made at Penrith, NSW in the 70 to 130 MHz frequency range between February and June 1949 (Wild and McCready, 1950) and the equipment and initial results discussed in this landmark paper are described below.

Burst radiation from the Sun was collected with a broad-band aerial connected to a receiver which was rapidly tuned or 'swept" over the 40 to 70 MHz frequency range. The tuner was mechanically driven so that the frequency sweep occurred in 0.07 second, and repeated about three times per second giving a time resolution for recording of 4 scans per second. The spectrum was displayed on a cathode-ray tube in the form of a graph of received power (vertical axis) versus frequency (horizontal axis) and then photographed.

2.2.1 The Penrith site

The site chosen for these observations was on Commonwealth Department of Defence land acquired in 1946 (Penrith Library, 2007) within easy walking distance (about 300 metres) north from the Penrith railway station which, at that time, contained a large shunting yard for steam locomotives travelling over the Blue Mountains The site was chosen for its easy access from Sydney and because it was relatively free from radio interference (Murray, pers. comm., 2007). It was most likely located in or near the current car park shown in Figures 6 and 7.

Figure 6 Photograph of the most likely site of the Penrith radiospectrograph (photo taken 2007).

Figure 7 Aerial photograph of the Penrith site taken in 2006.The white outline defines the Department of Defence land which was acquired in 1946. The *site* was located about 300m to the north of the old Penrith railway station in or near the current car park (photo courtesy of the Penrith Municipal Council).

2.2.2 The Rhombic Aerial

The aerial was of rhombic design (see Figure 8) with sides of length l = 6.4 m (3 wavelengths at 100 MHz) and angle $\Phi = 56.4^{o}$ giving an impedance (resistance) of 670 ohms and an effective area of almost 12 m^2 at centre frequency. A tapered line, three metres long, transformed this resistance to 300 ohms which matched into a two-wire line connected to the receiver located some distance away.

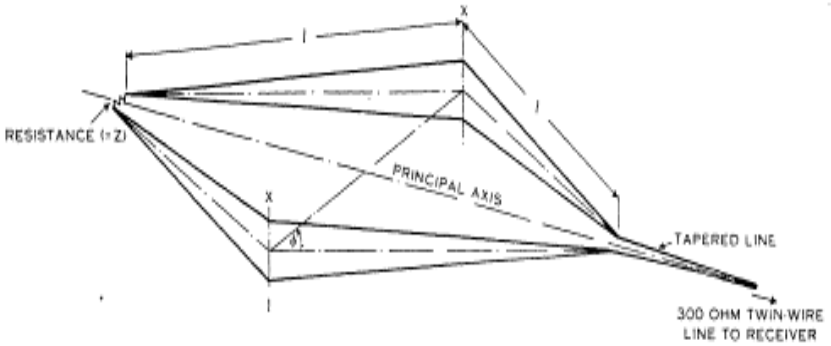


Fig. 1.—The rhombic aerial.

Figure 8 Rhombic aerial design (after Wild and McCready, 1950: Fig. 1).

The antenna was designed by Wild and constructed with a wooden frame under the supervision of K. MacAlister, a mechanical and electrical engineer who became well known over the years for the design and construction of low cost antennas at various Radiophysics astronomy sites. Wild derived the theoretical affective receiving area or "gain" of the aerial from first principles with some help from Chris Christiansen (see Appendix I of Wild and McCready, 1950).

Figure 9 Polar mount and declination axis for the rhombic aerial (Courtesy ATNF photographic archive).

During observations the aerial's principal axis of the rhombic was pointed towards the sun in order to receive maximum signal. This was achieved by moving the aerial by hand every twenty minutes by way of a rope and pulley system. The rhombic was rotated about a polar axis embedded in a concrete footing (as shown in Figure 9). The large rhombic aerial can be seen in Figures 10 and 11 with its supporting ropes. The principal axis of the rhombic was tilted in declination every few days to keep the Sun in the main lobe of the aerial. At night the aerial was lowered onto the supporting trestle shown in the bottom right-hand corner of Figure 11 (Murray, pers. comm., 2007).

Figure 10 Raising the rhombic aerial. The main spar of the aerial is pointing north with the polar mount at its base; Keith MacAlister kneeling (Courtesy ATNF photographic archive).

Figure 11 Photograph of the aerial and pulley system and Bill Rowe. In the background on the RHS, can be seen the railway locomotive shunting sheds. The three equipment trailers to the south of the aerial are now under cover. John Murray is up the pole (Courtesy ATNF photographic archive).

2.2.3 The Receiving System

Wild and McCready (1950: 390) described the receiving systems along the following lines:

> The receiver was of conventional superheterodyne design with a single stage of radio-frequency amplification. The local oscillator and the input circuits of the radio-frequency amplifier and the mixer were tuned by 'slit-stator' condensers on a single shaft which was rotated by a motor at about three revolutions per second [see example in Figure 17 below]. By using split-stator condensers, the need for making electrical contacts with rotating shafts was avoided.

Such contacts invariably lead to noisy performance. The intermediate-amplifier operated at 10 MHz with a bandwidth of 300 kHz. The signal was then detected, amplified and fed to the 'y-plate' of the cathode ray tube for display.

From what I can gather (Murray, pers. comm., 2007) the tuning condensers each worked on the principle of a parallel plate *butterfly* condenser whose capacity was varied by changing the area between the plates much like the way early radios were tuned. One plate was attached to the rotor and as it rotated the area inside the other plate varied with time. The capacitor was part of an LC tuning circuit which provided the local oscillator signal to the mixer.

2.2.4 The Display

The amplified receiver output was applied to the Y-plates of a 5 inch cathode ray tube. The frequency sweep was controlled by a variable condenser, coupled to the tuning shaft. An AC voltage was applied across a high resistance, in series with a quarter-wave transmission line terminated by the condenser. As the tuning shaft rotated the capacitance and its impedance varied producing a variable voltage across the terminals of the transmission line (Fig. 3 of Wild and McCready, 1950). This voltage was rectified and applied to the X-plate of the cathode ray tube, thus producing the required frequency sweep.

The display on the screen was a graph of receiver output (vertically) versus frequency (horizontally) as shown in Figure 12. This 'A-scan' was photographed with a hand- held Zeiss 16 mm movie camera, which meant that during times of solar activity the equipment hut was kept in darkness (Murray, pers. comm., 2007).

2.2.5 Presentation of Results

Records of solar bursts were obtained during 264 hours of observing at Penrith from February to June 1949. The observers were Wild and Rowe helped from time to time by Murray. The display was watched continuously and when a burst occurred the A-scan was photographed by a cine-camera. Each scan lasted about one third of a second. Time was recorded using a counter. Examples of recorded scans are shown in Figure 12.

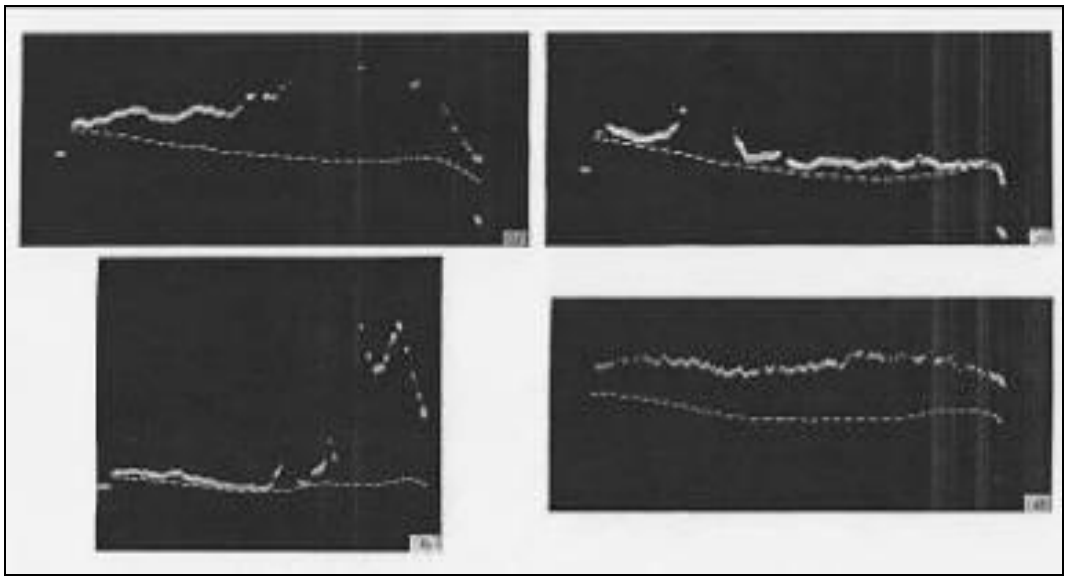


Figure 12 Examples of the display scans (after Wild and McCready, 1950: Plate I).

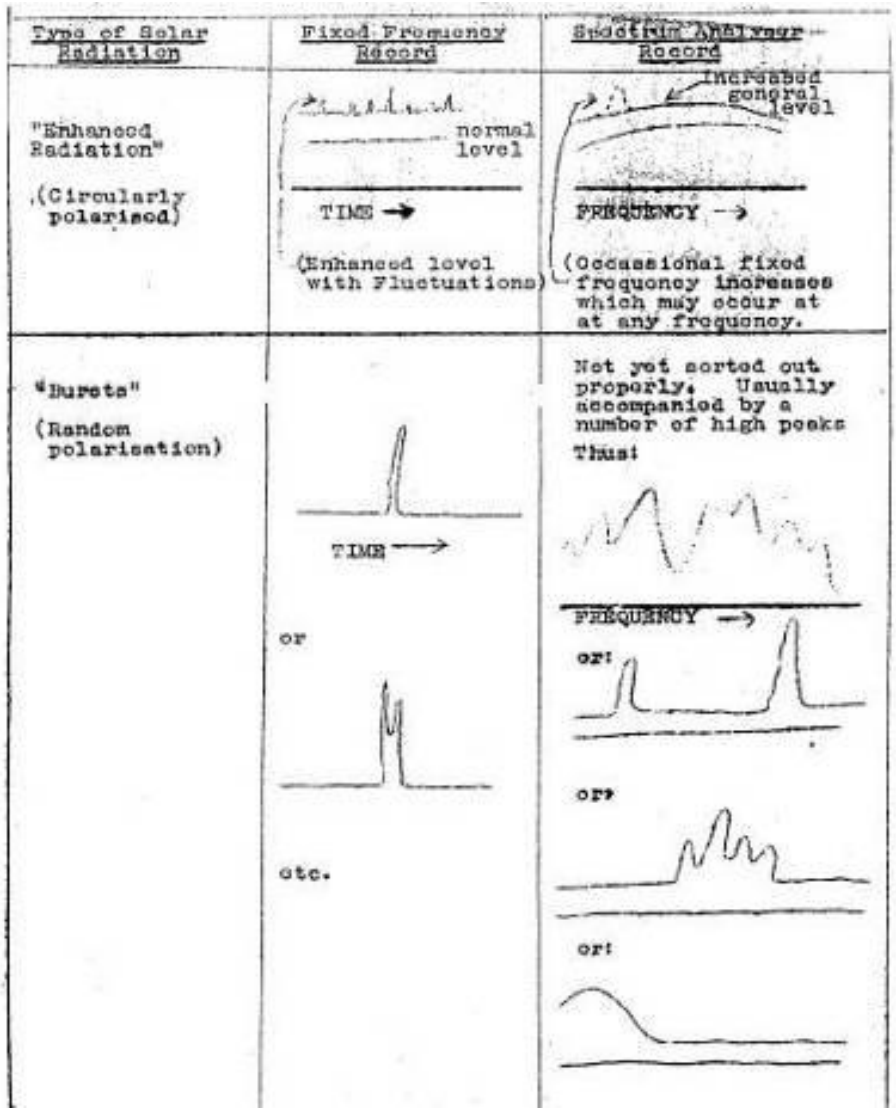
2.2.6 Reports on Progress of Observations during 1949

Wild reported to the Propagation Committee Meeting on 7th March, 1949 (National Archives, 2007) that solar activity had been recorded at Penrith during 3 days in February. He noted that:

> In order to correlate these observations with existing ideas on solar radiation it is desirable to know the type of polarization of each phenomenon. This is not possible with existing equipment. It was possible, however, to get an indication by comparison with the fixed frequency records of Miss Payne-Scott taken at that time [at Hornsby Valley Field Station]. The correlation between the well known fixed-frequency Type of record and the spectrum-analyser record seems to be as follows:

TABLE 2

COMPARISON OF SPECTRAL AND SINGLE FREQUENCY RECORDS



Then on the 7th July, 1949 McCready and Wild reported to the Radio Astronomy Committee (National Archives, 2007) that:

(a) Two Types of unpolarised bursts have been noted. “Moving” bursts in which the frequency for maximum amplitude decreases to one half in an interval of about five seconds.

(b) Non-moving bursts in which a sharp cut-off with frequency is often found. Outbursts show a very slow drift in frequency with time.

It also was noted that Steve Smerd should join McCready and Wild's team.

On 17th November, 1949 Wild reported to the Radio Astronomy Committee (National Archives, 2007):

> Work on the spectrum of bursts has been written up. An analysis has been made of bursts which appear during enhanced radiation. These bursts are usually of narrow bandwidth and at frequencies around 59 Mc/s. The design of a larger and better spectrum analyser is being considered.

2.3 Preliminary Results: First Spectral Classification of Solar Bursts into Three Distinct Types

The photographic records (such as shown in Figure 12) were converted into time-frequency diagrams for analysis. The intensity contours were plotted on a logarithmic scale. In a subsequent paper Wild (1950a) referred to these diagrams as *dynamic spectra* because they showed variations in intensity with time. Paul Wild told me once that he used his time travelling on the train each day from Penrith to reduce the data by hand.

The most outstanding result from this ground-breaking investigation was the ability to recognize distinctly different types of solar bursts from their spectral characteristics. According to Wild and McCready (1950), the dynamic spectra of the observed bursts were often complicated with widely different features but analysis showed that many conformed to one of three specific spectral types which were named *Type I, II and III.* Typical examples of each type were shown in Plate 2 of Wild and McCready (1950) and are reproduced here as Figure 13.

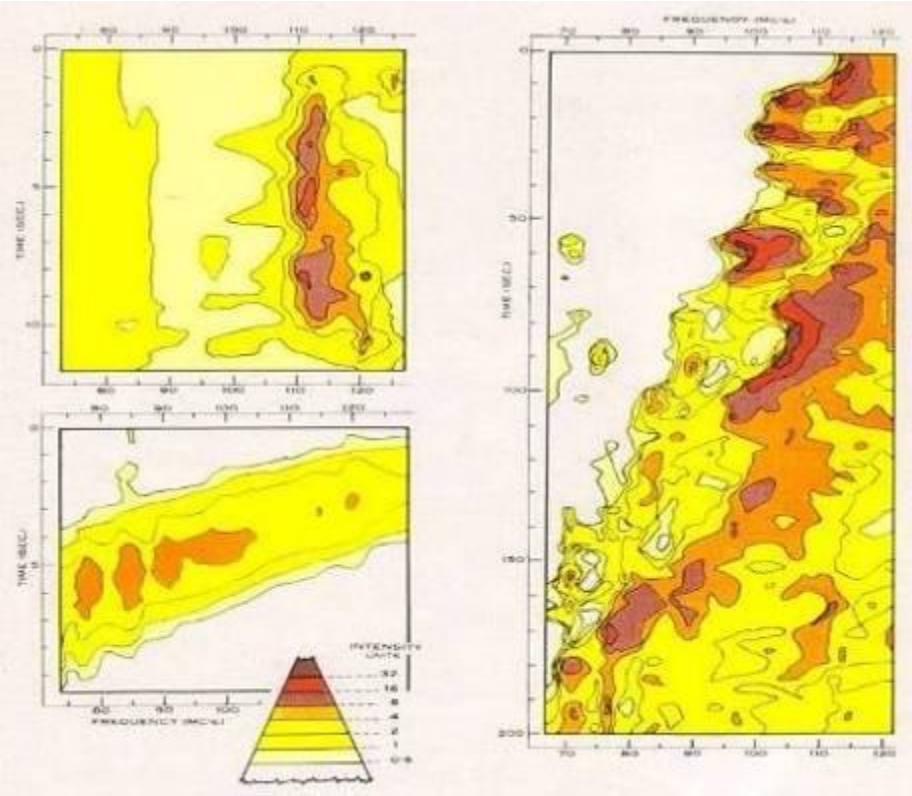


Figure 13 Time-frequency diagrams or 'dynamic spectra' of spectral Type I, II and III bursts (after Wild and McCready, 1950: Plate 2a, 2b and 2c).

2.3.1 Spectral Type I Bursts

Wild and McCready (1950: 393) wrote:

> Plate 2a is typical of bursts which occurred in hundreds during restricted periods, called "noise storms" by Allen [1947b]. Such periods usually last for hours, or even days, and were marked by a high, slowly-varying background continuum above which the bursts appeared. Bursts of this type rarely occurred as isolated phenomena. The type is characterized by its narrow spectrum, a few megacycles per second wide. The lifetime of the bursts is sometimes less than one second and sometimes as long as 20 seconds.

These storm bursts were the predominate type of activity observed at Penrith during the operation of the spectrograph. Other bursts occurred occasionally either singly or in small groups.

2.3.2 Spectral Type II Bursts

According to Wild and McCready (1950: 393):

> Plate 2b illustrates a type of burst of comparatively rare occurrence. In this Type, the spectrum at any instant near the start shows a distinct "cut-off" in frequency, little or no radiation being received at frequencies immediately below a critical frequency. The critical frequency varies with time and, on the average, drifts gradually towards the lower frequencies at a rate of ¾ (Mc/s.) sec.$^{-1}$ The bursts last for several minutes. Of five such bursts observed, three coincided with a large solar flare or sudden short-wave communication fade-out.

2.3.3 Spectral Type III Bursts

Again, according to Wild and McCready (1950: 394)

> In this type, illustrated in plate 2c, the frequency of maximum intensity drifts rapidly (at a rate of the order of 20 (Mc/s/sec^{-1}) towards the lower frequencies. The bandwidth of these bursts at any instant is not usually less than about 50 Mc/s. They last for a few seconds.

More information on the Penrith results are given in Chapter 3 where the publications by Wild (1950a, b and 1951) are reviewed in detail. The outstanding success of the Penrith spectrograph led to the immediate development of a much improved instrument described below.

2.4 The Dapto Radiospectrograph 1952

2.4.1 The Development Stage 1950-51

In a meeting of the Radiophysics Radio Astronomy Committee on 27 July 1950 the following minutes were recorded by Christiansen acting as secretary with Pawsey in the chair. (Courtesy of Miller Goss, pers. comm., 2008; from the late Don Yabsley's notes):

> Mr.Wild. The new model spectrum analyser (35-240 Mc/s) is under construction. Four papers have been written on solar spectroscopy in the range 70-130 Mc/s. Two papers have been accepted by the Aust.J.Sci.Res. and a third has been sent off. Some particular conclusions of these papers are:-
>
> 1. The spectrum of flare-accompanying 'outbursts' supports the hypothesis of an outward-moving disturbance in the solar atmosphere.
> 2. The frequency drift observed in some of the short duration 'isolated bursts' cannot be explained solely on the basis of group retardation from a fixed transient disturbance, but may be due to an outward-moving disturbance (~ $3x\ 10^{4}$ km/s.)
> 3. The background continuum, present during noise storms may be explained in terms of the resultant of a large number of 'storm bursts' if a plausible amplitude distribution is secured.

During the discussion on this report the use of the term *isolated burst* was responsible for an *outburst* from Miss Payne-Scott. This was obviously meant as a pun by Chris Christiansen but it is not clear from his minutes what Ruby's objections were. However, in her 1949 paper (Payne-Scott, 1949) Ruby had used the term *unpolarized* burst rather than the earlier term *isolated* burst, in describing the data she collected at Hornsby Valley Field Station in 1948, and had pointed out that the time delays might be due to an outward-moving source, although she favoured a group retardation explanation; a fact that Wild had failed to acknowledge.

Immediately after spectrograph observations ceased at Penrith in late 1949 John Murray and Bill Rowe were given the task of redesigning and extending the radio receiver, while

McAlister supervised the construction of three motor driven (wooden) aerials to cover the three new frequency bands (Murray, pers. comm., 2007).

Gordon Stanley (1994: 511). recalls a trip to the south coast from Sydney searching for suitable radio astronomy sites for the new spectrograph and a large interferometer that he and John Bolton were keen to build for radio source observations. He writes:

> Paul Wild invited me to join him on a trip down the south coast of New South Wales in September 1950, as he was looking for a new site for a solar telescope. We borrowed an old ambulance from the military and Paul, John Murray, Steve Smerd and I, as the only driver set off on our missions. The trip is an epic story in itself and full of the unexpected problems peculiar to neglected army vehicles. Following a major breakdown, Paul and Steve left us at Berry whilst John Murray and I travelled down the coast, close to the Victorian border. I chose a site at Jervis Bay and although it was never used, the idea of the interferometer was the genesis of the one built at Owens Valley in California.

On the 11th June 1951 the "Wollongong Times reported under the title:

> "RADAR EXPERIMENTAL STATION AT DAPTO WEST"
>
> "Part of the land at West Dapto which Council proposed to resume for a sanitary depot had been acquired for use for radar experiments, Ald. H.A Graham told Greater Wollongong Council last Wednesday night."

The article went on to include earlier questions from councillors such as:

> Is council aware that the Commonwealth Scientific and Industrial Research organization has resumed 80 acres in that area and s going ahead with further development of the land in connection with radar research?.....
> Is Council aware that this land was once used as a piggery and that the Health Department served notices on the owner that it had to be closed owing to contamination of the creeks running into Lake Illawarra?

Thus began in less than salubrious fashion the birth of the Dapto field station.

2.4.2 The Dapto Field Station

The site chosen (see Appendix I for letter from Wild to Pawsey dated 26 January 1951, also letter from McCready to Pawsey regarding the "bitch" of an FM radio transmitter in north Sydney dated 6 July 1948), part of a McLeod's dairy farm at Dapto, about 50 miles south of Sydney and shielded from radio interference from Sydney's transmitters by the Mt. Kembla range, can be seen in the photograph of Figure 14. Later, Wollongong TV stations would create a problem in the 140 – 240 MHz band.

Figure 14 Colour photograph of the site of the Dapto spectrograph showing the observatory hut, the three crossed rhombic aerial against the backdrop of the Mt. Kembla range (Courtesy of ATNF photographic archive).

2.4.3 Outline of Dapto Radiospectrograph

A block diagram of the instrument described by Wild, Murray and Rowe (1954) is reproduced in Figure 15. The spectrograph contained three receiving units operating over the frequency bands of 40 to 75 MHz, 75 to 140 MHz and 140 to 240 MHz respectively.

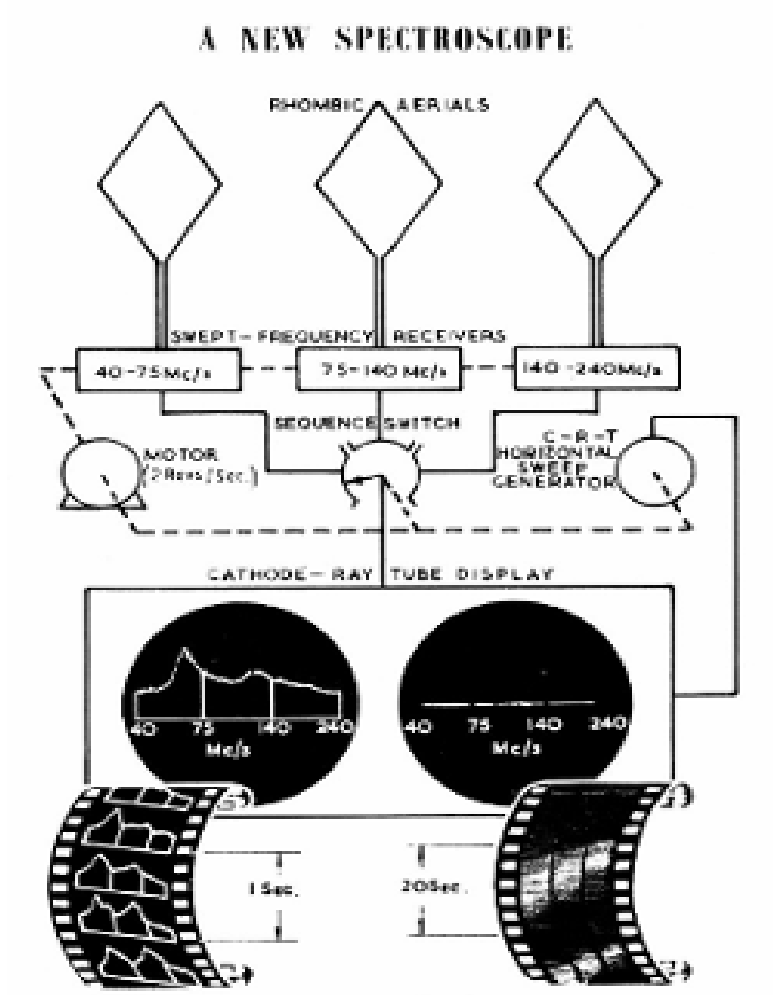


Figure 15 Block diagram of the Dapto radiospectrograph excluding polarization arrangements (after Wild, Murray and Rowe, 1954: Fig. 1).

2.4.4 The Aerials

The wooden aerials (red in Figure 16) were equatorially mounted and motor driven remotely to follow the Sun. By using two linearly-polarized rhombics at right angles, this allowed for the possibility of measuring the polarization as well as the intensity of the incoming radiation. MacAlister supervised the mechanical design and installation of the aerials which were motor driven from within the equipment hut (Figure 16).

Figure 16 Colour photograph of the three crossed rhombic aerials on their mounting towers (Courtesy of ATNF photographic archive).

2.4.5 The Receivers

Each of the three units consisted of a broadband linearly polarized aerial connected to a receiver, similar to one used in the earlier Penrith spectrograph (described in Section 2.2.2). Each receiver was tuned in succession by continuously rotating "butterfly" condensers connected to a common shaft driven by a motor at 2 r.p.s. Three tuning condensers belonging to one of the receivers can be seen clearly in the photographs of Figure 17. The three condensers were used to tune the RF amplifier, mixer and local oscillator stages. Bill Rowe and John Murray designed and maintained the receivers and displays.

Note there was provision for a duplicate receiving system for polarization measurements, but due to the difficulty of matching receivers and the unavailability of broadband phase switches at that time, the second channel was not used (Murray pers. communication). Instead, an alternative method for polarization studies was developed by Komesaroff (1958) and described below in Section 2.6.

Each of the three frequency ranges was swept in one-quarter of a revolution, the complete range in three-quarters. Thus a complete radio spectrum was swept out in 3/8 sec. and two complete spectra were obtained each second.

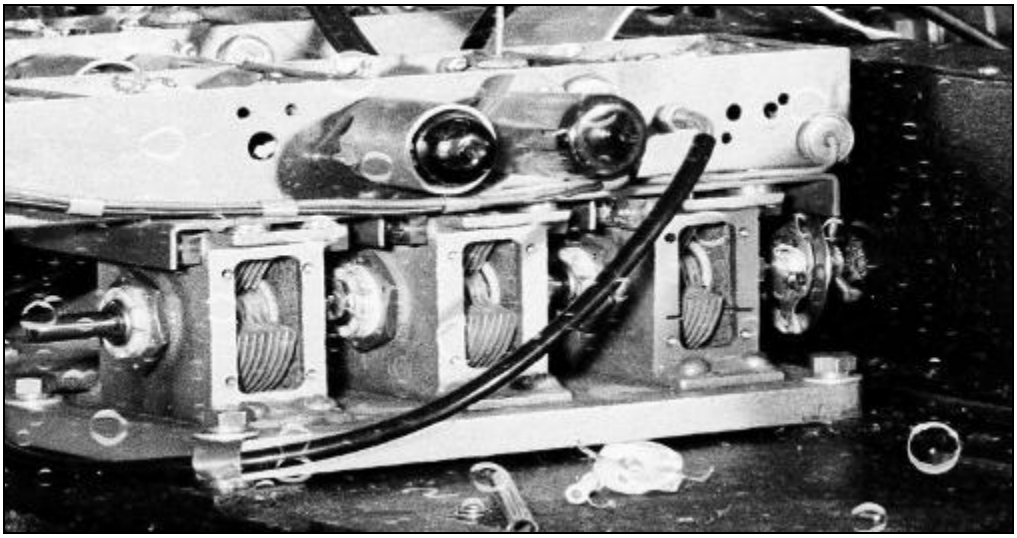


Figure 17 Photograph showing one set of the three tuning condensers in each spectrograph receiver, connected to a common, motor-driven shaft (Courtesy of ATNF photographic archive).

2.4.6 The Displays

The three units had their outputs connected to common displays. John Murray was responsible for the design and maintenance of the display system shown below in Figure 18.

One of the displays was similar to that used at Penrith and corresponded to the "A scan" of radar sets (LH cartoon of Figure 15 and also RH display of Figure 18). In this display frequency is plotted along the horizontal axis and intensity along the vertical. Such an arrangement was suitable for precise measurement of intensity but suffered from the disadvantages that (1) the rate of film consumption was excessive for continuous operation and (2) the process of reducing records to a useful form was too laborious for handling excessive data.

For continuous operation a second display was used. Here frequency was again displayed horizontally but the received intensity was shown by modulating the intensity of the cathode ray tube beam spot as it scanned across the screen. Using Ilford HP3 film a logarithmic display of

intensities over a 1000:1 range could be obtained. A film rate of 1 in/min or 120 scans per inch was sufficient to record data with no overlap of successive scans.

Figure 18 Photograph of Paul Wild (above left) and John Murray adjusting one of the two display units of the Dapto radiospectrograph (Courtesy of ATNF photographic archive).

2.4.7 Calibration

Frequency calibration was provided by injecting into the receivers signals from a standard signal generator at frequency intervals of 5 or 10 MHz.

Intensity calibration was provided by switching on temperature-limited noise diodes which were permanently connected across the aerial terminals of each receiver. This had the advantage that the diode formed part of the tuned circuit of the receiver and secondly, that

calibration could be obtained with the aerial pointing towards the Sun thus enabling the measurement of excess power above cosmic noise.

Time marks were obtained by photographing a clock beside the display which was illuminated by a flash at 1-min intervals.

2.4.8 Initial Results

Solar observations were commenced in August 1952 over the frequency range 40-140 MHz, and in November 1952 over the complete range from 40-240 MHz. The observations in the present paper cover the period August 1952 to August 1953.

The equipment was operated for about 1000 hr during the year, preference being given to periods of sunspot activity. John Murray (pers. communication) usually attended observations from Monday to Friday, Paul Wild from Tuesday to Thursday and Bill Rowe from Thursday to Monday. John was fortunate to be the first to observe a harmonic Type II burst. He is of the opinion that harmonic bursts were recorded at Penrith in 1949 but missed identification because of the restricted frequency range of the equipment. More detailed information on the observations is given in Chapter 3. Examples of the first identified harmonic Type II bursts recorded by the spectrograph on 21 November 1952 is shown in figure 19(a) and a harmonic Type III burst recorded on 5 June 1953 in Figure 19(b). These observations were very significant as they strongly supported the “plasma hypothesis” proposed earlier by Wild (1950a) (See Chapter 3 for details).

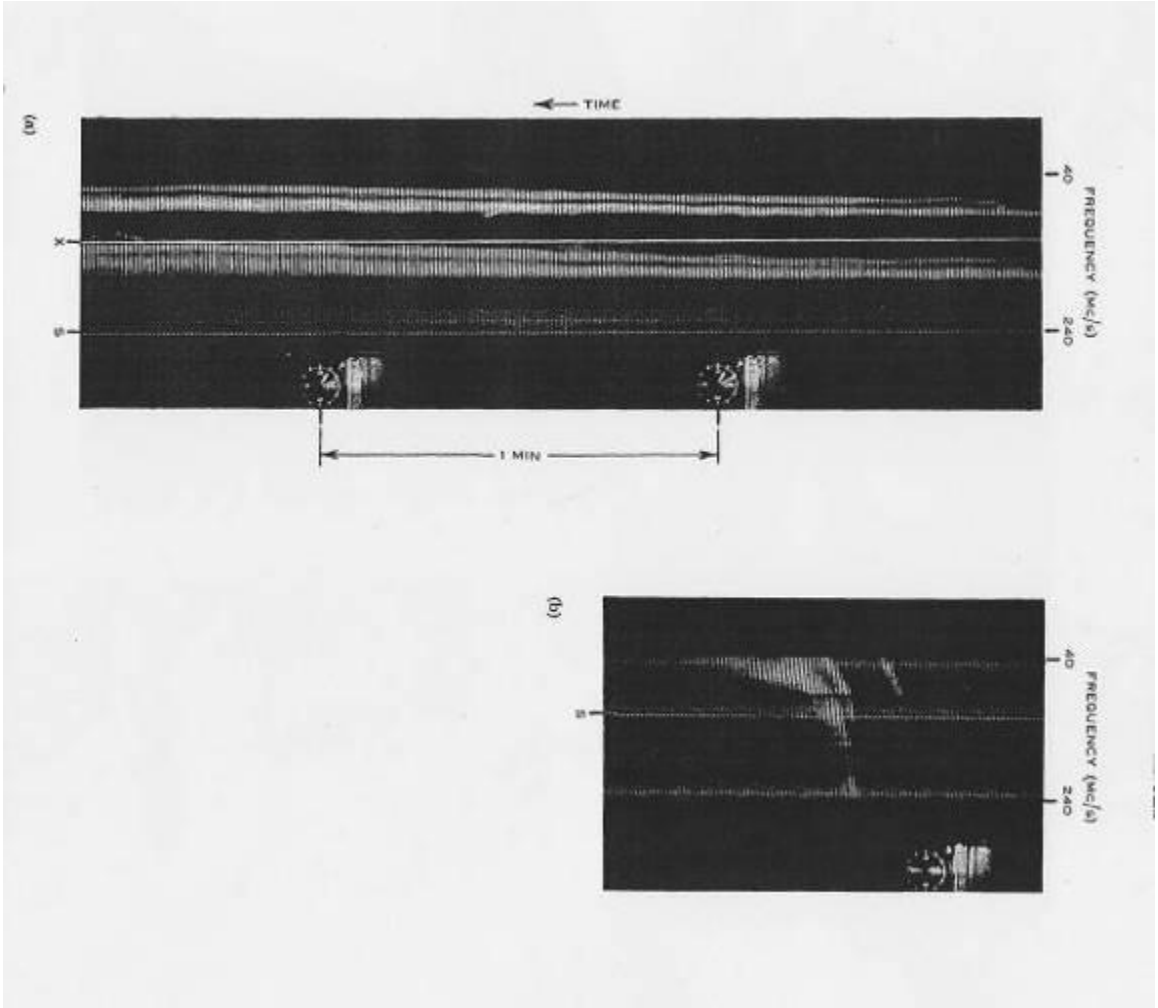


Figure 19 (a) Intensity-modulated record of the first identified fundamental and second harmonic Type II burst recorded on 1952 November 21 at 2350 UT (b) Harmonic Type III burst recorded on 1953 June 5 at 0132 UT (after Wild, Murray and Rowe, 1954b: Plate I).

Soon after these outstanding observations were taken Bill Rowe became sick and died of leukaemia, suspected to have been caused by his work in the high voltage laboratory during the war. Paul Wild was able to help Bill's wife received compensation from CSIRO (John Murray, pers. comm. 2007). John left the solar group to work on H-line receivers and was replaced by Jim Roberts and Max Komesaroff, who regularly visited from Sydney. Jack Joisce, who lived locally, was hired to assist with the daily running of the equipment.

2.5 Radio Scintillations Studies at Dapto 1952-54

2.5.1 Introduction

On 17 April 1953 Paul Wild submitted a report to Joe Pawsey, Lindsay McCready and Taffy Bowen on "Investigation of Cygnus Fluctuations at Dapto" (Commonwealth Archives) in which he wrote:

> Although the main long-term programme of work at Dapto is concerned with the sun, it has seemed desirable to find a supplementary line of research to enable the equipment to be put to maximum use during the sunspot minimum. With this in view, exploratory observations of the spectrum of Cygnus fluctuations in the frequency range 40-70 Mc/s have been carried out since September 1952.These observations and conclusions are summarized below:
>
> a. Records show intense ridges
>
> b. Records apparently showing interference patterns
>
> During the approaching winter period in which Cygnus fluctuations reach a maximum (say June to August inclusive), it is proposed to carry out an intensive programme of observations. Subsequently observations may be continued, but at less pressure, to January 1954 so as to include the summer maximum. It may then be appropriate to wind up the investigation completely. For this programme the following extensions are proposed.
>
> (1) Observation of the spectrum at 3 locations on the ground, arranged in a triangle with sides of the order of 0.5 to 1 Km.
>
> (2) Continuous observations of the apparent position of the source in an approx. E-W line, as a function of frequency using a swept-frequency interferometer.
>
> (3) Observations, at a fixed frequency, from a mobile station.

Later, (Wild and Roberts, 1956a: 56) showed that the introduction of spectral records led to a remarkable simplification in the interpretation of scintillations, which previously had been made at discrete frequencies only, and noted that:

The complete specification of a diffraction pattern on the ground requires measurement of both intensity and phase as functions of frequency and position on the ground. With these considerations in view, apparatus was built to record radio-star scintillations simultaneously in the following three ways:

(1) The recording of intensity at one point as a function of time and frequency, using a 40-70 Mc/s spectroscope.

(2) The recording of the phase gradient along one direction as a function of time and frequency, using a 40-70 Mc/s "swept-frequency interferometer."

(3) The recording of intensity at a fixed frequency (45 Mc/s) as a function of time at three points on the ground, arranged at the corners of an approximate equilateral triangle.

Since variations with time are due mainly to the motion of the diffraction pattern across the ground (a result confirmed by the present observations), the temporal variations in (1) and (2) can be expressed in terms of spatial variations by using the drift velocity deduced from (3).

The three instruments are illustrated in Figure 20. John Murray and Bill Rowe were involved with the instrumental development and installation while Jack Joisce, Max Komesaroff, Govind Swarup (during a visit from India) and Jim Roberts assisted with the observations (see Appendix II for Jim's recollections of this period).

2.5.2 Instrument No. 1: The modified Spectroscope

The spectroscope consisted of a broad-band aerial connected to a tuneable receiver which was part of the original Dapto spectrograph receiver described above. The aerial (as well as the other two aerials mentioned below) was a fixed horizontal rhombic arranged for maximum acceptance from the north with dimensions as follows:

Length of each side …… 31.1 m
Angle between wires at side corners……..148 ^{o}
Height from ground…….4.2 m

Apparently, these dimensions give approximately the optimum gain obtainable with a horizontal rhombic aerial for reception at an altitude of 15 ^{o} at 40 Mc/s and 70 Mc/s (Bruce, Beck

and Lowry, 1935). The aerial was connected to the receiver by means of 700-ohm open-wire transmission line.

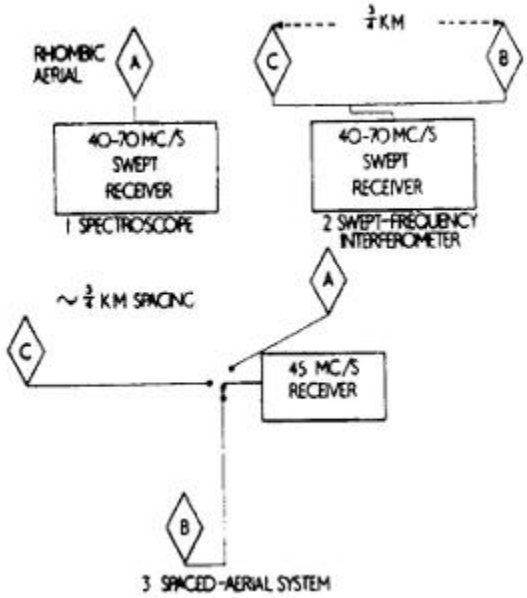


Figure 20 Principles of the three instruments used for observing radio-star scintillations (after Wild and Roberts, 1956a: Fig.5).

2.5.3 Instrument No. 2: The Experimental Swept-Frequency Interferometer

This was the first time a swept-frequency interferometer was used in radio astronomy. It was highly experimental and led to the development of the first working swept-frequency interferometer installed at Dapto in 1957 (Wild and Sheridan, 1958) which is discussed below in Section 2.7.

The two rhombic aerials (B and C of Figure 20) were located ¾ km apart on a baseline 118.5^{o} E of N (i.e. approximately east-west) and connected to the 40-70 MHz spectrograph receiver by 700-ohm transmission line. The aerial spacing was such that the angular separation of adjacent lobes was 33’ (minutes of arc) at 40 MHz and 19’ at 70 MHz allowing angular deviations of about one-fifth of a lobe-width to be recognized, giving a positional accuracy of about 4’ at 70 MHz. By varying the length of each aerial path the source could be observed in higher-order fringes near transit. Sudden changes in source position could then be seen as kinks in the lines of maximum intensity in the interference pattern.

An important advantage of using a swept-frequency interferometer rather than a single frequency one was that directional data could be obtained at a number of frequencies simultaneously. By using higher order fringes sudden movements in the source pattern could be observed across the 40-70 MHz frequency band as shown in the examples of Figure 21b.

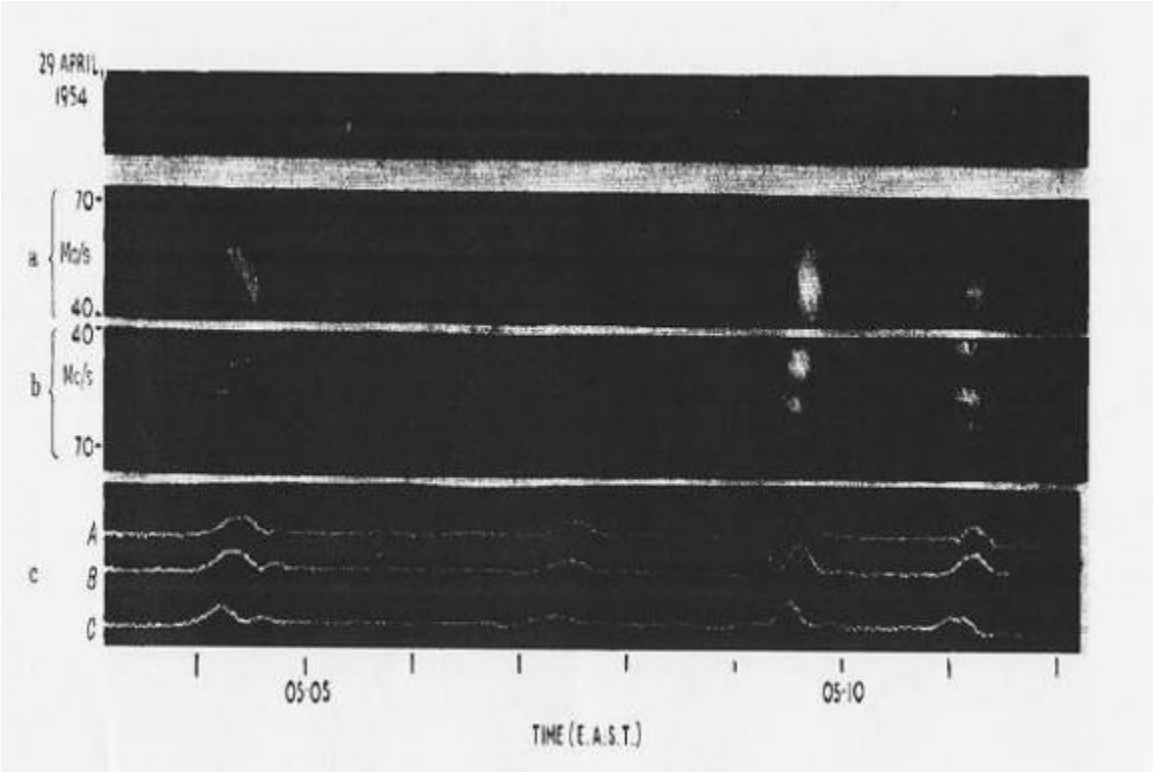


Figure 21 Complete record of ridge-type scintillations recorded on 29 April 1954. (a) The dynamic spectrum. (b) The swept-frequency interferometer pattern. (c) 45 MHz records with the spaced-aerial system showing systematic time delays (after Wild and Roberts, 1956a: Fig. 3).

2.5.4 Instrument No. 3: The Spaced-Aerial System

For measuring the scale size and movement of the diffraction pattern on the ground, the intensity was recorded almost simultaneously at three corner points of an equilateral triangle with sides of ¾ km. The three aerials (A, B and C of Figure 20) were connected to a 40-70 MHz swept-frequency receiver by long lengths of open-wire and the resulting signals displayed on a common cathode-ray tube once per second.

At first the whole spectrum at A, B and C was recorded but because similar features showed time-delays that were independent of frequency it was decided to record only at 45 MHz.

2.5.5 The Combined Operation of the Three Instruments

To accommodate these additions modifications were made to the motor and gearbox driving the tuning condensers of the 40-70 MHz receiver and to the two displays of the Dapto spectrograph (John Murray pers. comm., 2007). The sequence of switching for the aerial signals to the receiver was as follows:

(1) 0 to 1/8 second----Aerials B and C in combination to form an interferometer.
(2) 1/8 to ¼ second----Aerial A only.
(3) ½ to 5/8 second---Aerial B only.
(4) 5/8 to ¾ second---Aerial C only.

The receiver swept from 70 to 40 MHz during sub-periods 1 and 3, and from 40 to 70 MHz during sub-periods 2 and 4. The information was displayed on two cathode-ray tubes before being photographed.

(1) An intensity-modulated display in which the spectra of sub-periods 1 and 3 were displayed side by side in the X-direction.
(2) A display in which the signal obtained during sub-periods 2, 3 and 4 were displayed as a spot only when the tuning reached 45 MHz. Each spot was separated in the x-direction for zero output and then deflected by an amount proportional to the intensity of the signal.

Detailed information on results and interpretation are given in Chapter 3.

2.6 Polarization Studies of Solar Bursts over the 40-70 MHz Range 1955

The polarization measurements were conducted by Komesaroff using the Dapto spectrograph mainly from January to October 1955 near the start of the new solar cycle. According to John Murray (private communication, 2007) the polarization equipment was available since 1953 but the absence of burst activity prevented any study occurring an earlier. Observations included Type I bursts, Type II bursts and Type III bursts.

A preliminary account of the results of this investigation was presented in 1955 by Wild (1957) at the I.A.U. Symposium on Radio Astronomy held at Jodrell Bank. U.K. The final results were not published until 1958.

2.6.1 The Swept-Frequency Polarimeter

Komesaroff (1958: 202) wrote:

The method of polarization measurement is a variant on the crossed-aerial technique, adapted to a swept-frequency instrument. Each of the three pairs of rhombic aerials has a corresponding receiver and the individual aerials of each pair were connected to the common receiver by twin-wire transmission lines of different lengths [as shown in Figure 22]. If ΔL is the difference in line length, the system accepts one circularly polarized component when the receiver is tuned to a wavelength L such that ΔL = (2n+- ¼) λ, where n is an integer, the sign being determined by the sense of rotation of the electric vector. As the receiver tuning is varied the output goes through a series of maxima and minima. The differences in length ΔL of the pairs of feeders are measured by a standing wave technique. Each line is short-circuited at the aerial end and fed by a signal generator at the receiver end. The approximate length being known, the exact length is determined from the positions of the standing wave minima near the receiver, the determination being carried out at a number of frequencies.

The following equations apply

$$\Delta L = (2n+- ¼)\ \lambda \qquad (11)$$

phase angle of the polarization ellipse

$$\theta = 2\pi(n-f_n/\Delta f) \qquad (12)$$

and

$$\Delta f = c/\ \Delta L \qquad (13)$$

where c is the velocity of light.

For LH circular polarization $\theta = \pi/2$ and for RH polarization $\theta = 3\pi/2$.

The degree of circular polarization

$$\%\ circ = 100\ (P_{max} - P_{min})\ /\ (P_{max} + P_{min}) \qquad (14)$$

is given by the modulation pattern of the power spectrum where P_{max} and P_{min} are indicated in Figure 23.

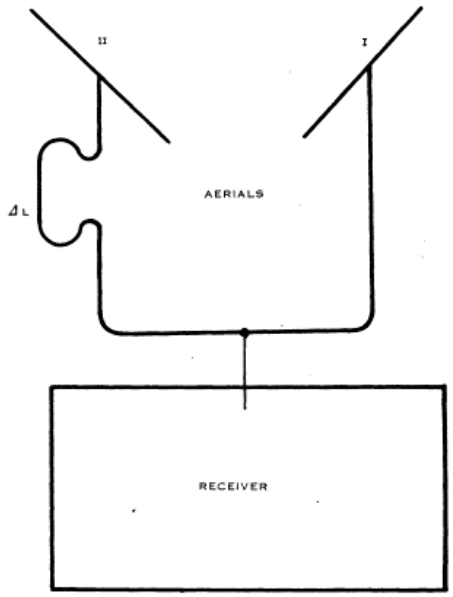


Figure 22 Block diagram of the Dapto swept-frequency polarimeter. One unit of this Type was used for each of the three frequency ranges of the Dapto spectrograph (after Komesaroff, 1958: Fig.1).

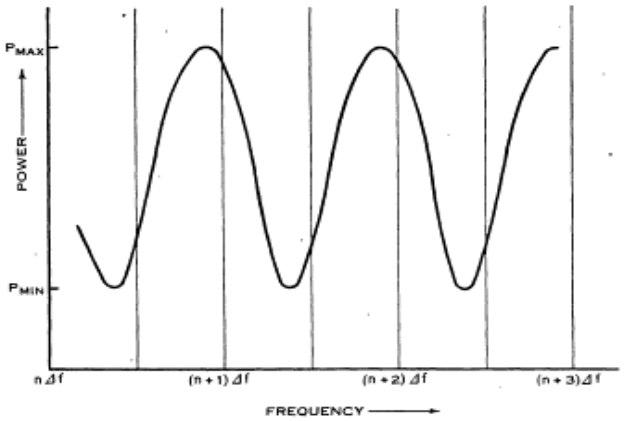


Figure 23 Schematic representation of a record of polarized radiation having a flat spectrum (after Komesaroff, 1958: Fig. 2).

The important results of Komesaroff's investigations are discussed in detail in Chapter 3. Briefly Max was able to confirm the earlier single frequency observations which showed that Type I bursts were highly polarized in the circular sense. He also made the important discovery that some Type III bursts also showed a degree of circular polarization and were not, as previously thought, completely unpolarized.

2.7 The Dapto Swept-frequency Interferometer 1957-58

2.7.1 The Principle of the Interferometer

The principle of the interferometer is illustrated in Figure 24 and first trialled in 1955 for radio scintillation studies (Section 2.5). In 1957 an improved version was installed at Dapto for regular solar observations (Wild and Sheridan, 1958). Radio waves incident at an angle θ with the normal travel through the antennas along paths which differ by $a sin\theta + l$, where a is the spacing between antennas and l is the extra feeder length in one side.

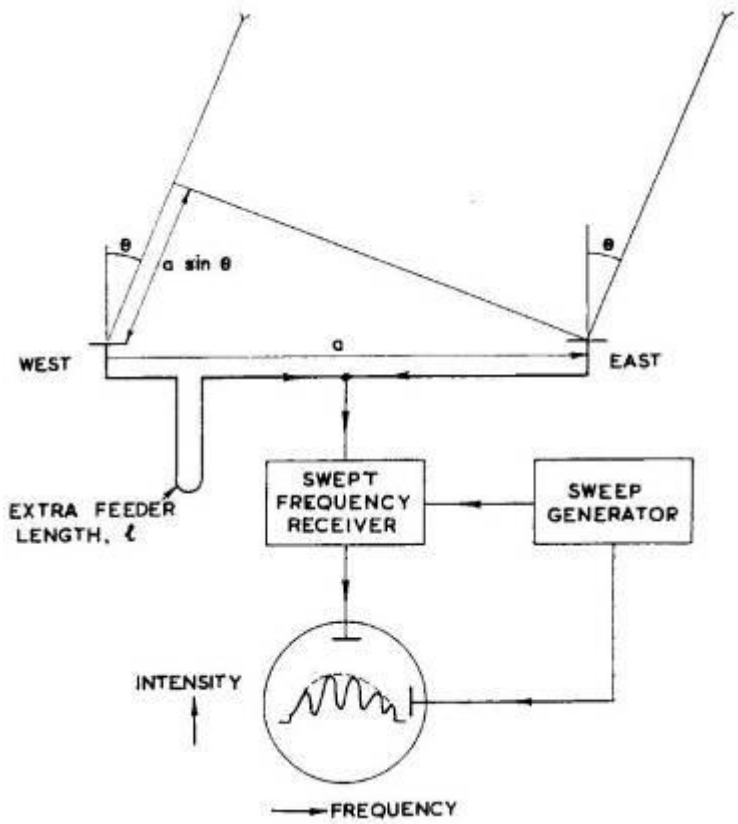


Figure 24 Block diagram of the Dapto swept-frequency interferometer (after Wild and Sheridan 1958: Fig. 1).

The interfering signals are received in a swept-frequency receiver and displayed on a cathode-ray tube which traces the pattern of intensity versus frequency. The pattern is just the spectrum of the source modulated with an interference pattern having maxima for which

$$a\ sin\theta + l = n\ \lambda \qquad (15)$$

and minima for which

$$a \sin\theta + l = (n + 1/2)\,\lambda \qquad (16)$$

where n is an integer If all frequencies arrive from the same direction, such maxima occur at equal intervals, Δf, in the frequency scale, given by

$$\Delta f = c / (a \sin\theta + l)\ (\theta < \pi) \qquad (17)$$

where c is the velocity of light. The value of Δf can be adjusted to any desired value by varying the length of the variable line *l*. If the spacing between maxima in the interference pattern becomes too large, the interference pattern is liable to become confused with the envelope of the natural spectrum; if too small the interference pattern would become blurred by the finite bandwidth (0.5 MHz) of the receiver. In practice, a value of $\Delta f \sim 5$ *MHz* was found to be most suitable. This requires the difference in path length to the two antennas to be approximately 60 m. The Dapto interferometer was designed to operate +- 2 hr from noon, during which time the rotation of the earth causes the path length difference to vary by about +- 480 m. The path length is compensated by a variable line, consisting of 5 loops of open-wire line of length 15, 30, 60, 120 and 240m, which are automatically inserted in the feeder line and adjusted to the correct length to keep $l \sim 60$m.

For source size measurements an *adding* interferometer was used. However, for precise position measurements a *multiplying interferometer* was used to eliminate background radiation and degrading effects due to finite source size and emission bandwidth. Figure 25b shows the sort of pattern that is observed for a partly resolved source by a multiplying interferometer.

The phase of the pattern and hence the direction of the position of the source can be accurately measured using the points at which the pattern crosses the zero line; this is contrasted with the adding interferometer pattern shown in Figure 25a which can be used to measure source size. Both Types were used at Dapto and automatically switched between each Type during alternate 1/2 seconds when the frequency was swept from 40 60 70 MHz. For polarization measurements the two spaced rhombic antennas were replaced by a single rhombic with orthogonal planes of polarization similar to the method employed by Komesaroff (1958) and described above in Section 2.6.

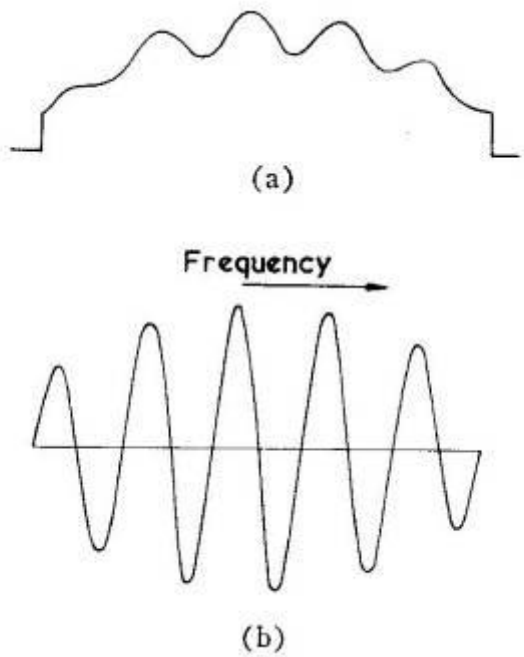


Figure 25 Characteristic patterns of intensity (vertical) versus frequency obtained with (a) an adding interferometer and (b) a multiplying interferometer (after Wild, Sheridan and Trent, 1958: Fig. 2).

2.7.2 The Adding Interferometer

A block diagram of the *adding interferometer* is shown in Figure 26. Wild and Sheridan (1958: 162) wrote:

> For source size measurements the signals are received in two identical broadband, wide beam antennas spaced 1 km apart on an east-west baseline. Connection to the receiver is made by long feeder lines, one of which includes a section capable of being varied from 0 to 480 m in steps of 15m. The signals are combined in a simple junction, detected by a 40-70 MHz swept-frequency receiver and displayed on a cathode ray tube. The receiver is swept at 2 revolutions per second with an operative period of 1/8 second and recorded photographically (in a manner similar to the Dapto radiospectrograph described in section 2.3). Facilities are provided for injecting standard power levels from a noise generator and frequency markers from a harmonic crystal generator. In practice, the most suitable interferometer pattern spacing is found to be $\Delta f \sim 5$

MHz, which requires the path-length difference from the source to the receiver to be approximately 60 m.

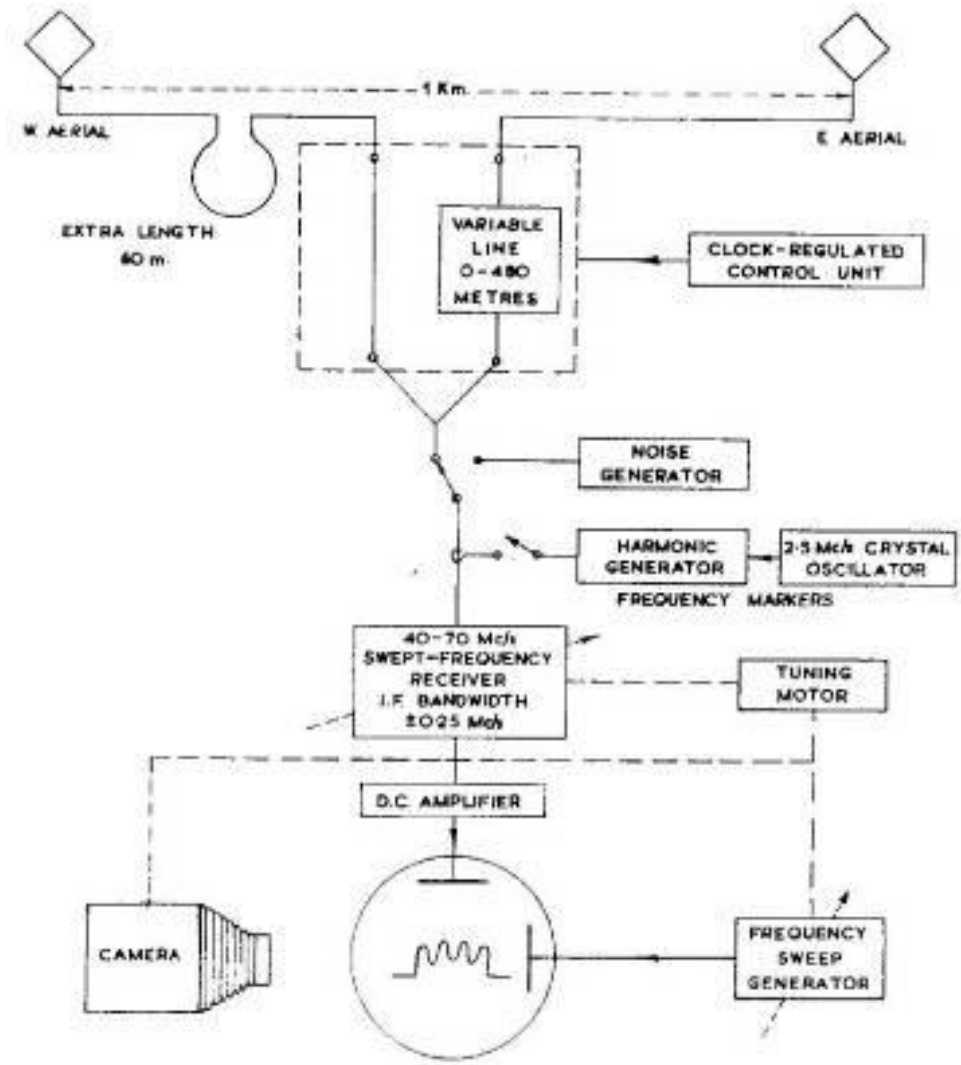


Figure 26 Block diagram of the adding interferometer (after Wild and Sheridan, 1958: Fig. 3).

2.7.3 The Multiplying Interferometer

A block diagram of the system is shown in Figure 27. Wild and Sheridan (1958: 163) described the instrument as follows:

> The antenna and feeder arrangements are the same as those of the adding interferometer but the signals in the two arms are amplified and converted to the intermediate frequency (30 Mc/s) before being combined. The frequency is swept

by tuning, in synchronism, each radio-frequency amplifier and mixer, and the common local oscillator [a similar tuning method was used for the radiospectrograph receivers]. The two 30 MHz signals are then multiplied by phase switching and phase detection; the technical arrangement is essentially similar to that used by Mills, Little, Sheridan and Slee (1958: 67). A high switching rate of 5 kHz is required and the output of the phase-sensitive detector is passed through a low-pass filter to the Y plates of the cathode ray tube.

For calibration purposes frequency markers are generated by a 2.5 Mc/s crystal oscillator and displayed. To determine the phase of the recorded interference pattern a noise generator signal is injected into the two receiver channels which are disconnected from the antennas; one signal is fed through an extra 60 m of cable so that an interference pattern is set up on the display corresponding to a source at the centre of the Sun.

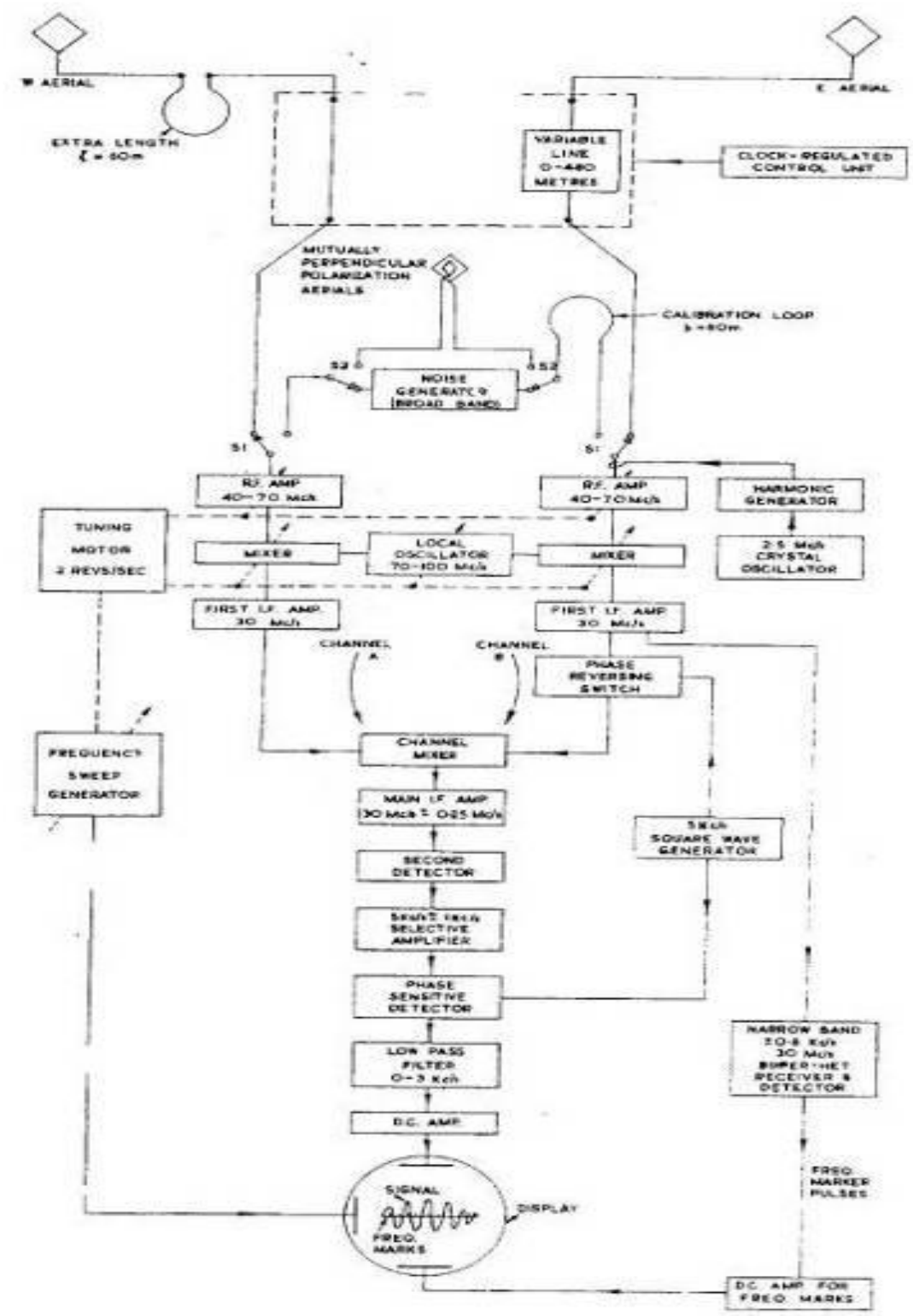


Figure 27 Block diagram of the multiplying interferometer (after Wild and Sheridan, 1958: Fig. 4).

Trial observations began on 6 June 1957 and examples of the final display are shown in Figure 28. The records include clock images displayed every 2 seconds.

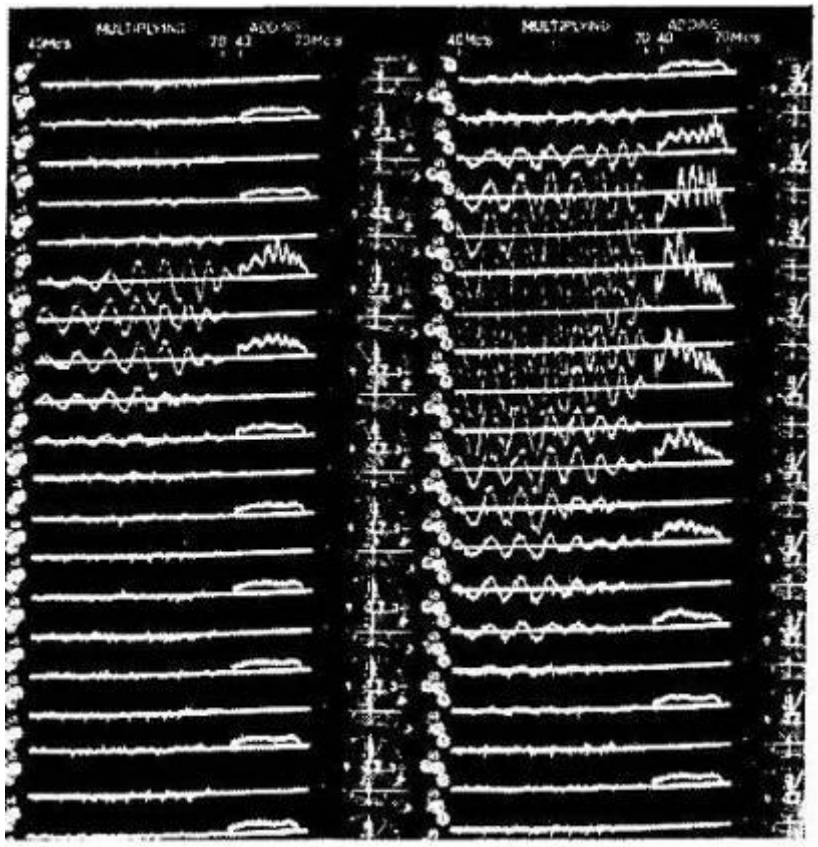


Figure 28 Typical records of Type III bursts obtained on 3 July 1957. Patterns of multiplying interferometer are recorded every second and adding interferometer every 2 seconds (after Wild and Sheridan, 1958: Fig. 5).

2.7.4 **Antennas and Feeders**

The spaced antennas of the interferometer are single wire rhombics each mounted on a wooden cross in the vertical north-south direction and pivoted to allow two declination settings (summer and winter); no azimuth movement is necessary because the beamwidth is wide enough to accommodate the Sun's daily motion during operation (noon +- 2 hr). The antennas are designed for uniform effective area of 9 m^2 over the 40-70 MHz operating band with a characteristic impedance of 700 ohms (Figure 29). The antenna is connected to a 700 ohm open-wire transmission line which is tapered near the receiving end to an impedance of 300 ohms.

Figure 29 Paul Wild next to one of the interferometer rhombic antennas. Behind is one of the posts for the open-wire transmission lines (Courtesy ATNF photographic archive).

2.7.5 Modifications to the Interferometer System

As a result of operating experience two major features were added to the multiplying interferometer (Figure 27). Firstly, an additional interferometer system with a shorter baseline of ¼ km was added for lobe identification (Figure 30). Secondly, a more convenient display system has been used and an automatic system of "following" and calibration has been used (Wild et al., 1959a). The latter facilities have resulted in a reduction, by an order of magnitude, in the time to analyse the records.

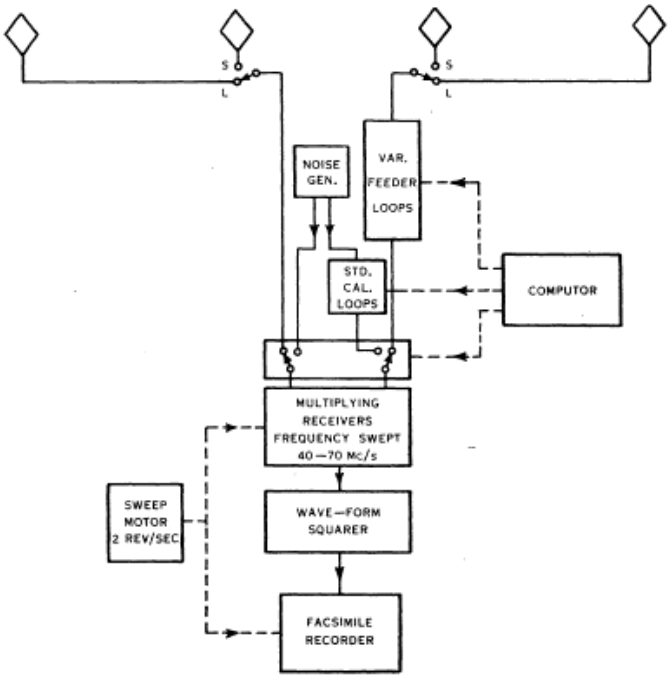


Figure 30 Simplified block diagram of the modified swept-frequency interferometer. Short-base and long-base interferometers are selected by the S/L switch (after Wild et al., 1959a: Fig. 1).

2.7.6 The Method of Display

In the new system each swept-frequency modulated pattern was converted into a square waveform and displayed as a single intensity-modulated line on paper records using a facsimile recorder (Figure 31).

Figure 31 Kevin Sheridan in front of the facsimile recorder (Courtesy of ATNF photographic archive).

Successive traces at ½ sec intervals were recorded one below the other, as in ordinary records of dynamic spectra. Each zero point in the interference pattern can then be recognized as a sudden change between a black and a white region. An idealized record is shown in Figure 32 where the 'black' record is shown as hatching.

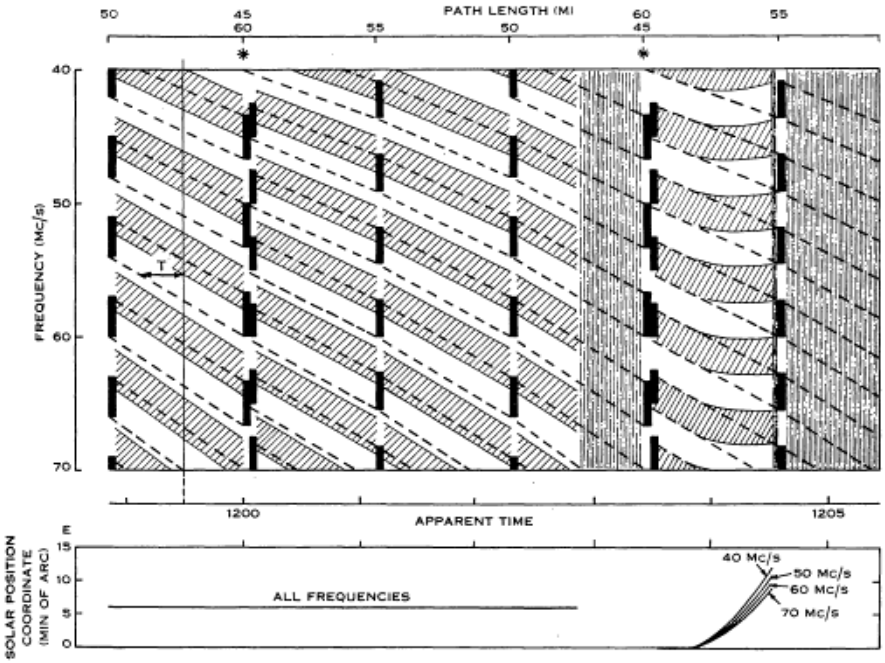


Figure 32 Idealized record obtained with the swept-frequency interferometer. The hatched bands, which appear black on the actual record, are produced by a hypothetical solar source, whose position is shown in the lower part. The dotted lines are drawn manually on the record by joining the appropriate calibration marks; asterisks denote times at which the relative lengths of the aerial feeder lines are changed by 15 m (after Wild et al., 1959a: Fig. 2).

Wild et al. (1959a: 373) wrote:

> As before the relative length of the aerial feeder length is capable of extensive variation in steps of 15 m; it is regulated throughout the day in such a way that the excess length of the path travelled by signals coming from the centre of the sun via in west aerial over that via the east aerial is constrained to lie within 45 to 60 m. This regulation is controlled by a computer system. In the method used to

analyse the records a reference pattern is generated corresponding to a source at the centre of the sun. To do this, the pair of aerial feeders at appropriate times are automatically disconnected from their receiver terminals and replaced for a few seconds by a pair of calibration lines connected to a broad-band noise generator. One line contains an additional loop of length *l* appropriate to the position of the centre of the sun at that time. In practice, four standard *l* values are used for calibration, namely 60, 55, 50 and 45 m. The times are calculated by a clock-driven computer described below. The calibration patterns appear as brief sections of extra blackness.

Rapid movements in the position of the source can be recognized by inspection of the record [such as that shown in the latter stages of Figure 32]. The position of the source can be calculated at several frequencies from the time differences [T of Figure 32] between the dashed lines representing the centre of the sun and the fringe zero points.

2.7.7 The Computer

If *l* is the difference in path length travelled by plane waves from the centre of the sun to the two aerials, then according to Wild et al. (1959a: 374):

The system requires a computer which delivers pulses at those times when, for integral values of *p*, *l* assumes the values;

(1) $l = p \times 15\ m$, for the purpose o changing the relative lengths of the feeder lines in steps of 15 m and

(2) $l = p \times 5\ m$, for the purpose of controlling the calibration system.

To satisfy (2) we require (Wild and Sheridan, 1959) that

$$(1/5\ a/A \cos \delta)\ (A \sin H_p = p \qquad (18)$$

where $A = 1.3750 \times 10^4$ and *a* is the baseline length in metres.

To produce the desired sequence of pulses a small commercially available hand calculator (*Curta*) is used as it is capable of adding a number *m* times, with an accuracy exceeding 1 in 10^7. The number (1/5 *a*/A cos δ) is set up on the computer each day and the shaft is driven at a rate such that the cumulative number of revolutions from noon is A sin *H*. Arrangements are made for a pulse to be delivered whenever the computer registers an integral value of *p*. From [Figure 32] it can be seen that the calibration sequence is 60, 55, 50, 45 m and then every third pulse the path-length reverts to 60 MHz. There are periods of about 3 sec (selected by the operator) during which the short baseline aerials are substituted. As the ratio of the baselines is 4:1 this poses no problems for calibration. At other times the crossed polarized aerial is substituted.

2.7.8 Modifications to the Source Size Interferometer

A further modification was made to the Dapto interferometer system (Sheridan, 1963) in 1961 when the adding interferometer was replaced by a phase-swept interferometer operating at 40 and 60 MHz where the lobes are swept rapidly across the source similar to the method first used by Little and Payne-Scott (1951) for solar observations at 97 MHz. The principle of operation is illustrated in Figure 33. If the shape of the source is assumed, the angular extent of the source can be derived from the visibility of the fringes. In practice both long and short baselines are used.

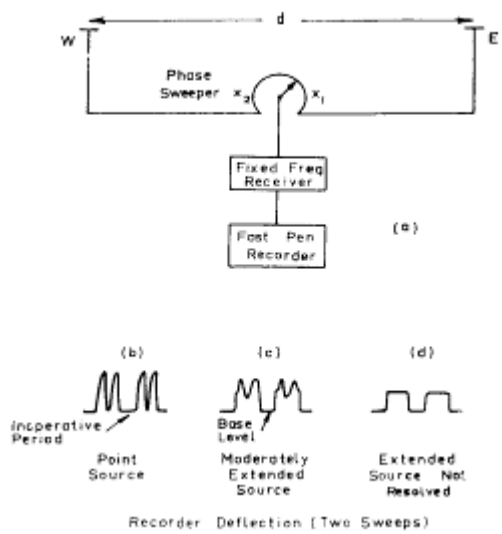


Figure 33 Principle of the phase-swept interferometer for angular size determinations (after Sheridan, 1963: Fig. 14).

2.7.9 Discussion of Interferometer Results

A considerable number of important research papers were published on the interferometer results and these are reviewed in Chapter 4. The most notable early result was the confirmation of the 'plasma hypothesis' for Type II and Type II bursts (Wild, 1950a, b) shown by the dispersion in source heights similar to the separation expected for corresponding plasma levels in coronal density models. Also, measurements were obtained on the transverse velocities of sources of Type II, III and IV bursts.

2.8 Extensions to the Dapto Radiospectrograph 1958-1963

2.8.1 1958 Extension down to 25 MHz

In 1956 Kevin Sheridan was transferred from the Mills Cross Group to the solar group and was asked by Joe Pawsey to extend the spectrograph to lower frequencies. Kevin had been working previously with Alex Little on the Mills Cross at the Fleurs field station. Gil Trent also joined the Dapto group to assist Sheridan.

A new spectrograph operating over the 24 to 40 MHz range was constructed and put into operation in October 1958. Sheridan et al. (1959: 51) noted that:

> The study of transient disturbances in the Sun's atmosphere by means of spectrographic observations in the radio spectrum is now being undertaken or planned by a number of radio observatories throughout the world. Most of the current spectrographs operate in the metre and decimetre wavelength bands at frequencies above about 50 Mc/s. These receive emissions which originate mainly in the denser levels of the solar corona below about $\rho = 1.3\ R_0$, where ρ is the distance from the Sun's centre and R_0 is the photospheric radius. However, the same technique offers unique possibilities of exploring events taking place at considerably greater distances simple by extending the wavelength into the decametric range. The final limitation to such an extension will be set by effects caused by the terrestrial ionosphere. An absolute limit to observations from ground level (as distinct from rockets and satellites) is set by the critical frequency of the ionosphere (~ 5 Mc/s) but long before such low frequencies are

> reached the observations will become seriously affected by interfering communication signals entering the spectrograph after low-angle reflection in the ionosphere. At just what frequency useful observations become impossible is not yet known.

As a first step to exploring the decametric frequency range, the Dapto equipment was extended downwards in frequency by adding a 25-40 MHz spectrograph in October 1958 to supplement the 40-210 MHz spectrograph. The new spectrograph employed a conventional swept-frequency receiver connected to a simple steerable rhombic aerial. A receiver bandwidth of 100 kHz was found to be sufficiently narrow to minimize most interference effects.

Examples of dynamic spectra recorded with the 25-210 MHz spectrograph are reproduced here as Figure 34. The examples were described in the following manner (Sheridan, Trent and Wild, 1959: 52):

> Plate IIA (a) shows a typical group of Type III bursts. The leading edge of each burst reaches the 24 MHz plasma level which occurs at a height of 1.7 R_0 in a Baumbach-Allen corona.
>
> Plate IIA (b) shows a double event in which a diffuse second harmonic, following a sharper fundamental, passes off the low-frequency border implying that the source is continuing out to or beyond the 12 MHz level plasma which lies at a height of at least 2.1 R_0. The occurrence of such events further strengthens the view that certain Type III sources escape entirely from the sun.
>
> Plate IIA (c) shows a complex event containing, near its start, a striking example of a Type III burst in which a complete reversal takes place in the sense of the frequency drift – presumably tracing a path which first moves away from the sun and subsequently falls back. Maxwell and Swarup (1958) have reported numerous such “inverted U” bursts in the frequency range 100-600 MHz, but this is the first example with a turn-over frequency as low as 35 MHz corresponding to a height of at least 1.5 R_0.

Plate IIB (a) shows part of a Type II burst with fundamental and second harmonic structure. The feature of special interest is the delayed occurrence of an intense group of Type III bursts which seem to originate from the Type II source itself when the latter has reached a great height in the corona, giving rise to the 'herring-bone' effect as described by Roberts (1958). If the sources of these Type III bursts are associated with cosmic ray particles it could explain the delayed ejection of cosmic rays from certain large flares.

Plate IIB (b) shows (in the 25-30 MHz band) the onset of a sudden ionospheric disturbance (S.I.D.) causing the absorption of short-wave communication signals which normally are reflected from the ionosphere. This S.I.D. is followed, a few minutes later by the start of a Type II burst at the higher frequencies. The latter frequencies reach the receiver at lower zenith angles and appear to be unaffected by any disturbance in the ionosphere.

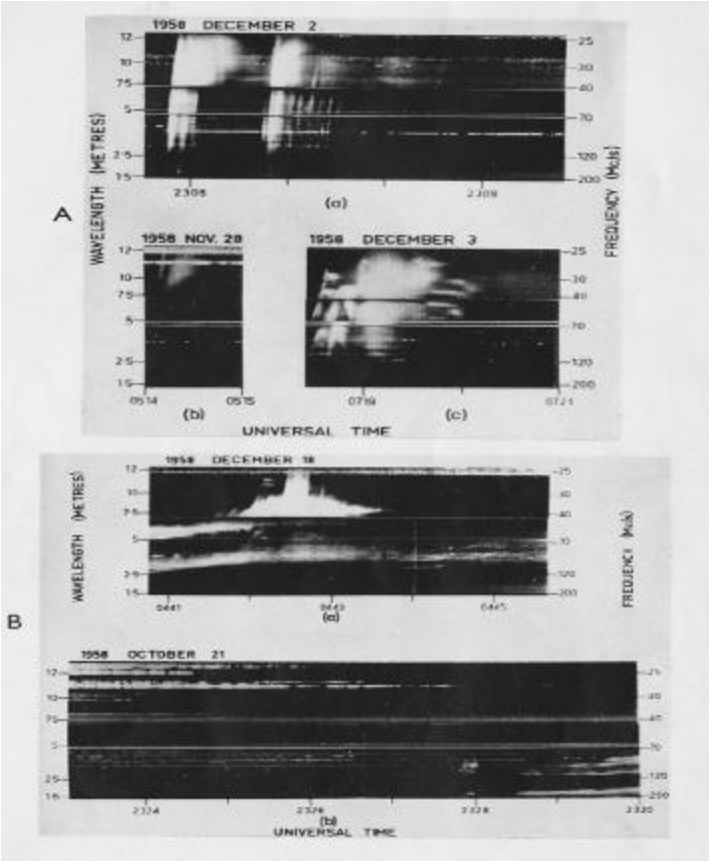


Figure 34 Examples of dynamic spectra recorded in the 25-210 MHz range (after Sheridan et al., 1959: Plate IIA & IIB).

2.8.2 1960 Extension down to 15 MHz

Sheridan and Trent (1961: 72) reported that the newly added 12-25 MHz extension:

> Uses a fixed, vertically polarized, rhombic aerial pointed in a northerly direction normal to the Earth's axis of rotation. The beamwidth of the aerial is great enough to allow useful observations to be made for at least 8 hours per day throughout the year. Since the new range is pervaded by a mass of interfering communication signals the receiver bandwidth has been made very small (9 kc/s) and precautions have been made to avoid paralysis by strong interfering signals.

Figure 35 shows a major outburst which occurred on 1960 November 15 and was recorded in the 15-210 MHz range.

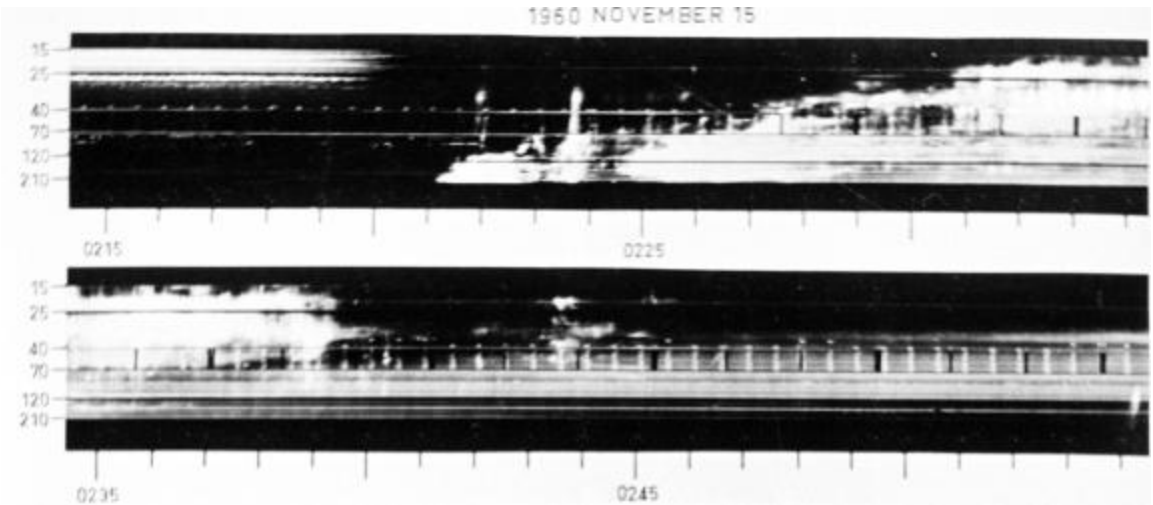


Figure 35 The major outburst of 1960 November 15 recorded over a 15-210 MHz frequency range. Times are shown under each strip. Vertical bars are interference (after Sheridan and Trent, 1961: Plate IIa).

The event was described by Sheridan and Trent (1960: 72) as:

> An event of special interest known to be associated with an increase in cosmic ray flux. The first indication of activity occurs at $02^h\ 20^m$ with the S.I.D. which eliminates interfering signals for some 30 to 40 minutes, after which a gradual recovery is evident. At $02^h\ 21^m$ the leading edge of a strong Type II burst is seen to appear at the 210 Mc/s edge of the record and drift across the entire frequency

> range of the equipment. Following almost immediately on the Type II event is a gradual rise in continuum first seen at the highest frequencies and extending to the lower frequencies at about the same rate as the Type II emission. These observations emphasize the great spectral width of the solar phenomena and indicate the importance of observations at still lower frequencies, including those from artificial satellites currently being planned.

2.8.3 1961 Extension down to 5 MHz

In 1961 Gil Trent transferred to the Parkes Radio Telescope team and Charlie Attwood joined Kevin Sheridan to add further extensions to the Dapto spectrograph. Sheridan and Attwood (1962: 155) report that:

> The new extensions were made in two steps: the first, from 15 to 10 Mc/s, making use of a mechanically tuned receiver of the double-conversion Type with an overall bandwidth of 9 kc/s. For the lowest range, 10 to 5 Mc/s, the receiver is again a double-conversion with bandwidth 9 kc/s, but the tuning is carried out electronically by a voltage-variable-capacitor (my spelling). Each receiver uses a fixed-mounted degenerate rhombic aerial with a sufficiently wide beamwidth to enable useful observations to be carried out for 8 hours per day.

Examples of solar bursts extending down to 10 MHz are shown in Figure 36 and down to almost 5 MHz in Figure 37. For the Type III bursts on 25 July 1961 it can be seen that those received near local noon (top RH strip) extend down to lower frequencies that those received well away from noon (top LH strip). The middle and lower strips show a complex, harmonic Type II burst covering the entire range from 210 to 10 MHz. Figure 37 shows groups of Type III bursts recorded with the full range (down to 5 MHz) of the equipment. Sheridan and Attwood (1962) noted that:

"These occurred several months later, in September, when the Sun's southward motion had reduced the angle of incidence of the rays on the ionosphere, lower frequencies again being recorded closer to noon. In many examples, the low frequency cu-off is rather sudden while the bursts are still quite strong, as for 28 September from 0005 to 0010 UT."

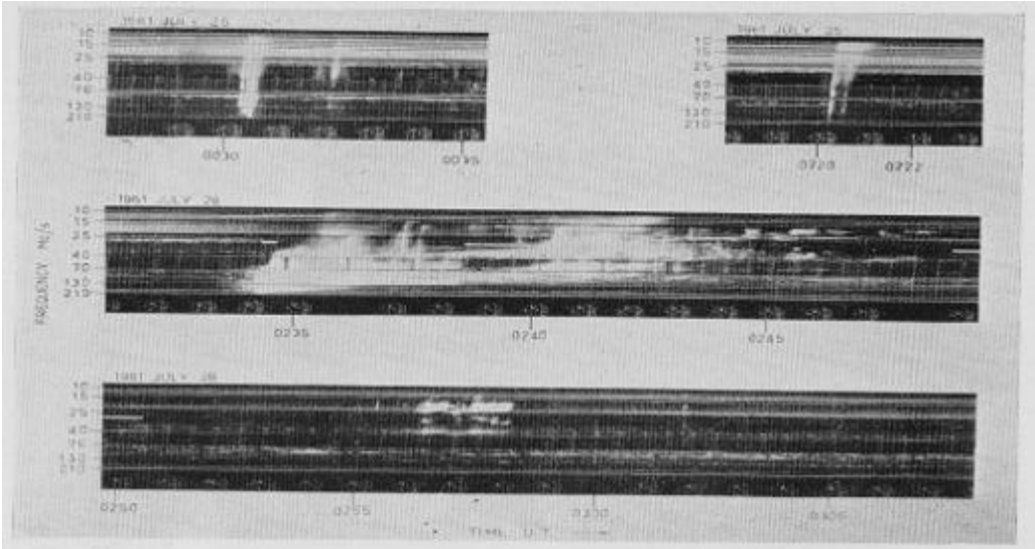


Figure 36 Dynamic spectra of solar bursts recorded in the frequency range 10-210 MHz (after Sheridan and Attwood, 1962: late IVA).

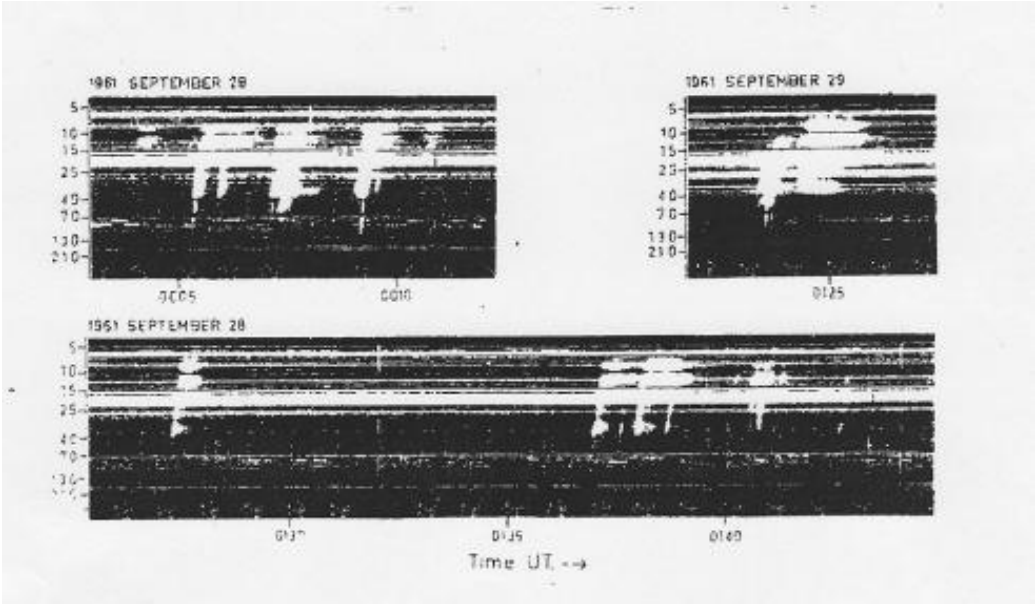


Figure 37 Groups of Type III bursts recorded in the range 5-210 MHz. The sudden cessation of the lower frequencies is attributed to ionospheric cut-off effects (after Sheridan and Attwood, 1962: Plate IVB).

Figure 38 shows a comparison of the lowest observed frequencies at Dapto for 11 August 1961, with the lowest expected frequencies calculated from ionosond measurements taken at Brisbane and Canberra. One can see that the critical frequency decreases towards noon in agreement with the Dapto observations. Figure 39 compares all available data from July to

December 1961. The r.m.s. deviation between observed and predicted critical frequency is only 1.14 MHz indicating that the general agreement is good and clearly establishes the ionospheric origin of the low frequency cut-off of the Dapto spectra.

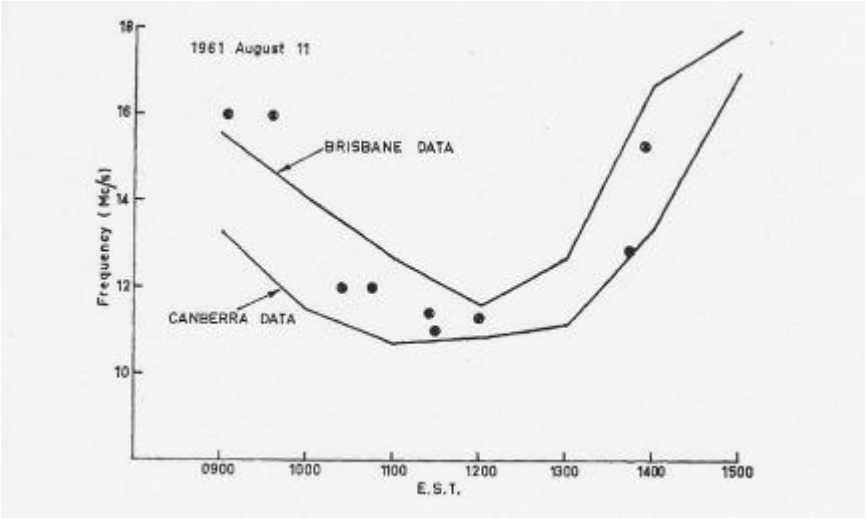


Figure 38 Comparison of lowest observed frequencies with expected frequencies for 11 August 1961 (after Sheridan and Trent, 1962: Fig. 1).

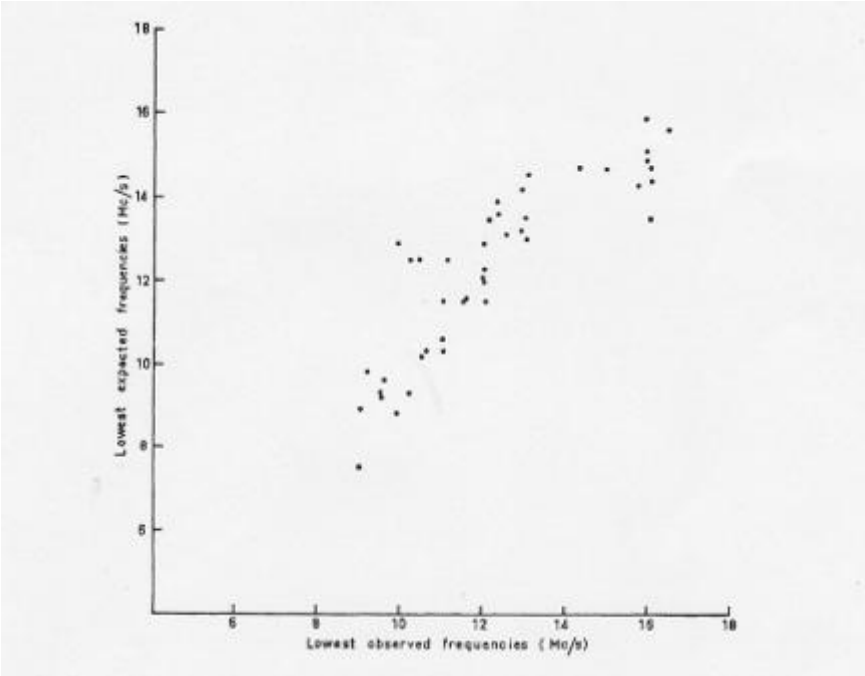


Figure 39 Comparison of lowest observed and expected frequencies (based on the means of Canberra and Brisbane ionospheric data) for the period 1961 July to December (after Sheridan and Trent, 1962: Fig. 2).

2.8.4 1963 Extension from 5 to 2000 MHz

In 1963 S. Suzuki developed a high frequency extension to the Dapto spectrograph while on leave from the Toyo Astronomical Observatory. He later became a permanent member of the Solar Group and helped design the Culgoora spectrograph and spectro-polarimeter. Suzuki et al. (1964: 55) reported that:

> The new extension of 10:1 (200-2000 Mc/s) employs a novel technique by which the entire band is covered with a single aerial and electronically tuned receiver. The aerial is a 30-ft. parabolic reflector with a broad-band log-periodic feed. The receiver is essentially a swept-frequency parametric up-converter, and the very wide frequency coverage is achieved by employing an "intermediate frequency" very much higher (X-band, 11.0 Gc/s) than the signal frequency. The input and matching circuits are quite un-tuned and the only circuit component that is variably tuned is the local oscillator (pump); this is a backward-wave oscillator that is electronically tuned to cover the required range of 9.0 to 10.8 Gc/s in ½ sec.

A simplified block diagram of the receiver is shown in Figure 40 and the reflector and log-periodic feed can be seen in the photograph of Figure 41.

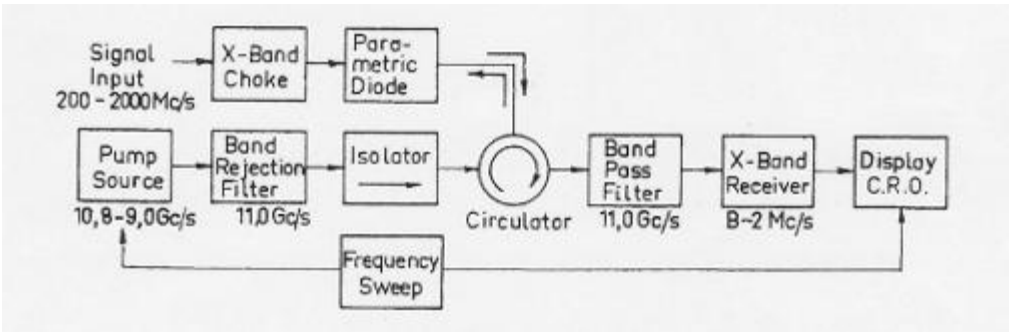


Figure 40 Simplified block diagram of the 200-2000 MHz receiver (after Suzuki et al., 1964: Fig. 1).

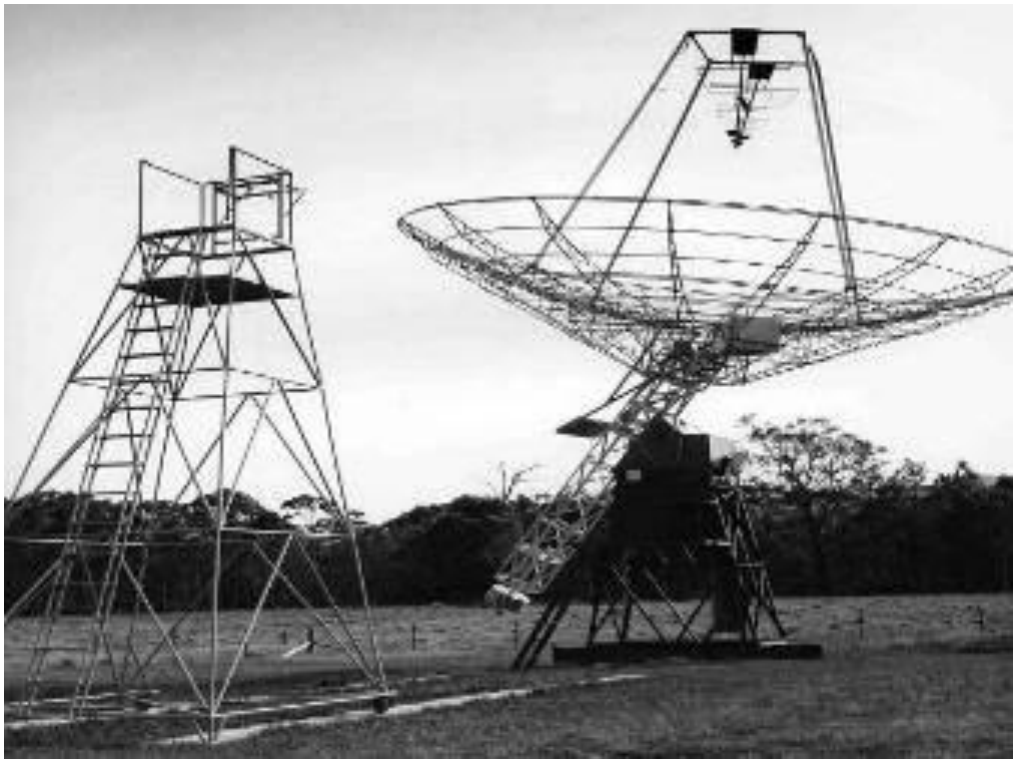


Figure 41 Dapto 200-2000 MHz reflector and broad-band feed receiver (after Suzuki et al., 1964: Fig. 2).

.

Figure 42 is one of two published examples of solar bursts observed with the extended spectrographs. In this event a fully-developed flare event is recorded over the entire 5-2000 MHz range.

Unlike earlier extensions to the Dapto spectrograph, this was the first time that the new development was not unique to solar radio astronomy. Spectrograph at the University of Michigan (100-580 MHz, 2000-4000 MHz; Haddock, 1958, 1959); Owens Valley Radio Observatory (500-950 MHz; Young et al., 1961; Kundu et al., 1961), and Harvard Station at Fort Texas (25-580 MHz, 2100-3900 MHz; Maxwell et al., 1958; Thompson, 1961) had described earlier dynamic spectra of solar bursts extending to these higher frequencies.

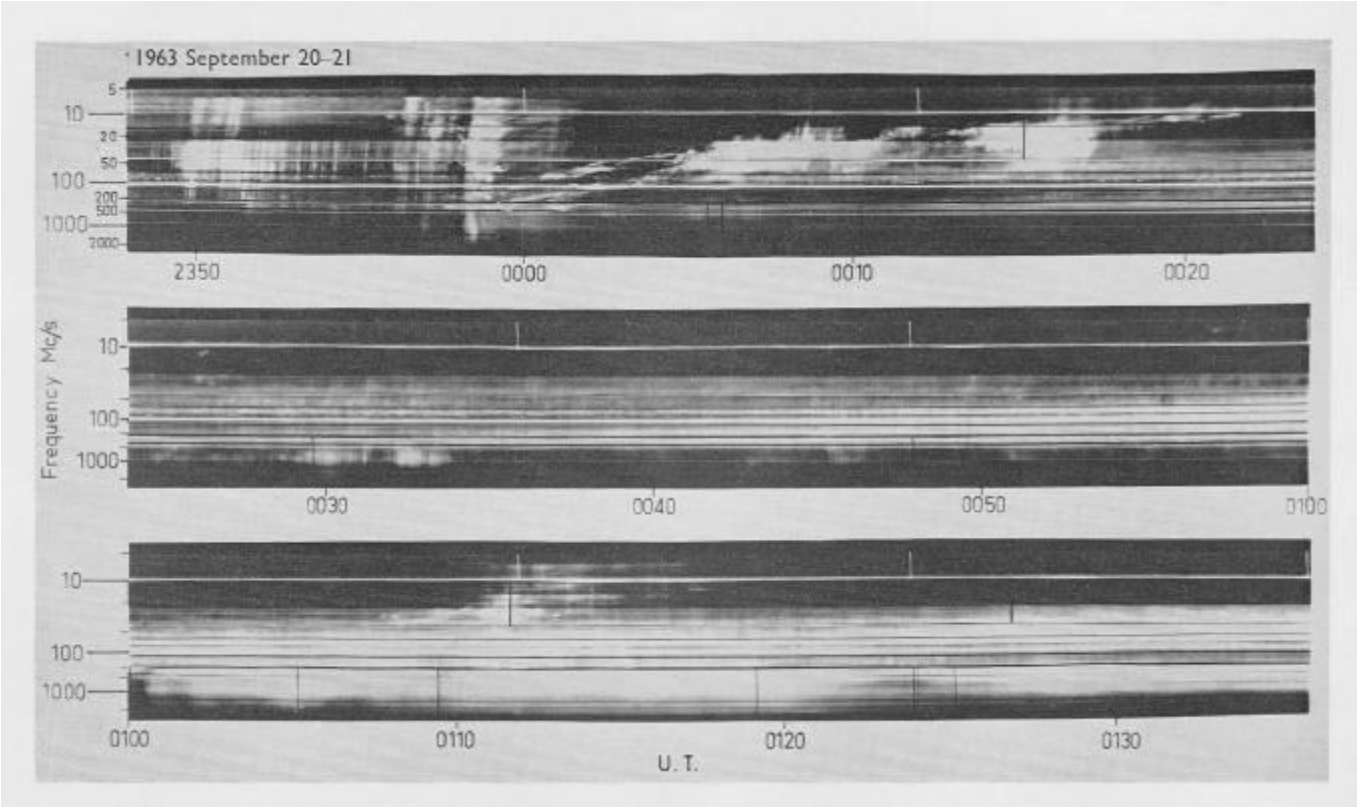


Figure 42 A major outburst recorded over the 5-2000 MHz range (after Suzuki, Attwood and Sheridan, 1964: Plate II).

2.9 Acknowledgements by Above Authors

Wild and McCready (1950) acknowledged J. D. Murray for the design and construction of the display system and to W.C. Rowe for considerable assistance throughout the project and to J.L. Pawsey and S. F. Smerd for advice and criticism in the preparation of the paper.

Wild, Murray and Rowe (1954) thanked J.A. Roberts and S.F. Smerd for valuable discussions on theoretical aspects of this work, and J. Joisce for assistance in the regular running of the equipment.

Wild and Roberts (1965a) acknowledged the contributions of J. D. Murray and W. C. Rowe in both instrumental and observational phases of this work, and to J. Joisce, M. Komesaroff, and G. Swarup for assistance in taking the observations, and J. L. Pawsey for his interest and for presenting preliminary results at overseas conferences during 1954.

Wild and Sheridan (1958) thanked J. A. Roberts and M. M. Komesaroff who participated in the early phases of this work, to G.H. Trent for assistance in construction of equipment, taking observations, and analysis of results, and to J. Joisce who assisted in the observing program.

Sheridan (1963) thanked J. P. Wild who initiated and directed every phase of the work, J. D. Murray, W. C. Rowe, J. Joisce, K. McAlister, S. Smerd, M. M. Komesaroff, G. H. Trent, D. McLean, C. F. Atwood, J. A. Roberts, A. A. Weiss and J. L. Pawsey who directed the Laboratory's radio astronomy programme from its inception and contributed mush helpful advice and encouragement.

2.10 Closure of the Dapto Field Station in 1964

On 1 March 1964 the Dapto Observatory was handed over to the Wollongong University College and a new spectrograph was installed at the CSIRO Culgoora site of the Radioheliograph (Sheridan, 1967). A continuous coverage of solar spectra was maintained by CSIRO until 1986 when the radio spectrograph was handed over to the Ionospheric Prediction Service and the Culgoora Radioheliograph was closed down to make way for the Australia Telescope; thus ended almost 40 years of outstanding observations of solar bursts by the CSIRO Division of Radiophysics Solar Group.

A number of important papers were published by the Solar Group using results from the Dapto Field Station. These papers are reviewed in detail in Chapters 3 and 4.

3. RADIOSPECTROGRAPH RESULTS 1949- 1964

In this chapter publications of the solar group relating to radiospectrograph observations are reviewed in chronological order to show the historical development of interpretation of the nature of solar bursts. Publications dealing with Dapto swept-frequency interferometer observations are dealt separately in Chapter 4. Because of the large number of papers presented here there inevitably is some repetition of ideas and results for which I apologise to the reader. However, I believe this approach gives a full account of the research activities of the Dapto group.

Chapter 3 deals mainly with the observed spectral properties of Type II and Type III bursts which are interpreted in terms of the *plasma hypothesis*. The validity of this hypothesis was confirmed by the swept-frequency interferometer measurements discussed in Chapter 4. Also discussed are studies of Types I, IV and V bursts, herring-bone stucture and reverse drift pairs. Other topics include correlation studies with solar flares and geomagnetic storms, polarization measurements, and radio star scintillations. Finally, a model of the Type IV burst is presented.

3.1 Analysis of Outbursts Recorded by the Penrith Radiospectrograph

3.1.1. Dynamic Spectra of Type II bursts

Five Type II outbursts were recorded at Penrith, NSW and analysed by Wild (1950a). The dynamic spectra of two of these are reproduced in Figure 43.

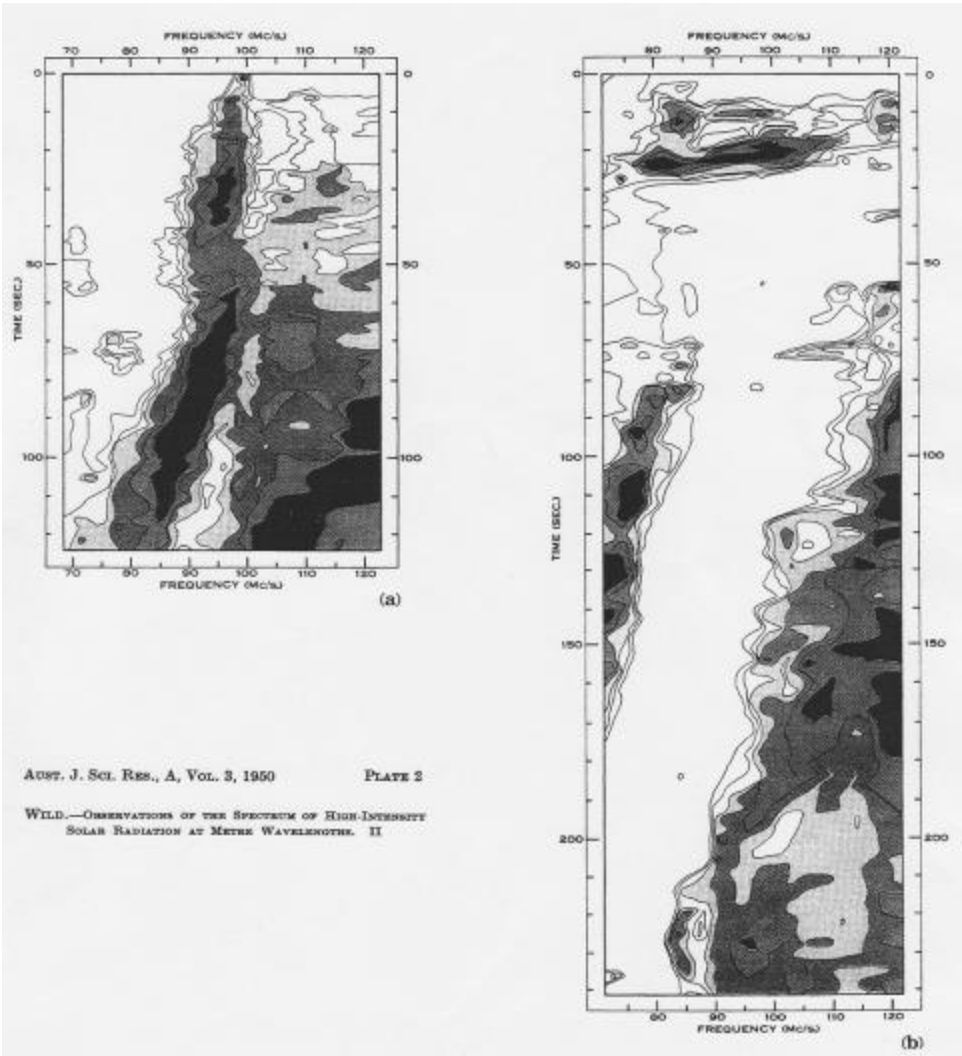


Figure 43 Dynamic spectrum of (a) Type II burst of 8 June 1949 and (b) 14 February 1949 (after Wild, 1950a: Plate 2).

In each of the five Type II bursts the following features were present:

(1) The occurrence of "emission" bands, separated by an abrupt frequency cut-off on the low frequency edge.

(2) Irregular drift of the emission bands towards lower frequencies.

These may be regarded as the defining features of 'spectral Type II' by which the outbursts were recognized by Wild (1950a). Other features of interest were the common occurrence of narrow-band emission peaks within the emission bands; the occurrence in at least two cases of several peaks within one emission band, each drifting "parallel" with the cut-off frequency; the occurrence in one case of two distinct emission bands which drifted in parallel formation (Figure 43b).

The latter burst is of particular interest because it appears to be an example of a fundamental and second harmonic Type II burst. However, because of the restricted frequency range this could not be verified. Later observations with the Dapto spectrograph, which had a much wider observing range from 40 to 240 MHz, recorded definite harmonic structure in Type II bursts; this was a very important discovery because it was strong evidence supporting the idea that Type II bursts were due to plasma oscillations (see Section 3.5).

3.1.2 Frequency Drift

The frequency drift of four of the bursts is shown in Figure 44. Points on the curves correspond to the position of the low-frequency "cut-off" edge. The four curves were superimposed by adjusting their starting points. The dotted line represents a constant drift rate of 0.22 MHz per second. The diagram shows that the average drift rate of each of the four bursts was close to this value and that the drift rate was constant with frequency.

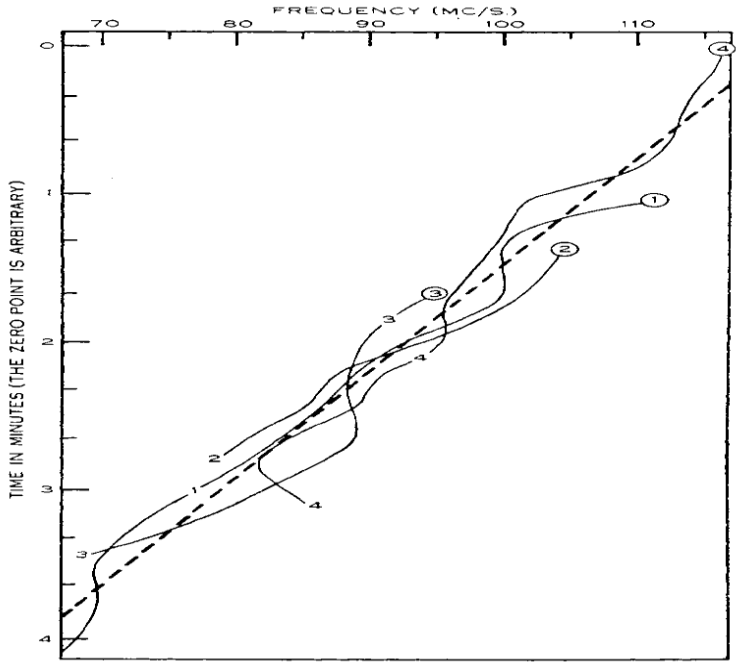


Figure 44 Smoothed curves of the variation with frequency of the low frequency cut-off of the four Type II bursts. (after Wild, 1950a: Fig. 1).

3.1.3 Interpretation of the Outburst Spectra

Wild used what he later referred to as the *'plasma hypothesis'* to interpret the frequency drift rate of the Type II outbursts shown in Figures 43 and 44. He identified the cut-off - frequency of the outburst with the local plasma frequency f_0 where the refractive index for electromagnetic waves reduces to zero. In the absence of a magnetic field f_0 is given by

$$f_0^2 = e^2 N / \pi m \qquad (19)$$

where N is the electron density of the medium,

e is the electronic charge (e.s.u.) and

m is the electronic mass.

Values of N, obtained from an optically derived electron density model for a spherically symmetric corona derived by Baumbach and modified by Allen (1947a), were used to produce the height versus time plot of Figure 45.

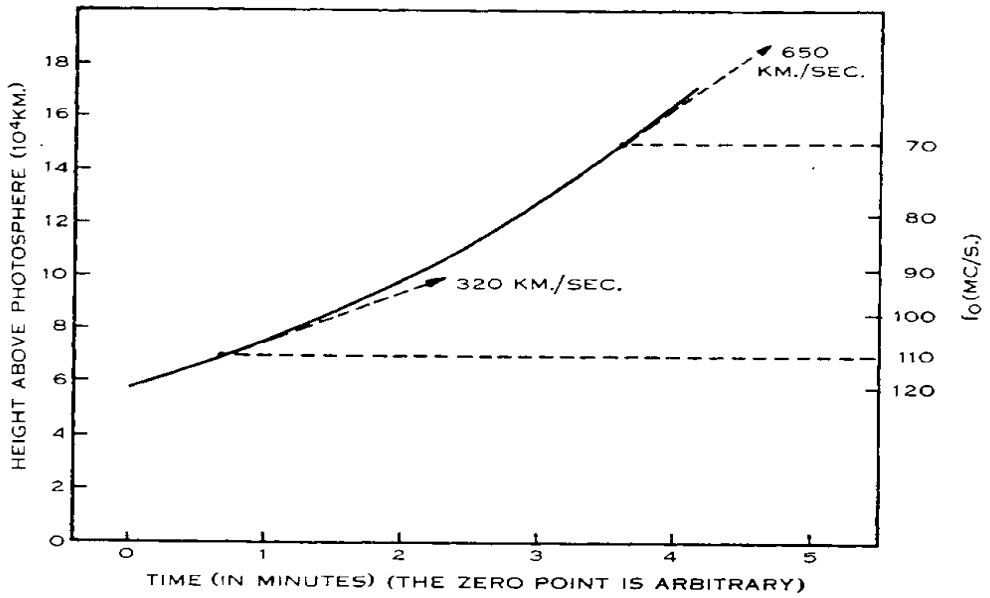


Figure 45 The curve shows the motion of the disturbance moving outwards through the solar corona producing a frequency drift corresponding to the dotted line of Figure 3.2 (after Wild, 1950a; Fig. 2).

Finally Wild (1950b) considered two known coronal phenomenon as possible candidates for the outburst disturbance. He first considered ‘ surge- prominences’ which he then discarded because they were observed to rise and then fall back towards the solar surface whereas the outburst showed a tendency to accelerate outwards through the corona. Instead, he was of the opinion that the most likely cause was associated with the fast particles, known to be emitted from the sun at the time of flares, which cause geomagnetic storms with sudden commencements about a day later. Indeed, two of the four Type II bursts analysed above were found to be associated with geomagnetic storm commencements 28-29 hours later. This idea had previously been suggested by Payne-Scott et al. (1947) and Pawsey (1950) to explain the outburst of 8 March 1947 (Figure 5).

One aspect of this paper worth noting is that Wild’s choice of coronal density model was the reason why the disturbance appeared to accelerate outwards from about 320 to 650 km/sec. through the corona as shown in Figure 45. Later systematic analyses of Type II bursts using more realistic density models showed that the disturbances travel outwards with more or less constant velocities but somewhat higher values.

3.2 Analysis of 'Isolated' Bursts by Wild (1950b)

In the second of a series of three papers describing the Penrith observations, Wild (1950b) discussed isolated bursts and in particular those of **'spectral Type III'.** Observations of isolated bursts with single-frequency equipment had been previously described by Pawsey (1950) and Payne-Scott (1949) who found the following characteristics:

(1) They are typically of short duration (several seconds).
(2) They often occur nearly simultaneously at widely spaced frequencies.
(3) They exhibit no circular polarization.

3.2.1 Description and characteristics of the Spectral Records.

In the course of observations taken between February and June 1949, spectra of many Type III bursts were recorded. In the abstract to this paper Wild (1965b: 541) wrote that:

> They occur sporadically, often in small groups; many hours sometimes elapse between successive bursts or groups…..some (referred to as 'Type III' bursts) are of a distinct spectral Type characterized by a rapid drift, with time, of the maximum intensity towards the lower frequencies, at a rate of the order of 20 Mc/s per second.

Some 32 isolated bursts or groups of bursts were recorded. Examples of the dynamic spectra of some of these bursts are shown in Figures 46 and 47.

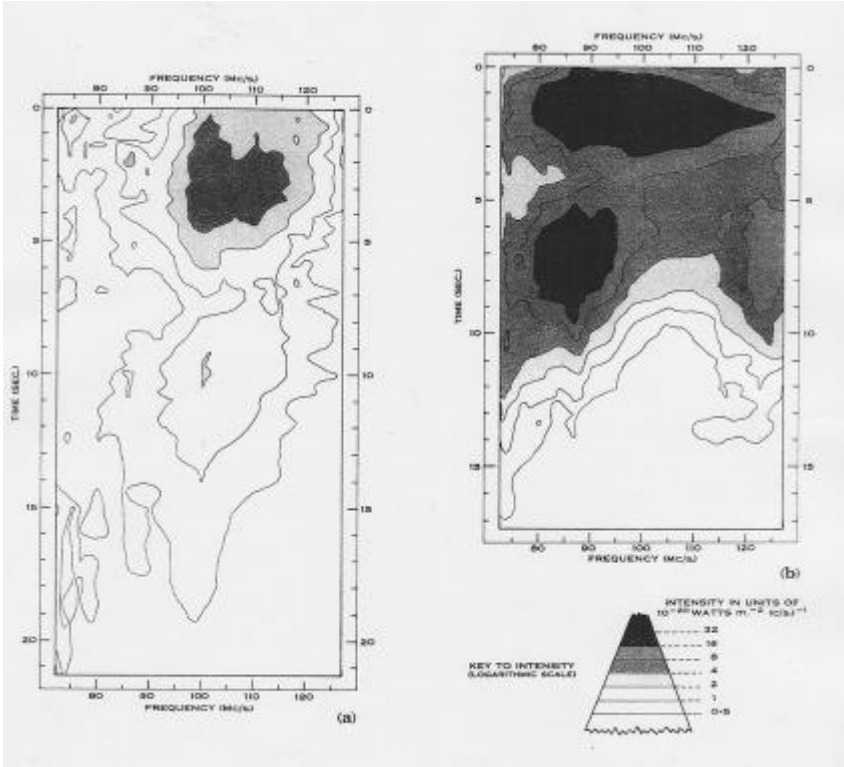


Figure 46 Examples of isolated bursts (after Wild, 1950b: Plate 1).

Figure 46 shows two examples of bursts with two maxima and rather long durations of at least 13 seconds at some frequencies.

I think that these two as well as the one in Plate 4b of Wild (1950b) are possible examples of *spectral Type V bursts*, a spectral type which was not identified until much later by Wild, Sheridan and Trent (1959) and analysed in detail by Weiss and Stewart (1964) (See details in Section 4.8 below).

In about half of the isolated bursts studied by Wild the frequency of maximum intensity drifted rapidly with time towards lower frequencies (Figure 47) and conformed to spectral Type III bursts.

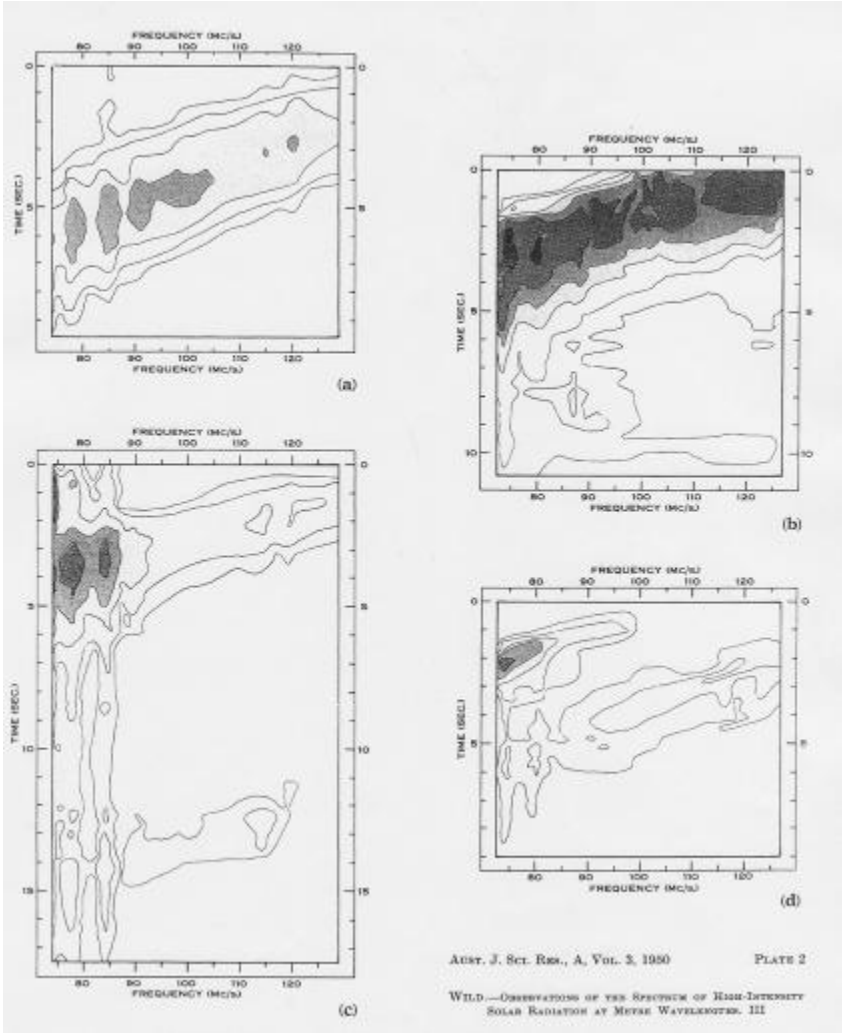


Figure 47 Examples of Type III bursts (after Wild, 1950b: Plate 2).

Often a burst was followed in short succession by others in groups such as the examples shown in Plate 4a & c of Wild (1950b).

3.2.2 Interpretation of Frequency Drift in Type III bursts

Wild considered three possible mechanisms for the rapid frequency drift of maximum intensity towards lower frequencies which is characteristic of Type III bursts such as shown in Plate 2b of Figure 47:

(1) Selective group retardation of the radiation from a localized, instantaneous disturbance in the corona. Jaeger and Westfold (1949) had found that such a

disturbance may be capable of producing a radio burst of short duration at the earth, where the higher frequencies would arrive before the lower ones, due to group retardation effects near the plasma level.

(2) The outward motion, through the corona, of a localized source that excites plasma oscillations of continuously decreasing frequency (similar to the mechanism discussed above in Section 3.1.3 for Type II outbursts).

(3) Some mechanism in which the wave frequency is controlled by an external magnetic field.

Wild dismissed mechanism (3) as a possibility because of the absence of observed circular polarization in Type III bursts. To decide between (1) and (2) Wild analysed the decay rate and frequency drift of the simple Type III bursts observed.

In noting that the time profiles of simple isolated bursts show a gradual rise to a maximum value followed by slower decay which appears to be approximately exponential in form, as found earlier (Payne-Scott,1949), and that the mean value of the normalized decay constant for 12 Type III bursts tends to decrease with decreasing frequency (Figure 48), Wild concluded that the result cannot be easily explained by mechanism (1) above but it can be explained by mechanism (2) if it is accepted that the decay constant is related to the electron-atom collision frequency (Westfold, 1949) which would decrease as the disturbance moves outwards through the corona (Smerd, 1950).

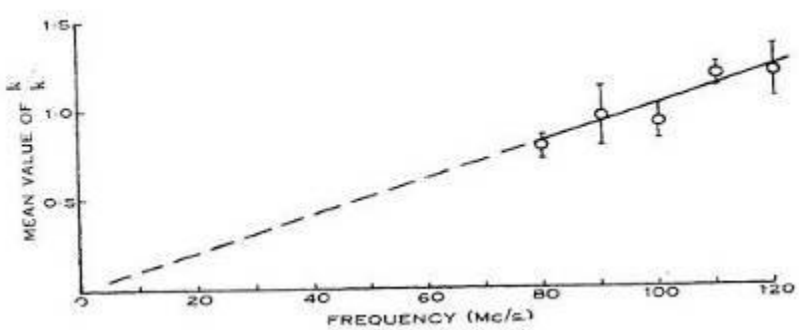


Figure 48 Plot of the average normalized decay constant $\kappa/\bar{\kappa}$ versus frequency for 12 Type III bursts (after Wild, 1950b: Fig. 4).

To test the frequency drift of mechanisms (1) and (2) further Wild constructed the graph shown in Figure 49.

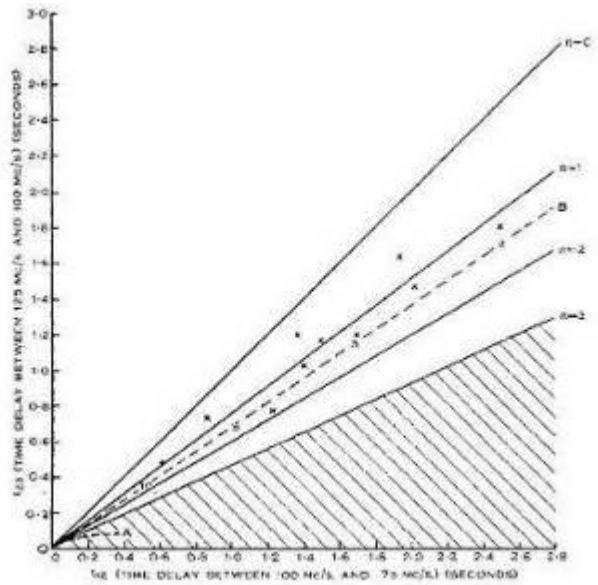


Figure 49 Diagram for studying the frequency drift of Type III bursts. Points for 10 Type III bursts are shown by crosses. Line OA shows the predicted results of selective group retardation in a Baumbach-Allen coronal electron density model. The shaded region shows selected group retardation in any atmosphere (after Wild, 1950b: Fig. 6).

Clearly the observations do not fit mechanism (1). On the other hand, mechanism (2) gives much better agreement. Here the line OB shows the prediction for an outward-moving source of constant velocity in a Baumbach-Allen atmosphere, where the numbers on the line refer to velocities in 10^4 km/sec. The other lines labelled n= 0, 1, 2, and 3 refer to a curvature of the intensity ridge line of the burst if the drift rate is proportional to f^n. The scatter of points on the graph suggests that a small acceleration of the source occurred as it moves outwards through the corona.

However, it should be noted that when more realistic density models for the corona became available further analysis indicated that the outward-velocity of the Type III burst remained more or less constant.

From the above analysis Wild (1950b: 554) concluded that:

> With the assumed electron density distribution, velocities of between about $2x10^4$ and 10^5 km./sec would be required to account for the observed drift rates. Corpuscular streams with these velocities have not been observed in the solar atmosphere, but in any case such streams would likely to be highly ionized and may consequently escape optical detection.

Wild's conclusions were vindicated when fast electron streams were detected in interplanetary space by spacecraft in the late 1960s and found to be directly related to Type III bursts.

3.3 Detailed Analysis of Enhanced Radiation by Wild (1951)

3.3.1 Background Continuum and Storm Bursts

Between February and June 1949 the solar spectrum in the frequency range 70 to 130 MHz showed noise storms occurring for many hours. The spectrum during severe storms showed a high steady level extending over the entire frequency range. Superimposed on this "background continuum" were short lived bursts called '*spectral Type I'*. Some examples are shown in Plate I of Wild (1951) and reproduced here as A-scans in Figure 50.

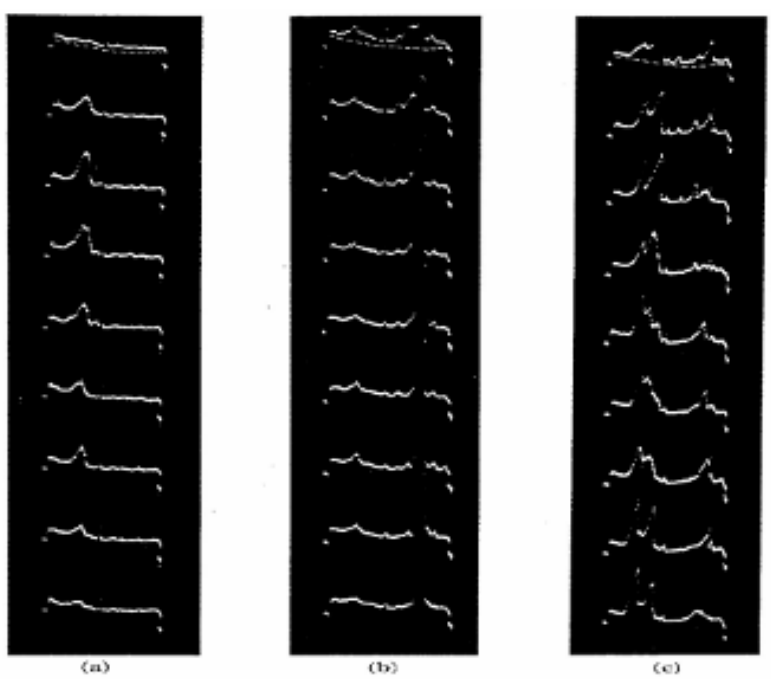


Figure 50 A-scans of three storm bursts each section of 3 seconds duration. Frequency varies from 70 MHz on the left hand side to 130

MHz on the right. Scans are separated by 1/3 second. The dotted lines show the background level in the absence of storm continuum. (a) A typical storm burst from start to finish. (b) Part of a large storm burst. (c) Storm bursts during a period of very high activity (after Wild, 1951: Plate 1).

The spectrum of these storm bursts showed two distinct features:

(1) It was quite narrow, typically about 4 MHz, between points of quarter-maximum intensity (see Fig. 51).
(2) The mid-frequency of the burst remained approximately constant throughout.
(3) Its lifetime which was usually less than 20 seconds (see Fig. 52).

Wild noted that bursts of duration less than 1 second, if they did occur, could not be recognized on records such as those of Figure 50.

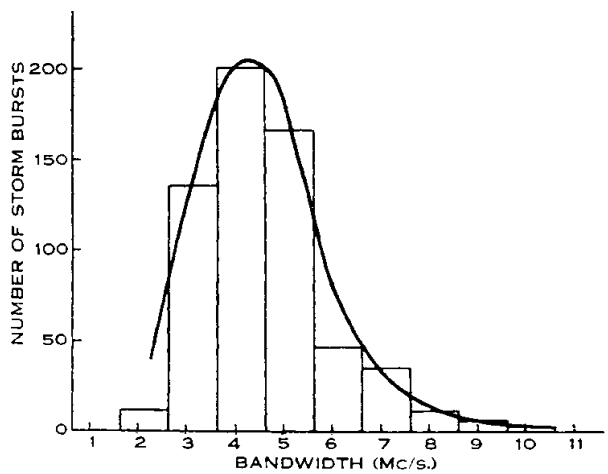


Figure 51 Histograms showing the distribution of recorded storm bursts with bandwidth (after Wild, 1951: Fig. 7).

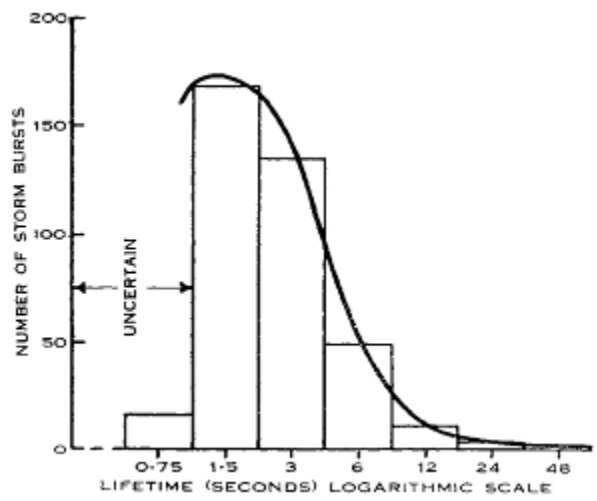


Figure 52 Histograms showing the distribution of recorded storm bursts with lifetime (after Wild, 1951: Fig. 8).

3.3.2 Comparison of Continuum and Type I Storm Bursts

To examine the correlation between the enhanced background continuum and the Type I bursts, Wild constructed two figures one of which is shown as Figure 53 below.

Wild summarized the main features of these and similar records of other active days as follows:

(1) The spectrum of the background continuum appears to change continuously with time.

(2) The average intensity of the background continuum on most days increases steadily with frequency.

(3) The spectrum due to the integrated effect of storm bursts (as indicated by the burst index) over a 20 minute period shows no relation to that of the background continuum.

(4) A high level background continuum can be present for an hour or so without any storm burst activity.

(5) Storm bursts show a tendency to occur during brief active periods of about 1 or 2 minute's duration.

(6) On some days storm bursts seem to occur in restricted frequency bands.

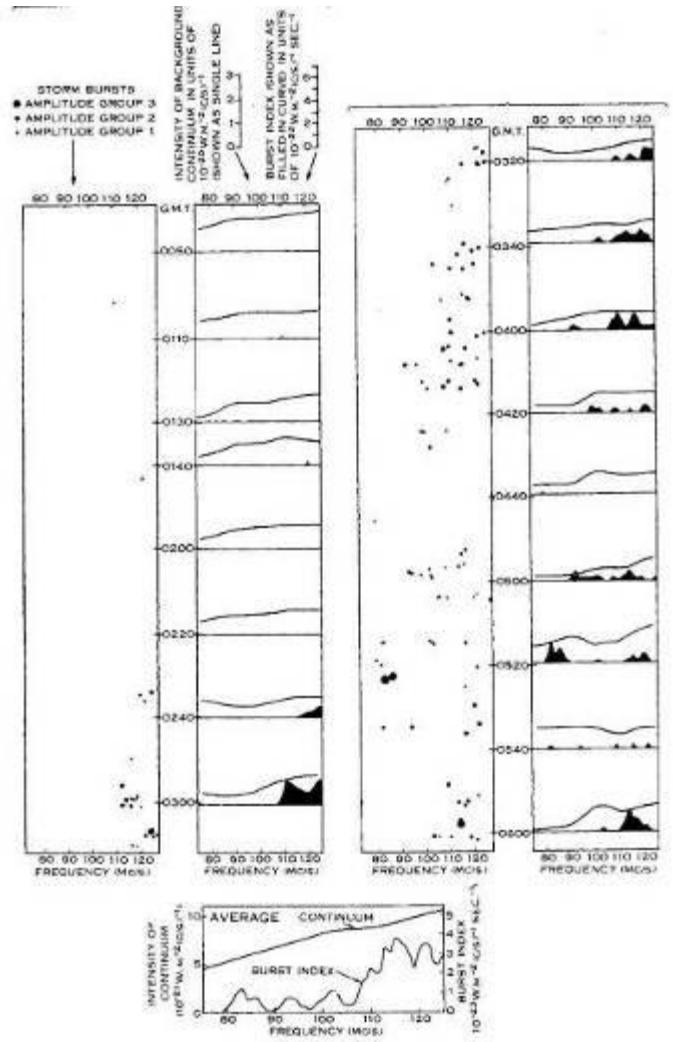


Figure 53 The LH plot shows the distribution of Type I storm bursts recorded on April 14, 1949 and the RH plot shows the continuum spectrum and the 'burst index' The latter, according to Wild (1951), gives a fair indication of the mean-intensity distribution of the Type I bursts (after Wild, 1951: Fig. 2).

3.3.1 The relation between the Background Continuum and Storm Bursts

It was suggested earlier by McCready, Pawsey and Payne-Scott (1947) and also Ryle and Vonberg (1948) that the background continuum may be the resultant of a large number of storm bursts, only the larger ones being recognized as distinct phenomena. This hypothesis is supported by (1) the observed circular polarization of both bursts and continuum and (2) the good general daily correlation of occurrence of the two components.

On the other hand, Wild pointed out that the opposite view, that the two components are fundamentally different, is suggested by;

(1) The usual small degree of fluctuation in the background continuum.

(2) Lack of correspondence between the spectrum of the continuum and the integrated spectrum of the bursts, and

(3) The fact that during some periods a high continuum level is observed without appreciable burst activity and at other times bursts without detectable continuum.

Wild concluded that more observations of noise storms were needed to resolve this question.

3.4 Summary of Observations and Analysis of Penrith Data

Wild and McCready (1950) showed that there were three distinct spectral Types of bursts in the recorded data. Wild (1950a, 1959b, 1951) then went on to analyse these three Types in more detail and reached the following conclusions:

(1) That more observations were required to resolve the question whether or not enhanced continuum during noise storms was the resultant of a large number of unresolved Type I bursts.

(2) That the frequency drift rates observed in Type II and Type III bursts could be explained by the 'plasma hypothesis' as being due to the outward motion through the corona of charged particles travelling at speeds of about 500 km/sec. and 10^4 to 10^5 km/sec. respectively.

3.5 Analysis of Fundamental and Second Harmonic Type II and Type III Bursts Recorded by the Dapto Radiospectrograph during 1952-53

3.5.1 Introduction

The discovery of harmonic structure in a Type II burst was reported briefly by Wild, Murray and Rowe (1953) and in Type III bursts by Wild, Roberts and Murray (1954). A more comprehensive account was given by Wild, Murray and Rowe (1954). The material presented below, unless

otherwise specified, comes from their 1954 paper. As argued by these authors the presence of both fundamental and second harmonic components in spectral records of solar bursts is compelling evidence that the emission occurs due to the excitation of plasma waves in the solar corona as postulated by Wild (1950a, 1950b).

This was a very significant discovery which, in my opinion, more than justified the construction of the Dapto spectrograph.

3.5.2 Harmonics in Type II Bursts

The first ever recorded harmonic Type II outburst occurred on November 21, 1952 (Figure 54). John Murray was on duty at Dapto on this momentous occasion (Murray, priv. comm. 2007). The dynamic spectrum is shown as a contour plot with corresponding A-scans in Figure 2.23. Wild, Murray and Rowe (1954: 445) reported that:

> Each band shows a fine structure which for most of the time consists of two well defined peaks. Two features are of special interest. Firstly, the structure of the two bands is strikingly similar; peaks appearing in one band seem to be displaced simultaneously in the other. Secondly, although the frequency of each band drifts over a range of at least 3:1, the frequency ratio of the corresponding features in the two bands remains approximately constant and lies within a few percent of 2.

The first of these features was interpreted as signifying that the two main bands were emitted from the same source; the second that the duplicity was due to emission from the source at a fundamental frequency and its second harmonic.

Comparison of the profiles of Figure 54 revealed that the main peaks in the second harmonic band (dotted lines) is consistently shifted slightly to the left of the fundamental band indicating a frequency ratio less than 2, the measured ratio of the peaks lying between 1.96 and 1.99.

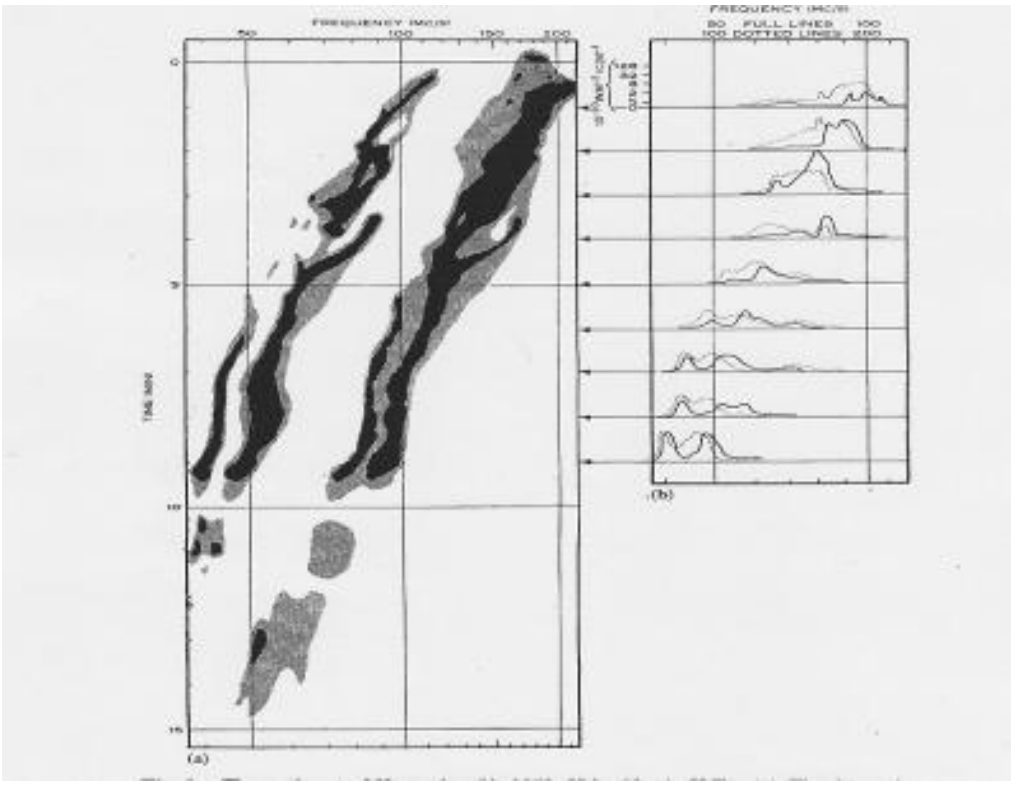


Figure 54 Type II burst of 21 November 1952 (a) The dynamic spectrum. (b) Profiles at 1-min intervals. The second harmonic is shown dotted and displaced in frequency by a factor of 2 (after Wild, Murray and Rowe, 1954: Plate 1).

The second recorded harmonic Type II burst occurred on 5 May 1953. The outburst was recorded on both displays, the A-scan record being used to derive the data presented in Figure 55. Because of the greater accuracy of the A-scans the profiles were plotted on a larger scale and at more frequent intervals. The dynamic spectrum of this event is simpler than the previous one shown in Figure 54. Also, the profiles show that the low-frequency edge of the fundamental band (full lines of Figure 55) is much steeper than the second harmonic suggesting a low frequency cut-off occurs. With the passage of time the ratio of peak frequencies gradually increases from about 1.7 near the start to 2.0 at the finish and the amplitude of the harmonic relative to the fundamental increases considerably.

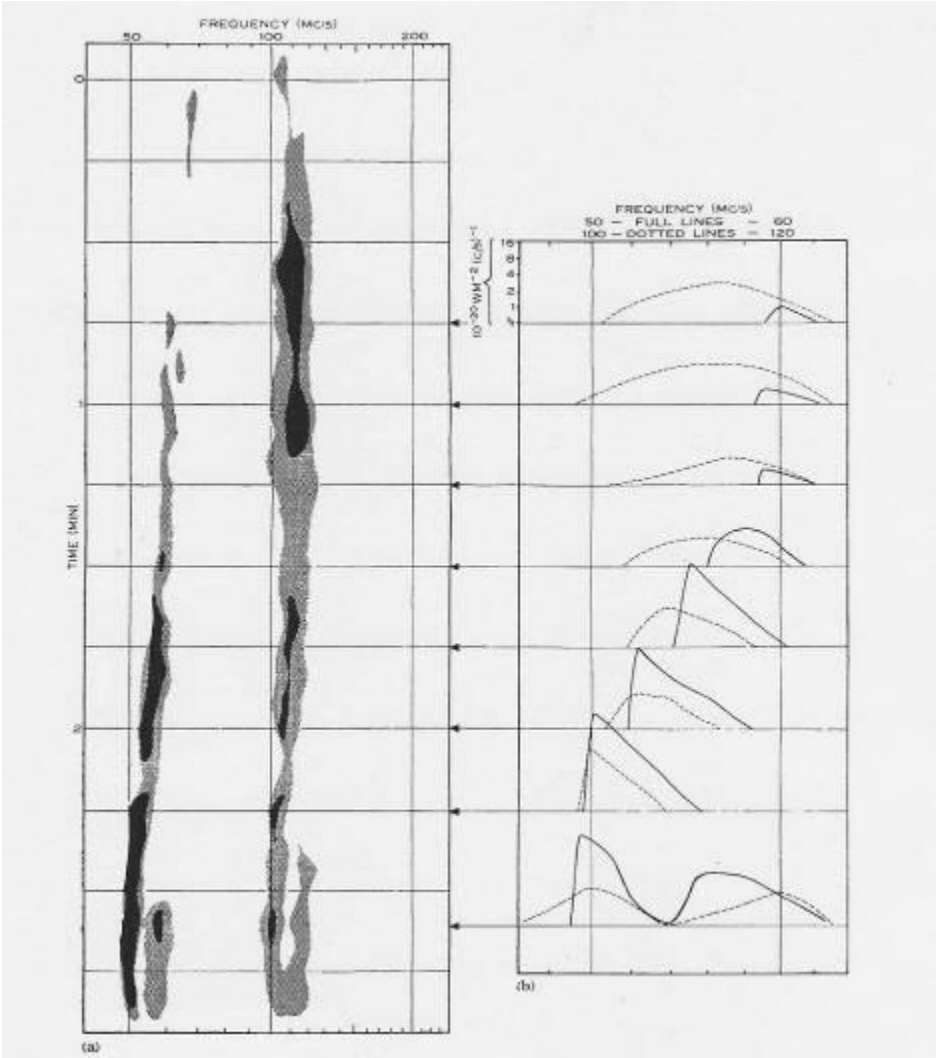


Figure 55 Outburst of May 5, 1953. (a) The dynamic spectrum, (b) profiles at 15-sec intervals (after Wild, Murray and Rowe, 1954: Plate 2).

3.5.3 Harmonics in Type III bursts

The fast-drift, short-lived bursts of spectral Type III recorded with a wider frequency range than previously (Wild 1950b) now often showed dynamic spectra consisting of two events in which the features of one are duplicated at about double the frequency. Examples are reproduced in Figure 56 and leave no doubt that the emission occurs at a fundamental frequency and its second harmonic. Two of these events (Figures 56 a and 56b) had been reported earlier by Wild, Roberts and Murray (1953).

Wild, Murray and Rowe (1954; 448) reported that:

In cases (a), (b), and (c) both fundamental and harmonic bands are seen to drift off the low frequency edge of the observed range, the rate of frequency drift decreasing continuously with time. In cases (d), (e), and (f), however, the frequency drift decreases so rapidly that one or both bands become almost stopped at a fixed frequency: the spectrum finishes in a vertical "tail". In all cases the fundamental and harmonic parts of the dynamic spectrum are similar in shape although the former tends to be of narrower relative bandwidth (Δf/f).

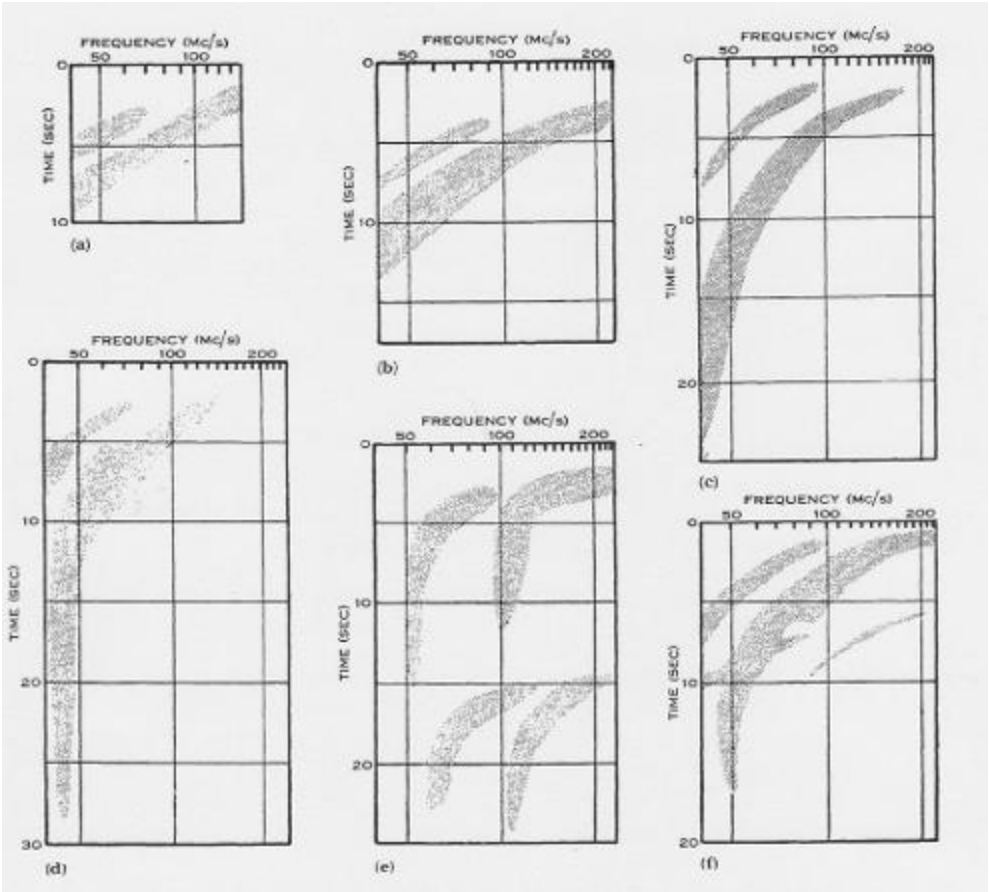


Figure 56 Dynamic spectra of Type III bursts. Dates of occurrence: (a) October 3, 1953. (b) June 7, 1952; (c) June 5, 1953, 01 hr 35 min; (d) June 5, 1953, 01 hr 37 min; (e) January 14, 1953; (f) June 5, 1953 (after Wild, Murray and Rowe, 1954: Fig. 4).

In Type II bursts it was found that the frequency ratio was often slightly less than 2:1 and a similar effect is demonstrated in Type III spectra of Figure 57 where the half-frequency harmonic profiles are consistently displaced to the left of the fundamental bands. In the great majority of cases the ratio lies between 1.85 and 2.00.

Of the several hundred Type III bursts recorded during this period, it was estimated that harmonics occurred in about 50 percent of the cases. This is an interesting statistic because Payne-Scott (1949) had reported earlier that about 50 % of the *unpolarized bursts* which she observed at Hornsby were double. Had she had access to spectral records she might have been the first person to identify harmonic Type III bursts.

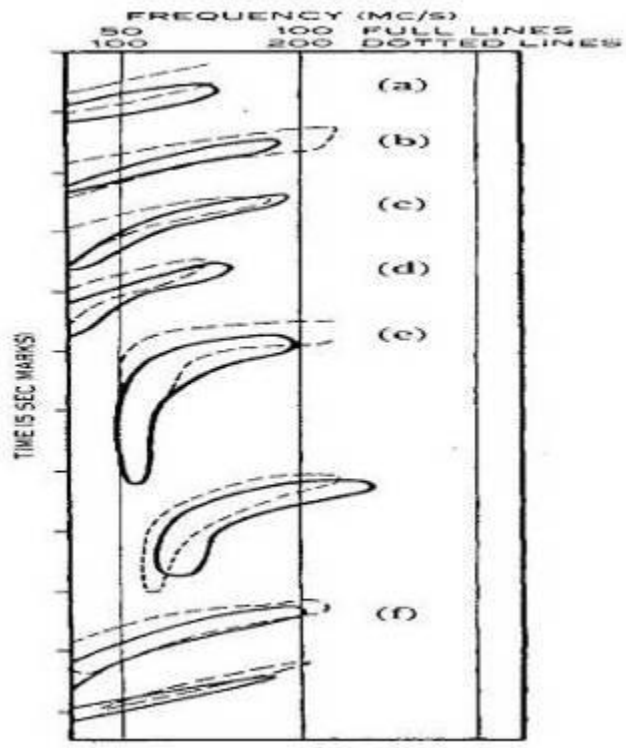


Figure 57 Comparison of the fundamental and second harmonic bands of the Type III bursts shown in Figure 3.14. The dotted profiles refer to harmonic frequencies reduced by a factor of 2 (after Wild, Murray and Rowe, 1954: Fig. 5).

3.6 Interpretation of Harmonic Structure

3.6.1 The Emission Mechanism

Wild, Murray and Rowe (1954) considered two emission mechanisms which were known to be capable of producing harmonic radiation in an ionized medium; electron gyro-frequency radiation from charged particles spiralling around magnetic field lines and plasma frequency oscillations.

(1) Electron Gyro Frequency

$$f_H = eH/2\pi mc \qquad (7)$$

Here *e* and *m* denote the electronic charge (e.s.u units) and mass (grams), *H* the magnetic field (gauss) and *c* the velocity of light (c.g.s units). It had been shown that the fundamental gyro frequency could not escape from the solar corona but the higher harmonics $2f_H$, $3f_H$, etc. could escape (Roberts, 1952). This would require the harmonic ratio of Type II and Type III bursts to be 3:2, 4:3 etc. and as this was not observed gyro frequency radiation was discarded as a possible mechanism.

(2) The Plasma Frequency

$$f_0 = e\,(N/\pi m)^{-1/2} \qquad (6)$$

Here *N* is the electron density of the medium (c.g.s units). As already discussed by Wild (1950a) several authors had suggested oscillations at the plasma frequency as the source of high intensity solar radio noise although no complete theory had yet been forthcoming. Difficulties arise for the fundamental because the plasma frequency coincides with the critical frequency at which the refractive index reduces to zero. Emission can only take place over a narrow cone normal to the surface of zero refractive index. No such escape restriction applies to the second harmonic. Provided the emission occurs over a rather narrow band of frequencies then both the fundamental and harmonic will be observed with a low frequency cut-off of the fundamental at the critical frequency. This prediction agrees with the observed harmonic ratio for Type II and Type III bursts being slightly less than 2:1.

3.6.2 The Escape of the Fundamental from a Model Corona

Using the theory of Jaeger and Westfold (1950) for the propagation and escape of radio waves from a Baumbach-Allen corona Wild, Murray and Rowe calculated the spectra for emission from

the 50 MHz plasma level at various angles to the line of sight. The derivations are reproduced in Figure 58.

For a source at the centre of the sun (θ= 0°), the ratio of peak frequencies of the fundamental and second harmonic is exactly 2, but the low frequency half of the fundamental band is completely absorbed. At θ= 10° the ratio reduces to 1.96 and to 1.90 at θ= 20°. The amplitude of the fundamental is greatly reduced and becomes zero at θ= 40°. The second harmonic can escape at wider angles up to θ= 70° but not greater (see Figure 59)

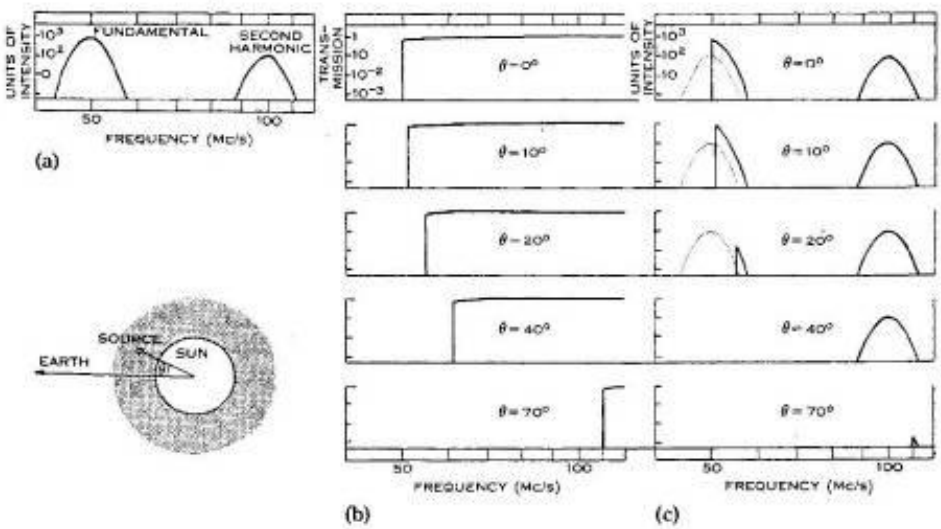


Figure 58 (a) Assumed natural spectrum for a point source at the 50 MHz plasma level in a Baumbach-Allen corona. (b) propagation characteristic (from Jaeger and Westfold, 1950) for various angles to the radial (c) the received spectrum (after Wild, Murray and Rowe, 1954: Fig. 6).

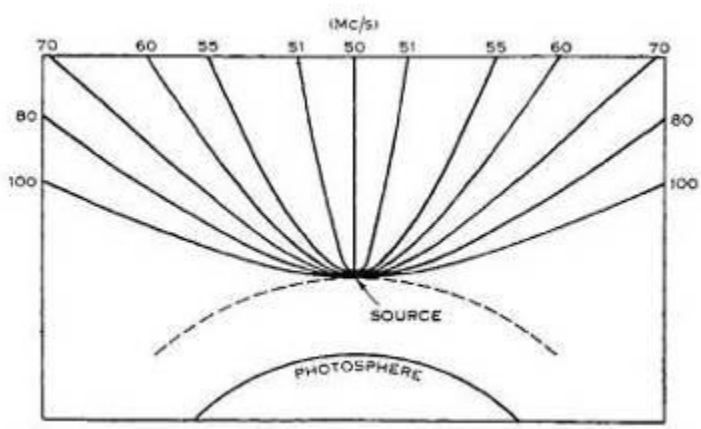


Figure 59 The limiting rays of outward emission at various frequencies from a point source at the 50 MHz plasma level in a Baumbach-Allen corona (after Wild, Murray and Rowe, 1954: Fig. 7).

3.6.3 Comparison with Observations

Wild, Murray and Rowe concluded that the above model could explain the following characteristics of Type II and Type III spectra:

(1) The occurrence of harmonic peak-frequency ratios slightly less than 2.0.

(2) The sharp low-frequency cut-off observed in the fundamental band.

(3) The reduction in amplitude of the fundamental peak relative to the harmonic as the peak-frequency ratio decreases.

3.6.4 The Position and Movement of Sources of Type II bursts

Wild et al. concluded that under idealized circumstances (assuming a standard electron-density model for the corona and using simple cases where the observed profiles fit the theoretical ones) it should be possible to determine (1) the plasma frequency (and hence the height in the corona) from the peak frequency of the second harmonic and (2) the critical escape frequency f_c (and hence the source angle), which according to Smerd (1950) can be expressed in terms of the fundamental plasma frequency f_0 as

$$f_c = f_0 \sec(0.87\theta) \qquad (20)$$

Figure 60 shows the results of applying this method to the harmonic Type II burst presented in Figure 55. The mean speed of the disturbance across the solar disk was found to be 4000 km/sec.

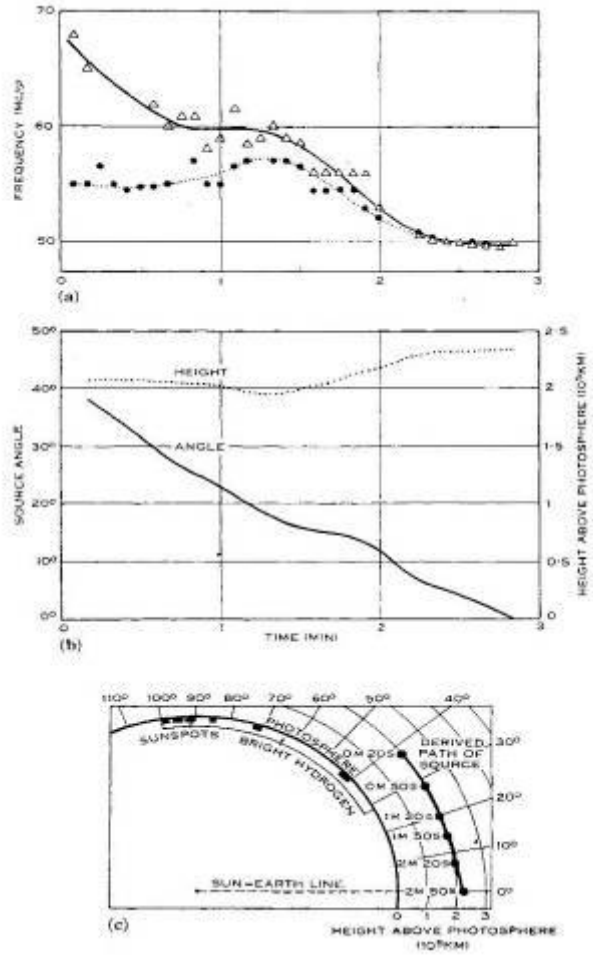


Figure 60 Position determinations for the Type II burst of Figure 55. (a) The variation with time of (1) the peak frequency of the fundamental (triangles) and (2) half the peak frequency of the second harmonic (dots); (b) The derived height and source angle; (c) Successive positions of the source at ½ min intervals. The heliographic longitudes of sunspots etc. are indicated (after Wild, Murray and Rowe, 1954: Fig. 8).

Unfortunately, as elegant as this derivation appears to be, it contained a fatal flaw not known at that time. Later observations (Roberts, 1958) showed that the fundamental Type II emission was detected over much wider angles than shown in Figure 59 indicating that both refraction and scattering processes were important for the escape of the radiation from the plasma level.

The outburst of Figure 54 was less suitable for the above analysis and Wild, Murray and Rowe (1954) that the peak-frequency ratio near 2 suggests a central location for the burst and that

a radial height time plot such as that shown in Figure 61 is justified. The plot indicates an approximately constant velocity of 475 km/sec over a 6:1 height range if one uses data points from both fundamental and harmonic bands.

Hence the detection of harmonic structure not only helped confirm the plasma hypothesis but also allowed the initiating disturbance to be tracked to much greater heights in the corona. This turned out to be one of the most important discoveries of the solar group and led to international recognition as well as support and funding by CSIRO for future studies.

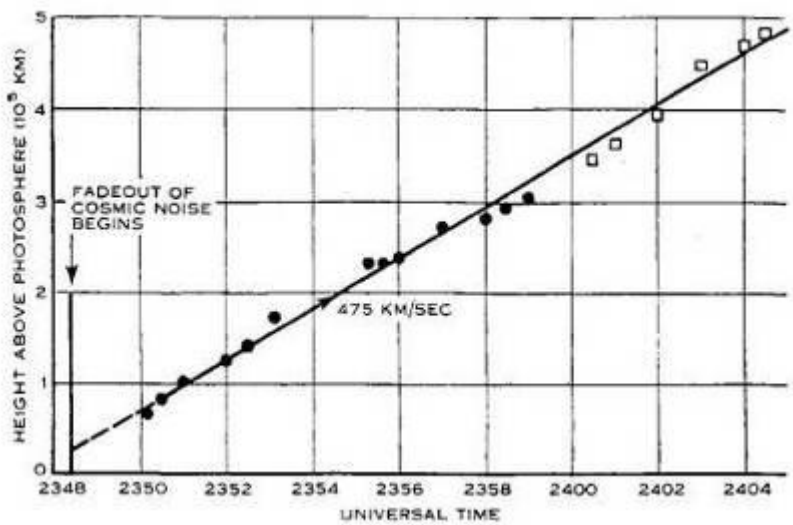


Figure 61 Derived height plot for the Type II burst in Figure 54. Where possible the heights are derived from the fundamental frequency band (dots). The range is extended to greater heights by using half the frequency of the second harmonic (squares) (after Wild, Murray and Rowe, 1954: Fig. 9).

Wild et al. were aware of the assumptions in their model such as the absence of density irregularities which would affect the refractive paths taken by the radiation. They noted that some coronal rays were known to have densities as much as 10 times those of the Baumbach-Allen spherically symmetrical corona. If such high densities were applicable to the outburst of Figure 61 the velocity would increase by a factor of about 1.6.

3.7 Radio Evidence for the Ejection of very fast Particles and Shock Waves from the Sun

In a second paper Wild, Roberts and Murray (1954) applied the plasma hypothesis to the observed spectra of both fundamentals and second harmonics in Type III bursts, thus extended the height range of each burst. The results are displayed in Figure 62. This figure shows some events displaying constant velocity with height and others showing deceleration.

The authors concluded that the Type III bursts are due to streams of fast particles (electrons or protons) ejected from the photosphere at the time of solar flares and that these particles travel outwards through the corona at velocities in the range $3x10^4$-10^5 (0.1c-0.3c). At such velocities electrons or protons could pass through the corona almost unimpeded by collisions. They noted that some events show deceleration but none acceleration. At a velocity of 0.3c particles reaching the earth could do so 50 min. after the onset of a flare and such a delay is typical of increases in cosmic-ray intensities that occasionally accompany flares (Wild, 1950b). It is possible that Type III bursts are caused by cosmic rays, but in that case the particles would have to be much heavier than protons to explain the energies derived by cosmic-ray investigators.

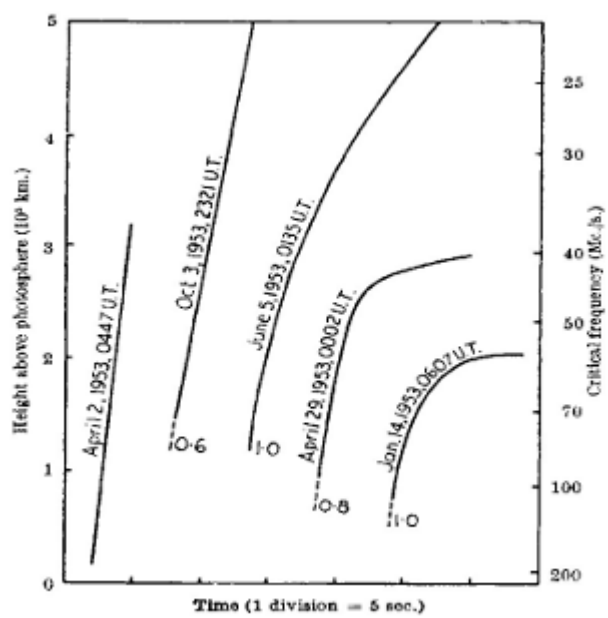


Figure 62 Derived height-time plots for harmonic Type III bursts assuming a Baumbach-Allen corona (after Wild, Roberts and Murray, 1954: Fig. 2).

3.7.1 Compound Type II-III bursts

Three compound Type II-III bursts were observed where the delays between the onsets of Type III and Type II bursts where the derived height-time plots (such as the example of Figure 63) suggested a common origin within 10^5 km. of the photosphere.

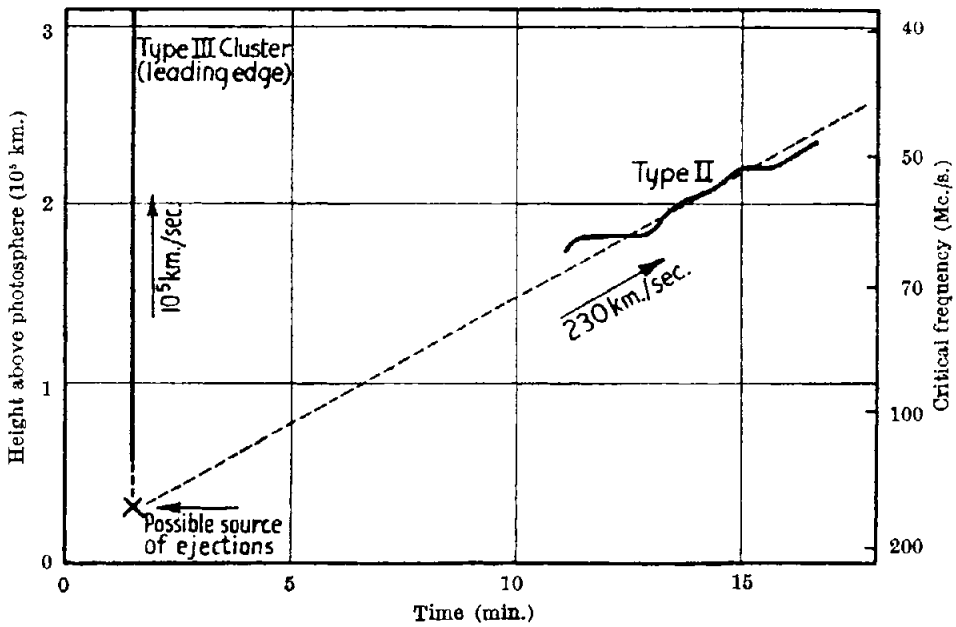


Figure 63 Plot of the derived motions in the solar atmosphere for a compound burst of 1 September 1952, 0336 U.T. (after Wild, Roberts and Murray, 1954: Fig. 3).

Wild, Roberts and Murray (1954: 173) discussed several mechanisms which could explain this phenomenon including a disturbance of some kind which gives rise to the combination of a fast corpuscular ejection and a shock wave. It is noteworthy that the typical slow (Type II) velocity is of the order of the mean speed of thermal protons in the corona, which may be identified with the velocity of sound.

This was the first time a shock wave origin for Type II bursts was considered. Later it was shown by Uchida (1960) and others that the shock wave was not a gas-shock but more likely a magneto hydrodynamic disturbance (m.h.d. shock).

The authors acknowledged Bill Rowe and Jack Joisce for their assistance with the observations. Work at Dapto continued with solar observations only when spots occurred on the disk because this was a time near solar minimum activity (John Murray. priv. comm., 2007). Instead, the spectrograph was used regularly during 1952-1955 to study the effects of ionospheric irregularities on the radio emission from Cygnus A. These observations are discussed next.

3.8 Radio Scintillations Studies at Dapto 1952-54

3.8.1 Introduction

On 17 April 1953 Paul Wild submitted a report to Joe Pawsey, Lindsay McCready and Taffy Bowen on "Investigation of Cygnus Fluctuations at Dapto" (National Archives, 2007) in which he wrote:

> Although the main long-term programme of work at Dapto is concerned with the sun, it has seemed desirable to find a supplementary line of research to enable the equipment to be put to maximum use during the sunspot minimum. With this in view, exploratory observations of the spectrum of Cygnus fluctuations in the frequency range 40-70 Mc/s have been carried out since September 1952. These observations and conclusions are summarized below:
>
> a. Records show intense ridges
>
> b. Records apparently showing interference patterns
>
> During the approaching winter period in which Cygnus fluctuations reach a maximum (say June to August inclusive), it is proposed to carry out an intensive programme of observations. Subsequently observations may be continued, but at less pressure, to January 1954 so as to include the summer maximum. It may then be appropriate to wind up the investigation completely. For this programme the following extensions are proposed:
>
> (1) Observation of the spectrum at 3 locations on the ground, arranged in a triangle with sides of the order of 0.5 to 1 Km.
> (2) Continuous observations of the apparent position of the source in an approx. E-W line, as a function of frequency using a swept-frequency interferometer.
> (3) Observations, at a fixed frequency, from a mobile station.

3.8.1 The Method of Observations

In the first of two publications of their results Wild and Roberts (1956a: 55) wrote:

> Observations taken simultaneously at different points on the ground have revealed that the fluctuations are due predominately to the motion of a relatively stable diffraction pattern over the ground at speeds of the order 100 m/sec. The outstanding problem is the interpretation of this pattern in terms of the ionospheric structure responsible for its formation.

Wild and Roberts showed that the introduction of spectral records led to a remarkable simplification in the interpretation of scintillations, which previously had been made at discrete frequencies only. They noted that:

The complete specification of a diffraction pattern on the ground requires measurement of both intensity and phase as functions of frequency and position on the ground. With these considerations in view, apparatus was built to record radio-star scintillations simultaneously in the following three ways:

(1) The recording of intensity at one point as a function of time and frequency, using a 40-70 Mc/s spectroscope.

(2) The recording of the phase gradient along one direction as a function of time and frequency, using a 40-70 Mc/s “swept-frequency interferometer.

(3) The recording of intensity at a fixed frequency (45 Mc/s) as a function of time at three points on the ground, arranged at the corners of an approximate equilateral triangle. Since variations with time are due mainly to the motion of the diffraction pattern across the ground (a result confirmed by the present observations), the temporal variations in (1) and (2) can be expressed in terms of spatial variations by using the drift velocity deduced from (3).

A complete record of a scintillation pattern is shown in Figure 64.

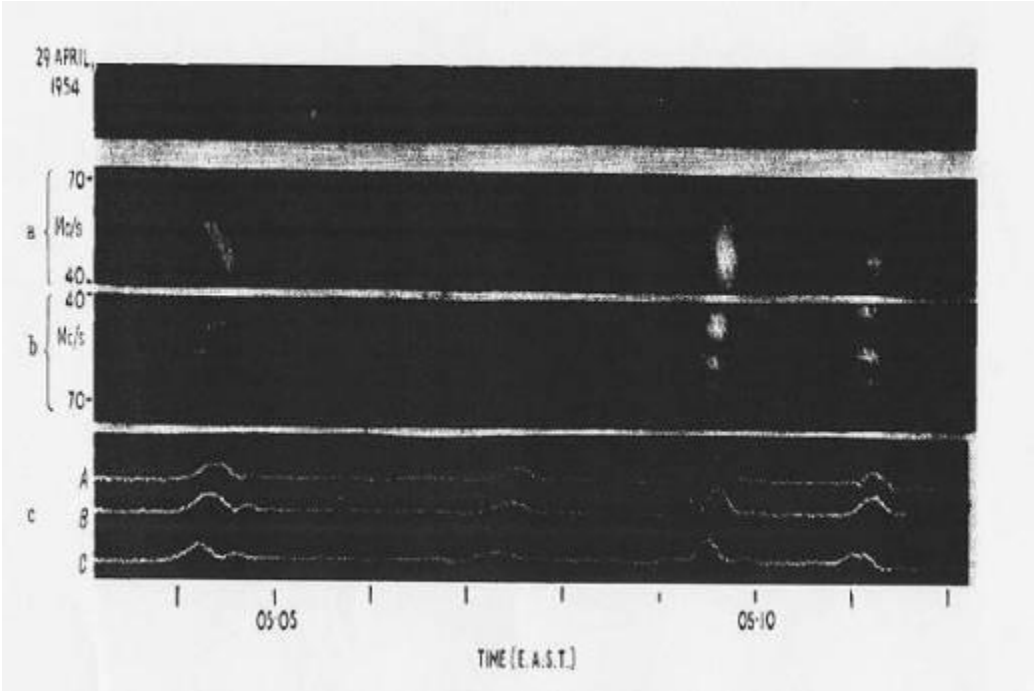


Figure 64 Complete record of ridge-Type scintillations recorded on 29 April 1954. (a) The dynamic spectrum. (b) The swept-frequency interferometer pattern. (c) 45 MHz records with the spaced-aerial system showing systematic time delays (after Wild and Roberts, 1956a: Fig. 3).

3.8.2 Characteristics of the Dynamic Spectra

Spectral records were taken between September 1952 and February 1955. Each record was of one to two hours duration being taken at the time Cygnus A transits Dapto and Sydney (e.g. about midnight on 21 July and noon on 19 January). Various Types of spectra were obtained and some of these are shown in Figure 65 while others are idealized in the sketches of Figure 66 below.

3.8.2 The Ridge Pattern

Figure 65 is typical of the commonest Type of record obtained at times of intense fluctuations. The duration of each ridge is between 10 and 60 seconds and the average spacing about two to five times the duration. The ridges do not appear to occur randomly but rather show some regularity such as seen by the seven successive ridges in Figure 65(b) between 1518 and 1531 E.A.S.T.

According to Wild and Roberts (1956a: 61): “Each ridge appears to result from the focusing effect of a single ionospheric “lens” consisting of a region of relatively low electron density - i.e., relatively high refractive index.”

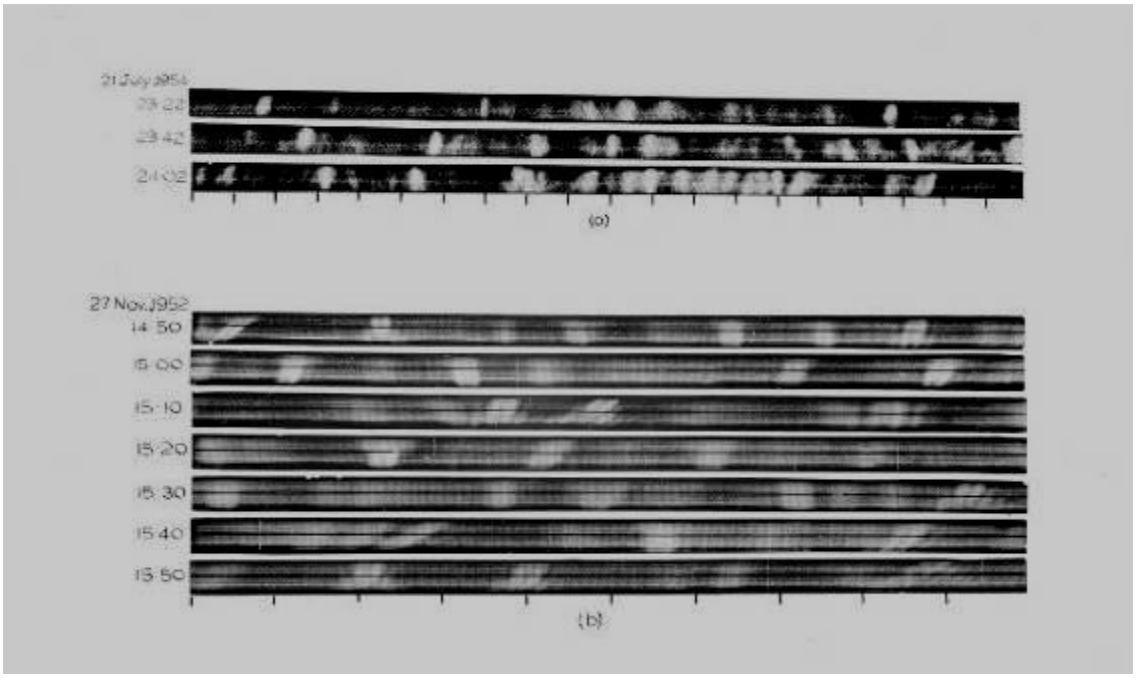


Figure 65 Dynamic spectra of ridge-Type scintillations (a) recorded on 21 July 1954 is typical of night-time (winter) records and (b) recorded on 27 November 1952, many of the ridges are seen to show an internal fine structure. Frequency increases vertically from 40 to 70 MHz, time horizontally (one minute marks shown). In each case the starting times in E.A.S.T. are shown on the RHS of each strip (afer Wild and Roberts, 1956a: Fig. 5).

3.8.3 Systematic Frequency Dispersion

In general there are systematic time delays between high and low frequencies causing the ridges to be inclined to the frequency axis (see Figure 66). Ridges recorded during the daytime (summer) showed more dispersion than those recorded during the night.

According to Wild and Roberts (1956a: 61):

> It was found that the three spectra (recorded simultaneously at each of the three spaced aerials) were normally similar, the systematic time delays between the same frequency at different positions being independent of frequency. Evidently

the frequencies are dispersed across the ground in the nature of a rainbow, and the whole pattern drifts coherently past the aerials. The phenomenon is attributed to dispersion by horizontal gradients of electron content in the ionosphere which act like huge prisms.

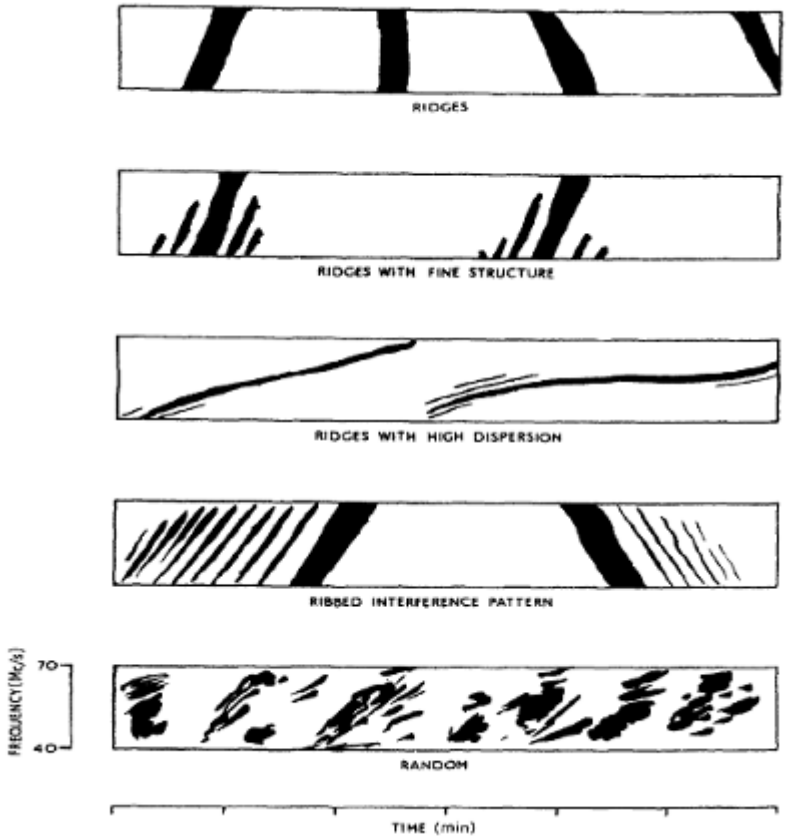


Figure 66 Idealized sketches of dynamic spectra (after Wild and Roberts, 1956a: Fig. 4).

3.8.4 Fine Structure in individual Ridges

Examples are shown in Figure 65(b) (and also in Figure 66) where the multiple bands in any one ridge are seen to be approximately parallel, but with a tendency to converge towards the lower frequencies. It was thought, but not shown, that this pattern is caused by diffraction and refraction by an ionospheric lens whose plane of best focus lies above the ground.

3.8.5 Interference Effects

Idealized sketches are shown in Figure 66 of this effect. According to Wild and Roberts (1956a: 62):

> Ribbed patterns are believed to arise when rays pass through a region of the ionosphere in which the large-scale horizontal gradient of ionization changes abruptly. Rays passing through the two gradients are bent towards each other and interfere. An optical analogy may be found in the Fresnel biprism.

3.8.6 Systematic and Random Effects

Wild and Roberts (1956a: 62-63) explained that:

> When the received radiation is due predominately to rays passing through a single element, variation of the frequency causes the phase along all rays to vary in a consistent fashion: hence the resultant pattern on the ground will show a systematic variation with frequency, and the dynamic spectrum will consist of a systematic pattern over the entire spectrum. Now the condition that an irregular screen will behave like a series of individual lenses is just that the scale-size of the finest structure of the screen exceeds the size of the first Fresnel zone (Little, 1951). Examination of the actual records shows that the great majority are dominated by systematic features.

A lower limit for the scale size of structure for systematic effects and an upper limit for random patterns was obtained by Wild and Roberts assuming a height of 400 km, which gives a slant height of 1200 km at 15° altitude, and the diameter of the first Fresnel zone at this distance is 2.3 km at 70 MHz and km at 40 MHz.. This gives a lower limit of 3 km for the scale-size of systematic effects and an upper limit of 2.3 km for random effects.

3.8.7 Size, Shape and Motion of the Pattern on the Ground

From Figure 64c it can be seen that the spaced aerial records are very similar but displaced in time. The delay between records A and B is much less than between B and C, and at any one time the intensities at aerials A and B are approximately equal, while that at aerial C is often different. This indicates that the pattern on the ground is elongated along the axis AB.

Equivalent ellipses were fitted to all the spaced aerial ridge records by computing the cross-correlation coefficients between records, taken in pairs. Figure 67 shows two typical examples one taken in winter and the other in summer. It was found that N-S orientation early always occurred for winter night-time records while daytime show no preferred orientation.

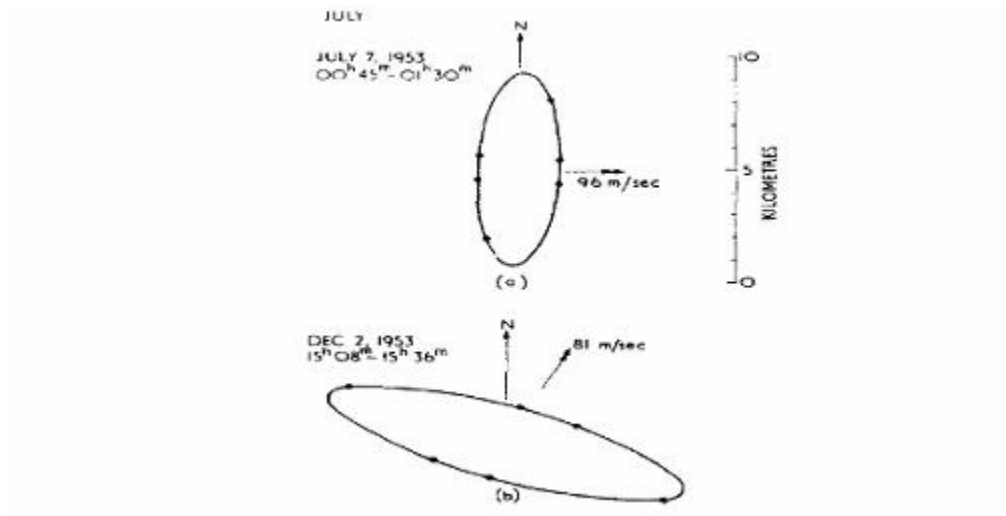


Figure 67 Ellipses showing the size and shape of the pattern on the ground for ridge-Type scintillations (after Wild and Roberts, 1956a: Fig. 10).

The apparent drift velocities were calculated from the relative time delays and the components are shown as monthly averages in Figure 68. The night-time velocities have a relatively low dispersion, and are clustered around a prevailing west-east motion of 80 msec^{-1}; in the daytime the dispersion is higher and the mean value is lower around 20 msec^{-1}. If the prevailing motions are attributed entirely to rotation of the earth this gives a height of 500 km for winter layers and 100 km for summer layers.

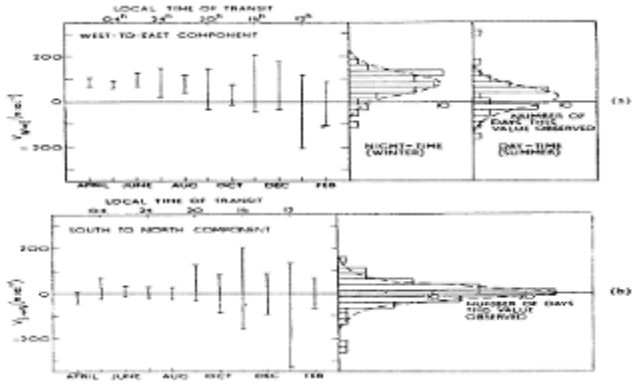


Figure 68 The annual variation of the velocity of ridge-Type patterns across the ground (after Wild and Roberts, 1956a: Fig. 13).

Wild and Roberts (1956a: 72) summarized their findings as follows:

(1) Observations of dynamic spectra indicate that the commonest Type of fluctuation is produced by the focusing effect of a single ionospheric irregularity

(2) The "focused" pattern is often dispersed across he ground like a rainbow. This effect is attributed to large-scale gradients in the ionosphere

(3) The pattern on the ground is usually highly elongated

(4) The degree of fluctuation shows a marked diurnal or annual variation, exhibiting maxima near midnight (winter observations) and midday (summer observations

3.8.8 Diurnal Variations in Scintillation Index

Mills and Thomas (1951) observing Cygnus A at an elevation of 15° found a correlation between scintillation and spread F echoes whilst Bolton, Slee and Stanley (1953) observing other sources at an elevation of 10° found a correlation with sporadic E only. Wild and Roberts in a second paper (1965b) resolved this discrepancy by showing that scintillations from Cygnus A observed during the night-time correlate with spread F but day-time observations correlate with sporadic E.

The diurnal variations of scintillation index are plotted in Figure 69 showing a peak around local noon in summer and a stronger peak around midnight in winter.

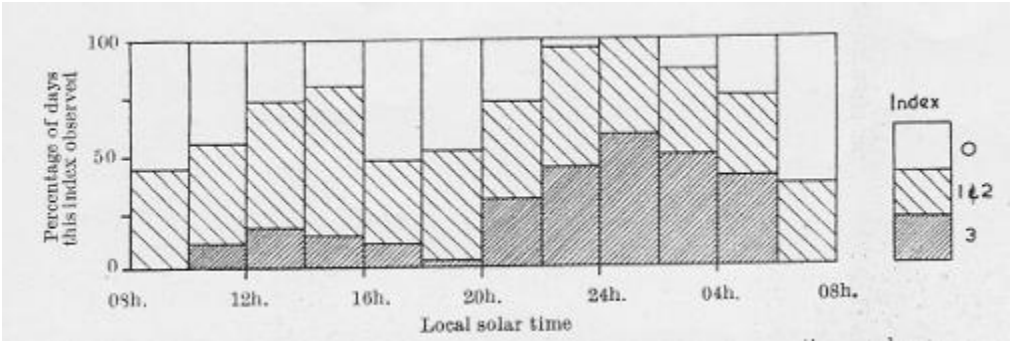


Figure 69 Solar time variation of the fluctuation index. Observations were made on 227 days during September 1952 – February 1955 (after Wild and Roberts, 1956b: Fig. 1).

Comparisons with Spread F observed at Townsville and sporadic E observed at Brisbane and Townsville showed the following correlations:

(1) Day-time scintillations: There is a marked tendency for high fluctuation indices to occur when the critical frequency of sporadic E echoes is high (Table 1 of Wild and Roberts (1956b).

(2) Night-time scintillations: There is a close association between the occurrence of high fluctuations and the appearance of spread F as shown by the data in Table 3.3 (Table 2 of Wild and Roberts, 1956b) but there is no evidence of any correlation with sporadic E (Table 3 of Wild and Roberts, 1956b).

3.8.9 Conclusion

Wild and Roberts (1956a: 55) wrote:

> Observations taken simultaneously at different points on the ground have revealed that the fluctuations are due predominately to the motion of a relatively stable diffraction pattern over the ground at speeds of the order 100 m/sec. The outstanding problem is the interpretation of this pattern in terms of the ionospheric structure responsible for its formation.

Jim Roberts (pers. communication, 2007) in reminiscences on his time at Dapto as well as giving a delightful insight into life at a field station in the early 1950s, said that Paul Wild asked him to write another paper on Cygnus A where the swept-frequency interferometer records would be discussed along with a mathematical model to explain the observed ridge pattern. He wrote (Appendix II):

> I was to produce Paper II, reporting and discussing the interferometer results, and presenting Paul's theoretical calculations. Other matters intervened and the paper was never completed. As a result neither Paul's calculations of the focusing by a density wave, nor the interference results were ever published. Perhaps this has contributed to the fact that what I believe to be important conclusions from these

observations never seem to have been accepted by some of the other workers in this field.

Although the swept-frequency interferometer scintillation measurements were not used, the principle of operation of this novel instrument was discussed and tested. Several measurements with the experimental interferometer were published by Loughead et al. (1957) and by Roberts (1958) (see Sections 3.13 and 3.14). In 1957 an improved version of the interferometer was installed for regular solar observations (Wild and Sheridan, 1958) and is described in Chapter 2.

3.9 Review Article on the Association of Radio Outbursts with Solar Flares

In 1954 in an article in *Vistas for Astronomy* Wild (1955a) reviewed what was known about solar radio outbursts at that time.

3.9.1 Association with Solar Flares

The first detection of high level noise from the Sun was made on British radar sets during February 1942. Hey (1946) concluded this increase was associated with a big solar flare. Appleton and Hey (1946) recorded six cases of a coincidence between an increase in solar noise in the frequency range 20-200 MHz and a solar flare or radio fadeout. Allen (1947) observing at 200 MHz noted that "sudden outbursts of radio noise occurred at the time of flares. These **outbursts** would last for a few minutes, fluctuate violently, and then disappear". Hey, Parsons and Phillips (1948) found that larger flares were more likely to be accompanied by a burst at 70 MHz (50% of class 2 and 3) while Dodson, Hedeman and Owren (1953) found an even higher correlation at 200 MHz (70%). Cases have been reported by Payne-Scott, Yabsley and Bolton (1947) and Wild (1950a) of outbursts being followed by great magnetic storms and aurorae (the effects due to the corpuscular emission from the Sun at the time of flares) after the elapse of the characteristic delay time of one to two days.

Wild (1955a: 575) noted, however, that "There is no evidence to suggest that outbursts have a closer association with any one of the accompaniments of flares than with the flares themselves."

3.9.2 Characteristics of Outbursts

Following the observations of Hey and Appleton in the 20-200 MHz range the detection of outbursts was extended to 480 MHz (Reber, 1946) then to 1200 MHz (Lehany and Yabsley, 1948), to 9500 MHz (Schulkin et al., 1948) and to 35,000 MHz (Hagen and Hepburn, 1952). The lowest frequency of detection was 9.2 MHz (Shain, unpublished data).

Two distinct phases occur at metre wavelengths in outbursts. In the first or main phase the level rises suddenly by a factor of some thousands, fluctuates violently and recedes after about 10 minutes. The second or storm phase starts soon afterwards with a more gradual rise. The storm may continue for hours or even days. The enhanced radiation appears as a relatively smooth continuum with frequent narrow-band Type I bursts. Polarization in the main phase is random while the second storm is circularly (Payne-Scott and Little, 1952). At higher frequencies the outbursts are smoother but sometimes show fluctuations as shown in the two examples of Figure 70.

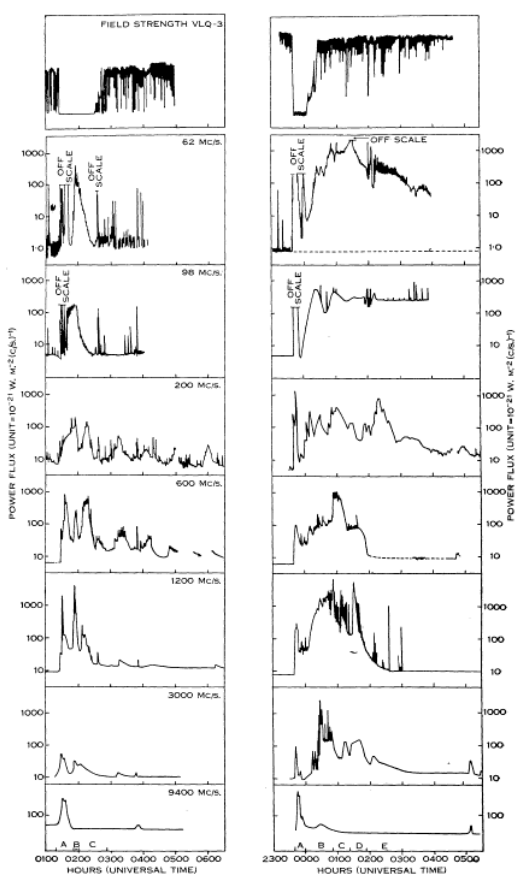


Figure 70 Two large outbursts recorded at 7 frequencies on 17th and 21-22nd of February 1950. The top record

shows the radio fadeout. (after Christiansen et al., 1951: Fig 1).

Spectral observations over the range 40-240 MHz by Wild, Murray and Rowe (1953) showed that in the outburst of 21 November 1952 the main phase contained a Type II burst with a frequency drift that, on the plasma hypothesis, converted to the height- time plot giving a constant outward source velocity of the order of 500 km per sec. The time delays due to the frequency drift of the leading edge of the Type II burst is consistent with those found in the 8 March 1947 outburst (Figure 5) observed by Payne-Scott, Yabsley and Bolton (1947).

Wild (1955a: 581) went on to point out that:

> We cannot yet be certain whether the sources of intense radio emission which are presumed to produce outbursts in their passage through the solar atmosphere correspond to any previously known phenomenon. Surge prominences sometimes attain outward velocities of 500 km per sec. and each heights of up to 5×10^{5} km above the photosphere before falling back to the Sun (Ellison, 1951).The unseen solar corpuscles responsible for generating terrestrial magnetic storms and aurorae travel between the Sun and Earth at mean velocities of about 800-1600 km per sec. Both are emitted at the time of flares and have velocities comparable with typical derived outburst velocities (500 km per sec.). On present evidence identification with the storm particles seems the more likely of the two because (1) frequency drifts have been observed only in one direction corresponding to outward motion and (2) the constant outward velocity is still maintained up to a height of 5×10^{5} km in the only observation at present available.

Swept-lobe interferometer observations at 97 MHz by Payne-Scott and Little (1952) detected outwards source motion in 5 of the 6 outbursts observed. A striking example is shown in Figure 71. By assuming that the sources moved radially outwards, velocities were found in the range 500-3000 km per sec. These velocities are comparable to or somewhat higher than those derived for Type II bursts and close to the velocities required to explain geomagnetic storms and aurorae.

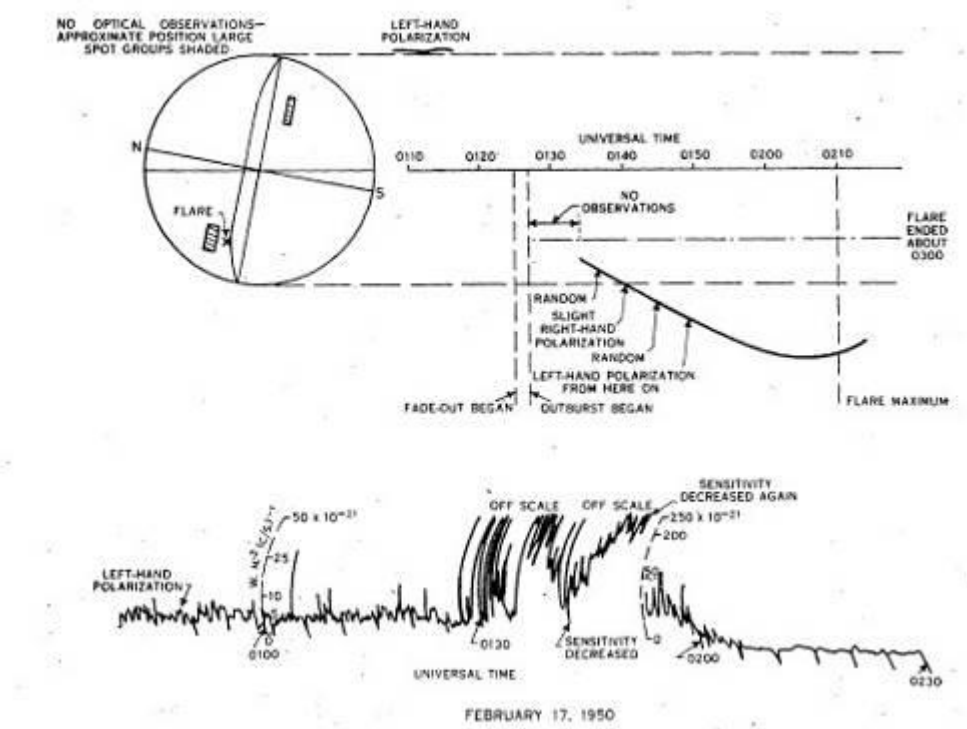


Figure 71 Observations of source position, polarization and intensity during the outburst of 17 February 1950 (after Payne-Scott and Little, 1952: Fig. 1).

3.9.3 Conclusions.

Wild (1955a: 573) summarized the observational evidence as follows:

> The present state of knowledge of the occasional large increases ("outbursts") of radio-frequency radiation from the Sun is briefly reviewed. Outbursts have been detected on frequencies ranging from 9-35,000 Mc/s. They last for several minutes and show a big correlation with solar flares. Recent investigations of their spectrum and position on the solar disk have indicated an origin in corpuscular streams ejected from flares. Current evidence suggests that the intense radio waves are excited at harmonics of the plasma frequency during the passage of the streams through the corona.

It is important to realize that at the time Wild wrote this article there was no distinction between the Type II burst and the continuum event which often accompanied it. Several years later Boischot (1958) using the Nancay interferometer at 169 MHz identified a polarized moving

continuum source, of relatively weak intensity following the Type II burst, which he called a *Type IV burst*. This is why there was a misconception that the Type II burst and the outwardly moving polarized source might be related to the same phenomenon. The moving events observed by Payne-Scott and Little (1952), mentioned above were most likely Type IV continuum but there was no radio spectral records available at that time to confirm this, otherwise I am fairly certain that they would have been the ones to discover the Type IV burst (see Section 3.18, 4.1 and 4.5 for more discussion).

3.10 Future Research Activities

On the 7th July 1954 Pawsey (National Archives, 2007) summarized the current program for the Radio Astronomy Group of the Division of Radiophysics as follows:

> "In the past, projects have been planned on the basis of a small group building apparatus and using it to get all the information possible. We are moving towards the observatory procedure, where complex equipment is used by a succession of observers to investigate explicit problems."

Regarding solar research at Dapto he wrote;

> "In the present period of low sunspot activity (say 18 months) thoroughly renovate gear and add facilities for: (a) polarization (b) direction finding in readiness for extensive work in new cycle."

He also noted that solar research activities would require (c) close liaison with optical workers.

3.11 1955 Review Article on Dapto Spectrograph Results

At the I.A.U. Symposium No. 4 on Radio Astronomy held at Jodrell Bank U.K. in 1955 Wild (1957) summarized the results obtained at Dapto since 1952 under the following headings.

3.11.1 Derived Velocities of Corpuscular Streams from the Sun

Histograms of velocities derived from the frequency drift of Type II and Type III bursts are compared with those inferred from the sun-earth time delays of terrestrial magnetic storms and cosmic ray increases and with H□ ejections from flares were presented (Figure 72).

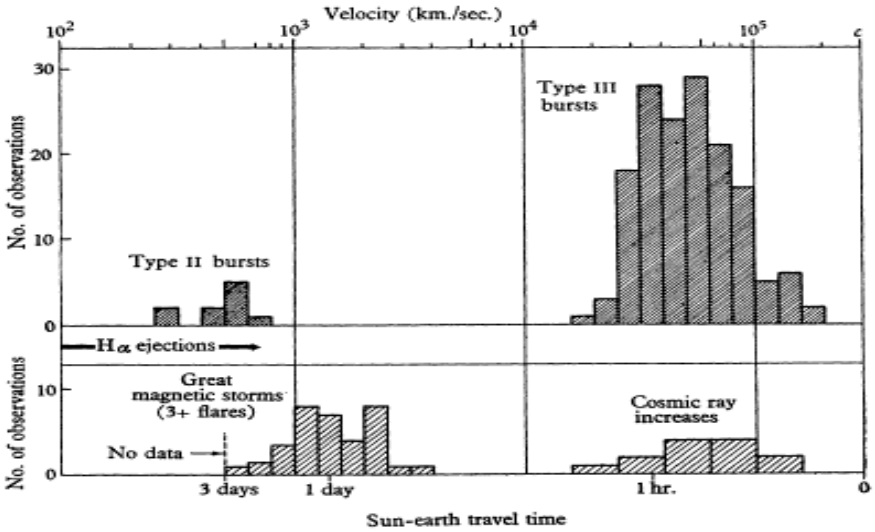


Figure 72 Histograms of velocities of solar corpuscular particles ejected fro solar flares (after Wild, 1957: Fig. 2).

Wild pointed out that the energies of Type III particles (~100 MeV if protons) are considerably lower than cosmic ray energies which would make any possible connection obscure. Also, the Type II velocities are distinctly lower than the geomagnetic storm velocities but the latter only refer to very big flares of importance 3 + whereas the Type II bursts were associated with smaller and presumably less energetic flares.

3.11.2 Two Classes of Solar Radio Storm

Two distinct classes of solar noise storm are now recognized. One kind consists of Type I bursts which are often clustered within restricted but variable bands superimposed on a slowly varying background continuum. The second consists of an intermittent sequence of Type III bursts occurring at a rate of the order of 10-100 per hour. Both kinds are associated with sunspot activity. Sometimes both kinds occur together.

3.11.3 The Macroscopic Pattern of a Type I Storm

In addition to irregular features, emission bands are often seen to drift repeated from high to low frequencies suggesting upwards motion of the source at speeds of the order of 100 km/sec. Other records occasionally show downward motion reminiscent of ascending and descending prominence material (see also the study of *Type I chains* in Section 3.20).

This is consistent with later results by Wild and Zirin (1956), who, in a statistical study of active regions associated with noise storms recorded at 167 MHz at HAO Observatory, Boulder Colorado during 1949-1955, found that there appeared to be a loose connection between the ordering of the coronal material by the magnetic field, producing loops and streamers, and the production of radio noise storms (Figure 73). They found several examples of eruptive loop prominences at the solar limb which appeared to be closely associated with noise storms. Surge activity in these events reached velocities of the order of 150-250 km/sec.

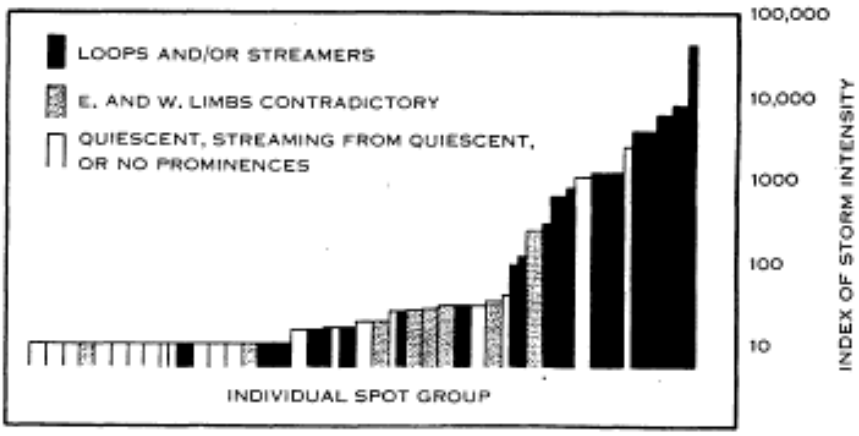


Figure 73 Spot groups arranged in order of increasing intensity, shaded according to limb characteristics (after Wild and Zirin, 1956).

3.11.4 Polarization Studies

Wild (1955) also mentioned that polarization studies had been initiated at Dapto. These are described in the following research paper by Komesaroff (1958).

3.12 Swept-Frequency Polarization Studies of Solar Bursts over the 40-70 MHz Range

The polarization measurements were conducted by Max Komesaroff using the Dapto spectrograph from January to October 1955 near the start of the new solar cycle. According to John Murray (2007) the polarization equipment was available since 1953 but the absence of burst activity prevented any study occurring an earlier. Observations included Type I bursts, Type II bursts and Type III bursts. The principle of the polarimeter is described in Section 2.5.

3.12.1 Type I Bursts

Altogether, 13 days of Type I activity were studied and it was found, in agreement with earlier studies, that the radiation was highly circularly polarized (>50 %) at all frequencies and usually showed the same sense of polarization throughout the frequency range and during any one day. This can be seen from Table 3 (Table 1 of Komesaroff, 1958).

TABLE 3

SENSE OF ROTATION OF POLARIZATION ELLIPSE

TABLE 1

SENSE OF ROTATION OF POLARIZATION ELLIPSE

(a) Type I Bursts			(b) Type III Bursts		
Date (1955)	U.T.	Sense of Rotation	Date (1955)	U.T.	Sense of Rotation
Jan. 6	0423–0845	L			
Jan. 10	0434–0450	L (M.F. range only)	Jan. 10	0801	L
	0514–0521	R (L.F. range only)		2052–2054	L
Jan. 11	0338–0530	L			
Jan. 12	0834–0837	L ?	Jan. 12	0705–0815	L
				2140	L
Jan. 13	2318–0634	L			
Jan. 15	0351–0841	L			
Jan. 16	2216–0511	L			
	2150–2211	L			
Feb. 2	0226–0436	R	Feb. 2	0634	R
				0712	R
				0754	R
			Mar. 3	0300	R
Mar. 4	0435–0488	R			
Aug. 12	0307–0609	R	Aug. 12	0536	R
				0538	R
Sept. 6	0003–0720	L			
Oct. 10	2242				
Oct. 11	0714	L			

Examples of the modulation pattern of polarization in the spectra of Type I noise storms are shown in Figure 74.

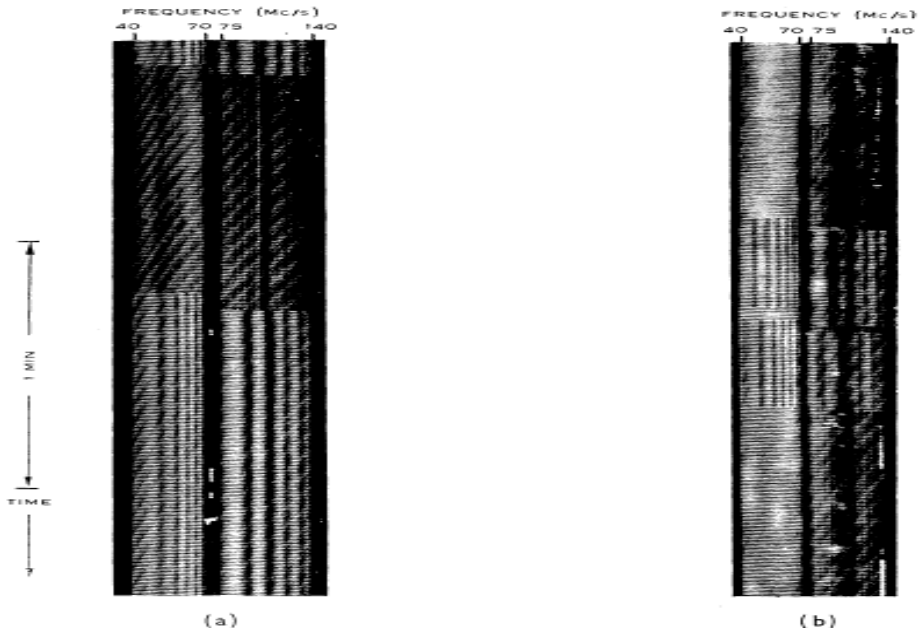


Figure 74 Single records of strongly polarized Type I radiation. The bright streaks parallel with the time axis are the maxima of the modulation pattern. Unpolarized sections obtained with single aerials are included. The faint sloping lines on the records are due to power lines producing a 50 Hz modulation (after Komesaroff, 1958: Plate 1).

3.12.2 Type II Bursts

Polarization measurements were obtained for 13 Type II bursts, eight of which were completely unpolarized, three showed weak modulation and two were indeterminate because of their narrow bandwidth. Only one record was polarized for a short period but the modulation at maximum was not greater than 30%. Komesaroff noted that Payne-Scott and Little (1951) had reported surges of activity at 97 MHz whose intensities and duration would suggest Type II bursts (although no spectral records were available at that time). They found that, although the radiation was initially unpolarized, it often went through a period of elliptical polarization. The apparent conflict could be resolved if it was assumed that this period represented the beginning of a Type I storm.

3.12.3 Type III Bursts

Over 500 Type III bursts were observed and about 50 % of these showed the modulation pattern of fairly strong circular polarization. Examples of the spectral records of polarized and unpolarized Type III bursts are shown in Figure 75.

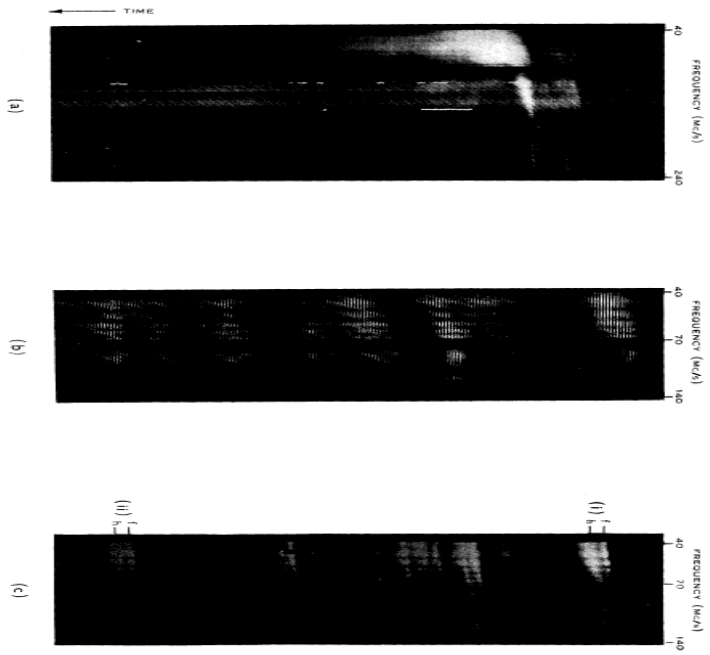


Figure 75 (a) Record of an unpolarized Type III burst observed on 15 August 1955 at 0155 U.T. (b) Polarized Type III bursts on 12 January 1955 at 0749 U.T. (c) Cluster of polarized Type III bursts observed on 9 June 1955 between 0246 and 0250 U.T. The numerals (i) and (ii) indicate bursts showing a definite harmonic structure. The fundamental and second harmonic components are designated by *f* and *h* respectively (after Komesaroff, 1958: Plate 2).

The burst in Figure 75 (a) would later be classified as a *spectral Type V* burst rather than a Type III burst (Section 3.19).

Because of the wide beamwidth of the rhombic aerials it is possible that some of the measured polarization was due to ground reflections which produce linear polarization. This was suggested by the observations that, in the period January to March 1955, the ratio of modulated to unmodulated bursts rose sharply for the higher solar zenith angles. However, Komesaroff argued that the majority of polarization measurements were genuine for the following reasons:

(1) Observations for the period May to October 1955 do not show the trend with zenith angle shown by the earlier results.

(2) Measurements of phase angle cluster around $\theta = \pi/2$ and $\theta = 3\pi/2$ indicative of genuine circular polarization (Figure 76).

(3) Polarization of Type III bursts occurring on the same day showed the same sense of polarization; moreover, it was the same as that of circularly polarized noise storm bursts occurring within one or two days (Table 1b).

(4) The occurrence of fundamental and harmonic components of Type III bursts both showing circular polarization but with the fundamental more highly polarized than the harmonic cannot be explained by ground reflections or any other known terrestrial effect.

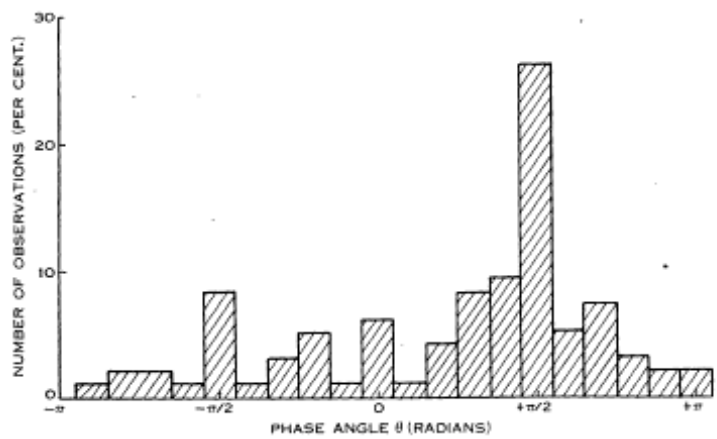


Figure 76 Frequency distributions of phase angles of 40 Type III bursts occurring throughout the year (after Komesaroff, 1958: Fig. 4).

To establish more definitely the solar origin of the polarization of Type III bursts, a sample record was chosen for detailed analysis. The record selected was that of 9 June 1955. Table 4 is a summary of the day's activity. Both polarized and unpolarized bursts occurred between 0008 and 0248 U.T. during which period the solar zenith angle changed only by about 6.5 ^{o}.

Komesaroff noted that Type III bursts previously were thought to be always unpolarized (Payne-Scott, 1949). However, this misconception was mainly due to terminology as Payne-Scott had labelled all short duration bursts as noise storm (Type I) bursts. However, a closer examination of a number of those bursts occurring almost simultaneously at 85 and 60 MHz (which were clearly Type III bursts) were found to be polarized (see Table 4; after Table 2 of Komesaroff, 1958).

TABLE 4

SUMMARY OF ACTIVITY OF 9 JUNE 1955

SUMMARY OF ACTIVITY JUNE 9, 1955

Time (U.T.)	Bursts	Observed Modulation
0001–0002	Type III	None
0008–0019	Main part of type II burst	None
0032	Tail of type II burst	No evidence of modulation
0033½	Cluster of type III bursts	High
0118–0120	Cluster of type III bursts	None
0246½–0250	Cluster of type III bursts some showing harmonic structure	High—up to 70 per cent.

3.12.4 The Origin of Polarized Radiation

According to Komesaroff polarization imposed by the medium may arise in two ways:

(1) Polarization by total internal reflection in a birefringent medium. He wrote (Komesaroff, 1958: 211):

> Now it is well known that, for radiation to escape from the corona (see for example Smerd, 1950) it must originate above the level for which the refractive index for the ordinary ray is zero.....
> In the presence of a magnetic field, there is another level, above the first, at which the refractive index for the extraordinary mode is zero. The separation between these two levels increases with the intensity of the magnetic field. Radiation in the region between them is polarized because only the ordinary mode can escape. For quite a wide range of angles between the direction of propagation and the magnetic field, the polarization is nearly circular. [Figure 77] is a plot of the heights of zero refractive index in an extreme case – above a very large sunspot whose magnetic field at the chromosphere surface is 3600 oersteds [Smerd, 1950].

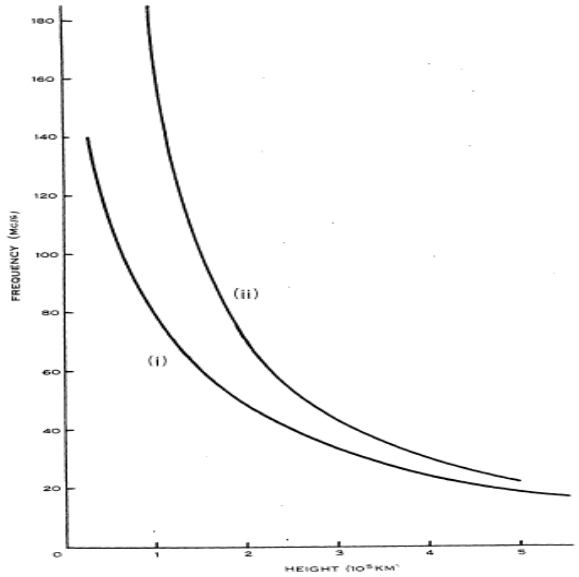


Figure 77 Heights of the levels of zero refractive index in the corona above an extremely large unipolar sunspot group having a surface magnetic field intensity of 3600 oersteds from Smerd (1950). The numbers (i) and (ii) refer to the ordinary and extraordinary mode respectively (after Komesaroff, 1958: Fig. 6).

It is possible to explain the polarization of Type I bursts over the frequency range 40-140 MHz by internal reflection but the source must extend over a very large distance, at least over a radial distance of 10^5 km.

On the other hand, we cannot explain the polarization of harmonic Type III bursts in terms of total internal reflection. The fundamental and harmonic frequency components originate from the same source (Wild, Murray and Rowe, 1954), and , referring again to Figure 6 [my Figure 3.35], we can see that in no case do the regions between the two reflection levels overlap for frequencies whose ratio is 2:1 when the lower frequency lies in the range 20-40 MHz.

(2) Polarization by differential absorption.

He also pointed out that a second way is by differential absorption of modes, which depends on the electron collision frequency. Although this

> might contribute to the fundamental component, it is quite inadequate to explain the polarization of the harmonic because the impressed polarization mainly occurs near the zero refractive index level.

Komesaroff concluded that the circular polarization of harmonic Type III bursts originates in the source region and not in the intervening medium.

Despite the difficulties incurred with this Type of measurement, Komesaroff's conclusions were essentially correct and vindicated when Rao (1965) found examples of very high circular polarization in some Type III bursts using the 40-70 MHz swept-frequency interferometer. Even the observation of weak polarization in several Type II bursts might have been a real effect caused by the undetected presence of herringbone structure, which Stewart (1966) found to be circularly polarized (Section 4.9).

Komesaroff's doubts about linear polarization being the result of ground reflections was also vindicated when Grognard and McLean (1973) showed that Faraday Rotation in the ionosphere was so high that any linear polarization imposed at the source would be randomized at 80 MHz. Hence claims of detecting linear polarization in Type III bursts (Cohen and Fokker, 1959) were probably spurious.

3.13 Correlation of Type III Bursts with Solar Flares

Following Wild, Roberts and Murray's (1954) suggestion that Type III bursts might be caused by solar cosmic rays it was decided that a joint investigation by the Divisions of Physics and Radiophysics be undertaken to study the association of solar flares with Type III bursts. Using the Dapto spectrograph and the Hα flare patrol telescope at Fleurs, NSW Loughhead, Roberts and McCabe (1957) undertook an investigation from November 1955 to July 1956 in which over 300 flares were investigated, of which 85% were sub-flares (of importance class 1-). About 20% of the flares were associated with Type III bursts, while more than 60% of the Type III bursts recorded occurred during the lifetime of a flare.

3.13.1 Position Measurements for Type III Bursts Associated with Solar Flares

An association was said to occur if a burst occurred within 2 min of the flare. Further evidence for an association was obtained on three days during the period of investigation when the east-west position of Type III bursts were measured to an accuracy of 4 min of arc by examining the interference fringe pattern of the first Dapto 40-70 MHz swept frequency interferometer records This experimental interferometer was constructed to study ionospheric scintillations from Cygnus A (see Section 2.4) which did not result in any published measurements (apart from the Type III burst positions mentioned here and the Reverse Drift Pair positions described below in Section 3.14). Examples of the interferometer fringe patterns recorded by the interferometer on 9 November 1955 are shown in Figure 78 along with their spectra.

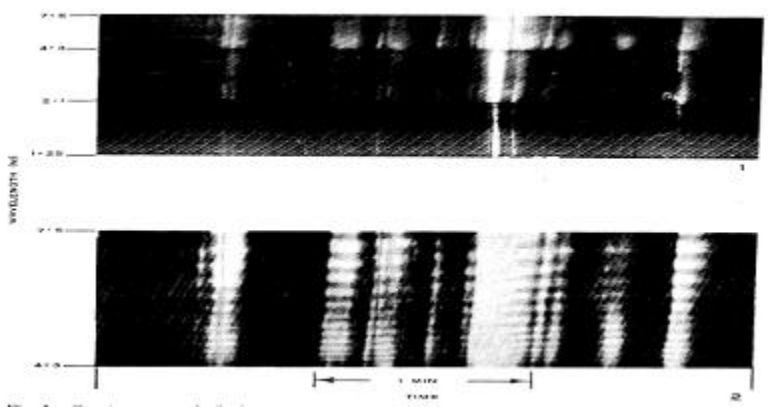


Figure 78 (a) Spectral record and (b) interferometer record of Type III bursts on November 9, 1955. Interference fringes are evident in (b) (after Loughhead et al., 1957: Plate 1).

Figure 79 shows a comparison of solar flare positions and Type III positions recorded on the same day. It can be seen that not all bursts appear to be associated with solar flares and not all recorded flares produce Type III bursts.

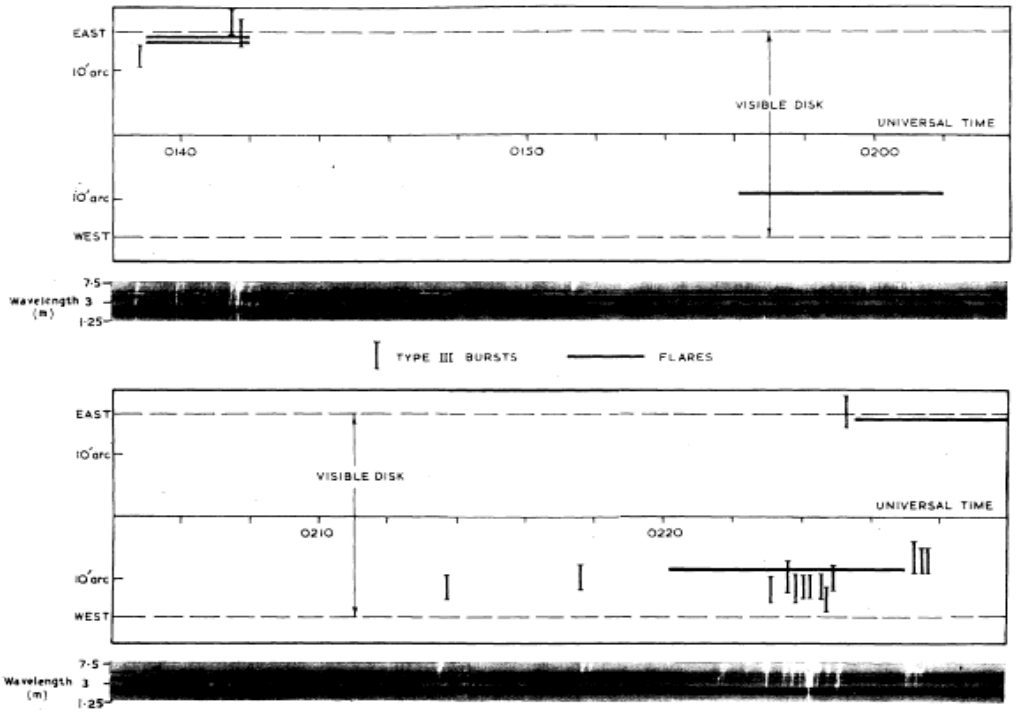


Figure 79 Comparison of the positions on the solar disk of the Type III bursts and chromospheric flares recorded in the period 0138-0230 U.T. on 9 November 1955 (after Loughead et al., 1957: Plate 4).

3.13.2 Dependence of Flare Association with Flare Area and Longitude

The dependence on the degree of association increased with flare area as shown in Figure 80, a result consistent with the findings of Hey, Parsons and Phillips (1948).

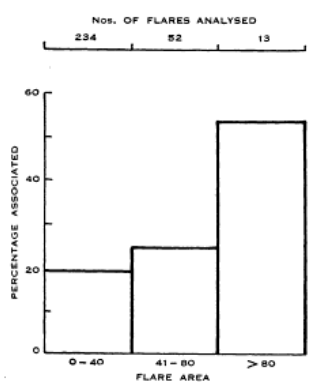


Figure 80 Histogram showing the dependence of association on apparent flare area (after Loughhead et al., 1957: Fig. 2)

The dependence on disk longitude is shown in Figure 81. There does not appear to be any preferred longitude apart from a deficit at the west limb, indicating a wide cone of emission for Type III bursts.

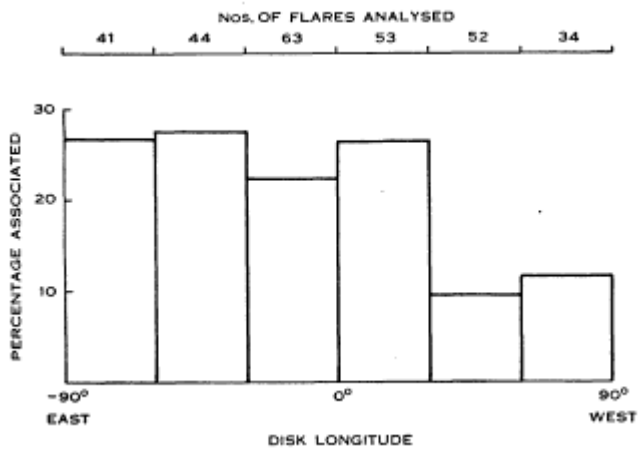


Figure 81 Histogram showing the dependence of disk longitude on the association of Type III bursts and solar flares (after Loughead et al., 1957: Fig. 3).

During the period of investigation Type III bursts showed a higher correlation with solar flares than was observed for Type I noise storms. The few Type II bursts observed during this period were associated with stronger flares

3.13.3 Conclusion

Loughhead et al. (1957) concluded that the radio bursts on metre wavelengths, which are associated with solar flares, are found to be mainly of spectral Type III with over 60% of the bursts occurring during solar flares, but not all flares or active regions on the sun produce Type III bursts.

Loughhead was a member of the CSIRO Division of Physics under the leadership of Ron Giovanelli and later with Bob Bray developed the 10 inch refracting solar telescope installed at the Culgoora Observatory. Later, Marie McCabe left the Division of Physics to join John Jefferies, Jack Zirker and Frank Orral at the Institute for Astronomy of the University of Hawaii. She was in charge of solar observations at Mt. Haleakala, Maui. I was fortunate enough to work with her there in 1972 on coronagraph observations just prior to the Skylab Mission in 1973-74.

3.14 Discovery and Nature of Reverse Drift Pairs 1955-57.

Observations over the previous five years with the Dapto 40-240 MHz spectrograph had shown that the majority of recorded bursts fell naturally into the three spectral classes Type I, II and III. However, on rare occasions a new Type of burst was observed termed a *reverse drift pair* (RDP) because of its spectral characteristics (Roberts, 1958). A preliminary report of these findings was presented by Joe Pawsey to the U.R.S.I. Assembly in Boulder, Colorado in August 1957.

3.14.1 Spectral Characteristics

The RDP burst is characterized by two narrow bands drifting from lower to higher frequencies at rates typically between 2 and 8 MHz per sec. The two elements of the pair are remarkably similar in form, although their intensities are sometimes very different. Often the pair begins at about same frequency but with a delay of 1.5 to 2.0 seconds and often terminate at about the same frequency. Examples are shown in Figure 82.

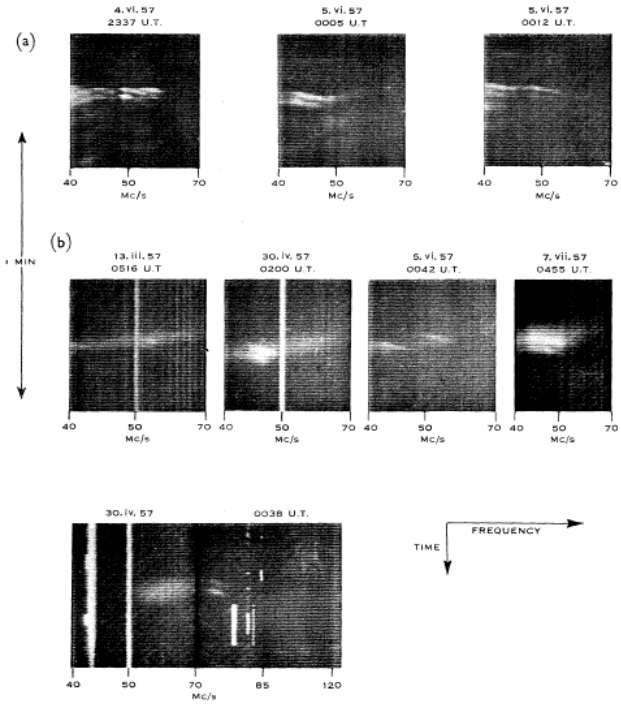


Figure 82 Examples of *reverse drift pairs* (a) showing sudden changes in the rates of frequency drift; (b) occurring within bursts of spectral Type III (after Roberts, 1958: Plate 2).

The RDP is quite rare only occurring on 38 out of the 250 days of records obtained from November 1955 to July 1957. About 10% of the hundreds of RDP observed occurred during Type III bursts and were easily recognized because of their greater intensity. The bursts have shorter durations and instantaneous bandwidths than Type III bursts and drift in the opposition direction hence their name.

The bursts appear to be restricted mainly to the 40-80 MHz frequency band. The observed frequency range of each burst element is shown in Figure 83(a) and total number observed at each frequency in Figure 83(b).

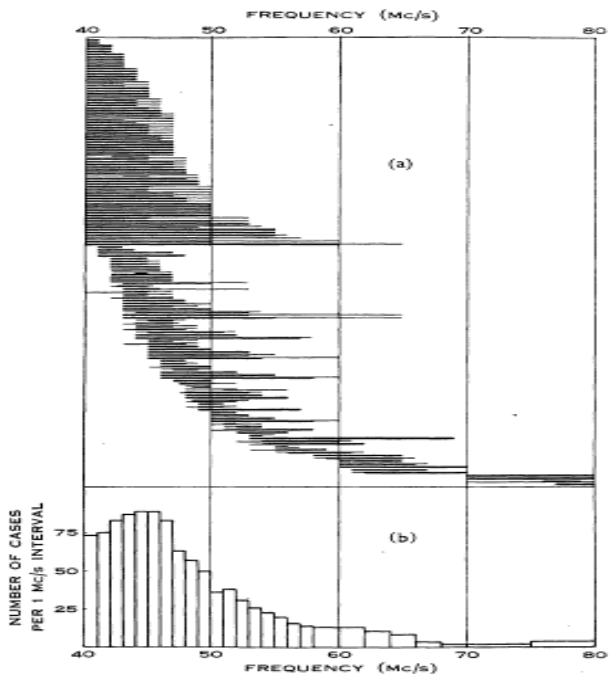


Figure 83 (a) Each reverse pair is represented by a pair of contiguous lines which show the frequency extent of the two elements of the burst. (b) Histogram showing the prevalence of bursts at different frequencies (after Roberts, 1958: Fig. 2).

Two variants of the pair are shown by the idealized sketches in Figure 85 but the vast majority of bursts conform to the time-delay model of Figure 84(b).

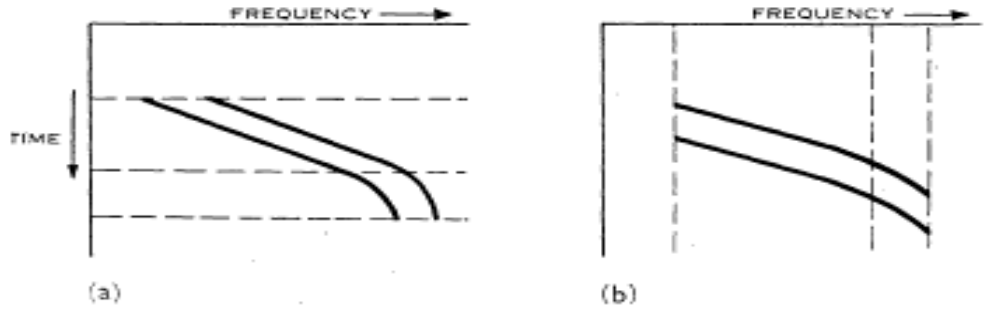


Figure 84 (a) The 'frequency-separation model'. (b) The 'time-delay model' (after Roberts, 1958: Fig. 3).

This is confirmed by the histograms of Figure 85 which show that in about 90% of the cases the two parts of the RDP begin and end within 1.5 MHz of each other.

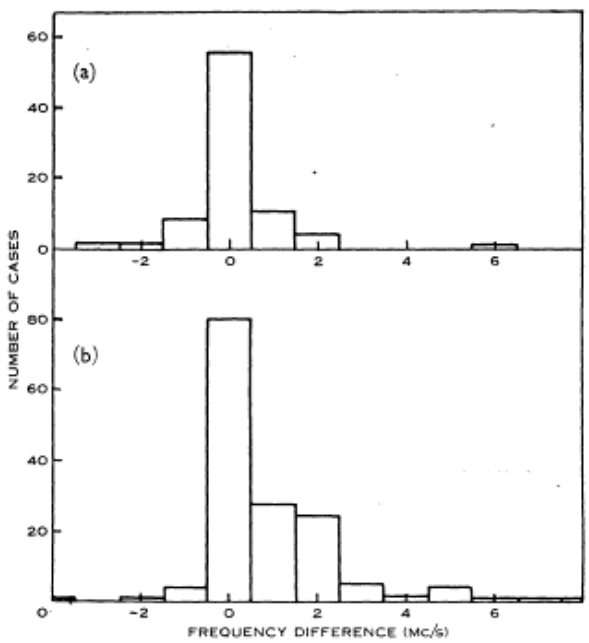


Figure 85 Histograms showing the differences in (a) the starting frequency, and (b) the finishing frequency of the two elements of the observed reverse pairs (after Roberts, 1958: Fig. 3).

3.14.2 Swept-Frequency Interferometer Observations of Reverse Drift Pairs

On 12 and 13 March 1957 some reverse pairs were observed with the experimental 40-70 MHz swept-frequency interferometer described earlier by Wild and Roberts (1956). Although not enough frequencies were observed to give an unambiguous position it was clear that at the

declination of the sun the burst positions would occur on the solar disk. The solar origin is supported by the close association of reverse pairs with Type III bursts.

On 4 and 5 June 1956 Kraus (1956) observed "double-humped" bursts at 27 MHz and gave an indirect argument which suggested the bursts originated on Venus. As the Dapto spectrograph had recorded a small storm of reverse pairs on 5 June 1956 it seems quite likely that Kraus also observed the same Type of bursts from the sun and not from Venus which was 10^0 away at that time.

3.14.3 The Echo Hypothesis for Reverse Drift Pairs

Roberts (1958) showed that the second element of the reverse pair is an approximate repetition of the first element with a time delay typically 1.5 to 2.0 seconds. This suggests that a single band is emitted but received via two paths with different propagation times. The most straight forward explanation for Roberts was to consider the possibility that emission occurred above the fundamental plasma level and that the radiation was received as both a direct and a reflected ray as shown in Figure 86.

Jaeger and Westfold (1950) had first suggested that the "double- humped" unpolarized bursts observed by Ruby Payne-Scott (1949) were due to echoes from a regular corona and had shown that such echoes should have time delays of several seconds at frequencies near 60 MHz. However, these double bursts were later identified as fundamental and second harmonic components of Type III bursts by Wild, Murray and Rowe (1954).

Roberts extended these ideas by assuming that in the case of the reverse drift pair the radiation only occurred at the second harmonic of the local plasma frequency. He then calculated the centre to limb variation in the echo time delay for a source at the 30 MHz plasma level in a Baumbach-Allen coronal density model by using the refraction equations developed by Jaeger and Westfold (1950).

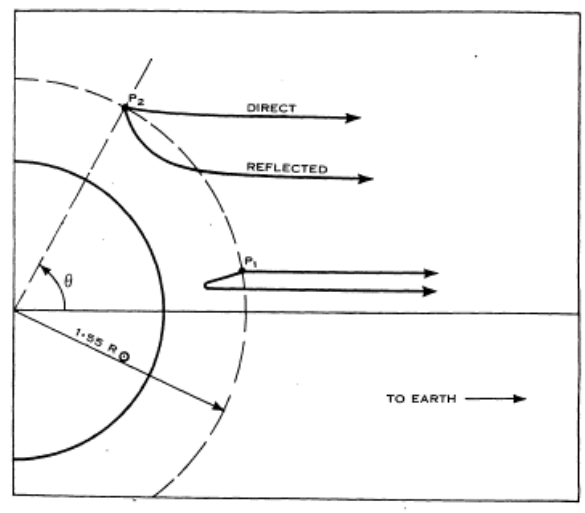


Figure 86 Diagram showing the paths of direct and reflected rays in the corona for a source located at the 30 MHz plasma level and radiating at 60 MHz. (after Roberts, 1958: Fig. 9).

Roberts' results are given in Figure 87(a) where it can be seen that the echo time delay for 60 MHz radiation varies from about 3 seconds at a viewing angle $\theta = 0^0$ to zero at an angle $\theta = 75^0$. As there were no measured positions for the reverse pairs in this study, this theory could not be verified by examining the variation of delay times with position on the disk. Indeed, to my knowledge, this theory has never been tested by any subsequent observations.

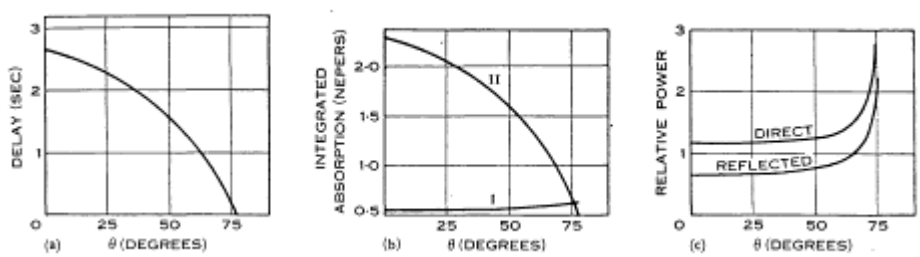


Figure 87 Centre to limb variation for a source at the 30 MHz plasma level radiating at a frequency of 60 MHz. The source position angle θ is defined in Figure 3.19. (a) time delay of the reflected ray after the direct ray. (b) Integrated absorption in the direct (curve I) and reflected (curve II) ray (after Roberts, 1958: Fig. 11).

3.14.4 Two Explanations for the Positive Frequency Drift

Roberts offered two explanations for the reverse drift pairs.

(1) Differential absorption

There were insufficient observations to test this effect but the large scatter in the observed ratio of intensities of the two elements of a reverse pair, which was much greater than that shown by the curves of Figure 87(c), suggested that some other mechanism such as scattering of the radiation might be more important.

(2) Coronal hills

The apparent association in at least 10% of the pairs with Type II bursts led Wild to suggest to Roberts that the reverse pair may be the result of the Type III stream of particles encountering a "hill" of electron density in the corona. But without knowing more information on the extent of such a hill it is difficult to decide if such an event could explain the observed properties of the RDP.

To this day, to my knowledge, there is still no satisfactory explanation for the reverse drift pair phenomenon or for that matter for other fine structure such as "stria bursts" sometimes associated with Type III bursts (see Kai, 1985 for more details).

3.15 Association of Type II Bursts with Solar Flares 1956-57

A collaborative program by the two CSIRO Divisions during 1956-57 investigated the optical disturbances which could be responsible for Type II outbursts (Giovanelli and Roberts, 1958, 1959). 15 Type II bursts were recorded during Hα flare patrol observations. All bursts were found to be associated with optical disturbances which produced H_a particle ejections. The results are summarized in Table 1 of Giovanelli and Roberts, 1959.

3.15.1 Chromospheric Activity Associated with Type II Bursts

Of the 13 definite identifications, nine are with flares on the disk, two with surges at the limb, and two with ejected prominences at the limb. The other two flares followed disappearing filaments which are the manifestation of eruptive prominences on the solar disk.. The linear velocities of all the eruptive events were supersonic and >200km/sec but somewhat lower than the radial

velocities derived from the Type II drift rates, assuming a Baumbach-Allen spherically symmetric coronal density model.

3.15.2 Disk Distribution of Flares Associated with Type II Bursts

The distribution of solar flare positions indicated that fundamental Type II bursts could be seen out to radial distances of 0.8 R_0 (Figure 88) suggesting a much wider cone of emission than expected from the theoretical calculations of refraction effects in a spherical corona (Jaeger and Westfold, 1950).

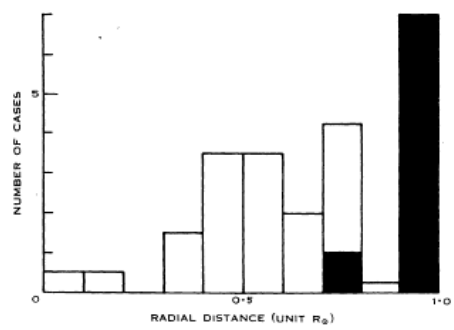


Figure 88 Distribution of Type II bursts with radial distance determined from the flare position. Shaded regions refer to bursts not showing harmonic structure while unshaded regions refer to bursts with fundamental and second harmonic bands (after Giovanelli and Roberts, 1958: Fig. 1).

3.15.3 Conclusions

It was concluded from these results that:

(1) the ejections seen in Hα could well be the exciting agency responsible for Type II bursts but that the case was by no means proven and

(2) a modified theory was required taking account of coronal structure, while more extensive observations were needed of limb ejections, with direst measurements of the position and movement of the radio sources.

3.16 Statistical Study of the Properties of Type II Bursts 1949-57

In 1958 Jim Roberts attended the URSI-IAU Joint Symposium on Radio Astronomy at Paris on his way to CALTECH California where he worked on Jupiter's radio emissions. Returning to Sydney he joined the Parkes Cosmic Group. At Paris he presented a preliminary account of his statistical study of Type II bursts (Roberts 1959a) A more detailed account was published in 1959 (Roberts 1959b). This was the most comprehensive study of Type II bursts at that time and deserves some attention to detail. He summarised the results as follows (Roberts, 1959b: 327):

> Approximately half the bursts show harmonic structure and about half are compound Type III-Type II bursts. Band-splitting the doubling of both the fundamental and second harmonic bands, is also relatively common. A rather less common feature is the appearance of herring-bone structure in which the slowly drifting band of the Type II burst appears to be a source from which rapidly drifting elements diverge towards lower and higher frequencies.
>
> Statistics are given of the rate of occurrence of the bursts, their frequency range, the rate of frequency drift, and the harmonic ratio.
>
> Many of the Type II bursts occurred near or after the maximum of the chromospheric flare. However, only about 3 per cent of flares (of Class 1 or greater) are accompanied by Type II bursts, although the figure rises to 30 percent for Class 3 flares.
>
> There is a greater tendency for the geomagnetic field to be disturbed in a few days following a Type II burst than there is after large flares which are not accompanied by Type II bursts, or after large radio bursts of spectral Type III. Statistically, the greater disturbance occurs after about two days, implying a mean speed of travel of about 1000 km/sec.

3.16.1 Frequency of Occurrence of Type II Bursts

The number of bursts observed each year from 1949 when radio spectrograph observations began until the end of 1957 is shown in Figure 89. The occurrence rate mimics the sunspot cycle which had a minimum around 1954.

Type II bursts are rare by comparison with Type I and Type III bursts occurring only about once per 50 hr on the average near sunspot maximum, whereas Type I and Type III bursts probably occur about one every few minutes. However, clustering of Type II bursts occur on a shorter time scale indicating that some active regions on the Sun produce many Type II bursts, while other regions produce none. This inference is consistent with the results of the earlier study of chromospheric flares associated with Type II bursts (Giovanelli and Roberts, 1958, 1959).

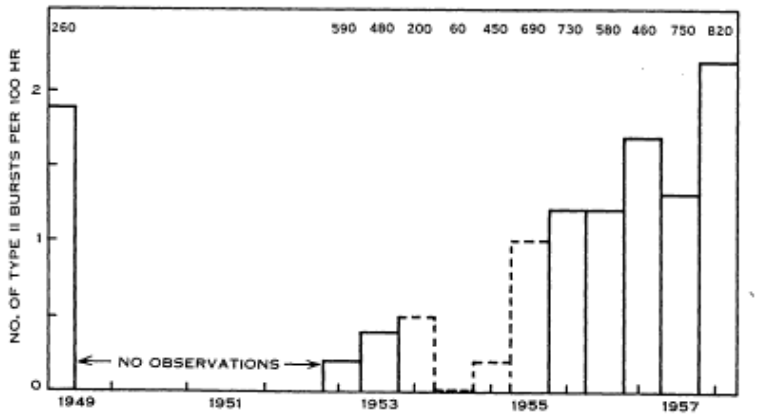


Figure 89 Histogram showing the frequency of occurrence of Type II bursts. The numbers at the top of the figure show the number of hours of observation in each 6-monthly period. During the time near sunspot minimum (1954), where the histogram is dashed, the observing time was confined entirely to occasions when sunspots were visible on the solar disk (after Roberts, 1959b: Fig. 1).

3.16.2 The Rates of Frequency Drift and the Inferred Speeds

The frequency drifts of 24 fundamental Type II bursts is shown in Figure 90 and the inferred speeds in Figure 91 which range from about 300 to 1000 km/sec above the Alfven speed for the lower corona [~ 300 to 400 km/sec] indicating a shockwave disturbance as previously noted by Wild, Roberts and Murray, 1954.

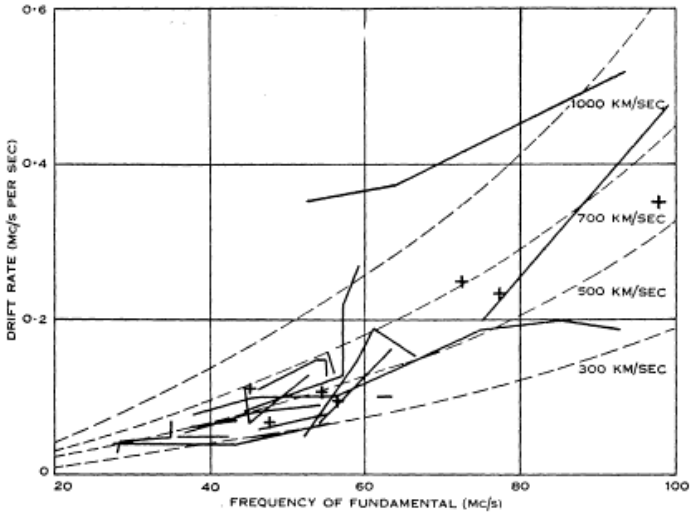


Figure 90 Frequency dependence of the drift rate in the fundamental band of 24 harmonic Type II bursts. Crosses refer to single measurements and lines to measurements at a number of frequencies within the band. Dashed curves show the drift rates expected for disturbances moving in a Baumbach-Allen model corona at constant radial speeds shown on the figure (after Roberts, 1959b: Fig. 3a).

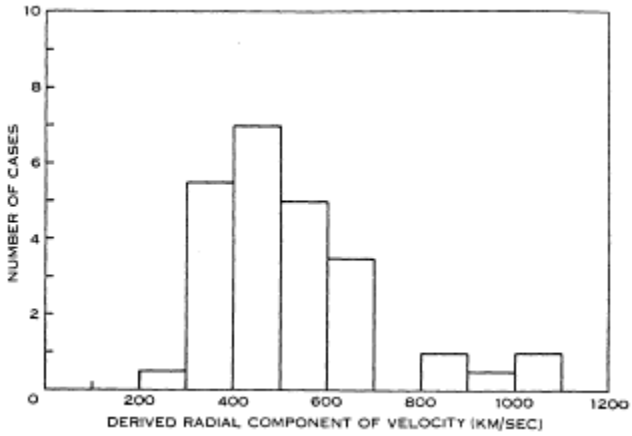


Figure 91 Histogram of the mean radial speeds of the 24 Type II bursts (after Roberts, 1959b: Fig. 3b).

3.16.3 Disk Distribution of Harmonic Ratios

Wild, Murray and Rowe (1954) showed that the harmonic ratio of Type II bursts was slightly less than 2.0 and explained this in terms of absorption of the lower part of the fundamental band. They showed that more of the fundamental band would be prevented from escaping from the corona at

larger angles to the line of sight by refraction and absorption effects in a spherically symmetric corona (Section 3.6). Roberts showed that the disk distribution of harmonic ratios for flare associated Type II reproduced in Figure 92 bursts does not agree with this theory.

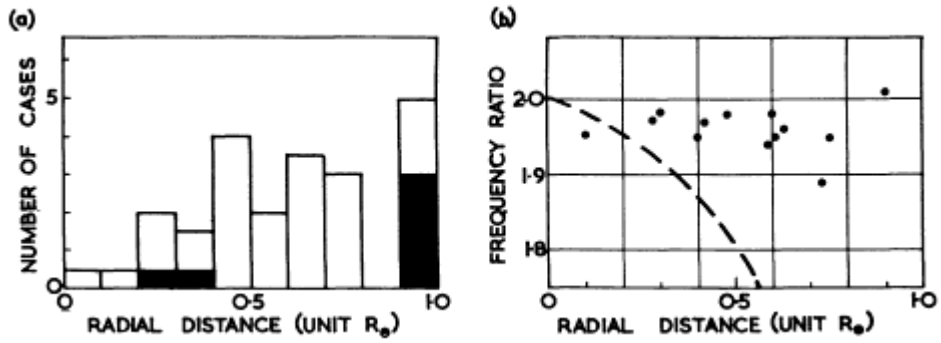


Figure 92 (a) Distribution of Type II bursts associated with a solar flare. Unshaded regions refer to bursts showing both fundamental and harmonic bands. Shaded regions refer to bursts where a harmonic was not observed. (b) Disk distribution of observed harmonic ratios (dots) compared with the predicted curve from Wild, Murray and Rowe (1954) (after Roberts, 1959a: Fig. 3).

To explain this result Roberts (1959a: 197) suggested that:

> Quantitative agreement may be possible if radiation in the fundamental band is strongly scattered by irregularities near the level of origin, so that it emerges in a wide cone and not in the very narrow beam predicted on the basis of (refraction in) regular spherical corona. Since the refractive index for the fundamental band is close to zero at the level of origin, small variations in the electron density could produce considerable scattering.

3.16.4 Band Splitting

The doubling of both the fundamental and second harmonic band is referred two as split-band structure and was first reported by Wild, Murray and Rowe (1954). Roberts found that about 20% of Type II bursts showed this effect. Examples are shown in Figure 93.

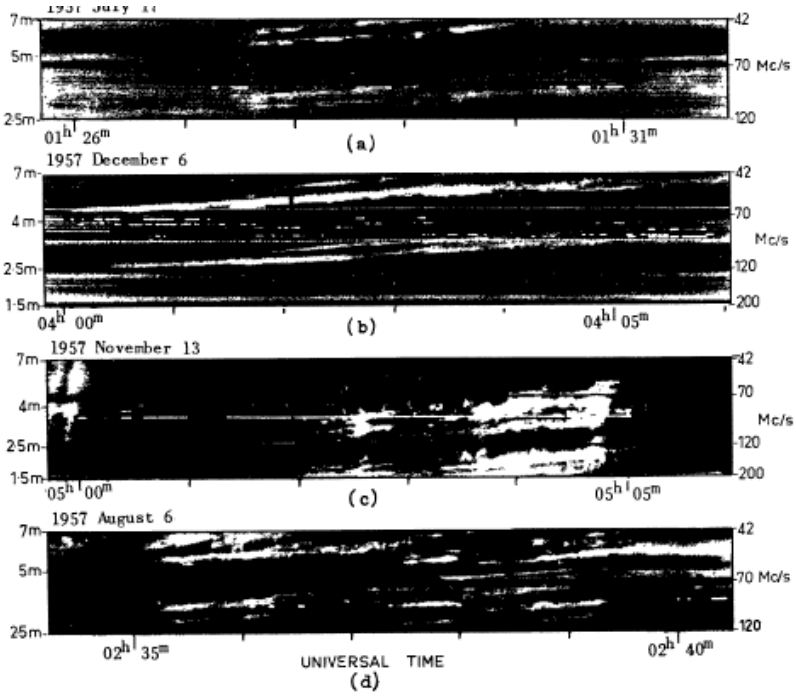


Figure 93 Examples of Type II bursts showing split-band structure (after Roberts 1959a: Fig. 2).

Often similar features are reproduced in both portions of the split-band suggesting radiation from a single source. The magnitude of the separation conforms with the idea that the splitting is a Zeeman effect as suggested by Wild (1950a). This is illustrated by Figure 94 where the frequency split is compared with the gyro frequency f_H of the corona above a large sunspot.

However, Roberts concluded that there was no general agreement between existing theory and observation on the excitation of radiation near the plasma level in the presence of a magnetic field (see Section 4.10 for more details).

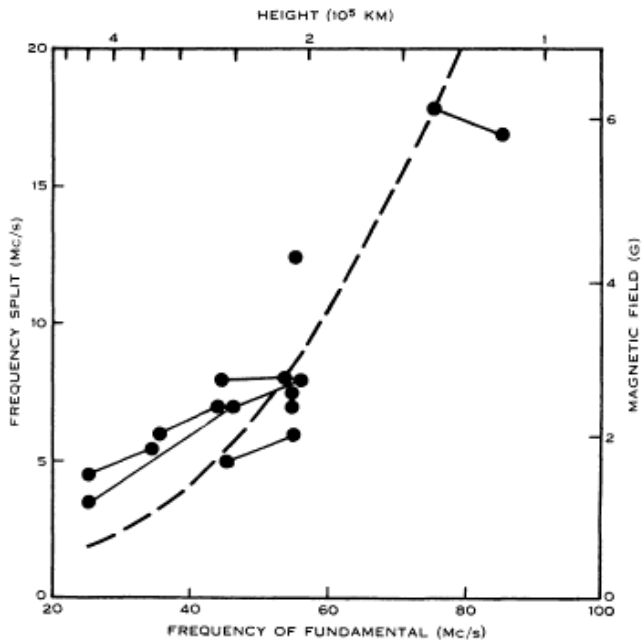


Figure 94 Points show the frequency separation in split-bands, referred to the fundamental band. The dashed curve shows the variation of the gyro-frequency (ordinate) with the coronal plasma frequency for a Chapman model sunspot of surface magnetic field 3000 Gauss and with the Baumbach-Allen model of coronal electron densities. Data from Smerd, 1950 (after Roberts, 1959b: Fig. 8).

3.16.5 Herringbone Structure

Roberts (1959a) reported that in some cases the drifting bands of the Type II burst contain considerable fine structure. Sometimes, the fine-structure elements are of broad bandwidth and short duration and drift at rates similar to Type II bursts (Haddock, 1958). An interesting form of this appears on the record as a *herringbone* pattern. Some examples are shown in Figure 95 (a) and (b). Here the slowly drifting and of the Type II burst appears to be a source from which rapidly drifting elements extend toward both high and low frequencies. Sometimes the pattern is not so pronounced extending over only a small range of frequencies as seen in Figure 95 (c); this may occur in about 20% of all Type II bursts. Sometimes only the forward drift elements are seen as in the example of Figure 95 (d).

Roberts interpreted the herringbone structure in terms of the theory for Type III bursts and concluded that the Type II disturbances are sometimes the source of high speed particle

ejections travelling both toward and away from the sun. Such secondary ejections are most likely generated by the Type II shock wave.

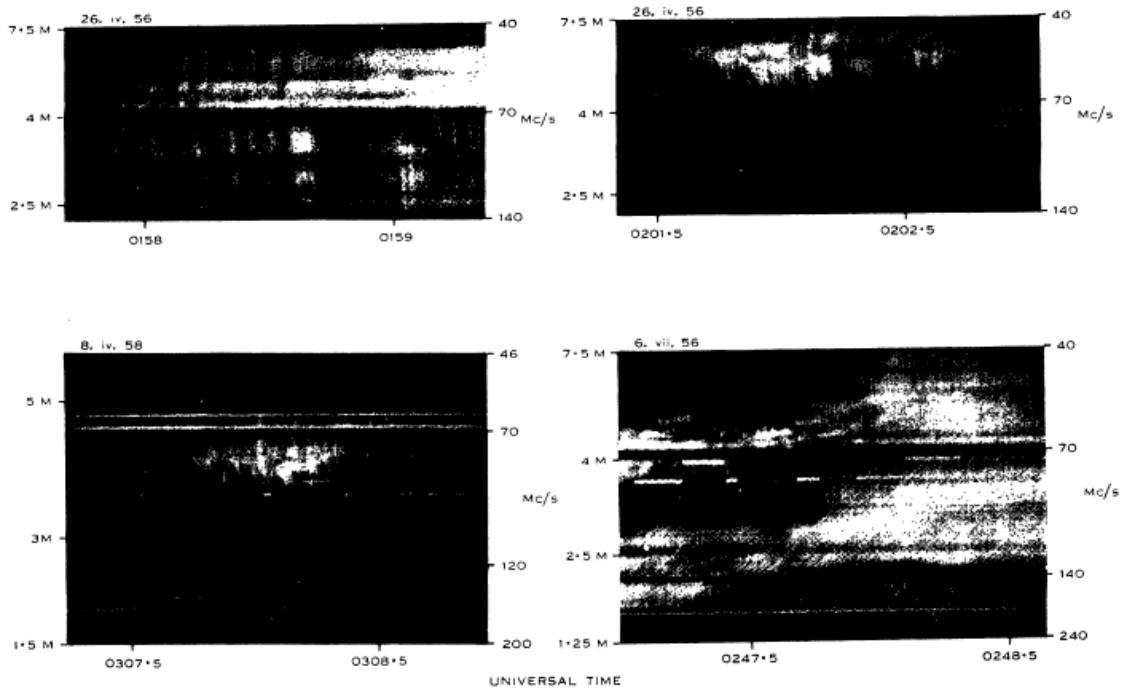


Figure 95 Examples of herringbone structure in Type II bursts. Only a small part of the burst is shown in each case; two sections of the burst on 1956 April 26 are shown in (a) and (b) (after Roberts, 1959a: Fig. 1).

3.16.6 Compound Type III-Type II Bursts

Wild, Roberts and Murray (1954) drew attention to the tendency for a Type II burst to be preceded by a group of Type III bursts. Roberts confirmed this phenomenon finding 60% of the Type II bursts he studied unambiguously were followed Type III bursts with a delay from 1 to 18 min. The height time plots for 13 of these events show that the straight line plots for the two Types of burst converge to a point within + - 10^5 km of the photosphere. Five examples are shown in Figure 96.

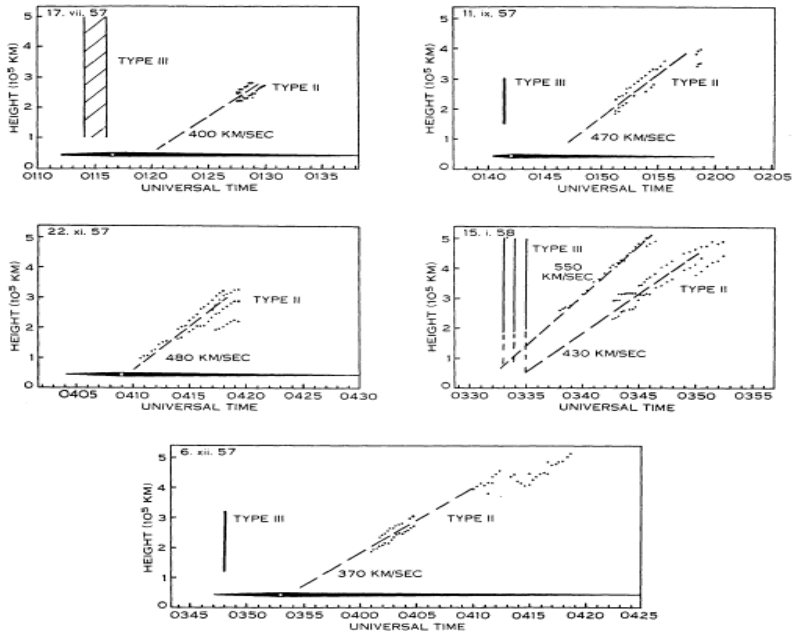


Figure 96 Derived height time plots for five harmonic Type II bursts assuming the Baumbach-Allen density model. .Associated flares are shown as tapered horizontal lines (after Roberts, 1959b: Fig. 4).

3.16.7 Type II Bursts and Chromospheric Flares

Giovanelli and Roberts (1958) found that at least 70 % of the Type II bursts and possible 80% were associated with chromospheric flares. Unfortunately, not all the bursts were covered by flare patrol observations from Sydney but 28 of the 65 Type II bursts studied by Roberts were found to occur at the time of a reported flare in the "Quarterly Bulletin of Solar Flares" (to December 1956), in the "Daily Maps of the Sun" issued by the Fraunhofer Institute, and in the "Solar-Geophysical Data" issued by the National Bureau of Standards.

Figure 97 refers to these 28 Type II bursts and clearly shows that the Type II and Type III bursts are associated with solar flares. A clear pattern is evident with the Type II burst commencing near the flare maximum and continuing beyond it while the Type III burst occurs before the flare maximum.

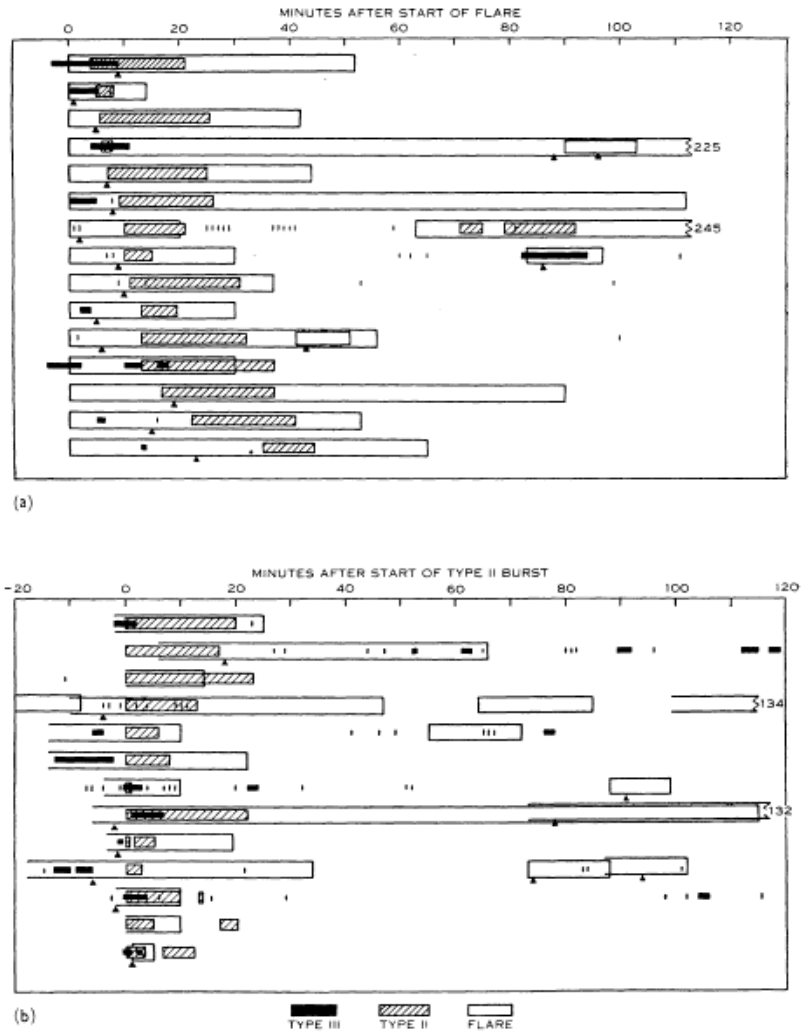


Figure 97 Temporal relationships between flares and Type II bursts. (a) Data for 15 events in which the start of the flare was observed. (b) Data for another 13 events in which the start of the flare was not observed (after Roberts, 1959b: Fig. 9).

3.16.8 Association with Geomagnetic Storms

Roberts (1959a) reported that a superposed epoch analysis of the magnetic variability on the earth following a Type II burst showed the field to be highly disturbed from 1 to 3 days after a burst on the sun (Figure 98) and that he probability of this occurring by chance was about one part in a thousand. No such significant peak was found for class 2 and 3 flares not accompanied by a Type II burst. The curve in Figure 98 (a) is similar to that found by Dodson (1958).

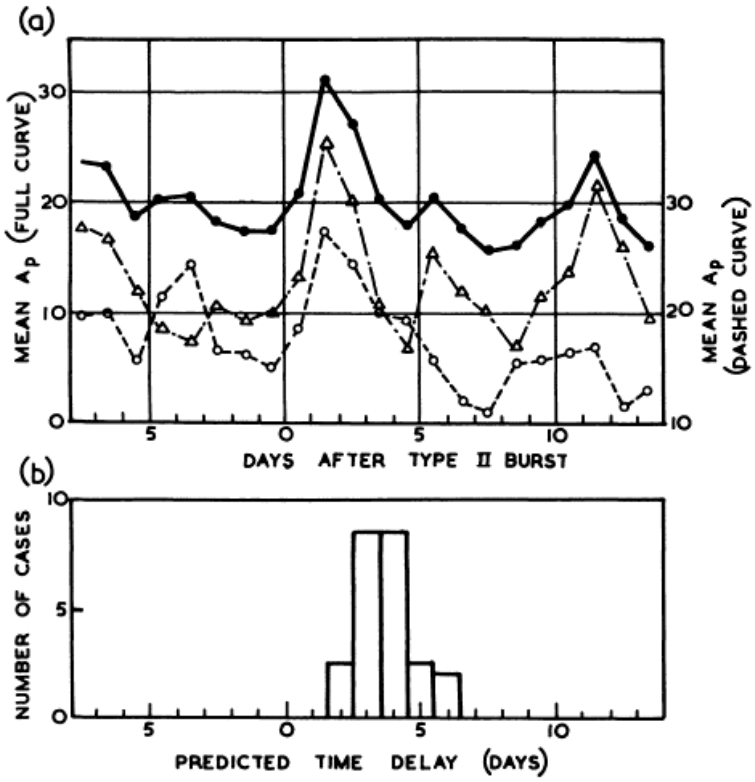


Figure 98 (a) Superposed epoch diagram showing the mean value of the geomagnetic index A_p on days before and after 60 Type II bursts recorded in the period 1955 January to 1958 March. The dashed curves give the corresponding diagrams for the first 30 and second 30 bursts respectively. (b) The predicted time delays inferred from the frequency drift of 24 of the Type II bursts (after Roberts, 1959a: Fig. 5).

Roberts also pointed out that the inferred speeds and time delays in of a Type II disturbance reaching the earth were highly dependent on the assumed coronal density model. Higher electron densities (or a smaller density gradient in the corona) might lead to faster speeds and smaller time delays.

Roberts was undoubtedly the best researcher after Wild in analysing the characteristics of solar radio bursts. Unfortunately he decided to continue his career in other aspects of radio astronomy and soon afterwards went to CALTECH to study radio emission from Jupiter. After his return to Sydney he joined the Parkes Group and later when Wild became Chief of the Division of Radiophysics he appointed Roberts as the editor of all research publications which he did with distinction. I am very aware of Jim's contribution and knowledge and am grateful for the advice he gave me on many occasions.

3.17 Model of a Type IV Burst

In 1959 Don McLean worked with the solar group as a vacation student from Sydney University. Under the supervision of Joe Pawsey he investigated the correlation of Type IV bursts with geomagnetic storms. In 1961 he was awarded a CSIRO scholarship and spent five years in Paris completing his doctorate before returning to Sydney to work on the Culgoora radioheliograph (McLean, private commun., 2008). His model of the Type IV burst illustrated his outstanding research skills for one so young and for many years it was accepted as the best explanation for the moving Type IV burst and its impact on the Geomagnetic medium. For this study his supervisor was Pawsey whose grasp and knowledge of solar radio astronomy would have been a great asset to a young graduate such as McLean.

3.17.1 Definition of a Type IV Burst

To distinguish between Type I and Type IV continuum bursts McLean (1959) used criteria based on Boischot's (1958) original classification of a Type IV bursts; a long duration (~ ½ to 6 hr), very smooth increase in intensity of solar radio emission extending through metre and decimetre wavelengths preceded by a Type II outburst. Boischot, using the 169 MHz multi-element interferometer at Nancay, France found that these bursts show rapid source motion away from the solar disk with speeds of ~ 1000 km/sec. during the first few minutes of their existence. Observing with a radio-spectrograph Haddock (1958) reported that occasionally a Type IV storm was not preceded by a Type II burst.

McLean also found that the low frequency cut-off of the spectral record of some Type IV storms drifted from high to low frequencies over an initial period of 10 min. or so suggesting an outward moving source. McLean distinguished Type I from Type IV storms by dividing the events into "burst" continuum which contained many short-lived bursts, which he called Type I storms, and those which showed "smooth" continuum which he called Type IV. A schematic of the various metre wavelength components of a large flare event is reproduced in Figure 99 from Boorman et al (1961).

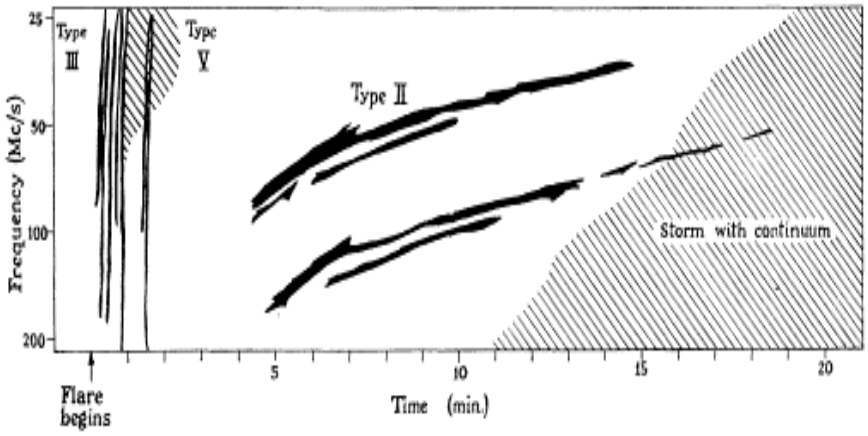


Figure 99 Idealized sketch of spectral record showing the metre wavelength components of a complete major radio event (after Boorman et al., 1961; fig. 1).

The period studied by McLean was from 1952 to 1958. Only 22 "discrete" storms, that is continuum lasting only a few hours, could be found on the Dapto spectrograph records, of which 12 were classified as Type IV, the other 10 being Type I. Three examples of Type IV storms are shown in Figure 3.58.

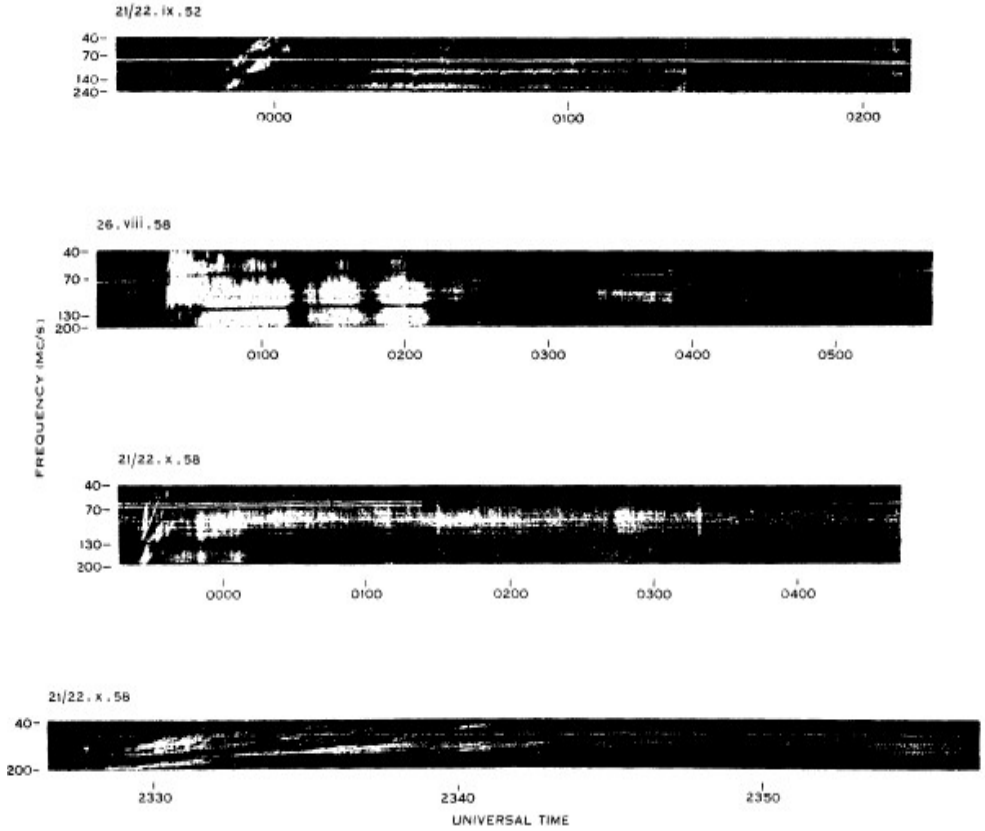


Figure 100 "Spectral appearance" of Type IV storms. The first three examples are reproductions of spectral records in which the time scale has been considerably compressed. The fourth shows the start of the third event on a normal time scale (Plate I of McLean, 1959).

3.17.2 Temporal Relationships between Type IV Storms with Type II Bursts and Major Flares

Figure 101(a) shows the time relationships between the 12 Type IV storms, Type II bursts and solar flares of importance 2 or greater (or with Sudden Ionospheric Disturbances S.I.D's. which are indicative of large flares). Figure 101 (b) shows a similar plot for the 10 Type I storms. These plots clearly show that although both storms often follow large flares, only the Type IV storms always follow Type II bursts. McLean suggested that a simpler definition for a Type IV burst would be "a storm which closely follows a Type II burst". He also noted that Haddock's (1958) observation on equipment with a low frequency limit of 100MHz, of smooth continuum without a Type II burst, was not contrary to this definition, as some Type IV storms occurred accompanied by a Type II burst at frequencies below 100 MHz.

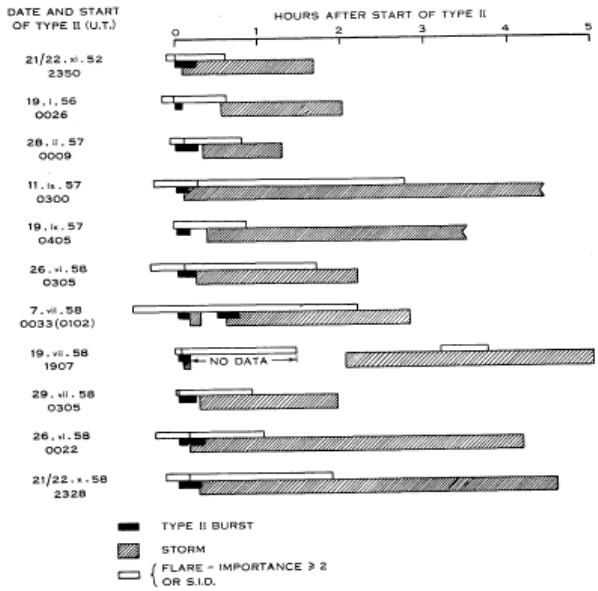


Figure 101 (a) Schematic diagram showing durations of eleven of the twelve Type IV storms observed and their relations in time to the Type II and big flare event (after McLean, 1959: Fig. 1a).

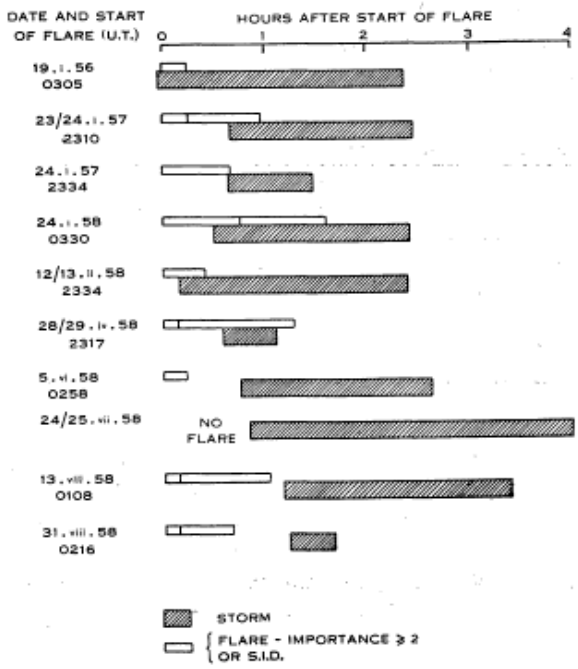


Figure 101 (b) Similar to Fig. 3.59 (a) but showing all the Type I storms observed (after McLean, 1959: Fig. 1b).

3.17.3 Association of Type IV Storms with Flare importance

Roberts (1959b) showed that about half the Type II bursts are associated with flares of importance 1 whereas Table 1 of McLean (1959) shows that Type IV storms occur only after major flares of importance 2 or greater.

3.17.4 Association of Type IV storms with geomagnetic storms

To show the association of Type IV storms with Geomagnetic Storms McLean (1959) plotted in Figure 102 the mean K_p index before and after the following (McLean, 1959; 411):

1) The ten most recent Type IV storms.
2) The ten Type I storms associated with solar flares.
3) Ten importance 3 flares not associated with any Type IV storms.
4) Thirty-six Type II bursts, none of which occurred within four days of a known Type IV storm observed from Dapto.

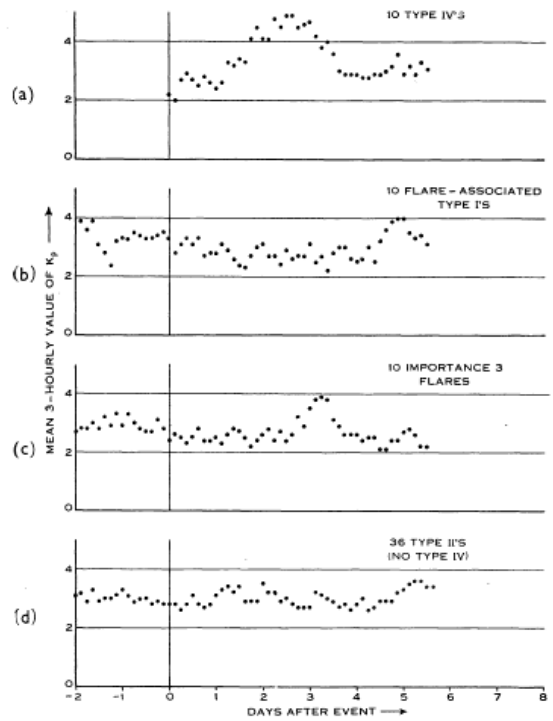


Figure 102 Mean K_p index for each 3-hourly period before and after (a) 10 Type IV storms (b) 10 Type I storms (c) 10 importance 3 flares (d) 36 Type II bursts (after McLean, 1959: Fig. 4).

McLean (1959: 412) noted:

> As can be seen [from Figure 102], the correlation of geomagnetic storms with Type IV storms is outstanding and is probably the only significant one; certainly Type II bursts without Type IV storms following them, do not appear to be associated in any but a small percentage of cases. This is in direct agreement with Sinno and Hakura (1958), but the conclusion is different from that of Dodson (1958), who associates geomagnetic storms with "major early bursts". It appears that the occurrence of a Type IV storm will become a reliable guide for the prediction of terrestrial disturbances 1-3 days later.

3.17.5 A Proposed Model for the Origin of Type IV Storms

McLean (1959: 413) combined the following ingredients into his model of a Type IV storm burst:

Boischot and Denisse's (Boischot 1958) have already proposed synchrotron radiation, from relativistic electrons spiralling in a magnetic field, as the mechanism for Type IV emission. Since Type II bursts, geomagnetic storms, and flares have been shown above to be closely associated with Type IV storms, the following results and ideas arising from previous work are relevant.

(i) Type II bursts are believed to be due to plasma oscillations in the solar corona (Wild, Murray and Rowe, 1954; Wild Sheridan and Trent, 1959); such oscillations being excited by the passage of a shock front ahead of a fast moving column of gas (Westfold, 1957; Roberts 1959).

(ii) Geomagnetic storms are thought to be due to the arrival at the Earth of a cloud of plasma ejected from the solar corona, and carrying trapped magnetic fields and highly energy protons (Kiepenheuer, 1953; Gold, 1959).

(iii) Type IV sources are observed with velocities of 500-300 km/sec; Type II sources and magnetic storm clouds are believed to have velocities of the same order (Boischot, 1958; Wild, Sheridan and Trent 1959).

(iv) Boischot (1958) has observed Type IV sources to have diameters of ~ 7-12 min of arc

(v) Although not unique, a fairly typical description of the start of a Type IV is as follows: a Type II burst occurs, then, after a short delay of minutes, a smooth increase in intensity commences t high frequencies and rises to a maximum in a period of about 10 min. Lower frequencies occur at later times, the effect being that of a low frequency cut-off drifting to lower frequencies at roughly the same rate as the Type Ii burst.

(vi) The spectrum is essentially smooth and changes slowly with time.

The sequence of events envisaged by McLean (1959: 413-414) is in four phases:

First phase [Figure 103a]. A flare occurs low in the solar atmosphere in a region of high magnetic field associated with a sunspot group. The explosion ejects a column of gas moving radially outwards.

*Second phase [*Figure 103b]. As the gas column moves outwards at a velocity ~ 1000 km/sec it is preceded by a shock front which excites the Type II burst. Particles accelerated in the explosion are tapped in "frozen in" magnetic fields travelling along with the compressed gas behind the shock front. The spiralling charged particles emit synchrotron radiation over a wide frequency range (Schwinger, 1949) to produce the Type IV burst.

Third phase [Figure 103c]. The gas behind the shock front will be at a higher density and a higher plasma frequency than that ahead of the front, where the Type II burst is assumed to be generated. Consequently, the Type II emission at say 40 MHz will escape from its plasma level earlier than the Type IV radiation at the same frequency. This explains why the Type IV storm commences several minutes after the Type II burst.

Fourth phase [Figure 103d]. Eventually the Type IV emission stops while the gas cloud with its frozen-in magnetic field continues outward to become the magnetic storm cloud reaching the Earth one or two days later.

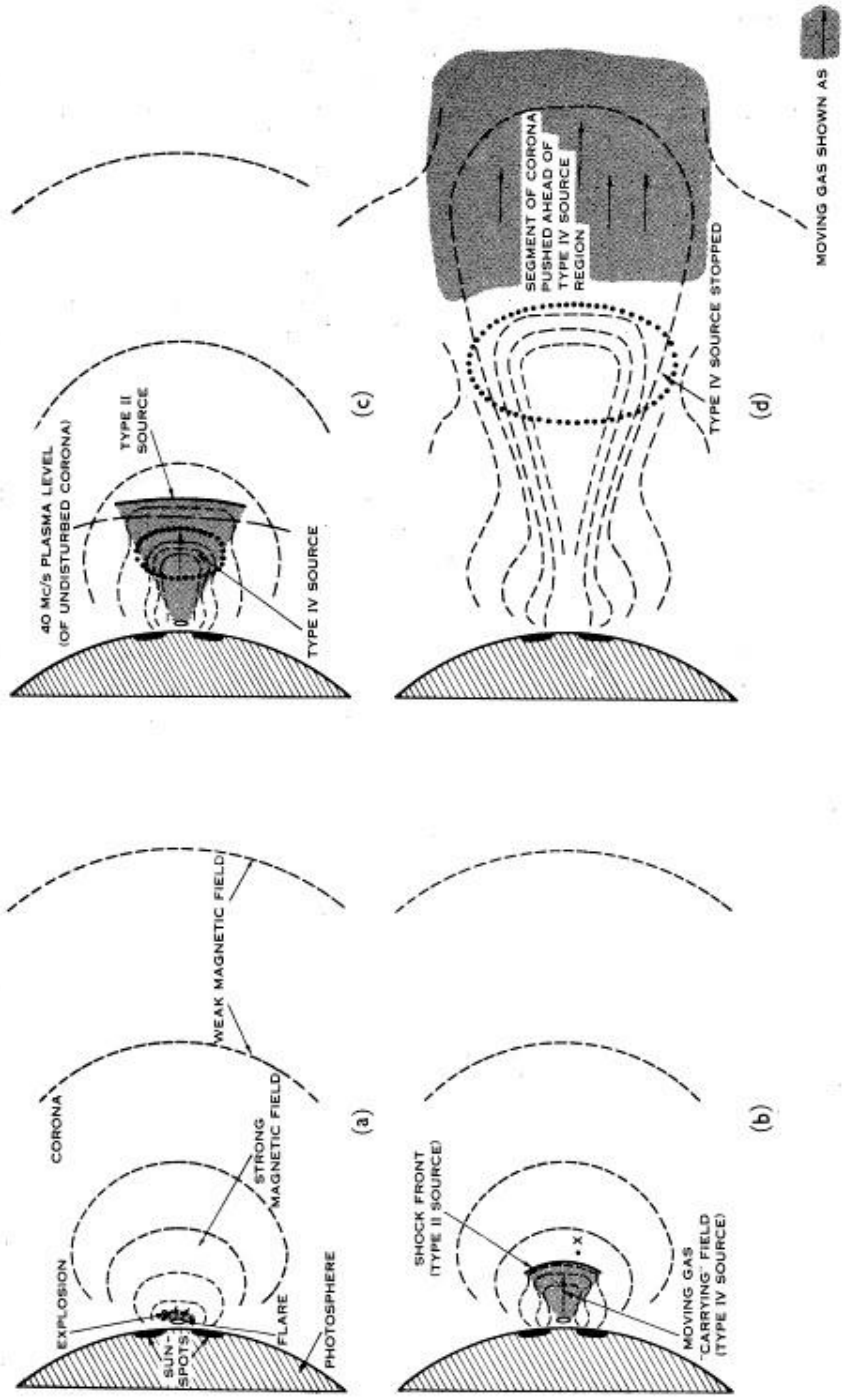


Figure 103 Proposed model of a Type IV storm; see text for details (after McLean, 1959: Fig. 5).

McLean's model was readily accepted as it presented a number of popular ideas. It also attempted to explain one of the recurring themes in solar radio investigations "What caused Geomagnetic Storms at the Earth and how was that linked to radio outbursts such as the Type II

burst?" This model also raised a new question "Was the initiating agent the Type IV storm rather than the Type II outburst?" Further investigations using the Dapto swept-frequency interferometer (Section 4.6) were to show that not all the smooth continuum events observed during large solar flares were associated with moving sources but rather that there were two components, one moving and one stationary, which became known as the *moving* and the *stationary* Type IV bursts. This complicated the picture and also restricted the number of genuine moving continuum events observed and made it difficult to undertake meaningful statistical analysis of the correlation of moving Type IV bursts with Geomagnetic Storms.

3.18 Association between Type III-V Bursts and Centimetre Bursts

In 1958 Tony Neylan who was at that time a student at Mt. Stromlo was given a CSIRO Research Grant to work with the solar group on the analysis of Type III burst positions recorded by the Dapto interferometer (Wild, Sheridan and Neylan, 1959) as well as the recently classified *spectral Type V burst* (Wild, Sheridan and Trent, 1959). When I asked Paul some years later what had become of Tony he replied with a smile "Oh he left me to become a Jesuit priest". (More details on the type V burst are presented in Sections 4.7 and 4.8.)

3.18.1 Introduction

The study by Neylan (1959) covered the period from July 1957 to March 1958. Records from the 40-210 MHz Dapto spectrograph were compared with single-frequency data (1000, 2000, 3750 and 9400 MHz) from the Research Institute of Atmospherics, Nagoya. Of some 2000 Type III events studied less than 10% occurred while a centimetre burst was in progress. On the other hand, there are a number of centimetre wavelength bursts of comparable intensity which are unaccompanied by metre wavelength bursts.

3.18.2 Description of the Type V Burst

On examining the spectral records of those Type III bursts accompanied by centimetre disturbances, a recurrent feature was noticed. The metre wavelength event normally began with a short duration (5 to 10 sec.) Type III, which was followed by a broadband enhancement extending over a frequency range of 100 MHz or so and lasting up to about 1 min. Three examples of this continuum radiation, classified as a "spectral Type V" burst (Wild, Sheridan and

Trent, 1959) are shown in Figure 104. In the first example shown the Type V merges with the Type III but in the second example the two are detached. In no case is a frequency drift evident in the Type V continuum burst and most Type V have a high frequency cut-off below 100 MHz.

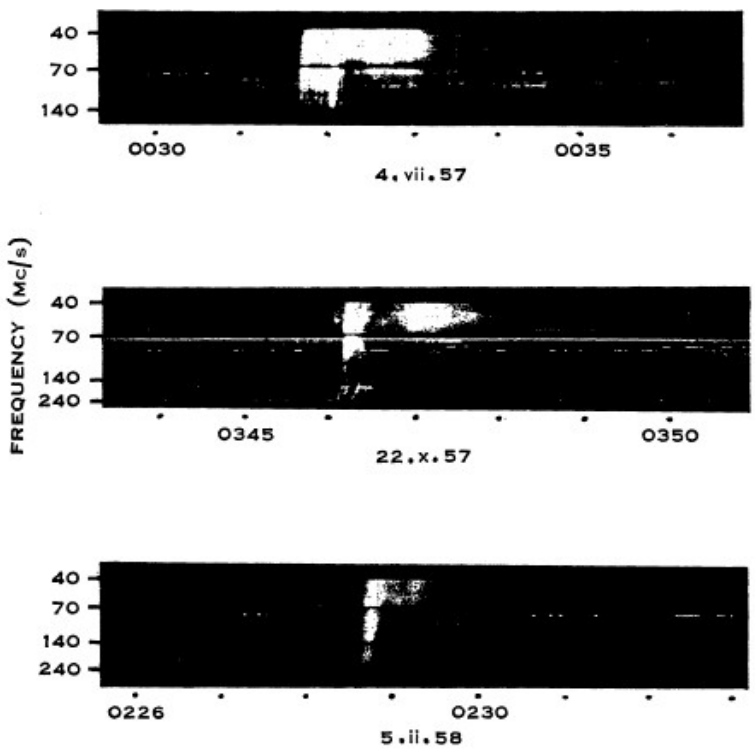


Figure 104 Three examples of Type III bursts followed by broadband Type V bursts (after Neylan, 1959: Plate 1).

3.18.3 Association of Type V with Centimetre Bursts

To test the correlation of Type III plus Type V bursts with centimetre events, two groups were chosen.

Group A consisted of 27 clear and distinct cases of Type III bursts followed by Type V. The examples of Figure 104 are from this group. Of the Group A events, 20 of the 27 occurred nearly simultaneously with bursts at centimetre wavelengths and mostly had similar durations.

Group B consisted of 26 sharply defined Type III bursts without Type V selected at random during the period of study. Examples from this group are shown in Figure 105. These

bursts were used as a control group. Of the 26 events, only 1 was found to occur at the time of a burst at centimetre wavelengths.

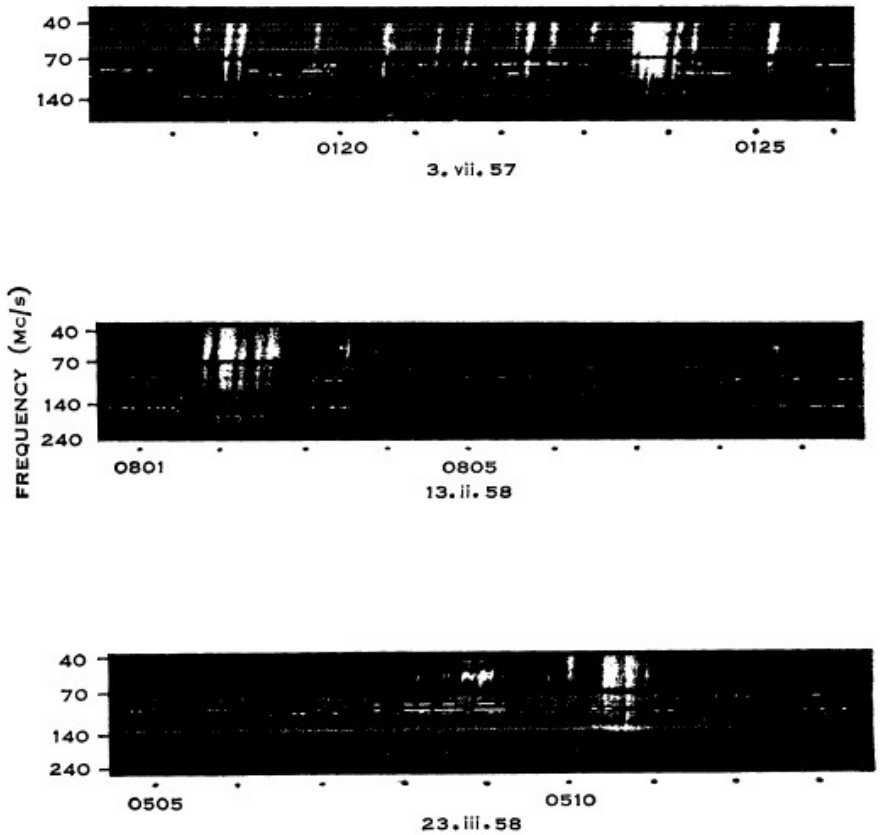


Figure 105 Three examples of groups of sharply defined Type III bursts not accompanied by Type V continuum (after Neylan, 1959: Plate 2).

Neylan concluded that while the number of events in Group A and B is not large, it seems sufficient to suggest strongly that the possibility of a Type III burst being accompanied by a centimetre burst is considerably increased by the Type III being followed by a Type V continuum.

3.18.4 Association of Type V Bursts with Flares

Covington and Harvey (1958) reported that most 10 cm bursts appear to be associated with solar flares. A similar association was found for Type V bursts by Neylan (1959) who found that of 15 Type V bursts, for which flare data was available, 14 occurred within a minute of the flare maximum and all appeared to be associated with sudden explosive Type flares which Giovanelli (1958) called flare “puffs”.

The association of puffs, high frequency events, and Type III-V bursts is neatly exemplified by Figure 3.64. Here the flare showed two sudden eruptions, or puffs, with an interval of about 15 minutes between peak intensities. Type V and centimetre radio emission was confined almost entirely to the periods of the flare puffs.

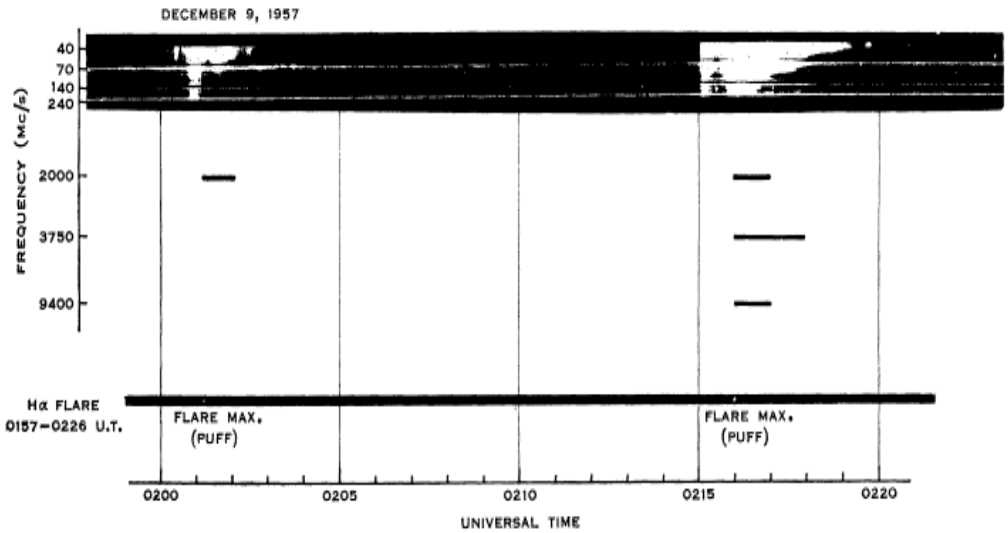


Figure 106 Radio and optical data showing the association of Type V bursts, centimetre bursts and flare puffs (after Neylan, 1959: Plate 3).

3.18.5 Emission Mechanism for Type V and Centimetre Bursts

Neylan (1959) noted that interferometer position measurements as well as refractive index arguments placed the Type V source in the upper corona whereas Fleurs Chris Cross position measurements placed an upper limit of 100,000 km on the height of the centimetre burst at 20 cm wavelength (Christianson, private communication) placing it in the lower corona. If, as Wild, Sheridan and Neylan (1959) propose, the Type V burst is due to synchrotron radiation then this requires the transport of highly energetic electrons from the flare region in the chromosphere into the upper corona.

Two possibilities exist to explain the associated centimetre burst. Firstly, some of the energetic particles from the flare could generate the burst as thermal radiation (bremsstrahlung) by collisional heating in the dense lower corona. Secondly, a more consistent explanation for the two events would be that both are generated as synchrotron radiation from the same stream of energetic electrons.

The author acknowledged the assistance of A. Kimpura of the Research Institute of Atmospherics, Nagoya University and S. Suzuki of Tokyo Astronomical Observatory, Mitaka in making the centimetre wavelength data available.

Later observations by Weiss and Stewart (1965) showed that the Type V burst was most likely to be plasma radiation (see Section 4.7).

3.19 Type I Noise Storms and the Coronal Magnetic Field

In 1964 Tony Tlamicha while on leave of absence from the Astronomical Institute of the Czechoslovak Academy of Sciences, Ondrejov and Paul Wild described a new feature found in the Dapto spectral records of Type I noise storms. I have fond memories of Tony producing a bottle of slivovich plum brandy at his farewell party. Sometime later on the train going home the effects of this powerful stuff made my head spin and ever since I have been aware of smiling Czechs bearing their local drinks.

3.19.1 Characteristics of Type I Chains

Wild and Tlamicha (1964) noted that a systematic macroscopic feature seen in noise storms was the occurrence of Type I bursts grouped together in tens or hundreds to form narrow-band “chains” with durations of the order of one minute or several minutes and bandwidths of the order of 10 MHz. An isolated example of this phenomenon was briefly reported by Wild (1955).

The characteristics of the Type I burst chains are illustrated by the examples of Figures 107 and 108, and in the left-hand columns of Table 5 (after Wild and Tlamicha, 1964: Table 1).

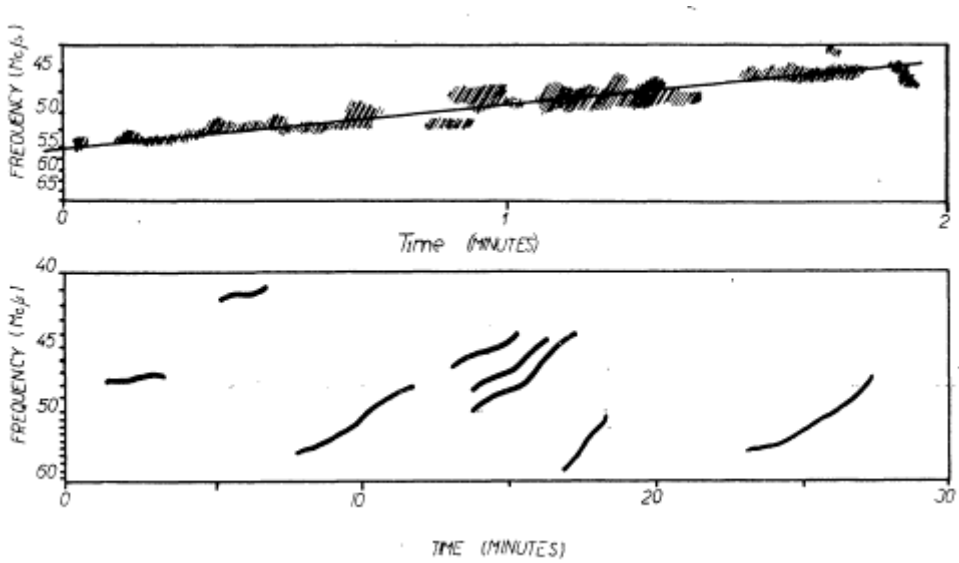


Figure 107 Tracings of dynamic spectra: (a) an individual burst chain, the hatched areas indicating concentrations of Type I bursts on 29 March 1960, 2352-54 UT; (b) several chains occurring in succession on 12 August 1960, 0215-0245 UT (after Wild and Tlamicha, 1964: Fig. 1).

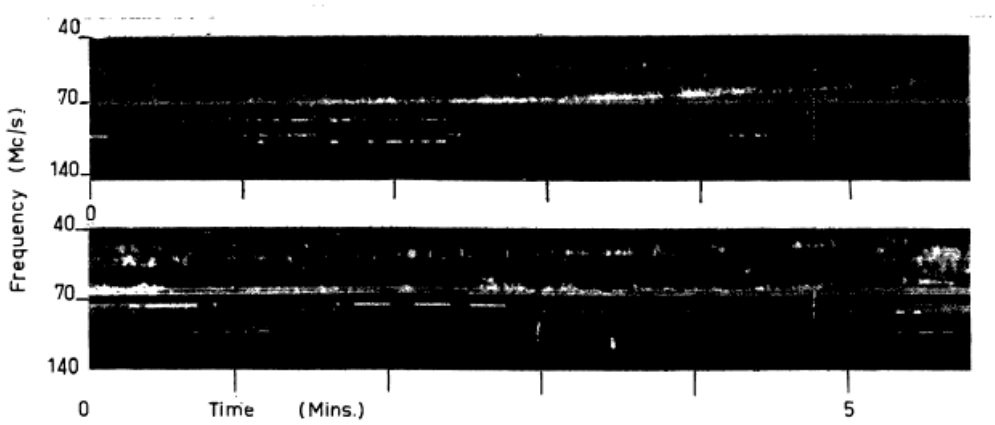


Figure 108 Dynamic spectra of Type I chains recorded on 12 August 1957 showing examples of a single and a double chain (after Wild and Tlamicha, 1964: Fig. 2).

Wild and Tlamicha claimed that many more examples may be found in the spectral records and that it was their subjective impression that the majority of Type I radiation may be resolved into chains. The chains may occur in any part of the metre-wave spectrum (30 – 300 MHz) and may drift systematically in frequency at a rate given by $(1/f)\ df/dt) \sim 0.1$ per min, the average rate being about half that of Type II bursts. Although the frequency drift is sometimes positive (from low to high frequencies) in most cases it is negative as in Type II bursts. The

chains sometimes dominate the storm record for periods of up to one hour. Measurements with the Dapto interferometer have shown that variations in position of several minutes of arc may accompany the drift in frequency.

3.19.2 Interpretation of Frequency Drift

The authors suggest two possible causes for the narrow – bandedness and frequency drift but they favour the latter cause:

(a) effects of propagation limiting and varying the frequency range of emission from a relatively large, broadband source or

(b) the motion of a localised source passing through regions of different electron density or magnetic field.

Other evidence supports the view that Type I bursts are due to plasma oscillations in which the frequency is determined by the local plasma frequency. Assuming the plasma hypothesis and Newkirk's coronal density model, Wild and Tlamicha derive upward source velocities given in Table 5.

TABLE 5

OBSERVED AND DERIVED CHARACTERISTICS OF CHAINS OF TYPE I BURSTS

Observed and derived characteristics of chains of type I bursts

Date	U. T.	Drift in frequency (Mc/s)	Duration (min)	Movement in height (10^5 km)	Upward velocity km/sec	H (gauss)
27 April 1953	0018	210 → 185	1·7	0·9 → 1·15	250	2·5
	0038	230 → 180	4·8	0·7 → 1·2	160	1·6
	0045	178 → 161	2·7	1·2 → 1·4	120	1·0
12 Aug. 1957	0223	56 → 48	4·2	4·3 → 4·9	240	0·6
	0229	50 → 44	3·4	4·75 → 5·3	260	0·6
	0239	55·5 → 48	4·1	4·4 → 4·9	260	0·7
	0449	63 → 58	1·8	3·9 → 4·2	270	0·8
	0458	58 → 51	2·0	4·2 → 4·7	410	1·1
	0512	48 → 44	5·5	4·9 → 5·3	110	0·25
	0514	61·5 → 60	2·1	4·0 → 4·1	65	0·2
29 March 1960	0602	47·5 → 45·5	0·8	5·0 → 5·15	380	0·9
		53 → 51·5	0·4	4·5 → 4·65	500	1·3
	0610	58 → 52	1·9	4·2 → 4·6	360	1·0
	2345	48 → 42	2·1	4·9 → 5·5	460	1·0
	2352	56 → 44	2·0	4·3 → 5·3	800	2·0

The heights and velocities are derived assuming the radiation to originate at the plasma levels determined from Newkirk's model of the solar atmosphere above an active region. The column H gives the radial component of the magnetic field derived from the assumption that the velocity is equal to the speed of the Alfvén waves.

3.19.3 Nature of the Type I Disturbance

The sources are seen to rise through a height range of 10^5 km at speeds of several hundred kilometres per second. The deduced velocities are too small to be identified with electron streams and most are in excess of the field-free velocity of sound in the corona by a factor between 1 and 5. The authors suggest that the most likely identity for the disturbance is a magnetohydrodynamic (m.h.d.) wave or a shock wave. (The high circular polarization of the emission clearly rules out a disturbance similar to that for Type II bursts.)

Assuming that the disturbances responsible for Type I chains travel at the speed of Alfven waves

$$v_a = 2 \text{ x } 10\ 4\ (H/f_p) \text{ km/sec} \qquad (21)$$

then the radial component of the coronal magnetic field H is found to be in the range 1 to 2.5 gauss for heights near 10^5 km and mainly from 0.2 to 1 gauss for heights near $5 \text{ x } 10^5$ km (Table 5). If the disturbance is any other Type of m.h.d. wave or a shock wave the derived values for H represent upper limits.

The detailed process of wave generation was not considered by them but they note that (Wild and Tlamicha, 1964: 75):

> Takakura (1963) has proposed a theory of Type I bursts in which radiation is attributed to plasma waves excited by suprathermal electrons which are accelerated between two packets of Alfven waves travelling in opposite directions. In terms of this theory a chain of Type I bursts might conceivably be attributed to encounters between a single, outward-moving wave packet and a series of inward-moving packets following one another in quick succession.

3.20 The Speed and Acceleration of Type III and V Sources over large Distances in the Corona

One of the first research tasks that I was given by Paul Wild after joining the CSIRO Division of Radiophysics in 1963 was to measure the radial velocities of Type III and Type V bursts which had been recorded over a wide frequency range by the Dapto spectrograph. I showed that the derived radial velocities for Type III and Type V bursts were fairly constant over a large range of

heights in the corona and incompatible with the suggestion that the Type V continuum was due to synchrotron radiation. I am greatly indebted to Paul's help and guidance in the analysis and writing of this, my first, scientific publication.

3.20.1 Statistical Studies of Source Radial Velocities.

In my first published paper I wrote (Stewart, 1965: 67-68):

> Wild, Sheridan and Neylan (1959) used the 40-70 MHz swept-frequency interferometer to confirm the plasma hypothesis and also to measure the radial velocities of Type III bursts. These ranged from 0.2 to 0.8c with a mean value of 0.45c. An alternative method of deriving source velocities on the assumption of radial propagation is to convert frequencies into heights by applying a standard electron density model for an active region. This method has been applied over various frequency ranges by the following authors: Wild 1950; Wild, Roberts and Murray, 1954, Malville 1962; Elgaroy and Rodberg 1963; Hughes and Harkness 1963. If a density model such as the Newkirk model for an active region (Newkirk 1962) or 10 x Baumbach-Allen model i assumed the results agree fairly well with the radial velocities derived by Wild, Sheridan and Neylan (1959).
>
> However, no systematic study showing the behaviour of *individual* Type III source velocities with height has been attempted before Stewart (1965). Often Type III bursts recorded by the Dapto spectrograph are observed extending from 210 MHz down to the limit imposed by the ionosphere (around 7 MHz). On the Newkirk (1962) model this represents a height range greater than two solar radii. This suggests that deceleration of the source if it occurs at all must be fairly small. Following this suggestion Stewart (1965) studied the variation of source velocity with height for 50 Type III bursts, 10 of which were followed by Type V continuum. The latter bursts are of particular interest since it has been proposed that the continuum is due to synchrotron radiation from relativistic electrons trapped in magnetic fields high in the corona (Wild, Sheridan and Neylan 1959). If this hypothesis is correct, we might expect to find evidence of higher source velocities and possibly acceleration for those Type III bursts followed by Type V continuum.

3.20.2 Measurement of Source Radial Velocity.

The radial component of velocity was derived from the formula (Wild, Sheridan and Neylan, 1959)

$$t_{f2} - t_{f1} = (1/v_r - 1/c \cos \alpha)\,(R_{f2} - R_{f1}) + \tau(\alpha) \qquad (22)$$

in which it is assumed that the source travels radially outwards and that all radiation of frequency f originates at the same distance R_f from the centre of the Sun. $t_{f2} - t_{f1}$ is the difference in times taken by the two signals of frequency f_1 and f_2 to propagate from their points of origin to the observer. This time difference depends on the heliocentric angle a between the path of the disturbance and the Sun – Earth line. The first term on the right-hand side of (3.4) is obtained from simple geometrical considerations on the assumption that the velocity of propagation is exactly the velocity of light c, while the second term $\tau(\alpha)$, the differential group delay between the two signals, is the correction required to allow for departures from this assumption. $\tau(\alpha)$ can become appreciable when the path of propagation passes through regions whose refractive index departs significantly from unity (e.g. near the appropriate plasma level).

Evaluation of $\tau(\alpha)$ can be difficult and depends critically on the model atmosphere used (Jaeger and Westfold, 1950). Wild, Sheridan and Neylan (1959) have plotted $\tau(\alpha)$ against sin α (see Figure 4) for f_1 = 45 and f_2 = 60 MHz, assuming the Newkirk model for an active region. Their calculation shows that $\tau(\alpha) \sim \tau(0)$ and is small provided $\alpha < \pi/2$. For Type III bursts processes such as scattering from small-scale irregularities in the corona and refraction by a quasi-symmetrical solar atmosphere are likely to be important.

Because of the uncertainty of the precise value of $\tau(\alpha)$ I restricted the study to 40 Type III bursts with flare-associated disk longitudes less than $\pi/4$. Also, 6 of the 10 Type V bursts had longitudes less than $\pi/4$. For the 50 bursts studied it was assumed that $\tau(\alpha) = \tau(0)$. The value of $\tau(0)$ was calculated for the six frequency ranges listed in Table 6, assuming two alternative density models, namely 10x Baumbach-Allen (Allen, 1947) and Newkirk active region (Newkirk, 1961). The two models were chosen for their differing density gradients at heights greater than 1 R_0 above the photosphere, where reliable radio observations of electron density are not available. Of the 50 bursts studied only 5 had definite harmonic structure. These bursts were converted to fundamental frequencies, the rest were assumed to be fundamentals.

TABLE 6

CONSTANTS USED IN THE DERIVATION OF RADIAL VELOCITY
For definition of symbols see text

f_1 (Mc/s)	f_2 (Mc/s)	Newkirk Active Region Model			10 × Baumbach-Allen Model		
		$\tau(0)$ (s)	R_{f1} (R_0)	R_{f2} (R_0)	$\tau(0)$ (s)	R_{f1} (R_0)	R_{f2} (R_0)
135	200	0·09	1·27	1·15	0·14	1·39	1·24
70	120	0·15	1·51	1·31	0·23	1·73	1·44
42·5	70	0·25	1·78	1·51	0·24	2·06	1·73
26	40	0·31	2·16	1·82	0·16	2·40	2·08
16	24	0·34	2·70	2·23	0·28	2·80	2·46
12	16	0·24	3·00	2·70	0·14	3·20	2·80

3.20.3 Statistical Results

In Figures 109 (*a*) to (*e*) time delays for the five frequency ranges 12 – 16, 16 – 24, 26 – 40, 70 – 120, and 135 – 200 MHz have been plotted against a sixth range 42-5 – 70 MHz. The last range was selected as abscissa in these plots because it was traversed by nearly all the Type III bursts. The diagrams show the statistical behaviour of radial velocity with height. The full and dashed lines are for constant radial velocity for the Newkirk and 10 x Baumbach-Allen models respectively. Most of the observations lie within the reading error of the lines of constant velocity. (Triangles refer to Type III bursts followed by Type V continuum and circles toType III bursts without).

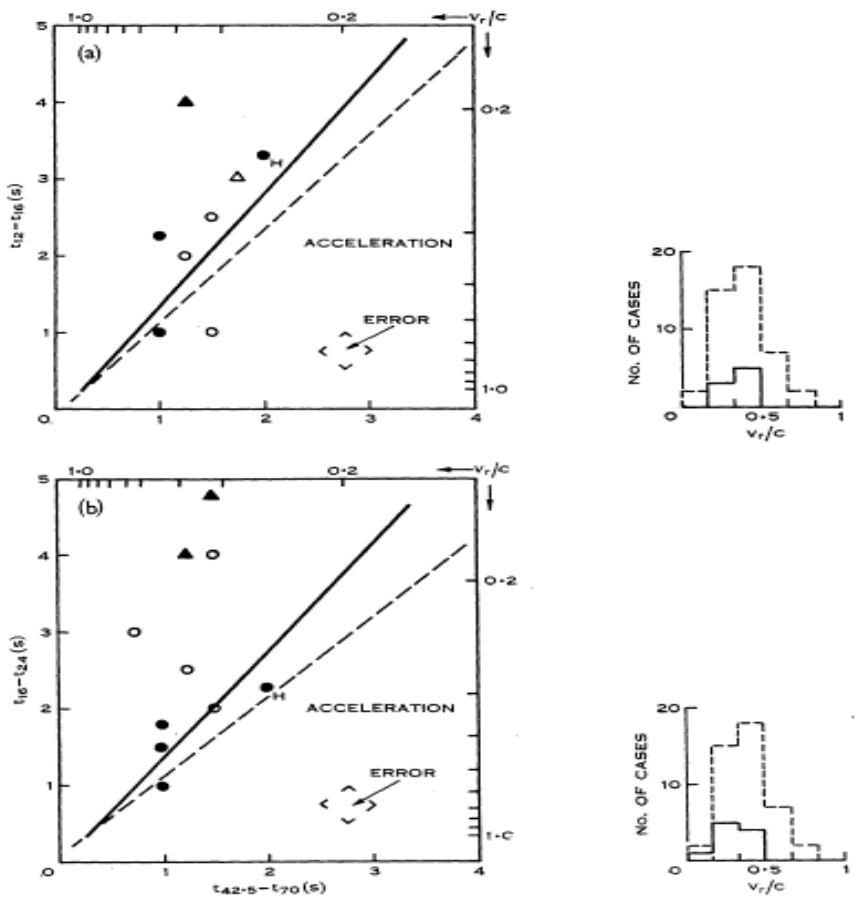


Figure 109 continued below

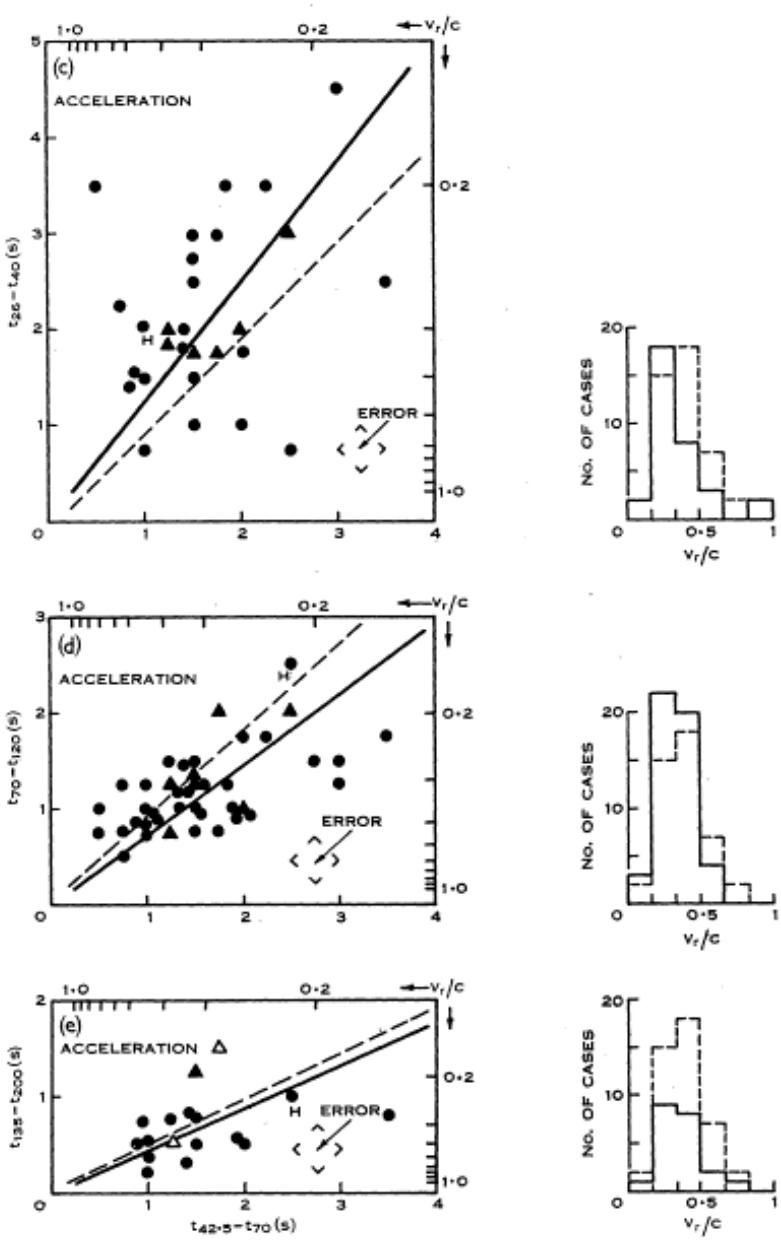


Figure 109 Plots showing the statistical behaviour of radial velocity with height (after Stewart, 1965: Fig. 1).

I concluded that the disturbance responsible for Type III or Type V burst moves, on the average, with a radial velocity of $v_r \sim c/3$. The histograms on the right-hand side of Figure 3.67 show a similar result. In every frequency range the majority of velocities range between $c/6$ and $c/2$, again indicating that the radial velocity remains constant with height from 0.2 R_o to 2.0 R_o above the photosphere and has a mean value of $\sim c/3$. This result is consistent with previous determinations of radial velocities for Type III bursts.

3.20.4 Comparison with Other Observations

Wild, Sheridan and Neylan (1959) using interferometer position data (see Section 4...) to determine $R_{f2} - R_{f1}$ of equation (3.4), derived values of v_r extending from 0.2c to 0.8c with an average value of 0.45c for the 45 – 60 MHz frequency range. Hughes and Harkness (1962) and Malville (1963) derived radial velocities from the frequency drift rates of Type III bursts recorded in the frequency ranges 400 – 25 MHz and 41 – 9 MHz respectively. The former used the 10 x Baumbach-Allen model sand the latter the Newkirk active region model. Hughes and Harkness found velocities of the order of ~ 0.4c, with some evidence for radial deceleration. Malville derived an average radial velocity of 0.24c. Neither took into account the $\tau(\alpha)$ correction. This omission would lead to underestimates of v_r, particularly at low frequencies.

3.20.5 Results of Individual Cases

In Figure 110, values of v_r have been plotted for individual cases. The plots are arranged in order to show the variation of the behaviour of the source velocity with frequency in 30 bursts for which v_r was derived over at least three frequency ranges. Corresponding height ranges are also given. The diagram shows a few cases of radial acceleration or deceleration (top left-hand corner and bottom right-hand corner respectively), and a greater number of intermediate cases in which v_r remains constant or varies irregularly with frequency. Some of this irregular variation is probably caused by reading errors.

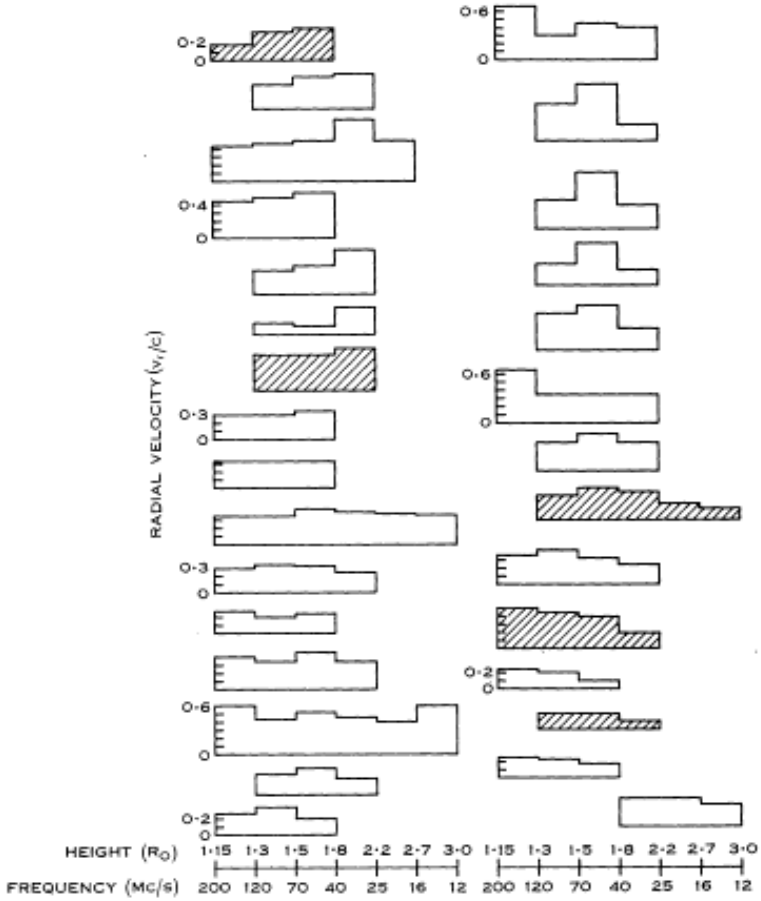


Figure 110 Plots of radial velocity for 30 individual Type III bursts. Cross hatching refers to bursts followed by Type V continuum. The abscissa refers to the Newkirk model for an active region (afte Stewart, 1965: Fig. 2).

Examples in which v_r was derived over at least five of the six frequency ranges are re-plotted in Figure 111, together with reading errors. In Figures 111(a) and (b), v_r remains constant from 200 to 12 MHz, that is, from 1.15 to 3.0 R_o above the photosphere. Figure 111(c) may represent slight radial acceleration although the reading errors are quite large. In Figure 111(d) the reading errors are small and there appears to be radial deceleration from 70 to 12 MHz.

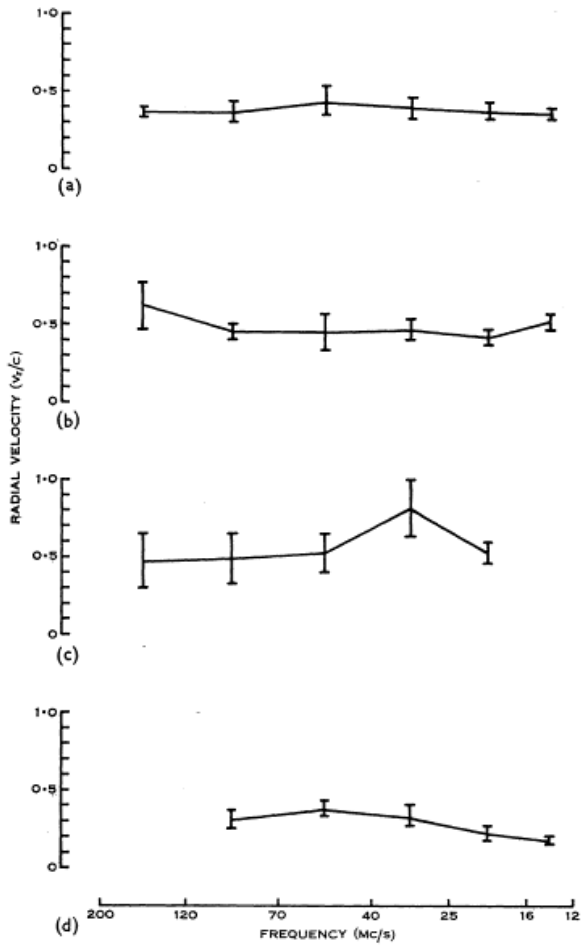


Figure 111 Plots of radial velocity against frequency for four Type III bursts for which reliable measurements were possible over at least five of the six frequency ranges. Errors are shown by bars (after Stewart, 1965: Fig. 3).

I concluded that the radial velocities derived for individual bursts show a tendency to remain constant over a great range of heights in the corona. This was later confirmed by spacecraft observations of type III electron streams near the Earth's orbit.

3.20.6 Discussion of Results

From Dapto unpublished data I inferred that Type III sources are rarely ejected at angles larger than 30^0 to the radial direction. Hence the derived velocities may be taken as representative (though on the average slightly lower than) the actual speed of the disturbance. Also the result that the Type III disturbances at approximately constant radial velocities often travel over large distances in the corona implies that the paths of these disturbances are approximately rectilinear.

Wild, Sheridan and Neylan (1959) proposed that the Type V continuum was due to synchrotron radiation from Type III electrons trapped in the magnetic field high in the corona. However, as shown below, the derived radial velocities ($v_r \sim c/3$) are incompatible with such high electron speeds.

I argued that (Stewart, 1965: 75);

> If the source is guided quasi-radially outwards through the corona by a magnetic field configuration such as that contemplated by Weiss and Wild (1964), then the individual electrons can travel faster than the source as a whole, owing to their spiral path. However, if spiralling does occur with substantial pitch angles, the radial velocity of the source can only remain constant if either (1) the pitch angles and therefore the magnetic field remained constant with height from at least 0.2 to 2.0 R_o or (2) if the pitch angles are redistributed by collisions in such a way that the radial velocity of the source remains constant. Both conditions seem extremely unlikely and what is in more keeping with our rudimentary picture of magnetic fields in the high corona is that the motion of the electrons is rectilinear (i.e. the pitch angles are very small). On this interpretation the speed of the individual electrons is to be identified with the observed speeds of Type III sources.

3.21 Conclusion to Chapter 3

In the discussion above all the papers relating solely to Dapto radiospectrograph observations have been reviewed in detail. The next chapter deals with the remaining publications of the Dapto solar group (apart from several theoretical and review papers to be discussed in Chapter 5), which include Dapto swept-frequency interferometer measurements of source position, size or polarization over the 40 to 70 MHz frequency range.

4. INTERPRETATION OF INTERFEROMETER OBSERVATIONS 1957-64.

A number of papers were published by the members of the Dapto solar group on the swept-frequency interferometer observations during the period 1958 to 1966. These studies were complimented by Dapto radio spectrograph observations. The papers are reviewed in chronological order, as before, to show the development of ideas for the interpretation of the characteristics of the five spectral types of solar bursts. Although there is some repetition here I feel it is justified. For example, it was important to confirm the plasma hypothesis separately for Type II, Type III and Type V bursts because this was crucial to understanding the nature of the disturbances giving rise to these bursts as well as determining the radio emission mechanisms involved. A similar comment applies to radial source heights and coronal density distribtions.

4.1 Preliminary Results

Wild and Sheridan (1958) after describing the swept-frequency interferometer and how the instrument measure source position, size and polarization presented preliminary observations on Type I and Type III bursts. These observations measured the apparent size of the sources and show that the size increased with decreasing frequency.

4.1.1 Observations of a Type I Storm – 20 June 1957, 11:30 to 12:30 E.A.S.T.

The storm was right hand circularly polarized and its source size decreased from 10 min. of arc at 50 MHz to 6 min. of arc at 65 MHz (Figure 112). The maximum instantaneous brightness temperature in this period was estimated to be 2.3×10^{10} ^{O}K.

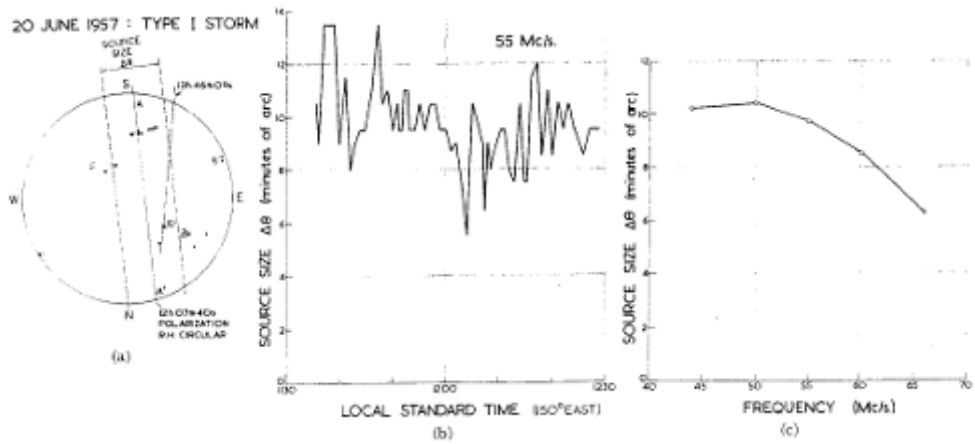


Figure 112 (a) Two Type I storm source position measurements averaged over time (full lines); (b) source size at 55 MHz as a function of time; (c) variation of mean source size with frequency (after Wild and Sheridan, 1958: Fig. 14).

4.1.2 Observations of Type III bursts – 3 July 1957, 10:15 to 12:30 E.A.S.T.

In this period 26 individual bursts were analysed. Figure 113 (a) shows the location of a burst at 10:39 above a large sunspot with a flare in progress. Figure 113 (b) shows the distribution of source sizes at 55 MHz and Figure 4113 (c) shows the variation of source size with frequency.

Wild and Sheridan (1958) concluded from these results that both Type I and Type III sources cover a remarkably large portion of the solar disk. The result that the size increases with decreasing frequency suggests that the emitting region in the corona could be funnel-shaped with the diameter increasing with height. They also pointed out that the measured source size does not necessarily correspond to that of the actual emitting region since refraction and scattering of the radiation in the solar atmosphere could disguise its real form. Indeed, refraction in the corona could lead to higher source velocities.

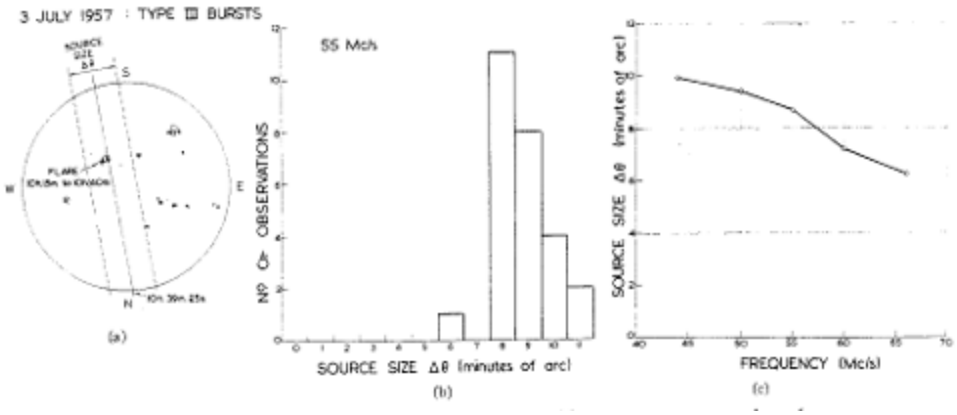


Figure 113 (a) An instantaneous position measurement averaged over frequency; (b) histogram showing the 55 MHz source sizes for the 26 bursts; (c) the average spectrum of source size during the burst referred to in (b) (after Wild and Sheridan, 1958: Fig. 15).

4.2 The Transverse Motions of the Sources of Type II, III and IV Solar Bursts

At the IAU Paris Symposium on Radio Astronomy in 1958 Jim Roberts presented a paper on behalf of Wild, Sheridan and Trent (1959) which described more observational results from the swept-frequency interferometer, including source positions of Type II, III, IV and V bursts.

4.2.1 The Source Positions and Transverse Velocities of Type III Bursts

In general, the source position at a single frequency was constant. However, different frequencies were found to arrive from different directions, often being dispersed across an appreciable fraction of the solar disk, the variation being greater for sources near the solar limb than for sources near the centre of the disk (Figure 114).

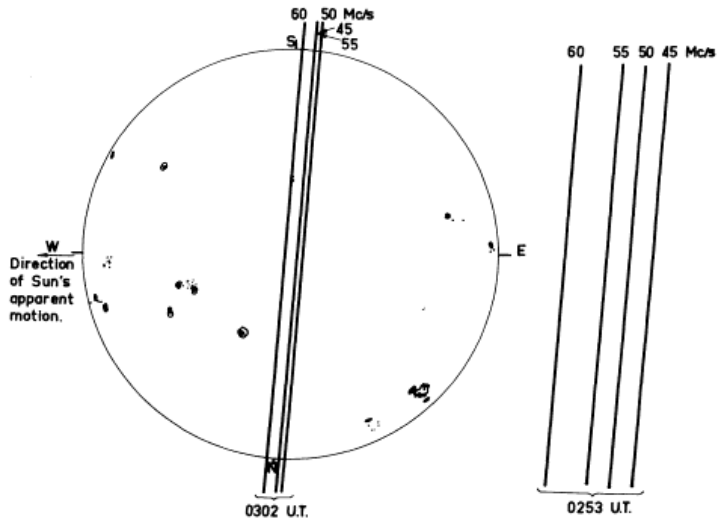


Figure 114 Showing the lines on which the centroids of the sources of two groups of Type III bursts were located at different frequencies by the swept-frequency interferometer on 1958 June 5 (after Wild, Sheridan an Trent, 1959: Fig. 1).

The positions (East or West angular displacement from the centre of the solar disk) of 11 Type III burst groups are plotted as a function of frequency in Figure 115. These observations show that the lower frequencies originate not only at later times but also at greater heights than the higher frequencies, strongly supporting the hypothesis of an outward-travelling exciting agency. The transverse velocities are found to exceed 10^5 km/sec for limb events, 2 to 5 times greater than the radial velocities derived from spectra. This suggests that the velocities ma be closer to the velocity of light than previously suspected (Section 3.2.2). The higher transverse velocities also suggest that the electron densities above active regions are larger than those given by standard models (see Section 4.3 for more details).

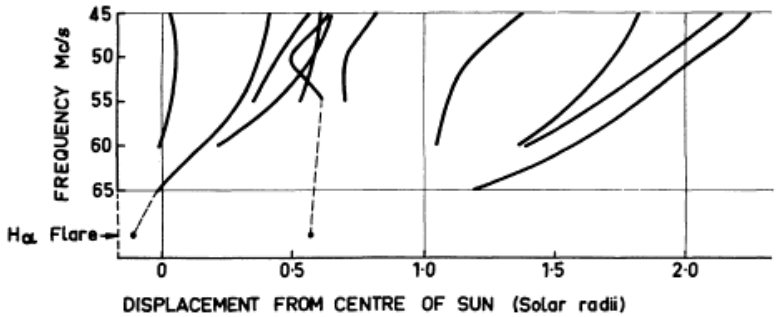


Figure 115 The variation with frequency of the positions of eleven sources of Type III bursts or groups. The events were recorded on different days between 1958 June 4 and July 7 (after Wild, Sheridan and Trent, 1959: Fig. 2).

4.2.2. Transverse Motions of Type II Bursts

Wild, Sheridan and Trent (1959: 180) write that:

> On the 'plasma hypothesis' it is expected that the Type II source positions to be similar to that of Type III bursts in these respects; the positions should be independent of time but should show increasing angular displacement with decreasing frequency. The two Type III bursts recorded to date both supported this conclusion. In the first example [Figure 116 below] the flare is located near the central meridian and the Type II disturbance moves away from the flare with an east-west component of transverse velocity of about 250 km/sec.; in the second event [Figure 117 below] the flare is located near the east limb and the transverse velocity is of the order of 2000 km/sec. Again, the velocities are greater than those calculated from the spectra and correspond more closely with those of the corpuscular streams (Roberts, 1959) which have been postulated to account for the terrestrial magnetic storms and aurorae which follow 1 to 3 days after certain flares.

4.2.3 Transverse Motions of Type IV Bursts

Boischot (1958) reported that the Type II burst at 169 MHz is often followed by a weak, smooth enhancement lasting some tens of minutes during which the source may more outward with a velocity of the order of 500 km/sec. This he called the Type IV burst (see Section 3.18). Wild, Sheridan and Trent (1959: 181) acknowledge that:

> It now seems probably that at least some of the earlier observations of transverse motions, which were made by Payne-Scott and Little (1952) at 97 Mc/s, referred to this class of event. Haddock (1958) and Maxwell, Swarup and Thompson (1958) have also reported phenomena that they believe to be Type IV bursts in the frequency range 100 to 600 Mc/s.

One of Payne-Scott and Little's (1952) events is shown in Figure 118 below for comparison with the swept-frequency measurements of Figures 116 and 117. It is immediately

clear that the transverse motions in each of these three cases refer to examples of Boischot's moving Type IV burst (See also my comments on Wild's (1955a) review of *outbursts* in Chapter 2.]

Describing the first event (Figure 116) Wild et al., 1959: 181) wrote:

> The flare (near the central meridian) accompanies an outburst consisting of three distinct phases; the Type III group, which occurs near the start of the flare; the Type II burst, which follows after 5 minutes and lasts for 6 minutes; and the Type IV burst which lasts an additional 10 minutes. In the Type IV burst no systematic dispersion is evident, all frequencies arriving from about the same source region. From the observed angular velocity of the source, we deduce a westward component of about 5000 km/second.

Describing the second event (Figure 117) they wrote (Wild et. al., 1959: p.181):

> The flare (near the east limb) accompanies an outburst containing bursts of Type II and IV only. The positional data conform to a general pattern similar to the first case, but here, during the Type IV phase, we witness the remarkable phenomenon of a source that moves transversely from near the flare position to a position nearly 4 solar radii beyond the limb.

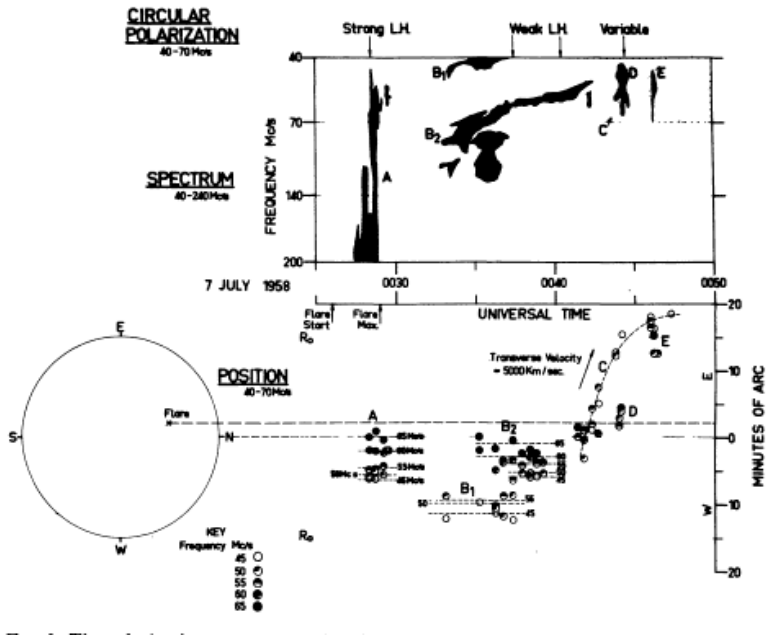


Figure 116 The polarization, spectrum and position data recorded during an outburst at the time of a solar flare of importance 2. Dark areas in the spectral diagram correspond to regions of high intensity in the time-frequency plane. A is a group of Type III bursts and associated Type V continuum, B1 and B2 are two bands (not obviously harmonically related) of the Type II burst, C is a Type IV burst, and D and E are transient features (after Wild, Sheridan an Trent, 1959: Fig. 3).

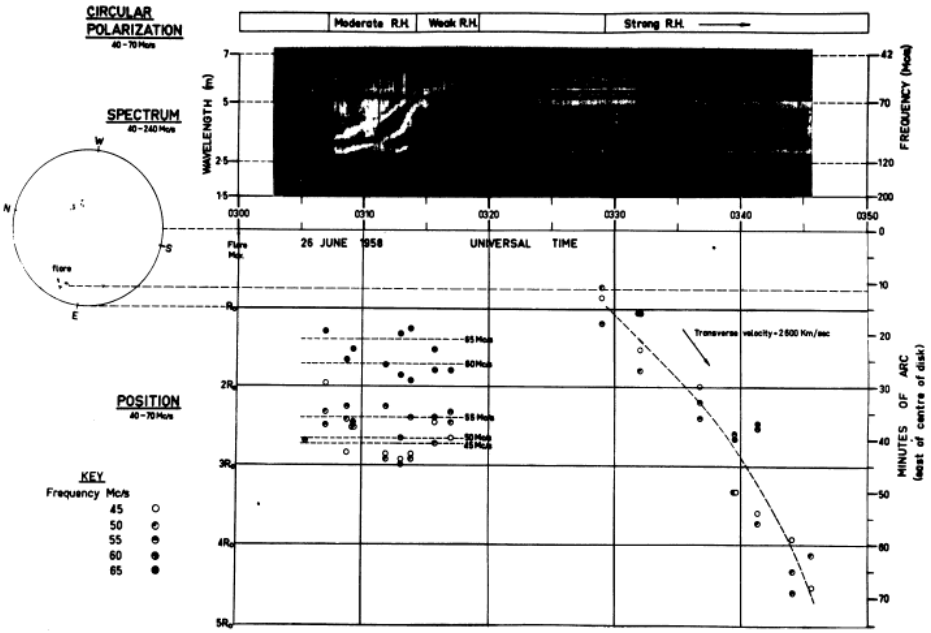


Figure 117 Polarization, spectrum and position data recorded during an outburst at the time of a solar flare of importance 2. The earlier section of the outburst is a Type II burst, the later a Type IV (after Wild, Sheridan ad Trent, 1959: Fig. 4).

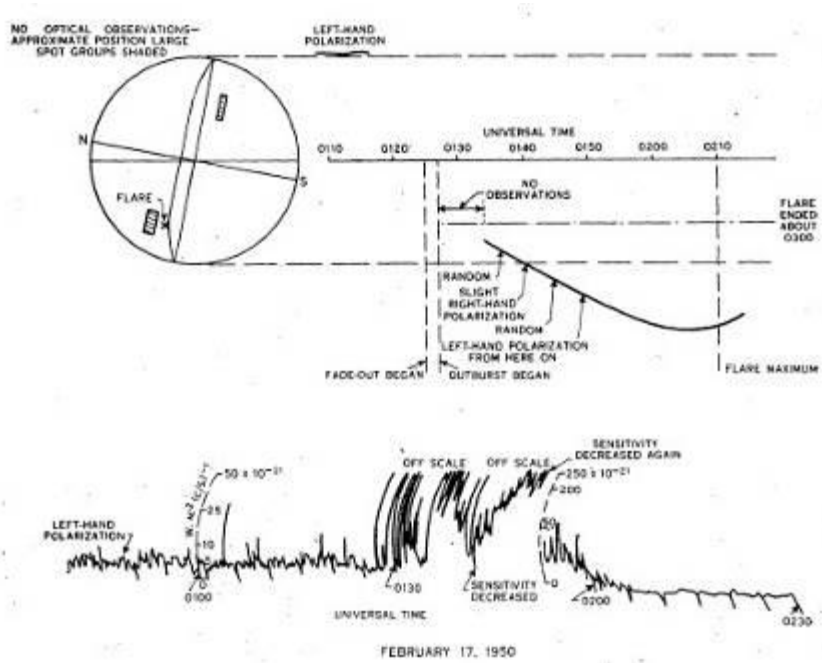


Figure 118 Observations of source position, polarization and intensity during the outburst of 17 February 1950 (after Payne-Scott and Little, 1952: Fig. 1b).

4.24 Identification of a New Spectral Class of Event the Type V Burst

Wild et al. (1959: 181-182) noted that:

> In the course of this investigation we have recorded positions of a number of broad-band enhancements that are often observed at the time of, or shortly after, the occurrence of Type III bursts. Such enhancements can last from 30 seconds to 3 minutes and can reach very high intensities (comparable to the Type III burst) with a peak frequency usually below 100 MHz. The complete frequency range of the enhancement is not known but Neylan (1959) has found a correlation with centimetre wavelength bursts [Section 3.18]. This suggests the possibility of extremely broadband emission. On several occasions the source has been observed to exhibit substantial outward transverse motions with velocities of the order of 3000 km/sec. In this respect they appear to be similar to Type IV bursts. It is possible that they are initiated high in the corona by the Type III disturbance, while the Type IV may be initiated by the Type II disturbance.

Wild et al. suggested that this new Type of emission be called a 'Type V burst' (see Section 4.7 for a more rigorous analysis of the properties of Type V bursts).

4.3 Investigation of the Speed of the Disturbances Responsible for Type III Radio Bursts

Wild, Sheridan and Neylan (1959) reported on the Dapto interferometer measurements of the relative positions and derived speeds of 100 Type III bursts or isolated groups of bursts recorded between June and December 1958. Inspection of the records showed that in the majority of cases the positions at any given frequency remained constant to within about ±1 min of arc throughout the lifetime of an individual burst.

4.3.1 The Variation of Position with Frequency of Events Associated with Limb Flares

Only those Type III bursts which occurred between the start and maximum of isolated flares were recognized. In all only 8 events were found and in each case the source positions given in Figure 119 are seen to lie beyond the solar limb with the distance from the centre increasing with decreasing frequency. These results strongly support the hypothesis that the different frequencies originate at different levels in the path of a disturbance travelling outwards through the corona. If it is assumed that the path of the disturbance is assumed to be radial, then the positions combined with the drift rate given by the dynamic spectrum can be used to calculate the velocity of the disturbance.

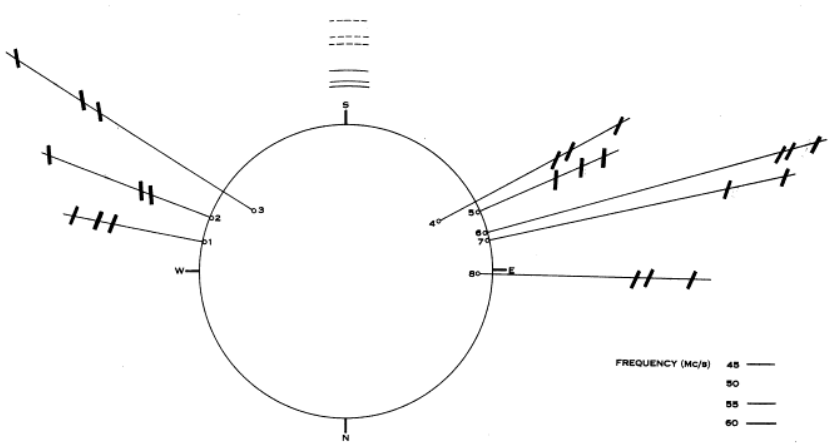


Figure 119 Source positions of eight Type III bursts (short arcs) associated with limb flares (open circles). The lines on which the radio sources are located are only showed in part closest to the radial through the flare position. The circular arcs at the top of the figure show the levels of the fundamental (full lines) and second harmonic (dotted lines) of the plasma frequency, assuming the Baumbach-Allen corona (after Wild, Sheridan and Neylan, 1959: Fig. 7).

4.3.2 Statistical Analysis of Radio Positions

The spread of position with frequency, clearly evident in Figure 119, is shown in Figure 120(a) using the complete set of radio observations. Roughly, the points are seen to be scattered about a straight line passing through the origin. The linear component is shown in Figure 120(b), in which mean values of the ordinates of Figure 120(a) have been plotted for successive narrow ranges of the abscissa.

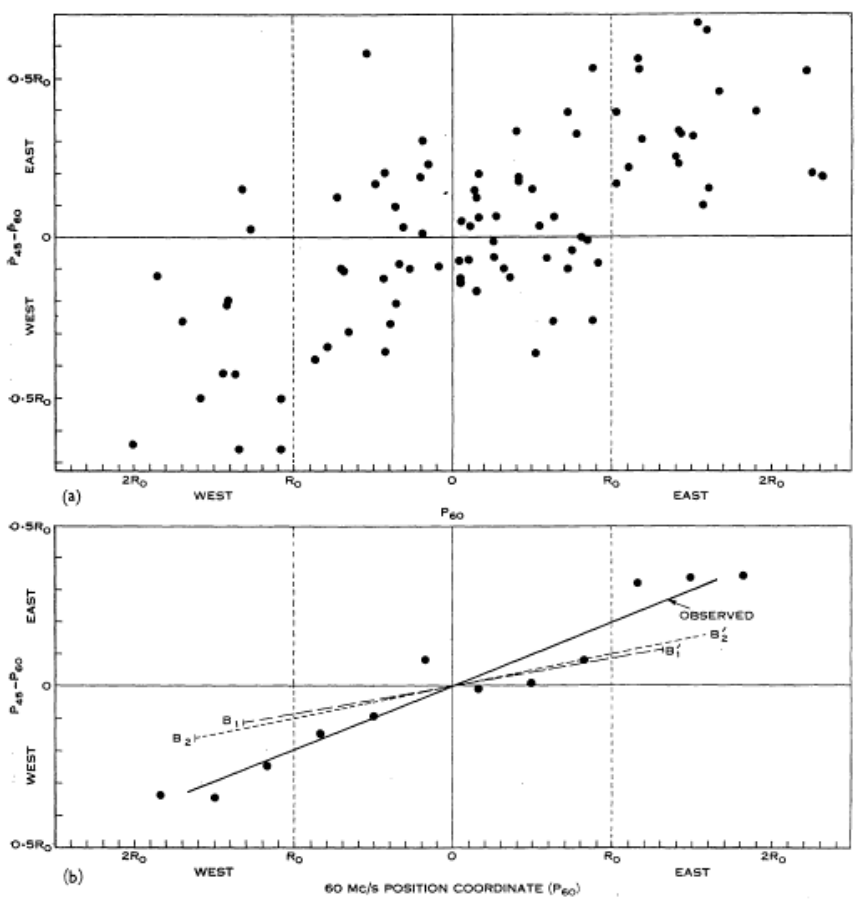


Figure 120 Distribution with 60 MHz position on the disk of the amount of spread in Type III bursts (as measured by the difference between 45 and 60 MHz positions) in (a) each burst or group is shown as a dot. In (b) the mean positions in each abscissa group are

shown. The full line through the observed points is compared with that predicted by the plasma hypothesis assuming the Baumbach-Allen corona. B_1B_1 / refers to the fundamental plasma level and B_2B_2 / to the second harmonic level (after Wild, Sheridan and Neylan, 1959: Fig. 8).

Figure 120(b) may be interpreted in terms of the simple model of Figure 121, where different frequencies are assumed to originate at different fixed levels in the atmosphere. The presence of a systematic (linear) component in Figure 120 is taken to be further evidence that different frequencies originate at different levels in the corona, and the gradient of this line can be used to obtain information on the electron density distribution.

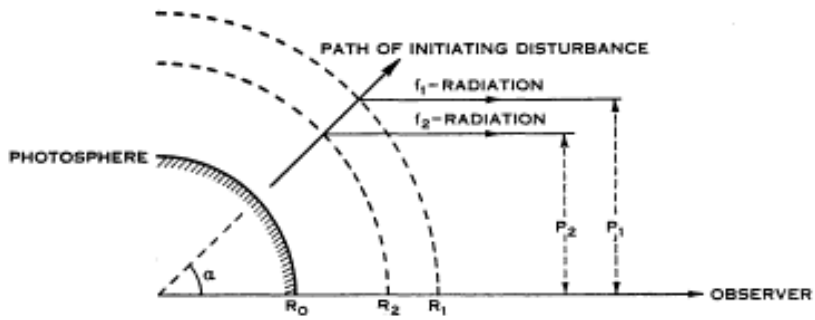


Figure 121 Idealized diagram showing the radio emission from a radially ejected Type III disturbance (after Wild, Sheridan and Neylan, 1959: Fig. 9).

The scatter component of Figure 120 (a) was considered to be due to several possible causes such as: irregular refraction in the terrestrial and solar atmospheres, variations in the heights of emission levels, variations in the angle between the path of the disturbance and the radial direction, and variations due to different angles between the path of the disturbance and the scanning direction of the interferometer.

The data of Figure 120 may be used to derive approximate mean radial distances, $\boldsymbol{R_{45}}$ and $\boldsymbol{R_{60}}$, at which sources of 45 MHz and 60 MHz bursts radiate. From Figure 122 it is seen that the distribution of 60 MHz positions is fairly uniform out to 1.66 R_0 hence it is assumed that $\boldsymbol{R_{60}}$ ~ 1.66 R_0. From Figure 120 (b) $\boldsymbol{R_{45}}$-$\boldsymbol{R}_{60}$ ~ 0.34 R_0 giving $\boldsymbol{R_{45}}$ ~ 2.0 R_0.

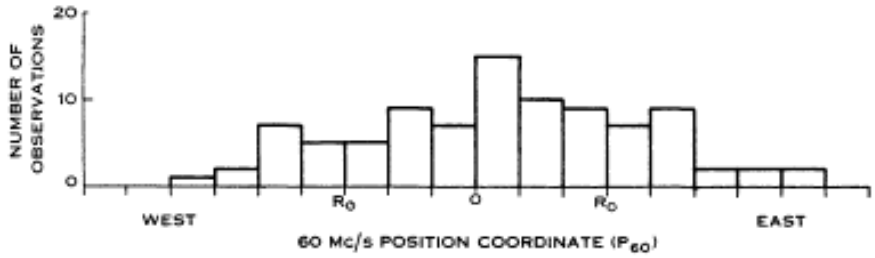


Figure 122 Distribution across the disk of the 60 MHz sources of Type III bursts (after Wild, Sheridan and Neylan, 1959: Fig. 10).

Finally, the east-west component of the transverse velocity is given by $(P_{45}-P_{60})/(t_{45}-t_{60})$, where t_{45} and t_{60} are the times of maximum intensity at 45 and 60 MHz. Figure 123 shows how this velocity varies from centre to limb, using the 60 MHz position as abscissa. Each point represents the mean of about ten bursts, and the total length of the line through each point denotes the standard deviation. The transverse velocity is seen to increase from about zero at the centre to about 0.5*c* at the radio limb. Thus, neglecting any possible effects of systematic refraction, this is further evidence for mean outward velocities of about 0.5*c*.

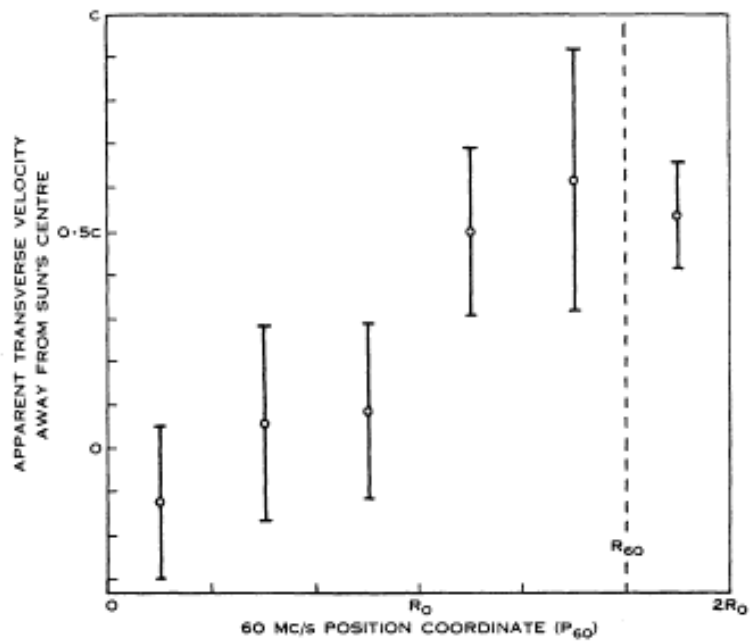


Figure 123 Variation with 60 MHz position of the transverse component of apparent outward velocity of Type III disturbances. Each point represents the mean of about ten values of independent events, and total lengths of the vertical lines signify the standard deviations (after Wild et al, 1959: Fig. 11).

4.3.3 Implications of the Plasma Hypothesis

Wild et al. conclude that the evidence presented above confirmed the widely accepted hypothesis that the frequency emitted from a given level in the corona for the Type III (and II) burst is either the fundamental plasma frequency or its second harmonic (Section 3.1).

4.3.4 The Escape of the Fundamental and Second Harmonic Frequencies

In a spherically symmetrical corona the fundamental can only escape along a narrow cone abut the radial direction if only refraction effects are important (Jaeger and Westfold, 1950: Wild Murray and Rowe, 1954 (Section 3.5). However, Figure 124 shows that the fundamental Type III can escape from the whole disk, as Roberts (1959b) also demonstrated for the Type II burst (Section 3.17). The distribution of harmonic pairs in Figure 4.13 can be explained by assuming that the fundamental is stronger in intensity than the second harmonic except near the solar limb.

Wild, Sheridan and Neylan (1959) assume that near its start the path followed by the fundamental meanders in all directions through the highly refracting irregularities, while on the average the direction of escape is radial i.e. the mean path is deviated away from the centre of the disk. Subsequently, the path should curve inwards because of the effects of spherical refraction (Jaeger and Westfold, 1950). As pointed out by Shain and Higgins (1959), these two opposing effects are likely to be comparable in magnitude. Therefore, it seems reasonable to assume that the position of the fundamental is unaffected by refraction in the solar atmosphere. In support of this conclusion, it is noted that Wild, Sheridan and Trent (1959) found no evidence for refraction in the fixed position of a Type IV source of broadband emission from 4to 70 MHz (Section 4.2).

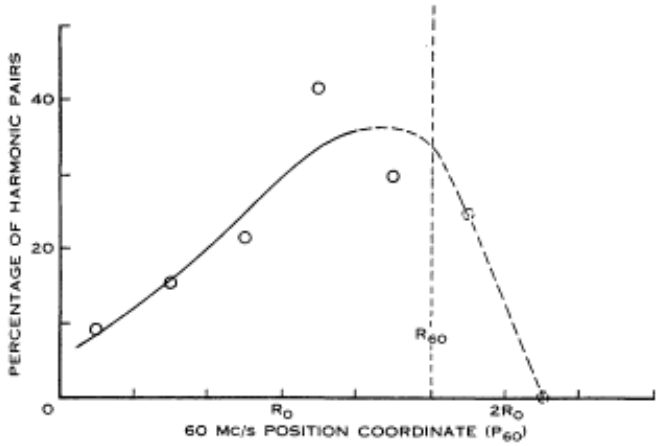


Figure 124 Distribution with 60 MHz position on the disk of the percentage of Type III bursts which show recognizable harmonics (after Wild, Sheridan and Neylan, 1959: Fig. 12).

4.3.5 The Radial Distribution of Electron Density

Wild, Sheridan and Neylan (1959) identified the mean radial distances $\boldsymbol{R_{45}}$ and $\boldsymbol{R_{60}}$ derived in section 4.3.2 with those of the 45 and 60 MHz plasma levels to obtain the values of electron density plotted in Figure 125 below. A third point (19.7 MHz) was obtained by Shain and Higgins (1959) using a similar method. The radio values are seen to be an order of magnitude greater than the Baumbach-Allen standard model, but only slightly higher than the densities derived by Newkirk for a coronal streamer. Wild, Sheridan and Neylan (1959) conclude that this result suggests that Type III disturbances may actually travel outwards along coronal streamers.

4.3.6 The Distribution of Velocities

From the above analysis the mean radial velocity derived from a small number of bursts near the solar limb was 0.5*c*. Using all the available bursts Wild, Sheridan and Neylan (1959) derived the distributions shown in Figure 126 by using the formula

$$t_{45} - t_{60} = (1/v - 1/c \cos\alpha\ R_{45} - R_{60} + \tau(\alpha) \qquad (22)$$

where $\tau(\alpha)$ is a time delay correction for the decrease in velocity of radio signals from near the plasma level and is given by Figure 127.

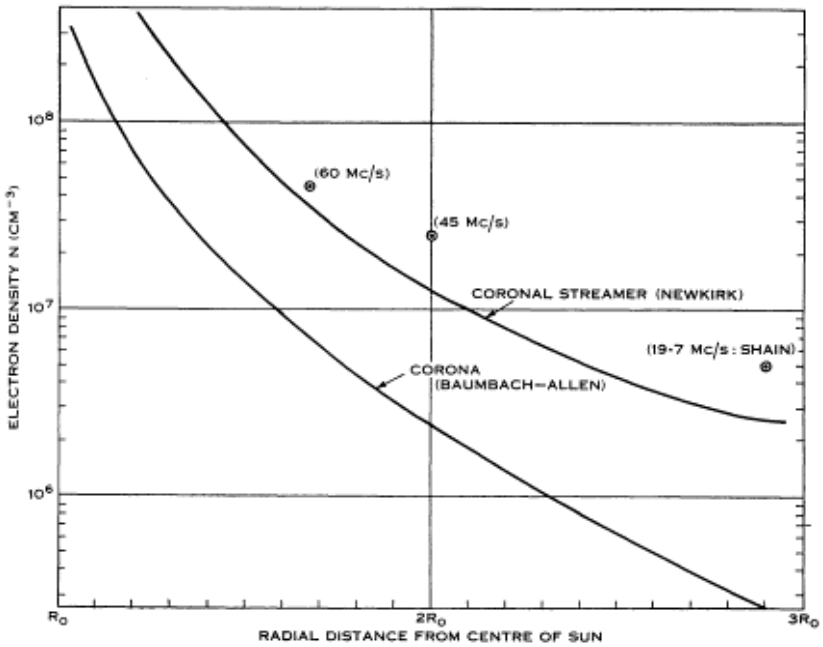


Figure 125 Electron densities in the corona as a function of radial distance (after Wild, Sheridan and Neylan, 1959: Fig. 13).

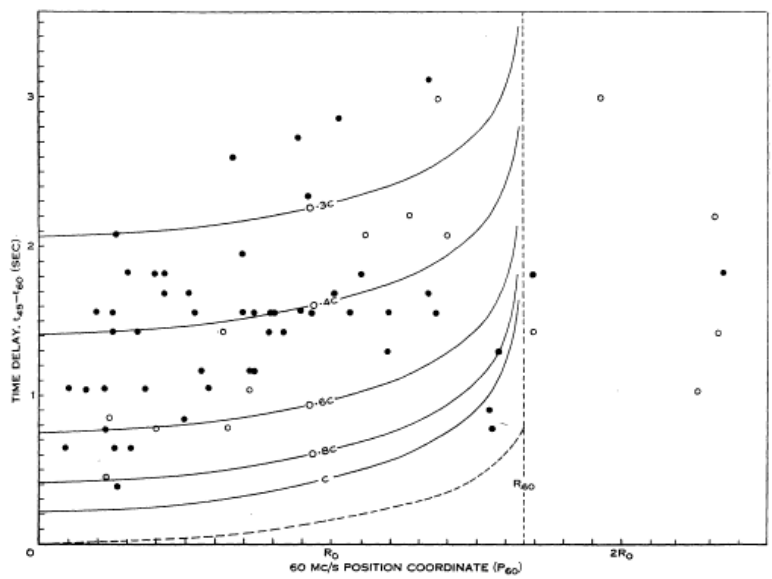


Figure 126 Distribution with 60 MHz position on the disk of the time interval between times of maximum intensity at 60 and 45 MHz for observed Type III bursts. Open circles refer to bursts followed by Type V emission (after Wild, Sheridan and Neylan, 1959: Fig. 14).

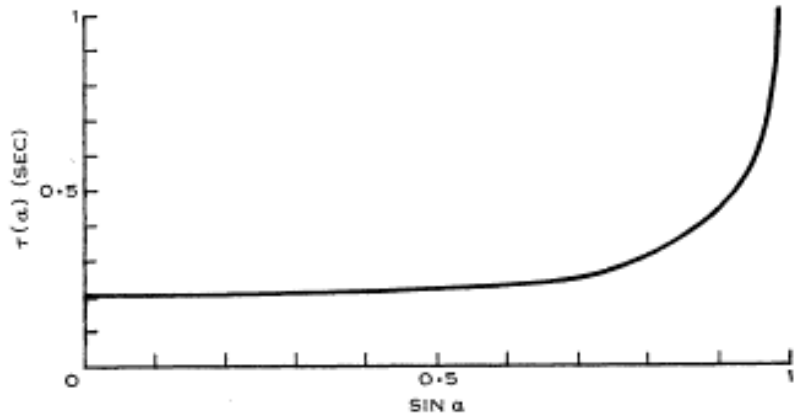


Figure 127 Time delay of radio signals near the plasma level (after Wild, Sheridan and Neylan, 1959: Fig. 16).

The time delay correction $\tau(\alpha)$ is difficult to evaluate correctly and seems to be important near the solar limb. Consequently, only the points of Figure 127 for $P_{60} < R_{60}$ were used to derive the velocity distributions of Figure 128, where the dashed lines refer to values with $\tau(\alpha) = 0$. From this figure the mean radial velocity is 0.45*c* with values ranging from 0.2 to 0.8*c*.

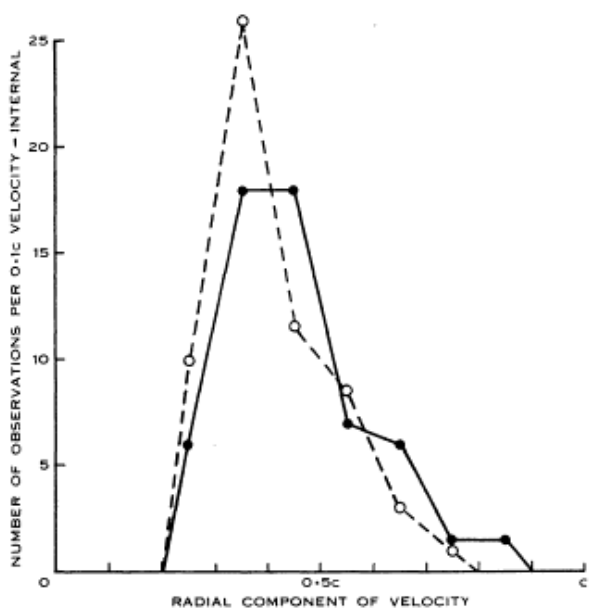


Figure 128 Distribution of radial velocities of Type III bursts. Dashed curve refers to $\tau(\alpha) = 0$ (after Wild, Sheridan and Neylan, 1959: Fig. 17).

4.3.7 Testing the Synchrotron Hypothesis for Type V bursts

To test this hypothesis Wild, Sheridan and Neylan (1959: 393-394) wrote:

> To test the feasibility of the synchrotron hypothesis, we note that synchrotron radiation from an electron of energy E (MeV) spiralling with an angle of θ in a magnetic field of flux density B (gauss) shows a maximum where
>
> $$f_c = 16\ BE^2 \sin\theta \quad \text{(MHz)} \qquad (23)$$
>
> and that above tis frequency the energy falls off rapidly. Hence, for f_c = 100 MHz, $BE^2 \sim 6$. Taking 1.5 G as a reasonable upper limit to the coronal magnetic field, and sin θ ~1, they find that electron energies of at least 2 MeV are required.
>
> The total power radiated by each electron is approximately $6 \times 10^{-22}\ B^2E^2\sin^2\theta$ watts, and, assuming this power to be radiated in an effective bandwidth of ½ fc, it can be calculated that the maximum flux density at the Earth due to each electron is
>
> $$S = 2.7 \times 10^{-22}\ B \sin\theta\ \text{W m}^{-2}\ (\text{Hz})^{-1} \qquad (24)$$
>
> Hence, neglecting self-absorption, the total number of electrons required to generate a flux density of 10^{-18} W m $^{-2}$ $(\text{Hz})^{-1}$ is $n \geq 3 \times 10^{33}$ since it may be assumed that $B \sin\theta \leq 1.2$.

Substituting a radiating volume of 10^{22} cm^3, based on the observed source size, Wild et al. found a required density of relativistic electrons of 30 cm^{-3} which compared favourably with the 100 cm^{-3} density estimated by Boischot and Denisse (1957) for Type IV bursts. They concluded that if these energetic electrons are to be supplied by the Type III burst, which have radial velocities of only 0.5 *c*, then it is necessary to postulate that the Type III electrons spiral along magnetic field lines as they move outward from the flare region. A theoretical treatment of possible spiralling effects for Type III electrons was presented by Weiss and Wild (1964).

4.4 Relative Positions of Fundamental and Second Harmonic Type II and III Bursts

During the period May 1958 to November 1960 a total of 4 Type II bursts and six independent groups of Type III bursts in which both fundamental and second harmonic bands were recorded on both the swept-frequency interferometer and the Dapto radiospectrograph. The positions of these burst sources are listed in Table 1 of Smerd, Wild and Sheridan (1962).

4.4.1 The Type II Burst Positions

Observations of spectrum and position for a typical Type II burst are shown in Figure 129. The positions of the fundamental and harmonic are given at the four frequencies 45, 50, 55 and 60 MHz. with each full line denoting the mean of many independent measurements.

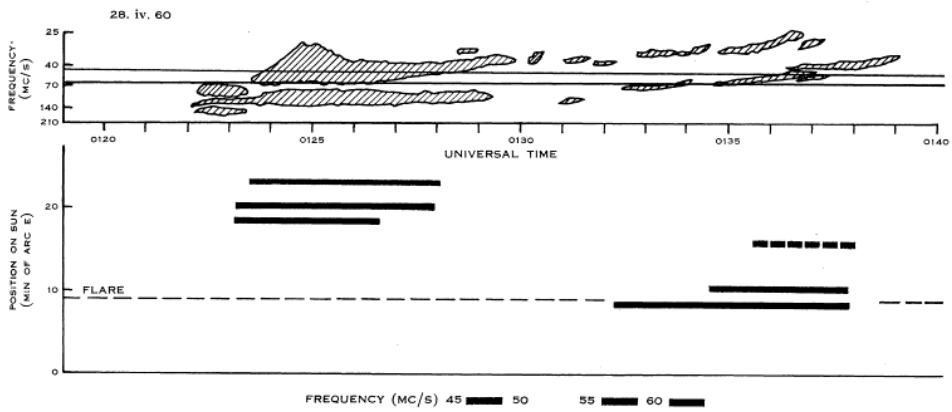


Figure 129 Dynamic spectrum and East-West positions of the 28 April 1960 Type II burst (after Smerd, Wild and Sheridan, 1962: Fig.1).

In Figure 130 are given positions on the solar disk of fundamental and harmonic bands of the four Type II bursts together with those of the associated flares. In all four cases the harmonic is located inside the fundamental position.

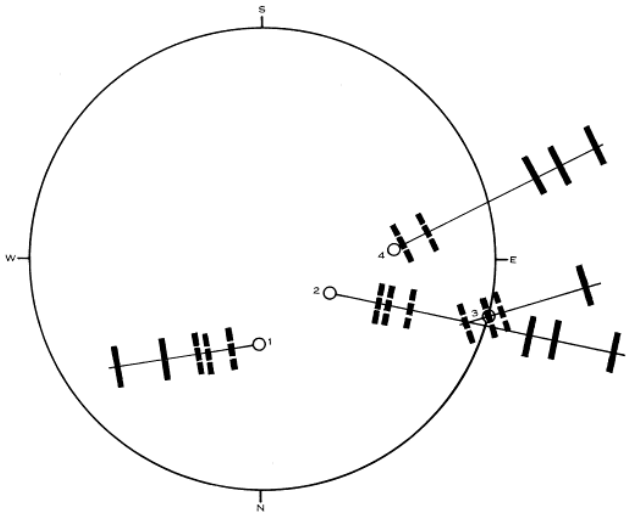


Figure 130 Mean positions of the fundamental and harmonic bands of the four Type II bursts shown as short lines perpendicular to the radial from the associated flare position. Dashed lines refer to the harmonic. Circles refer to the flare positions (after Smerd, Wild and Sheridan, 1962: Fig. 2).

4.4.2 The Type III Burst Positions

In the examples of Type III bursts in two cases the harmonic position was inside the fundamental, in one it was outside, and in three no appreciable shift was found (Figure 131).

Smerd et al. concluded that these results were inconclusive and indicate the need for further investigation but that their results seem to provide evidence that a pronounced outward shift of the harmonic relative to the fundamental is not observed in the majority of cases. Later Weiss (1963) found a similar result for his sample of Type II bursts (Section 4.5).

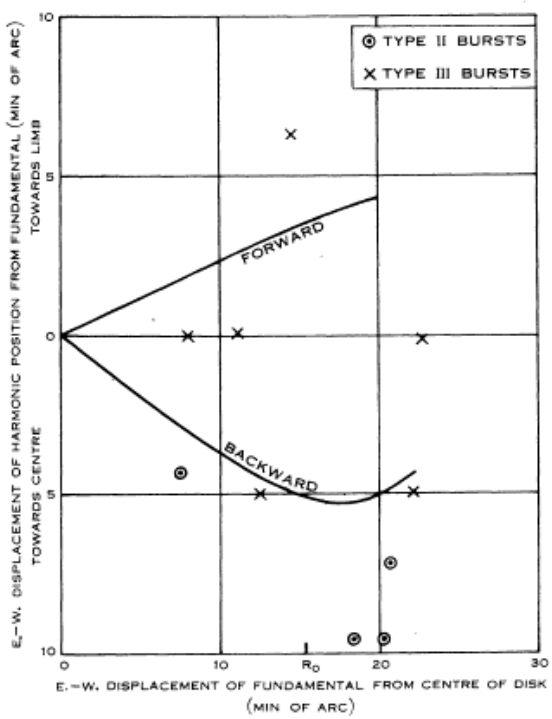


Figure 131 Plot showing the relative displacements between fundamental and harmonic Type II and Type II bursts. The full lines show theoretical curves on which the points would lie according to a simple model discussed below with propagation of the harmonic along forward and backward rays respectively (after Smerd, Wild and Sheridan, 1962: Fig. 3).

4.4.3 Interpretation

Several possible explanations for the harmonic appearing lower in the corona than its fundamental plasma (**f_0**) level were suggested. Denisse (1960) proposed that the harmonics arise from non-linear components of plasma waves, and that the coupling between plasma and electrodynamic waves at the second harmonic plasma frequency occurs lower in the corona near the **$2f_0$** plasma level. This was rejected by the authors because it requires the inward moving plasma waves to be set up by an outward-moving disturbance. A more preferred explanation is that the anomalously central position of the harmonic results from an effect of reflection or refraction in the solar atmosphere. Jaeger and Westfold (1950) showed that radiation can escape the corona along a direct and also a reflected path provided the frequency exceeds **f_0** (Figure 131).

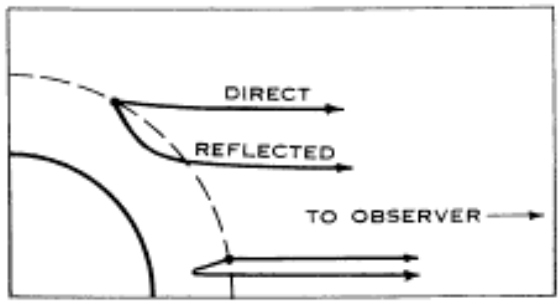


Figure 132 Showing direct and reflected rays escaping from above the plasma level (after Smerd, Wild and Sheridan, 1962: Fig. 4).

Ginzburg and Zhelezniakov (1958) suggested that the second harmonic of solar bursts arises from the combination scattering of pairs of plasma waves of frequency $\mathbf{f_0}$ to produce an electrodynamic wave of frequency $\mathbf{2f_0}$. Smerd et al. used this process to calculate the direction of the resulting electrodynamic wave. To a first order the longitudonal plasma wave, set up by the outward-moving stream of electrons via the Cerenkov effect is represented by the linear equation

$$\mathbf{E(r,t) = E_0\, e^{\,i(\omega t - k.r)}} \qquad (25)$$

where K is related to the angular frequencies ω, the angular plasma frequency ω_0 an the phase velocity v, by the well known dispersion relation

$$\omega = (\omega_0{}^2 + k_2 v_t^2)^{1/2} \sim \omega_0 \qquad (26)$$

whence

$$k \sim \omega_0 / v \qquad (27)$$

The dispersion relation (4.5) is shown in Figure 133, where the determination of ω and k is exemplified by the point P for a wave set up by an electron stream with velocity c/3.

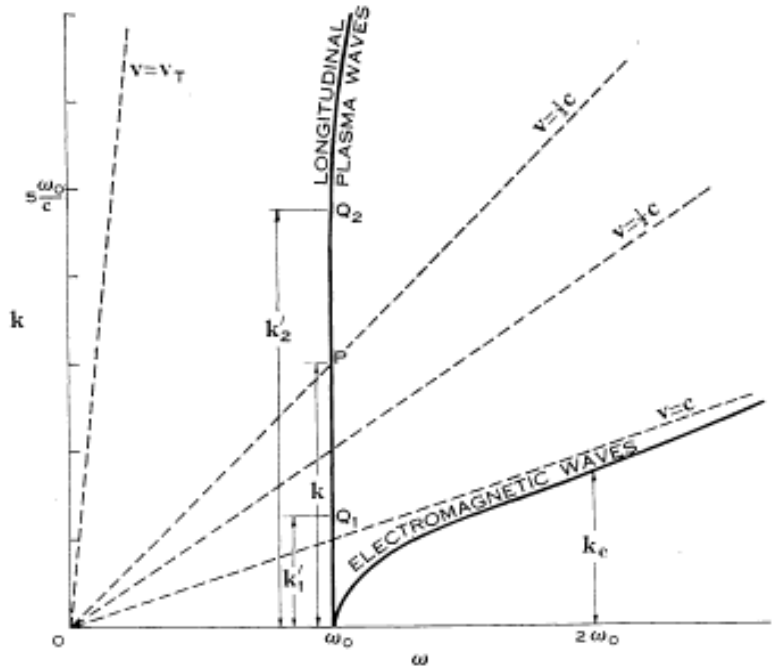


Figure 133 Dispersion relationship for longitudinal plasma waves and electrodynamic waves in a thermal plasma in the absence of a magnetic field (after Smerd, Wild and Sheridan, 1962: Fig. 5).

The travelling plasma wave encounters electrical charge fluctuations which produce plasma waves with wave numbers $\mathbf{k}'$**,** and then scattering produces combination plasma waves with wave numbers $\mathbf{k} + \mathbf{k}'$**.** Only the longer combination waves are not suppressed by Landau damping.

Figure 133 shows two special conditions. The point Q_1 gives the value of $\mathbf{k}'$ necessary for electrodynamic radiation to propagate in the same direction as the stream, and Q_2 in the opposite direction.

Whatever the values of **k and** $\mathbf{k}'$ the high frequency combination wave is unable to propagate in the form of a longitudonal plasma wave because of Landau damping. However, certain components may propagate as transverse electromagnetic waves for which

$$\mathbf{k} + \mathbf{k}' = \mathbf{k_e} \qquad (28)$$

Ginzburg and Zhelezniakov (1958) give the intensity of the radiation in the direction making an angle θ with that of the forward-moving plasma wave as

$$F(\theta) = (n_{k/})^2 \sin^3 \theta \tag{29}$$

where $n_{k/}$ is the fluctuating electron density due to irregularities in the corona.

Adopting a result of Kahn (1959) and Saltpeter (1960) that

$$(n_{k/})^2 \sim k^{/2} \tag{30}$$

and from the vector triangle

$$k^{/2} = k^2 + k_e^2 - 2\, kk_e \cos \theta \tag{31}$$

Smerd et al. (1962) using the above equations then derive

$$F(\theta) \sim \sin^3 \theta\, [1 + 3\, (v/c)^2 - 2\, \{3\, (v/c) \cos \theta\}^{1/2}] \tag{32}$$

giving the distribution shown in Figure 132.

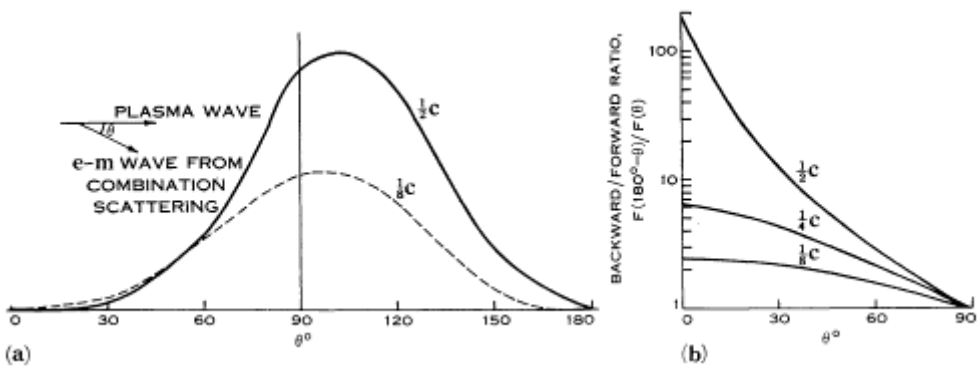


Figure 134 (a) Calculated angular power spectrum for radiation at the second harmonic of the plasma frequency (b) The backward/forward ratio of intensities (after Smerd, Wild and Sheridan, 1962: Fig. 6).

Smerd et al. (1962: 191) write:

[Figure 134] implies that the harmonic radiation will be emitted most strongly in a direction backwards of the transverse direction. The higher the radial velocity v_r, of the plasma wave, the more backwards the beaming becomes, and when $v_r >$ c/2, the backward emission exceeds the forward by an order of magnitude. Hence

under these conditions much more radiation will escape along the reflected ray than the direct.

They conclude that for Type III bursts where $v_r \sim c/2$, the reflected source of harmonic radiation should dominate the direct source as observed; for Type II bursts, where $v_r \sim 1000$ km/sec, this could not happen unless the shock wave disturbance accelerates c/2 electrons which travel outwards through the corona. Support for this idea comes from the observation of 'herringbone' structure in some Type II bursts [Roberts, 1959b].

4.5 The Positions and Movements of Sources of Type II Bursts 1963

Alan Weiss joined the Dapto group in 1961 having transferred from meteor studies at Adelaide. He was responsible for supervision of the analysis of all Dapto interferometer records until his untimely death from Leukaemia in December 1964. In that short period of time he wrote 4 major papers on Type II, IV and V bursts, a theoretical paper on electron propagation and a comprehensive review paper on the properties of solar bursts (Wild, Smerd and Weiss, 1963).

His first Dapto work (Weiss, 1963a) was a statistical study of the source positions and movements of 39 Type II bursts which complemented the earlier spectral study by Roberts (1959) discussed in Section 3.17. He used a statistical analysis of the position data of the Type II bursts and the Type III data of Wild, Sheridan and Neylan (1959), discussed in Section 4.2, to reveal a remarkable similarity in the general behaviour of the two Types of bursts, which confirmed the hypothesis of generation of the radio emissions by plasma oscillations. The times and positions of the 39 Type II bursts used in this study, together with the preceding Type III bursts and associated flares are listed in Table 1 of Weiss (1963a).

4.5.1 Multiplicity of events

Of the events 22 events listed, three are characterized by multiple bursts, separated in time, which are associated with the same flare. The example of 14 July 1959, reproduced in Figure 135, shows widely separated source positions for the two Type II events. Seven other examples were identified from their widely separated source positions.

Two further outstanding examples of multiple bursts are illustrated below in Figures 136(a) and 137. They are characterized by overlapping spectral bands with different frequency drift rates indicating different disturbances moving independently through the corona at the same time but with different speeds. The complexity of the Type II event may be matched by the complexity in the associated flare, as was the case in the two events mentioned here.

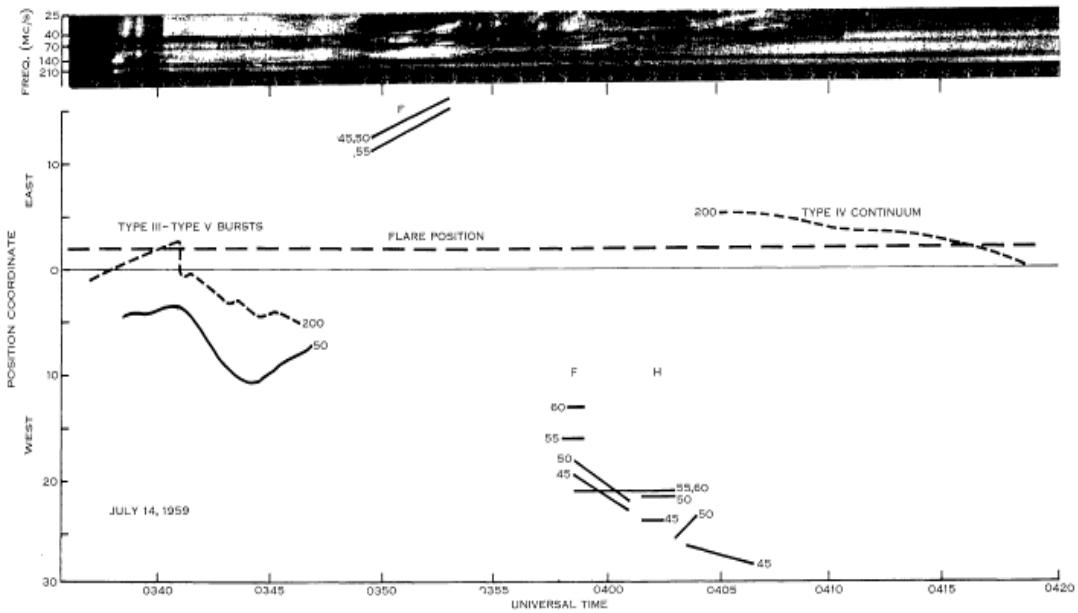


Figure 135 Multiple event of 14 July 1959 showing the positions of two widely separated Type II sources. F and H refer to fundamental and second harmonic components (after Weiss, 1963a: Plate 1).

4.5.2 Tangential Source Motion

Weiss notes that 13 of the 39 Type II bursts listed in his Table I, show systematic source movement at a single frequency. As this is not a characteristic of ionospheric refraction which would affect all observed frequencies, it is assumed to represent tangential source motion. Two examples are discussed. In the event of 14 July 1959 (Figure 135) the displacements in source position of the two separate bursts of this event, if extrapolated backwards in time, intersect near the projected position of the flare and near the time of the Type III burst that presumably was generated by the same initial explosion in the flare. In the burst of 6 April 1961 (Figure 136(b)) the rates of change in position with time confirm the constancy of apparent motion. Assuming that each frequency is excited at a constant height in the corona, as required by the *plasma hypothesis*, then the rates of change of position with time in the 13 bursts mentioned above imply tangential speeds of the order of 1000 – 2000 km/sec.

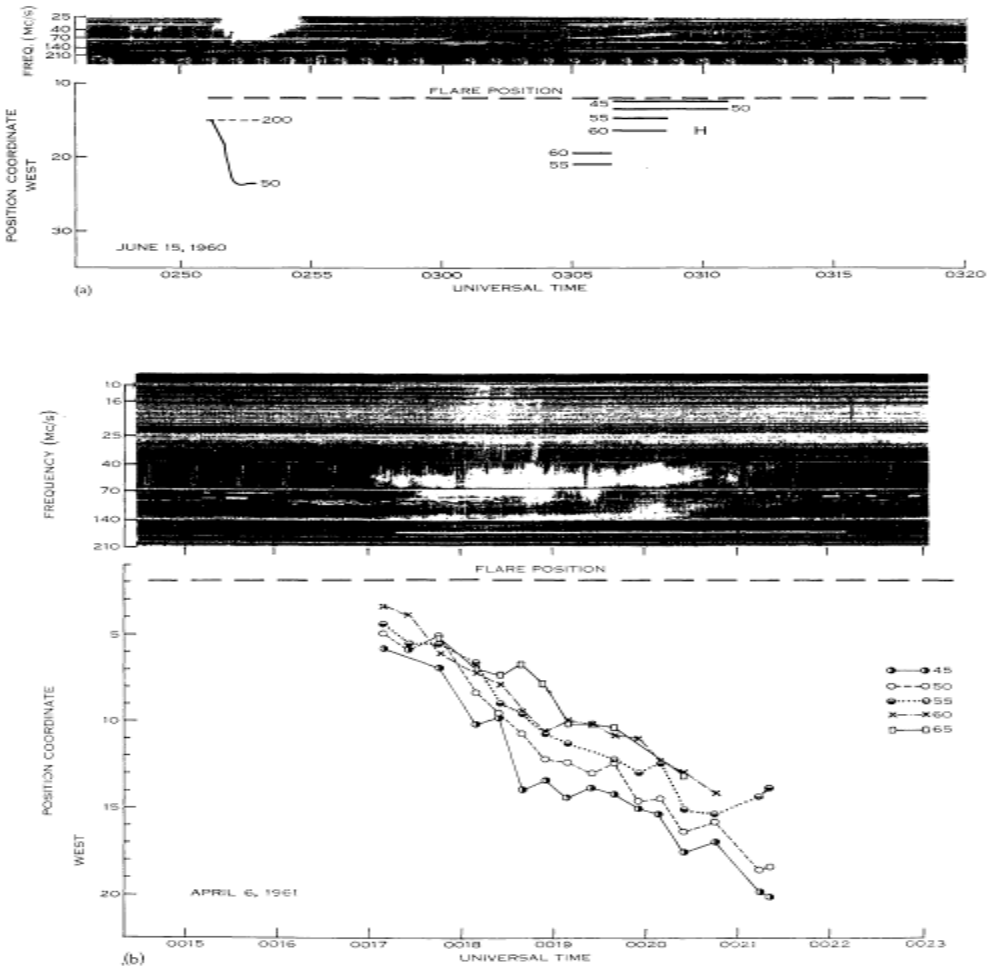


Figure 136 (a) Multiple Type II event of 15 June 1960 showing two sources in different positions and with different drift rates (Plate 3 of Weiss, 1963a). (b) The event of 6 April 1961 showing low drift rate and systematic transverse motion and 'herringbone' structure (after Weiss, 1963a: Plate 3).

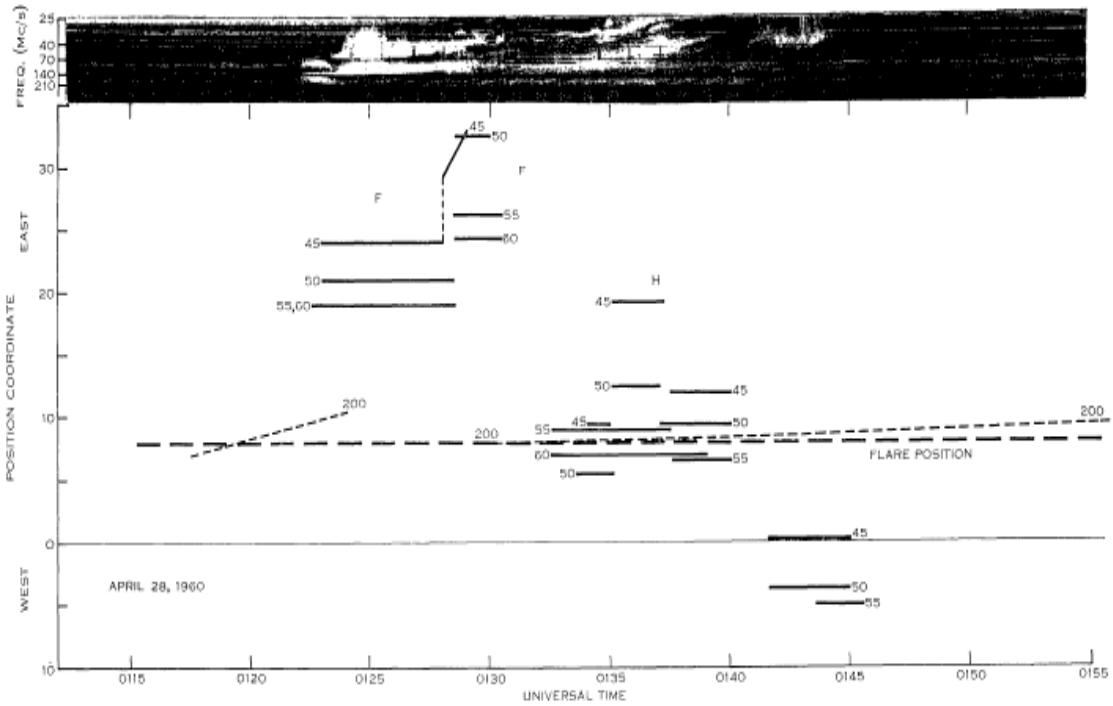


Figure 137 Multiple Type II event of 28 April 1960 showing three separated sources associated with different spectral features in the Type II burst (after Weiss, 1963a: Plate 2).

4.5.3 Position on the Disk and Spectral Features

As can be seen from Figure 138 both Type II bursts and associated flares are approximately uniformly distributed in position coordinates over the radio and optical disks. The distribution of flares is similar to those already obtained by Roberts (1959) in Section 3.17 and by Maxwell and Thompson (1962). The distribution of Type II bursts resembles closely that obtained by Wild, Sheridan and Neylan (1959) for Type III bursts (Section 4.4). The association of bursts with limb flares has been taken as evidence that the radiation is emitted in a very wide cone.

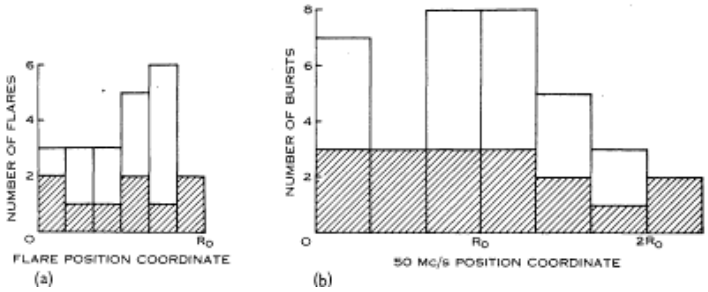


Figure 138 Disk distribution of (a) associated flares and (b) Type II bursts. Cross hatching refers to events east of centre (after Weiss, 1963; Fig. 1).

Weiss (1963a: 249) noted that:

> Perusal of the spectra of the bursts in the present sample indicates that the intensity of the second harmonic band tends to be much stronger than the fundamental for events nearer the limb (heliographic longitudes > 45°). A similar result was found by Wild, Sheridan and Neylan (1959) for Type III bursts. These observations suggest that the escape of harmonic radiation is unimpeded in all directions within a cone of 180°, whereas for limb events the fundamental suffers heavy attenuation and irregular scattering during its outward passage. If as it seems probable that Type II and III bursts are generated in dense coronal streamers, then the poor definition of the fundamental near the limb suggests that density irregularities scatter the radiation less efficiently at wide angles to the axial direction.

4.5.4 Testing the Plasma Hypothesis

To explore the validity of the *plasma hypothesis*, which predicts that the burst position at any frequency is a linear function of flare position, the data was plotted in Figures 139 as 50 MHz position versus flare position for (a) the Type II bursts and (b) the preceding Type III bursts.

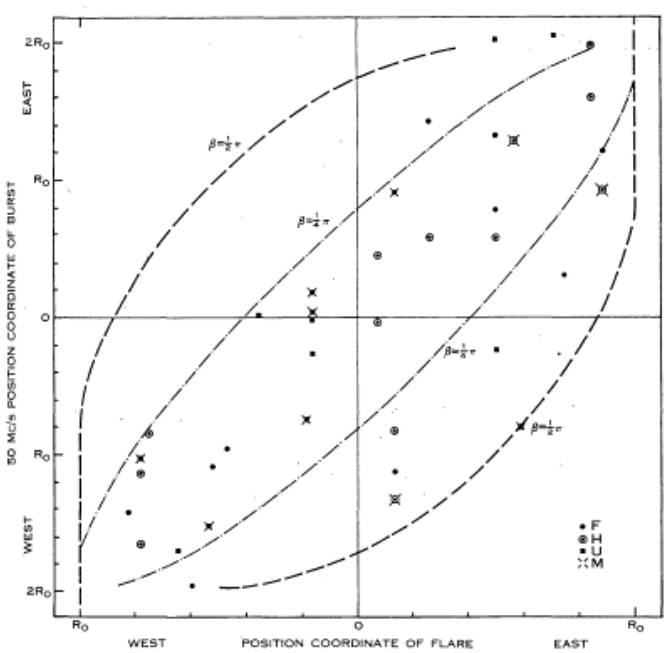


Figure 139(a) Observed 50 MHz position coordinates of the Type II bursts plotted against flare position. F refers to fundamental, H harmonic, U an unidentified band and M the mean position. is the angular dispersion from the radial. The dashed curves are drawn for $R_{50}/R_0 = 2.0$ (after Weiss, 1963a: Fig. 2a).

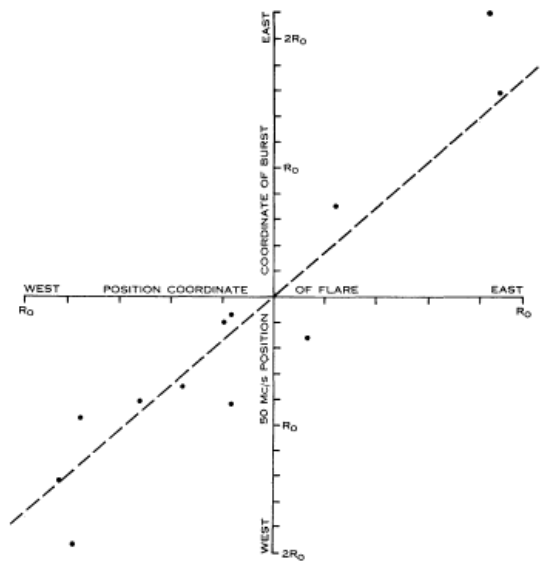


Figure 139(b) Observed position coordinates of the sources of Type III bursts at 50 MHz plotted against the position of the associated solar flares. The dashed line shows the least squares fit to the data (after Weiss, 1963a: Fig. 2b).

The plasma hypothesis also predicts that the variation $P_1 - P_2$ between the positions for any two frequencies is a linear function of the burst position P_2 (see also Section 4.2). To test this hypothesis again Figure 140 compares the difference $P_{45} - P_{60}$ with the 60 MHz position for (a) the Type II bursts and (b) for the sample of Type III bursts in Wild, Sheridan and Neylan,1959 (Section 4.2).

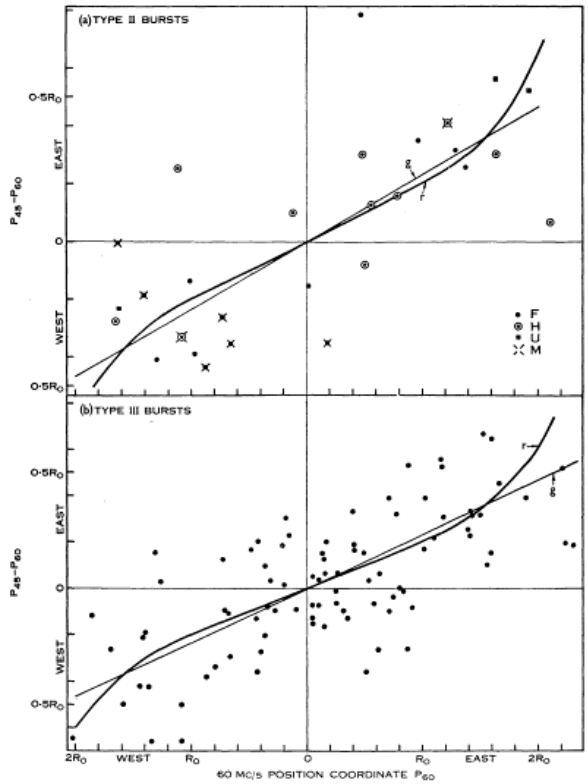


Figure 140 Diagrams showing the dependence of variation of position with frequency for (a) Type II bursts and (b) Type III bursts (after Weiss, 1963a: Fig. 3)

On the average the data conforms to the plasma hypothesis with the considerable scatter for the small sample of Type II bursts and less scatter for the Type III bursts. The scatter could be caused by any one of the following three factors discussed below:

(1) irregularities in the electron density distribution in the corona;
(2) non-radial ejection of the exciting disturbance;
(3) irregular refraction in the corona and ionosphere.

4.5.4.1 Variations in Height of the Plasma Level

Irregularities in the corona will produce variations in the heights of the plasma levels from event to event. The scatter in burst positions at a single frequency should vanish at the centre of the sun and increase towards the limb. This was not observed so Weiss concluded that this was not a

dominant effect and also noted that random variations in electron density would not produce any systematic variation with frequency.

4.5.4.2 Departures from Radial Motion

The envelopes sketched in Figure 139(a) were evaluated with a simple model (Figure 141) and show that for most Type II bursts departures from radial motion are no larger than $\pi/4$.

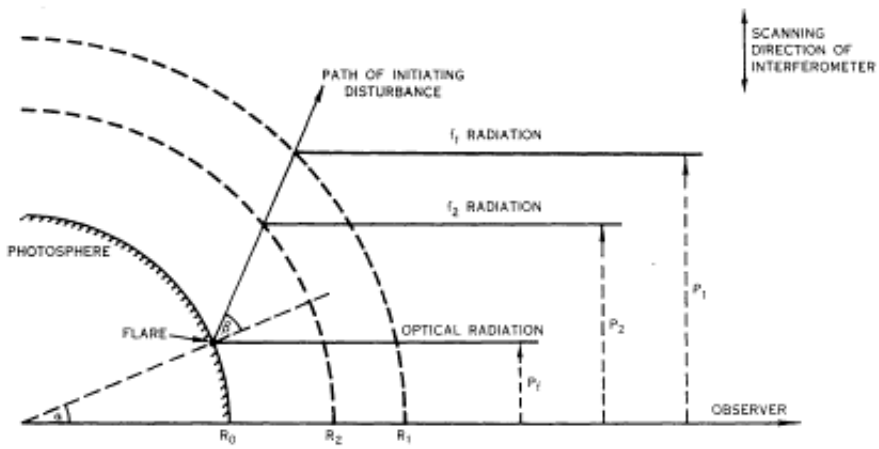


Figure 141 Model adopted in treating non-radial motion of the exciting disturbances of Type II bursts (after Weiss, 1963a: Fig. 7).

4.5.4.3 Irregular Refraction

Weiss (1963a) adopted the conclusions of Wild, Sheridan and Neylan (1959) and Shain and Higgins (1959) that the effects of scattering on small scale density irregularities are approximately cancelled out by any systematic refraction in the corona (see Section 4.3). He also pointed out that the most troublesome complication in the test of the plasma hypothesis at these frequencies is undoubtedly irregular ionospheric refraction, which can generate a systematic variation of apparent source with frequency (in the same sense as that predicted by the plasma hypothesis) as well as scatter in the measured positions. This systematic component of ionospheric refraction arises from a combination of two factors:

(1) displacement of source position by wedge Type refraction is frequency sensitive (approximately proportional to $1/f^2$;

(2) a source observed close to or beyond the radio limb is much more likely to have been refracted in the direction *away from* than *towards* the centre of the disk.

Since the effect of irregular ionospheric refraction could not be isolated only an upper limit was derived on the assumption that all scatter in Figure 139(a) was due to this effect. Weiss (1963) showed that the systematic variation with frequency predicted by the plasma hypothesis will only be increased due to ionospheric refraction by less than 20%.

Taking both these effects into consideration the best fit to the data of Figure 140 gives

$$(P_{45} - P_{60}) / P_{60} = 0.2 \qquad (33)$$

where the full lines refer to a true east-west distribution of the sources on the disk to be either Gaussian (straight line *g*) or rectangular (curve *r*).

4.5.5 Confirmation of the Plasma Hypothesis

For the purpose of confirming the plasma hypothesis the data were first analysed by the method of least squares and the results listed in Table 3 of Weiss (1963a). Figure 140 shows that for both Type II and Type III bursts the systematic variation of position with frequency increases from centre to limb. The ratio of $P_{45} - P_{60}$ to P_{60} is 0.20 + - 0.039 for Type II bursts, and 0.20 = - 0.22 for Type III bursts and would be somewhat less if irregular ionospheric refraction was taken into account.

The second test is provided by ranking of position with frequency, illustrated in Figure 142 for all (19) Type II bursts with $| P_{45} | > 15'$. Most points exhibit a systematic ranking, with positions for the lower frequencies farther removed from the centre of the disk, as predicted by the plasma hypothesis.

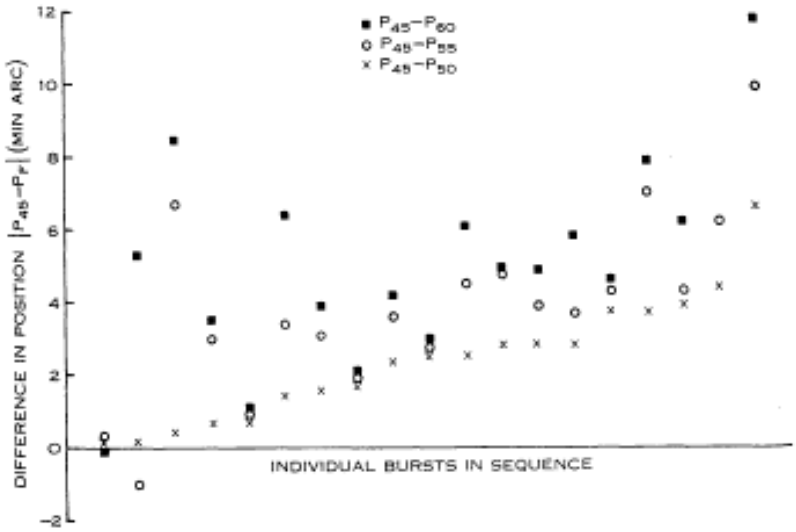


Figure 142 Possible differentials | P_{45} – P_f | for non-central Type II bursts with |P_{45}| >15′.Each group of three points refers to an individual burst. Bursts are arranged in order of increasing | P_{45} – P_{50} | (after Weiss, 1963a: Fig. 4).

Weiss (1963a: 257) concluded that "These two tests indicate that different frequencies originate at systematically different levels in the corona, and so provide confirmation of the plasma hypothesis."

4.5.6 Comparison of Positions of Bursts of Types II and III

Weiss noted a remarkable agreement between the statistical parameters which describe the average behaviour of the positions of the sources of Type II and Type III bursts. The agreement is most noticeable amongst the variation of position with frequency, whose regression on burst position and scatter (after correction for sample size) are identical for the two types of burst. The linear relation deduced between Type II burst position and flare position fits Type III bursts equally well. These points of agreement are strong evidence that the radio emissions of Type II and III sources of the same frequency are generated in equivalent, though nor necessarily identical, regions in the corona.

The exciting disturbances generating Type III bursts are believed to be fast streams of electrons which are unlikely to modify appreciably the electron density of thermal electrons in the corona, and hence the heights of emission level. It might be expected, however, that the far more slowly moving shock fronts exciting Type II bursts may well modify the coronal electron

densities locally. The similarity of the average emission levels for Type II and Type III bursts thus establishes the important result that the Type II shock waves are unable to modify the coronal electron density distribution in the source regions.

4.5.7 Anomalous Positions of Sources of Harmonic Bands

Weiss found that the variation of position with frequency for second harmonic Type II bands is less than for fundamental bands, and that the positions for the second harmonic tend to lie inside the fundamental in agreement with the earlier observations of Smerd, Wild and Sheridan (1962) discussed in Section 4.4.

4.5.8 The Radial Distribution of Electron Density in the Corona

Heights of the mean plasma levels in the frequency range 40 – 60 MHz can be estimated from the position data in Table 3 of Weiss (1963a). The resulting points (filled squares) for the small sample of Type II bursts are plotted in Figure 143 along with the Type III results of Wild, Sheridan and Neylan (1959), Shain and Higgins (1959) and Morimoto (1962).

The points are in good agreement with twice the values derived by Newkirk (1961) for the electron densities in a coronal streamer (uppermost curve of Figure 143).

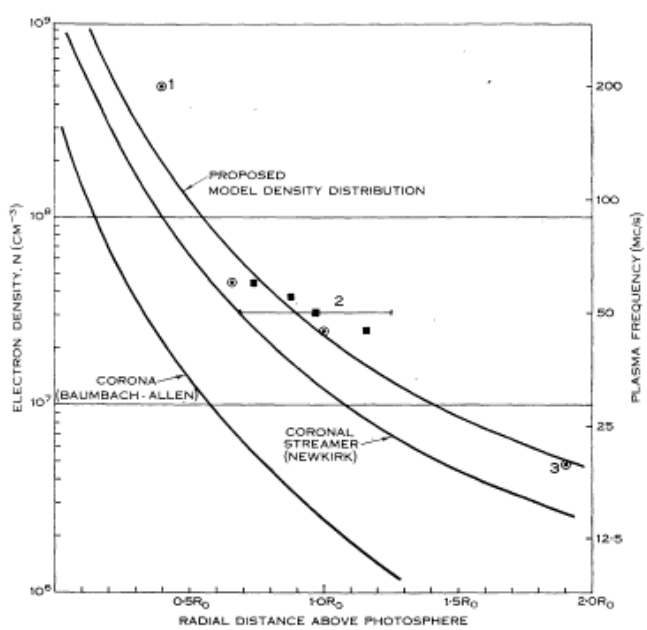


Figure 143 Average electron densities in the corona as a function of height. Squares refer to Type II bursts and circles to Type III bursts. Circle labelled 1 refers to 200 MHz position observed at Mitaka (Morimoto, 1962); circle 3 the 19.7 MHz position observed by Shain and Higgins, 1959 at Fleurs; and the two unmarked circles the 60 and 45 MHz observations of Wild, Sheridan and Neylan,1959 (after Weiss, 1963a: Fig. 5).

4.6 Statistical Study of the Properties of Type IV Bursts 1963

Before this detailed study by Weiss (1965b), the only systematic measurements of the characteristics of metre wavelength Type IV bursts, other than spectral features, were conducted at 169 MHz with the Nancay interferometer (Boischot, 1958) and the 201 MHz Tokyo interferometer (Morimoto, 1961). At lower frequencies, only isolated measurements had been reported at 97 MHz (Payne-Scott and Little, 1951); at 87 MHz (Kundu and Firor, 1961); and from 40-70 MHz (Wild, Sheridan and Trent, 1959). The spectral features of Type IV bursts have already been described by McLean (1959). Similar features had been observed by Thompson (1962) using the 25-580 MHz the Harvard radiospectrograph.

Weiss adopted McLean's criteria for a Type IV burst (Section 3.17), namely that the spectrum be smooth and associated with a Type II burst, to select 17 Type IV bursts recorded at Dapto and divided them into two classes; bursts which lasted for a comparatively short time (a few hours or less) and the long-duration events classified as continuum storms by Pick-Gutmann (1961). He included another 7 continuum storms, (which had been identified by the French, and were in progress when Dapto observations began.

Note that the use of the terms Type IV burst and continuum storm in this analysis is somewhat confusing but later in the analysis Weiss clarified the situation by introducing the terms 'moving' and 'stationary' Type IV bursts to refer to continuum associated with moving and stationary sources respectively and produced evidence to show that the two bursts were separate phenomenon.

4.6.1 Temporal Relations between Type IV and Type II Bursts

From Figure 144 it is seen that the Type IV burst starts about 10 minutes after the associated Type II burst and reaches maximum intensity after about 20 minutes. On the other hand, the

storm continuum may start sometimes before, but mainly after the Type II burst and lasts much longer.

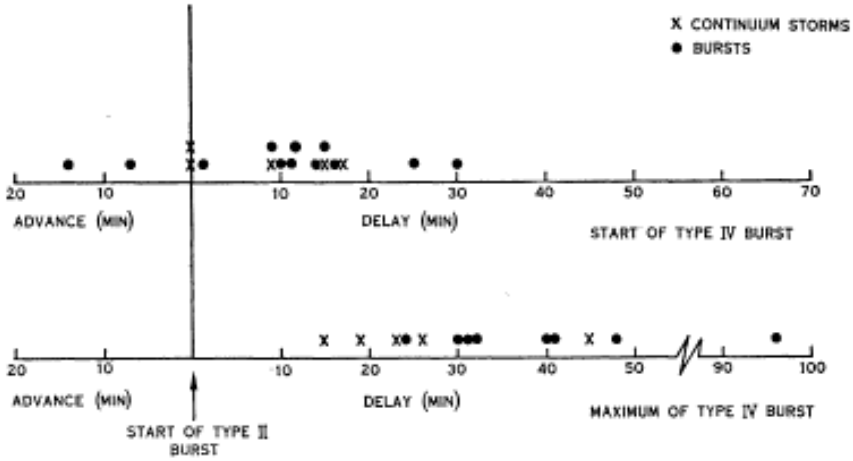


Figure 144 Temporal relations between the start and time of maximum intensity of Type IV bursts and the start of the associated Type II burst (after Weiss, 1963b: Fig. 1).

4.6.2 Position of Type IV burst and Storm Continuum

Weiss (1963b: 530) noted that:

> The sources of Type IV bursts almost invariably show movement at some stage during their lifetimes. The movement may be irregular, or consist of quasi-periodic oscillations about a stable position, or be systematic in time. Characteristically such systematic displacements occur at the start of the burst, when they are rapid and pronounced; if they occur later in the burst the movement is comparatively slow. In most cases it is possible to specify a stable position, to which the source settles down. The position data is summarized in Figure 145.

The sources of Type IV emission exhibit little or no angular dispersion with frequency and the positions of Figure 145 are obtained by averaging over all frequencies in the range 45-65 MHz. If it is assumed that on the average the Type IV source lies radially above the flare, the mean height of the stable positions is given by the slope of the line of Figure 4.35 to be 2.11 + - 0.26 R_0, which is close to the value 1.97 + - 0.28R_0 derived for Type II bursts (Weiss, 1963a).

This suggests that the Type IV sources are located close to the mean plasma level for the range 45-65 MHz. A similar result is indicated at 169 and 201 MHz by the results of Pick (1960) and Morimoto (1961) respectively."

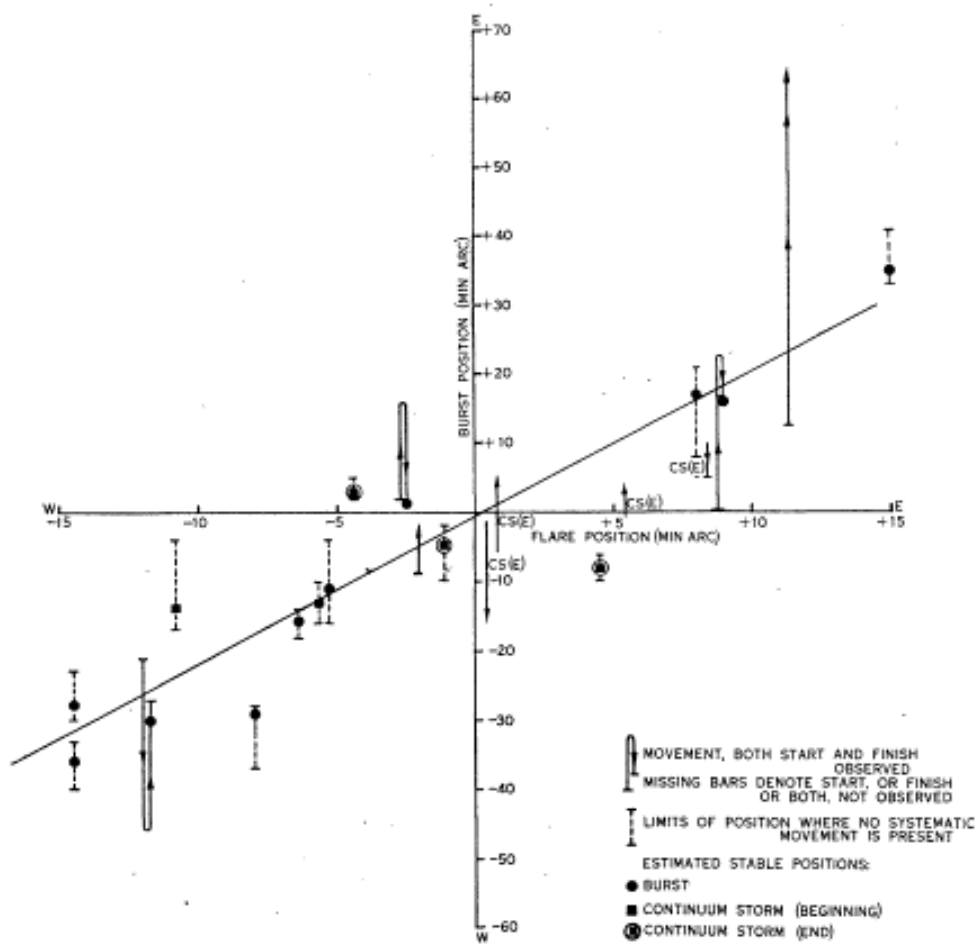


Figure 145 Position data showing movements and stable positions of Type IV sources. The full line represents the least squares fit to the stable positions for bursts and the beginnings of continuum storms, CS(E) denotes ends of continuum storms without stable positions (after Weiss, 1963b: Fig. 2).

4.6.3 Variation of Position with Frequency

Mean positions P, averaged within frequency bands 5 MHz wide, are listed in Table 1 of Weiss (1965b). The variation in $P_{45} – P_{60}$ is plotted against mean P in Figure 146. Clearly these data contain no suggestion that there is a systematic variation with frequency such as occurs for Type II and Type III bursts. The absence of dispersion is also a characteristic of "moving" Type IV bursts (Wild, Sheridan and Neylan, 1959) but it seems to conflict the result that the mean heights of the stationary sources is close to the mean plasma level. More work is required to remove this discrepancy.

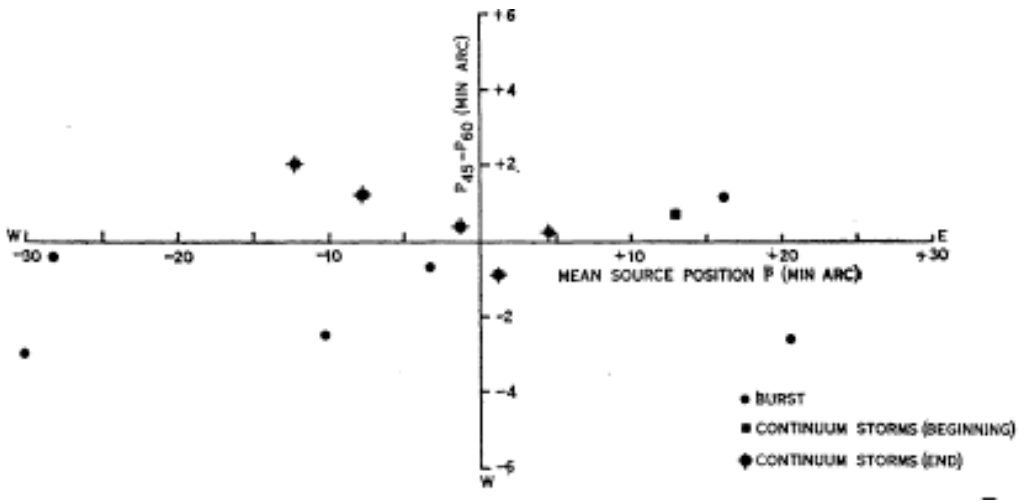


Figure 146 Variation of position as a function of stable position for Type IV bursts (after Weiss, 1963b: Fig. 3).

4.6.4 Source Movement

Of 12 bursts whose positions were recorded from the start of emission, only 4 showed evidence of rapid movement. In all causes the initial direction of movement was outwards from the centre of the disk; this stage lasted 5-20 minutes. The position changes are shown in Figure 147. In three of the four cases outward movement was followed by a slower inward movement to a final stable position. The projected speeds are between 2.2 and 4.4 x 10^3 km/sec.

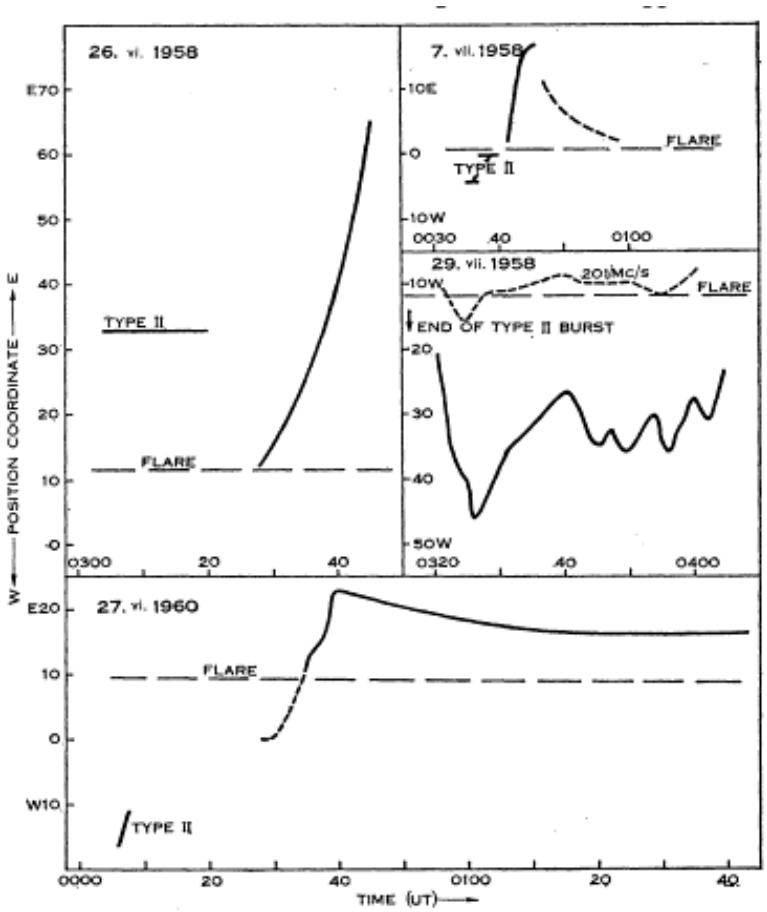


Figure 147 Type IV bursts which show initial rapid movement. For the event of 29 July 1958 (Tokyo) the movement is partly suppressed by blending with a coexisting stationary Type I source (after Weiss, 1963b: Fig. 4).

Bursts that do not show the initial outwards movement are shown in Figure 148. In the event of 5 April 1960 there appears to be two distinct sources of Type IV emission. The events of 26 August 1958 and 19 November 1960 developed into continuum storms.

Weiss (1963b: 535) notes that:

> Some care is required in the interpretation of the apparent inwards movements..... If two sources are present simultaneously the interferometer will only record the centre of gravity. Hence the inwards return to a stable position could be produced by the weakening of an outward moving source and the strengthening of a lower stationary source. On this view, which is supported by the preponderance of stationary sources, the moving and stationary sources are separate phenomenon.

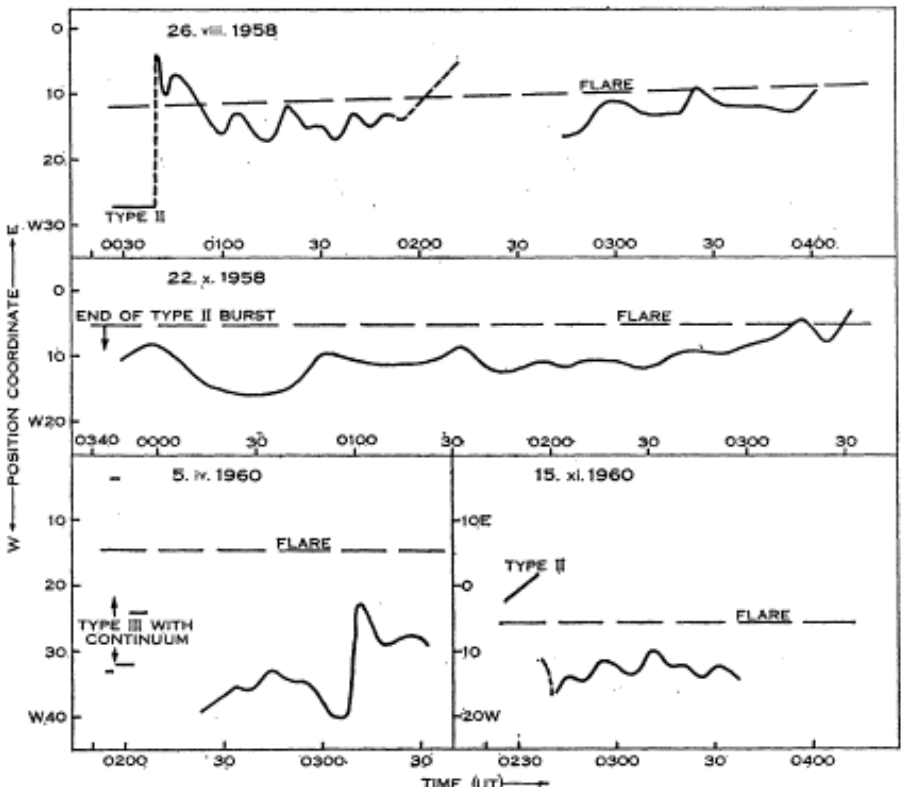


Figure 148 Examples of stationary Type IV bursts (after Weiss, 1963b: Fig. 5).

4.6.5 Positions of associated Type II and Type IV sources

The events shown in Figures 146 to !48 show a further characteristic, that the initial position of the Type IV source, whether stationary or moving, is displaced from the position of the Type II burst (Figure 149). Weiss concludes from this evidence that in general, the sources of Type II and IV sources, although initiated by the same disturbance, must be regarded as moving independently through the corona.

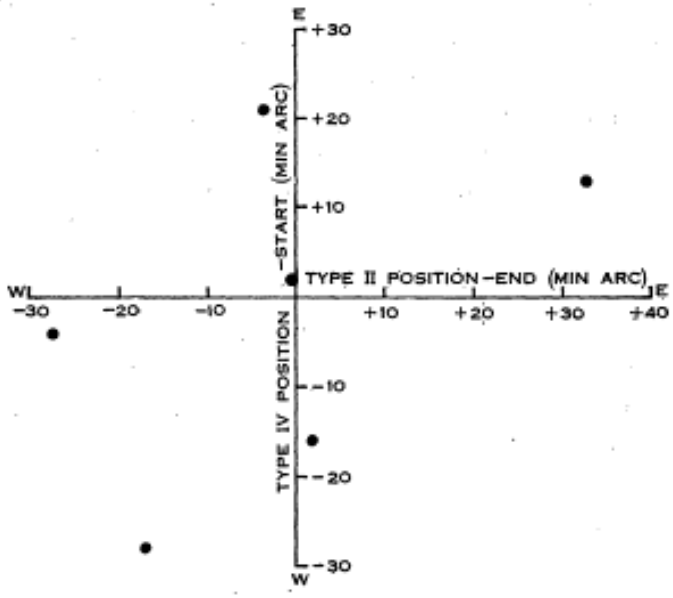


Figure 149 Relative positions of Type IV and Type II bursts (after Weiss, 1963b: Fig. 6).

4.6.6 Sense of Circular polarization

The sense of circular polarization measured by the Dapto swept frequency interferometer was determined for 23 events. None were found to be unpolarized. Data for all events is plotted in Figure 150.

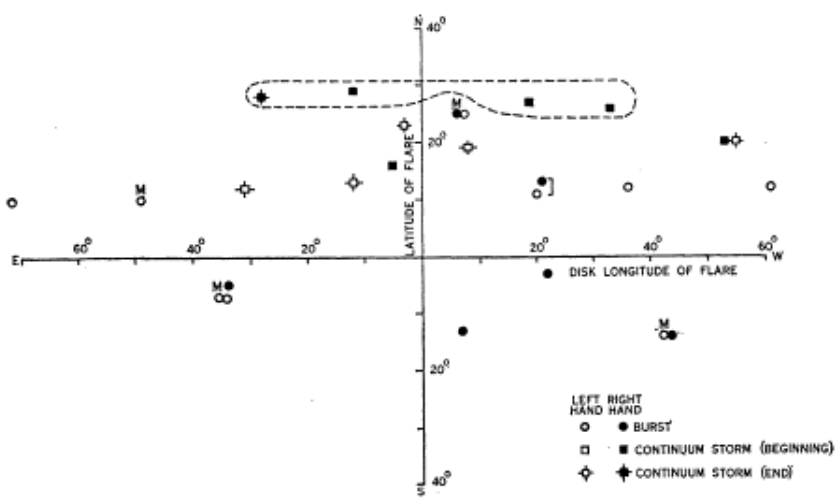


Figure 150 Sense of circular polarization of Type IV bursts plotted against disk coordinates of the associated flare. Events in the November 1960 group are enclosed in a dotted envelope. Pairs of touching points represent moving and stationary sources belonging to the same event; the moving bursts are designated by the symbol M. The

bracketed pair of points refer to separate Type IV bursts occurring in the same active region (after Weiss, 1963b: Fig. 7).

To interpret these data in terms of the magneto-ionic theory, Weiss notes that in the northern hemisphere of the sun *left-hand* polarization corresponds to emission of the *ordinary* mode, if we assume that the sense of polarization is determined by the polarity of the *leading* spot for that solar cycle. The opposite is true for the southern sunspots. The following tendencies are noted:

(1) Bursts with initial movement are polarized in the extraordinary mode.
(2) After the source position of a burst is stabilized it is polarized in the ordinary mode.
(3) At the start of the present sample of continuum storms the polarization is in the extraordinary mode
(4) Ends o continuum storms are polarized in the ordinary mode.

Weiss concludes that these results support the French suggestion (Boischot and Pick, 1962) that moving and stationary Type IV bursts are distinguished by the sense of polarization. On the leading spot hypothesis, the usual mode is extraordinary for the moving burst and ordinary for the stationary burst.

4.6.7 Degree of Circular Polarization

In the initial stages of a continuum storm the degree of polarization appears to follow a typical development. When the emission is first detected at 40 and 60 MHz, the degree of circular polarization is quite low, usually only 10-20%. Later in the burst the degree increases to 50-100%. An example of the initial growth in polarization is shown in Figure 4.40. Information on the degree of polarization of Type IV bursts, on the other hand, is quite fragmentary. Only one event was adequately observed and this showed a similar development to that of the five continuum storms.

4.6.8 The 15 November 1960 Event

Many of the properties of the Type IV event is illustrated by the comparative study of the 15 November event compiled by S. Suzuki who extended the frequency range from 9400 MHz to 15

MHz (Figure 151). Weiss confines his remarks to the spectrum, degree of polarization, and the relations between them. The three intense features with Type II-like frequency drift at decimetre wavelengths between 0220 and 0235 UT can be traced to frequencies as low as 40 MHz on the original records. The drift of the low frequency edge of the continuum is especially noticeable. There seems to be a similar drift in the time of onset of strong polarization. The parallel growth of intensity and of degree of polarization at fixed frequency is also evident.

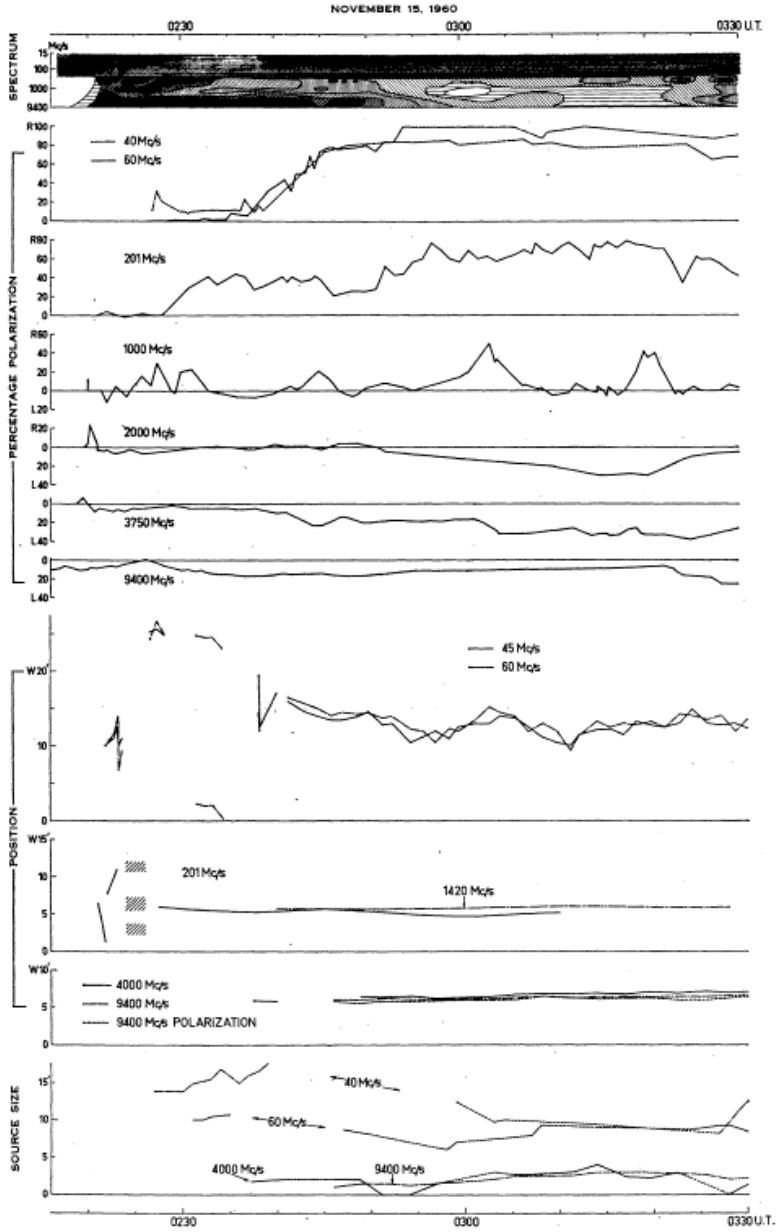


Figure 151 Properties of the sources of Type IV emission of 15 November 1960 as compiled by S. Suzuki from Dapto and Japan. Source size has been determined under the assumption of Gaussian brightness distributions (after Weiss, 1963b: Fig. 9).

4.6.9 Conclusions

The physical properties of Type IV bursts in the frequency range 40-70 MHz are summarized by Weiss (1963b: 541) as follows:

(1) Two varieties of the Type IV burst have been recognized. They appear to be distinct phenomenon. On the basis of position measurements, these two varieties have been designated “moving” and “stationary” Type IV bursts.

(2) The moving Type IV burst is characterized by fairly short duration, ill-defined spectral features, rapid outward movement, broad cone of emission, and polarization in the extraordinary mode

(3) The stationary Type IV burst is characterized by long duration, broad continuous spectrum, a height close to the plasma level, and strong polarization in the ordinary mode. It includes the long-lived continuum storms. It may occur with or without a moving Type IV burst.

(4) There appears to be no physical distinction between the stationary Type IV bursts and the beginnings of the long-lived continuum storms. The aging of the storms is marked by an increase in ‘burstiness’ in the spectrum; the bursts are often broad-band but sometimes narrow-band Type I bursts are present.

(5) In neither variety of Type IV burst is there any detectable systematic variation of source position with frequency in the 45-65 MHz range. This absence for the stationary Type IV burst is puzzling and requires further investigation.

(6) The initial position of both varieties of Type IV burst is often widely separated from the position of the associated Type II burst suggesting that they do not follow the same trajectories through the corona.

4.7 Statistical Study of the Properties of Type V Bursts 1965

Previously, Wild, Sheridan and Neylan (1959) had proposed that the bursts were due to radiation from relativistic electrons spiralling in magnetic fields in the corona (Section 4.3). However, Stewart (1965) found that the speeds of Type III bursts followed by Type V continuum were no different to those of isolated Type III bursts (~ c/3) and that the electron energies responsible for these bursts were too small to generate synchrotron radiation (Section 3.20).

In order to arrive at a better understanding of the Type V event, Weiss and Stewart (1965) undertook a systematic examination of the spectral features, polarization, positions and angular sizes of Type V bursts recorded by the Dapto spectrograph and the swept-frequency interferometer.

4.7.1 Selection Criteria

For this study only comparatively pure continuum bursts with durations greater than 1 min at a frequency ~ 50 MHz were selected. Dynamic spectra of some of these bursts are reproduced in Figure 152.

4.7.2 Spectral Characteristics

In nearly every case studied, the Type III burst preceding the Type V continuum could be identified by its clearly defined leading edge or by an abrupt change in intensity before the Type V which appears as a diffuse prolongation of the Type III with a duration which increases with decreasing frequency. These are referred to as *attached* bursts (Figure 152 b, d and e). The Type V continuum often extends to the lowest observing frequency, such as in Figure 4.41 a where the spectrum extends down to about 7 MHz (the cut-off imposed by the ionosphere).

When a distinct break occurs following the Type III it is referred to as a *detached* Type V bursts (Figure 152 a, c and f). Sometimes these bursts have a high frequency spectral cut-off which initially drifts fairly rapidly to higher frequencies. Examples are shown in Figures 152 (f) and in Figure 155 below.

No clearly defined fundamental and second harmonic structure has been found in Type V bursts, although some of the preceding Type III bursts have both components. A few Type V bursts have been observed in which the existence of harmonic structure is possible (Figure 152 b)). However, the large bandwidth of the Type V would make the recognition of harmonic structure difficult.

Example (b) of Figure 152 is one of a number of Type V bursts in which there appears to be an association between the Type V continuum and the fast frequency-drifting "inverted U" burst (Maxwell and Swarup, 1958).The continuum appears within seconds of the disappearance of the U burst. It covers the same frequency range and lasts four to five times longer. This association is used later as an important clue to the origin of the Type V burst (Section 4.7.6).

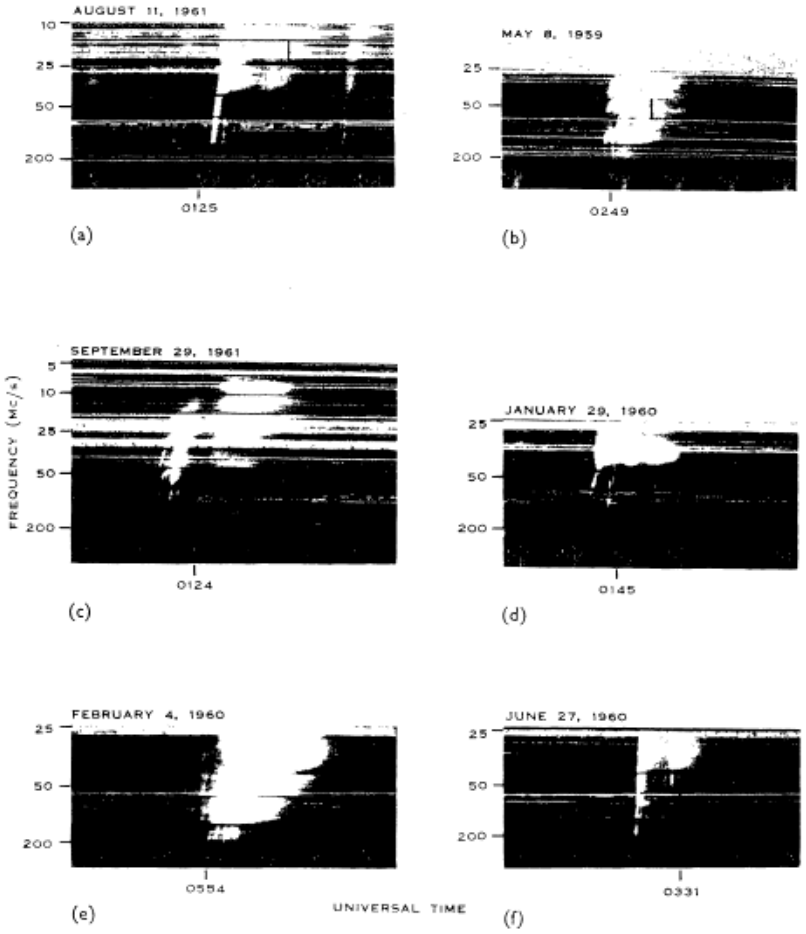


Figure 152 Examples of Type V bursts illustrating: *attached* bursts e.g. (b), (d), (e); *detached* bursts e.g. (a), (c), (f); a high frequency cut-off remaining steady e.g. (f); a close relationship in frequency between inverted U bursts and Type V continuum with a suggestion of harmonic structure e.g. (b) (after Weiss and Stewart, 1965: Plate 1).

4.7.3 Initial Bandwidth

The initial bandwidth and upper frequency limits of 59 Type V bursts are plotted in Figure 153. It can be seen that the Type V continuum often extends to the lowest recorded frequency. Typically the Type V burst is observed from < 40 to ~ 120 MHz. Some Type III bursts show such large instantaneous bandwidths but part of this is due to a combination of the frequency drift and finite decay time. Hence we conclude that the *excitation* bandwidth, which we define as that part of the total instantaneous bandwidth which is due to the simultaneous excitation in depth of the coronal plasma by virtue of the finite extent of the source region, is larger for the Type V burst than it is for the accompanying Type III burst.

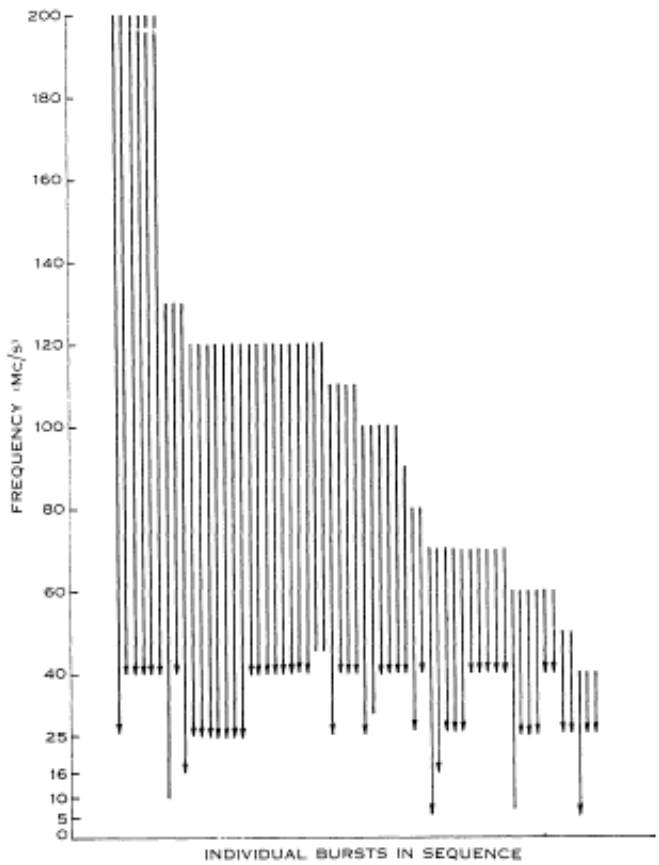


Figure 153 Observed initial bandwidths of 59 Type V bursts. Arrows indicate that the lowest frequency was not observed (after Weiss and Stewart, 1965: Fig. 1).

4.7.4 Average Duration

The average duration of 59 Type V bursts is plotted in Figure 4.43 as a function of frequency. The points are consistent with the relation $T = k/f^{½}$ (where T is the average duration in seconds, f is the frequency in MHz, and k = 500) although the exponent of f may vary by ± 30 %. This relation agrees with the results of Maxwell and Thompson (1962), who measured the ratios of the average durations of a large sample of Type V bursts at frequencies between 125 and 25 MHz. There results are shown as open circles on Figure 154.

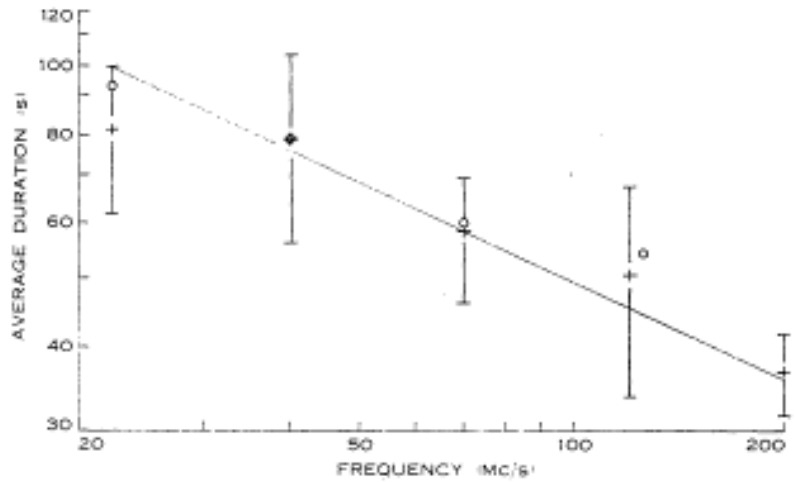


Figure 154 The average durations of 59 Type V bursts recorded at Dapto (+) compared with Thompson an Maxwell's (1962) results (o) normalized to our duration of 79 seconds at 40 MHz (after Weiss and Stewart, 1965: Fig. 2).

4.7.5 Position and Movement on the Disk

Positions of 24 Type V bursts, obtained with the Dapto swept-frequency interferometer, are listed in Table 1 of Weiss and Stewart (1965). Measurements were made at intervals of ½ seconds to an accuracy of ± 2 minutes of arc of the east-west coordinated of the centroid position of the source. Possible effects of refraction have been ignored. In 18 of the 24 cases the initial position of the Type V continuum source (after the end of the Type III burst) could be determined unambiguously. In five of the six remaining cases there was no discontinuity in the position records or gap in the spectrum, between the Type III burst and the Type V continuum.

Initial and final Type V positions, averaged over the frequency range 45-60 MHz, are compared with the average positions of their associated Type III bursts in Figure 155(a). A histogram of the differences between the Type III and initial position of the Type V bursts is given in Figure 155(b). We see from this figure that 12 out of the 23 cases have a position shift greater than the reading error (1.5´) and that these 12 include 7 detached Type V bursts for which the difference is at least 3´. We see from Figure 155(a) that the shift in position is unrelated to the location on the solar disk, and is not larger for final than for initial Type V positions. Hence, if any source movement occurs it is usually small and unrelated to position on the disk. Indeed, only 2 of 24 Type V bursts were found to have a transverse movement greater than 3 min of arc/min, which corresponding to a speed, if real, of the order of 2000 km/s.

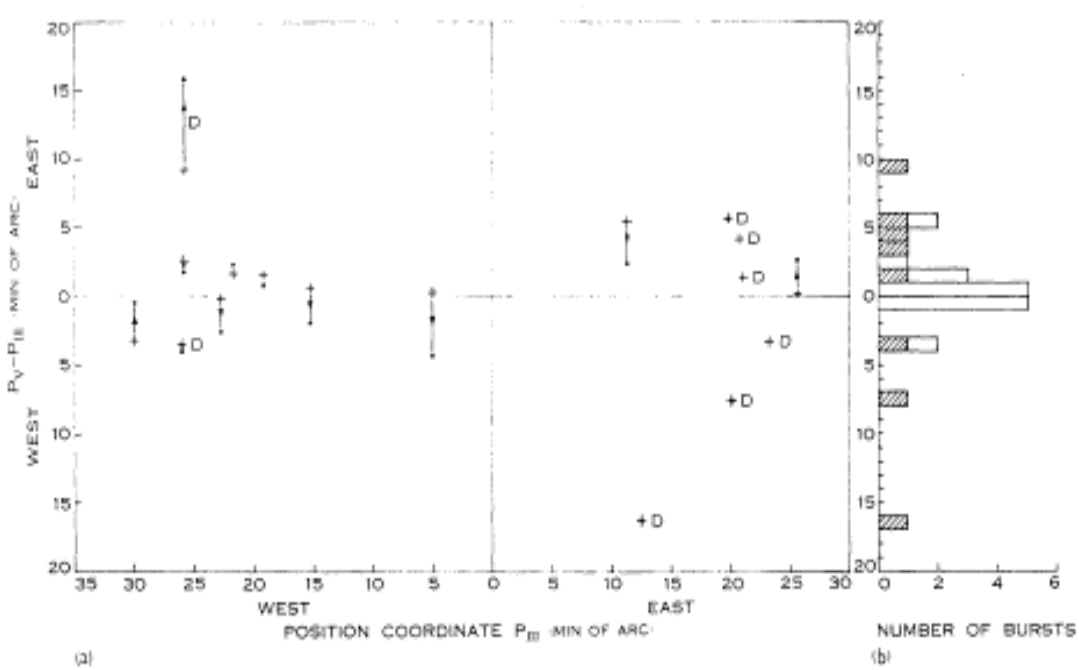


Figure 155 (a) Comparison of observed initial (+) and final (•) positions of 17 Type V bursts averaged over the frequency range 45-60 MHz with the averaged positions of the associated Type III bursts. Detached Type V bursts are denoted by D. (b) Distribution of the differences $P_v - P_{III}$ between 23 initial Type V positions and he associated Type III positions. Cross-hatching refers to detached Type III bursts (after Weiss and Stewart, 1965: Fig. 3).

A convincing example of abrupt position shift between a Type III and a detached Type V burst is shown above in Figure 156. The position of the Type III burst is fairly stable and then shifts to a stable position throughout the Type V burst.

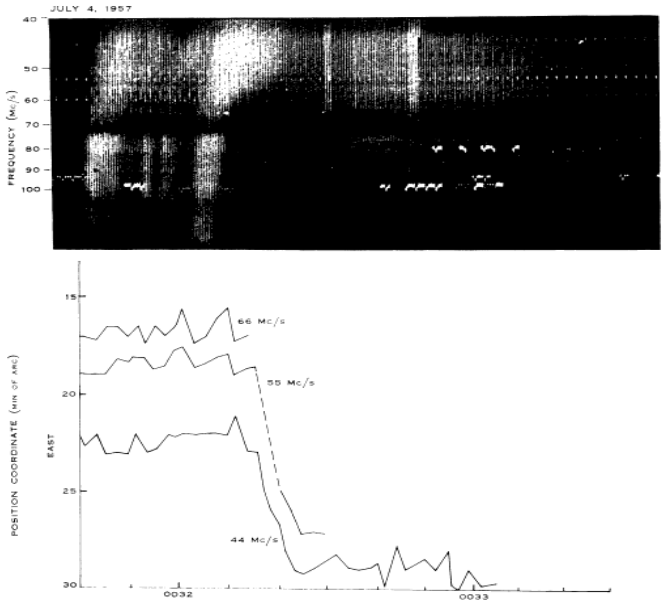


Figure 156 Example of a *detached* Type V burst, in which the frequency cut-off of the continuum drifts to higher frequencies and, in which there is a large discontinuity in position between the Type III and Type V bursts. The intense broken features are due to radio interference (after Weiss and Stewart, 1965: Plate 2).

Thus the evidence suggests that there is often a real discontinuity in position between Type III and Type V sources. Since we observe only the projection on the solar disk, such a discontinuity in position coordinates may represent either a radial or a tangential displacement. On the former assumption, the observed displacements correspond to the physical displacements shown in Figure 157(b), on the latter assumption, to those of Figure 157(c).

The histograms clearly show that the majority of attached Type V sources are initially located within a distance of 1/3 R_0 from the Type III position. For detached Type V sources the positional shits, which become measurable some 30 seconds or so after the Type III burst are greater than 1/3 R_0.

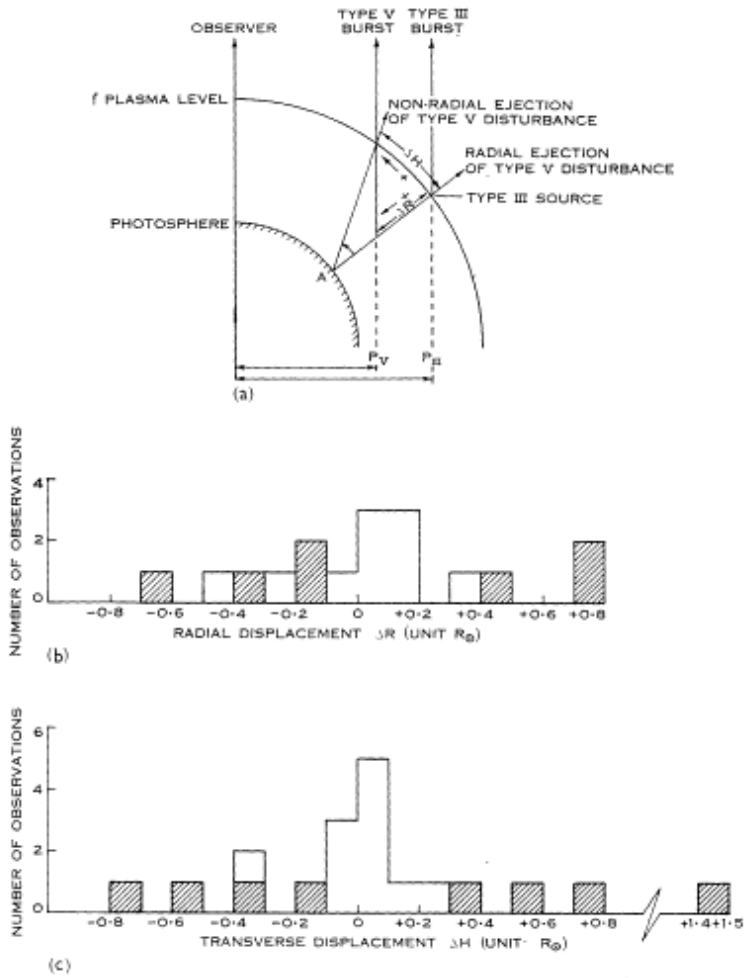


Figure 157 (a) Model to interpret the displacements between Type III and Type V sources. (b) Histogram of the possible radial displacements. (c) Histogram of possible horizontal displacements. In (b) and (c) cross-hatching refers to detached Type V bursts (after Weiss and Stewart, 1965: Fig. 5).

4.7.6 Average Height

From Figure 157 it is expected that the average height of the Type V source to be similar to that of the Type III source. To determine this height directly we have plotted in Figure 158 the average initial coordinates (effective frequency ~ 50 MHz) of 10 Type V sources against the positions of their associated solar flares. On the assumption that the Type V disturbance travels radially outwards from the flare, this figure gives a height of 2.2 ± 0.2 R_0 which is close to the value of 2.07 ± 0.1 R_0 found by Morimoto (1964), for 30 Type III bursts observed at a frequency of 52.5 MHz at Mitaka, Japan.

These direct measurements confirm our inference, from Figure 158, of the similar heights between Type III and Type V sources. Hence, if we accept the plasma hypothesis for Type III bursts, it appears that Type V as well as Type III emission originates at or near the local plasma level.

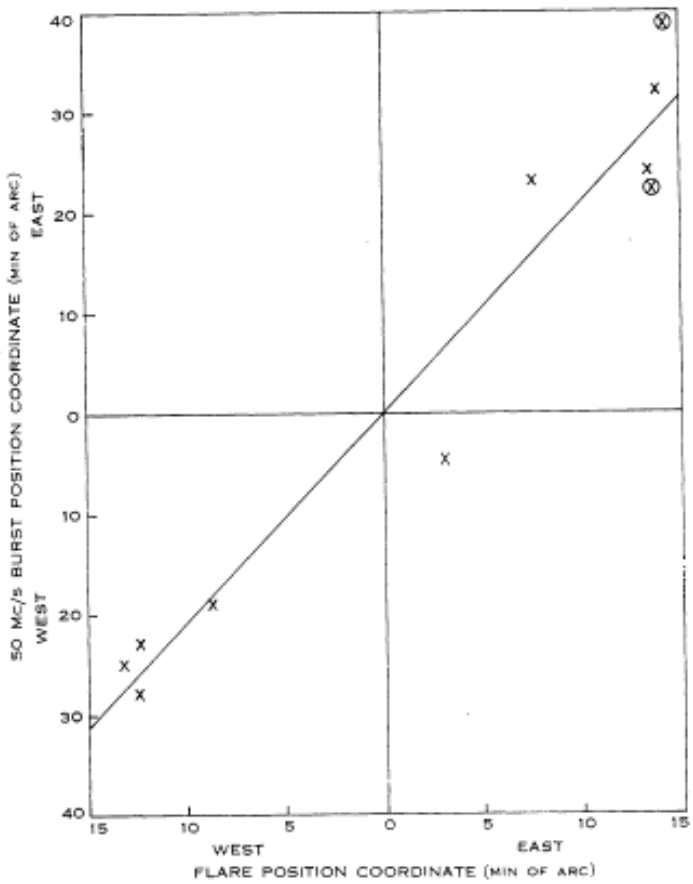


Figure 158 Plot of the 50 MHz position coordinates of 10 Type V bursts against the associated flare position. Closed circles refer to detached bursts (after Weiss and Stewart, 1965: Fig 6).

4.7.7 Dispersion of Position with Frequency

The dispersion of position with frequency for Type V bursts, measured a the difference between the 45 and 60 MHz position coordinates, is plotted in Figure 159(a) against the dispersion of the associated Type III burst, and in Figure 159(b) against the initial Type V position coordinate (effective frequency 52.5 MHz). It can be seen that the dispersion is of the same magnitude for Type III and Type V bursts, and increases with distance from the centre of the Sun in a way similar to that found by Wild, Sheridan and Neylan (1959) (Section 4.3.2). This leads us to

seriously consider that the Type V continuum is also due to the excitation of plasma waves by fast electrons rather than synchrotron radiation from relativistic electrons.

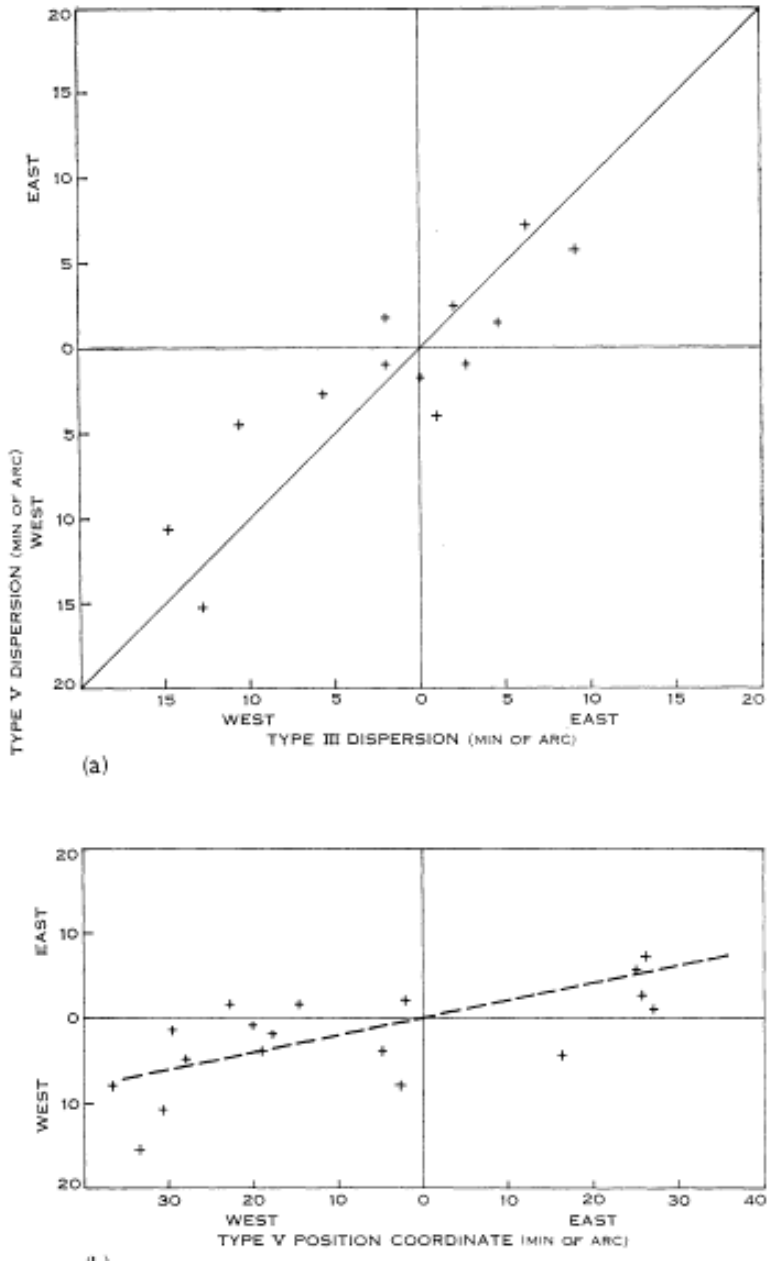


Figure 159 (a) Comparison of the observed dispersion of position coordinates with frequency for 13 Type V and associated Type III bursts. (b) Relation between dispersion and 52.5 MHz position coordinates for 18 Type V bursts. The dashed line gives the average relation found by Wild, Sheridan and Neylan (1959) for Type III bursts (after Weiss and Stewart, 1965: Fig. 7).

4.7.8 Disk distribution

The disk distribution of the average positions of 24 Type V bursts is given in Figure 160(a). The dashed line is the disk distribution calculated on the assumption that the radio sources originate radially above flares, uniformly distributed in longitude and similar to that found by Thompson and Maxwell (1962) for the flares associated with Type V bursts; such a flare distribution has been confirmed by our own data. This figure suggests that the Type V source is equally visible from any position on the disk, and we conclude that the cone of emission must be of the order of 2π. By way of contrast, the distribution of Type III positions found by Wild, Sheridan and Neylan (1959), reproduced in Figure 160(b), indicates that the cone of emission for Type III bursts is much narrower.

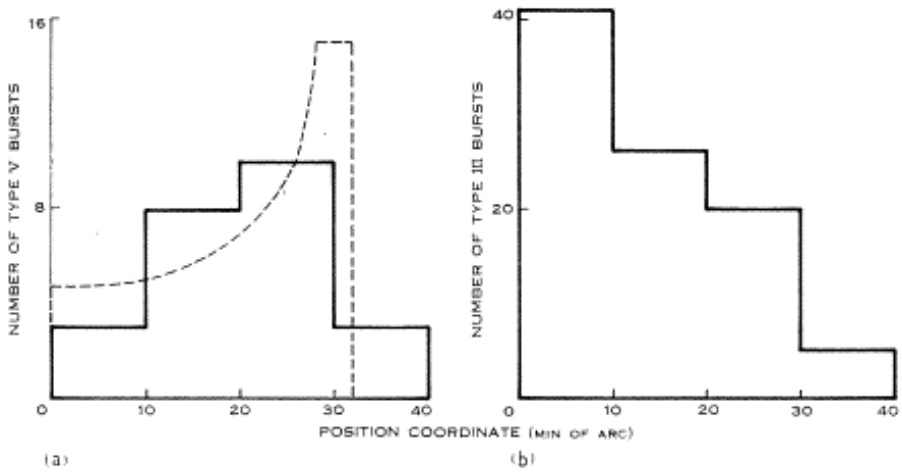


Figure 160 Observed disk distribution for (a) Type V bursts and (b) Type III bursts. The dashed line gives the prediction for a cone of emission of 2π (after Weiss and Stewart, 1965: Fig. 8).

4.7.9 Source Size and Polarization

A measure of the angular size of a radio source can be obtained from the modulation or fringe visibility of the interferometer pattern of the Dapto swept-phase interferometer (Sheridan, 1963; see Section 2.69). Measurements were made at 40 and 60 MHz with a long baseline (1 km) and short baseline (1/4 km). In Figures 161(a) and (b) are shown the maximum and average recorded visibilities for 12 Type V and associated Type III bursts. From these figures we conclude that the sizes of Type V and Type III sources are comparable.

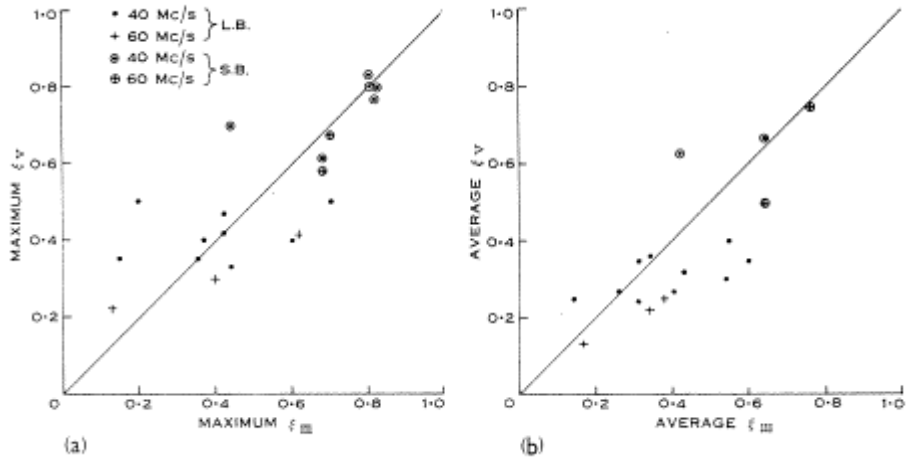


Figure 161 Comparison of the long (LB) and short baseline (SB) visibilities of Type V and associated Type III bursts. Slopes of the full lines are 45 ^{o} (after Weiss and Stewart, 1965: Fig. 9).

The polarization of Type V bursts was measured at frequencies of 40 and 60 MHz by the Dapto interferometer. Only 1 of the 14 bursts recorded had a degree of circular polarization >20%. This result contradicts the preliminary finding of Wild, Sheridan and Neylan (1959) which reported that Type V bursts may often be polarized.

4.8 A Proposed Model for the Type V Burst 1965

Alan and I (Weiss and Stewart, 1965) proposed a model for the generation of Type V emission based on the following observed characteristics (described in Section 4.7):

(1) The peak flux may exceed 10^{-18} Wm^{-2} Hz^{-1} for the more intense bursts

(2) The excitation bandwidth is large, often 100 MHz or more and equal to the centre frequency

(3) The mean observed duration can be described by $T = 500\ f^{-1/2}$ where T is in seconds and F in MHz.

(4) There is no definite evidence of harmonic structure.

(5) In some cases the Type V continuum is detached from the Type III burst and shows drift towards higher frequencies.

(6) If the source is detached it is usually at a distance > 1/3 R_o from the Type I source.

(7) The Type V source height at 50 MHz is, on the average, similar to that of the Type III source which is assumed to lie near the local plasma level.

(8) On the average, the dispersion of position with frequency is the same for Type V and Type III bursts.

(9) Type V sources appear to have similar source sizes to Type III bursts.

(10) Most Type V sources are stationary on the disk.

(11) Type V radiation is remarkably isotropic.

(12) Type V emission is only weakly polarized or completely unpolarized.

4.8.1 Basic Considerations and Assumptions

In formulating a model we start with the basic assumption that the Type V burst is produced by fast electrons with speeds comparable to those responsible for the Type III burst. According to Stewart (1965) these speeds are ~ c/3, and remain constant over a wide range of heights in the corona. Now the equivalent temperature of a *c/3* electron is only 2×10^8 °K, which is much less than the brightness temperatures observed in Type V bursts. For example, substituting the observed flux ($S \sim 10^{-18}$ Wm^{-2} Hz^{-1} at $\lambda = 7.5$ m), and source size (diameter ~ 5 arcmin, subtending a solid angle $\Omega \sim 2 \times 10^{-6}$ steradians) into the standard formula

$$S = 2.77 \times 10^{-23} T_b \Omega / \lambda^2 \qquad W\ m^{-2}\ (Hz)^{-1} \qquad (34)$$

We obtain $T_b \sim 10^{12}$ K. Hence the Type V emission cannot be thermal in origin nor can it be due to any other non-coherent emission mechanism such as synchrotron or gyro radiation. Synchrotron radiation is also excluded because it requires the presence of relativistic electrons. Two known emission mechanism remain to be considered; amplified gyro radiation and coherent plasma waves. The former can be excluded by the large bandwidths observed. Thus we conclude that the Type V burst, like the Type III, is due to coherent plasma wave excitation. This conclusion is supported by items (7) and (8) above.

4.8.2 The Model

With the above considerations in mind we proposed the following model illustrated in Figure 162:

(1) The Type III and associated Type V bursts are produced by a cloud of electrons with velocities ~ *c/3* ejected from a common origin, and spreading out over a considerable region above the flare.

(2) Part of the electron cloud is guided approximately radially away from the flare region without encountering any substantial transverse component of the coronal magnetic field. These electrons give rise to the Type III burst.

(3) The remaining electrons are initially guided along field lines with a substantial transverse component and become trapped at heights at which the Type V bursts is observed.

(4) These electrons excite coherent plasma waves as they oscillate in depth within the trap, so producing the broad-band Type V burst.

As indicated schematically in Figure 4.51 it is assumed that the electrons are confined by repeated reflection between mirror points of converging magnetic field lines.

The discontinuity in positions P_v – P_{111}, is a measure of the horizontal displacement between the centroids of the Type III and V sources, and indicates the extent of the divergence of the magnetic field lines.

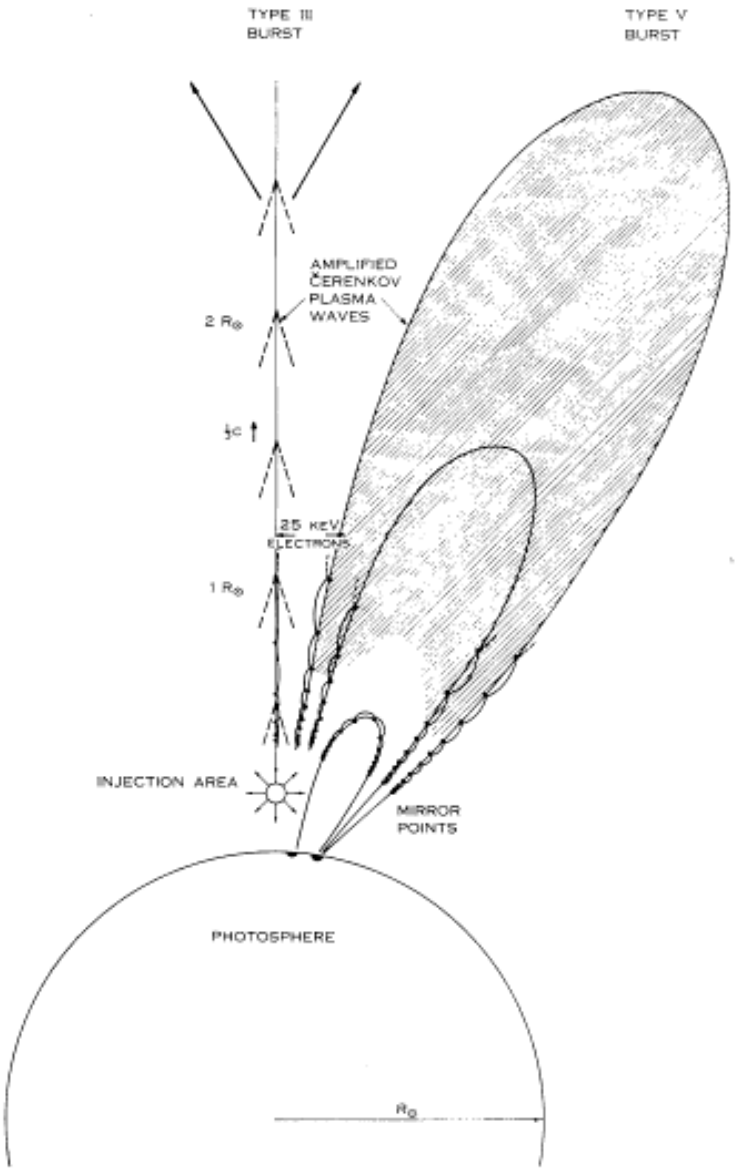


Figure 162 Proposed model for the physical state of the corona at the tie of a Type V burst. The magnetic configuration is such that some of the fast (~25 keV) electrons ejected during the flare are trapped in the corona for a minute or longer. It is suggested tat the fast electrons generate plasma waves which, after conversion to electromagnetic radiation, produce the Type V burst (after Weiss and Stewart, 1965: Fig. 13).

4.8.3 Excitation of Plasma Waves

The equilibrium theory for the excitation of coherent plasma waves (in which the wave amplitude is limited by collisions between the fast electron stream and the background plasma) gives for the

source brightness temperature, under conditions appropriate to Type III bursts, the formula (Wild, Smerd and Weiss, 1963)

$$T_b = 10^{16} (N_s/N)^8 (v/v_{th})^9 \qquad (35)$$

Here N_s/N is the ratio of stream to coronal density, and v and v_{th} are the average velocity of the stream and the thermal velocities of the coronal plasma. Weiss and Stewart (1965) find from the above formula that bunches of *c/3* electrons would require a density ~ 10^6 to explain the observed intensities of Type V bursts. However, they note that there has not as yet been any theoretical investigation of the excitation of coherent plasma waves by bunches of fast electrons spiralling with substantial pitch angles along magnetic field lines, and the above formula mat require version.

4.8.4 Burst Duration

We consider four processes which may effect the lifetime of the Type V burst:

(1) Loss of energy of the fast electrons due to the generation of coherent plasma waves.
(2) Loss of energy of the fast electrons due to collisions with the thermal plasma.
(3) Redistribution of pitch angles of the fast electrons due to coulomb collisions or to scattering on magnetic irregularities.
(4) Upward drift of mirror points due to the increase in pitch angles due to collisions.

We consider redistribution of pitch angles to be the most important, and, to obtain an indication of this effect we use a formula from Spitzer (1956) for the deflection time t_d for the pitch angles to be changed by 90°. Under conditions relevant to the generation of Type V bursts this formula becomes

$$t_d \sim 2.5 \times 10^{-20} v^3 / N \quad \text{seconds} \qquad (36)$$

where N (cm^{-3}) is the average particle density encountered over the trajectory by electrons with velocity v (cm/s).

To estimate N we use numerical integration to calculate the average particle density along the undisturbed spiral path of an electron gyrating in the magnetic field of a dipole buried 0.1 R_o below the photosphere. The results are N = 6 x 10^8, 3 x 10^8 and 2 x 10^8 cm $^{-3}$ respectively for electrons whose maximum heights correspond to the 100, 40 and 20 MHz plasma levels in a Newkirk model corona. Substituting these values into (2) with $v = c/3$ gives durations of t_d = 40, 80 and 120 s respectively, which is in reasonable agreement with observations.

4.8.5 U bursts and Type V Bursts

The magnetic field configuration in the Type V bust model is somewhat similar to that proposed by Maxwell and Swarup (1958) for the inverted U Type III burst. We (Weiss and Stewart, 1965) speculated that:

The Type V and the U burst are related but arise due to differences in their injection conditions. At one extreme, the electrons may be injected with high, approximately uniform velocities over a very short interval of time and over a small area; under such conditions the electrons ill remain bunched over the whole of their first passage around the magnetic loop. If the magnetic field intensity where the loop joins the photosphere is low, the electrons will encounter no mirror point and the U burst will result. If, on the other hand, the field intensity at re-entry is high, the electrons will be reflected repeatedly to produce the Type V continuum. The detached Type V burst may be the diffuse trailing limb of a slow, dispersed U burst.

4.9 Polarization of Herring-bone Type II Bursts

Roberts (1959b) has reported the existence of *herring-bone* structure consisting of a rapid succession of short-lived broadband elements, which have fast frequency drifts of both positive and negative signs and appear to diverge from the core of a slowly drifting Type II burst (see Section 3.17.5). The polarization of Type II bursts has been studied over a wide frequency range (40 to 240 MHz) by Komesaroff (1958) and to be very weak, if polarized at all (see Section 3.12.2). A more recent study by Rao (1965) has shown that Type III bursts of very short durations (1-2 seconds at 40 MHz) are often highly circularly polarized (up to 70%). Since these bursts show a remarkable resemblance to the fast drifting elements in herring-bone structure, I decided to examine the Dapto swept-frequency interferometer records for evidence of circular polarization in such structure (Stewart, 1966).

4.9.1 Limitation of Observations.

From the Dapto records for the period 1958 to 1963, sufficient information was obtained to study the polarization of 20 Type II bursts, 9 of which contained herring-bone structure. A reliable measurement of polarization was only obtained for signals that are moderately or strongly circularly polarized. Faraday rotation in the corona and ionosphere (Akabane and Cohen, 1961) is so high that a signal that was linearly polarized at emission appears to be unpolarized. Consequently, any measured linear polarization is likely to have been caused by ground reflections.

4.9.2 Observations

The polarization data for the 20 Type II bursts are given in Table 7 where I make the distinction between herring-bone features close to and far removed from the core of the Type II burst. The degree of polarization has been called *weak* if less than 20%, *moderate* if between 20 and 40% and *strong* if greater than 40%. It can be seen from Table 7 that Type II bursts without herring-bone structure in general (15 out of 17 cases) exhibit weak polarization. The remaining two have narrow band features which are more highly polarized. On the other hand, when herring-bone features are preset the polarization is moderate t strong (5 out of 6 cases) for frequencies far from the Type II core. Closer to the Type II core the polarization is weaker (3 out of 3 cases). The polarization seems to refer to only the fundamental component of the Type II burst.

An example of a Type II burst containing herring-bone structure is reproduced in Figure 163, together with a plot of the degree of polarization measured at 40 MHz (full line) and 60 MHz (dashed line). The herring-bone is present in the early stages of the Type II burst (0424 to 0429 U.T. During this period the polarization reaches a higher value at 40 MHz (40 to 60%) than at 60 MHz (20 to 40%). However, the 60 MHz readings are closer to the core of the Type II burst and may be lessened by contributions from the much weaker polarized emission from the core. Later in the event, when the herring-bone structure is no longer present, the polarization at both frequencies drops below 10%. From these results it is concluded that the Type II burst is only weakly polarized, if at all, but when herring-bone is present, features far from the core are highly polarized (See section 4.9.1 for comments on linear polarization measurements).

TABLE 7 (after Stewart, 1966: Table 1)

DEGREE AND APPARENT PHASE OF POLARIZATION OF 20 TYPE II BURSTS, 9 OF WHICH CONTAIN HERRING-BONE STRUCTURE

Readings that refer to herring-bone or any other short-lived features are noted

Date		Starting Time of Type II Burst (U.T.)	Degree of Polarization	Apparent Phase of Polarization	Special Feature	Remarks
1959						
May	13	0516	moderate	circular	herring-bone	Far from type II core
July	14	0349	weak	linear†		
Aug.	28	0040	moderate	circular	short-lived feature	Bandwidth ~1 Mc/s
			weak	circular		
1960						
Feb.	18	0111	weak			
Apr.	28	0122	moderate		herring-bone	Far from type II core
			weak		herring-bone	Close to type II core
			weak			
Apr.	29	0213	weak			
May	13	0523	weak	linear†		
June	15	0305	weak	circular		
June	20	0138	weak	elliptical		
June	27	0007	no reading*	circular	herring-bone	Close to type II core
June	27	0423	strong		herring-bone	Far from type II core
			moderate		herring-bone	Close to type II core
			weak			
June	27	0503	strong		herring-bone	Far from type II core
			weak		herring-bone	Close to type II core
			weak			
July	26	0334	strong	circular	herring-bone	Far from type II core
Aug.	11	0258	weak	elliptical		
Sept.	2	0545	strong	circular	short-lived feature	Bandwidth ~1 Mc/s
			weak	linear†		
Sept.	26	0543	weak			
Nov.	15	0221	weak	circular		
1961						
Apr.	6	0017	no reading*	circular	herring-bone	Far from type II core
			no reading*	elliptical	herring-bone	Close to type II core
July	28	0234	weak		herring-bone	Far from type II core
			weak			
1962						
Aug.	14	0246	no reading*	circular	herring-bone	Far from type II core

* From the intensity of the phase pattern we would expect the degree of polarization to be moderate or strong.

† Linear polarization may result from ground reflections (see Section II).

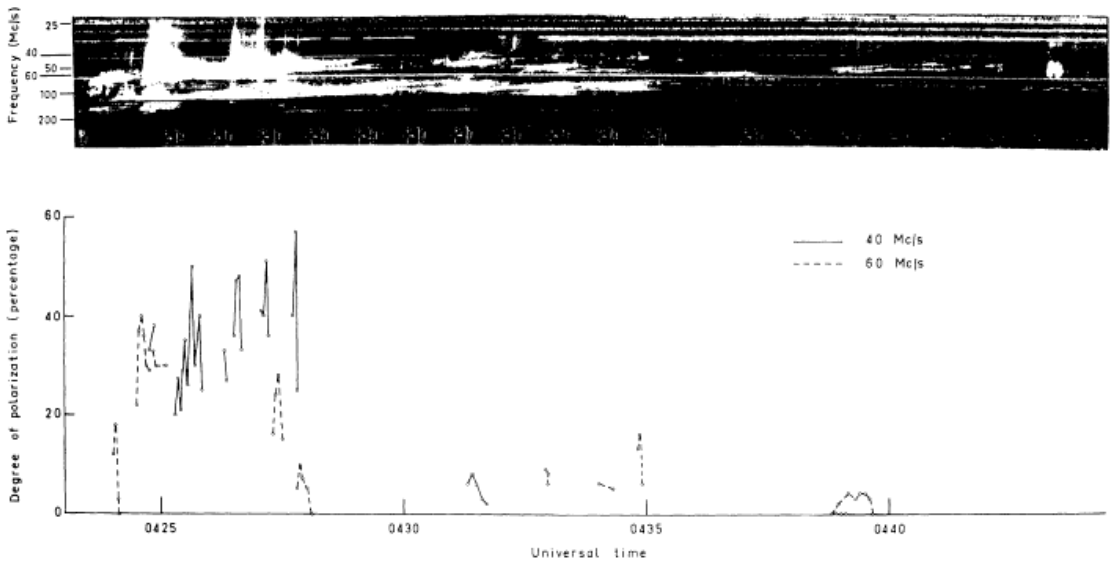


Figure 163 An example of the spectrum and degree of polarization at 40 and 60 MHz of a Type II burst containing herring-bone structure (after Stewart, 1966: Plate 1).

4.9.3 Discussion

I wrote (Stewart, 1966: 212) that:

> The observation of circular polarization in both fundamental and second harmonic components of some Type III bursts led Komesaroff (1958) to the conclusion that the polarization was imposed at emission and not by propagation between the source and observer. Unfortunately, we d not have sufficient information to determine whether the herring-bone features of Type II bursts are polarized in the second harmonic. However, there is a striking resemblance in the dynamic spectrum of herring-bone features and polarized Type III bursts, which tend to be of shorter duration than unpolarized Type III bursts (Rao, 1965). The resemblance suggests that the two phenomena are generated in the same way.
>
> Now the Type III burst is supposed to result from oscillations in the corona at the plasma frequency (Wild 1950b) due to the excitation of coherent Cerenkov plasma waves (Bohm and Gross, 1949). These waves are thought to be excited by a pulse of fast electrons ejected during a soar flare. The conversion from longitudinal to transverse electrodynamic waves may be accounted for by the

scattering mechanism proposed by Ginzburg and Zheleznyakov (1958). An appealing feature of this mechanism is that it gives emission preferentially at the fundamental and second harmonic plasma frequencies in agreement with observations.

On the other hand, the source of the herring-bone feature, though similar to Type III b bursts, appears to be initiated in the disturbance responsible for the Type II burst. This disturbance is thought to be a magnetohydrodynamic shock front, driven by a cloud of ions and electrons ejected from the flare region and capable of exciting plasma oscillations in the corona (Wild 1962).Wild (1964) has suggested that the herring-bone structure arises when the disturbance travels across a radially directed magnetic field. Some of the fast electrons produced by the disturbance could then escape from the Type II source region along radial field lines to both higher and lower regions of the corona and set up plasma waves. This model is very appealing as it explains not only the appearance of both positive and negative frequency drifts in herring-bone features but also the unusually slow drift rates (Wild, 1964) often observed in Type II bursts with herring-bone structure. Evidence for tangential source motion in herring-bone events has been given by Weiss (1963).

4.10 The Nature and Velocity of the Sources of Type II Solar Radio Bursts.

4.10.1 Introduction

It is fitting that I should conclude this thesis with the last paper written by Alan Weiss before his untimely death from leukaemia in December 1964. In this paper (Weiss, 1965) he derived the velocities of Type II sources from the observed frequency drift rates using a coronal streamer density model. He then interpreted these velocities to derive an estimate of the magnetic field strength at coronal heights of 0.5 R_o and 2 R_o. His subsequent death was a great loss to the Solar Group.

Weiss (1965: 167) wrote:

Although the solar radio burst of spectral Type II has been recognized for nearly 15 years, the precise nature of the exciting disturbance is still unknown.

Considerable attention has been given in recent years to the hypothesis that the disturbance is a shock wave generated by a flare explosion and propagating along a coronal streamer, and since the corona is pervaded by magnetic fields, such a shock may well be magneto hydrodynamic (Westfold, 1957; Uchida 1960; Tidman, 1962). Also a magnetic origin for one of he characteristic structural features of Type II bursts, namely band splitting, has been explored (Roberts, 1959). The question of the validity of these magnetic theories for the Type II source is important since, if they prove to be well founded, observations of Type II bursts will enable us to estimate magnetic field strengths high in the corona hitherto inaccessible to optical observations.

4.10.2 Source Velocities

Weiss (1965) derived the radial velocities from the frequency-drift rates (Figure 164) of 21 Type II bursts observed at Dapto. The drift rates are compared with the averaged curve of Maxwell and Thompson (1962) for Type II bursts recorded at somewhat higher frequencies by the Harvard radiospectrograph.

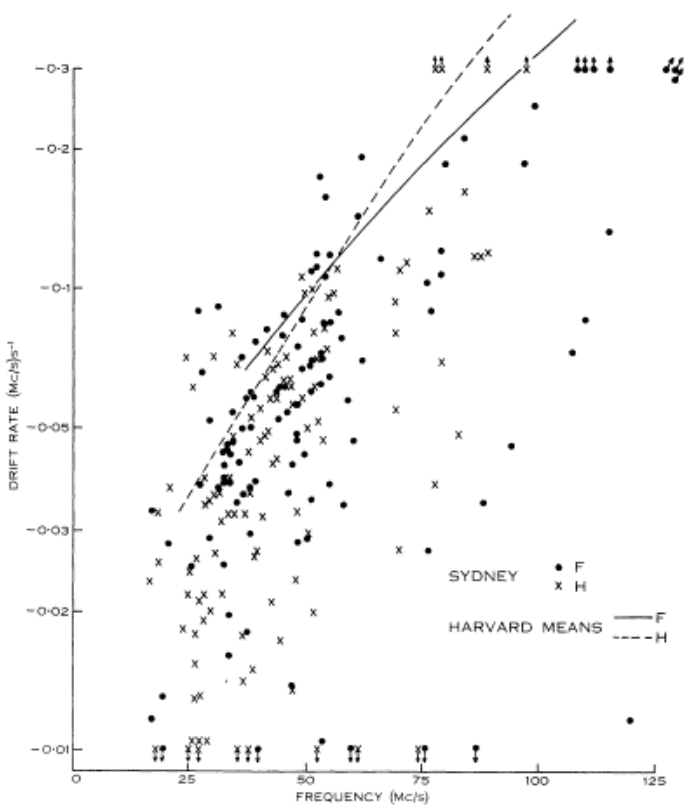


Figure 164 Scatter diagram of the frequency drift rates of 21 Type II bursts compared with the averaged result of Maxwell and Thompson (1962) for fundamental (full lines) and second harmonic (dashed lines) bursts (after Weiss, 1965: Fig. 1).

Averaged velocities determined from Figure 164 are shown in Figure 165.

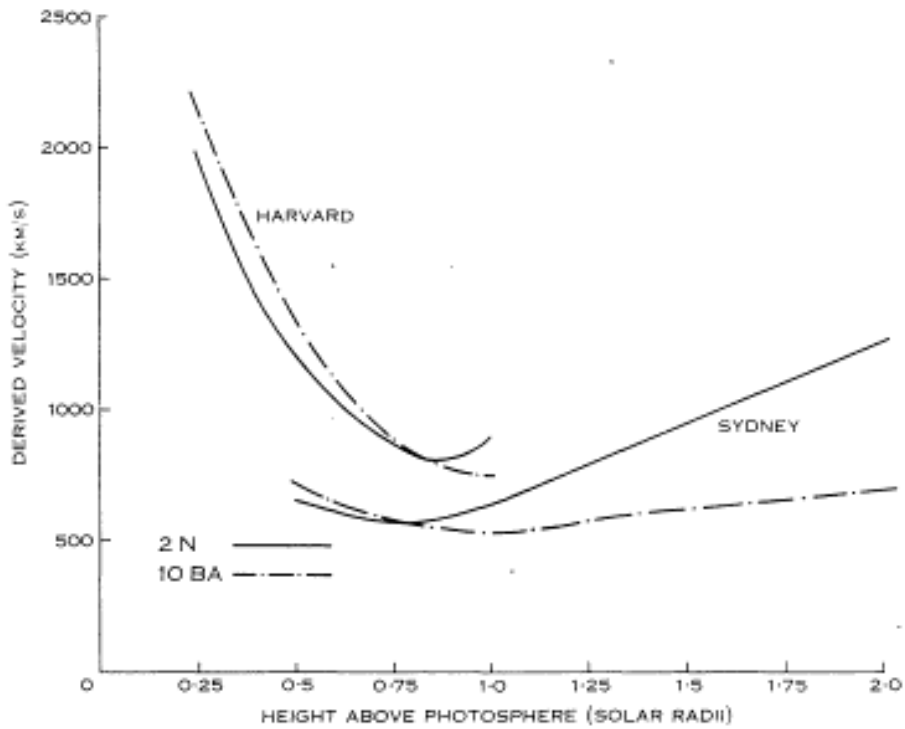


Figure 165 Averaged derived velocities for Type II bursts derived from 2 x Newkirk and 10 x Baumbach-Allen density models (after Weiss, 1965: Fig. 5).

4.10.3 Theory of Shocks

According to Weiss (1965) it can be shown that, for a perpendicular magnetohydrodynamic shock in a medium of infinite conductivity, the shock strength (η) can be specified by the parameters

$$\eta = H_1/H_0 = \rho_1/\rho_0 \qquad (37)$$

where H is the magnetic field strength, ρ is the electron density, and subscripts 0 and 1 refer to the undisturbed plasma and to the interior of the shock respectively.

For a non-magnetic shock the Mach number M is given by

$$M = 3\eta / (4 - \eta) \qquad (38)$$

where $M = V / a$ (V is the velocity of the shock and a is the Alfven velocity).

For a shock expanding spherically

$$V = \text{const.}\ (R - R_o)^{-1}\ \rho_0^{\ -1} \qquad (39)$$

Values for V given by 4.12, normalized to V = 1000 km/sec at R = 2 Ro, are sketched in Figure 166.

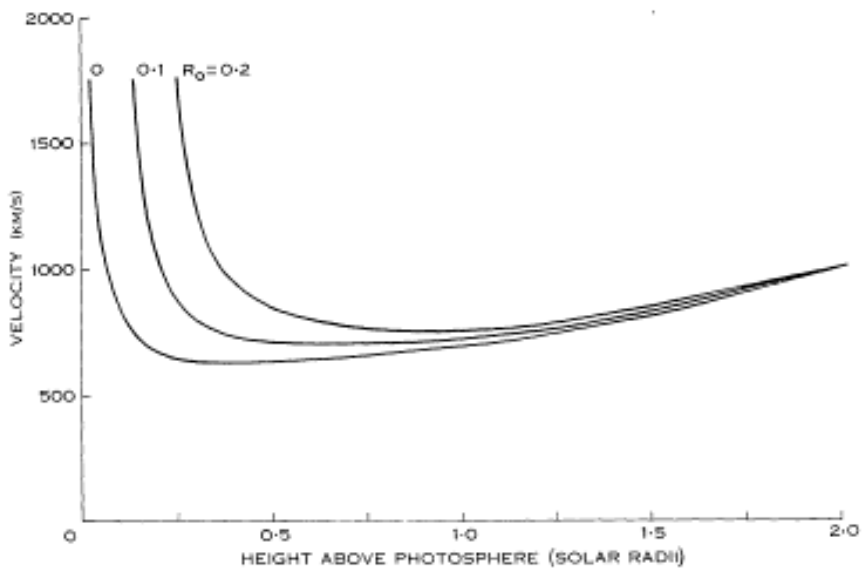


Figure 166 Source velocities predicted fro the shock energy equations on the assumption that the energy and shock strength remain constant as the shock spreads spherically (after Weiss, 1965: Fig. 10).

This behaviour is reminiscent of the derived velocities for Type II bursts shown above in Figure 165 where the velocity initially decreases with coronal height but then increases. This result differs from that of Uchida (1960) who considered only the dissipation of weak shocks and found that the shock speed is almost the modified sound speed which is a monotonically decreasing function of height. Weiss (1965) concludes that it would be interesting to investigate both spreading and dissipative effects on shock velocities.

4.10.4 Coronal Magnetic Field Strengths Derived from Type II Velocities

Using equation (38) Weiss finds Mach numbers in the range 3 to 8 and shock density ratios of 3.2 to 3.8 for the Type II bursts assuming they are caused by non-magnetic shocks. For oblique

magnetic shocks an upper limit to the magnetic field strength can be found by equating the shock speed to the Alfven velocity, thus

$$H_{max} = V(4\pi\rho_0)^{1/2} \qquad (40)$$

Magnetic field strengths for Type II bursts using equation (40) are given in Figure 167. Weiss remarks that it is satisfactory that the derived fields decrease with increasing height and exceed the critical field by an adequate margin but that it should be emphasized that the results only apply if the shock is not parallel or near-parallel to the magnetic field lines.

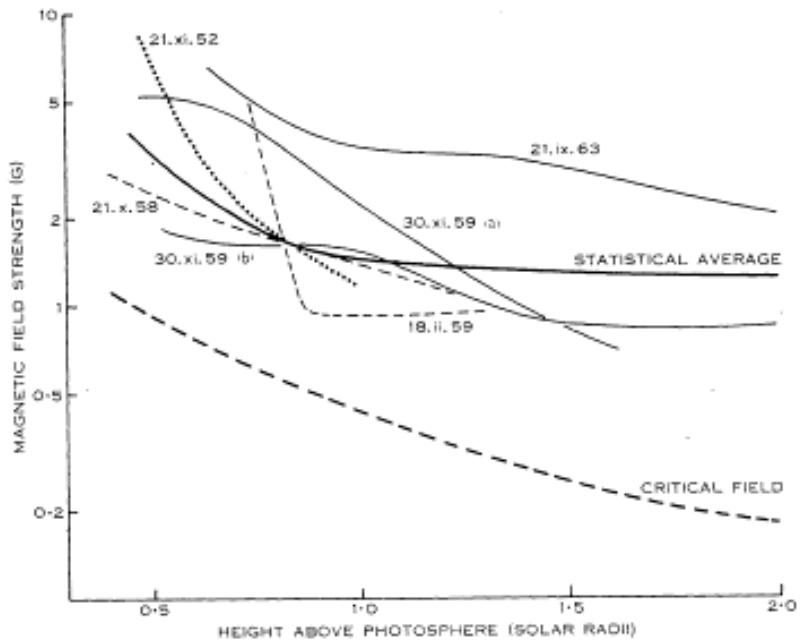


Figure 167 Coronal magnetic field strengths derived on the assumption that the Type II disturbance is a perpendicular shock. The heavy full line is the value obtained by averaging over all the 21 Type II bursts. The dashed full line is the minimum value, for which gas pressure = magnetic pressure (after Weiss, 1965: Fig. 11).

4.10.5 Coronal Magnetic Field Strengths Derived from Band Splitting

Weiss noted that two magnetic theories of band splitting had been proposed. In the first the two frequencies in the split band correspond to frequencies at which the refractive index vanishes in a magneto-ionic plasma. Here the frequency split is given (Roberts, 1959; see Section 3.)

$$\delta f_{MI} \sim \tfrac{1}{2} f_H \qquad (f_0 > f_H) \qquad (41)$$

where f_H is the gyro frequency.

In the second theory (Sturrock, 1961) preferential excitation of the two frequencies occurs at the extremes of the band of plasma waves that propagate at different angles to the magnetic field. Here

$$\delta f_S \sim ½ f_H{}^2 / f_0 \qquad (42)$$

Weiss considered a third possibility that had not been supported by theory namely that

$$\delta f_h = f_H \qquad (43)$$

Magnetic field strengths based on these three formulae are shown in Figure 168 compared with values derived from magnetic shock theory shown in Figure 167.

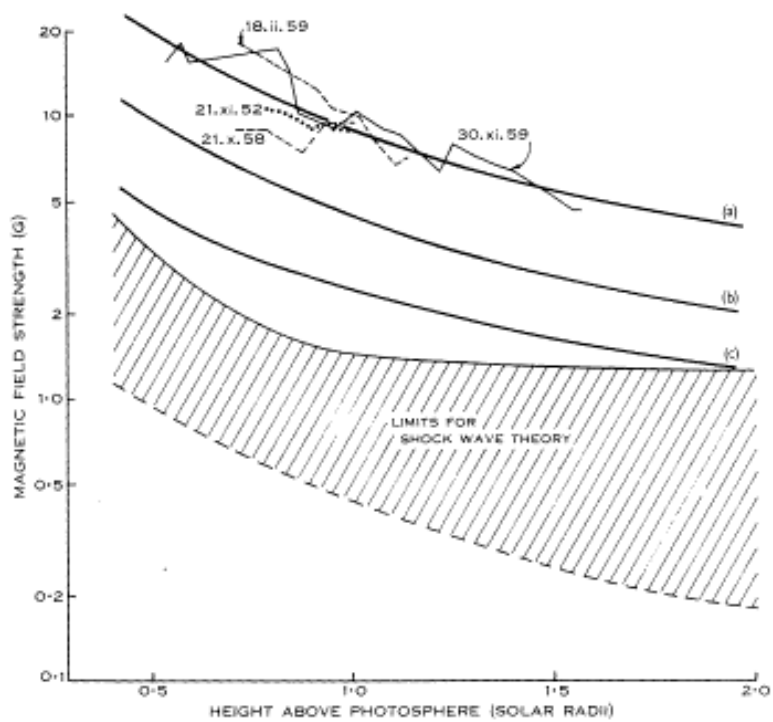


Figure 168 Coronal magnetic field strengths derived from band-splitting for 4 Type II bursts using (a) δf_S (b) δf_{MI} (c) δf_h . Shaded portion shows values derived from magnetic shock theory (after Weiss, 1965: Fig. 12).

Weiss concluded that the much higher values for coronal magnetic field strengths found from the split-band theories indicated that none of these were tenable. A later, more satisfactory

magnetic model for split-band structure in Type II bursts was presented by Smerd, Sheridan and Stewart (1974) in which the two frequencies of the split-band are excited ahead of and behind the shock front.

4.11 Unpublished Study of Type I Bursts

Orchiston (pers. commun., 2009) has reminded me of a detailed study he carried out with Weiss of Dapto interferometer and radiospectrograph observations of Type I bursts which unfortunately was never published due to the untimely death of Alan Weiss.

4.12 Conclusion to Chapter 4

This concludes my discussion on contributions to solar physics by members of the Dapto solar group using data from the 40-70 MHz swept frequency interferometer and polarimeter. All published papers have been discussed in detail except for one or two in obscure journals which are inaccessible; the latter have been referred to and their main contributions noted above.

Not only was the plasma hypothesis confirmed for Type II and Type III bursts but it was also found to apply to Type V bursts. Positional measurements showed that the shock waves exciting Type II bursts sometimes travelled non-radially across magnetic field lines disturbances producing polarized herringbone features and that the Type IV burst had a moving and stationary component. The stationary Type IV burst often degenerated several hours later into a storm of Type I bursts and continuum which could last several days. Sometimes storms of Type III bursts also resulted from flare activity. Estimates of the coronal magnetic field strength were obtsained from shock wave theory. the relative positions of fundamental and second harmonic sources was explained in terms of plasma wave theory

5. SIGNIFICANT CONTRIBUTIONS TO METRE WAVELENGTH SOLAR ASTRONOMY 1942 - 63

5.1 Introduction

In describing the Penrith and Dapto Field Station work so far I have not included any accounts of concurrent studies by outside groups except where referenced in the Solar Group publications. It is worth stressing that my thesis is only concerned with metre wavelength solar bursts. It is not concerned with other types of solar radio emission such as the weak background thermal radiation from the Quiet Sun which becomes appreciable at frequencies above 200 MHz or with the Slowly Varying Component associated with sunspot groups which has been studied by observers using grating arrays operating at decimetre and centimetre wavelengths such as the one at Potts Hill, Australia (Wendt, 2008) and elsewhere. For a comprehensive review of this important early work see the recent articles by Pick and Vilmer (2008).

It is my contention that most of the important contributions to our knowledge of the nature of metre wavelength solar radio bursts during the period from 1949 to 1964 came from the instrumental developments and observations at the Penrith and Dapto Field Stations, following the excellent pioneering work of Joe Pawsey and his original solar group, beginning with single frequency observations in late 1945 at Dover Heights, Sydney (Orchiston et al., 2006). Multi-frequency solar observations continued for a number of years at a number of CSIRO Field Sites including Potts Hill and Hornsby Valley. The metre wavelength solar work at the Dapto Field Station ceased in 1964 and commenced again at Culgoora in 1967 following the construction and operation of the world's first radioheliograph, which began operation at a frequency of 80 MHz in 1966 and was later extended to 160, 43 and 320 MHz. Operations at Culgoora ceased in 1984 to make way for the Australia Telescope.

5.2 Importance of Spectral Records

In Table 8 I have listed in chronological order what I consider to be the most significant contributions to metric wavelength solar astronomy during the period 1942 when the first radio waves from the Sun were detected until 1963 shortly before the closure of the Dapto Field Station. Contributions from the CSIRO Division of

Radiophysics are shown in italics. These include early observations at Dover Heights, Potts Hill, Penrith and Dapto. All solar radio observations before 1949 were made at discrete frequencies; the availability of dynamic spectral records in 1949 from the Penrith radiospectrograph removed much of the confusion from these earlier records and led to the classification of the spectral Type I, II and III solar bursts (Section 2.3); the improved radiospectrograph installed at the Dapto Field Station in 1952 led to the important discovery of fundamental and second harmonic structure in Type II and Type III bursts (Section 2.4). Extensions to the frequency range of the Dapto radispectrograph from 1958 to 1963 led to a greater understanding of the nature of these bursts (Section 2.8).

From 1957 onwards other countries began building radiospectrographs in the metre and decimetre range (see Table 8). The first overseas observations of solar radio burst spectra began at Fort Davis, Texas in 1956 (Maxwell et al., 1958), seven years after the first spectral observations at Penrith. Radiospectrographs also operated at the University of Michigan from 1957 (Haddock, 1958); the University of Oslo from 1959 (Elgaroy, 1961); and at the Owens Valley Radio Observatory from 1959 (Young et al., 1961). These instruments also played an important role in gathering new information on the characteristics of sporadic solar radio emission at metre and decimetre wavelengths.

TABLE 8

SIGNIFICANT CONTRIBUTIONS TO METRE WAVELENGTH SOLAR ASTRONOMY 1942 - 63

(CSIRO Radiophysics contributions are highlighted by italics).

1942.

- Solar radio noise first detected on radar sets at 35-70 MHz and found to be associated with sunspots (Hey, 1946)

1943.

- Quiet sun detected at 160 MHz (Reber, 1944).

1945.

- *Detection of solar radio emission at 200 MHz correlated with total sunspot area (Pawsey et. al., 1946).*

1946.

- *Temperature of the corona found to be 1 million degrees from 200 MHz observations of the quiet Sun (Pawsey, 1946); in agreement with theoretical predictions of Martyn (1946b) and Ginzburg (1946, 1984).*
- *Sea-interferometer used to identify 200 MHz emission with a large sunspot group in February 1946 (McCready et al., 1947). First use of an interferometer in radio astronomy.*

- Variable baseline interferometry in July 1946 at 169 MHz measured the size of the radio source to be associated with a large sunspot group and found the emission to be circularly polarized (Ryle and Vonberg, 1946).
- Solar noise storms found to exhibit circular polarization (Martyn, 1946a).
- Association of radio outbursts with solar flares (Appleton and Hey, 1946).

1947.

- *A large outburst recorded simultaneously at 200 from Mt. Stromlo and at 150 and 60 MHz from Dover Heights shows a systematic delay in onset times towards lower frequencies, inspiring the development of the Penrith radio spectrograph (Payne-Scott, Yabsley and Bolton, 1947).*
- April eclipse curve from Brazil shows that radio emission at 200 MHz comes from the solar corona (Khaikin and Chikhachev, 1947) as predicted by Martyn (1946b) and Ginzburg (1946).

1948.

- *Solar observations at 18.3, 19.8, 60, 65 and 85 MHz conducted in the Hornsby Valley (Payne-Scott, 1949).*
- Solar monitoring at 75, 140 and 200 MHz from 3 sites in the Netherlands; extended in 1951 to a world-wide network for the study of solar effects on the ionosphere (de Voogt, 1952; see also Strom, 2005).
- Solar observations at 555 MHz from Meudon, France (Laffineur and Houtgast, 1949); extended to 255 MHz in 1949 (Laffineur, 1954; see also Orchiston et al., 2007).

1949.

- *Radio spectrograph operating from 70 to 140 MHz at Penrith, NSW, led to the classification of Type I, II and III bursts (Wild and McCready, 1950).*
- *Swept-lobe interferometer installed at Potts Hill, NSW to measure source positions and polarizations of solar bursts at 97 MHz (Little and Payne-Scott, 1951; see also Wendt, 2008).*
- Solar monitoring in Japan at 200, 100 and 60 MHz from Tokyo Astronomical Observatory, Mitaka (Tanaka, 1984).
- Metre wavelength studies of the sun conducted by FIAN in the Crimea, Russia (Chikhachev, 1950; Salomonovich, 1984).

1951.

- French observations of a partial solar eclipse at Makala, Africa on 1 September 1951 together with a total eclipse at Dakar, Africa on 25 February 1952; both showed that the quiet corona at 169 MHz had an ellipsoidal shape with maximum extension along the solar equator (Blum et al., 1952; see also Orchiston and Steinberg, 2007).

1952.

- *Radio spectrograph observations at Dapto, NSW operating over an extended frequency range from 40 to 240 MHz. First detection of harmonic structure in Type II and III bursts (Wild et. al. 1954a, b*).

1953.

- Map the quiet sun derived at metre wavelengths using aperture synthesis (O'Brian, 1953).

1954

- Multi-frequency observations at 200 MHz of the quiet sun during a partial eclipse on 30 June 1954 from NERA, Kootwijk and the Hague (Seeger, 1955; Fokker et al., 1955; see also van Woerden and

Strom, 2006).

1956.

- Fort Davis (Harvard) radiospectrograph began recording solar bursts over the 100-580 MHz band (Maxwell et al., 1958; extended to 25-580 MHz in 1959 and 2100-3900 MHz in 1960 (Thompson, 1960).
- Le 169 MHz grande interferometer de Nancay, France consisting of 32 x 5 m antennas on a 1600 m east-west baseline began observations. (Blum et al., 1957); a north-south arm was added in 1959.

1957.

- University of Michigan 100-580 MHz radio- spectrograph observations of solar bursts (Haddock, 1958).
- East-west grating array observations at 340 MHz and 87 MHz conducted by the Dept. of Terrestrial Magnetism, Carnegie Institute of Washington (Firor, 1959, Kundu and Firor,1961.
- *Swept frequency interferometer operating from 40-70 MHz at Dapto (Wild and Sheridan, 1958).*

1958.

- *Dapto swept frequency interferometer confirmed the "plasma hypothesis" for the emission of Type II and III bursts (Wild, Sheridan and Trent, 1958) and first identified the Type V burst (Wild, Sheridan and Neylan, 1959).*
- *Dapto radiospectrograph extended from 25 to 210 MHz. (Sheridan et al., 1959).*
- Type IV solar bursts first identified using the Nancay 169 MHz grande interferometer (Boischot., 1957)
- Four element multi-phase 201 MHz interferometer at Mitaka, Japan to measure source positions of solar bursts (Suzuki. 1959).

1959.

- 15-38 MHz radio spectrograph together with two-element interferometers operating at 18 and 38 MHz used to study low frequency Type I noise storms and Type III bursts. High Altitude Observatory, University of Colorado (Boischot et al., 1959).
- University of Oslo high time and frequency resolution spectrograph operating over the 140-170 MHz and 310-340 MHz bands (Elgaroy, 1961, 1977).
- Owens Valley radiospectrograph began operating in the 500 – 900 MHz range (Young et al., 1961)
- 254 MHz interferometer and 200 MHz polarimeter at NERA, the Netherlands used to study noise storms (Fokker, 1960; Cohen and Fokker, 1959).
- *Statistical study of Type II bursts including split-band and herringbone structure by Roberts (I1959)*
- *Model of a moving type IV burst by McLean (1959)*
- *Discovery of 'herringbone structure' in Type II bursts (Roberts, 1959).*

1960

- Fokker (1961) used data from the following observatories to synthesise the complete spectra of 3 major Type IV bursts during 1960-61:
- NERA, the Netherlands; 9200, 2900 MHz
- Heinrich Hertz Institute, Berlin; 9400, 2000, 1500 MHz
- Astron. Observatory, Ondrejev, Czechoslovakia; 808, 551, 231 MHz

- Universtats Sterwarte, Kiel; 460, 240 MHz
- Astrophysical Observatory, Potsdam; 510, 234, 111, 60, 40, 30, 23 MHz
- *Dapto radiospectrograph extended from 15-210 MHz in 1960 (Sheridan and Trent, 1960).*

1961

- *Dapto radiospectrograph extended from 5-210 MHz in 1961 (Sheridan and Attwood, 1962).*

1963

- *Annual Review of Astrophysics paper on Solar Bursts (Wild, Smerd and Weiss, 1963).*

5.3 Importance of Interferometer Observations

The spectral records revealed how complex large flare associated radio events could be. Initially these radio events were called *outbursts* by Allen (1947) and when Wild and McCready (1950) discovered the Type II burst it was assumed that this constituted the outburst at metre wavelengths (Wild 1950a; see Section 3.1). Then Payne-Scott and Little (1951) observed a moving source at 85 MHz in two outbursts. This led to some confusion between the Type II burst and the moving source (see my comments in Section 3.9.3). The confusion was resolved at least partly when Boischot (1957) using the 169 MHz 32 element array at Nancay recognised that this moving source was associated with a new phenomenon which he called the *Type IV burst.* Boischot and Denisse (1957) interpreted the type IV emission as being due to synchrotron radiation from relativistic electrons spiralling in the coronal magnetic field. This led McLean to assume that all smoothly varying continuum events following large flares were moving Type IV bursts (see Section 3.17). The Type IV label was then applied by researchers to all outbursts across the centimetre to metre wavelength range. One of several proposed models is shown in Figure 169 and discussed below; comparing this to Wild's earlier 1952 review of 'outbursts' (Section 3.9) one sees that the metre wavelength event now includes both *moving* and *stationary* Type IV bursts as well as the Type II burst.

Although Monique Pick (Pick-Gutmann, 1961) presented evidence to show that that there were two distinct phases to the continuum event following flares her *first phase* was not represented in type IV models such as the one shown in Figure 169, where only the moving type IV burst (IVmA and the stationary type IV burst (IVmB) are indicated (Wild et al., 1963). This situation was rectified about 10 years later. In the words of Pick and Vilmer (2008: 10):

The first phase (called *flare continuum* by Wild, 1970) corresponds to a broad band emission, from centimetre to metre wavelengths which starts near the flash phase of the optical flare: the intensity variations are roughly similar at all frequencies and the radiation has little directivity. The second phase, called *continuum storm* (*stationary type IV burst* in the 1963 Wild et al. terminology) is characterized by a smooth continuum in the dm-m wavelengths which can last many hours and progressively an ordinary type I storm. The emitting source is stationary, but has a small angular diameter, is strongly polarized in the ordinary sense and is directive. Taking in consideration all these properties, the continuum storm was interpreted as due to a plasma [wave] emitting mechanism. In addition to these two phases, subsequent radioheliograph observations revealed, 10 years later, that the moving type IV burst identified by Boischot (1957) originates from the same solar position as the first phase, i.e. from the position of the flare continuum (Robinson and Smerd, 1975).

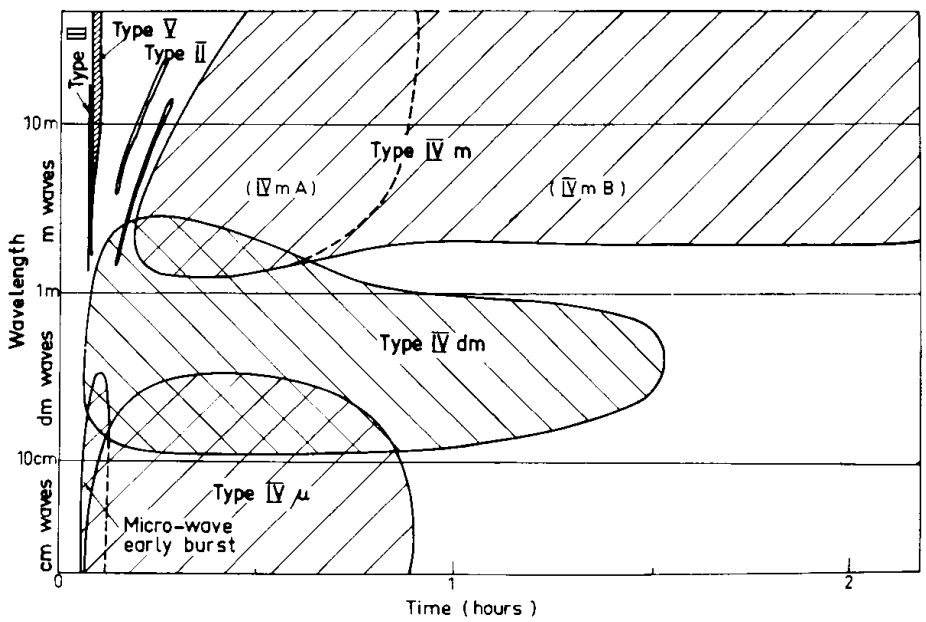


Figure 169 The main components of a solar outburst (after Wild, Smerd and Weiss, 1963: Fig. 16).

Apart from the 97 MHz swept-phase interferometer study by Payne-Scott and Little (1951) at Potts Hill during 1949-50, the next systematic interferometer studies at metre wavelength of solar bursts were undertaken from 1957 at the following sites: at Dapto, using the 40-70 MHz swept-frequency interferometer (Wild and Sheridan, 1958); at Nancay, France using

the 169 MHz 32 element interferometer array (Blum et al., 1957; Boischot, 1957); at Washington, USA using 340 MHz and 87 MHz arrays (Firor, 1959) and at Mitaka, Japan using the 201 MHz four element multi-phase interferometer (Suzuki, 1959). Several other interferometers followed soon afterwards including 18MHz and 38 MHz two-element interferometers at the University of Colorado, USA (Boischot et al, 1959) and the 254 MHz interferometer at NERA, the Netherlands (Fokker, 1961) . From 1957 onwards more countries became more involved in the study of metre wavelength bursts especially France, USA, Japan, Holland and Norway with either spectral or interferometer observations.

An important result from the Dapto swept-frequency interferometer observations was the measurement of source heights for Type III and Type II bursts (Wild, Sheridan and Neylan, 1959; Weiss, 1963a); this led to confirmation of the *plasma hypothesis* as well as providing a clearer picture of how shock waves and electron streams moved through the corona at the time of solar flares. (see Sections 4.3 and 4.5).

5.4 A Model of the Complete Flare Event

The discovery of herring-bone structure in some Type II bursts (Section 3.16) and the quasi-transverse motion of the Type II source in these events (Section 4.3) led Wild (1963) and Wild, Smerd and Weiss (1963) to propose a *two phase acceleration process* in solar flares. This model (Illustrated in Figure 170) created a lot of interest amongst researchers involved in the study of solar-terrestrial events (Pick and Vilmer, 2008).

According to Wild (1963) the sequence of events in a major flare as revealed by the current evidence available at that time could be summarized as follows (Wild, 1963: 173):

1. Preliminary heating, presumably due to magnetic compression, causes the microwave intensity from part of the active region to increase gradually, giving the *gradual rise and fall*.

2 Minutes later the flash phase occurs; materially this constitutes the sudden ejection, from the chromosphere or lower corona, of several packets of electrons with energy in the 20 to 200 kev – each packet containing some 10^{33} to 10^{35} electrons. Of those travelling upward in the corona, some escape freely along radial

field lines or neutral planes and generate plasma radiation to give the *type III bursts*, others are trapped in or bent round enclosed loops to give the type *V* and *U bursts*. Those travelling down into a trapped region within the surrounding chromosphere cause the microwave *impulsive burst* and *x-ray burst* by the synchrotron and bremsstrahlung processes, respectively.

3. The same eruption initiates also shock waves which propagate in fragmentary form in various directions; those moving out through the corona issue bunches of fast electrons which in turn generate the *type II burst* by plasma radiation. The shock is also responsible for generation Alfven waves within the field structure, and these waves cause acceleration of the electrons and protons trapped in the field. The electrons thus accelerated generate the various components of the *type IV burst* by synchrotron and plasma processes, while some of the protons, accelerated to much greater energies, are those responsible for the *solar proton event* detected at the earth.

The model of Figure 170 also shows the shock wave initiating a geomagnetic disturbance at the Earth in keeping with the radio correlation studies of Roberts (159) and McLean (1959) (Sections 3.16 and 3.17)

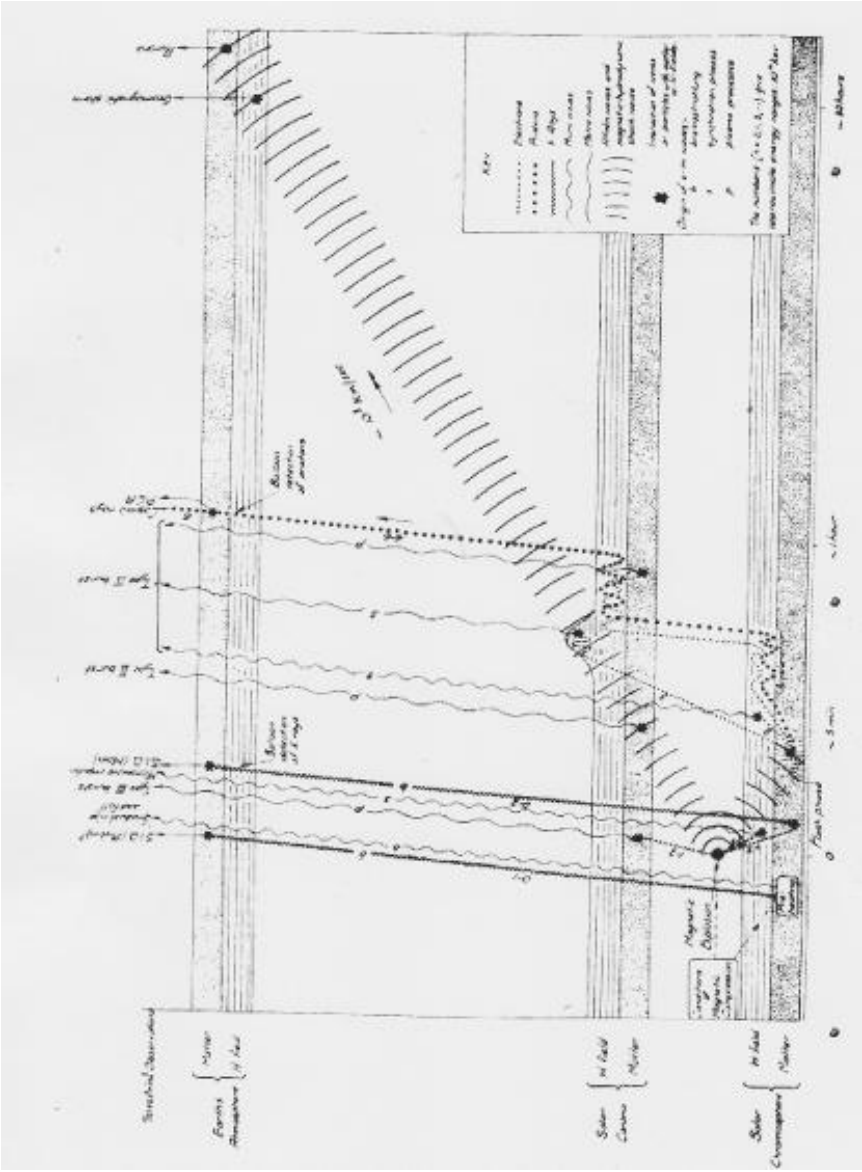


Figure 170 Diagram showing the origin of radio emission, x rays and corpuscular effects of solar flares (after Wild, 1963: Fig. 21-9; after Wild et al., 1963: Fig. 18).

5.5 Theoretical Contributions

The Dapto solar work was concerned mainly with instrumental development, observational data and interpretation. Little if any theoretical work was carried out with the exception of early work by Jager and Westfold (1959), who worked with Pawsey's earlier solar group, and Steve Smerd, who had a poor reputation when it came to publishing (Wild, 1980). However, his vast knowledge of the theoretical literature was invaluable in aiding other members of the Dapto group with interpretation of observational data. According to Wild (1980) perhaps the best

summary of Smerd's unpublished contributions can be found in the review paper on solar radio bursts by Wild, Smerd and Weiss (1963), which included a discussion of coherent emission mechanisms (see Figure 171 below).

Before joining the Dapto Solar Group in 1951 Smerd had worked with Westfold. Christiansen (1984: 116) writes:

> S.F. Smerd and K.C. Westfold, who formed a theoretical group in the Radiophysics laboratory, worked out the theory of the quiet sun radiation by adapting the equation of transfer, used to investigate stellar interiors, to the ray paths that they determined for the ionised atmosphere of the Sun. This work (Smerd and Westfold, 1949) remains a standard reference to the present time. One of the predictions from this work (Smerd 1950c) was that radio limb-brightening of the solar disk should be found at certain wavelengths.

Limb brightening was detected subsequently by Christiansen and Mathewson (1951) and Swarup and Parthasarthy (1955) using the Potts Hill Grating array (see also Wendt, 2008).

5.5.1 Coherent Emission of Plasma Waves

Wild, Smerd and Weiss (1963) and Smerd (1965) showed how the high observed brightness temperatures in Type II and Type III bursts were consistent with the emission being the result of the generation by coherent plasma waves.

According to Smerd (1965: 406):

> The properties of coherent plasma waves have been derived by Bohm and Gross (1949a, b); these authors have introduced the concept of 'trapped' electrons. The latter have velocities sufficiently close to the phase velocity of the plasma wave to remain trapped for a while in a potential trough; in this way the electrons can interact strongly with the plasma wave. Those electrons which are slightly faster than the wave on the whole give up energy and the wave grows. The slower electrons lead to damping. If we denote the velocity distribution in the electron stream by $F_s(v)$ the condition for growth is

$$(dF_s/dv) > 0 \quad when\ v = v_{ph} \qquad [44]$$

This is equivalent to the condition for wave amplification illustrated in Figure 1c [my 172c].

Ginzburg and Zheleznyakov (1958) used Bohm and Gross's value for the amplified plasma wave and expressions for the efficiency of conversion to electromagnetic waves to estimate the stream velocities and densities which could account for the observed properties of Type III bursts. Similar calculations by Wild, Smerd and Weiss (1963) on the bases of the more recent observational results suggest that we can explain a brightness temperature of 10^{11} K from a *c*/4 stream with $N_s/N \sim 0.02$ and a c/2 stream with $N_s/N \sim 0.06$.

A similar interpretation of the slow – drifting Type II burst is possible only if we assume the Type II source to harbour and at times eject electrons of Type III velocities. This same assumption was needed to explain (Smerd et al., 1961) the relative positions of the fundamental and harmonic sources in Type II bursts [Section 4.4].

The conditions for incoherent and coherent radiation derived by Wild, Smerd and Weiss (1963) are given below in Figure (171).

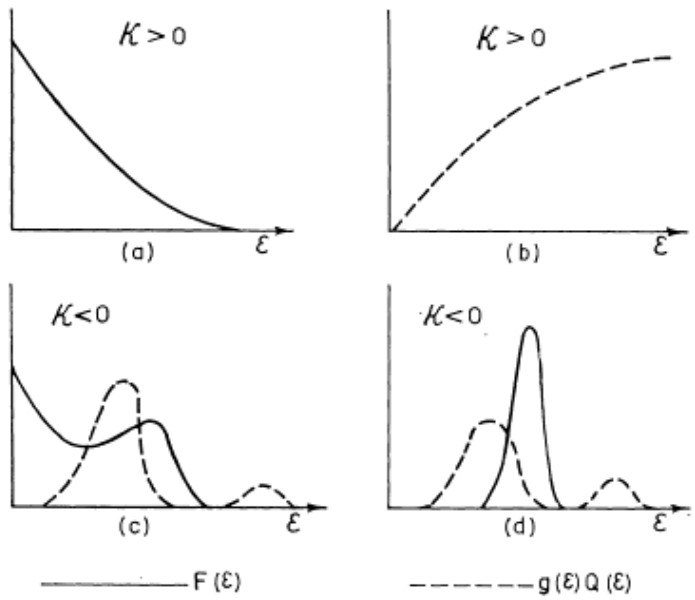


Figure 171 (a) and (b) show the conditions required for incoherent emission; (c) and (d) the conditions for coherent emission. Where K is the absorption coefficient, *F (ε)* is the energy distribution, *g (ε)* is the statistical weight and *Q (ε)* is the mean electron emissivity (after Wild et al., 1963: Fig. 20).

5.6 Concluding Remarks

A number of overseas researchers have acknowledged the important contributions of the Radiophysics Solar Group to international solar astronomy including the following:

In 1963 Professor M.G.J. Minnaert when introducing the Utrecht Symposium on *"The Solar Spectrum"* (1965: 21-22) wrote that:

> The history of solar radio-spectroscopy is mainly the history of Australian work on this subject. At each meeting of the IAU, at each important Symposium on radio-astronomy, highly competent specialists such as Wild, Smerd and Christianson, headed by the dynamic personality of our regretted Pawsey [*deceased*], were able to announce spectacular progress. As you see, the history of solar-radio-astronomy extends over hardly fifteen years, but how momentous these years have been!

In a later review M. Kundu made the following points (Kundu, 1986):

● I received my doctoral degree (Docteur des Sciences) from Sorbonne in 1957.

● After Paul Wild built his first spectrum analyser, there as a lot of activity all over the world including the US.

● Analysis of radio spectra produced good science: discovery of electron beams and shocks in the solar atmosphere.

● I was associated with one such instrument at Michigan (Fred Haddock) – my first job as a post-doc.

● The next big step was taken by Paul Wild again – he designed and built the first imaging array for the Sun; the Culgoora RadioHeliograph (1967: 96 antennas in a circle of 3 km diameter). So the Australian group was once again in a dominant situation – spectra and images of solar active regions and flares.

The latter claim is not strictly correct as Christiansen had designed and built the 1420 MHz Chris – Cross (Christiansen et al., !960; see also Orchiston and Mathewson, 2009) which produced full 2D images of the Sun over several hours which was sufficient time to map the slowly varying component of radio emission from chromosperic plage regions. In contrast to the Chris-Cross, the Culgoora Radioheliograph images were produced in only one second thus allowing the study of the source evolution of solar bursts initially at a frequency of 80 MHz (Wild, 1967), supported by 158 MHz north-south and east-west interferometers (Stewart, 1967) and a new radiospectrograph operating from 8- 2000 MHz (Sheridan, 1967). The Culgoora radioheliograph observations were extended initially to 160 MHz, then to 43 MHz and finally to 327 MHz (Sheridan et al., 1983)

6. CONCLUSION

In this thesis I have given a detailed account of the research activities of the CSIRO Division of Radiophysics Penrith and Dapto solar group participants, who, during the period 1949 to 1964, achieved an international reputation in Solar Radiophysics by innovative design of observing equipment and ground breaking investigations into the nature of metre wavelength solar radio bursts and the disturbances which gave rise to them. As well as classifying most types of bursts by their spectral appearance the group presented models to interpret their characteristics.

The planning, development and implementation of the world's first radiospectrograph at the Penrith field station in 1949 and its extensions to increasingly lower frequencies at the Dapto field station from 1952 to 1963 is outlined with archival material, interviews and published literature.

The Penrith observations led to the first spectral classification of Type I, II and III bursts. The observed frequencies of the leading edges of the slowly drifting Type II bursts and the rapidly drifting Type III bursts were converted to radial heights by using a standard coronal density model and by assuming that the radio emission occurred at the fundamental plasma frequency. This was later referred to as the *plasma hypothesis*. The derived height-time plots suggested that the disturbances exciting the radio emissions moved outwards through the corona with velocities of the order of 1000 km/sec for Type II bursts and 100,000 km/sec for Type III bursts. This was the first evidence for the flare ejection of corpuscular material and shock waves to such great heights in the corona. It was suggested that the Type II disturbance upon reaching the Earth might be responsible for initiating geomagnetic storms which disrupt radio communication. Likewise the fast moving Type III disturbance was considered to be a possible candidate for solar cosmic rays, although the exact nature of the particles involved in the excitation of the Type III burst was not known at that time.

The development of a new improved radiospectrograph at Dapto led to the discovery in 1954 of fundamental and second harmonic components in both Type II and III bursts. This discovery gave further support to the *plasma hypothesis* and allowed the initiating disturbances to be

extended to even greater heights in the corona. Further low frequency extensions to the Dapto spectrograph from 1956 to 1961 pushed the investigations to greater and greater coronal heights until it was established that the fast moving electron streams responsible for the Type III burst moved virtually unimpeded out to heights of at least 3 solar radii above the photosphere. This was the limit that could be observed by ground based radio observations because of absorption effects in the Earth's ionosphere. Similarly, the Type II disturbance was traced to corresponding heights indicating that the shock waves responsible for these bursts also escaped into interplanetary space and possibly initiate geomagnetic disturbances upon arriving at the Earth. Later spacecraft observations detected Type III electron streams near the Earth and also Type II interplanetary shock waves accompanying coronal mass ejections.

Final confirmation of the *plasma hypothesis* was obtained with the development of the Dapto swept-frequency interferometer at Dapto in 1957. The radial heights found subsequently for Type II and III sources were in good agreement with coronal density models assuming, as before, that the emission occurs at the fundamental and second harmonic plasma level. An earlier experimental model of the interferometer, the first of its kind, had been installed at Dapto in 1954 for the study of radio scintillations from the source Cygnus A.

The Dapto observations also led to the classification of the Type V burst which sometimes followed Type III bursts. A model was proposed for this event in which some of the Type III electrons became trapped in coronal magnetic fields to produce the longer duration and broader bandwidth Type V burst. Other phenomena discovered at Dapto included the *reverse drift pairs* (RDPs) which were closely associated with Type I storms and the *split-band* and *herring-bone* structures in Type II bursts. The RDPs were thought to be evidence for radio echoes in the corona while several magnetic theories were proposed for the split-band structure in Type II bursts. The herringbone features were found to be highly polarized in a circular sense and this was taken as evidence that the Type II shock wave could excite streams of fast electrons as it moved across magnetic field lines in the corona.

The only metre wavelength spectral type burst not discovered by the Australian group was the Type IV, first classified by the French in 1957, who attributed it to synchrotron radiation from electrons spiralling along field lines in a magnetic field. Dapto interferometer observations revealed that the Type IV had two components, an early moving component, called the *moving Type IV burst*, and a later stationary component known as the *stationary Type IV burst*. A model

was proposed to account for the observed characteristics of the *moving Type IV burst*, which involved an ejected plasmoid, containing relativistic electrons generating synchrotron radiation, behind a *Type II shock wave*. It was assumed that the fast electrons generating the emission in the stationary source were trapped in magnetic fields above the flare region; after several hours the *stationary Type IV burst* often degenerating into a *Type I storm*. Observations of slowly drifting *Type 1 Chains* were taken as evidence that the bursts were excited by Alfven waves.

Although the Solar Group concentrated mainly on the collection and interpretation of the observed properties of solar radio bursts at metre wavelengths, several important contributions of a theoretical nature also were produced and theories reviewed. These concerned the propagation of electron streams and shock waves in the corona, as well as the conditions required for coherent plasma wave emission which occurs in Type II and Type III bursts.

By the early 1960s the Division of Radiophysics had been granted funding to build a radioheliograph at Culgoora, NSW. As a result the Dapto Field Station was closed down in 1964. Solar radio observations continued at Culgoora from 1967 until 1984 but this is not part of my thesis. Suffice it is to say that the Solar Group went on to achieve even greater status and, I believe, a pre-eminent reputation in solar radio research during this period. A detailed study of the Culgoora Field Station activities would be, in my opinion, an excellent PhD project for a student interested in the history of '*big science'* in Australian radio astronomy.

The Culgoora instruments were developed and operated by the CSIRO Radiophysics Solar Group which grew out of the Penrith and Dapto groups. The radioheliograph played a leading supporting role in both the Skylab Missions of 1973-74 and the Solar Maximum Mission of 1980-81 providing real-time observations of coronal activity. In 1984 the Culgoora radioheliograph was de-commissioned to make way for the Australia Telescope. The Culgoora site was renamed the Paul Wild Observatory in recognition of Wild's contribution. The Culgoora radiospectrograph was transferred to the Ionospheric Prediction Service where it is still used today for space weather monitoring of solar activity. At my last count there were listed on the Internet at least 20 ground based radiospectrographs operating around the world, almost 60 years after the first spectral observations of solar bursts were made at the CSIRO Penrith Field Station.

In 1969 Paul Wild was awarded the prestigious Hendryk Artwski Gold Medal by the US National Academy of Science and the Balthasar van der Pol Gold Medal by the International Union of Radio Science for his contributions to solar radio astronomy. I was fortunate enough to work under his leadership from 1963 to 1979 when he was appointed Chief of CSIRO. It is with great pleasure that I dedicate this thesis to the memory of John Paul Wild, Steve Smerd and Kevin Sheridan who assisted and inspired me for many years during my career in solar radiophysics.

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8 APPENDICES

8.1 Archival Letters Regarding Spectrum Analyser Development

National Archives of Australia

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File: 45.1[8]

- Letter from McCready to Pawsey dated 7th October 1947

"Spectrum Analyser – Not started yet due to other duties mainly preparing a solar noise exhibit for the Royal Society [C....] tomorrow evening."

- Letter from F.J. Lehany to Pawsey dated 13th October 1947

"Paul Wild has joined Lindsay on the Spectrum Analyser project."

- Letter from McCready to Pawsey dated December 1947.

"The spectrum analyser is proceeding slowly. It is impossible for me to do much or rather have any continuity. Always some interruption. Nevertheless there is progress. Rhombics & their mounts are in the shop & satisfactory experimental results obtained with a 200-600 Mc/s Rhombic (SWR > 2/1 over the range). The required 70-140 aerial will give no troubles. Work now proceeding on the receiver. Wild is a good man & good balance between theory & experiment but inclined to be too much of a perfectionist in the matter of detail."

- Letter from McCready to Pawsey [undated but probably early 1948]

"My own job is progressing slowly but I am unable to spend much time on it. It will be different when Chris [Christiansen] finds his feet and you return. Rhombic is under construction and the motor tuned R.F. unit (MkI) is almost ready. The remainder of the show is straight forward & the new chap Murray is very useful and appears to be able to handle it, in good engineering fashion at any rate. My eventual aim is to have two analysers covering 1. 50-200

Mc/s and 2. 200-600 Mc/s. I think it can be done with good butterfly Type tuned circuits and attention to engineering details. Owning to the sunspot max now almost past and the difficulty of polar axis mounting of large rhombics I think it would be risky impairing receiver sensitivity by taking the easy course of omitting an r.f. stage (on the 20-200 Mc/s range at any rate). Should you come across any suitable butterfly Type condensers over there we could use them. Even drawings would save time. Such things will have to be made in our own workshop. At the moment we are using a semi-butterfly [unreadable word] Type pinched from some P58 English Search receivers (B.T.H) and only attempting to cover 70-140 Mc/s until we establish & finalise receiver details. RCA co-as line noise diode will be a boon for receiver calibrations."

- Letter from Pawsey to McCready 5th May 1948

"Spectrum presentation. I would like to see you try this in a simple manner first – e.g. 30 Mc/s spread near 110 would be a first rate initial experiment. The point I wish to clear is the "delay" question. I find some people over here [written from England] do not believe our sequence "high frequency precedes low frequency" is correct. Surely the move is to push on with what you can make easily."

- Letter from McCready to Pawsey dated 6th June 1948

"As far as the spectrum analyser is concerned I am sorry I did not express myself clearly in my last. I was originally interested in extending the range as a long term project if the position warranted it later & thought it could be done very quickly later on. [some unreadable lines]...getting respectable coverage above 100 Mc/s. We are pushing ahead with the simple scheme & have a r.f. unit now covering 80-130 Mc/s with almost the theoretical noise factor over the range. The rhombic is nearly out of the shop & most of the display ancillary development is completed, but still a bit to be done on the recording & calibration techniques. F.M. is becoming a curse & we must choose a site that does not merely tell us what F.M. stations are on the air around Sydney. There are other projected stations coming on within our range apart the bitch at Crows Nest now continually radiating 1-2 KW (the National Programmes) on 92 ½ Mc/s. During the last week Wild & I have been carefully studying maps & touring all over Sydney district with the spectrum analyser receiver in back of a truck. If nothing else we know a lot about Sydney's environs – the weather was perfect & there was one occasion when I did moan about the scarcity of car drivers in our groups!!! Valleys & Gulleys are, in general, offer no protection if reasonably close to Sydney as the signal just bounces off the appropriate sides & hits you. The requirement

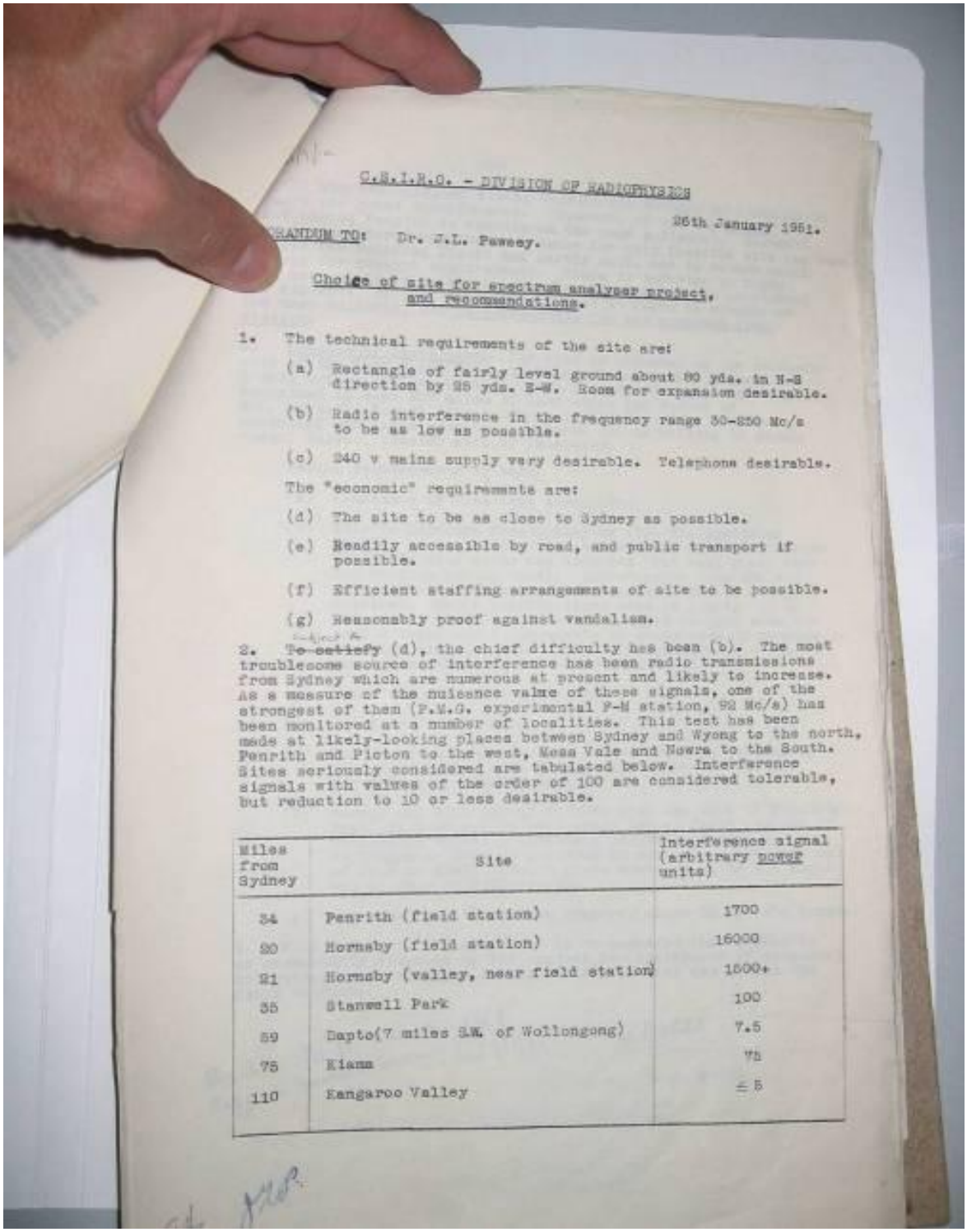
is, of course, a site in the shadow of a hill & clear view north so we have a good horizon for observing. I am afraid there is insufficient space to give you all the reasons why are the moment we are thinking of establishing [unreadable line but no doubt referring to the Penrith site] ... important reason is that Wild & Rowe can by virtue of the site being almost at the station & as they themselves being domiciled in the western suburbs, reckon they will never be any excuse for them not arriving at the site before 9:20 am. Interference of course has been checked & results good. I have my own vehicle & can get there in reasonable time particularly during week-end activity."

- Letter from McCready to Pawsey 25th June 1948

"I'm having a hectic time trying to get our rhombic installed on a temporary basis at Penrith pending proper tests for site noise etc. Difficulties are organisational & personal rather than technical (e.g. retaining unofficially good relations with a farmer etc)."

"Regret the slow progress on the spectrum analyser but it is due to many causes. Finally I have little time to attend to detail & secondly my staff tend to be a little too thorough & of the perfectionist Type. All very well in due course but as you've already said "Do it simply first to check general features etc & then see if it is worth developing a properly engineered model". However I think you'll find Wild & Murray a very keen & useful physicist and engineer respectively on your return. Do not regard the delay as waste – there has to be a quiescent nurturing period with some men embarking on their first research job (are exceptions of course e.g. John Bolton but I do hope the latter's energy, enthusiasm & imagination is not going to be spoilt by other factors)."

Below is a photocopy of a two page memorandum from Paul Wild to Joe Pawsey on the "Choice of site for spectrum analyzer project and recommendations." Dated 26th January 1951.



C.S.I.R.O. - DIVISION OF RADIOPHYSICS

26th January 1961.

MEMORANDUM TO: Dr. J.L. Pawsey.

Choice of site for spectrum analyser project, and recommendations.

1. The technical requirements of the site are:

(a) Rectangle of fairly level ground about 80 yds. in N-S direction by 25 yds. E-W. Room for expansion desirable.

(b) Radio interference in the frequency range 50-250 Mc/s to be as low as possible.

(c) 240 v mains supply very desirable. Telephone desirable.

The "economic" requirements are:

(d) The site to be as close to Sydney as possible.

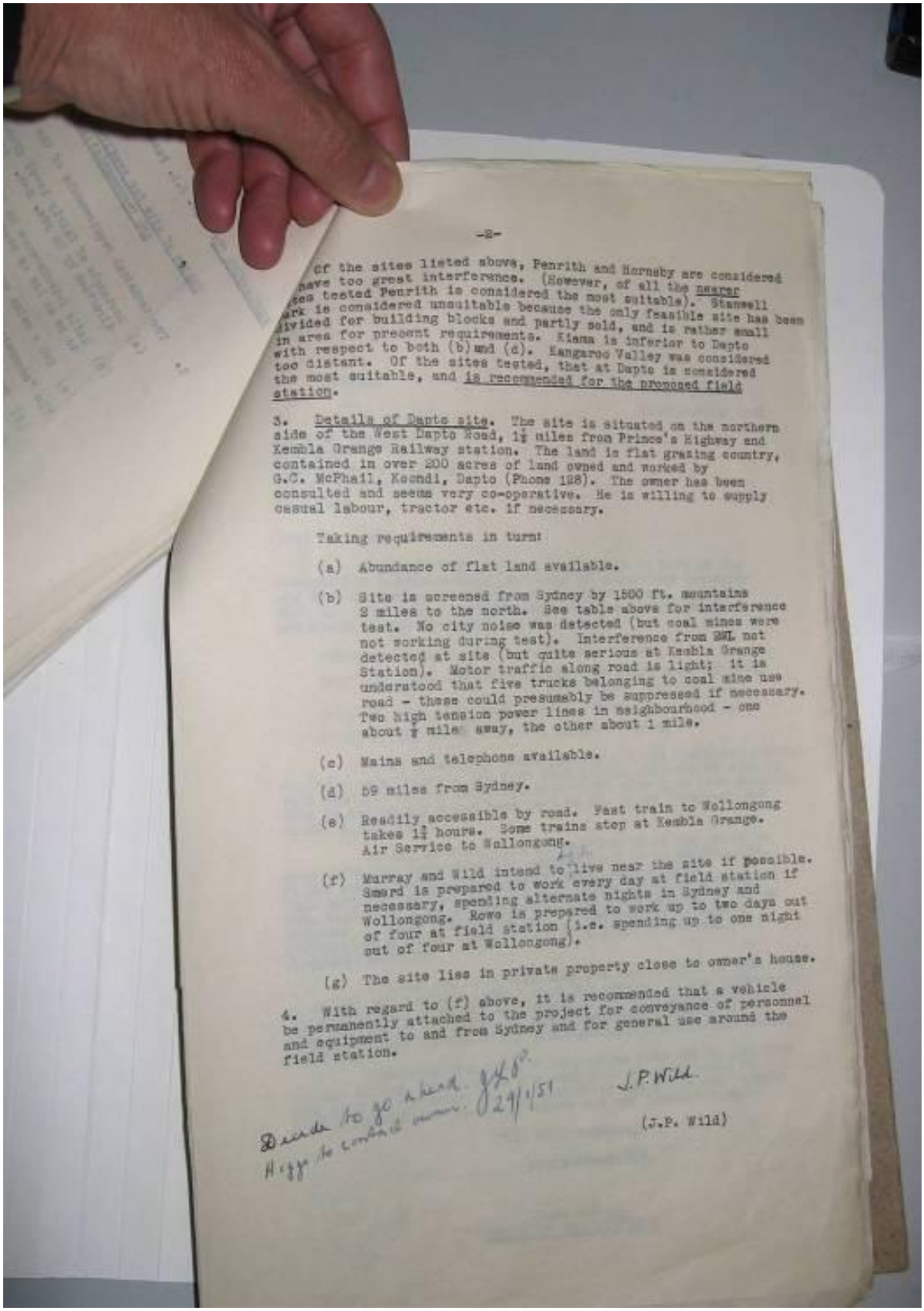
(e) Readily accessible by road, and public transport if possible.

(f) Efficient staffing arrangements of site to be possible.

(g) Reasonably proof against vandalism.

2. ~~To satisfy~~ (d), the chief difficulty has been (b). The most troublesome source of interference has been radio transmissions from Sydney which are numerous at present and likely to increase. As a measure of the nuisance value of these signals, one of the strongest of them (P.M.G. experimental F-M station, 92 Mc/s) has been monitored at a number of localities. This test has been made at likely-looking places between Sydney and Wyong to the north, Penrith and Picton to the west, Nowra Vale and Nowra to the South. Sites seriously considered are tabulated below. Interference signals with values of the order of 100 are considered tolerable, but reduction to 10 or less desirable.

Miles from Sydney	Site	Interference signal (arbitrary power units)
34	Penrith (field station)	1700
20	Hornsby (field station)	16000
21	Hornsby (valley, near field station)	1600+
35	Stanwell Park	100
59	Dapto(7 miles S.W. of Wollongong)	7.5
75	Kiama	7b
110	Kangaroo Valley	≤ 5



-2-

Of the sites listed above, Penrith and Hornsby are considered have too great interference. (However, of all the nearer sites tested Penrith is considered the most suitable). Stanwell Park is considered unsuitable because the only feasible site has been divided for building blocks and partly sold, and is rather small in area for present requirements. Kiama is inferior to Dapto with respect to both (b) and (d). Kangaroo Valley was considered too distant. Of the sites tested, that at Dapto is considered the most suitable, and is recommended for the proposed field station.

3. Details of Dapto site. The site is situated on the northern side of the West Dapto Road, 1½ miles from Prince's Highway and Kembla Grange Railway station. The land is flat grazing country, contained in over 200 acres of land owned and worked by G.C. McPhail, Koondi, Dapto (Phone 128). The owner has been consulted and seems very co-operative. He is willing to supply casual labour, tractor etc. if necessary.

Taking requirements in turn:

(a) Abundance of flat land available.

(b) Site is screened from Sydney by 1500 ft. mountains 8 miles to the north. See table above for interference test. No city noise was detected (but coal mines were not working during test). Interference from 2WL not detected at site (but quite serious at Kembla Grange Station). Motor traffic along road is light; it is understood that five trucks belonging to coal mine use road - these could presumably be suppressed if necessary. Two high tension power lines in neighbourhood - one about ½ mile away, the other about 1 mile.

(c) Mains and telephone available.

(d) 59 miles from Sydney.

(e) Readily accessible by road. Fast train to Wollongong takes 1¼ hours. Some trains stop at Kembla Grange. Air Service to Wollongong.

(f) Murray and Wild intend to live near the site if possible. Sward is prepared to work every day at field station if necessary, spending alternate nights in Sydney and Wollongong. Rowe is prepared to work up to two days out of four at field station (i.e. spending up to one night out of four at Wollongong).

(g) The site lies in private property close to owner's house.

4. With regard to (f) above, it is recommended that a vehicle be permanently attached to the project for conveyance of personnel and equipment to and from Sydney and for general use around the field station.

Decide to go ahead. J.K.O'C. 29/1/51
Hugh to contact owner.

J.P. Wild

(J.P. Wild)

8.2 Extract from Reminiscences of Jim Roberts

MY TIME AS A SOLAR RADIO ASTRONOMER

For Ron Stewart.

Ron. What follows is extracted from something I wrote some years ago. It might give you the flavour of Dapto. I did notice that I say quite clearly that the interferometer was constructed to measure the speed of Type III's. In the article I intended to tell the truth, but I certainly didn't check my 'facts' in the way that would be necessary if writing a history of science.

Jim Roberts 12 September 2007

November 1952. My two years of study with Bailey at Sydney University, and three years with Hoyle at Cambridge, have taught me something about radio emission, and the propagation of radio waves. Now I join the CSIRO Division of Radiophysics, famous for its Radio Astronomy research, and the Chief of the Division asks me, as my first task, to calculate the coalescence of raindrops! . . .

Bowen asked me to calculate this falling and coalescing process. The project didn't appeal to me; I was interested in electromagnetic radiation . . . .

After about six months I suggested to Bowen that I wasn't getting anywhere, and I was transferred to the radio astronomy programme, to a group studying the 'bursts' of radio waves emitted by the sun.

Roast shoulder of lamb, cooked and served in huts out in the middle of McPhail's dairy farm - that's my first memory of being a solar radio astronomer. I had travelled by train to Dapto, 60 miles south of Sydney, where I was met by John Murray. He was the chief technical person of the group, and the designer of the electronic equipment. On this occasion he was the chef, and produced this succulent baked dinner in the minute kitchen on the end of the equipment building.

Radio astronomy was under the general direction of Dr J.L. (Joe) Pawsey, the Assistant Chief of the Division. The group I was attached to, headed by Paul Wild, was studying the

intense metre-wavelength radio emissions that are sometimes received from the sun when there are large spots on the sun . . .

In 1947 it had been found that some outbursts - the name given to the most intense radio bursts from the sun - started at higher frequencies (shorter wavelengths) and drifted downward in frequency over the next ten minutes or so. To learn more about these drifting bursts, in 1949 Paul Wild and his collaborators had built a radio spectrograph . . . These initial spectral studies covered the frequency range from 70 MHz to 130 MHz and used a fairly primitive aerial and recording system that had been assembled at Penrith, west of Sydney. Because of the success of these observations a second, more permanent, spectrograph had been built on the dairy farm at Dapto. Here a range of hills to the north provided protection from the radio interference produced in the city of Sydney, and the extensive paddocks meant there was plenty of space for remote aerials - of which more anon. So picture this establishment out in the middle of these cow-paddocks: three colourful aerials - they were painted orange with green bases - and three nearby small buildings.

The equipment hut was a longish building with the aforementioned minute kitchen on one end, and a similarly-sized workshop on the other end. In between there was a small office (which I shared with Paul Wild on our visits) and the equipment room. Sleeping and eating took place in the adjoining single-roomed weatherboard hut; it had probably come there on the back of a truck. It was furnished with a table down the middle, and camp stretchers round the sides. On winter evenings the primuses from the kitchen were brought in and put under the table, and before long the air would be thick . . . In later years that little kitchen was the great gathering place while dinner was being cooked. At day's end some of us might go across to the dairy at milking time, to collect milk for the station, or cream to take back to Sydney. Max Komesaroff, John Murray's successor, would likely get into a political discussion with McPhail, the dairy farmer. It was one of those discussions that ended with McPhail's much-quoted comment to Jewish Max 'Well, anyway, Max, we're all Christians!'

After the milk had been collected the others would adjourn to the pub in Dapto. Being pretty well a teetotaller I would instead take a walk across the paddocks, or perhaps up towards rain-forested Mt Kembla, to the railway line, where during the day we occasionally saw goods trains struggling up the incline, with two steam engines at the front, and one at the back. Post-pub Paul Wild would produce the sherry bottle in that tiny kitchen, while Max cooked Wiener Schnitzel. Conversation would be animated as Max hammered the veal steak. On the primus the

butter would be burning in the frying pan, egg and flour would be scattered far and wide, and the atmosphere would be thick with fug. But it was great schnitzel! . . .

The day to day running of the station was in the hands of Jack Joisce. Each weekday Jack took the train from his home at Woonona down to Dapto, where he collected his bicycle (stored at the station), and rode out to McPhail's. For all the years that the station operated it was Jack who made sure that the equipment was running, that the aerials were tracking the sun, and that the film had not run out. We Sydney-siders normally spent three days each week at the field station, driving down and back by car. In fact I learned to drive on Paul Wild's car, a Wolseley. Initially he had me drive it across the paddocks at Dapto, and later I drove it down from Sydney. I suppose Paul gained some return on his investment in teaching me to drive. As a teetotaller I was sometimes asked to drive him back from the Dapto Christmas parties. These became annual events, with many invitees from the laboratory in Sydney making the trip down to Dapto to celebrate with various activities, including rides across the paddocks on a horse-drawn sleigh provided by McPhail….

The weekly three-day visits to the Dapto field station allowed Paul to see to general supervision, and provided a great environment for examining the observational results, and attempting an interpretation. At the same time Paul gently educated this new recruit on subjects such as aerial temperature and available power, in sessions over extended morning teas, taken sitting at a table out in the sunshine. Discussion would be accompanied by Paul repeatedly stabbing his teaspoon into his teacup, trying to dissolve all the sugar he had added! It was at one of those leisurely morning teas that Paul mused 'I wonder if Type III bursts really are caused by particles travelling out from the sun at close to the speed of light', which led to the first Radiophysics Publication including my name as an author, a letter to the journal Nature, with authors Wild, Roberts and Murray, dated December 14, 1953, and entitled Radio Evidence of the Ejection of Very Fast Particles from the Sun . . .

Paul had me examine questions such as whether particles of near-relativistic speeds would be able travel out through the corona, or whether they would be stopped by collisions with the ionized gas. We also considered how the particles might be accelerated, finding a nuclear explosion in the lower corona unlikely, and vaguely suggesting some Type of electromagnetic acceleration, with the Type III's being caused by ejected particles, and the Type II by a following shock wave. Some years were to pass before directional measurements with the Dapto interferometer provided direct proof that Type III disturbances travel at these enormous speeds.

Those observations were made just after I left the solar group in 1958: the results were sent to me to report at the Paris Symposium on Radio Astronomy. Later again, when spacecraft began operating in the sun-earth environment, electrons streaming from the sun at near-relativistic speeds were encountered shortly after the occurrence of Type III bursts. And as I write this in February 2000, more than 45 years after that Dapto paper, I hear warnings on the radio of possible damage to spacecraft as ton-weight clouds of charged particles have been detected being ejected from the sun at speeds of one third of the speed of light.

In the years around solar minimum sunspots do appear occasionally, so a small telescope equipped with a dark filter was used to make a daily check, and when spots were seen Jack Joisce would set the Dapto equipment recording. But for much of the time around sunspot minimum Paul Wild used the Dapto equipment for another project, studying the scintillation, i.e. the twinkling, of the radio source Cygnus A. In the next chapter I talk about this scintillation project, and about two other projects in which I was involved in the solar minimum years. Here I'll complete the story of my association with the solar studies at Dapto . . .

Scintillations:

In the years around sunspot-minimum Paul Wild used the Dapto sweep-frequency equipment to study scintillations, i.e. the minute-to-minute variations in the strength of the signals received from some of the 'discrete radio sources' . . . Present-day radio astronomers are not greatly interested in the ionosphere, but for the radio astronomers of that era, who worked at metre wavelengths and often had a background in ionospheric studies, it seemed natural to use this opportunity to learn about the ionosphere...The main purpose of the project was to use the Dapto equipment to study the spectrum of the scintillations, the variation of the strength of the scintillations across the frequency band. For the first time the signal from a scintillating source was recorded essentially simultaneously across a wide range of frequencies, and that turned up some unexpected features. When the scintillations were strongest the film records showed black 'ridges' sloping right across the film. So the signal was strong across the whole range of frequencies from 40 to 70 Mhz. Paul Wild argued that such systematic behaviour implied that the non-uniformities of the ionosphere causing the scintillations must be orderly structures, not irregularities. The current theory attributed the scintillations to completely irregular, 'random', structures in the ionosphere, and assumed that the signal received at any one point on the ground consisted of waves that had been deviated by numerous irregularities. Such a theory could not explain these broad-band systematic patterns in the dynamic spectra.

Wild argued that the radiation producing each strong 'ridge' must come predominantly via a single non-uniformity which 'focussed' like an imperfect lens. In fact he proposed that the inhomogeneities were density-waves travelling through the ionosphere, and that each wave-trough acted as imperfect, one-dimensional, lens. (In an ionized gas troughs, rather than peaks, cause focussing, because, unlike glass, the refractive index of an ionized gas is less than 1.) To prove his point he made calculations of the pattern of intensity expected below a wave-pattern of ionization. Of course there were no desktop computers in those days. The values of the Fresnel integral required for these calculations were read from a large Cornu spiral which Paul drew on a piece of cardboard. Jack Joisce spent many days reading values off the spiral. The calculations were very successful, and they reproduced many of the details that were found in the observed spectra. ...

I explained in the last chapter that two of the Cygnus scintillation aerials were used to form an interferometer which was later used to measure the movement of Type III radio sources across the face of the sun. At the time of the scintillation project this interferometer was operating in a rudimentary way and the interferometer records provided confirmation of some of the ideas sketched above. The fringe-pattern from the interferometer showed that as one of the strong ridges drifted past the waves arrived first from one side, then from straight ahead, then from the other side, just as would be expected for waves focussed by a lens. Unfortunately a more detailed analysis of the interferometer patterns never came to pass. A publication with Wild and Roberts as authors, and meant as Paper I, gave a description of the scintillation observations, some examples of dynamic spectra, and some discussion of the implications. I was to produce Paper II, reporting and discussing the interferometer results, and presenting Paul's theoretical calculations. Other matters intervened and this second paper was never completed. As a result neither Paul's calculations of the focussing by a density wave, nor the interferometer results, were ever published. Perhaps this has contributed to the fact that what I believe to be important conclusions from these observations never seem to have been accepted by some of the other workers in this field.