

JCU ePrints

This file is part of the following reference:

Stewart, Ronald Thomas (2009) *The contribution of the CSIRO Division of Radiophysics Penrith and Dapto Field Stations to international radio astronomy*. PhD thesis, James Cook University.

Access to this file is available from:

<http://eprints.jcu.edu.au/10660>



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

STATEMENT OF ACCESS

I, the undersigned, author of this work, understand that James Cook University will make this thesis available for use within the University Library and, via the Australian Digital Theses network, for use elsewhere.

I understand that, as an unpublished work, a thesis has significant protection under the Copyright Act and;

I do not wish to place any further restriction on access to this work.

Signature:

Date:

1/12/09

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

STATEMENT OF SOURCES

DECLARATION

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

Signature:

Date:

1/12/09

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

STATEMENT OF CONTRIBUTION BY OTHERS

DECLARATION

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.

Signature:

Date:

1/12/09

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

ELECTRONIC COPY

DECLARATION

I, the undersigned, the author of this work, declare that the electronic copy of this thesis provided to the James Cook University Library is an accurate copy of the print thesis submitted, within the limits of the technology available.

Signature:

Date:

1/12/09

ACKNOWLEDGEMENTS

I wish to acknowledge the considerable assistance and encouragement given to me by my thesis supervisors Professor Wayne Orchiston and Professor Bruce Slee, who suggested that I undertake this thesis at this stage of my life. I must say that I was pleasantly surprised to make the mental journey back some 40 years in time and to relive some of the excitement of discovery and research. I now have a better understanding of what my colleagues achieved as I was rather myopic regarding research being done by others at that time.

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.

Also, I am grateful for the opportunity to speak with John Murray and Jim Roberts who gave me invaluable insights into the early days at the Penrith and Dapto Field Stations and for the assistance of Christine Van der Leeuw at the ATNF library who helped me find obscure references.

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

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

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.

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

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 Alfvén 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 proposed 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.

TABLE OF CONTENTS

| | page |
|--|-------------|
| 1. INTRODUCTION..... | 20 |
| 1.1 Thesis Topic..... | 20 |
| 1.2 Explanation of Terms..... | 20 |
| 1.3 Methodology | 26 |
| 1.4 Justification of Chosen Topic | 27 |
| 1.5 Penrith and Dapto Team Members | 30 |
| 1.6 Outline of Thesis..... | 36 |
| 1.7 Publications arising from The Thesis | 38 |
| | |
| 2. INSTRUMENTAL DEVELOPMENTS 1947-1963 | 39 |
| 2.1 Planning the World's first Radiospectrograph 1945-48 | 39 |
| 2.2 The Penrith Radiospectrograph 1949 | 46 |
| 2.3 First Spectral Classification of Solar Bursts | 54 |
| 2.4 The Dapto Radiospectrograph 1952..... | 57 |
| 2.5 Radio Scintillations Studies of Cygnus A | 66 |
| 2.6 Polarization Studies of Solar Bursts | 70 |
| 2.7 The Dapto Swept-frequency Interferometer | 73 |
| 2.8 Extensions to the Dapto Radiospectrograph 1958-1963 | 85 |
| 2.9 Acknowledgements by above Authors | 94 |
| 2.10 Closure of the Dapto Field Station in 1964 | 95 |
| | |
| 3. RADIOSPECTROGRAPH RESULTS 1949- 1966 | 96 |
| 3.1 Analysis of 'Outbursts' Recorded by the Penrith Radiospectrograph 1950 | 97 |
| 3.2 Analysis of 'Isolated' Bursts 1950 | 101 |
| 3.3 Analysis of 'Enhanced Radiation' 1950 | 106 |
| 3.4 Summary of Observations and Analysis of Penrith Data | 110 |
| 3.5 Analysis of Fundamental and Second Harmonic Type II and Type III Bursts 1954 | 110 |
| 3.6 Interpretation of Harmonic Structure 1954 | 116 |
| 3.7 Evidence for the Ejection of Very Fast Particles and Shock Waves from the Sun 1955 | 121 |
| 3.8 Radio Scintillations Studies at Dapto During 1952-54 | 123 |
| 3.9 Review Paper on the Association of Radio 'Outbursts' with Solar Flares 1955 | 132 |
| 3.10 Proposed Future Research Activities | 136 |
| 3.11 Review Paper on Spectrograph Results 1957 | 136 |
| 3.12 Swept-frequency Polarization Studies of Solar Bursts 1958 | 139 |
| 3.13 Correlation of Type III bursts with Solar Flares 1957 | 145 |
| 3.14 Discovery of Reverse Drift Pairs 1958 | 149 |
| 3.15 Association of Type II Bursts with Solar Flares 1958 | 154 |
| 3.16 Statistical Study of the Properties of Type II Bursts 1959 | 156 |
| 3.17 A Proposed Model for the Origin of Type IV bursts 1959 | 166 |

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

| | | |
|----------|---|------------|
| 3.18 | Association between Type III-V bursts and Centimetre Bursts 1959 | 174 |
| 3.19 | Type I Solar Radio Noise Storms and the Coronal Magnetic Field 1964 | 178 |
| 3.20 | The Speed and Acceleration of Type III and V Sources over Large Distances in the Corona 1964 | 181 |
| 3.21 | Conclusion to Chapter 3 | 190 |
| 4 | INTERPRETATION OF INTERFEROMETER OBSERVATIONS 1957-64 | 191 |
| 4.1 | Preliminary Results 1957 | 191 |
| 4.2 | The Transverse Motions of the Sources of Type II, III and IV Solar Bursts 1958 | 193 |
| 4.3 | Investigation of the Speed of the Disturbances responsible for Type III Radio Bursts 1958 | 199 |
| 4.4 | Relative Positions of Fundamental and Second Harmonic Type II and III Bursts 1961 | 208 |
| 4.5 | The Positions and Movements of Sources of Type II Bursts 1963 | 213 |
| 4.6 | Statistical Study of Type IV Bursts 1963 | 224 |
| 4.7 | Statistical Study of the Properties of Type V Bursts 1965 | 235 |
| 4.8 | A Proposed Model for the Type V Burst 1965 | 245 |
| 4.9 | Polarization of 'herring-bone' Type II Bursts 1966 | 250 |
| 4.10 | The Nature and Velocity of the Sources of Type II Bursts 1965 | 254 |
| 4.11 | Unpublished Study of Type I Bursts | 260 |
| 4.12 | Conclusion to Chapter 4 | 260 |
| 5 | SIGNIFICANT CONTRIBUTIONS TO METRE WAVELENGTH SOLAR ASTRONOMY 1942 – 63 | 261 |
| 5.1 | Introduction | 261 |
| 5.2 | Importance of Spectral Records | 261 |
| 5.3 | Importance of Interferometer Observations | 265 |
| 5.4 | A Model of the Complete Flare Event | 267 |
| 5.5 | Theoretical Contributions | 269 |
| 5.6 | Concluding Remarks | 272 |
| 6 | CONCLUSION | 274 |
| 7 | BIBLIOGRAPHY | 278 |
| 8 | APPENDICES | 291 |
| 8.1 | Archival Letters regarding Radiospectrograph Development | 291 |
| 8.2 | Reminiscences of Jim Roberts | 296 |

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

LIST OF TABLES

page

| | | |
|---------|---|------|
| Table 1 | List of locations for each spectral type and instrumental development | 36 |
| Table 2 | Comparison of early spectral and single frequency records | 53 |
| Table 3 | Sense of rotation of polarization ellipse | 139 |
| Table 4 | Summary of activity of 9 June, 1955 | 143 |
| Table 5 | Observed and derived characteristics of chains of Type I bursts | 180 |
| Table 6 | Constants used in the derivation of radial velocity | 184 |
| Table 7 | Degree and phase of polarization of 20 Type II bursts | 252 |
| Table 8 | Significant contributions to metre wavelength solar radio astronomy during 1942-64 | 262. |

LIST OF FIGURES

page

| | | |
|----|---|----|
| 1 | A typical interferometer pattern where “d” is the spacing between the two aerials | 22 |
| 2 | Illustration of (a) linearly polarized (b) circularly polarized (c) elliptically polarized wave | 24 |
| 3 | The Radiophysics cricket team in the late 1950s | 33 |
| 4 | Photograph of members of the solar group circa 1965 | 35 |
| 5 | An outburst recorded simultaneously at three frequencies | 40 |
| 6 | Most likely site of the Penrith radiospectrograph | 46 |
| 7 | Aerial photograph of the Penrith site taken in 2006 | 47 |
| 8 | Penrith rhombic aerial design | 48 |
| 9 | Polar mount and declination axis for the Penrith rhombic aerial | 48 |
| 10 | Raising the Penrith rhombic aerial | 49 |
| 11 | Photograph of the aerial and pulley system | 50 |
| 12 | Examples of the display A scans | 52 |
| 13 | Time-frequency diagrams or ‘dynamic spectra’ of spectral Type I, II and III bursts | 55 |
| 14 | Colour photograph of the site of the Dapto spectrograph | 59 |
| 15 | Block diagram of the Dapto radiospectrograph | 60 |
| 16 | Colour photograph of the three crossed rhombic aerials at Dapto | 61 |
| 17 | Photograph showing one set of the three tuning condensers | 62 |
| 18 | Photograph of Paul Wild and John Murray at the display | 63 |
| 19 | Spectral record of the fundamental and second harmonic (a) Type II and (b) Type III bursts | 65 |
| 20 | Principles of the three instruments used for observing radio-star scintillations | 68 |
| 21 | Complete record of ridge-type scintillations | 69 |
| 22 | Block diagram of the Dapto swept-frequency polarimeter | 72 |
| 23 | Schematic representation of a record of polarized radiation | 72 |
| 24 | Block diagram of the Dapto swept-frequency interferometer | 73 |
| 25 | Characteristic patterns of an adding and a multiplying interferometer | 75 |
| 26 | Block diagram of the adding interferometer | 76 |
| 27 | Block diagram of the multiplying interferometer | 78 |
| 28 | Patterns obtained with multiplying interferometer | 79 |
| 29 | Paul Wild standing next to one of the interferometer antennas | 80 |
| 30 | Simplified block diagram of the swept-frequency interferometer | 81 |
| 31 | Kevin Sheridan sitting in front of the facsimile recorder | 81 |
| 32 | Idealized record obtained with the swept-frequency interferometer | 82 |
| 33 | Principle of the phase-swept interferometer | 84 |
| 34 | Examples of dynamic spectra recorded in the 25-210 MHz range | 87 |
| 35 | A major outburst recorded over the 15-210 MHz range | 88 |

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

| | | |
|----|--|-----|
| 36 | Dynamic spectra of solar bursts recorded in the frequency range 10-210 MHz | 90 |
| 37 | Groups of Type III bursts recorded in the range 5-210 MHz | 90 |
| 38 | Comparison of lowest observed frequencies with predicted critical frequencies | 91 |
| 39 | Comparison of lowest observed and measured critical frequencies | 91 |
| 40 | Simplified bloc diagram of the 200-2000 MHz receiver..... | 92 |
| 41 | Dapto 200-2000 MHz reflector and broad-band feed | 93 |
| 42 | A major outburst recorded over the entire 5-2000 MHz range | 94 |
| 43 | Dynamic spectrum of (a) Type II burst of 8 June 8 1949 and (b) 14 February 1949..... | 97 |
| 44 | The variation with frequency of the low frequency cut-off of the four Type II bursts | 99 |
| 45 | The motion of a Type II disturbance moving outwards through the solar corona | 100 |
| 46 | Examples of the dynamic spectrum of isolated bursts | 102 |
| 47 | Examples of Type III bursts | 103 |
| 48 | Plot of the average normalized decay constant versus frequency for 12 Type III bursts..... | 104 |
| 49 | Diagram for studying the frequency drift of Type III bursts | 105 |
| 50 | A-scans of three noise storm bursts - each section of 3 seconds duration | 106 |
| 51 | Histograms showing the distribution of recorded storm bursts with bandwidth | 107 |
| 52 | Histograms showing the distribution of recorded storm bursts with lifetime | 108 |
| 53 | LH plot shows the distribution of Type I storm bursts and the RH plot shows the continuum spectrum and the 'burst index' | 109 |
| 54 | Outburst of 21 November 1952 (a) The dynamic spectrum (b) Profiles at 1-min intervals | 112 |
| 55 | Outburst of 5 May 1953 (a) The dynamic spectrum, (b) profiles at 15-sec intervals | 113 |
| 56 | Dynamic spectra of harmonic Type III bursts extended to greater heights by using half the frequency of the second harmonic | 114 |
| 57 | Comparison of the fundamental and second harmonic bands of Type III bursts | 115 |
| 58 | (a) Assumed natural spectrum for a point source at the 50 MHz plasma level in a Baumbach-Allen corona, (b) propagation characteristic for various angles to the radial and (c) the received spectrum | 117 |
| 59 | The limiting rays of outward emission at various frequencies from a point source at the 50 MHz plasma level in a Baumbach-Allen | 118 |
| 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 | 119 |
| 61 | Derived height-time plot for the Type II burst of Figure 54 | 120 |
| 62 | Derived height-time plots for harmonic Type III bursts assuming a Baumbach-Allen corona | 121 |
| 63 | Plot of the derived motions in the solar atmosphere for a compound burst of 1 September 1952 | 122 |
| 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 | 125 |
| 65 | Dynamic spectra of ridge-type scintillations (a) and (b) many of the ridges are seen | |

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

| | | |
|----|---|-----|
| | to show an internal fine structure | 126 |
| 66 | Idealized sketches of dynamic spectra | 127 |
| 67 | Ellipses showing the size and shape of the pattern on the ground for ridge-type scintillations | 129 |
| 68 | The annual variation of the velocity of ridge-type patterns across the ground | 129 |
| 69 | Solar time variation of the fluctuation index | 130 |
| 70 | Two large outbursts recorded at 7 frequencies on 17 and 21-22 February 1950 | 133 |
| 71 | Observations of source position, polarization and intensity during the outburst of 17 February 1950 | 135 |
| 72 | Histograms of velocities of solar corpuscular particles ejected from solar flares | 137 |
| 73 | Spot groups arranged in order of increasing intensity, shaded according to limb characteristics | 138 |
| 74 | Single records of strongly polarized Type I radiation | 140 |
| 75 | (a) Record of an unpolarized Type III burst (b) Polarized Type III bursts (c) Cluster of polarized Type III bursts | 141 |
| 76 | Frequency distributions of phase angles of 40 Type III bursts | 142 |
| 77 | Heights of the levels of zero refractive index in the corona above an extremely large unipolar sunspot group | 144 |
| 78 | (a) Spectral record and (b) interferometer record of Type III bursts Interference fringes are evident in (b)..... | 146 |
| 79 | Comparison of positions on the solar disk of Type III bursts and chromospheric flares | 147 |
| 80 | Histogram showing the dependence of association on apparent flare area | 147 |
| 81 | Dependence of disk longitude on the association of Type III bursts and solar flares | 148 |
| 82 | Examples of reverse drift pairs (a) showing sudden changes in the rates of frequency drift; (b) occurring within bursts of spectral Type III | 149 |
| 83 | (a) Each reverse drift 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 | 150 |
| 84 | (a) The 'frequency-separation model'. (b) The 'time-delay model' of reverse drift pairs | 151 |
| 85 | Histograms showing the differences in (a) the starting frequency, and (b) the finishing frequency of the two elements of the observed reverse drift pairs | 151 |
| 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 | 153 |
| 87 | Centre to limb variation for a source at the 30 MHz plasma level radiating at a frequency of 60 MHz (a) time delay of the reflected ray after the direct ray (b) Integrated absorption in the direct (curve I) and reflected (curve II) ray | 153 |
| 88 | Distribution of Type II bursts with radial distance determined from the flare position | 155 |
| 89 | Histogram showing the frequency of occurrence of Type II bursts | 157 |
| 90 | Frequency dependence of the drift rate in the fundamental of 24 harmonic Type II bursts | 158 |
| 91 | Histogram of the mean radial speeds of 24 Type II bursts | 158 |
| 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 | |

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

| | | |
|-----|--|-----|
| | 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) | 159 |
| 93 | Examples of Type II bursts showing split-band structure | 160 |
| 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 | 161 |
| 95 | Examples of herringbone structure in Type II bursts | 162 |
| 96 | Derived height time plots for five harmonic Type II bursts | 163 |
| 97 | Temporal relationships between flares and Type II bursts | 164 |
| 98 | (a) Superposed epoch diagram showing the mean value of the geomagnetic index A_p on days before and after 60 Type II bursts .(b) The predicted time delays inferred from the frequency drift of 24 of the Type II bursts | 165 |
| 99 | Idealized sketch of spectral record showing the metre wavelength components of a complete major radio event | 167 |
| 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 | 167 |
| 101 | (a) Schematic diagram showing durations of eleven of the twelve Type IV storms and their relations in time to the Type II and big flare event (b) Similar to Fig. 100 (a) but showing all the Type I storms observed | 168 |
| 102 | Mean K_p index for each 3-hourly period before and after (a) 10 Type IV storms (b) 10 Type I storms and (c) 10 importance '3' flares (d) 36 Type II bursts | 170 |
| 103 | Proposed model of a Type IV storm; see text for details | 173 |
| 104 | Three examples of Type III bursts followed by broadband Type V bursts | 175 |
| 105 | Examples of groups of sharply defined Type III bursts not accompanied by Type V bursts | 176 |
| 106 | Data showing the association of Type V bursts, centimetre bursts and flare puffs | 177 |
| 107 | Tracings of dynamic spectra (a) an individual burst chain (b) several chains occurring in succession | 179 |
| 108 | Dynamic spectra of Type I chains recorded on 12 August 1957 showing examples of a single and a double chain | 179 |
| 109 | Plots showing the statistical behaviour of radial velocity with height | 185 |
| 110 | Plots of radial velocity for 30 individual Type III bursts. Cross hatching refers to bursts followed by Type V continuum | 188 |
| 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 | 189 |
| 112 | (a) 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 | 192 |
| 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)..... | 193 |

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

| | | |
|-----|--|-----|
| 114 | Showing centroids of the sources of two groups of Type III bursts were located at different frequencies by the swept-frequency interferometer on 5 June 1958 | 194 |
| 115 | The variation with frequency of the positions of sources of Type III bursts or groups recorded on different days between 4 June and 7 July 1958 | 194 |
| 116 | The polarization, spectrum and position data recorded during an outburst at the time of a solar flare of importance 2 | 197 |
| 117 | Polarization, spectrum and position data recorded during an outburst. The earlier section of the outburst is a Type II burst, the later a Type IV | 197 |
| 118 | Observations of source position, polarization and intensity during the outburst of 17 February 1950 | 198 |
| 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 | 199 |
| 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) | 200 |
| 121 | Idealized diagram showing the radio emission from a radially ejected Type III disturbance | 201 |
| 122 | Distribution across the disk of the 60 MHz sources of Type III bursts | 202 |
| 123 | Variation with 60 MHz position of the transverse component of apparent outward velocity of Type III disturbances | 202 |
| 124 | Distribution with 60 MHz position on the disk of the percentage of Type III bursts which show recognizable harmonics | 204 |
| 125 | Electron densities in the corona as a function of radial distance | 205 |
| 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 | 205 |
| 127 | Time delay of radio signals near the plasma level | 206 |
| 128 | Distribution of radial velocities of Type III bursts | 206 |
| 129 | Dynamic spectrum and East-West positions of the 28 April 1960 Type II burst | 208 |
| 130 | Mean positions of the fundamental and harmonic bands of the four Type II bursts | 209 |
| 131 | Plot showing the relative displacements between fundamental and harmonic Type II and Type III bursts | 210 |
| 132 | Showing direct and reflected rays escaping from above the plasma level | 211 |
| 133 | Dispersion relation for longitudinal plasma waves and electrodynamic waves in a thermal plasma in the absence of a magnetic field | 212 |
| 134 | (a) Calculated angular power spectrum for radiation at the second harmonic of the plasma frequency (b) The backward/forward ratio of intensities | 213 |
| 135 | Event of 14 July 1959 showing positions of two widely separated Type II sources | 215 |
| 136 | (a) Multiple Type II event of 15 June 1960 showing two sources in different positions and with different drift rates | 216 |
| 137 | Multiple Type II event of 28 April 1960 showing three separated sources associated with different spectral features in the Type II burst | 217 |
| 138 | Disk distribution of (a) associated flares and (b) Type II bursts | 217 |

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

| | | |
|--------|---|-----|
| 139(a) | Observed 50 MHz position coordinates of the Type II bursts plotted against flare position..... | 218 |
| 139(b) | Observed position coordinates of the sources of Type III bursts at 50 MHz plotted against the position of the associated solar flares | 219 |
| 140 | Diagrams showing the dependence of variation of position with frequency for (a) Type II bursts and (b) Type III bursts | 220 |
| 141 | Model adopted in treating non-radial motion of the exciting disturbances of Type II bursts..... | 221 |
| 142 | $ P_{45} - P_f $ for non-central Type II bursts with $ P_{45} > 15$ min. of arc | 223 |
| 143 | Average electron densities in the corona as a function of height. Squares refer to Type II bursts and circles to Type III bursts | 224 |
| 144 | Temporal relations between the start and time of maximum intensity of Type IV bursts and the start of the associated Type II burst | 226 |
| 145 | Position data showing movements and stable positions of Type IV sources | 227 |
| 146 | Variation of position as a function of stable position for Type IV bursts | 228 |
| 147 | Type IV bursts which show initial rapid movement | 229 |
| 148 | Examples of stationary Type IV bursts | 230 |
| 149 | Relative positions of Type IV and Type II bursts | 231 |
| 150 | Sense of circular polarization of Type IV bursts plotted against disk coordinates of flare | 231 |
| 151 | Properties of the sources of Type IV emission of 15 November 1960 | 233 |
| 152 | Examples of Type V bursts | 236 |
| 153 | Observed initial bandwidths of 59 Type V bursts | 237 |
| 154 | The average durations of 59 Type V bursts recorded at Dapto (+) compared with Thompson and Maxwell's (1962) results (o)..... | 238 |
| 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 the associated Type III positions | 239 |
| 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 | 240 |
| 157 | (a) Model to interpret the displacements between Type III and Type V sources (b) Histogram of the possible radial displacements and (c) Histogram of possible horizontal displacements | 241 |
| 158 | Plot of the 50 MHz position coordinates of 10 Type V bursts against the flare position | 242 |
| 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 | 243 |
| 160 | Observed disk distribution for (a) Type V bursts and (b) Type III bursts | 244 |
| 161 | Comparison of the long (LB) and short baseline (SB) visibilities of Type V and associated Type III bursts | 245 |
| 162 | Proposed model for the physical state of the corona at the time of a Type V burst | 248 |
| 163 | An example of the spectrum and degree of polarization at 40 and 60 MHz of a Type II | |

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

| | | |
|-----|--|-----|
| | burst containing herring-bone structure | 253 |
| 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 | 255 |
| 165 | Averaged derived velocities for Type II bursts derived from 2 x Newkirk and 10 x Baumbach-Allen density models | 256 |
| 166 | Source velocities predicted from the shock energy equations on the assumption that the energy and shock strength remain constant as the shock spreads spherically | 257 |
| 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 | 258 |
| 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 | 259 |
| 169 | The main components of a solar outburst | 266 |
| 170 | Diagram showing the origin of radio emission, x rays and corpuscular effects of solar flares | 269 |
| 171 | Conditions required for incoherent and coherent emission | 272 |