From Jets to GEMSS:*
Pan-Spectral Detection, Observation & Characterization of the M-Dwarf Exoplanet System Gliese 876 -- and Beyond

Transit Photometry, Radial Velocity, and Millimeter Interferometry to Constrain and Characterize the Nearest Multiple Planet System

By

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for the degree of
Doctor of Philosophy
In the School of Maths, Physics and IT
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**in title: Global Exoplanet M-dwarf Search-Survey*

‘Twixt titian glow, we chase the whirring planets - go

To eta-Earth... from 'scope to teeming sky,

And clear that dirth of knowledge borne

Of dim dwarfs shorn with spectral light,

From terra-low to stratos-high!

An' 'ere now tap the shimm'ring light

Of ruddy wand'rers hove near…

Which begs to know that occulted place?

Both dim and cynosure in space -

Where man will find what counts most dear:

A Kuiper-fathered globe sweeps near!

We surf the water-stars to find

The twirl of two-plus-one aligned

In confluenc’d dance --

‘Ere grip expanse of soul and mind,

And with Magellan, dine

'Pun -- serendipity!

-PDS

Image credit: NASA (May 2005)

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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 Information derived from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

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vi. Contribution of Others Including Financial & Editorial Help

This statement outlines the contributions of others to the intellectual, physical, and written work set here for this thesis. This thesis also contains work that is also part of jointly published papers; the contribution by me and of others is clearly stated at the beginning of each relevant chapter and the publication details clearly cited. Otherwise, the contribution of others is:

• Fees: All fees, web costs, books, referencing, professional memberships, academic and publishing materials, instrumentation (except as noted), journal subscriptions, and are or will be borne by the author, directly, or through The Education Resources Institute (TERI) / International Educational Finance Corporation (IEFC) commercial student loan (though Wachovia Bank). Though qualified for U.S. Dept. of Education Financial Aid as identified by the "Free Application for Federal Student Aid" (http://www.fafsa.ed.gov/) administrators, the James Cook University (JCU) and Australian at-large interpretation on the Bush 2006 Education Reform Act disallowed my use of government financial aid. Except as noted throughout, the author purchased materials, designed, developed and operated various telescopes (including optics), charge-coupled device (CCD) photometric cameras, cooling and drive systems, electronic interfaces, and data collection. Where noted herein, commercial software was used, and some programming was done; these also will be identified.

The costs for publishing Chapter 6 in the *Astrophysical Journal* (ApJ) in December 2006 were borne by the University of California (UC) and Lick Observatory. The Lick Observatory-related research was funded through by a NASA grant for the relevant work.

The costs for publishing Chapter 8 in the *Astronomical Journal* (AJ) paper submitted December 2007, was shared between the National Radio Astronomy Observatory (NRAO) (three fifths) and the U.S. Naval Observatory (USNO) (two fifths).

USNO also provided ongoing non-fiscal support in terms of extensive and dedicated telescope time, some instrumentation fabrication, cryogenic support, extensive library use, some computer hardware and LAN time, and flexibility with my employment.

The U.S. Naval Academy (USNA) provided some instrument support (Santa Barbara Instruments CCD camera of $6695 USD value for 5 months, then the indefinite loan of a Princeton Instruments Versarray cryogenic ccd camera of $138,500 USD value) .

• Stipend support: Stipend support was not paid to the author per se; however, the tuition - and costs the author bore above - were met through employment as a U.S. Navy commander assigned as the Director of Plans, Programs & Requirements at the USNO, Washington, D.C.; before that as commanding officer of Strike Training Squadron Nine, where Navy pay was earned. Further incidental support included approval to do airborne-stratospheric CCD imagery during other missions, from the tactical jets assigned to the squadron.

Two week-long academic trips to UC Santa Cruz (UCSC)/ Lick Observatory in 2005 and pending 2007 were paid for, one to the U.S. Navy through a gift to the Navy from the UCSC Department of Astronomy & Astrophysics / Lick Observatory, and the other as direct support.

• Supervision: My research supervisor at JCU was Dr. David Blank. My general supervisor was Dr. Graeme White. Some supervisory advice was obtained from Dr. Greg Laughlin at UCO/Lick, and from my boss, Dr. Ken Johnston, USNO Scientific Director.

• Other collaborations: Modern astrophysics has become an exercise in broad collaborations; consequently, the author participates extensively in such due to the nature of the project(s) supporting this thesis, and considers it the crucible for orchestrating powerful, distributed data flow and facilitating the collection of otherwise unattainable data. One of the key concepts for success in such a network is unwavering leadership. As principle investigator of teams of as large as 45 collaborators at once, protracted leadership was required as a principle part of this dissertation.

Details for other specific collaborations will be annotated fully within. Collaborators came from numerous institutions, including: JCU; USNO; UCSC/UCO/Lick; USNA; NASA Goddard Spaceflight Center (GSFC); San Francisco State University (SFSU); Perth Observatory; Yale University, University California Berkeley; Carnegie Institute Washington (CIW); Naval Research Laboratory (NRL); American Association of Variable Star Observers (AAVSO); CDS Strasbourg, France; California State University, Fresno (CSUF); Tennessee State University (TSU); University of Florida (UF); Georgia State University (GSU); University of Adelaide; University Southern Queensland; Anglo-Australian Observatory (AAO); Bronberg Observatory, Pretoria S. Africa; University New S. Wales (UNSW); National Radio Astronomical Observatory (NRAO; Socorro and Green Bank); Australia Telescope National Facility (ATNF; Narrabri); NASA/California Institute of Technology (Caltech) Jet Propulsion Laboratory (JPL); NASA Houston Johnson Spaceflight Center (JSC); NASA Ames Research Center; NASA Dryden Test Flight Center; and Southwest Research Institute (SWRI).

• Statistical support: Other than work review by advisors and collaborators, specific statistical support was not used from a statistics-specific facility. During photometric reduction and millimeter image synthesis, software with built-in statistical algorithms and statistical reducing websites were used. Software will be noted herein as appropriate. Primary software included Astronomical Image Processing for Windows (AIP4WIN), TheSky 6Pro, CCDSoft, Image Reduction and Analysis Facility (IRAF), Guide8, Astronomical Image Processing System (AIPS), Multichannel Image Reconstruction, Image Analysis and Display (MIRIAD), the Pennsylvania State University (PSU) Astrotatistics website[1] , the St. Johns University website[2], and Excel. Occasionally Georgia State University (GSU) *Hypermath* website[3] was used for reference, while the USNO web applications website was used to obtain some catalog data, ephemerides, and related statistical variances[4].

• <u>Editorial assistance</u>: Editing was performed by the author, overseen by JCU supervisors. In the case of the *ApJ*, *AJ* and other publications noted herein (noted at the

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[1] http://astrostatistics.psu.edu/statcodes/index.html
[2] http://www.physics.csbsju.edu/stats/Index.html
[3] http://hyperphysics.phy-astr.gsu.edu/hbase/math/statcon.html#c1
[4] http://aa.usno.navy.mil/data/

beginnings of relevant chapters), editorial review was performed by the collaborators, the USNO Editorial Review Board, peer-reviewers and journal editorial staffs. Dr. Jennifer Bartlett, a recent addition to the USNO staff, also generously read early drafts to provide some grammatical and typographical feedback.

This thesis was typeset in the USA using Word 2003, Rapid-Pi Equation Editor, Procite bibliographical software, Chikrii TeX2Word, Photo Editor, and Adobe Acrobat Pro -- on Windows XP, Vista Business and Apple OS/X; peer-reviewed papers which comprise Chapters 6 and 8 were processed with LaTeX/AASTeX, BibTeX, MiKTeX, DVIView, FITSView, Ghostscript/Ghostview, Adobe Acrobat Pro, and WinEdt -- on Windows XP, Vista Business, Linux Fedora Core 4, and Apple OS/X. Printing was done separately at JCU in Townsville.

• Research assistance: Collaborations and assistance will be indentified in the course of the text. Two undergraduate Naval Academy scholars were mentored by the author as interns mid-2005 and 2006 --John Pepin and Jeffry Jacglowicz. These students were most used to hone teaching skills, operate instruments under some direction, and shared observing responsibilities when two or more observers were used. Undergraduate Zachary Dugan of Yale University was also employed by USNO as an intern much of 2006, who operated the author's instrumentation in support of the GEMSS program, developed GEMSS target strategies, and troubleshot hardware failures at the telescope under the author's tutelage and then often solo, reporting observations and supporting the overall research with zeal. In each case, the author trained the undergraduates in general astronomy, photometry, observing, and exoplanet astrophysics; and, in turn, these students performed a number of the visual observations at the USNO 0.6-meter telescope. In various cases, the research assistance was useful, but in others, it was more of an educational development for the student.

• Any other assistance: Other assistance is noted in the text where applicable.

• Project costs: Excluding any masters and doctoral tuition costs and costs-of-life, total cost of this project, begun in 2002, is approximately $86,800 USD to the author, $11,500 USD to UCO/Lick, $9800 USD to USNO, and $2500 USD to miscellaneous others. The total cost is $110,600 USD. The amount can be attributed in part to additional costs required to produce doctoral-level (and global-infrastructure-based) research while assigned to the USNO in the USA, while concurrently enrolled at JCU in Australia.

• Use of infrastructure external to JCU: As noted elsewhere, infrastructure outside of JCU includes at USNO, UCO/Lick, AAVSO, and all the collaborators' facilities noted above. Financial infrastructure included loan-related discourse with the U.S. Department of Education, TERI, and Wachovia Bank.

• Use of infrastructure external to organizational unit within JCU: Outside the JCU Centre for Astronomy, the International Student Centre was the next most frequent interface used. The author worked extensively with outstanding Finance Support Officer Nicole Stathooles on a number of very difficult fiscal issues regarding IEFC and TERI, and even more challenging issues regarding US Dept. of Education Stafford and Federal Family Education Loans -- and their [in]application at JCU in light of the U.S. 2006 Education Reform Law. The author is indebted to her protracted efforts to cauterize significant fiscal haemorrhaging.

________________________________	2008 May 10
Paul D. Shankland	Date

vii. Acknowledgements

As is always the case, no dissertation can be done without a large and varied support team, and perhaps most of all a supportive family. Such pivotal support is no more completely the case here. The path to this thesis was strewn with impediments (landmines), and there would not have been any chance for completion without this extensive, dynamic support.

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Most of all I thank my patient family -- Cathy, Nick, Rudger, Heather, Nicole, … I am grateful you allowed extended distractions, a laptop everywhere I went, lost family time, fiscal adjustments, and nodding kindly when listening to incomprehensible astronomical discourse. I am a very fortunate soul, and I dedicate this thesis to you.

viii. Abstract

The results of this thesis put constraints on the physical properties, and dynamics of the exoplanetary system around the 4.69 pc-distant M4 star, Gliese 876. M dwarfs are proving to be what the initial dynamical predictions here have suggested, that they could be statistically viable places to detect terrestrial planets in habitable zones. Gl 876 [5] itself harbors three exoplanets: two outer gas-giants with resonating orbits, and a recently discovered 'Super-Earth'. Differential transit photometry was conducted to put constraints on the inclination of the system, and radial velocity (RV) curves were constructed from high resolution spectroscopic data in order to discern any possible Rossiter-McLaughlin effect. Despite an initial 2003 detection of an optical flux dip, the comprehensive 2004 campaign and RV analyses produced no further transits to 3σ. Following these optical investigations, 3- and 7- mm radio-interferometric synthesis observations were performed using the Very Large Array (VLA) and Australia Telescope Compact Array (ATCA). The radio observations were optimized to detect and resolve any regenerative ~20K dust disk and further characterize its mass, inclination, resonances, and gaps. The ~400 AU primary beams afforded a sensitivity and aperture not found in previous Gl 876 studies.

The observations produced a null result, which put tighter constraints on any disk mass, which placed an upper limit of 0.0006 $M_{Earth} \pm 0.0001$. This lack of dust infers that Jovian planets orbiting in-close sweep dust clear, and infers a small population of dust-producing planetessimals in the system, which is also consistent with its [Fe/H] = -0.5 metallicity. The optical observations constrain the inclination of the Gl 876 system to ~50^o rather than its previously thought ~90^o inclination, and this result is consistent with the millimeter observations. The masses of planets "b", "c" and "d" are optically constrained to $2.5 \pm 0.M_{Jup}$, $0.8 \pm 0.01\ M_{Jup}$, and $7.5 \pm 0.7\ M_{Earth}$. It was further shown that novel network-distributed, targeted photometric detection schemes can produce rigorously scientific data, and further, that video-rate photometry from the stratosphere was viable.

[5] To maintain continuity with the author's published journal papers (chapters 6 and 8), the "Gl" shorthand was chosen for Gliese catalog shorthand throughout this thesis, vice GJ, for the later, Gliese-Jahreiss edition.

IX. CONTENTS

xii. List of Figures in Text

xiv. Prologue

Fig 1: Gl 876, taken by the author, 2005, using TIP-TOPhAT

Always a popular if not imaginative public topic, extrasolar planet research has more recently achieved solid scientific stature, owing to the clear rigor lent to detections beyond the Solar System. Truly, the study of exoplanets has become captivating to everyone. The implications of these discoveries resonate with the human imagination, and [re]kindle fires about the real possibilities that not-too-distant exo-worlds do exist, to which our species may someday even travel. More intriguing still, one may harbor life. This thesis, *From Jets to GEMSS*, describes one study to uncover first possible steps on a path to such discoveries.

Since the dawn of history, humankind has asked whether our habitat is unique, and more fundamentally, whether we are alone in the universe. Until recently, these questions were primarily philosophical, but discoveries in the past fifteen years have driven such questions to a strongly empirical bent. More recently, the door to that investigation has been widened further, with the possibility of locating terrestrial planets within a few parsecs of Earth. Improved capabilities and improved understanding have increased the momentum across the gamut of exoplanet astrophysics. With an aim to balance and characterize the exoplanet census, while improving the odds of earth-like detections, red dwarfs are an excellent choice to study. This thesis begins with stratospheric and terrestrial observations of the curious red dwarf, Gliese 876, and proceeds into the future by developing programs for the age-old question:

"Do there exist many worlds, or is there but a single world? This is one of the most noble and exalted questions in the study of Nature."

-Albertus Magnus 1193-1280