Radio Variability and Interstellar Scintillation of Blazars

Hayley Emma Bignall

Department of Physics and Mathematical Physics
University of Adelaide

A thesis submitted in fulfilment
of the requirements for the degree of
Doctor of Philosophy

February, 2003

♡♡♡♡♡♡

This thesis is dedicated to my mother, Kay Bignall, for always giving me love, support, encouragement, and the freedom to ask questions and to wonder at the Universe.

Abstract

This thesis presents several observational studies based on radio variability and interstellar scintillation of extragalactic flat-spectrum radio sources. Such sources are commonly called "blazars", a term used to describe the phenomenon observed when the jet of a radio-loud Active Galactic Nucleus (AGN) is directed towards the observer. These sources provide unique "laboratories" for studying the physics of relativistic jets.

Observations of selected samples of blazars, made with the Australia Telescope Compact Array (ATCA) and the Australia Telescope Long Baseline Array are presented here. Statistics for long-term (months–years) and short-term (intraday) variability in both total and linearly polarized flux density at several frequencies are presented. The sensitivity and flux density measurement accuracy of the ATCA make it particularly useful for observations of intraday variability (IDV). Resolving the question of what is the mechanism for radio IDV was of great importance at the time this thesis was being undertaken, since if intrinsic, IDV implies extremely high brightness temperatures, far in excess of the Inverse Compton limit for incoherent synchrotron radiation. Most source models are fundamentally based on the assumption that the radiation from radio to optical, and sometimes soft X-ray, energies is produced by the incoherent synchrotron mechanism, so any result which challenges this has serious implications.

There is now strong evidence that interstellar scintillation (ISS) is the principal cause of radio IDV, which substantially lowers the implied source brightness temperatures from those calculated assuming intrinsic variability. Some of the results presented in this thesis have made an important contribution to the "paradigm shift" from IDV to ISS, by showing unequivocally that the rapid IDV observed in PKS 1257−326 is a result of scintillation due to a nearby scattering "screen" in the ionised interstellar medium (ISM) of our Galaxy. This unusual source, serendipitously discovered during the course of my PhD, has also proved extremely valuable in showing that ISS can be used as a probe of microarcsecond-scale source structure and also of the local Galactic ISM. Such high angular resolution is not currently achievable even with space interferometer baselines.

Statement of Originality

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying.

_____

Hayley E. Bignall

Date:_____

Preface

As the observational data presented in this thesis were collected for large projects involving a number of people, it is appropriate to outline my contribution.

I was directly involved in all of the observations presented in this thesis from 1998 onwards. Dr Tasso Tzioumis was initially principal investigator on the southern blazar radio monitoring programs presented in Chapters 3 and 4, which commenced in 1997, before I became involved with the project in early 1998. From March 1998 onwards, I was present at either the ATCA or the Mopra telescope for nearly all ATCA and LBA observations, and thus gained a great deal of hands-on experience in observing and scheduling observations, and also in writing telescope proposals.

The LBA observing was supported by staff from ATNF, the University of Tasmania, and Hartebeesthoek Radio Astronomy Observatory in South Africa. Additional observing support was often provided by staff and students from the University of Adelaide. I was responsible for the correlation of most of the LBA data presented. Dr John Reynolds, Dr Tasso Tzioumis and Dr Warwick Wilson provided a great deal of assistance with setting up and correlating at the LBA correlator.

A number of the co-investigators on ATCA project C927, the intraday variable source monitoring program which commenced in early 2001, assisted with the observations: in particular, Dr Tasso Tzioumis, Dr Dave Jauncey, Dr Jim Lovell, Dr Lucyna Kedziora-Chudczer, Dr Dave Rayner and Dr Steven Tingay.

I was responsible for the reduction and subsequent analysis of all data from the ATCA and the LBA which is presented here. The software and techniques used for data reduction mainly involved the use of standard packages (e.g. MIRIAD, AIPS and Difmap). The IDL software package was used for much of the subsequent analysis and presentation of data; I wrote various procedures and functions in IDL to perform the required tasks, generally making use of already available routines from the IDL library. Dr Barney Rickett provided code used for calculating expected scintillation velocities (Chapter 6).

I was also responsible for processing of data from the VLBA (Chapter 3) and the VLA (Chapter 6), except for the initial fringe-fitting and *a priori* calibration of the VLBA data, which was performed by Steven Tingay, and the VLA images presented in Chapter 6, which were produced by Jim Lovell.

I was involved with the development of calibration procedures for LBA data, including bug-fixes in AIPS to allow amplitude calibration of data from the LBA correlator, and derivation of gain curves for the Hobart antenna, using data provided by Dr Marco

Costa. I also derived gain curves for the ATCA antennas for correction of the gain-elevation dependence in ATCA 3 cm data. Dave Rayner created a MIRIAD task to apply these corrections to ATCA data.

A large part of Chapter 6 formed a research paper written in collaboration with 8 co-authors, which is to be published in The Astrophysical Journal.

Acknowledgements

It is a pleasure to finally be able to thank all those people who have made this work possible, and those who have helped me along the way. After almost 5 years, and thanks to the transient nature of my lifestyle during this time, this seems to have become a very large number of people! To avoid adding many more pages to the thesis, I have tried to make these acknowledgments brief and general. Specific contributions of others to the work presented in this thesis are acknowledged in the text; also see the earlier preface.

Firstly, I thank my supervisors, Dr David Jauncey and Dr Tasso Tzioumis from ATNF, and Dr Roger Clay from the University of Adelaide. Although Dave was not "officially" my supervisor, he enthusiastically became involved, and steered the project in new and exciting directions. I am deeply grateful for his invaluable input of many ideas and much inspiration. I also thank Dave for his careful reading of text and many suggestions for this thesis. To Tasso, from whom I have learned a great deal about life, the Universe and interferometry: my warmest thanks for providing tremendous support over the last five years, for not giving up even when it looked doubtful that I'd ever finish, and for a final careful reading of the thesis. I extend many thanks to Roger for his encouragement, and for uncomplainingly tolerating my "remote"ness from the group at Adelaide.

A number of other people have also provided assistance and advice over the course of this work. In particular I thank Drs Lucyna Kedziora-Chudczer, David Rayner, Bob Sault, Neil Killeen, Jim Lovell and Helen Johnston for advice and assistance with calibration and analysis of ATCA data. I must also thank Jim for various nifty computer-related tips & tricks, and for showing me around Socorro! For help on the VLBI side of things, I am grateful to Drs John Reynolds, Steven Tingay, Warwick Wilson, Richard Dodson and Roopesh Ojha. And for many illuminating discussions on the interpretation of scintillation data, I thank Drs Jean-Pierre Macquart, Barney Rickett and Mark Walker. I also thank Prof Ron Ekers, and Drs Stefan Wagner, Ray Protheroe, Tiziana Venturi, Travis Rector and Paolo Padovani for useful discussions. I am very grateful to Dr Shaun Amy for providing the LaTeX 2ε template for this thesis, and for other computer-related help at various times. Although no optical data are presented in this thesis, during my PhD I was priveleged to be introduced to optical observing and photometry by Dr Charlene Heisler, who was always inspiring to work with.

All of the ATCA staff, and especially Drs Robin Wark, David McConnell, Ravi

Subrahmanyan and Mark Wieringa, deserve a special mention for being always willing to answer questions and just generally making the observatory a pleasant place to be. I also thank John Giovannis for computer support, and more importantly, for organising pub nights in Narrabri! At the ATNF headquarters in Marsfield, I have always found a positive working environment and friendly atmosphere. I am extremely grateful for the support provided by ATNF, including especially the accommodation at ATNF lodges during my many long "visits"! Extra thanks go to Vicki Drazenovic for the initial binding of the thesis for submission.

I acknowledge the financial support of a Faculty of Science Scholarship from the University of Adelaide, and various travel funding over the course of my PhD, including an ANSTO grant, a Research Abroad Scholarship from the University of Adelaide, contributions from the Physics Department, a travel scholarship from the Australian Institute of Physics, and funding from ATNF to visit Socorro in May 2002. Tasso is deserving of extra thanks for funding many of my travel costs out of his own research budget.

I must also add thanks to Dr Huib Jan van Langevelde and JIVE for allowing me the time and resources to complete my thesis in my first couple of weeks here at JIVE — it's a great relief to have finished at last.

On the Sydney side of my life, in addition to the people already mentioned above, there is a great bunch of Bolton fellows, other ATNF staff & students who I would like to thank for their company and friendship during my time at ATNF, in particular Naomi McClure-Griffiths, Aaron Chippendale, Vince McIntyre, Tony Wong, D.J. Pisano, George "Nyima" Warr, Jürgen Ott, Tracy Getts, Malte Marquarding, Bärbel Koribalski, Erwin de Blok, George Hobbs, Jess O'Brien, Daniel Mitchell and Andrew Wright, and Stephen Giugni from CTIP. The AAO "Friday night club" was also responsible for some fun social activities, thanks especially to Liz Corbett, Anna Moore, Sonia Cianci, and Roger Haynes. Thanks also to Ivan Baldry especially for the indoor rock climbing, and Matt Howlett for the fantastic walk in Tasmania. I'm sure I've left some names off the lists that should be there - but thanks everyone! I also thank the Tzioumis family for welcoming me into their lives for a couple of stints; I enjoyed the responsibilities of being a "temporary guardian" (strong emphasis on "temporary") while Tasso & Leonie were overseas.

And back in good old Adelaide, I am grateful to many members and former members of the High Energy Astrophysics group for their support and friendship, in particular Ken Simpson, Bruce Dawson, Greg Thornton, Paddy McGee, Phil Edwards, Gavin Rowell, Steven Dazeley, Rishi Meyhandan, Troy Porter, Martin Debes, Jose Bellido, Gail Higginbottom, Anita Mücke, Alina Donea, Russell Pace, and Chris Wilkinson. Melanie Johnston-Hollitt, being a joint-supervised Adelaide/ATNF student like myself, could always provide an understanding ear & good advice and I thank her for many interesting conversations. There are a number of other Adelaide PhD students whose company I've appreciated at various times, especially Peter Dawson, Stewart Wright, James Zanotti, Sundance Bilson-Thompson, Shu-Yen Lee and Andrew Costanzo. Thanks also to Alex Hemming, Aidan Brooks & Matt Heintze for providing mental distraction in the form of footy tipping competitions.

I have many good friends I would like to thank for just being there despite frequent geographical separation, especially Grace, Jenny W., Jessica D., Michael H. and Jeremy K. Also, thanks Rob G. for motivational email exchanges towards the end. And to my former Adelaide housemates at Hinton St — it was a great place to be!

I would also like to acknowledge the members of the Adelaide University Boat Club, especially the former intervarsity women's squad, for both the fitness & the great camaradarie that rowing provided, both of which I have missed in the last two years. Special thanks to Chris B., Cassie, Chelsea, Bels, Milly, Hannah, Natalie, Emma S., Fiona, Eve, Amelia R., and especially Christine for tolerating my frequent absences from training due to travel for my PhD.

Finally, I am infinitely grateful to my extended family, and especially my mum, for constant support — it has meant more to me than anything else.

The Australia Telescope Compact Array and the Australia Telescope Long Baseline Array are part of the Australia Telescope which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc. This research has made use of NASA's Astrophysics Data System, and of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

List of Publications

Publications related to work presented in this thesis:

- **Radio continuum monitoring of blazars**, Venturi, T., Bondi, M., Dallacasa, D., Orfei, A., Tzioumis, A., & **Bignall, H.** 1999, Mem. Soc. Astron. Ital., 70, 213.

- **Radio Monitoring of Blazars Observed with SAX**, **Bignall, H.**, Tzioumis, A., Mantovani, F., Venturi, T., Dallacasa, D., & Padovani, P. 1999, in BL Lac Phenomenon, ed. L.O. Takalo & A. Sillanpää, 71.

- **Intra-Day Variability, origins and implications**, Jauncey, D.L., Kedziora-Chudczer, L., Lovell, J.E.J., Macquart, J.-P., Nicolson, G.D., Perley, R.A., Reynolds, J.E., Tzioumis, A.K., Wieringa, M.H., & **Bignall, H.E.** 2001, in Particles and Fields in Radio Galaxies, ASP Conference Series Vol. 250, ed. R.A. Laing and K.M. Blundell, 123.

- **Examples of extreme intraday variability**, Kedziora-Chudczer, L., Jauncey, D.L., Wieringa, M.H., Tzioumis, A.K., & **Bignall, H.E.** 2001, Ap&SS, 278, 113.

- **Radio Intra-Day Variability: Answers and Questions**, Jauncey, D.L., Kedziora-Chudczer, L., Lovell, J.E.J., Macquart, J.-P., Nicolson, G.D., Perley, R.A., Reynolds, J.E., Tzioumis, A.K., Wieringa, M.H., & **Bignall, H.E.** 2001, Ap&SS, 278, 87.

- **Intraday variability and microarcsecond structure in blazar cores**, Jauncey, D.L., Kedziora-Chudczer, L., Lovell, J.E.J., Macquart, J.P., Nicolson, G.D., Perley, R.A., Reynolds, J.E., Tzioumis, A.K., Wieringa, M.H., & **Bignall, H.E.** 2001, in Galaxies and their Constituents at the Highest Angular Resolutions, IAU Symposium No. 205, ed. R.T. Schilizzi, 84.

- **New Results from an ATCA Study of Intraday Variable Radio Sources**, **Bignall, H.E.**, Jauncey, D.L., Kedziora-Chudczer, L.L., Lovell, J.E.J., Macquart, J.-P., Rayner, D.P., Tingay, S.J., Tzioumis, A.K., Clay, R.W., Dodson, R.G., McCulloch, P.M., & Nicolson, G.D. 2002, PASA, 19, 29.

- **Rapid Variability and Annual Cycles in the Characteristic Time-scale of the Scintillating Source PKS 1257–326**, **Bignall, H.E.**, Jauncey, D.L., Lovell, J.E.J., Tzioumis, A.K., Kedziora-Chudczer, L., Macquart, J.-P., Tingay, S.J. Rayner, D.P., & Clay, R.W. 2003, ApJ, 585, 653.

- **Interstellar Scintillation and Radio Intra-Day Variability**, Jauncey, D.L., **Bignall, H.E.**, Lovell, J.E.J., Macquart, J.-P., Rickett, B.J. 2003, to appear in Radio Astronomy at the Fringe, ASP Conference Series, ed. J.A. Zensus, M.H. Cohen and E. Ros.

Publications resulting from work conducted during my Ph.D. candidature, but not presented in this thesis:

- **PKS 0405–385**, Kedziora-Chudczer, L., Jauncey, D., Tzioumis, A., Reynolds, J., Wieringa, M., Nicholson, G., & **Bignall, H.** 1998, IAU Circ., 7066, 2, ed. D.W.E. Green.

- **Centaurus A: multiwavelength observations of the nearest active galaxy from radio to gamma-rays**, Steinle, H., Bonnell, J., Kinzer, R.L., Tzioumis, A., **Bignall, H.**, Schönfelder, V., Bennett, K., Hermsen, W., & Ryan, J. 1999, AdSpR, 23, 911.

- **VSOP Observations of Bright, Compact Southern Hemisphere AGN**, Tingay, S.J., Reynolds, J.E., Jauncey, D.L., Tzioumis, A.K., Preston, R.A., Murphy, D.W., Jones, D.L., Meier, D.L., Costa, M.E., Moffet, D., McCulloch, P.M., Nicolson, G., King, E.A., Edwards, P.G., Piner, B.G., Lovell, J.E.J., Hirabayashi, H., Tornikoski, M., Muecke, A., **Bignall, H.** & Clay, R.W. 2000, in Astrophysical Phenomena Revealed by Space VLBI, Proceedings of the VSOP Symposium, ed. H. Hirabayashi, P.G. Edwards, and D.W. Murphy, ISAS, 31.

- **The Deep X-Ray Radio Blazar Survey (DXRBS) - II. New identifications**, Landt, H., Padovani, P., Perlman, E.S., Giommi, P., **Bignall, H.** & Tzioumis, A. 2001, MNRAS, 323, 757.

- **5 GHz VLA IDV survey of the northern sky**, Lovell, J.E.J., Jauncey, D.L., **Bignall, H.E.**, Kedziora-Chudczer, L., Macquart, J.-P., Rickett, B.J. & Tzioumis, A. 2002, in Active Galactic Nuclei: from Central Engine to Host Galaxy, ed. S. Collin, F. Combes and I. Shlosman. ASP Conference Series, Vol. 290, p. 347.

Contents

List of Tables

List of Figures