Final Report: 1997 October 1 – 2003 September 30

Senior People: Beverley J. Wills, D. Wills

Service:

B. Wills carried out reviews for faculty tenure, served on dissertation committees, reviewed 3 'binational' astrophysics proposals, and also acted as PhD advisor for 3 students, advised one undergraduate student, and did much refereeing for ApJ, A&A, MNRAS, PASJ, and AJ. She served as panelist for peer reviews for The National Science Foundation, and for Cycle 3 observing time with Chandra X-ray Observatory.
D. Wills continues as technical editor for the popular science program "Earth and Sky", on National Public Radio.

Science:

Introduction

All my current projects investigate aspects of radio-loud, radio-quiet, BAL QSOs, and buried (IRAS-selected) QSOs and the relationships among these different classes, with the aim of probing the nature of accretion onto the massive central black hole – via relativistic jets, X-ray and optical absorption outflows, and the kinematics of the surrounding gas whose emission lines are excited by the accretion continuum.

Emission Lines, Continua, and the Energy Source in Radio Quiet Quasars

In collaboration with A. Laor (Technion, Israel), B. J. Wilkes (Harvard-Smithsonian Center for Astrophysics), G. Ferland (Univ. Kentucky), D. Wills and M. Brotherton (LLNL), we continue to investigate relations of UV and optical broad emission lines, absorption lines, and continua, with the ROSAT X-ray spectra. This is for a complete subset of 23 of the Palomar-Green (B-V -selected) sample having redshift <0.4 and Galactic hydrogen columns $< 1.9 \times 10^{21}$ cm^{-2} (Laor, Fiore, Elvis, Wilkes, & McDowell 1997, ApJ, 477, 93). Observations and all data reductions are complete, but some latest STScI re-calibration is being completed by grad student, Zhaohui Shang. This research has turned up more exciting new results, extending well-known Fe II, [O III], line-width, and X-ray relationships to ultraviolet emission lines. Correlations are among the strongest found in AGN spectroscopy and show great promise for understanding several 'classic' problems – the great strength of Fe II and other low-ionization broad emission lines (the energy budget problem), the 'Baldwin effect' and the meaning of 'eigenvector 1' relationships. Results have been presented at the QSO Broad-Line Region conference in Nebraska, 1998, and at the La Serena 'QSOs as Standard Candles' workshop in Chile (1997). In the two years, PhD student, Zhaohui Shang, has reduced and combined all optical and space-based data, and is preparing a paper on the spectral principal component analysis of this sample. The latter analysis reveals 3 orthogonal relationships among emission line and continuum properties – one involves an anticorrelation between luminosity and the strength of low-velocity emission from the Broad Emission Line Region (BLR) that is related to the Baldwin Effect, another involves an anticorrelation between optical Fe II emission and [O III] strengths that is similar to Boroson and Green's (1992) 'eigenvector 1', and the third involves the UV continuum slope and may simply represent the differences in spectral energy distributions among the sample QSOs, including the effects of (possible dust) reddening. We have interpreted these relationships as driven by accretion rate, Eddington accretion ratio, and dust reddening. We have shown how it may be possible to extend these analyses to larger samples, and higher redshift to investigate QSO evolution.

D. Grupe (now at MPE, Garching) obtained and reduced complete spectrophotometry for a revised version of his soft-X-ray-selected AGN sample. The data paper will be submitted this week. B. Wills, D. Grupe, K. Leighly (Columbia Univ.) are investigating the emission-line properties of the sample, with ASCA and Chandra follow-up. In addition, we (with Hans-Christoph Thomas of MPE-Garching) have obtained NIR spectroscopy at McDonald Observatory, to investigate the strengths of hydrogen Paschen emission lines (published).

Intrinsic Absorption in QSOs vs. Luminosity

In collaboration with A. Laor and W.N. Brandt, B. Wills has completed an investigation of the relation between UV and X-ray absorbing material in AGNs, and we have also investigated absorption-luminosity relationships. Three papers are published. This research is not completely distinct from the above study of emission lines and continua.

The Synchrotron Continuum in Radio-Loud Quasars

Feng Ma and B.J. Wills investigated the characteristic signature of CIV λ emission line variability, predicted by the expected collisional excitation excited by the beamed, infrared, jet emission in radio-loud quasars (cf Ma and Wills 2001). Ma has received his PhD degree (December 2000).

Three investigations of broad-band polarization in radio-loud quasars are in preparation: (i) A paper by Wills, Tran, Wills and Yuan concerns variability of blazar polarization over a 20–30-year timescale, (ii) Wills and Cross describe day timescale UBVRIJHKL′ variability of synchrotron polarization in the bright quasar 3C 273), and (iii) B. J. Wills has investigated the synchrotron polarization of a sample of radio core-dominated quasars, including model-fitting of accretion disk and synchrotron continua. Undergraduate, Marty Bitner, and graduate student Michael Yuan, are helping with this.

Buried AGN: A Complete Sample of Warm IRAS-selected QSOs

In collaboration with D.C. Hines, K. Gordon, M. L. Sitko, and G. Schmidt, B. J. Wills is investigating HST polarization and imaging, of the dusty, IRAS AGN in our complete sample of luminous IRAS-detected AGN (continuing project).

Some Other Projects

Other projects are coordinated STIS/Chandra spectroscopy of UV/X-ray Absorption in the Seyfert Galaxy NGC 4051 (completed, with Collinge et al. 2001), and a major FUSE project, 'The Far-UV Spectral Energy Distributions of Quasars' – to observe our previously and presently-investigated PG sample).

We have investigated HST imaging of the narrow line region (NLR) in a complete sample of low-redshift radio quiet quasars (collaborators are Andrew Wilson and Heino Falcke).

We have obtained quasi-simultaneous Chandra–HST spectroscopy of the brightest BAL QSO, PG 2112+059, and investigated dramatic X-ray spectral variability, as well as analyzing the line locking exhibited in new and archival HST (STIS and FOS) spectral data.

We have investigated the use of widths of [OIII]λ5007 lines as a surrogate for bulge velocity dispersion of QSOs' host galaxies, and compared the resulting stellar velocity dispersions with estimates of blackhole mass obtained from the width of Hβ and continuum luminosity. QSOs at moderately high redshift extend the relationship found by Nelson (2000).

Other projects and results are also included in the Publication list.

Publications: 1997 Oct. 1 – 2003 Sept. 30

The Optical Polarization and Warm Absorber in IRAS 17020+4544, Leighly, K. M., Kay, L. E., Wills, B. J., Wills, D., Grupe, D. 1997, ApJ, 489, 137L.

Scattering and Absorption in Soft X-ray Selected AGN: An Optical Polarization Survey, Grupe, D., Wills, B.J., Wills, D., & Beuermann, K. 1997, A&A, 333, 827.

Spectropolarimetry of 3C 68.1: A Highly-Inclined Quasar, Brotherton, M.S., Wills, B.J., Dey, A., van Breugel, W., & Antonucci, R. 1997, ApJ, 501, 110.

Ring Structure and Warp of NGC 5907: Interaction with Dwarf Galaxies, Shang, Zhaohui, Brinks, E., Zheng, Z., Chen, J., Burstein, D., Su, H., Byun, Y.-I., Deng, L., Deng, Z., Fan, X., & 15 coauthors 1998, ApJ, 504, L23.

Optical Polarization of Blazars, Visvanathan, N., & Wills, B. J. 1998, AJ, 116, 2119.

Does Every Quasar Harbor a Blazar? Ma, Feng & Wills, B. J. 1998, ApJL, 504, L65.

The Misdirected Central Engine of the "QSO 2" IRAS P09104+4109, Hines, D. C., Schmidt, G. D., Wills, B. W., Smith, P. S., & Sowinski, L. G. 1999, ApJ, 512, 145.

Introduction to Principal Components Analysis (invited review), Francis, P. J., Wills, B. J. 1999, "Quasars and Cosmology", A.S.P. Conference Series (1999), eds. G.Ferland, J.Baldwin (San Francisco: ASP) 162, 363.

Introduction to Unified Schemes (invited review) Wills, B. J. 1999, "Quasars and Cosmology", A.S.P. Conference Series, eds. G.Ferland, J.Baldwin (San Francisco: ASP) 162, 101.

The PG X-Ray QSO Sample: Links between the Ultraviolet-X-Ray Continuum and Emission Lines, Wills, B. J., Laor, A., Brotherton, M. S., Wills, D., Wilkes, B. J., Ferland, G. J., Shang, Zhaohui 1999, ApJ (Letters), 515L, 53.

PKS 1004+13: A High Inclination, Highly Absorbed Radio-Loud QSO - The First Radio-Loud BAL QSO at Low Redshift? 1999 Wills, B.J., Brandt, W.N. & Laor, A. ApJ (Letters), 520, L91.

On the Nature of Soft X-ray Weak Quasi-Stellar Objects, Brandt, W. N., A. Laor, A., Wills, B. J. 2000, ApJ, 528, 637.

H-beta Line Width and the UV-X-ray Spectra of Luminous AGN, Wills, B.J., Shang, Zhaohui, Yuan, M. J., 2000, New Astronomy Reviews, 44, 511.

Heavy X-ray Absorption in Soft X-ray Weak Active Galactic Nuclei, Gallagher, S. C., Brandt, W. N., Laor, A., Elvis, M., Mathur, S., Wills, B.J., & Iyomoto, N. 2001, ApJ, 546, 795.

Discovery of Hidden Blazars, Ma, F., & Wills, B. J. 2001, Science, 292, 2050.

High-Resolution X-ray and Ultraviolet Spectroscopy of the Complex Intrinsic Absorption in NGC 4051 with Chandra and HST, Collinge, M. J., Brandt, W. N., Kaspi, S., Crenshaw, D. M., Elvis, M., Kraemer, S. B., Reynolds, C. S., Sambtuna, S. M., Wills, B. J., 2001, ApJ, 557, 2.

HST Ultraviolet & Ground-based Optical Spectropolarimetry of IRAS QSOs: Dusty Scattering in Luminous AGN, Hines, D. C., Schmidt, G. D., Gordon, K. D., Smith, P. S., Wills, B. J., Allen, R. G., & Sitko, M. L. 2001, ApJ, 563, 512.

HST STIS Observations of PG 0946+301: The Highest Quality UV Spectrum of a BALQSO, Arav, N., de Kool, M., Korista, K. T., Crenshaw, D. M., van Breugel, W., Brotherton, M., Green, R. F., Pettini, M., Wills, B., de Vries, W., Becker, B., Brandt, W. N., Green, P., Junkkarinen, V. T., Koratkar, A., Laor, A., Laurent-Muehleisen, S. A., Mathur, S., Murray, N. 2001, ApJ, 561, 11.

Size and Structure of the Narrow-Line Region of Quasars, Bennert, N., Falcke, H., Schulz, H., Wilson, A. S., & Wills, B. J., 2002, ApJ, 574, L105.

The Black Hole – Bulge Relationship in QSOs, Shields, G. A., Gebhardt, K., Salviander, S., Wills, B.J., Xie, Bingrong, Brotherton, M. S., Yuan, J., & Dietrich, M. 2002 ApJ, 583, 124.

Multiband VLA Observations of the Faint Radio Core of 3CR 68.1, Brotherton, M. S., Ly, Chun, Wills, B. J., Laurent-Muehleisen, S. A., van Breugel, W., Antonucci, R. R. J. 2002 AJ, 124, 1943.

A Study of a Complete Soft X-ray selected Sample of AGN, Matsumoto, C., Moore, J., Leighly, K. M., Grupe, D., & Wills, B. J. 2002 Space Science Reviews, 000, 000.

Principal Components in the PG X-ray Sample, Shang, Zhaohui, Wills, B. J., & Robinson, E. L., 2002 Space Science Reviews, 000, 000 (astro-ph/0301560).

Black Hole Accretion and the X-ray Spectra of QSOs, Yuan, J. M., Wills, B. J. 2002 Space Science Reviews, 000, 000.

Indicators of Black Hole Mass and Eddington Accretion Ratio from QSO X-ray and UV Spectra, Wills, B. J., & Shang, Zhaohui 2002 Space Science Reviews, 000, 000.

Outflows & Unification (invited review), Wills, B. J. 2003 in "Active Galactic Nuclei: from Central Engine to Host Galaxy", Eds.: S. Collin, F. Combes and I. Shlosman (ASP (Astronomical Society of the Pacific), Conf. Ser.) 290, 303.

Eddington Accretion and QSO Emission Lines at $z \sim 2$, Yuan, M. J., & Wills, B. J. 2003, ApJL, 593, L11.

The Baldwin Effect and Black Hole Accretion: A Spectral Principal Component Analysis of a Complete Quasar Sample, Shang, Zhaohui, Wills, B. J., Robinson, E. L., Wills, D., Laor, A., Xie, Bingrong, Yuan, Juntao 2003, ApJ, 586, 52.

Dramatic X-ray Spectral Variability of the Broad Absorption Line Quasar PG 2112+059, Gallagher, S.C., Brandt, W. N., Wills, B. J., Charlton, J. C., Chartas, G., & Laor, A. 2003, ApJ, submitted.

A Complete Sample of Soft X-ray Selected AGN: I. The Data, Grupe, D., Wills, B. J., Leighly, K. M., Meusinger, H. 2003, ApJ, submitted.

Conference Papers

X-Rays from Quasar Jets: New Insights from ROSAT, Shastri, P., Wilkes, B. J., Elvis, M., Wills, B. J., Spinrad, H. in "Relativistic Jets in AGNs, Proceedings of the International Conference", 26.

'Warm' and cold absorption in soft X-ray selected AGN, Grupe, D., Wills, B. J., Wills, D., Leighly, Karen M., in Astronomische Gesellschaft Meeting Abstracts, 14, H05 (Meeting of the Astronomische Gesellschaft at Heidelberg, September 14–19, 1998, talk H05).

Blazar Optical Polarization Over a 20 to 30 Year Time-span, Yuan, J., Tran, H. D., Wills, B. J., Wills, D. 1998, Bull. Am. Astron. Soc., 19310714.

The PG X-ray QSO Sample: Ionizing Continuum and Properties of the Fueling Gas, Wills, B. J., Laor, A., Brotherton, M. S., Wills, D., Shang, Zhaohui, Wilkes, B. J., Ferland, G. J. 1998, Bull. Am. Astron. Soc., 19310705.

Variability of CIV Emission Line in Radio Loud Quasars, Ma, F., Wills, B. J., Yuan, J. 1998, Bull. Am. Astron. Soc., 193.2001.

The Polarization of 3C 273, Cross, L. L., Wills, B. J. 1998, Bull. Am. Astron. Soc., 193.0508.

Searching for Hidden Blazars Via Emission Line Variability, Ma, F., Wills, B. J. in "Structure and Kinematics of Quasar Broad Line Regions", Ed. C. M. Gaskell, W. N. Brandt, M. Dietrich, D. Dultzin-Hacyan, & M. Eracleous. 1999 (ASP Conference Series) 175, 415.

Optical Polarization and Warm Absorbers, Leighly, K. M., Kay, L. E., Wills, B. J., Wills, D., Grupe, D. in "Structure and Kinematics of Quasar Broad Line Regions", Ed. C. M. Gaskell, W. N. Brandt, M. Dietrich, D. Dultzin-Hacyan, & M. Eracleous. 1999 (ASP Conference Series) 175, 385.

Warm and Cold Absorption in Polarized Soft X-ray AGN, Grupe, D., Wills, B. J., Wills, D. in "Structure and Kinematics of Quasar Broad Line Regions", Ed. C. M. Gaskell, W. N. Brandt, M. Dietrich, D. Dultzin-Hacyan, & M. Eracleous. 1999 (ASP Conference Series) 175, 347

The PG X-ray QSO Sample: Links among X-ray, UV & Optical Spectra, Wills, B. J., Brotherton, M. S., Laor, A., Wills, D., Wilkes, B. J., Ferland, G. J. Ed. C. M. Gaskell, W. N. Brandt, M. Dietrich, D. Dultzin-Hacyan, & M. Eracleous. 1999 (ASP Conference Series) 175, 241.

Absorption and scattering properties in polarized bright soft X-ray selected ROSAT AGN, Grupe, D., Wills,

Beverley J., Wills, D., Leighly, K. M. 1999, in "Highlights in x-ray astronomy : international symposium in honour of Joachim Trumper's 65th birthday", ed.: B. Aschenbach & M. J. Freyberg (Garching : MPI), 272, 136.

On the Nature of Soft X-ray Weak Quasi-Stellar Objects, Brandt, W. N., Laor, A., Wills, B. J. 1999, Bull. Am. Astron. Soc., 194.3405.

Are There Intrinsically X-Ray Quiet Quasars? Gallagher, S. C., Brandt, W. N., Laor, A., Elvis, Martin, Mathur, S., Wills, Beverly J., Iyomoto, N. 2000, SAO Technical Report, 91583.

Hβ line width and the UV-X-ray spectra of luminous AGN, Wills, B. J., Shang, Z., Yuan, J. M. 2000 New Astron. Rev., 44, 511.

The HET Echo Mapping Project, Welsh, W., Robinson, E. L., Hill, G., Shields, G., Wills, B., Brandt, N., Eracleous, M., Kollatschny, W., Horne, K., Gallo, L. 2000, Bull. Am. Astron. Soc., 197.3913.

Optical-IR Polarimetry of the Blazar 3C 273: Orthogonal Synchrotron Components during a Flare, Wills, B. J., Cross, L. L., Hough, J. H., Bailey, J. A., Wills, D. 2000, Bull. Am. Astron. Soc., 197.3905.

X-ray Absorption in Radio-Quiet QSOs, Brandt, W. N., Gallagher, S. C., Laor, A., Wills, B. J. 2001, "X-ray astronomy : stellar endpoints, AGN, and the diffuse X-ray background" AIP conference proceedings (ed.: N. E. White, G. Malaguti, & G.G.C. Palumbo.) 599, 53.

Discovery of Hidden Blazars inside Quasars, Ma, F., Wills, B. J. 2001, in "Blazar Demographics and Physics" Eds.: Paolo Padovani and C. Megan Urry. (San Francisco: ASP) 227, 212.

Spectral Principal Component Analysis of a PG X-ray QSO Sample: – Three Independent Sets of Relationships in QSO's UV-Optical Spectra, Shang, Z., Wills, B. J., Robinson, E. L., Yuan, J. 2001 Bull. Am. Astron. Soc., 198.9305.

Three Principal Components in QSO spectra, Shang, Z., Wills, B., Robinson, E., Yuan, J. 2001 Bull. Am. Astron. Soc., 199.7704.

HST UV and Ground-Based Optical Spectropolarimetry of IRAS QSOs: Dusty Scattering in Luminous AGN, Hines, D. C., Schmidt, G. D., Gordon, K. D., Wills, B. J., Smith, P. S., Allen, R. G., Sitko, M. L. 2001 June AAS Meeting No. 198, paper 74.08.

A Polarization Flare in 3C 273: A Clue to Jet Physics, Cross, L. L., Wills, B. J., Hough, J. H., & Bailey, J. A. 2001, in Blazar Demographics and Physics, Astronomical Society of the Pacific Conference Series, Vol. CS-227 (P. Padovani and C. M. Urry eds).

The Physics of Blazar Optical Emission Regions I: Alignment of Optical Polarization and the VLBI Jet, Yuan, M. J., Tran, H., Wills, B. J., Wills, D. 2001, in Blazar Demographics and Physics, Astronomical Society of the Pacific Conference Series, Vol. CS-227 (P. Padovani and C. M. Urry eds).

The Physics of Blazar Optical Emission Regions II: Magnetic Field Orientation, Viewing Angle and Beaming, Yuan, M. J., Tran, H., Wills, B. J., Wills, D. 2001, in Blazar Demographics and Physics, Astronomical Society of the Pacific Conference Series, Vol. CS-227 (P. Padovani and C. M. Urry eds).

A Principal Component Analysis of a Complete QSO Sample, Shang, Zhaohui, Wills, B. J., Robinson, E. L., & Yuan, M. J. 2001 January AAS Meeting No. 197, paper no. 000.

The Physics of Jets in 3C 273 and oter Blazars: Clues from Optical-IR Polarization, Wills, B. J. presented at the annual Stromlo Agn meeting, in honor of Charlene Heisler, 2000 December, Mt. Stromlo Observatory, ACT, Australia.

X-ray Absorption in Radio-Quiet QSOs, Brandt, W. N., Gallagher, S. C., Laor, A. & Wills, B. J. 2001, Astroph.

Lett. and Comm., (Proceedings of the Bologna conference on "X-ray Astronomy 1999: Stellar Endpoints, AGN, and the Diffuse X-ray Background"), 000.

Science from the refurbished FOS/BLUE archive: Interstellar absorption lines in a sample of low red-shift quasars, Kerber, F., Wills, B., Alexov, A., Bristow, P., Seifahrt, A., Rosa, M. R. 2002 Bull. Am. Astron. Soc., 200.4018

QSO Emission Lines and the Black Hole-Galaxy Bulge Relation, Shields, G. A., Gebhardt, K., Salviander, S., Wills, B. J., Yuan, M., Xie, B., Dietrich, M. 2002 Bull. Am. Astron. Soc., 200.1705.

M Dwarfs to Quasars: The Chandra Multiwavelength Project (ChaMP) X-ray Survey, Hooper, E. J., Wilkes, B. J., Green, P. J., Silverman, J. D., Wills, B. J., Kim, D.-W., Grindlay, J. E., Cameron, R. A., Tananbaum, H., ChaMP Collaboration 2002 Bull. Am. Astron. Soc., 200.1312.

Study of UV-Optical Properties of A Complete Sample of QSOs, Shang, Z., Wills, B. J., Robinson, E. L. 2002 Bull. Am. Astron. Soc., 20112506.

Are BALQSOs extreme accretors? Yuan, M. J., Wills, B. J. 2002 Bull. Am. Astron. Soc., 20111402.

Indicators of Black Hole Mass and Eddington Ratio for High Redshift QSOs, Wills, B. J., Shang, Zhaohui 2002 Bull. Am. Astron. Soc., 20111401.

X-ray polarimetry of AGN with XEUS, Grupe, D., Wills, B. J. 2003 in "XEUS - studying the evolution of the hot universe, Ed.: G. Hasinger, Th. Boller, and A.N. Parmer, MPE Report 281, 259.

Structure of ionized gas around AGN, Falcke, H., Bennert, N., Schulz, H., Wilson, A. S., Wills, B. J. 2003 in "Active Galactic Nuclei: from Central Engine to Host Galaxy", Eds.: S. Collin, F. Combes and I. Shlosman (ASP (Astronomical Society of the Pacific), Conf. Ser.) 290, 203.

Black Hole Accretion and Outflows at Redshifts near 2, B.J. Wills, M. Lacy, M.J. Yuan, P.B. Hall, M.S. Brotherton, D.E. Vanden Berk, G.T. Richards, A. Laor, R.H. Becker 2003, to appear in "AGN Physics with the Sloan Digital Sky Survey", ed.: G. T. Richards and P. B. Hall (San Francisco: ASP), 000, 000.

Principal Component Analysis of AGN Spectra, Zhaohui Shang, B. J. Wills 2003, to appear in "AGN Physics with the Sloan Digital Sky Survey", ed.: G. T. Richards and P. B. Hall (San Francisco: ASP), 000, 000.

Invited talks

"Are Most QSOs Buried? – A Polarization Survey of IRAS-selected AGN", IGPP, LLNL, April, 1998

"Are Most QSOs Buried?", 2000 April, Columbia University.

"Optical-IR polarimetry of the Blazar 3C 273: Orthogonal Synchrotron Components during a Flare", 2001, April, Joint Astronomy Center, Hilo, Hawaii.

"AGN Outflows and Unification", 2002, in conference, 'Active Galactic Nuclei: from Central Engine to Host Galaxy', held Meudon, France, July 23–27.

"Quasars' Supermassive Black Holes", Department of Physics, Sam Houston State University (Huntsville), 2002 Nov. 21.

Thesis Supervision/Advising

Feng Ma, Discovery of Hidden Blazars inside Quasars, PhD degree awarded December, 2000.

Zhaohui Shang, Study of Ultraviolet-Optical Properties of A Complete Sample of QSOs, PhD degree awarded Summer, 2003.

Juntao (Michael) Yuan – thesis in progress.