Reverberation Mapping of Quasars at Wyoming

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Advisor: Associate Professor Michael Brotherton

School: University of Wyoming

Department: Physics and Astronomy

Abstract

Reverberation mapping is an observational technique developed to measure the masses of black holes powering quasars and other active galaxies. These measurements form the basis of a number of relationships demonstrating that the growth of black holes is intimately tied to the growth of the galaxies they live inside. Even though the technique of reverberation mapping has revolutionized the field, only some 50 objects have been studied because it is time consuming and labor intensive. We have the telescope resources in Wyoming to contribute significantly to the effort, and make real progress to understand and correct for large sources of uncertainty in the mass measurements. The key to doing this is to study a specially selected sample of objects in order to determine how the geometry of gas around these black holes biases the mass measurements. These objects are called radio-loud quasars, as they possess strong jets shooting out their spin axes that are powerful radio emitters, and their jets allow us to measure system orientations. We plan to measure black hole masses for 6-10 of these quasars and determine the effects of geometry on the measurements. We should have results and a paper by Spring of 2012.

1. Project Description

Quasars are feeding supermassive black holes that live in the centers of galaxies and manage to outshine those host galaxies by orders of magnitude. They represent the some of the most luminous objects in the universe and some of the most extreme physics.

The black hole mass is the most fundamental quasar parameter. The best and most reliable way of measuring black hole masses in quasars is with a technique called reverberation mapping. The technique is conceptually simple. The time lag between the variations of the continuum emission, ionizing surrounding gas, and the broad emission lines responding to that continuum, provides a size of the broad line region. This is because the speed of light is finite, and the regions are the size of light weeks. See Fig. 1.

The Doppler-broadened width of the variable emission line provides a velocity. Introducing the scaling factor, f, to characterize the unclear geometry of the broad line region, the black hole mass is calculated using gravitational dynamics:

$$M_{\rm BH} = f\frac{R_{\rm BLR}\Delta V^2}{G}. \tag{1}$$

This is known as a virial mass estimate, which is supported by observations of different emission lines with different time lags in the same AGNs (Peterson & Wandel 2000).

Over the past two decades approximately 50 AGNs have been spectrophotometrically monitored (e.g., Bentz et al. 2009). determining BLR sizes and, with some assumptions about f, masses. Many derivative relationships involving black hole masses depend on reverberation masses, so it is essentially to get them right and reduce sources of uncertainty, which can be large (factors of 3 or so).

We wish to tackle the problem of geometry (and that factor f) in determining black hole masses. Studies of radio-loud quasars, for which radio jet morphology can indicate the inclination angle to the line of sight, show that the Doppler width of broad emission lines depends on orientation. For similar luminosities, quasars with jets pointed in our direction (face-on) have narrower Hβ lines than those with jets in the plane of the sky (edge-on). This has been interpreted as evidence for Hβ being emitted from a flattened disk (e.g. Wills & Browne 1986, Brotherton 1996).

If the apparent velocity of the broad line region gas depends on not only the luminosity and mass of the central black hole, but also on orientation, then orientation must be a significant source of uncertainty in reverberation masses. Only four of quasars with reverberation masses are radio-loud with orientation information. Two of these were observed at WIRO in October 2010 to test performance (Fig. 3 shows our SNR=100 spectra, and also shows how the broad line width and shape can vary for two quasars with similar luminosity but

Geometric and Dynamical Models of Reverberation Mapping Data 3

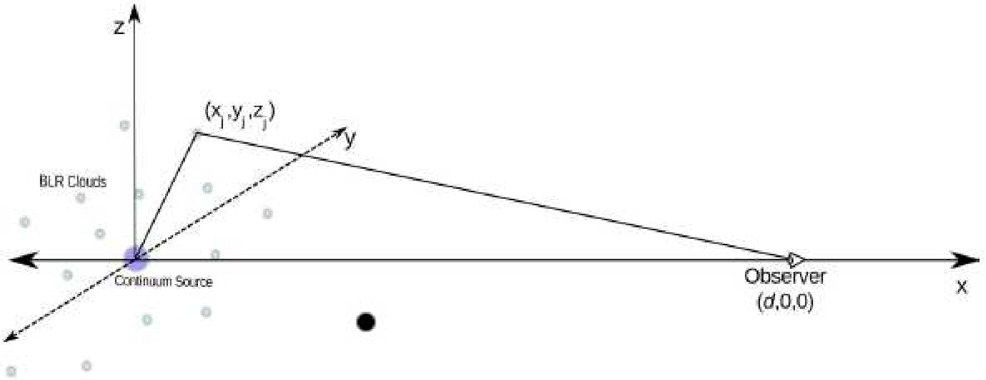

FIG. 1.— BLR clouds around the central ionizing source (central engine). The extra path length the light must travel from the central engine to the BLR cloud and then to the observer is the cause of the delayed response of the line flux.

very different viewing angles). The profile shape, pointier in face-on objects and flat-topped in edge-on objects (Brotherton 1996) may be a clue to how to correct for orientation rather than accepting the velocities as is and concluding that 3C 390.3 has a much more massive black hole than 3C 120. That may just be an inclination effect.

This project proposes to monitor a sample of 6-10 radio-loud quasars with known orientation over the summer and fall using Red Buttes Observatory (continuum brightness) and WIRO (spectroscopy to measure the broad lines and their widths).

Our goal is to obtain mass measurements using the reverberation technique for as many of our objects as possible. Some luck is required, as we need the quasars to vary, of which most are expected to do so over the campaign. Our secondary goal is to compare these masses with other techniques of mass estimation (e.g., ref.), to test the hypothesis that orientation biases the measurements. A third goal will be to use our results to develop a correction to the mass measurements based on orientation. This is the next crucial step in developing the best way of measuring black hole masses in the centers of active galaxies like quasars. Basically, the long term goal is determining the f factor.

To evaluate success, any time lags obtained will allow us to determine black hole masses. That's the first order evaluation. Ultimate success is the publication of a paper in 2012.

2. Rolls and Responsibilities of the Student

The student will assist with observations at Red Buttes and WIRO starting in the summer of 2011 (likely June). More limited observations will be done during the fall of 2011 in a way designed not to negatively impact studies. The student will also read papers and learn the science involved in measuring black hole masses. Some data reduction and analysis

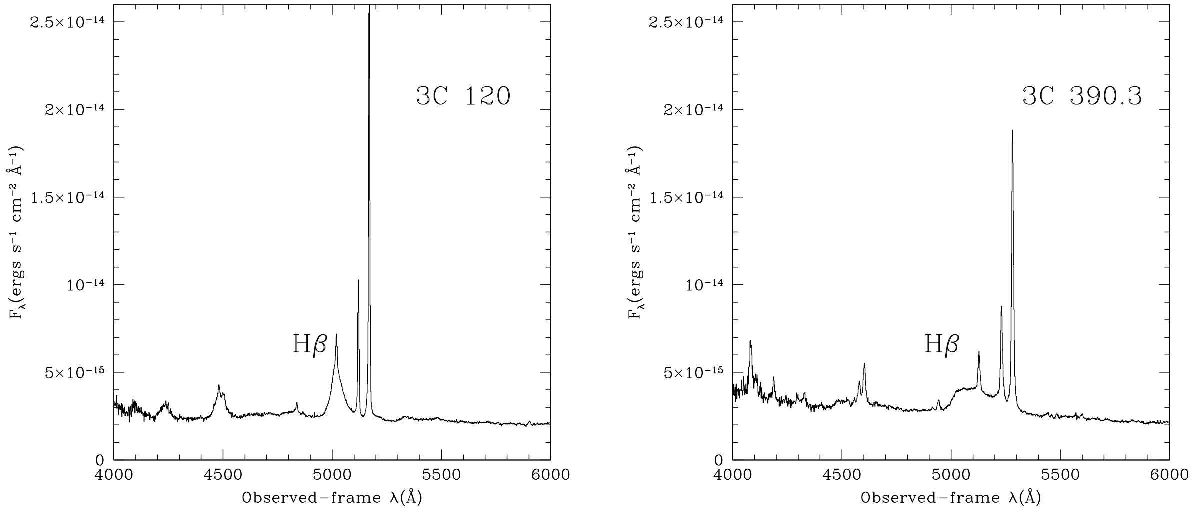

Fig. 1.— Example spectra taken at WIRO of two radio-loud quasars in past reverberation mapping campaigns. Exposure times were 40 minutes and we achieved SNR=100 in the continuum. 3C 120 has radio structure indicating a face-on orientation, with the narrowish Hβ broad line, while 3C 390.3 is edge-on, and shows an extremely broad Hβ broad line. This consistent with Wills & Browne (1986) and Brotherton (1996).

will also be learned/done in collaboration with graduate students and the advisor.

3. Timeline

May 2011: Reading papers and learning about the science and observational procedures. June-August 2011: Full time work observing and learning data reduction. September-October: Assisting with observations in a limited capacity, time and studies permitting. October-April: Data reduction and analysis, assisting with production of a journal article about the work. Presentation at one or more events.

4. References

Bentz, M. C., et al. 2009, ApJ, 705, 199

Brotherton, M. S. 1996, ApJS, 102, 1

Peterson, B. M., & Wandel, A. 2000, ApJ, 540, L13

Wills, B. J., & Browne, I. W. A. 1986, ApJ, 302, 56

Award Request and Time Share

The request is $5000 dollars. We are planning for essentially all of this to go toward student salary at $8.75 an hour. The student is likely to work 12 weeks during the summer full time (40 hours per week), for 480 hours. That will leave 90 hours during the school year, which will be 9 weeks at 10 hours a week, but that will be limited to a lower figure to ensure that studies are negatively impacted. The funds are likely to endure into the spring semester and be exhausted by April 2012.

Mike Brotherton, the faculty advisor, will spend significant time on this project and working with the student one on one. The time will be substantial in summer, an estimated 60 hours, and something like an hour per week during the school year (25 hours), for a total of 85 hours.

Advisor CV

Curriculum Vitae for Michael S. Brotherton

Professional Preparation

Rice University Physics and Electrical Engineering B.S. 1990
University of Texas at Austin Astronomy M.S. 1992
University of Texas at Austin Astronomy Ph.D. 1996

Appointments

2008 – Associate Professor, Department of Physics & Astronomy, University of Wyoming
2002 – 2008 Assistant Professor, Dept. of Physics & Astronomy, University of Wyoming
1999 – 2002 Research Associate, Kitt Peak National Observatory
1996 – 1999 Postdoctoral Fellow, Lawrence Livermore National Laboratory

Publications

(i) Publications Most Relevant to This Research

R. Nemmen, M. Brotherton, "Quasar Bolometric Corrections: Theoretical Considerations", MNRAS, 408, 1598N (2010)

Z. Shang, M. Brotherton, et al., "Quasars and the big Blue Bump", ApJ, 619, 41S (2005)

M. Brotherton, "The Profiles of Hβ and [O III] λ5007 in Radio-Loud Quasars, ApJS, 102, 1B (1996)

B. Wills, M. Brotherton, "An Improved Measure of Quasar Orientation", ApJ, 448L, 81W (1995)

H. Netzer, M. Brotherton, B. Wills, M. Hand, D. Wills, J. Baldwin, G. Ferland, I. Browne, "The Hubble Space Telescope Sampel of Radio-Loud Quasars: The Lyα/Hβ Ratio", ApJ, 448, 27N (1995)

(ii) Other Significant Publications

Wold, M.; Brotherton, M. S.; Shang, Zhaohui, "The dependence of quasar variability on black hole mass" MNRAS, 375, 989 (2007)

Shields, Gregory A.; Gebhardt, Karl; Salviander, Sarah; Wills, Beverley J.; Xie, Bingrong; Brotherton, Michael S.; Yuan, Juntao; Dietrich, Matthias, "The Black Hole-Bulge Relationship in Quasars" ApJ, 583, 124 (2003)

Brotherton, M. S.; Tran, Hien D.; Becker, R. H.; Gregg, Michael D.; Laurent-Muehleisen, S. A.; White, R. L. "Composite Spectra from the FIRST Bright Quasar Survey" ApJ, 546, 775 (2001)

Synergistic Activities

(i) Participation in Outreach Activities

Astro Camp Science Fiction Writing 2006-2008
Launch Pad Astronomy Workshop for Writers 2007-2008
Science Fiction Novels: Star Dragon (2003), Spider Star (2008)
Science Fiction Conventions, Numerous public science talks (2001-)
Science Blogging, www.mikebrotherton.com

(ii) Courses Taught: 2002-2010

Two or three courses taught per year for last six years, including non-major astronomy, graduate-level cosmology, undergraduate astronomy-major astrophysics, and Science and Science Fiction as a non-major elective

Collaborators and Other Affiliations

(i) Graduate and Postdoctoral Advisors

B. J. Wills (U Texas), W. van Breugel (IGPP/LLNL), R. Green (KPNO/NOAO)

(ii) Undergraduate (7) and Graduate (5) Students Supervised

1. Aleks Diamond-Stanic (Undergraduate 2003, currently a Graduate Student at Arizona)
2. Tim Weinzirl (Undergraduate 2004, currently a Graduate Student at Texas)
3. Catherine Grier (Undergraduate 2006, currently a Graduate Student at Ohio State University)
4. Rebecca Stoll (Undergraduate 20052007, currently a Graduate Student at Ohio State University)
5. Brian Scoggins (Undergraduate 2002present, University of Wyoming)
6. Sabrina Cales (Graduate 2005present, University of Wyoming)
7. Cassandra Paul (Graduate 2002-2004, University of Wyoming, currently graduate student at UC Davis)
8. Stevie Fawcett (Graduate 2005-2008, University of Wyoming)
9. Mike Di Pompeo (Graduate 2007-present, University of Wyoming)
10. Anirban Bhattacharjee (Graduate 2006-present, University of Wyoming)
11. Jessie Runnoe (Undergraduate 2007, Started grad school at University of Wyoming in 2008)
12. Benjamin Kelly (Undergraduate 20072008, University of Wyoming)