Project Theta: Radio-Quiet Quasar Orientation

1. Overview and Objectives for the Proposed Research

Quasars are the most luminous form of active galactic nuclei (AGNs), signposts of massive black holes accreting at high rates, which appear to play an important role in the evolution of galaxies. The observable properties of quasars depend not only on their mass and accretion rate, but also on their orientation to the line of sight given their nature as axisymmetric objects. Although the central engines are too small and far away to resolve, the large scale jets present in the radio-loud quasar subclass have enabled us to determine orientation and learn how their properties depend on viewing angle. Radio-loud quasars represent only about 10% of the quasar population, however, leaving no obvious way to determine the orientation of the radio-quiet majority.

We have recently demonstrated the effectiveness of one optically based quasar orientation indicator, the ratio of an orientation-biased to an unbiased black hole mass measurement ($M_{H\beta}/M_{\sigma*}$). Our primary objective is to improve this orientation indicator with additional predictors, and to calibrate it well enough to create a ubiquitous tool for extragalactic astronomy. Orientation is a known source of significant scatter in determining quasar luminosity and black hole mass, which together determine the Eddington fraction. Moreover orientation effects create additional biases in surveys and sample selection, further affecting the accuracy as well as the precision in determining these fundamental physical parameters. Tackling orientation in quasars generally is a vital step that must be successfully undertaken to advance the field, and the time is now ripe to do so.

2. Quasar Geometry

Many lines of evidence demonstrate that quasars are axisymmetric, and that their observed properties can vary dramatically with viewing angle (e.g., Antonucci et al. 1993; Marin 2016 – see Fig. 1). For instance, highly inclined systems appear as "type 2" objects, showing only narrow emission lines in the optical-UV region, because a dusty torus hides the broad lines and continuum visible in less inclined "type 1" quasars. The large-scale radio jets that emerge from the some 10% of quasars referred to as radio-loud represent perhaps the most obvious example of axisymmetry, and provided one of the earliest techniques for determining orientation.

These jets are relativistic, which boosts the emission in the direction of motion. This Doppler beaming effect permits the use of radio morphology and spectral index as orientation indicators (e.g., Orr & Browne 1982; Wills & Brotherton 1995; DiPompeo et al. 2012). A boosted flat-spectrum core component dominates in jet-on/face-on quasars with a large core dominance parameter (R = core/extended radio flux at 5 GHz rest-frame) while it is steep-spectrum extended lobes dominating over the radio core in more edge-on systems. While radio-based orientation indicators have been useful, there are compelling reasons why we need to develop alternatives that can be applied to radio-quiet quasars. These reasons include:

- The vast majority of quasars, some 90%, are radio quiet.

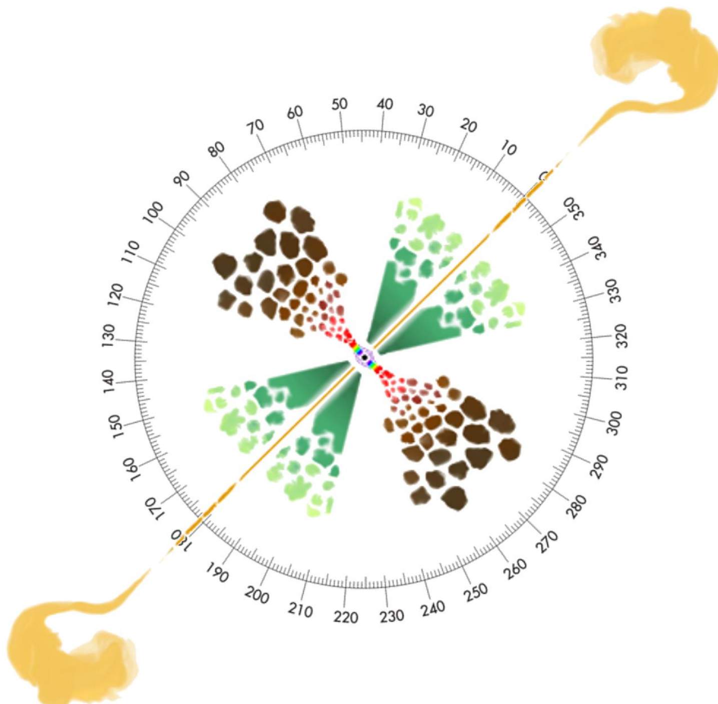


Fig. 1.— From Marin (2016), an unscaled sketch of AGN unification, in which a type 1 AGN is seen at inclinations up to 60 degrees ("edge-on" for a type 1), and type 2 AGN at larger inclinations. The central black hole is black, the surrounding X-ray corona is violet, the multitemperature accretion disc is shown with a rainbow, the flattened broad line region (BLR) is in red and light brown, the circumnuclear dust is in dark brown, the polar ionized winds are in dark green and the final extension of the NLR is in yellow-green. A double-sided, kilo-parsec jet is added to account for radio-loud AGNs.

- Larger radio-quiet quasar samples will allow better statistical studies of orientation effects.
- Radio jets themselves can contribute significantly to quasar emission, particularly at X-ray energies, complicating efforts to determine the intrinsic spectral energy distribution (SED).
- Orientation has effects upon the determination of many quasar properties such as bolometric luminosity (Nemmen & Brotherton 2010) and black hole mass (Runnoe et al. 2013a) – and hence also the Eddington fraction L/L_{Edd}. We want to be able to correct these orientation biases in radio-quiet quasars.

There have been some recent and ongoing attempts to develop an optically based orientation indicator for quasars. For instance, Boroson (2011) proposed a scheme based on velocity shifts of narrow [O III] emission, thought to contain outflows, and broad optical Fe II emission, suggested to have inflows; Sulentic et al. (2012) failed to find the Fe II velocity shifts, and our own investigation of radio-loud quasars failed to confirm the orientation indicator.

In a series of papers, most recently Bisgoni, Marconi, & Risaliti (2017), the equivalent width (EW) of narrow [O III] has been proposed as an orientation indicator. While we agree that EW [O III] correlates with viewing angle due primarily to the anisotropy of the accretion disk producing the continuum emission, the effect suffers from large scatter (e.g., Runnoe et al. 2013b) coming from variations in Eddington fraction and luminosity (e.g., Shen & Ho 2014) that dominate over orientation. While we will consider EW [O III] as a contributing predictor of orientation, this measure alone is poor at best.

Fischer et al. (2014) have developed a method for determining orientation in radio-quiet Seyfert galaxies, but it depends on spatially resolved spectroscopy of the narrow-line region emitting [O III], which is not generally available for higher redshift quasars. Moreover, within type 1 radio-loud quasars, Brotherton (1996), for instance, failed to fine any significant correlation between the [O III] line profile and orientation (and actually this point will be crucial to our own proposal).

Our approach focuses on another known effect: the correlation of the velocity width of the Balmer lines with viewing angle, the primary evidence for a flattened BLR region as seen in Fig. 1. Many papers over the years have confirmed this effect and how it biases black hole masses based on broad emission lines (e.g., Krolik 2001; Jarvis & McLure 2006; Runnoe et al. 2013a). A few have proposed using this effect to determine orientation (e.g., Wu & Han 2001; Collin et al. 2006). We have developed and expanded on these latter ideas .

3. A Radio-Quiet Orientation Indicator

Wills & Browne (1986) first clearly demonstrated that the Full Width at Half Maximum (FWHM) of broad Hβ is inversely correlated with the radio core dominance (Fig. 2, left). They interpreted this result to indicate that the Hβ emission line comes from an axisymmetric disk structure, with smaller velocities when seen at smaller inclination angles, and larger velocities at larger angles, consistent with components of turbulence and rotation, the latter subject to a geometric projection effect.

What is critically important about this result is that this orientation effect biases black hole mass determinations that are built on reverberation mapping of the Hβ line (e.g., Peterson et al. 2004). The FWHM of Hβ sets the velocity scale (ΔV), which, when squared, enters into the virial mass calculation along with the size scale of the BLR which can be estimated using the continuum luminosity L:

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

The exponent γ is consistent with 0.5 (Bentz et al. 2009), and the latter expression is used for single-epoch black hole mass estimates (e.g., Vestergaard & Peterson 2006).

The velocity width of Hβ depends on both orientation and black hole mass. It alone does not make for a good predictor of viewing angle – or even black hole mass – without some additional work. What ought to be a good estimator of viewing angle would be the Hβ-based black hole mass if it could be normalized by an orientation-independent black hole mass measurement.

An alternative way to estimate the mass comes from the M-σ_* relationship where σ_* is the stellar velocity dispersion of the host galaxy (e.g., McConnell & Ma 2013, Fig. 2, right). This

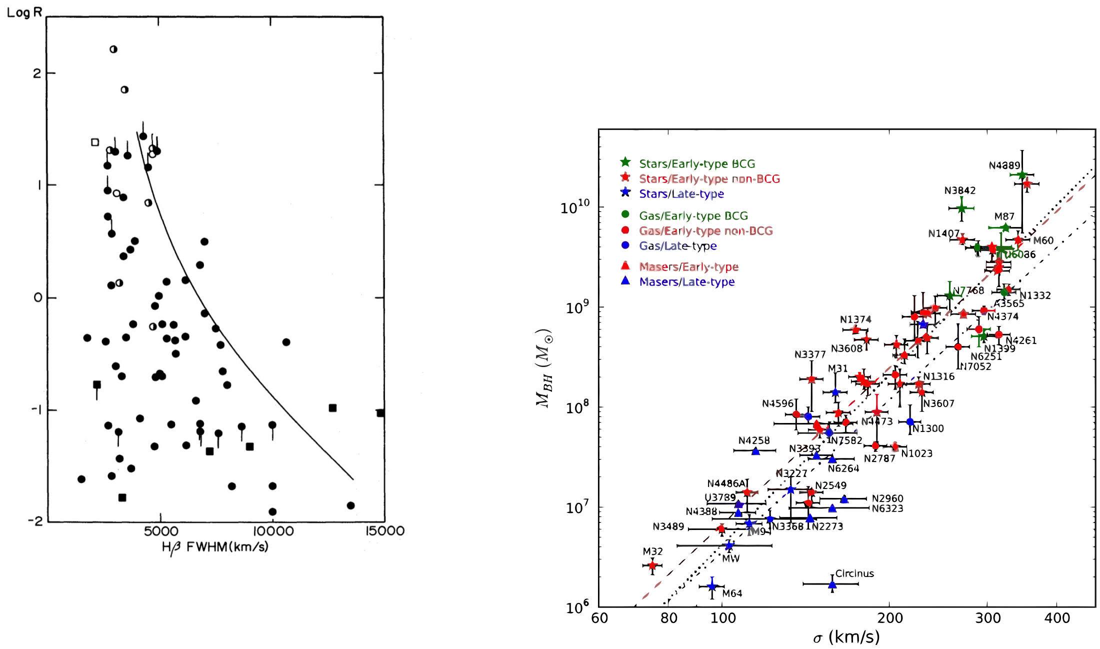


Fig. 2.— *Left.* The transformative Wills & Browne (1986) plot showing the inverse correlation between the core dominance parameter log R (large values face-on, small values more edge-on) and FWHM of Hβ. The solid line shows the behavior of a simple model that contains a disk-like component of the emitting gas, with face-on core-dominated quasars with log R showing systematically narrower Hβ. *Right.* An updated version of the M-σ_* relation from McConnell & Ma (2013).

latter parameter is independent of quasar orientation (see Brotherton et al. 2015). Taking the ratio of orientation-biased mass determined from Hβ to unbiased mass predicted from σ_* results in an optically based orientation indicator that correlates with radio-core dominance: $\mathrm{M}_{H\beta}/\mathrm{M}_{\sigma*}$.

Wu & Han (2001) and Collin et al. (2006), who also proposed this indicator, did not do much to test or otherwise follow-up this idea. We have, constructing a sample of 389 radio-loud quasars selected from the Sloan Digital Sky Survey (SDSS) quasar catalog (Schneider et al. 2010), computing log R using FIRST maps (Becker et al. 1995), and estimating σ_* from the FWHM of [O III] using a new, improved calibration (Brotherton et al. 2015). We found a highly significant correlation between the radio-loud orientation indicator log R and our orientation-biased mass ratio $\mathrm{M}_{H\beta}/\mathrm{M}_{\sigma*}$. We have recently updated our result, filtering the sample down to 147 quasars using a lower frequency radio selection that is less biased with respect to orientation (Westerbork Northern Sky Survey or WENSS; Rengelink et al. 1998). Figure 3, the key figure for this proposal, illustrates the result. The y on x regression line appropriate for predicting log R is:

$$\log \mathrm{R} = 0.60(\pm 0.14) - 1.09(\pm 0.14)\log(\mathrm{M}_{H\beta}/\mathrm{M}_{\sigma *}) \tag{2}$$

While the figure shows a very significant correlation (correlation coefficient = -0.53 corresponding to the 7 σ level), there is room for improvement. The radio core dominance measurements are based on 5 arcsec resolution FIRST maps and are not always high enough resolution to separate the core and lobe components (Jackson & Browne 2012), especially in "Compact Steep Spectrum" or CSS quasars (e.g., Odea 1998), which can constitute up to 20% of strong radio sources. Finally, we also need to replace the upper limits with detections.

We have been awarded eVLA A-array time at 10 GHz (0.2 arcsec resolution, 25 times better than FIRST) in order to resolve the lobes and measure clean core fluxes for the entire sample. The first half of the observations have been made, and the rest will be completed soon. We expect Fig. 3 to tighten up and allow us to obtain the best possible relationship between our radio and optical orientation indicators. While the traditional radio core dominance measure can predict viewing angle to about 10 degrees (Marin & Antonucci 2016), a radio core dominance using the optical flux to normalize the radio core is likely even better (e.g., Wills & Brotherton 1995; van Gorkom et al. 2015), and we will test that as well, noting that the radio core dominance measures can be mapped to angles empirically or by theory (e.g. Wills & Brotherton 1995; Drouart et al. 2012). This is our immediate task, improving the radio side as much as possible to permit the best possible calibration of our radio-quiet orientation indicator, but we believe that can also be improved.

4. Developing our Radio-Quiet Quasar Orientation Indicator

Now that we've quantitatively shown a highly significant correlation between $\mathrm{M}_{H\beta}/\mathrm{M}_{\sigma *}$ and log R, demonstrating that we can predict orientation based on optical quasar properties, there are several steps to take. Based on Fig. 3 and it's imminent improvement, our current orientation indicator, $\mathrm{M}_{H\beta}/\mathrm{M}_{\sigma *}$, is good enough for statistical studies with large samples. Our ultimate goal is enough improvement to apply to individual objects. We will approach the problem via the statistical analysis of the scatter in an updated Fig. 3 and its correlation with additional properties that are likely correlated with orientation:

1. **Other optical measures:** Echoing and amplifying previous studies, Brotherton (1996) noted a number of observables in addition to FWHM Hβ that correlate with log R in radio-loud quasars. Radio-loud quasars seen close to jet-on had broad Hβ lines with more sharply peaked, more Lorentzian profiles, while more highly inclined systems had broader and flatter profiles. Figure 4 illustrates this difference with spectra of 3C 120 (jet-on) and 3C 390.3 (more edge-on), each typical of their extreme orientation. In addition to the Hβ profile shape, the optical Fe II/Hβ line ratio, sometimes also called R Fe II, is stronger in face-on objects than in those more edge on. Finally, as previously mentioned, EW [O III] is weaker in face-on objects most likely due to continuum isotropy. Multivariate statistical analyses can determine to what extent these, individually or together, can help improve Fig. 3 in our eVLA sample. A more complex scheme may also be needed, for instance, to remove other sources of scatter

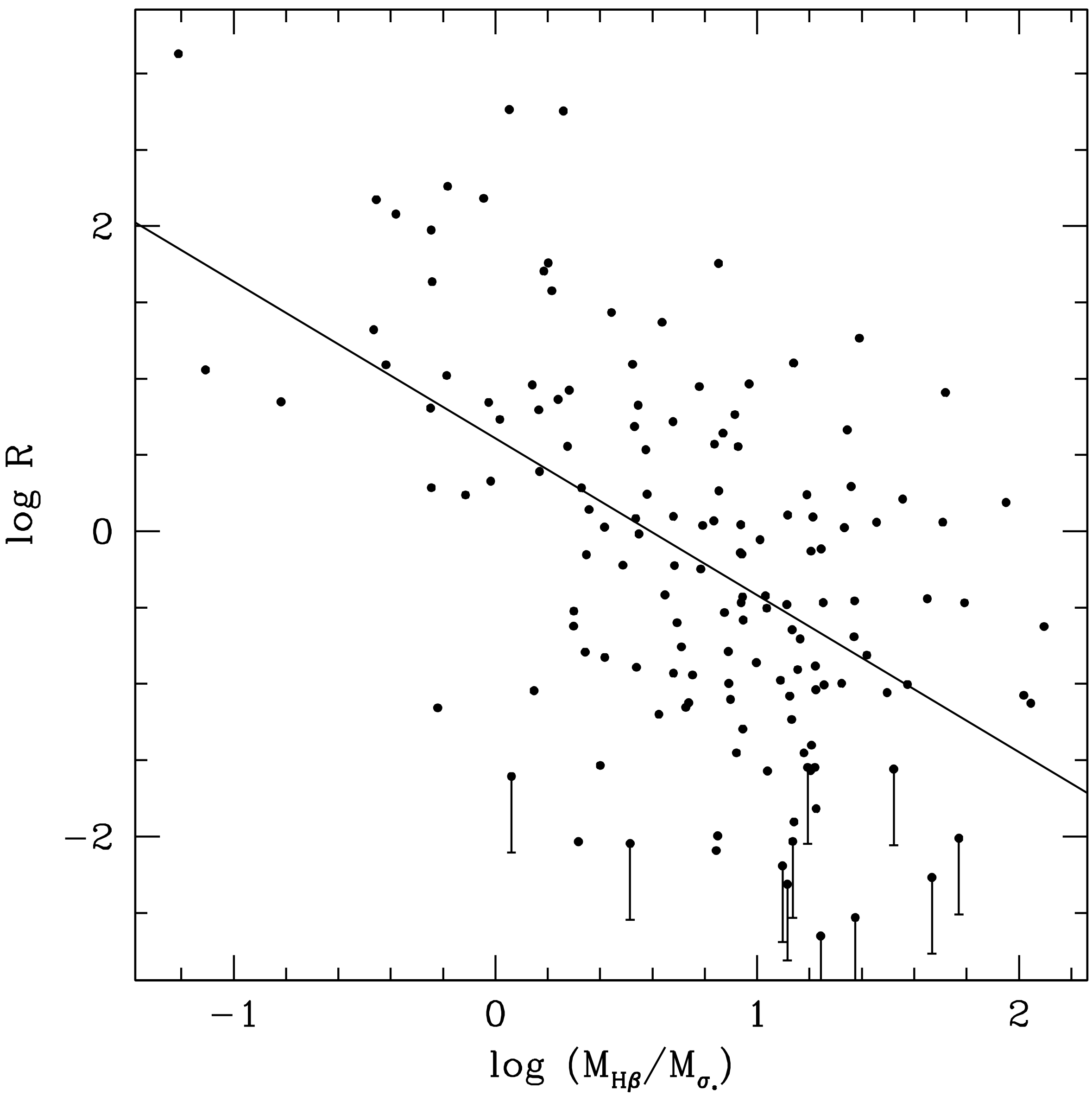


Fig. 3.— An updated version of Fig. 5 from Brotherton et al. (2015). We plot the radio-based orientation indicator log R (core/extended luminosity k-corrected to 5 GHz rest-frame) against the new optical orientation indicator $M_{H\beta}/M_{\sigma*}$ for 147 quasars selected in a largely orientation-unbiased manner. We have used spectral measurements and the scaling relationship of Vestergaard & Peterson (2006) to determine the biased Hβ-based black hole mass, and the M-$\sigma*$ relation of McConnell & Ma (2013) to obtain the normalizing black hole mass. The solid line is the y on x regression line (assuming the upper limits as detections), appropriate for predicting log R from $M_{H\beta}/M_{\sigma*}$. The correlation coefficient is -0.53, and significance level is approximately 7 σ.

such as that due to the Eddington fraction that dominates in the case of R Fe II and EW [O III]. We will discuss this more below in the context of SDSS quasars.

2. **Spectral Principal Component Analysis (SPCA):** Instead of looking to traditional line measurements, it can be more powerful to let the statistical variance of the data itself lead to physical parameters. SPCA in the optical easily recovers the first principal component of Boroson & Green's (1992) traditional analysis (Shang et al. 2003), for instance. No one has previously identified a component from PCA or SPCA clearly identified with orientation, until now. We have recently performed an SPCA of the optical Hβ region using several thousand SDSS spectra. The first principal component is the inverse correlation between [O III] and Fe II, as long established. The second SPCA involves the continuum color and Balmer line rations, and may be at least in part a reddening effect. The third component, SPCA3, accounting for over 10% of the spectral variance, correlates quite significantly with the radio core dominance (4σ) and even more strongly with $M_{H\beta}/M_{\sigma*}$ (brand new results, Fig. 5). The SPCA3 spectrum itself is a combination of continuum variation, Hβ, Fe II, and [O III] components that appear to represent the spectral variation due to orientation in a direct way. This may represent an unbiased way of mixing the optical measures discussed in item 1 in an optimal way to predict orientation.

3. **Infrared:** The near-infrared to mid-infrared colors of AGNs correlate with orientation as demonstrated by Drouart et al. (2012), for instance (see also Marin 2016). This is expected theoretical as well (e.g., the torus models of Pier & Krolik 1993 and Nenkova et al. 2008). These studies have been effective when looking at the entire range of angles, from type 1 to type 2 AGNs, and less effective when considering type 1s only. We plan to include data from 2MASS, UKIDSS, and WISE to see if we can do better using our eVLA type 1 quasar sample, being careful to screen for contaminating synchrotron associated with jet-on blazars. We fully expect improvement associated with the previous two items, and acknowledge that this one is more speculative, but we are conducting a full assault on orientation and will try this and any other ideas that may work.

Given the results cited above, we are optimistic that our search for additional correction terms will yield additional quantitative improvements, and the updates already underway to the Brotherton et al. (2015) are significant. We do want to acknowledge one caveat here, however. Implicit in the orientation-based mass ratio is the consistency of the M-σ_* relation. If there is significant evolution or large variation across the host types of luminous quasars, there may be issues with the generality of our orientation indicator, so we are very keen to make it more robust with additional terms; we note that the use of quasar broad-lines to estimate masses in the first place relies on calibration relative to the M-σ_* relation (cite), so if this is an objection to our approach it is an objection to quasar mass determination more generally.

5. Samples of Interest to Investigate using a Radio-Quiet Orientation Indicator

We plan investigate three samples: SDSS quasars with $z < 0.75$, the PG quasars of Boroson

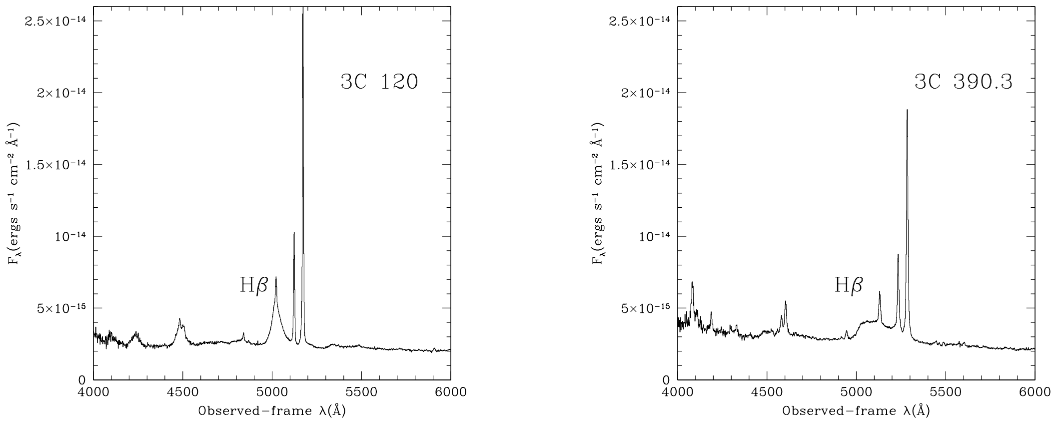


Fig. 4.— Example optical spectra taken at the Wyoming Infra-Red Observatory (WIRO) of two radio-loud quasars: 3C 120 with log R = 1.38 indicating a jet-on geometry, and 3C 390.3 with log R = −0.98 indicating a relatively large inclination angle. Note the broad Hβ lines (keeping in mind the narrow-line Hβ component sitting on top of each). The face-on 3C 120 shows an Hβ profile that is narrow and sharply cusped. The more edge-on 3C 390.3 shows and Hβ profile with quite a different shape, much broader with a larger fraction of the flux in the line wings.

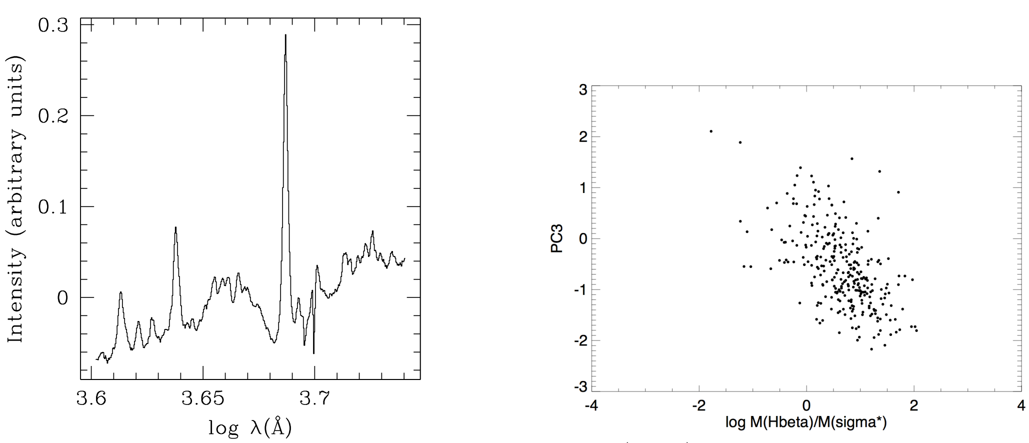


Fig. 5.— *Left.* The third spectral principal component (PC3) plotted in linear intensity verses log rest wavelength. Features associated with Balmer lines, optical Fe II blends, and [O III] are present. *Right.* The PC3 weights plotted against $M_{H\beta}/M_{\sigma*}$ for radio-loud quasars, showing a very highly significant correlation. The PC3 weights also correlate with the radio core dominance log R at the 4 σ level, indicating the variation in this complex spectrum is also an orientation indicator.

& Green (1992), and Reverberation Mapped (RM) quasars (Bentz & Katz 2015).

SDSS: We will start with the Sun & Shen (2015) sample of nearly 7000 SDSS low-redshift quasars for which the stellar velocity dispersion σ_* has been cataloged and made public. While this sample is statistically large and will be useful to investigate orientation effects, we would like to determine orientation more generally for as many of the SDSS quasars as possible. To that end, we will measure the FWHM [O III] in the ∼13,000 DR7 quasars and use the predictive equation of Brotherton et al. (2015) to provide σ_* as we have previously done for radio-loud quasars (scatter in the prediction is only ∼30%, not too bad given the total range). We note that $M_{H\beta}$ measurements are already available from Shen et al. (2011) or Sun & Shen (2015) for all these objects, including corrections for host galaxy contamination to the continuum luminosity, but we may need to measure other quantities ourselves (e.g., Hβ line shape). One particular objective is to verify the "main sequence" figure of Shen & Ho (2014), which purports to explain the diversity of low-redshift quasar spectra with two properties: Eddington fraction (L/L_{Edd}) and orientation. R Fe II is their Eddington ratio proxy, which we already know has some bias with orientation, and is likely better replaced with [O III]/Hβ, which does not (Brotherton 1996). In particular, we should see orientation segregate systematically along their y-axis, FWHM Hβ, to test their proposal.

PG Quasars: The 87 PG quasars of Boroson & Green (1992) represent a much studied and nearly complete sample. It is natural to want to add orientation. Direct measurements of σ_* are not readily available or easy to make in the majority of these luminous PG quasars. We will again use the FWHM [O III] as a proxy, and will measure that line from new R=2000 longslit spectroscopy using the WIRO 2.3 meter telescope (ample time is available to Wyoming faculty and students). One particular objective will be to look at the orientation distribution in a complete flux-limited sample, which has been considered through simulations by DiPompeo et al. (2014) in the context of how orientation biases luminosity functions in flux-limited samples. The orientations are not expected to be random.

Reverberation-Mapped (RM) Quasars: Finally, we want to look at RM quasars. Again, we will have to use WIRO to obtain optical spectra with high enough spectral resolution to obtain FWHM [O III] as a proxy for σ_*, although there are already about two dozen direct σ_* measurements (e.g., Woo et al. 2010) out of the more than 60 RM AGNs. The important objective for this sample is to look for orientation bias (compared to the complete PG quasar sample, for instance), which would affect all the masses determined from single-epoch scaling relationships (e.g., Vestergaard & Peterson 2006; Park et al. 2013). Given that face-on quasars are expected to be brighter on average than edge-on quasars, as we will discuss in more detail below, it would be surprising if there were not an orientation bias given the smaller telescopes historically involved in RM campaigns.

6. Improvement of Quasar Mass Determinations

The entire premise of our orientation indicator is based on the inclination-dependence of FWHM Hβ and the corresponding effect on mass. Figure 6 (from Runnoe et al. 2013) shows the difference between Hβ and orientation-unbiased C IV masses and how it correlates with log R,

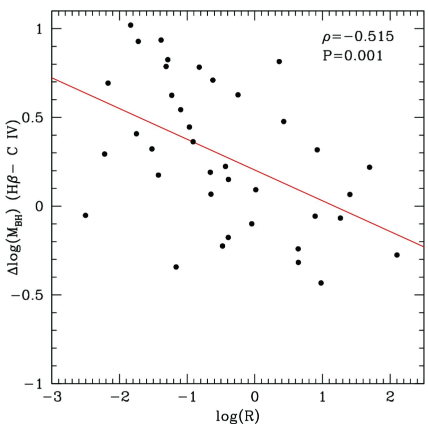


Fig. 6.— From Runnoe et al. (2013a), the black hole mass difference between formulations using Hβ and C IV based on the scaling relationships from Vestergaard & Peterson (2006) is plotted against the radio core dominance log R. The red line shows the y on x regression line that can be used to correct for orientation effects in the Hβ masses.

permitting us to calculate an orientation correction term:

$$\text{Corrected } \log(\frac{M_{\rm BH}}{M_{\odot}}) = \log(\frac{M_{\rm BH}}{M_{\odot}}) + 0.173(\pm 0.051)\log\text{R} \tag{3}$$

Given the range in log R runs from approximately -2 to 2, this corresponds to an effect of up to 0.7 dex, rather large, and a significant part of the $\sim$0.4 dex 1 σ uncertainty (Vestergaard & Peterson 2006) inherent in single-epoch virial mass estimates, perhaps the dominant part.

There are issues with C IV masses themselves (e.g., Runnoe et al. 2013c), and our sample size was not so large, and the new work will result in a better correction. Brotherton et al. (2015) shows how to replace a log R term with a $\text{M}_{H\beta}/\text{M}_{\sigma*}$ term. Using $\text{M}_{H\beta}$ in a term to correct $\text{M}_{H\beta}$ does have the weakness of susceptibility to large errors and outliers, while using $\text{M}_{\sigma*}$ (or the [O III] FWHM as a proxy for σ_*) can be dangerous if the relationships have mass dependencies or evolve with redshift. It is for these reasons that we are also looking to SPCA and other line measures to strengthen the optical orientation indicator more generally.

7. Improvement of Bolometric Corrections and the Anisotropy of Quasar SEDs

Correlations between radio-based orientation indicators and other properties reveal the geometry and inclination-dependent properties of unresolved quasar structures. For instance, the optical-UV continuum, and X-rays, are brighter in jet-on sources (e.g., Jackson et al. 1989). This empirical result has also been extended to a similarly anisotropic near-mid-infrared (Runnoe et al. 2013b), with jet-on systems also being systematically brighter by a factor of 2-3. Figure 7 shows the average SEDs of face-on vs. edge-on radio-loud quasars with the same intrinsic extended radio luminosity, an isotropic property.

The optical-UV from quasars likely arises from some form of an accretion disk (e.g., Shields 1978; Malkan 1983). Increasingly sophisticated models have been created, from the thin "α disk" of Shakura & Sunyaev (1973) to more modern numerical treatments like that of Hubeny et al. (2000), who include not just a Newtonian cosine factor for the projection of a flattened disk when

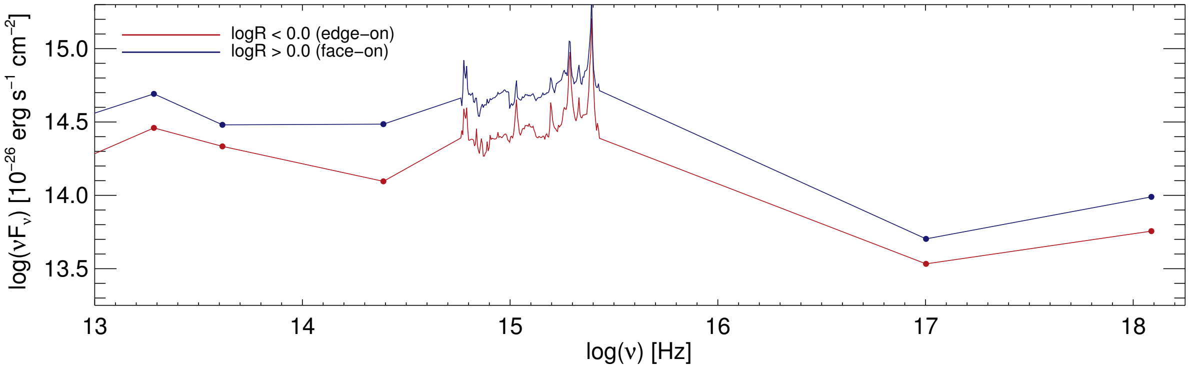


Fig. 7.— From Runnoe et al. (2013b). Composites SEDs of face-on (log R >0) and edge-on (log R < 0) are compared. Note that the radio-loud sample was selected based on isotropic extended luminosity at 6 cm, and that the energy scale is not arbitrary. Edge-on type 1 sources (likely seen at 30-60 degrees from the jet axis) are a factor of 2-3 fainter at all energies than their more face-on counterparts (seen at angles < 30 degrees).

determining observed flux, but also limb darkening and lensing effects. Nemmen & Brotherton (2010) investigated in detail how orientation affects observational properties of the Hubeny models, both in terms of luminosity and in shape of the "big blue bump" through the optical into the ultraviolet (Fig. 8). While there are some differences as a function of luminosity, theory suggests quasars seen within the opening angles of broad-lined objects have a viewing angle dependence not too different from simple Newtonian projection effects. Factors of ∼2 change are possible within likely opening angles for type 1 quasars. Furthermore, both the optical and UV behave similarly, although the UV peak emission may shift with angle.

Theory here seems roughly consistent with the Runnoe et al. (2013b) results for radio-loud quasars, but do radio-quiet quasars behave the same? They appear to have big blue bumps through the optical-UV no different from radio-loud quasars, suggesting they do. Anisotropic optical-UV continuum emission needs to be understood and included in bolometric corrections. Techniques that ignore anisotropy are likely wrong by ∼30% on average (Runnoe et al. 2012).

Radio-loud and radio-quiet quasars do not behave the same in X-rays, however. X-rays arise from a very small region in the inner accretion disk region of quasars (e.g., MacLeod et al. 2015). Compared to radio-quiet quasars, however, radio-loud quasars, display stronger and harder X-rays, which likely results from an extra component associated with the powerful jet (e.g., Elvis et al. 1994). The jet may account for much or all the X-ray anisotropy seen in radio-loud quasars. What is the true emission pattern for X-rays that are not associated with the jet?

Recent theoretical quasar models for the X-ray emitting corona (Chen et al. 2013; Xu 2015) predict nearly isotropic X-ray emission over quasar opening angles (Fig. 9 left), mostly due to

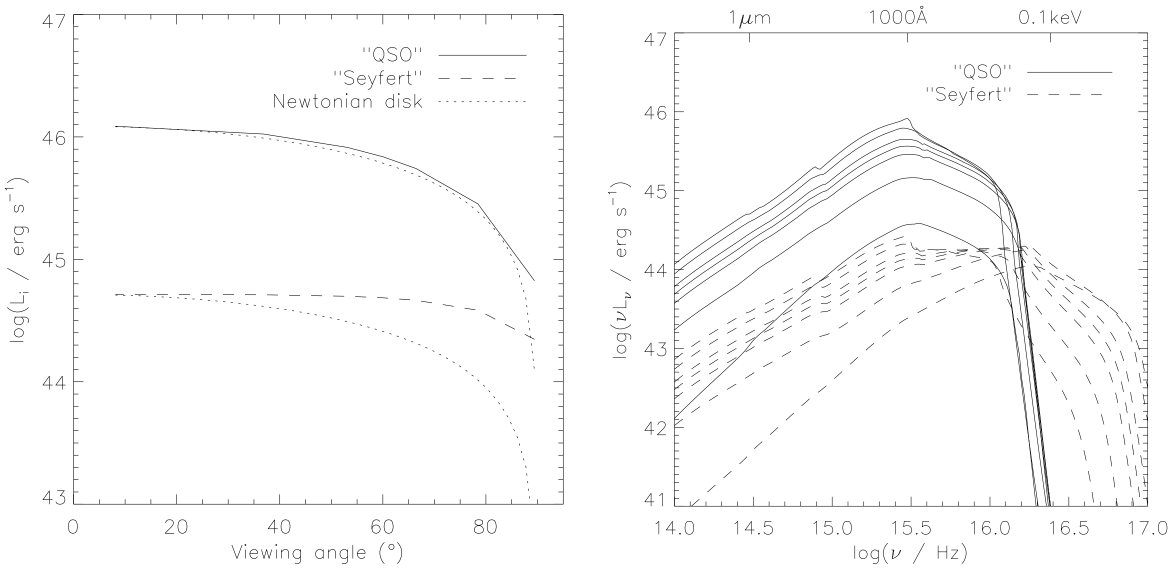


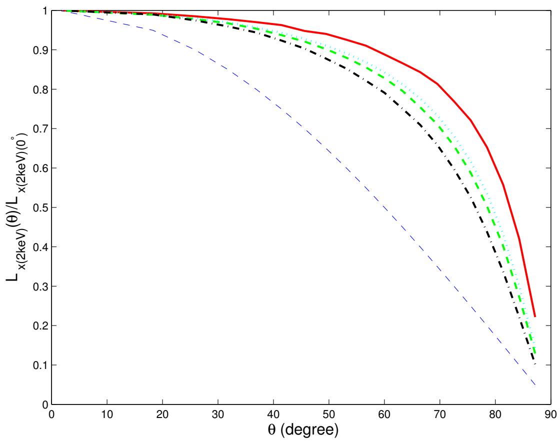
Fig. 8.— From Nemmen & Brotherton (2010). *Left.* The spectrally integrated output of two characteristic thin disk models models (Hubeny et al. 2000) as a function of viewing angle. The dotted lines show a cosine function for comparison. *Right.* Spectra of the models as a function of viewing angle from face-on to totally edge-on. Within a luminosity class, the optical/UV ratio is nearly constant with angle.

the small size of the emitting region and lensing effects of the black hole. These models therefore predict a significant change in α_{ox} (the optical to X-ray spectral index) of about 0.12 (factor of 2) between face-on and more edge-on quasars. What really needs to be done to test the model is to use a sample of radio-quiet quasars for which orientation may be determined, while also limiting other "confounding variations" that can affect the ratio of optical/UV light to X-ray emission, such as luminosity and L/L$_{Edd}$ (e.g., Gibson et al. 2009).

We have started preliminary analyses of the Young et al. (2009) sample of DR5 SDSS quasars observed with Chandra and XMM, keeping 67 objects with good enough quality data to measure the Hβ and [O III] lines, and good quality X-ray observations. We find a trend (Fig. 9 right), looking at $\Delta\alpha_{ox}$ (the residuals after fitting the "confounding variations" with luminosity and Γ (a proxy for L/L$_{Edd}$, Shemmer et al. 2008) against our orientation indicator. Again we point out that there is no correlation like this seen in radio-loud samples. We believe this is an exciting result and the first empirical test of its kind of X-ray corona models. More X-ray data is available in current archives, and new surveys will be available in the near future (e.g., eROSITA, Merloni et al. 2012), making this work very relevant.

8. Team and Research Management Plan

The PI and collaborator Jessie Runnoe are experts in observational quasar studies, including orientation issues, with dozens of papers on the topic, many using approaches described above but



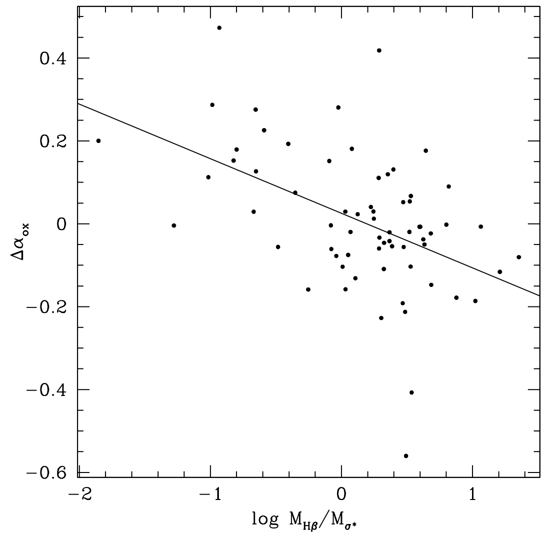


Fig. 9.— *Left.* From Xu (2015). X-ray flux density (2 keV) vs. viewing angle for the same four models. The X-ray emission is much more isotropic than for cosine θ (blue dashed line) for < 60 degrees. The models indicate a variation in α_{ox} of a little less than 0.3, due to the optical to X-ray flux ratio changing by a little less than a factor of 2, over typical quasar opening angles. *Right.* New result. For 67 radio-quiet quasars from Young et al. (2009). The Y-axis plots residuals between observed α_{ox} and α_{ox} predicted from a multiple regression using both the continuum luminosity at 5100 Å and the hard photon index Γ, an indicator of the Eddington ratio. The y-axis plots our optical orientation indicator, with more edge-on systems to the right. The solid line shows the y on x regression line. The Pearson correlation coefficient is -0.48 significant at the 5 σ level, indicating that indeed edge-on systems appear to have α_{ox} approximately 0.2 steeper than face-on systems, very different from what is found for radio-loud quasars.

previously focused on radio-loud quasars. The PI is will directly supervise graduate student Jaya Maithil who will develop her thesis as a major part of this project. She has previous experience with radio observations of AGN jets, helpful background to get a fast start.

The first project will be to improve on the initial work of Brotherton et al. (2015), using our less biased sample and the new eVLA radio observations, along with the development of additional correction terms based on Hβ shape and perhaps other properties. Additionally, we will measure FWHM [O III] in $\sim 10^4$ $z < 0.75$ SDSS quasars and obtain R=2000 WIRO spectroscopy of the PG quasars and RM samples. We will produce prescriptions for, and catalogs of, orientations, corrected black hole masses, and bolometric luminosities. We will also publish a paper on the anisotropy of the X-ray in radio-quiet quasars. We will share all our data via electronic tables published with our papers, as well as a dedicated website at Wyoming (http://physics.uwyo.edu/agn/).

9. Public Education and Outreach

The PI is an active promoter of astronomy to the public through some unconventional avenues. He writes scientifically accurate science fiction novels published by Tor books that have reached tens of thousands of readers. Star Dragon (2003) is about a trip to the cataclysmic variable star SS Cygni, while Spider Star (2008) is about a dark matter "planet" for want of a better word. He also writes short fiction and has edited or co-edited two anthologies of astronomy-related stories (*Diamonds in the Sky*, 2008 with NSF funding, and *Launch Pad*, 2013, co-edited by Jody Lynn Nye). A new anthology *Science Fiction by Scientists* is coming out just now from Springer, which includes explanations of the science as afterwords to each story. The PI gives astronomy talks 2-3 times a year to packed rooms at science fiction conventions where there is a great appetite for science. Brotherton was the official "science guest of honor" at the science fiction conventions at Windycon in Chicago in 2011, and FenCon, in Dallas in 2016, speaking to hundreds of engaged astronomy fans. He was also a guest on NPR's nationally syndicated program "On Point," speaking about science in the movies.

In 2007, the PI founded the Launch Pad Astronomy Workshop for Writers (www.launchpadworkshop.org), which has enjoyed funding from NASA, NSF, STScI, and the Science Fiction and Fantasy Writers of America. Launch Pad is a week-long workshop designed to provide writers and other creative professionals with large, diverse audiences a crash-course in modern astronomy, as well as the foundation, inspiration, and confidence to pursue astronomical knowledge beyond our program. The rationale for Launch Pad is two-fold: first, many scientists were inspired to pursue their careers by science fiction and other science-rich entertainment (e.g., *Nova* and *Cosmos* on PBS, *Star Trek*), and, second, the adult public continues to learn – for better or worse – from the entertainment they consume. By educating and motivating writers to include more and better astronomy in their work, our short-term effort focused on writers can reap these long-term goals by reaching much larger numbers in their readership over the rest of their professional careers.

Launch Pad is already a well-regarded program with a national reputation that has produced over 150 alumni during its ten years of operation, and together they have an audience numbering in the millions. Past participants include: Robert Sawyer (whose novel *Flashforward* became a primetime drama on NBC), Marc Laidlaw (lead writer on the Half-Life 1 and 2 video games, which sold over 7 million copies), Steven Gould (whose novel *Jumper* became a blockbuster movie), Ann Leckie (whose novel *Ancillary Justice* won the Hugo and Nebula awards), New York Times best sellers Julie V. Jones, Carrie Vaughn, N. K. Jemison, and others. We get talented people excited about astronomy and about getting it right in their work. They, in turn, can reach potentially huge audiences with stealth education and also inspire the next generation of scientists. The footprint we make to the general public is, quite literally, astronomical.

Launch Pad is already a success based on ongoing overwhelmingly positive and passionate feedback from participants and the science fiction writing community, as well as direct evidence in the form of the work produced by our alumni and its wide distribution to the public. As part of an STScI E/PO grant, we had an external evaluation done last year and here is the summary:

"The findings of this study suggest that the Launch Pad workshop was a major success in increasing the basic astronomy knowledge of its participants, their ability to present astronomy concepts in their writing and confidence in their ability to include more accurate science in their work. The sense of self-efficacy in science that was developed in participants as a result of their participation in the Launch Pad workshop was noticeable in every measure. These authors also increased their understanding of the scientific practices of astronomers, although not to the same extent they improved their basic astronomy knowledge. Workshop participants were confident that they were including the NASA/HST astronomy resources in their writing based on survey data, however were not able to produce many concrete examples when asked in the interview process. Based on the writing samples that were produced, and the ideas shared during the interviews, these authors are not only including more accurate science in their writing, but as an outcome of the workshop have put greater importance on having accurate science in all their work, regardless of the genre."

10. Results from Prior NSF Support

NSF proposal ID AST-1010022, $65k, 09/15/10 – 09/15/12

Officially "New Perspectives on Quasar Outflows," but only the educational/outreach portion **"The Launch Pad Astronomy Workshop for Writers,"** was funded.

The grant supported the Launch Pad Astronomy Workshop for Writers for the summers of 2011 and 2012, reaching 32 professionals. The workshop is described above. Publications resulting from the NSF Award:

Brotherton, M. S., 2012, "The Launch Pad Astronomy Workshop for Writers," In: 2012 summer issue of the Science Fiction Writers of America Bulletin

Brotherton, M. S., 2013, "A Gram of Prevention is Worth a Kilogram of Cure: Teaching Writers Science," In Hollywood Chemistry–When Science Met Entertainment," edited by Nelson, Grazier, Paglia, & Perkowitz, ACS Symposium Series, Vol. 1139, American Chemical Society, 25-33

Launch Pad (2013, Wordfire Press), edited by Jody Lynn Nye and Mike Brotherton, a short story collection by participants of the 2012 Launch Pad workshop.

11. Broader Impacts

The research activities described here will significantly advance our understanding of quasars, particularly in the determination of their fundamental parameters: orientation, black hole mass, bolometric luminosity, and Eddington fraction. Our improved catalogs of these quantities, and the formulas to produce them, will be published and available to the community for all sorts of investigations. This proposal, in essence, is direct service to quasar astronomers of all sorts, and can be expected have have a broad impact. We will train a female PhD student (Jaya Maithil) in research. The outreach activities will reach many hundreds of thousands of readers, or more, indirectly through the writers participating in the Launch Pad Astronomy Workshop, and directly through Dr. Brotherton's own science fiction, blogging, and public appearances.