Contents

Understanding the Post-Starburst Quasar Population

1 Personnel and Work Efforts

This request is primarily for summer salary for the PI and full salary for a post-doc/research scientist, along with additional funding for travel to meetings, some computing upgrades, and page charges over the lifetime of the grant. Brotherton's current post-doc is Zhaohui Shang, but who likely will not remain in Wyoming another five years although his collaboration would be expected to continue. Shang is requesting additional support in an ADP proposal. In the event that both are approved, Shang would split his time between projects and a new postdoc or data aides/graduate students would be hired to help, probably in year 2, to work full-time on this project. This project, if funded, will be the major research focus of the PI (current job description: 45% research during the 9-month academic year, 100% research in the summer), enabling a 50% yearly effort. Dan Vanden Berk is an expert on the SDSS quasar spectra and will contribute his expertise as needed. The table below summarizes the work effort of the proposers.

Personnel Work Effort Summary

Investigator Year:	% Effort 1	% Effort 2	% Effort 3	% Effort 4	% Effort 5
Michael Brotherton (PI)	50	50	50	50	50
Dan Vanden Berk (Co-I)	5	5	5	5	5
Zhaohui Shang (Co-I) and/or Future Postdoc	100	100	100	100	100

2 Science Abstract

We propose a comprehensive program of multi-wavelength study of post-starburst quasars now being found in significant numbers for the first time using the Sloan Digital Sky Survey. Post-starburst quasars are broad-lined active galaxies that display massive stellar populations with ages on order of 100 megayears, and like their cousins the post-starburst galaxies, these systems appear to be the direct result of galaxy interactions. Our program will investigate the following questions: What is the role of a post-starburst quasar phase in the evolution of a galaxy and its central black hole? What is the relationship of post-starburst quasars to the general class of quasars? To ultraluminous infrared galaxies? To post-starburst galaxies? Do post-starburst quasars reveal how black hole-bulge mass correlations arise? Even though galaxy interactions are widely believed to be an important – if not the most important – trigger of nuclear activity, there are few large, systematic observational investigations that address this topic in as a direct manner as we propose.

3 Science Background

3.1 The AGN-Starburst Connection

There has long existed various sorts of anecdotal evidence for a connection between nuclear activity and the presence of starbursts, but it has only been in recent years that such connections have started to become quantitative and convincing.

Probably the most notable piece of quantitative evidence has come from the development of being able to make reliable estimates of black hole masses in both normal galaxies and active galaxies. There exists a tight correlation between galaxies' central black hole masses and measures of their bulge masses, particularly the stellar velocity dispersion (the so-called "M-σ" or "M-sigma" relation, e.g., Tremaine et al. 2002, and many others). This result indicates that the growth of black holes is intimately linked to the formation and evolution of their host galaxies. Theorists trying to understand the connection have put forward models in which the black hole comes first, the stars come first, and models in which both grow together. A recent result (Shields et al. 2003) is consistent with tandem growth to $z \sim 3$, perhaps supporting models in which hierarchical galaxy formation fuels both bulge and black hole growth over cosmic time.

Rapidly accreting massive black holes shine as quasars. Galaxy bulges forming or growing are experiencing massive starbursts. While it is possible that black hole and bulge growth are related in a complex manner through secondary processes, it is most natural to look for a more primary connection. For instance, Sanders et al. (1988) hypothesized that ultraluminous infrared galaxies (ULIRGs: $L_{IR} > 10^{12} L_{\odot}$), strongly interacting merger systems heated by both starburst and AGN power sources, evolve into normal blue quasars after the central engine clears away the dust associated with the massive star formation. Such mergers and the ensuing activity could lead to the observed relationships. There are other possibilities, as binary quasars are seen that

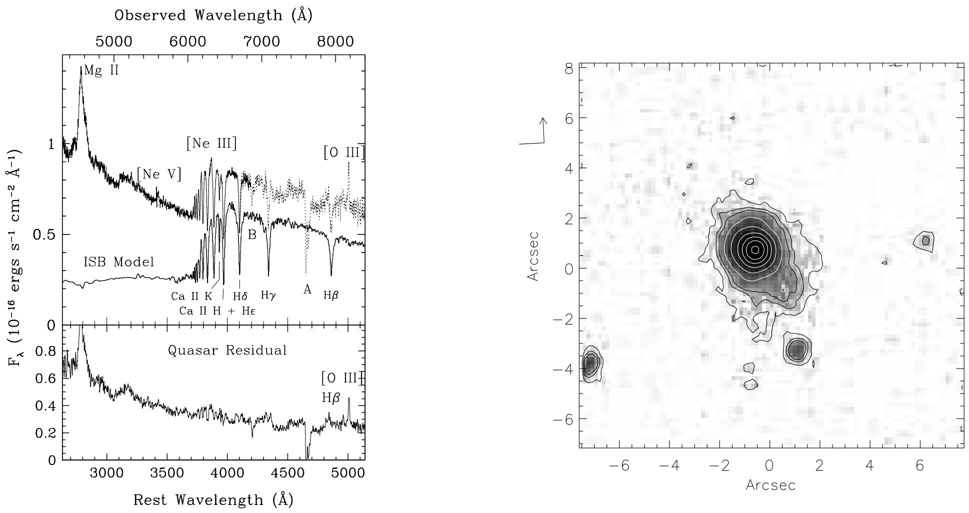

Figure 1: **Left.** A Keck spectrum of UN J1025–0040 (Brotherton et al. 1999), with a 400-Myr-old starburst model and residual. **Right.** Ground-based K-band Keck image of UN J1025–0040, 0.5 arcsec seeing, showing surrounding fuzz and an interacting galaxy (Brotherton et al. 1999, Canalizo et al. 2000).

are clearly pre-merger, and a sizable fraction of host galaxies show no evidence for interactions. Still, there is a population of *post-starburst quasars* that may represent the transition phase of the Sanders et al. scenario, or may simply represent, in a more general sense, types of interactions that lead to both black hole growth and to bulge growth.

3.2 The Post-Starburst Quasars

Post-starburst quasars show simultaneously an AGN and a massive luminous starburst ~100 Myr old, with composite spectra displaying broad emission lines as well as the Balmer jumps and strong Balmer absorption lines characteristic of type-A stars. The most extreme post-starburst quasar and class prototype is UN J1025−0040 (Figure 1; Brotherton et al. 1999a). The strong starburst component has an age of ~ 400 Myr, and a bolometric luminosity of $10^{11.6}L_\odot$, equal to that of the quasar component within the uncertainties. A younger UN J1025−0040 (tens of Myrs after the starburst) would have a more luminous stellar population and would likely be dust enshrouded, placing it in the ULIRG class. Canalizo et al. (2000) show that UN J1025−0040 has a nearby companion galaxy also in a post-starburst phase. HST WFPC2 imaging (Brotherton et al. 2002) shows that the starburst is nuclear, the host resembles a merger remnant, and a less massive young starburst is present. UN J1025−0040 is a plausible transition between ULIRGs and quasars.

Brotherton et al. (1999b) discovered another post-starburst quasar in a binary quasar system. FIRST J1643+3156B is clearly pre-merger and does not fit the picture of being an evolved ULIRG. The starburst in FIRST J1643+3156B is younger than the one seen in UN J1025−0040, however, and less massive. There surely must be a link between the type of galaxy interaction transpiring and the amount and timing of star formation/AGN activity present. For reasons we discuss below, this question is best addressed statistically and requires looking at samples of objects.

We note that we use the terminology of "post-starburst quasars" here in analogy to "post-starburst galaxies" (Dressler & Gunn 1982), which may be related objects (§8). Post-starburst galaxies are also known as "E + A" or "k + A" galaxies after the composite nature of their stellar populations, and we have sometimes similarly referred to post-starburst quasars as "Q + A" galaxies.

3.3 The Potential of Post-Starburst Quasars

The quasar lifetime is not well known, and neither is it well known how often, if at all, galaxies experience quasar activity. Some general trends do exist, however, that indicate quasar activity and star formation have both evolved strongly and similarly from redshifts of 2-3 to the present, quieter epoch (e.g., Boyle & Terlevich 1998), a finding that reinforces the notion of an AGN-starburst connection. Arguments about quasar energetics, efficiencies, and the observed masses of central black holes, suggest lifetimes on order of 10^8 years or less (see, e.g., Ferrarese 2002). Interesting enough, this is the same order of magnitude as the lifetimes of type-A stars that characterize post-starburst populations.

It has been suggested that aging starbursts associated with AGN can provide a clock indicating when the AGN ignited (e.g., Stockton 1999). This may be true, in at least a statistical sense, but is complicated by a number of factors that can be impossible to sort out for individual objects. For instance, in galaxy interactions, starbursts presumably occur first, and then after a delay the AGN is fueled by gas sinking into the center, but the timescale for that can vary depending on the type of interaction. Furthermore, the AGN accretion timescale is shorter than galaxy interaction timescales, and may not vary monotonically (e.g., dropping slowly and systematically following ignition as the fuel reservoir is depleted), making any relationship between quasar accretion rate and starburst age difficult to infer from individual objects. Furthermore, interactions that fuel AGN may span a wide range of types (as in both post-merger and pre-merger systems). Large samples of objects would be required to sort through a possibly heterogeneous set of interactions and establish general trends.

ULIRGs are recognized as an important population of sources as they provide information about galaxy evolution and nuclear activity. Post-starburst galaxies are recognized as an important population as they provide information about galaxy evolution. Post-starburst quasars may be directly related to one or both classes as an evolutionary stage, or there may be alternative evolutionary paths altogether. What is clear is that we are now in a position to define statistically large samples of post-starburst quasars and figure out how they fit into the evolution of quasars and their host galaxies.

4 Post-starburst Quasars in New Quasar Surveys

While detailed studies of individual objects, especially extreme individual objects, can teach us important lessons, studying populations and variations across populations is often more scientifically profitable. The new large quasar surveys, specifically the 2dF and SDSS quasar surveys, provide for the first time the opportunity to assemble statistically large samples of post-starburst quasars.

We searched the spectroscopic database of the 2dF Quasar Survey (e.g., Croom et al. 2001). We find 70 of the 2939 quasars (2.4%) with $z < 0.75$ show high-order Balmer line absorption (at $> 3\sigma$ detection levels) indicating post-starburst components (with an average of 30% of the total flux at wavelengths longer than the Balmer jump). The redshift distribution is peaked at $z \sim 0.4 - 0.5$, as higher redshift post-starbursts are being missed because the intrinsically more luminous high-redshift quasars reduce the contrast of the Balmer lines.

We have also searched for post-starbursts among the quasars in data release 1 (DR1) of the SDSS using an automated algorithm based on the one that Zabludoff et al. (1996) used to select post-starburst galaxies. Our code measures the equivalent width of the Hδ absorption line, the Balmer jump strength, and related uncertainties. The classification criteria is more complicated than in post-starburst galaxies, however; for instance, the presence or absence of [O II] λ3727 is not relevant in post-starburst quasars since the AGN can provide the ionizing photons, and narrow Balmer lines may be emitted from such emission-line regions diluting the stellar absorption features (which is why we use only Hδ rather than Hδ, Hγ, and Hβ as do Zabludoff et al.). Compared to the 2dF Quasar Survey, the higher quality SDSS data and less-biased selection results in a higher fraction of post-starburst quasars, especially at lower redshifts ($z \sim 0.1 - 0.2$) where the incidence is about 5%. Our least restrictive selection criteria produced a catalog of 365 objects with $z < 0.5$. Figure 2 shows, in a couple of ways, the incidence of post-starburst quasars in the SDSS DR1.

We are refining our selection criteria to ensure we are finding objects with massive post-starburst populations and are not confused by weak AGN with significant host galaxy contributions, or other sorts of interlopers. Our more restrictive selection criteria includes looking at the equivalent widths of Hδ, the Ca II H and K lines, the Balmer jump, the SNR, and the absolute magnitude. These more conservative conditions result in a smaller catalog of 114 objects in DR1, but the starbursts can all be expected to represent significant increases in stellar mass. We are continuing to work to understand the selection criteria – ideally, when we have a final set of criteria, we will be able to describe robust limits on age and mass and find all the objects occupying the important parts of parameter space. We recognize this isn't the easiest problem, but we are confident that we can address it and at a minimum are capable of finding and characterizing the most extreme objects that can teach us the most about the phenomenon. Figure 3 shows some example post-starburst quasar spectra from the SDSS and their corresponding images.

We have examined the SDSS images of our spectroscopically selected post-starburst quasars. At the $\sim 1.2''$ seeing characteristic of the SDSS, about 40% appear to be close interacting doubles or have companion objects within $10''$. Even the single sources

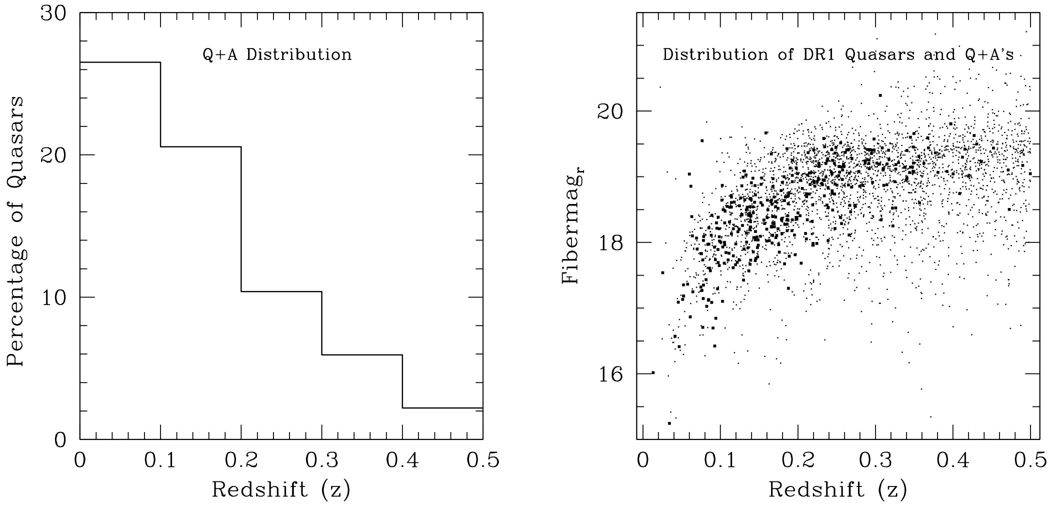

Figure 2: Distributions of post-starburst quasars in the SDSS DR1, as a percentage of the total (left) and as filled squares in a redshift-magnitude diagram (right).

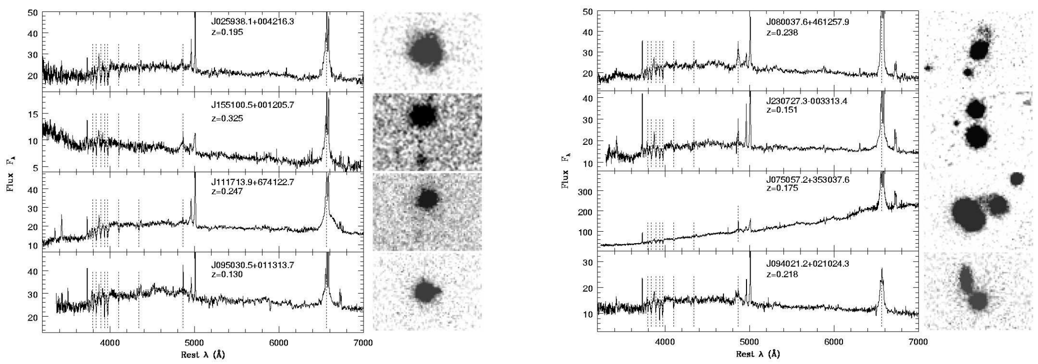

Figure 3: **Left.** SDSS spectra/images of four "single" post-starburst quasars. **Right.** SDSS spectra/images of four "double" post-starburst quasars. Dashed lines indicate stellar absorption. Images are about 30″x 20″and displayed with a hard stretch. All show signs (at least hints) of recent mergers/interactions.

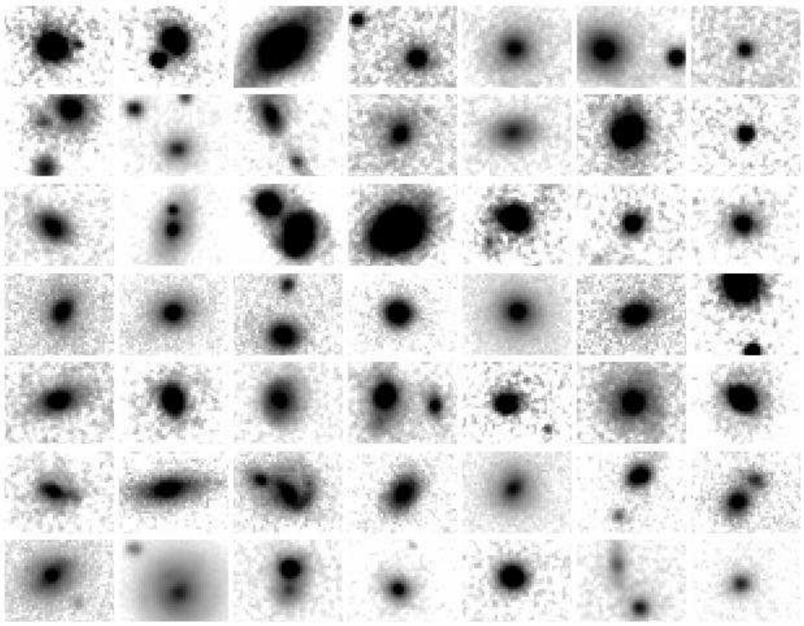

Figure 4: SDSS i band $12'' \times 16''$images of 49 post-starburst QSOs. We have applied a hard logarithmic stretch to pull out fuzz detail, and shifted centers to reveal nearby companions. About 40% appear to be interacting or to have nearby companions at the $1.2''$SDSS resolution.

show at least some extended fuzz from the host galaxy, and often features like tidal tails indicative of merger activity. This is reminiscent of the post-starburst galaxies which are uniformly interacting or merger systems (§8). Figure 4 shows 49 random examples. Some systems appear to be clearly pre-merger – two interacting galaxies with a separation – while others appear post-merger – disturbed morphologies with stray tidal features, while others will require additional observations to determine their nature. Note that typical "normal" quasars when seen in their SDSS images like this appear to be point sources or just a little fuzzy.

Subsequent sections describe what we know about the post-starburst quasars from other types of observations, particularly data archives we propose to use, and what types of new observations we plan to make to extend our understanding.

5 Post-starburst Quasars in X-rays

5.1 Archival Data – ROSAT

In our larger, least restrictive catalog of the 365 objects in SDSS DR1, 56 were detected by ROSAT (typically from the ROSAT All Sky Survey, RASS), or about 15%. In our more conservative catalog of 114, the percentage rises to 25% – likely the result of a bias to brighter sources with better quality data. While these percentages are not too different from those of normal quasars in the SDSS Early Data Release (Vignali et al. 2003), there are some interesting points to consider here. These

ROSAT-detected post-starburst quasars are all quite X-ray bright compared to normal radio-quiet quasars with optical-to-X-ray spectral indices of $\alpha_{ox} \sim -1$ (where $S_\nu \propto \nu^{\alpha_{ox}}$). Normal radio-quiet quasars have an average $\alpha_{ox} \sim -1.5$. (Note: We have computed α_{ox} for the post-starburst quasars without first subtracting off the stellar component, which would increase the apparent X-ray loudness of these sources).

This X-ray brightness is potentially very interesting. These post-starburst quasars are young, or recently refueled quasars, in one scenario, which may be expected to have larger than average accretion rates and enhanced soft X-rays (e.g., similar to BAL quasars and narrow line Seyfert 1 galaxies, ala Mathur 2000). It is also possible that more recent or ongoing starburst activity exists in these quasars that can contribute to enhancing the soft X-ray emission. It is more likely, however, that the ROSAT results arise from selection biases: SDSS specifically targets the vast majority of all ROSAT sources, and the ROSAT All Sky Survey limit is such that many of the 18th magnitude quasars of normal X-ray brightness would not be detected. The X-ray emission from the prototype UN J1025−0040 is unknown, and the distribution of α_{ox} for post-starburst quasars in general, is unknown. We will, but have not yet, performed survival analyses including all the upper limits to draw the strongest conclusions possible regarding the X-ray properties of post-starburst quasars based on ROSAT and other available archival X-ray data.

5.2 New Observations

We plan to use the Chandra X-ray Observatory and XMM-Newton to observe representative samples of post-starburst quasars that span the full range of properties (e.g., looking at both isolated systems that may be post merger, and interacting systems that appear pre-merger). With the number of sources in the eventual catalog, we can expect to have some additional serendipitous observations available from archival data. For the pending Chandra cycle we have already proposed to obtain ACIS-S images/spectra of the eight post-starburst quasars seen in Figures 3 and 4, as well as UN J1025−0040, which is likely to be fainter than the eight in the X-rays as it is optically fainter, but which is the most luminous and best studied case of a post-starburst quasar to date.

6 Post-starburst Quasars in the Infrared

6.1 Near Infrared

While in some sense the near-infrared is just an extension of the optical, with similar physical processes, the near-infrared provides important extra diagnostics. Whereas the stellar population contributes about half of the red optical light in an extreme post-starburst quasar, the stellar contribution is even larger in the near-infrared (e.g., UN J1025−0040, see Canalizo et al. 2000). Models fit to the optical can be tested and, if necessary, revised based on near-infrared magnitudes.

In our most comprehensive DR1 catalog of 365 objects, 308 appear in the 2MASS point source catalog in at least one band, and a few additional sources appear associated with 2MASS extended sources, so for more than 85% of our catalog, the catalog that includes the faintest sources, we already have near-infrared magnitudes. We note that this is an (at least somewhat) higher fraction than for ($z < 0.5$) SDSS quasars in general (60% in 2MASS), and it is likely because the objects that we select have redder optical-NIR colors due to their prominent stellar populations. We can use the Goddard Infrared Camera at the Wyoming Infrared Observatory's (WIRO) 2.3 meter telescope to obtain near-infrared magnitudes of the fraction of sources too faint to appear in 2MASS.

We note here that NSFCAM on NASA's Infrared Telescope Facility (IRTF) now has AO capabilities when targets have a guide star close enough. Our sample will be large enough to be sure of having a subsample that can be observed with AO, and studying the host galaxies at 0.2 arcsecond resolution with IRTF can complement the optical SDSS images and HST imaging work (§9). In general, an analysis of extended light in different wavebands can be used as an additional way to separate AGN and stellar components, assuming that the stellar component is resolved.

6.2 Mid and Far Infrared

At mid and far-infrared wavelengths, the primary emission mechanisms in both AGNs and starburst populations involves radiation from heated dust. Stockton (1999) discusses how quasars have warm IRAS colors, and starbursts have cool IRAS colors, but that there does exist a handful of intermediate objects in which both AGN and starbursts are present, some of which are classified as quasars (e.g., 3C 48) and others that have multiple classifications (e.g., Mrk 231). In any event, mid-IR colors have diagnostic capability since quasars and stars tend to heat dust to different temperatures.

In our large SDSS DR1 sample, only six objects appear to be IRAS sources, and even these are not detected in every waveband. We expect this number to grow somewhat with additional data releases as our catalog expands, but it is unlikely to provide much insight. It's probably best to think of the IRAS detections as a small pilot program for working with Spizter.

All three instruments on Spitzer can provide diagnostics of the contributions from the different components of post-starburst quasars. Dale et al. (2001) illustrates how the spectral energy distributions of AGNs and star-heated dust differ in the near to far infrared (Fig. 5), and thus IRAC and MIPS can put our objects on diagnostic color-color diagrams. Better, but more expensive in terms of telescope time, would be to obtain mid-infrared spectroscopy for a carefully selected representative sample. Genzel et al. (1998) used ISO to obtain mid-infrared spectroscopy of ULIRGs in an effort to sort out the energetic contributions from AGN and stellar sources, and showed how the PAH features (the emission lumps short of 10 microns, e.g., 7.7 microns, in Fig. 5) and certain mid-infrared emission line ratios (e.g., [Ne V]/[Ne II]) can be used as diagnostics. PAH features are not present in the dust associated with AGN, so the equivalent width of such features provides a measurement of the relative amounts of dust heated by each component. We note there is some controversy on

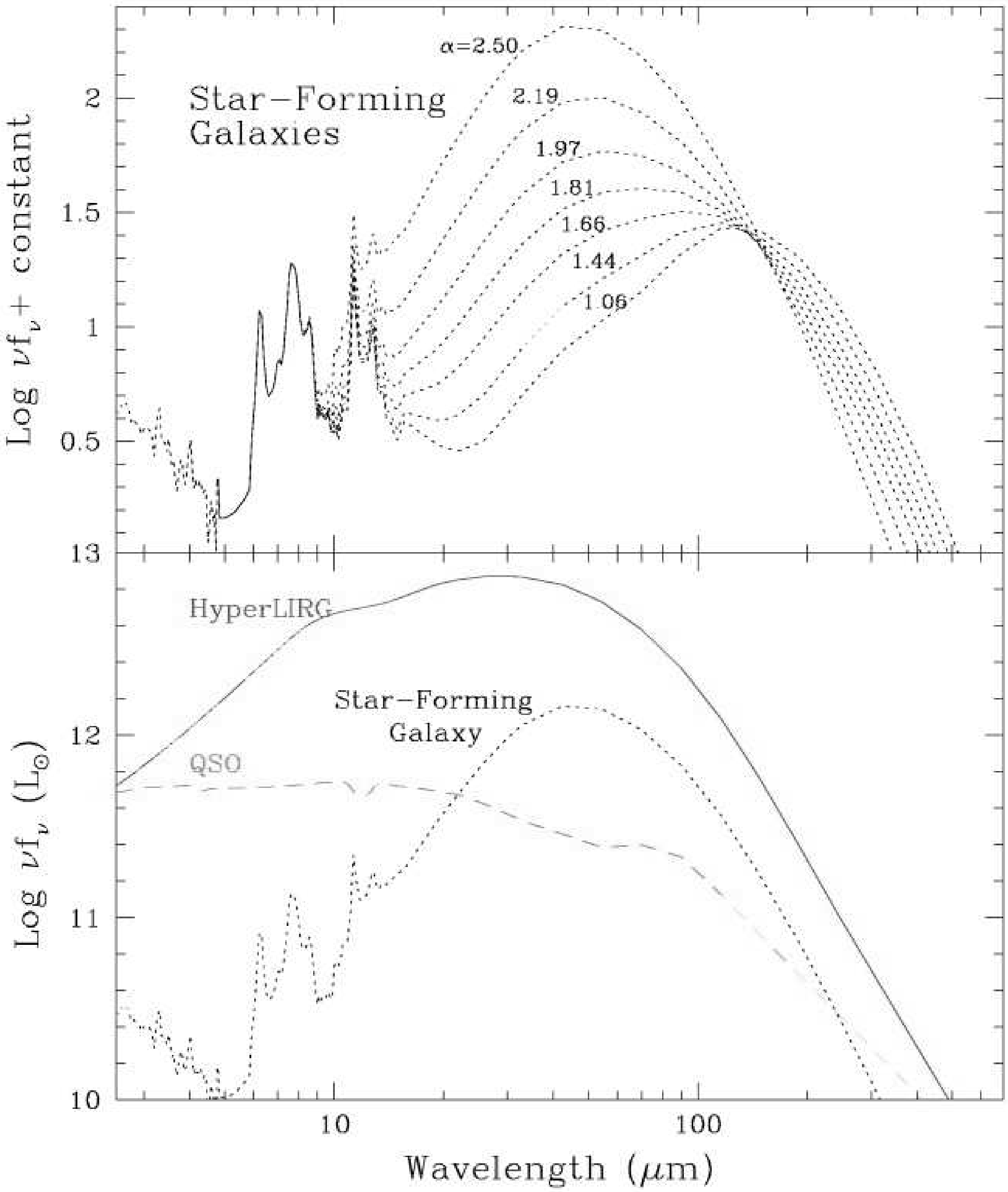

Figure 5: Near to far-infrared spectral models of a Hyper ULIRG, a normal radio-quiet quasar and star-forming galaxy (bottom), with a range of galaxy models (top). From Dale et al. (2001).

the diagnostic quality of certain PAH features, e.g., 7.7 microns, Farrah et al. 2003, component template fitting to mid-to-far infrared data remains a viable approach.

7 Post-starburst Quasars with HST

The Hubble Space Telescope, as long as it continues to fly, provides two unique capabilities: high spatial resolution and ultraviolet sensitivity. Both high-resolution imaging and ultraviolet spectroscopy can provide important information about post-starburst quasars.

The ground-based optical SDSS images in Figure 4 already show that interactions appear quite common in post-starburst quasars, but the SDSS images can be greatly improved upon. For instance, are the isolated post-starburst quasars advanced merger remnants? Or are they pre-merger with double-nuclei that are not resolved and tidal features too faint to easily see?

The extreme UN J1025−0040 at z=0.634 is a point source in SDSS but is clearly a disturbed system as seen in our Keck K-band image (Fig. 1). We obtained HST WFPC2 images in two bands (Fig. 6) to attempt to resolve the starburst from the AGN, which the F450W and F814W images just manage, showing that the bulk of the star light ($\sim 6 \times 10^{10}$ $M_{\odot}$) is contained within a central radius of about 600 parsecs, and lacks clear morphological structures at this scale. Equating the point-source light in each image with the AGN contribution, we determined the ratio of AGN-to-starburst light. This ratio is 69% in the red F814W image, consistent with our previous spectral analysis, but $\leq 50\%$ in the blue F450W image whereas we had predicted 76%. The *HST* images are consistent with previous photometry, ruling out variability (a fading AGN) as a cause for this result. We can explain the results if there is a previously unknown young stellar population present, 40 Myr or younger, with as much as 10% of the mass of the dominant 400-Myr-old population. This younger starburst may represent the trigger for the current nuclear activity. The multiple starburst ages seen in UN J1025−0040 and its companion galaxy indicate a complex interaction and star-formation history.

Our new catalog will provide many new post-starburst quasars, brighter and closer than UN J1025−0040, enhancing our ability to determine what is occurring in the inner kiloparsec of these sources. We will propose a snapshot program to image several dozen post-starburst quasars, letting us determine morphology and separations of multiple nuclei on sub-arcsecond scales. The HST lifetime permitting, we anticipate following up with spectroscopy to look at the properties of the spatially resolved stellar populations – this would be the ideal way to cleanly separate the AGN and stellar spectra, allowing for much better determinations of the properties of each.

8 Secondary Ground-Based Support Projects

We have previously mentioned supplementing 2MASS with our own observations at WIRO and using AO at IRTF to study host galaxies for the post-starburst quasars

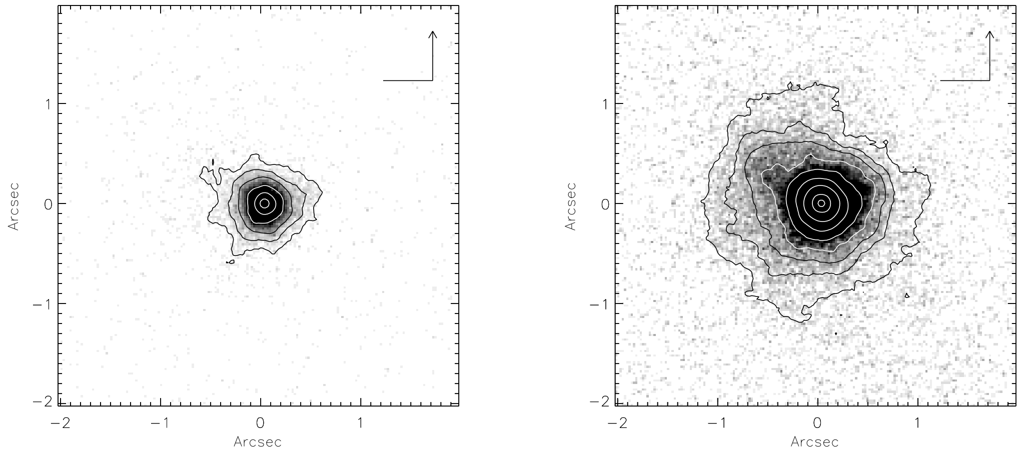

Figure 6: Blue (left) and red (right) HST WFPC2 images of UN J1025−0040 (Brotherton et al. 2002).

with available guide stars (§6.1). We anticipate at least one additional program, that will likely require a few observing runs: using the KPNO 4-meter telescope to obtain higher signal-to-noise ratio spectra of post-starburst quasars, and spectra of their companion objects for redshift determination and classification.

Higher signal-to-noise spectra of the fainter post-starburst quasars will permit significantly better starburst modeling using stellar synthesis population codes (e.g., Bruzual and Charlot 2001). Since the quasar continuum level and slope is not know a priori, things like the break strength and stellar spectral shape are uncertain. The most reliable age indicator is the ratio of the Ca II absorption line equivalent widths to those of the higher-order Balmer adsorption, and this is the primary modeling issue that requires the high signal-to-noise ratio spectra. The Ca II H & K lines are stronger in older F and G stars, while the Balmer lines are stronger in type A stars, so the relative strengths of the absorption lines are a strong constraint on model ages.

By rotating the position angle of the long slit, we can also obtain spectra of nearby companion objects and confirm if they're at the same redshift, and classify them. They may have post-starburst populations themselves (e.g., UN J1025−0040) or may be AGNs themselves (e.g., FIRST 1643+3156A). SDSS fibers cannot be placed too close to each other and essentially none of the nearby companion objects have SDSS spectra.

9 Analyses

The activities described above will provide a host of information for our post-starburst galaxies. The key elements:

- Morphology: single or double, number of companions, separations, host galaxy properties.

- Spectral Energy Distribution: X-rays are directly indicative of AGN power and accretion rate, while optical through far infrared data together can be used to separate AGN and stellar contributions.
- Starburst Properties: mass and age can be determined from stellar synthesis population models, and checked with infrared data.
- Quasar Properties: primarily black hole mass and Eddington accretion fraction using virial estimation techniques based on continuum level and broad line widths of Hβ and Mg II λ2800 (see, e.g., Kaspi et al. 2000, Vestergaard et al. 2002, McLure and Jarvis 2002).

There will be a lot of information, but most of it will fall into the above areas. We will employ a number of statistical techniques, including multivariate techniques like principal component analysis (used to great effect in quasar studies by Boroson & Green 1992), to look for relationships among these properties. For instance, we hypothesize that clearly pre-merger systems will have younger stellar populations than post-merger systems, and that objects with younger stellar populations will have higher accretion rates, and that quasars with more massive black holes will have more massive starbursts and more luminous hosts. A more subtle effect might be that might be expected is that these objects may fall off the M-sigma relation because their black holes have not yet finished their current growth spurt. Some of these expectations may sound trite, but right now we don't know for sure which are true. Moreover, these spectroscopically selected post-starburst quasars may constitute a heterogeneous set of interactions, something we cannot determine until we examine their properties in a systemic statistical fashion.

9.1 Comparison to SDSS Quasars, ULIRGs, & Post-Starburst Galaxies

We can obtain much of the same information on "normal" SDSS quasars (much more easily since they are 20 times more numerous and hence more common in current and near-future archives) and determine how the post-starburst quasars differ. For instance, if we match objects in black hole mass, do their accretion rates differ? Do their X-ray luminosities differ? Does their dust content differ?

IRAS-selected ULIRGs are bright enough to have already been studied in many ways with IRAS, ISO, and soon Spizter will extend the population of ULIRGs to higher redshifts comparable to our sample of post-starburst quasars. We will examine our sample to determine if it is consistent with being a post-ULIRG evolutionary phase.

Similarly, comparisons with post-starburst galaxies will be of interest. Other groups are constructing catalogs of such objects from the SDSS (Quintero et al. 2004). Why do some galaxy interactions that produce massive starbursts also display AGN activity while others don't? Is there an evolutionary relationship since the quasar lifetime can likely be shorter than a post-starburst phase? Or do certain types of interactions fail to channel fuel to the nucleus? In any event, the combination of post-starburst quasars and post-starburst galaxies can provide important constraints to those who model galaxy mergers (see, e.g., Burkert & Naab 2003 and references therein). Models developed in the next few years will have greater dynamic ranges than those in the past and can be expected to incorporate star formation, nuclear accretion, and feedback processes between the two.

9.2 Comparison to Theory

We expect that our catalog and associated data set will not only be of interest to those who numerically model galaxy interactions, but also to those who produce more general models. Following the discovery of the M-sigma relation, many theoretical papers have flooded the literature trying to explain how it happens (e.g., Granato et al. 2004; Di Matteo et al. 2003; Adams et al. 2003; Menci et al. 2003; Volonteri et al. 2003; Archibald et al. 2002; Burkert & Silk 2001; Haehnelt & Kauffmann 2000, Kauffmann & Haehnelt 2000; many others). A subclass of those models makes the case that hierarchical galaxy assembly naturally leads to both black hole growth and to galaxy bulge growth. The post-starburst quasars may illustrate the last remnants of this activity in the $z < 0.5$ universe. We note that we are not proposing for support to do any modeling ourselves in this request, but do plan to compare our population statistics, stellar masses, black hole masses, and growth rates, with whatever models are state of the art in the next five years and detailed enough for such comparisons.

10 Catalog Compilation and Dissemination

We will produce a catalog of $\sim 10^3$ post-starburst quasars. The exact number of sources will depend upon the final size of the spectroscopically observed SDSS, and our final selection criteria. The catalog will include both multi-wavelength properties as well as derived properties. We anticipate developing and maintaining a website dedicated to the catalog, providing the catalog in digital form along with data products or links to data products.

11 Our Proposal and Plan of Research

11.1 Project Overview

The specific tasks involved in this program will include:

- Using the Sloan Digital Sky Survey to construct the first large catalog of post-starburst quasars (at least hundreds of objects).
- Obtaining images and spectra from archival sources (ROSAT, 2MASS, IRAS), new space-based observations (Chandra, Hubble, Spitzer), and some supplementary ground-based observations (IRTF, NOAO, WIRO).

- Using the data to measure and derive a range of properties such as starburst masses, starburst ages, black hole masses, accretion rates, stellar/AGN power fractions, morphological properties, and general population statistics.
- Performing multivariate statistical investigations, like principal component analysis, to determine relationships among system properties.
- Determining the relationship of the post-starburst quasar population to other possibly related populations like ULIRGS, post-starburst galaxies, and normal quasars.
- Comparing our results to theoretical models when possible with the goal of testing which provide the best explanations of AGN triggers, the M-sigma relationship, quasar lifetimes, and more.
- Disseminating results through publications and through a website clearing house of multi-wavelength observations of post-starburst quasars.
- Determining, as a primary ultimate scientific goal, to what extent post-starburst quasars represent a fundamental step in the evolution of all galaxies/AGN.

11.2 Management Details

Brotherton and Shang will share duties and between them have experience using the SDSS, 2MASS, Chandra, XMM-Newton, as well as obtaining near-infrared images and optical spectroscopy. Both are experienced with multivariate statistical techniques and dealing with large data sets. The project schedule is by necessity tied to the SDSS schedule (see table) and the schedule of NASA spacecraft proposals and observations. During years 1 and 2 we will revise our selection techniques and try to understand our selection biases as the SDSS is completed and released. The final SDSS release should be completed in year 2, and we anticipate producing our final catalog by year 3. Archival work can commence during year 1 with our partial catalog, and we have already submitted new proposals this year (e.g., Chandra). We anticipate proposing for and conducting new observations through year 4. During years 3-4 the focus will be upon the statistical analyses, and our results by year 3 may have suggested new observations that we cannot yet anticipate. While we expect to publish papers every year, Year 5 will be focused on wrapping up loose ends and publishing our final results, and in particular on comparing our results with other classes of objects (e.g., normal quasars, ULIRGs, post-starburst galaxies) and with the newest galaxy evolution models. It is unlikely that Shang will remain in Wyoming as a post-doc for the full duration of the grant period, and his replacement would likely be selected to have expertise in areas relevant to the last 2-3 years of the project.

SDSS Data Release Schedule for the 5-Year Baseline Survey

Data Release	Baseline Schedule	Actual/Forecast	Photometry (sq. deg.)	Spectroscopy (sq. deg.)
EDR	July 2001	5-Jun-2001	462	386
DR1	Jan 2003	4-Apr-2003	2099	1360
DR2	Jan 2004	15-Mar-2004	3324	2627
DR3	Oct 2004	Oct 2004	5300	4600
DR4	July 2005	July 2005	6500	5800
Final	July 2006	July 2006	7700	7000

12 Summary

Post-starburst quasars are a rare type of active galaxy in which there exists simultaneously luminous nuclear activity associated with fueling a super massive black hole and a massive starburst of similar luminosity representing a significant contribution to galactic bulge growth. Such objects may represent the chance occurrence of two rare events in the lifetime of a galaxy. Alternatively, these objects may represent a key evolutionary phase in the life cycle of massive galaxies in which some incident, most likely a merger, has ignited both massive star formation and nuclear activity. If post-starburst quasars represent an evolutionary phase they likely will provide essential observational constraints on models attempting to explain why central black hole masses correlate so tightly with their host galaxies' stellar bulge mass.

The new large quasar surveys, in particular the Sloan Digital Sky Survey (SDSS), are enabling post-starburst quasars to be identified in statistically significant numbers (hundreds of sources) for the first time. This project represents a significant effort in obtaining new observations, analyzing new and archival data, making statistical tests, and relating the observations and statistics to the larger issues of galaxy evolution using various modeling techniques. This will be the definitive work on this new and potentially important class of objects, and will result in a broad impact on a number of fields in extragalactic astronomy.

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14 Facilities and Equipment

The University of Wyoming Department of Physics and Astronomy provides offices, office staff, library facilities (including on-line journal subscriptions), fax machines, copiers, and all the things expected from an academic department. Faculty start-up provided money for computer purchases and Brotherton and his research group have four linux workstations with several hundred GBs of hard drive storage (over the five years of support requested we plan to upgrade computers once or twice, likely in year two or three as described). Finally, we have abundant access to the 2.3 meter telescope at the Wyoming Infra-Red Observatory (WIRO) which will be used to supplement 2MASS and provide near-infrared magnitudes for the fainter sources in our program.

15 Curriculum Vitae for Michael Brotherton (PI)

Present Position (2002-present):
Assistant Professor
University of Wyoming, Department of Physics and Astronomy
Dept. 3905
Laramie, Wyoming 82071
(307) 766-5402

Postdoctoral Positions:
1999-2002 Kitt Peak National Observatory, Tucson, AZ (Richard Green)
1996-1999, IGPP, Lawrence Livermore National Laboratory, CA (Wil van Breugel)

Citizenship: US

Professional Memberships: American Astronomical Society

Education:
University of Texas at Austin, Ph.D. 1996 (Astronomy, Bev Wills Adviser)
University of Texas at Austin, M.A. 1992 (Astronomy)
Rice University, B.S. 1990 (Electrical Engineering)

Selected Publications:

- Brotherton, M. S., Grabelsky, M., Canalizo, G., van Breugel, W., Filippenko, A. V., Croom, S., Boyle, B., & Shanks, T. 2002, PASP, 114, 593, Hubble Space Telescope Imaging of the Poststarburst Quasar UN J1025-0040: Evidence for Recent Star Formation

- Brotherton, M. S., Green, R. F., Kriss, G. A., Oegerle, W., Kaiser, M. E., Zheng, W., & Hutchings, J. B. 2002, ApJ, 565, 800, Far Ultraviolet Spectroscopic Explorer Observations of the Seyfert 1.5 Galaxy NGC 5548 in a Low State

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

- Brotherton, M. S., et al. 1999, ApJ, 520, L87, A Spectacular Poststarburst Quasar

- Brotherton, M. S., Gregg, M. D., Becker, R. H., Laurent-Muehleisen, S. A., White, R. L., & Stanford, S. A. 1999, ApJ, 514, L61, Discovery of a Radio-loud/Radio-quiet Binary Quasar

16 Curriculum Vitae for Daniel Vanden Berk

Present Position (2004-present):
Research Associate Professor
Dept. of Astronomy and Astrophysics
Pennsylvania State University
525 Davey Lab
University Park, PA 16802
(814) 863-6091

Previous Positions:
2002-2004 Research Associate, University of Pittsburgh
1999-2002 Research Associate, Fermilab
1997-1999 Harlan J. Smith Fellow, University of Texas

Citizenship: US

Professional Memberships: American Astronomical Society

Education:
University of Chicago, Ph.D. 1997 (Astronomy, Donald G. York Advisor)
University of Chicago, M.S. 1991 (Astronomy)
University of Wisconsin, Madison, B.S. 1990 (Physics and Astronomy)

Selected Publications

- "An Empirical Calibration of the Completeness of the SDSS Quasar Survey", Vanden Berk, et al. 2004, AJ, submitted
- "The Ensemble Variability of 25000 Quasars in the Sloan Digital Sky Survey", Vanden Berk, et al. 2004, ApJ, 601, 692
- "Composite Quasar Spectra from the Sloan Digital Sky Survey", Vanden Berk, et al. 2001, AJ, 122, 549
- "QSOs and Absorption Line Systems Surrounding the Hubble Deep Field", Vanden Berk, Stoughton, Crotts, Tytler, & Kirkman, 2000, AJ, 119, 2571

17 Curriculum Vitae for Zhaohui Shang (Co-I)

Zhaohui Shang
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University of Wyoming
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Laramie, WY 82071
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Education

2003: Ph.D. in Astronomy, University of Texas at Austin
1998: M.A. in Astronomy, University of Texas at Austin
1991: M.Sc. in Astrophysics, Nanjing University, China
1988: B.Sc. in Astrophysics, Nanjing University, China

Professional Experience

2003 –	Postdoctoral Research Associate University of Wyoming
1996 – 2003	Research Assistant/Teaching Assistant University of Texas at Austin
1992 – 1996	Visiting Scholar Beijing Astronomical Observatory, Beijing, China
1991 – 1996	Assistant Researcher Purple Mountain Observatory, Nanjing, China

Selected Publications

- Quasars and the Big Blue Bump
  Shang, Z.; Brotherton, M.; Green, R.; Kriss, G.; Scott, J.; Kim, J.; Blaes, O.; Hubeny, I.; Zheng, W.; Kaiser, M.; Oegerle, W.; Hutchings, J. 2004, *ApJ*, submitted

- The Baldwin Effect and Black Hole Accretion: A Spectral Principal Component Analysis of a Complete QSO Sample
  Shang, Zhaohui; Wills, Beverley J.; Robinson, Edward L.; Wills, D.; Laor, Ari.; Xie, Bingrong.; Yuan, Juntao 2003, *ApJ*, 586, 52.

- The PG X-Ray QSO Sample: Links between the Ultraviolet–X-Ray Continuum and Emission Lines
  Wills, B.; Laor, A.; Brotherton, M.; Wills, D.; Wilkes, B.; Ferland, G.; Shang, Z. 1999, *ApJ*, 515, L53.

- Ring Structure and Warp of NGC 5907: Interaction with Dwarf Galaxies
  Shang, Zhaohui; Brinks, Elias; Zheng; Zhongyuan et al. 1998, *ApJ*, 504, L23.

18 Current and Pending Support

Pending: This LTSA proposal, Understanding the Post-starburst Quasar Population,NASA LTSA, $600k, Brotherton PI

Pending: ADP proposal, Quasar Spectral Energy Distributions: The Next Generation, $180k, Shang PI, (Brotherton 10% effort)

Pending: A Deep X-ray Look at the Radio-Loud Broad Absorption Line Quasar FIRST J1556+3517, XMM-Newton Guest Observer (NASA), $44,000, Brotherton PI

Current: A Decade of HST SEDs, Hubble Space Telescope Archival Program (NASA), $55,000, Brotherton PI

June 22, 2004

Dear NASA,

I am aware that Michael Brotherton has named me as a co-investigator on his Long Term Space Astrophysics proposal "Understanding the Post-Starburst Quasar Population," $< LTSA04 - 000 - 0031 >$ and I am prepared to participate in the project as described.

Sincerely,

Dr. Zhaohui Shang
University of Wyoming, Department of Physics and Astronomy

June 22, 2004

Dear NASA:
I acknowledge that I am identified by name as Collaborator to the investigation entitled "Understanding the Post-Starburst Quasar Population," $< LTSA04 - 000 - 0031 >$ that is submitted by Dr. Michael Brotherton to the NASA Research Announcement ROSS-2004 NNH04ZSS001N-LTSA, and that I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal.

Sincerely, Daniel E. Vanden Berk

Dept. of Astronomy and Astrophysics Pennsylvania State University
525 Davey Lab University Park, PA 16802

19 Budget Explanation

The bulk of the requested funds is for the annual salary of a postdoctoral researcher (currently Zhaohui Shang) and summer salary for Brotherton. We have a smaller request in year one since we have some pending support and some other projects to complete. We note that Shang is submitting an independent ADP proposal, and in the event that both proposals are funded he would split his time and we would hire an additional person: another postdoc if we have enough funding, or a data aide/graduate student to assist with the project. Fringe benefits add 33 percent to the base salary. We have assumed salary increases of 2 percent per year. We include $2000 for travel each year (for Brotherton and/or a postdoc to present results at meetings), $3000 for page charges (20 pages annually at about $150 per page), $300 for supplies (e.g., printing charges for posters). We have also budgeted $2000 for new computers in years one and three. We have budgeted $2000 per year for the first three years for travel expenses to make our supporting ground-based observations (in particular, new observations at NASA's IRTF telescope and the Kitt Peak National Observatory 4-meter). Vanden Berk at Penn State has access to the HET and telescopes at McDonald Observatory that might also be used for supporting observations. The University of Wyoming has a 40.5 percent rate charged for indirect costs on federal grant contracts.