Offset Broad Line Regions: Supermassive Pairs, Ejected Black Holes, or Jet Outflows?

1 Science Background

Leading models for galaxy evolution invoke galaxy mergers to explain the properties of present-day galaxies, as well as the correlation between the mass of their central supermassive black hole (SMBH) and various host galaxy properties (e. g. ??). An inevitable consequence of these models is the formation of close, SMBH binaries (separations of $\ll$10 pc), which eventually coalesce, at the late evolutionary stages of a galaxy merger. The discovery of close binaries or post-coalesence black holes would constitute an important test of these evolutionary scenarios and contribute invaluably to current and upcoming gravitational wave science (??, e. g.). However, no such systems have yet been soundly evidenced at these separations; 0402+379, the smallest binary currently known, lies at a 7 pc projected separation (?). This dearth is easily attributed to the lack of definitive indicators for late-stage mergers and small-orbit binary systems. Signatures of small-orbit binaries have previously been suggested, but then superseded by more likely physical origins (e. g. ?/?; ?/?). For any indirect signature such as peculiar jet or gas-emission structures, follow-up studies are critical to either find support for the late-stage-merger hypothesis, or to demonstrate that another mechanism is at work in the system.

Recently, velocity-offset broad line regions (BLRs) have garnered fresh attention as a potential signature of late-stage galaxy mergers. These systems have emission lines characteristic of an active galactic nucleus, except that the BLR velocity peak is offset from that of the galaxy, whose reference frame is identified by the narrow emission lines (e.g. ?). Three hypotheses have been advanced to explain these features. The **binary black hole** hypothesis suggests that an accreting SMBH/BLR system is orbiting a companion SMBH, thus exhibiting BLR emission that is doppler-shifted with respect to the galaxy, analogous to single-lined spectroscopic binary systems (?). The **gravitational recoil** theory calls on numerical relativity calculations (e. g. ?) which predict that the coalescence of a SMBH binary can induce a high-velocity ejection from the galactic center of the product SMBH, which is accompanied by its virially-bound BLR. Finally, the **jet-induced outflow** hypothesis suggests that radio jets can entrain ambient BLR gas (e. g. ?), similar to what can occur in the narrow-line regions of single-core quasars and radio galaxies (e. g. ?).

Fewer than five offset-BLR objects have been studied over the past half-decade with ambiguous conclusions, largely because the data (high-res. optical spectroscopy and low-res. radio imaging) and small sample sizes (typically one) could not differentiate between the theorized physical origins (see e. g. ?).

2 Our Target Sample and Scientific Goals

The study of ? recently identified 88 objects with velocity-offset broad Hβ emission lines at $>$1000 km s^{-1}, in a magnitude- and redshift-limited sample of $\sim$15,900 Sloan Digital Sky Survey quasars (Fig 1). In follow-up spectroscopic observations, 20% of the 70 re-observed objects showed shifts in their BLR velocity by 100–300 km s^{-1} over a time scale of 5–10 years. These changes are consistent with the expected motion of a small-orbit SMBH binary of average mass ($\sim$10^8 M$_\odot$) and orbital orientation.

Radio observations of this sample will provide several distinct critical points of information to understand the objects in terms of each hypothesized physical origin. Support from these data for any of the theories would allow valuable conclusions to be drawn about closely-related science:

- *Jet outflows* can be tested by looking for an overabundance of one-sided jets (i.e., the approaching jet is strongly beamed, thus the jet angle is relatively small), as compared to a carefully-chosen sample of AGN with non-offset BLRs (for example, the sample of Seyfert I galaxies of **?**). A high frequency of such formations, particularly if the coincidence is higher with blue-shifted BLR regions, would be indicative of a direct BLR gas kinematics/jet connection. Whether jets can influence the kinematics of the BLR gas yet remains an open question. Traditionally the broad-line widths have been used as an indicator of SMBH mass under the assumption that the motions are Keplerian; contradictions to this assumption could greatly impact this method of SMBH mass determination.
- *Recoils*: A recoiling SMBH can actively emit for $\sim 10^7$ years, causing it to appear spatially-offset at projected distances of a few pc to a few kpc (i. e. up to a few arcsec) from the galactic center (e. g. **?**). Radio emission related to the SMBH can be accurately located over this range with standard radio imaging.[1] Because recoil velocities depend on the properties of the spins in parent SMBHs, and spins can be affected by the accretion of gas (e. g. **?**) identification of recoiling remnant SMBHs would provide valuable constraints on the importance of the environment for the spin distribution of merging SMBHs.
- *Binary SMBHs:* The candidate SMBH binaries from **?** have orbital separations that are expected to range from a few hundredths of a parsec to $\sim$10 pc, with characteristic separations of order 0.1 pc and periods up to a few hundred years. If both SMBHs are radio-active, they will be identifiable as two unresolved radio cores in the same tradition as **?**. Systems of sub-pc orbital scales are *direct* progenitors (and in some cases, the selfsame systems) to gravitational-wave-emitting binaries detectable by pulsar timing (**?**). As such, the identification of one would make game-changing contributions to gravitational-wave science with pulsar timing and to open discussions on the gravitational wave signal expected from binary SMBHs (e. g. **?**).

The Eracleous sample is exceptional for our radio study for a number of reasons. First, statistical evaluations of this sample are enhanced by the correlation noted by Eracleous et al. between skewedness of BLR lines with the magnitude of the offset in all of the objects, suggesting that the same physical process is at work in all objects. Thus, in the event of a common origin of binary SMBHs or recoils, the likelihood of detection is drastically increased over searches of general object populations (which, for instance, was thought to be a strong contributor to the low detection rate of **?** in their search for SMBH pairs in archival radio data). Critically, the positive identification of even one or a few offset or binary SMBH in this sample would yield potential ramifications for the full sample, even if a subset of the objects are unidentifiable in our data due to, for instance, a binary's projected orbital separation that is too small for us to resolve, or due to radio components below our detection limit. Nevertheless, the low mean redshift of the sample ($\langle z \rangle = 0.32$; 20%

[1] Identifying relative offsets also requires precisely locating the position of the host galaxy's nucleus. Supporting optical imaging will be obtained with the Hubble Space Telescope and the Gemini Adaptive Optics system through proposals to be submitted in February and March 2012, respectively. Ultimately the positional accuracy of AGN offset measurements will be limited by these observations, set essentially by the resolution limit of HST (0.1 arcsec) rather than the optical and radio astrometric reference frame alignment, which can be made to $\sim$1 mas. In the unlikely case that our optical proposals are not successful this semester, the EVLA data will still have lasting value, and can be used by us or other groups in the future when high-resolution optical imaging becomes available.

of objects at $z < 0.2$) allows us to resolve scales of $\ll$10 pc with the VLBA, which is critical for the identification of potential binary SMBHs at a large range of probables masses and orbital orientations. Likewise in the case of recoils, the optical galactic center used as a reference for radio-offset tests can be located to $\sim$100 mas precision, so that offset-AGN searches can be performed to more than an order of magnitude below the largest predicted offsets.

3 Proposed Observations

Observations with the EVLA of the full 88-source Eracleous sample will be the foundational step in our exploration of the three hypothesized physical origins for these objects. We require these observations to establish: 1) the presence and large-sale morphology of radio emission in the objects, and 2) the flux density and location (on scales up to a few arcseconds) of any compact emission associated with a single or binary black hole, thus providing an assessment of both whether it is widely offset, and of its potential for high-resolution follow-up to search for a compact binary.

To balance the ideal frequency to image radio jets (which have generally steep spectra) and the frequency required to eventually achieve very high resolution imaging with the VLBA (pushing to the highest observing frequencies), we will perform our EVLA search with the 8-12 GHz receivers. This will give $\sim$240 mas resolution in the EVLA A-configuration, which is sufficient to constrain the position of targets that will be selected for follow-up high-resolution imaging with the VLBA. Of the full sample, 84 sources were covered by the FIRST survey (**?**), and 35 (42%) of those are radio-emitting at $f = 1.4$ GHz above a 5-sigma threshold of 0.75 mJy. We aim to surpass that detection rate by improving on the FIRST sensitivity by a factor of two, as extrapolated to our observing frequency assuming a typical spectral index of $\alpha = -0.7$ (where the radio flux $S_f \propto f^{\alpha}$). At a mean frequency of 9 GHz, we will require a sensitivity of 20 μJy to reach this goal. Assuming an array of 22 antennae, this requires an average on-source time of $\sim$3 minutes per source if using the observing setup given by the attached proposal specifications. Accounting for calibration, setup, and slewing overheads, we request a total of 7 hours to follow up the full 88-object **?** sample. A snapshot observation near the source's zenith will provide the best morphological constraints. Based on the broad position range of the targets, the observations would ideally be divided into four blocks, three of length 2 h commencing around R.A. = 08h 30m, 11h 30m, and 15h 00m, with a final block commencing at approximately R.A. = 01 h and lasting one hour. We note that the FIRST resolution of 5" will also be improved upon in these observations, giving vastly improved constraints on object positions and radio morphologies.

The data from this proposal round will be searched for both asymmetric jets and core-related compact emission. The positions of compact components will be catalogued for comparison with the high-resolution optical imaging being pursued to identify recoiling SMBHs. Following the analysis of our EVLA data, we will pursue VLBA observations of any objects in our EVLA sample that contain compact emission. These will be pursued with high-resolution imaging to search for the presence of resolved, small-orbit binary SMBHs.

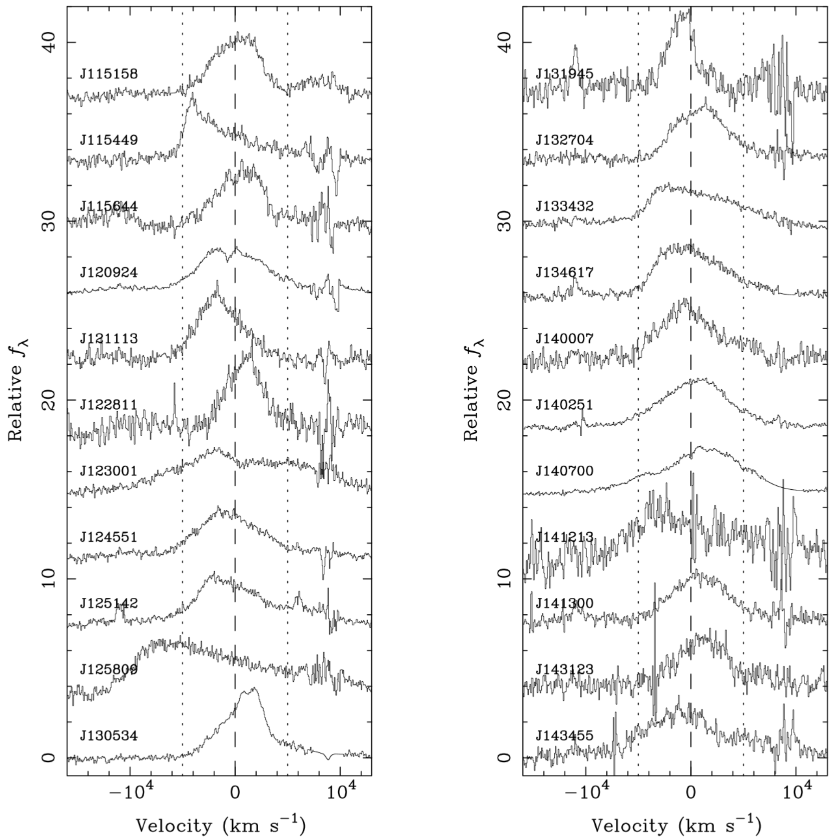

Figure 1: Here we show examples of offset broad Hβ lines reported by **?**. Narrow lines and underlying continuum emission were subtracted. Each profile is offset vertically for clarity. The dashed line shows the location of the narrow Hβ line, representing the rest-frame velocity of the galaxy host. The vertical dotted lines indicate a window of $\pm 5000\,\mathrm{km\,s^{-1}}$ from this line. Both red- and blue-shifted BLR systems are visible here.

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