What is the Structure of Relativistic Jets in AGN on Scales of Light Days?

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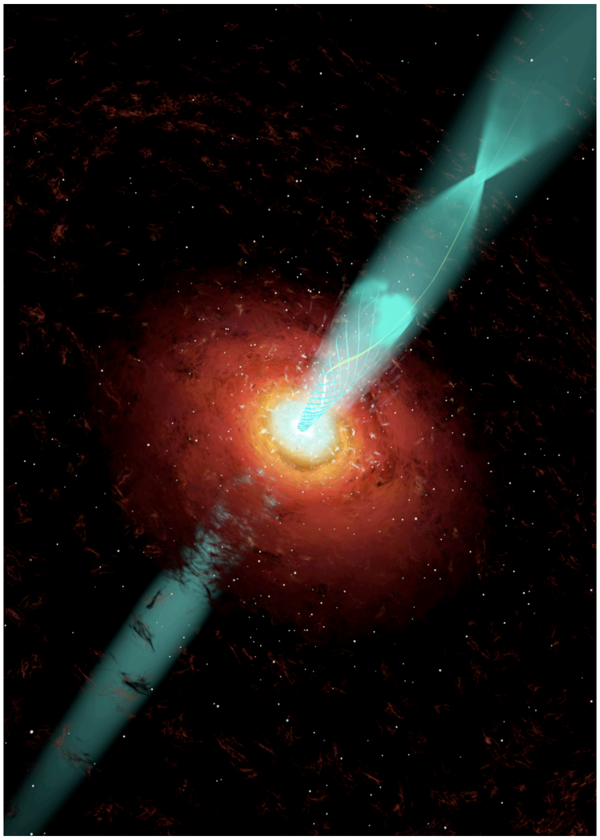

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White Paper for Astro2010 "Galaxies Across Cosmic Time" 11 Feb 2009

Abstract

The structure of relativistic jets in AGN on scales of light days reveals how energy propagates through jets, a process that is fundamental to galaxy evolution. A deeper understanding of jet physics will clarify the differences between radio-loud and radio-quiet quasars that manifest themselves near the supermassive black hole. We can also use relativistic jets to identify supermassive binary black holes remaining from galaxy mergers, and use orbital motion to derive the masses of the black holes. The search for binary black holes in the nuclei of galaxies will yield important information on their overall lifetime and on the processes occurring in galaxies that affect black holes and quasars. High-precision astrometric measurements, made using the technique of optical interferometry on a space-based platform, such as SIM Lite, are the key to answering these questions.

1. Introduction

According to current AGN models, a supermassive black hole, with mass scaling as 0.1 percent of its host galaxy's spheroidal bulge, is surrounded by an accretion disk and corona, and in some cases a pair of relativistic jets. Unifying schemes seek to relate a few underlying physical parameters (mass, accretion rate, spin, magnetic field, viewing geometry) to the diverse observed properties of AGN. Observationally, in radio-quiet quasars (which make up 90 percent of all known quasars), the optical emission has a continuum power law, emission lines, and a thermal Big Blue Bump. Radio-loud quasars have an additional nonthermal power-law continuum attributed to strong relativistic jets. Figure 1 shows the canonical quasar model.

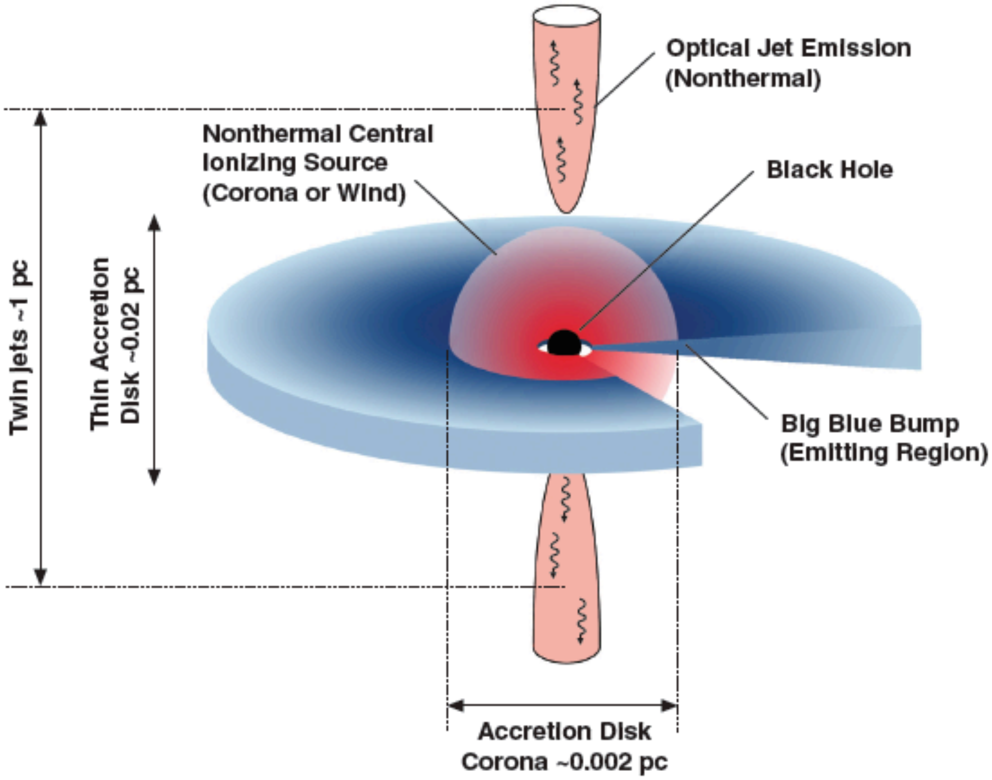
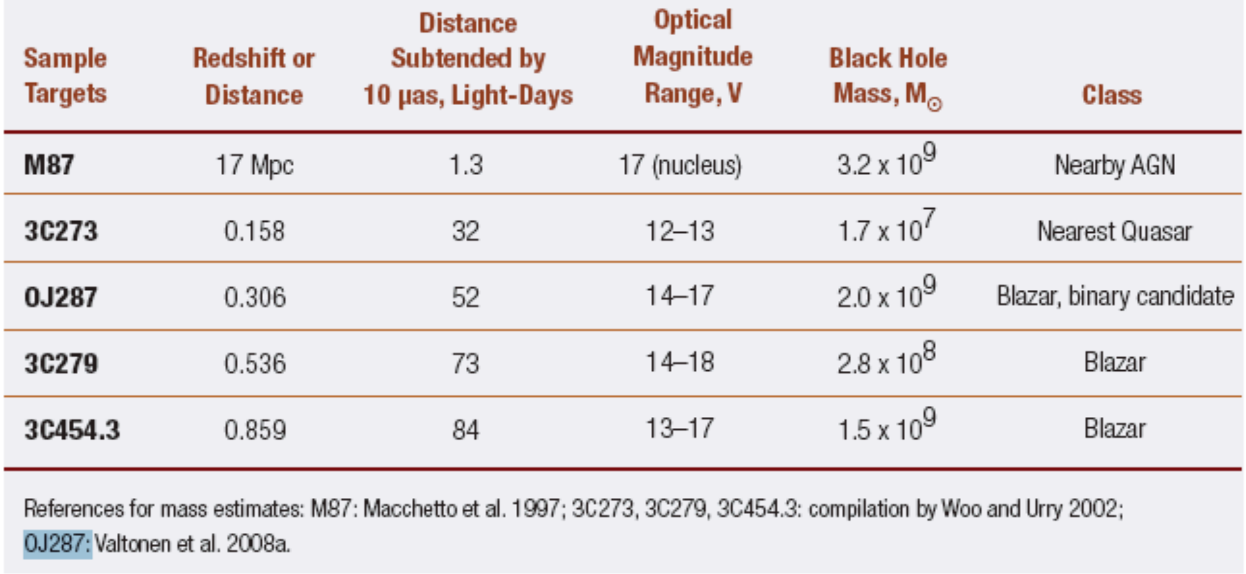


Figure 1. The origin of optical emission from a quasar nucleus (shown schematically, with logarithmic scaling) on scales that are not resolved by any imaging telescope.

Spin-up of the newly-merged black holes in major merger galaxies may provide the immediate trigger for acceleration of strong relativistic jets in radio-loud quasars and galaxies. On the scale of light days to light weeks, the jets are triggered, collimated and accelerated. The inference of accretion disk spin rates from Iron K-alpha lines has given new insight into the situation near the central supermassive black hole (e.g., Reynolds and Fabian 2008). However, the angular resolution needed to directly measure motions in the inner tenth of a parsec in quasars is beyond the reach of current optical and near-infrared ground- and space- based telescopes (Hubble 100 mas, Keck and Very Large Telescope Interferometers ~10 mas). Table 1 lists some key objects and their characteristics. Direct measurement of motions and position differences on scales of tens to hundreds of Schwartzschild radii has previously been achieved only at radio wavelengths with VLBI. We need similar angular resolution at optical wavelengths.

Table 1. Key Objects and their Characteristics.



Sample Targets	Redshift or Distance	Distance Subtended by 10 µas, Light-Days	Optical Magnitude Range, V	Black Hole Mass, $M_\odot$	Class
M87	17 Mpc	1.3	17 (nucleus)	3.2×10^9	Nearby AGN
3C273	0.158	32	12–13	1.7×10^7	Nearest Quasar
OJ287	0.306	52	14–17	2.0×10^9	Blazar, binary candidate
3C279	0.536	73	14–18	2.8×10^8	Blazar
3C454.3	0.859	84	13–17	1.5×10^9	Blazar

References for mass estimates: M87: Macchetto et al. 1997; 3C273, 3C279, 3C454.3: compilation by Woo and Urry 2002; OJ287: Valtonen et al. 2008a.

2. Comparing the structures of radio-loud and radio-quiet quasars.

We think that radio-loud and radio-quiet quasars have similar structures within the inner few light weeks of the supermassive black hole: a hot corona and accretion disk, with a strong well-collimated jet in radio-loud quasars and a weak (or missing) jet in radio-quiet quasars. Such a model can be tested by astrometric observations with very high resolution in red and blue light.

What are the relevant size scales? In the high-accretion case, the accretion disk produces a thermal peak in the near-ultraviolet region. For a typical 10^9 M_o black hole system, accreting at 10 percent of the Eddington rate, the diameter of the disk region that is radiating at a temperature of 10^4 K or above is ~ 3.6×10^{16} cm, or 0.012 pc (Shakura 1973). At a nearby distance of 15 Mpc, this region would subtend an angular size of ~160 µas, while at moderate redshift ($z = 0.6$), the angular size would be only ~2 µas. Coronal emission is probably nonthermal — either optical synchrotron or inverse-Compton-scattered emission from a radio synchrotron source. For most quasars, this is not beamed optical radiation from a relativistic jet, because there is no evidence that the geometry is that of a narrow cone, so the corona is expected to emit fairly isotropically. Models of this ionizing source (e.g., Band and Malkan 1989) indicate a size of only ~70 Schwarzschild radii. At moderate redshift ($z = 0.5$), this subtends an angular size of only ~1 μas, centered on the black hole and comparable in size to the region emitting the Big Blue Bump radiation. The physical process by which jets are accelerated is an active area of research. For example, a powerful jet may not be produced unless the central black hole is spinning rapidly (Wilson and Colbert 1995; Blandford 1999; Meier et al. 2001).

We can directly test the currently suggested AGN models by measuring a color-dependent position shift in radio-loud quasars and radio-quiet quasars. A relative positional displacement in optical photocenter between the red and blue needs to be measured on the μas level. This color-dependent displacement, its time derivative in variable sources, and its direction on the sky can be compared to the orientation of a radio jet imaged by VLBI. We do not expect to see such a shift in radio-quiet quasars because of the absence of any contribution of a relativistic jet whose optical emission might introduce an astrometric asymmetry. The red emission from the corona and the blue emission from the disk both should be coincident with the central black hole within ~1 μas. Any color-dependent astrometric shift seen in radio-quiet quasars would challenge the current models of accreting systems in AGN. See Figure 2 for an illustration of color shifts in radio-loud quasars contrasted with those of radio-quiet quasars.

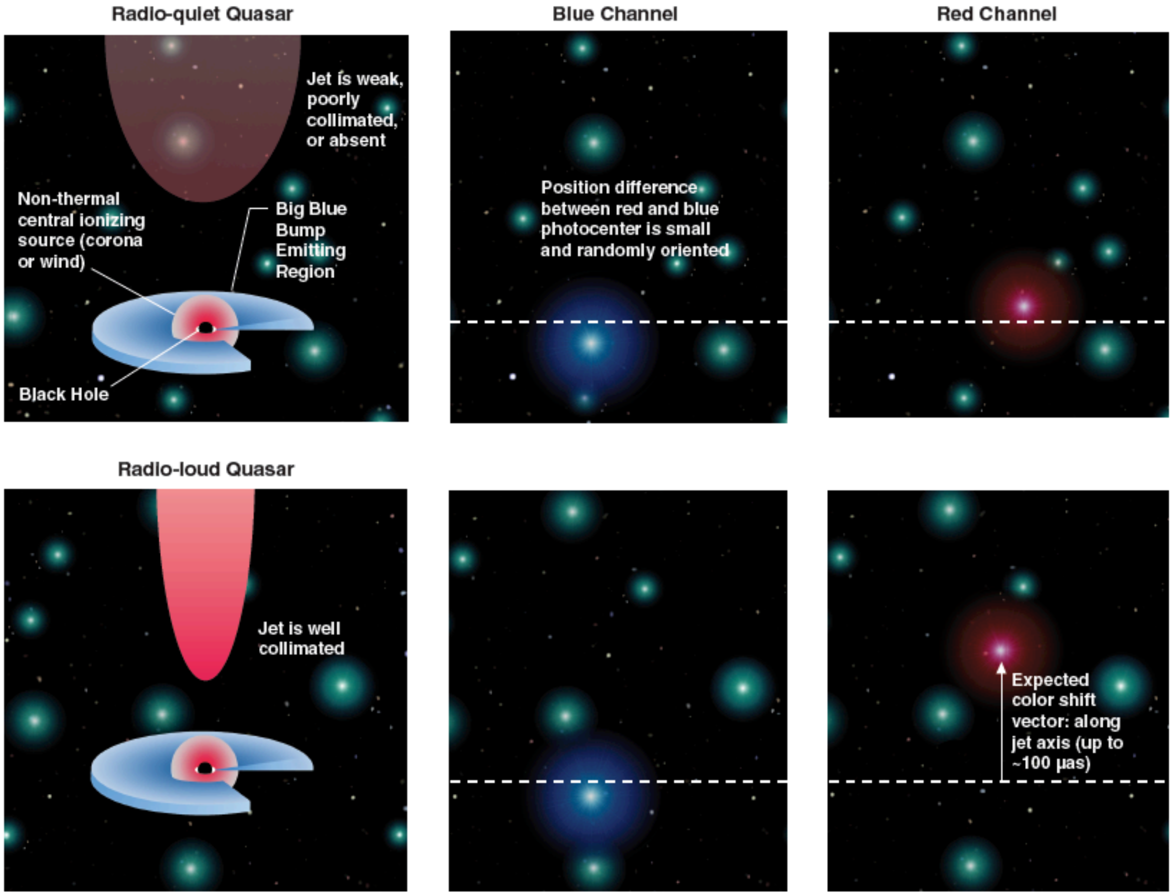


Figure 2. Upper panel: in a radio-quiet quasar, any color shift is expected to be small and random. Lower panel: in a radio-loud quasar, a strong asymmetry is expected in the astrometric position between red and blue light; this shift should be aligned with the jet axis.

By contrast, the astrometric position may be strongly color-dependent in any object with strong optical jet emission. So while the blue end of the spectrum should be dominated by the thermal disk, the red region may be dominated by steep-spectrum power law emission from the beamed relativistic jet. Furthermore, we would expect any variable position shift to be aligned on the sky with the direction of the shift itself (Figure 2). An example of a moderate-redshift jet-dominated quasar is 3C345 (z = 0.6), for which the red optical jet emission should be offset by ≈10 μas from the 22 GHz radio emission, at about 80 μas from the black hole. For 3C273 (z = 0.16), the separation may be as large as 300 μas. Not only is such a large shift readily detectable using a space-based optical interferometer, but we could also detect variations in the offset with time.

3. Measuring the relative locations of radio and optical- emitting regions in the relativistic jets of radio-loud quasars.

The recent launch of *Fermi*, which has detected dozens of blazers in its first few months, will revolutionize our understanding of gamma-ray production in relativistic jets. With the Compton Gamma Ray Observatory, we saw gamma-ray flares occur with the ejection of compact radio knots detected with high resolution VLBA observations (Jorstad et al. 2001); we begin to put together a multiwavelength view of the blazar structure. A new model developed by Marscher et al. (2008), based on simultaneous VLBI and optical polarization monitoring, suggests that knots of optical emission move outward through an acceleration and collimation zone toward a standing conical shock region thought to be the quasar "core" at millimeter wavelengths (Figure 3). Absolute position offsets between optical observations and radio positions need to be measured on the ~10-50 μas level. This requires a stable, space-based optical interferometer and contemporaneous VLBI measurements.

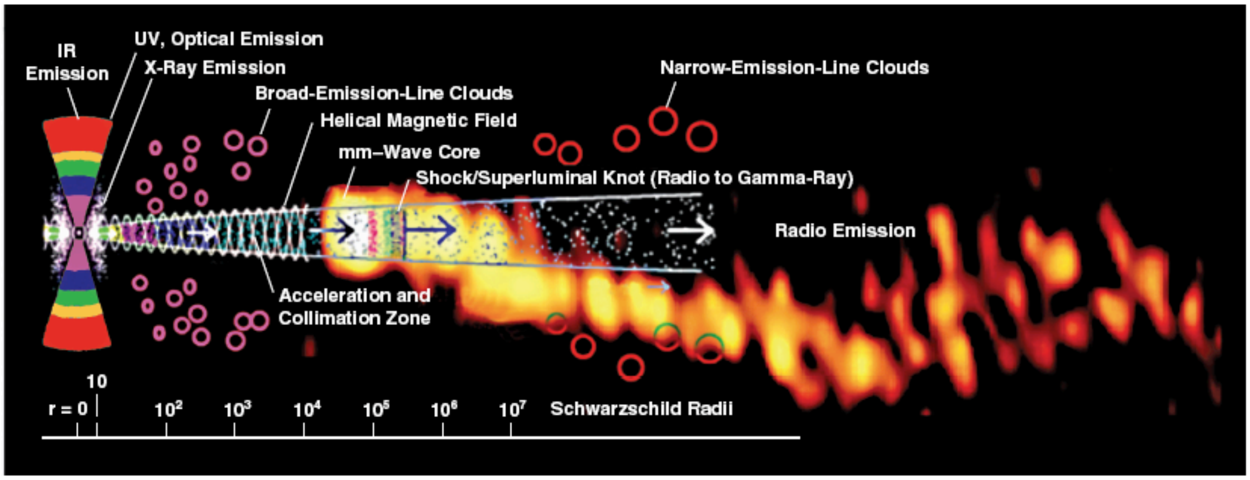
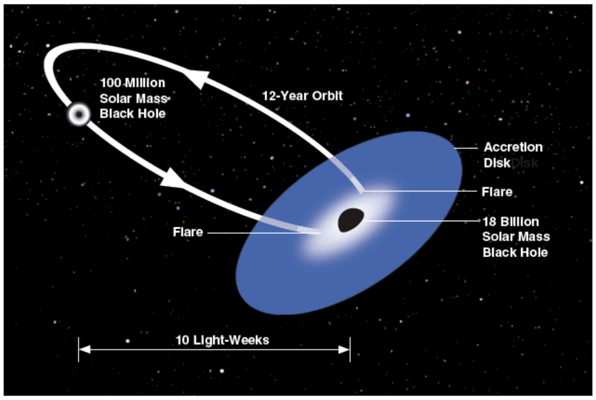


Figure 3. Overlay of a 3 mm radio image of the blazar 3C454.3 (Krichbaum, et al. 1999) on a diagram of a quasar from Marscher et al. (2008), not to scale. Knots of optical emission move outward from the black hole's accretion disk (left) through an acceleration zone toward the millimeter and radio "cores" and radio jet (right). Concurrent optical interferometer and VLBI observations will register and track the wander of the optical photocenter relative to the radio core.

4. Using relativistic jets to identify binary black holes remaining from galaxy mergers

Compact optical emission from galactic nuclei, e.g., optical jets, can be activated in the aftermath of a major galaxy merger. If massive binary black holes are found, we will have a new means of directly measuring their masses and estimating the coalescence lifetimes of the binaries. We can detect binary black holes in a manner analogous to planet detection: by measuring positional changes in the quasar optical photocenters due to orbital motion

Time scales for the galaxy nuclei themselves to merge, and the black holes to form a binary of approximately one pc in size, are fairly short (on the order of several million years) and significantly shorter than the galaxy merger time (a few hundred million years). Furthermore, once the separation of the binary becomes smaller than 0.01 pc, gravitational radiation also will cause the binary to coalesce in only a few million years (Krolik 1999). However, the duration of the “hard” binary phase (separation of 0.01 to 1 pc) is largely unknown, and depends critically on how much mass the binary can eject from the nucleus as it interacts with ambient gas, stars, and other black holes (Yu 2002; Merritt and Milosavljevic 2005). Depending on what processes are at work, the lifetime in this stage can be longer than the age of the Universe (implying that binary black holes are numerous) or as short as the “Salpeter” time scale $(M_1 + M_2) / M_{Edd} \sim 5 \times 10^7$ years (implying that binaries might be rare). Therefore, the search for binary black holes in the nuclei of galaxies will yield important information on their overall lifetime and on the processes occurring in galaxies that affect black holes and quasars.



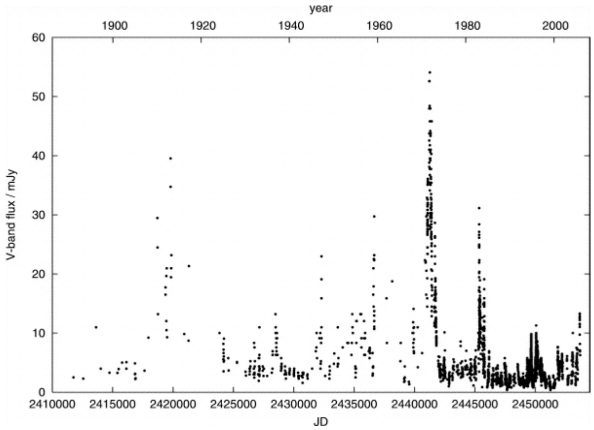


Figure 4a. Artist’s impression of a binary black hole pair in OJ287 (image courtesy Mauri Valtonen, Tuorla Observatory). SIM Lite will be able to track the motion of the suspected binary. Figure 4b. Historical light curve of OJ 287 from Valtonen et al. (2006) showing outbursts at 12 yr intervals. Each outburst is composed of two sharp peaks.

OJ287 is one of the most promising binary black hole candidates. It shows quasi-periodic brightness variations that come in pairs separated by one or two years, and each pair occurs about 12 years apart (Kidger 2000; Valtonen et al. 2006, 2008). This behavior is best modeled as a secondary black hole piercing the accretion disk of the primary black hole, producing two impact flashes per period (Lehto and Valtonen 1996). For an assumed orbital period of 12years, a binary black hole system with a mass of at least 10^{10} solar masses has a mean separation of 0.05 pc. For OJ287 (z = 0.306), this separation subtends 11 μas, and the orbital motion expected during a five-year span is about 14 μas.

5. A space-based optical interferometer is needed

In summary: first, understanding the structure of relativistic jets provides evidence for how energy propagates through jets. Second, through observed differences in their compact emission regions, the cause of the dichotomy between radio-loud and radio-quiet quasars can be explored. Third, we can use jets to identify supermassive black holes remaining from galaxy mergers, and use orbital motions to derive mases of the black holes. As we have seen from the size scales of the phenomena we need to observe, space-based optical interferometers will be needed to obtain the required angular resolution. Only SIM Lite, which will perform astrometry relative to reference stars and quasars (Unwin et al. 2008), will provide the astrometic precision high enough to enable the observations described here. SIM Lite's single measurement precision will exceed Gaia's by a factor of 10-20 for quasars with magnitudes 16-17, and its end-of-mission precision will be 6-10 times better than Gaia's end-of-mission precision.

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For more information about SIM Lite, please see http://sim.jpl.nasa.gov**.**