IV

Supermassive Black Holes and Quasars

Does the most compact optical emission from an AGN come from an accretion disk or from a relativistic jet?

Are there binary black holes? What are their orbits?

Does the separation of the radio core and the optical photocenter of the quasars used for the reference frame tie change on the time scale of the photometric variability, or is the separation stable?

Black holes are perhaps the most exotic objects to impinge on the cosmic consciousness.

Christopher Reynolds

11 Quasar Astrophysics

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ABSTRACT

Active galactic nuclei (AGN) can be studied by SIM Lite at unprecedented μas scales. This capability opens up direct study of areas within light-days of the central supermassive black hole. Topics to be addressed include the triggering of relativistic jets, the search for binary black holes, and the cause of the radio-loud/radio-quiet dichotomy.

11.1 Introduction

The 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). The region contains the central billion-solar-mass black hole and its accretion disk, including the starting location of relativistic jets and their initial collimation into narrow cones. SIM Lite's single-measurement precision for 16th to 17th magnitude quasars will exceed Gaia's by a factor of 10 to 20, and its end-of-mission precision will be 6 to 10 times better than Gaia's end-of-mission precision (Table 11-1).

Table 11-1. Estimated errors for SIM Lite and Gaia quasar observations.

Spacecraft	End-of-Mission Accuracy, µas	Single-Measurement Error, µas	V mag	No. of AGN and Quasars Observed	No. of Obs.	Radio-Loud Fraction
SIM Lite: Science	4	11	13–18	50	150[b]	80%
SIM Lite: Grid	4	16	16	50	150[a]	40%
Gaia	25	150	<16	200	80–100[c]	10%
	70	400	<18	20,000	80–100[c]	10%
	200	1200	<20	500,000	80–100[c]	10%

[a] Measurement cadence matches grid star measurement cadence
[b] Measurement cadence determined by science
[c] Measurement cadence determined by mission design

The ability of SIM Lite to measure motions and position differences on µas scales means that we can study AGN on scales of tens to hundreds of Schwarzschild radii, which previously has been achieved only at radio wavelengths with very long baseline interferometry. Some of the most exciting theoretical questions in quasar research today are:

1. Where are relativistic jets triggered?
2. Do the cores of galaxies harbor binary supermassive black holes remaining from galaxy mergers?
3. What makes some quasars highly variable and radio-loud but most quasars radio-quiet?

Specific observational questions that SIM Lite can address include:

1. Does the compact optical emission from an AGN come from an accretion disk, a corona, or a relativistic jet?
2. On what physical scales does collimation into a narrow jet occur?
3. Are different regions visible when a quasar flares or fades? How stable is the separation of the radio core and the optical photocenter of the quasars used for the reference frame tie?
4. Is there direct evidence of orbital motion in the cores of quasars and other active galactic nuclei?
5. How are the Broad-Line-Region clouds stratified at distinct distances from the continuum-emitting nucleus: in cones, filaments, or "smoke rings" across the nuclear region?

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, according to current AGN models. Unifying schemes seek to relate a few underlying physical parameters (mass, accretion rate, spin, magnetic field, viewing geometry) to the observed properties. Observationally, in radio-quiet quasars (RQQs, which make up 90 percent of all known quasars), the optical emission has continuum power laws, emission lines, and a thermal Big Blue Bump (BBB). Radio-loud quasars have an additional nonthermal power-law continuum attributed to strong relativistic jets. To understand how SIM Lite observations can provide insights into the physical processes in AGN, we depict the canonical quasar model in Figures 11-1a and 1b. Table 11-2 lists candidate targets for SIM Lite.

Figure 11-1a. Schematic diagram (logarithmic scaling) of the structure of a typical quasar on scales from 0.002 to 100 pc, after Elvis (2000) and Niall Smith (private communication, Cork Institute of Technology). Differential astrometry with SIM Lite allows us to study the central regions (the Broad-Line Region and the base of the jet) on a scale of μas far below the resolution of any imaging telescope.

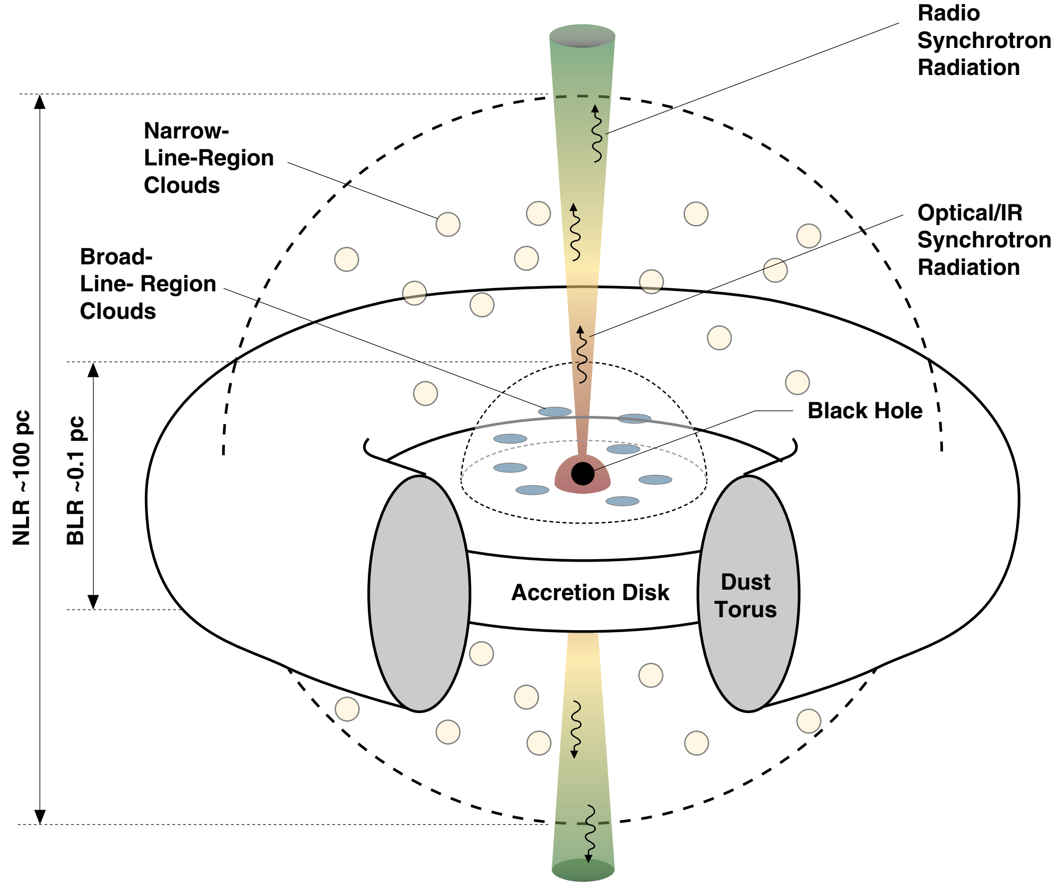

Figure 11-1b. The origin of optical emission from a quasar nucleus (shown schematically, with logarithmic scaling) on scales that are not resolved by any imaging telescope. SIM Lite astrometry can directly probe the emission on the scale of the corona, the thin disk, and the base of the relativistic jet. The astrometric signal, its spatial alignment, and its variability depend on the relative strength of these components.

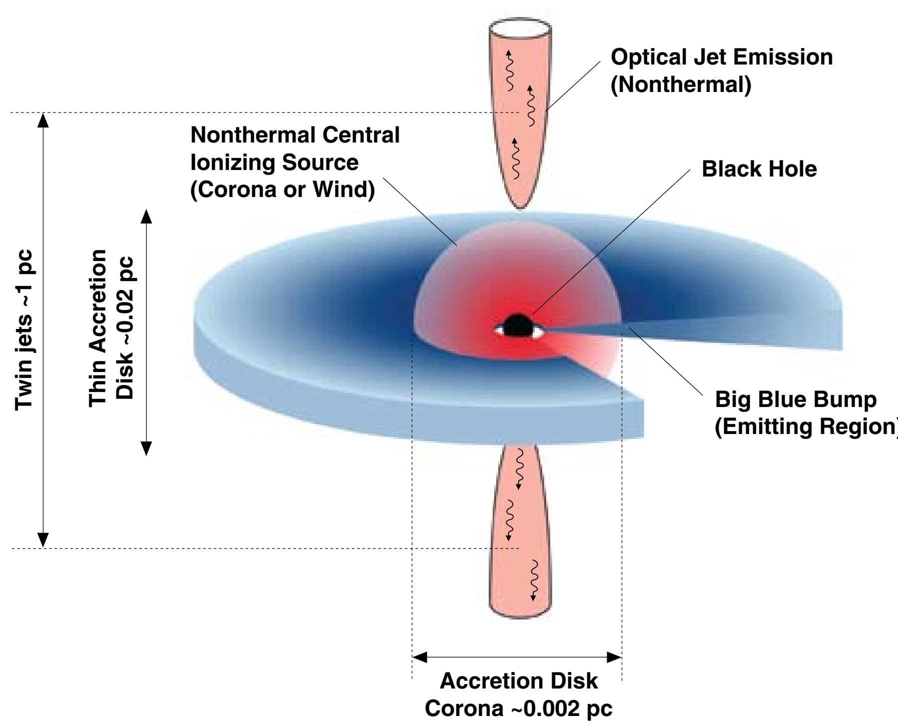

Table 11-2. Characteristics of candidate quasar and AGN targets.

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.

11.2 Accretion Disk, Corona, or Jet: Distinguishing AGN Models Using Color-Dependent Astrometry

SIM Lite can directly test the currently suggested AGN models by measuring a color-dependent positional shift in radio-loud quasars (RLQs) and radio-quiet quasars (RQQs). A relative positional displacement in optical photocenter between the red and blue ends of the SIM Lite passband can be readily measured on the μas level and is very insensitive to systematic errors. SIM Lite measurements will be primarily limited by photon noise, not instrument errors. 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 or the VLA. We do not expect to see such a shift in RQQs 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 RQQs would challenge the current models of accreting systems in AGN. 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 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 11-2).

An example of a moderate-redshift jet-dominated quasar is 3C345 ($z = 0.6$), for which the red optical jet emission should be roughly coincident offset by ≈10 μas with 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, but SIM Lite could also detect variations in the offset with time.

In the nearby radio galaxy M87 we expect the red optical emission to be dominated by the accretion disk corona because its jets are not pointing within a few degrees of our line of sight. Therefore, SIM Lite should not see a significant shift of the optical photocenter as a function of color in this source. However, M87 is so close that we might see an absolute position offset between the measured radio center and the optical photocenter because the location of the last scattering surface is farther from the black hole for radio photons than for optical photons. This radio-optical position offset should be even larger for this low-redshift radio galaxy than for 3C345 — perhaps in the 1000 μas range.

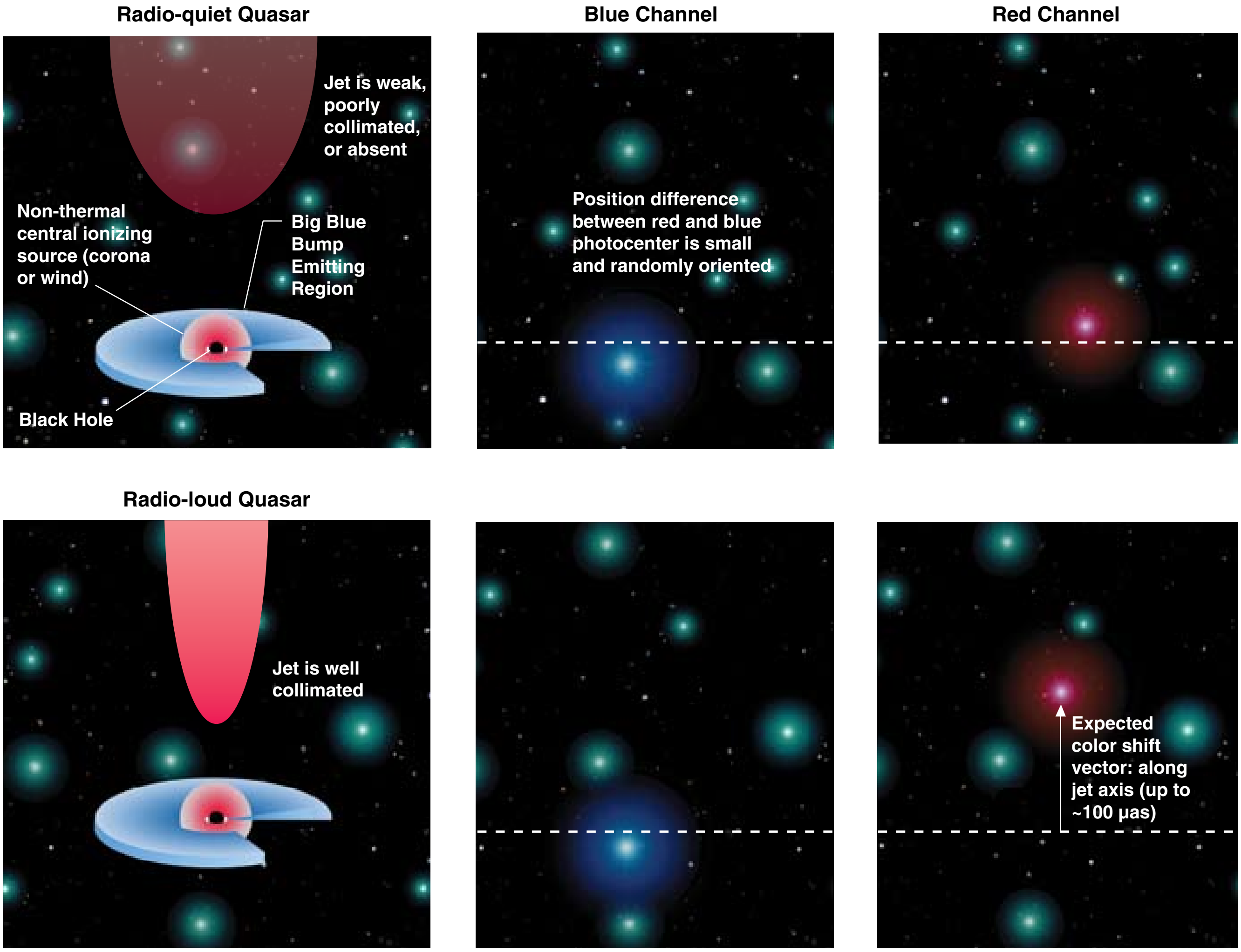

Figure 11-2. SIM Lite can use color-dependent astrometry to directly probe the collimation region at the base of a quasar's relativistic jet. Upper panel: in a radio-quiet quasar, any color shift is expected to be small and random. Lower panel: in a radio-loud quasar, a strong asymmetry is expected in the astrometric position between red and blue light; this shift should be aligned with the jet axis. If the quasar is variable, the astrometric variability should be along the same axis.

11.3 Physical Scales on Which Jet Collimation Occurs

In the high-accretion case, the accretion disk produces a thermal peak in the near-ultraviolet region. For a typical 10^9 $M_\odot$ black hole system, accreting at 10 percent of the Eddington rate, the diameter of the portion of the disk 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 (R_S). 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 Big Blue Bump.

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). The Konigl (1981) model for relativistic jets predicts that the majority of the optical emission comes not from synchrotron emission from the base of the jet but from synchrotron-self-Compton emission in the region of the jet where the synchrotron emission peaks in the radio or millimeter (Hutter and Mufson 1986). An alternative 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 "core" at millimeter wavelengths.

Absolute position offsets between SIM Lite optical observations and radio positions can be measured on the ~10 μas level (limited by the definition of the radio frame) because the SIM Lite inertial coordinate frame will be aligned to the radio International Celestial Reference Frame (ICRF) (see Section 11.4).

11.4 Quasar Flaring and Fading and the Effect on the SIM Lite Reference Frame

About 10 percent of RLQs (i.e., about 1 percent of all quasars) are blazars — strong and variable compact radio sources that also emit in the optical (mainly red and near-infrared) and in x-rays and gamma rays and viewed by us nearly end-on to the jet. Looking down the jet allows us to "stick our heads in the beam" of the most energetic particle accelerators in the Universe. In many cases, their radio jets flow at relativistic speeds (Lorentz factors of 10 or more; 99 percent of the speed of light). Relativistic beaming toward the observer produces an order of magnitude or more increase in apparent radio luminosity as well as apparent "superluminal" proper motions of jet components of up to 1000 μas yr^{-1}. Tiny changes in the intrinsic brightness of the jet or in its direction with respect to the line of sight alter the observed brightness significantly. The jet components are identified with moving and stationary shocks in the plasma flow (see, for example, Marscher et al. 2008). If they display similar internal proper motions in their optical jets, these would be readily detectable with SIM Lite. We expect that when a quasar is in a faint state, the optical emission from the BBB and corona are revealed, and when the quasar brightens by 30 to 100 times during a flare, the synchrotron jet emission completely swamps the other components.

SIM Lite can measure absolute proper motions to the level of its global reference frame. Observations of grid stars and quasars will provide this inertial reference frame on the ~4 μas per year level, exceeding the accuracy of the current ICRF (see Chapter 12).

Nearly 100 percent of the ICRF sources are known or assumed to be blazars because they are the most compact radio sources. However, ICRF sources are optically faint (~15 to 25 mag in V), polarized, and variable by up to 5 magnitudes on time scales of months. A sample of non-ICRF RQQs will be defined and observed that will have a typical optical magnitude of V ~15 to 16. SIM Lite will observe 30 ICRF sources in order to tie the SIM Lite optical and ICRF radio reference frames together. An additional 25 non-ICRF RQQ sources will be observed for the SIM quasar reference frame itself and for astrophysical research.

11.5 Finding Binary Black Holes

Do the cores of galaxies harbor binary supermassive black holes remaining from galaxy mergers? 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.

SIM Lite 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. If a quasar photocenter traces an elliptical path on the sky, then it could harbor a binary black hole; if the motion is random, or not detectable, then the quasar shows no evidence of binarity. How is it possible that an entire AGN black hole system could be in orbit about another similar system (Figure 11-3)? Such a situation can occur near the end of a galactic merger, when the two galactic nuclei themselves merge. Time scales for the 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

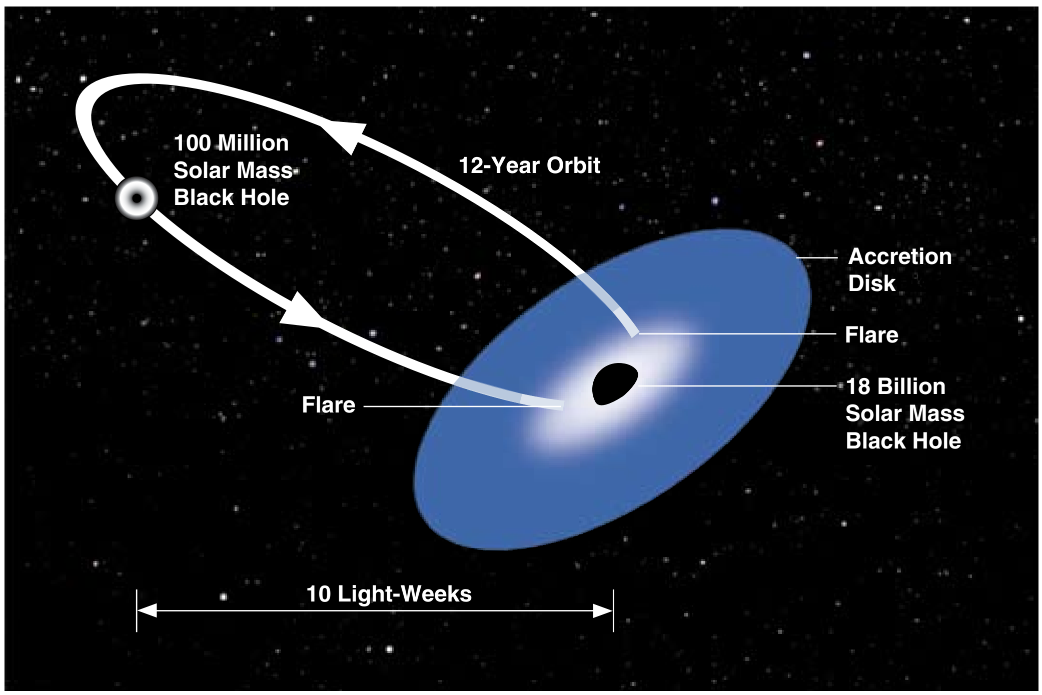

Figure 11-3. Artist's impression of a binary black hole pair in OJ287 (image courtesy Mauri Valtonen, Tuorla Observatory). SIM Lite will be able to track the motion of the suspected black hole pair.

$(M_1 + M_2) / \dot{M}_{Edd} \sim 5 \times 10^7$ 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. A promising candidate may be an object that looks like a quasar (with broad lines and optical–UV continuum) but with absolute luminosity being somewhat less than 10 percent of the Eddington limit expected from the central black hole. These might be objects with a large, but dark, primary central black hole that is orbited by a secondary black hole of smaller mass; the secondary would have cleared out the larger hole's accretion disk interior, but still will be accreting prodigiously from the inner edge of the primary's disk (Milosavljevic and Phinney 2005). In this case, the astrometric motion would indicate the full orbit of the secondary about the primary, which could be a few to a few hundred μas, depending on the source distance.

When the optical emission is dominated by the nonthermal jet that is some distance from the black hole, rather than by the thermal accretion disk that is centered on the hole, an unusual time-dependent astrometric signature (such as a corkscrew) might be seen instead of an ellipse.

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, 2008a). 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). This model is supported by the recent observation of a predicted optical outburst (Valtonen et al. 2008a) and the detection of a predicted soft x-ray excess bump by the Rossi X-Ray Timing Explorer (RXTE) and the X-Ray Multi-Mirror (XMM-Newton) observatory (Valtonen 2008b). For an assumed orbital period of 24 years, a binary black hole system with a mass of at least 10^{10} solar masses has a mean separation of 0.07 pc. For OJ287 ($z = 0.306$), this separation subtends 15 μas, and the orbital motion expected during a five-year span is about 19 μas. For closer systems (e.g., 3C273, M87), SIM Lite will be sensitive to binaries of much lower mass.

About a half dozen of low-redshift quasars and AGN such as 3C273 will be observed with SIM Lite to look for possible binary black holes. These observations require a very high single-epoch positional accuracy and many individual epoch observations over the lifetime of the mission. Thus, only compact, bright, and nearby targets are considered.

11.6 Distribution and Location of the Broad-Emission-Line Clouds

Within the inner pc, clouds of ionized gas that emit lines Doppler-broadened by a few percent of *c* are observed in the optical spectra of many quasars and Seyfert galaxies (Figure 11-4). Narrow-line (<0.1 percent *c*) clouds appear tens to hundreds of pc from the nucleus.

The technique of reverberation mapping measures the time delay between changes in the continuum and resulting changes in the broad lines, and so the distance in cm. As the line width gives a size in Schwarzchild radii, the mass of the central black hole can be measured (for a review, see Peterson

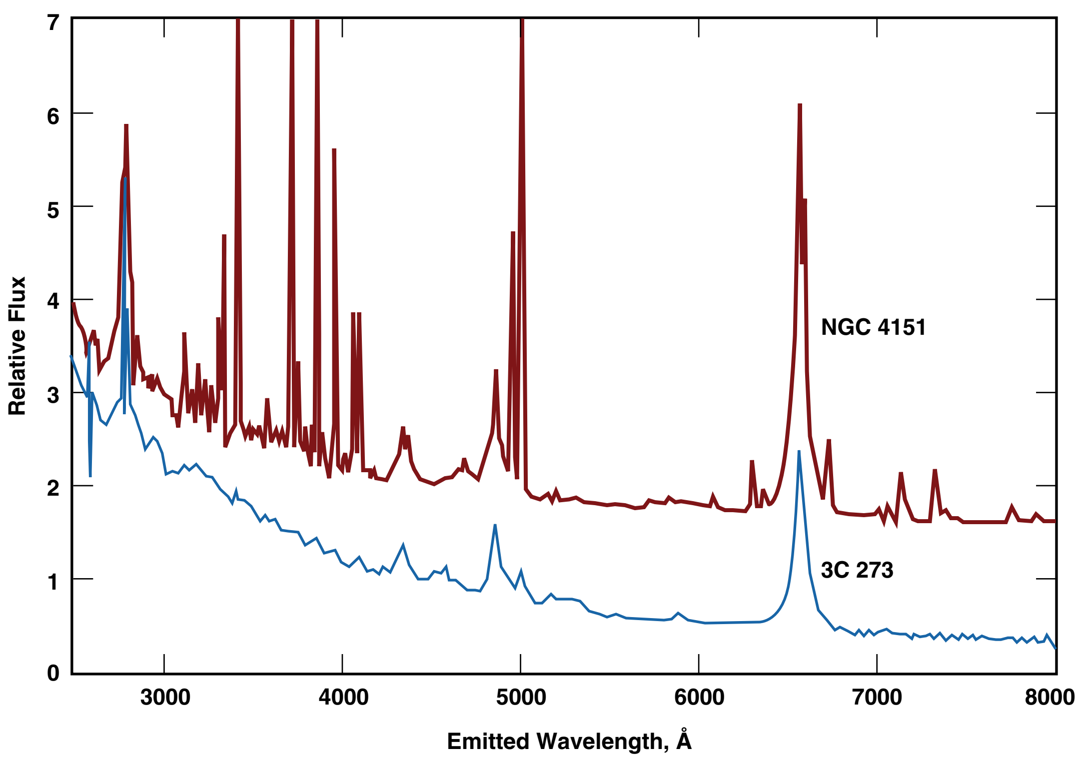

Figure 11-4. Broad lines, e.g., Magnesium II and Hydrogen α, β, and γ, are emitted from Seyfert galaxies like NGC4151, radio galaxies, and quasars like 3C273. The structure of the broad-line region can be elucidated with SIM Lite phase offset observations that show the relative positions of high and low ionization line-emitting gas and the continuum source. Image courtesy of William Keel.

1993, and for analysis and compendium see Peterson et al. 2002). The light detected by the 80 channels of SIM Lite's CCD can be binned to separate the light from emission lines and the intervening continuum emission. Pioneering observations of Be stars made with this technique are underway at the Navy Prototype Optical Interferometer.

Using the same technique as the red/blue color differential measurement described in §11.2, the measured phase offsets from various emission lines may be compared to each other and to the continuum. Lines with different ionization potential are produced at different radii from the central ionizing source, with higher ionization lines nearer to the center than lower ionization lines; i.e., the ionization structure is stratified. For example, distant low-ionization clouds producing Fe II, broad Mg II (2798 Å), and the broad Balmer lines may be an outer extension of the accretion disk. However, some fraction of the Balmer-line-emitting clouds may arise along with higher ionization lines such as He II (4686 Å) and C IV (1549 Å) as part of a wind escaping the disk (Murray and Chiang 1995) in a system of filaments or thin sheets on either side of the nucleus along the cone surfaces (e.g., Elvis 2000), as shown in Figure 11-5. For example, reverberation mapping from ground-based and space-based telescopes has shown the Hβ and Mg II clouds are about seven light-days from the central continuum source in NGC4151 (Bentz et al. 2006; Metzroth, Onken, and Peterson 2006), although there is currently little to constrain the geometry of the line-emitting region (Ulrich and Horne 1996). Understanding the structure and distribution of the broad-line clouds will remove the factor of 2 to 3 geometric uncertainty in reverberation-based

Figure 11-5. The Broad-Line Region (0.1 pc) subtends 25 µas in a quasar at redshift 0.5; the central accretion disk about 1 µas. Spectral lines with different ionization potential are produced at different radii from the central ionizing source, with higher ionization lines nearer to the center than lower ionization lines; i.e., the ionization structure is stratified, as indicated by the change in colors with radial distance from the central region. SIM Lite can illuminate the structures present with red/blue color differential measurements. Artist's concept by David Hinkle, JPL.

masses of the central supermassive black hole, which is of fundamental importance in understanding the physics of AGN, and of the origin of the relationship between black hole mass and velocity dispersion (Ferrarese and Merritt 2000; Gebhardt et al. 2000) that revolutionized our understanding of black hole–Galaxy co-evolution.

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