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Quasar Astrophysics with the Space Interferometry Mission

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Abstract: Precision optical astrometry of quasars and active galaxies can provide important insight into the spatial distribution and variability of emission in compact nuclei. SIM — the Space Interferometry Mission — will be the first optical interferometer capable of precision astrometry on quasars. Although it is not expected to resolve the emission, it will be very sensitive to astrometric shifts, for objects as faint as R magnitude 20. In its wide-angle mode, SIM will yield 4 microarcsecond absolute positions, and proper motions to about 2 microarcsecond/yr. A variety of AGN phenomena are expected to be visible to SIM on these scales, including time and spectral dependence in position offsets between accretion disk and jet emission. SIM should be able to answer the following questions. Does the most compact optical emission from an AGN come from an accretion disk or from a relativistic jet? Do the relative positions of the radio core and optical photocentre of quasars used for the reference frame tie change on the timescales of their photometric variability? Do the cores of galaxies harbour binary supermassive black holes remaining from galaxy mergers? In this paper we briefly describe the operation of SIM and the quasar measurements it will make. We estimate the size of the astrometric signatures which may be expected, and we discuss prospects for using astrometry as a fundamental tool for understanding quasar nuclei.

Keywords: galaxies: active — galaxies: jets — techniques: interferometric

1 Introduction

One of the most challenging questions in astronomy today is to understand the origin, structure, and evolution of the 'central engines' in the nuclei of quasars and active galaxies (AGN). The favoured theory involves the activation of relativistic jets from the fuelling of a supermassive black hole through an accretion disk. In some AGN an outer optically thick 'dusty torus' is seen orbiting the black hole system. This torus is probably related to an inner accretion disk-black hole system that forms the actual powerhouse of the AGN. In radio-loud AGN two oppositely directed radio jets are ejected perpendicular to the torus/disk system.

Although there is a wealth of observational data on AGN, some very basic questions have not been definitively answered. The Space Interferometry Mission (SIM) should be able to address, and hopefully answer, the following three key questions about AGN.

1. Does the most compact optical emission from an AGN come from an accretion disk or from a relativistic jet?
2. Does the separation of the radio core and optical photocentre of the quasars used for the reference frame tie, change on the timescales of their photometric variability, or is the separation stable at the level of a few microarcseconds?
3. Do the cores of galaxies harbour binary supermassive black holes remaining from galaxy mergers? It is not known whether such mergers are common, and whether binaries would persist for a significant time.

These questions are the subject of a SIM Key Project, awarded to the authors of this paper (PI: A. E. Wehrle). Of the ten key projects selected in November 2000 by NASA to be conducted with SIM, this proposal and one other (PI: K. Johnston, USNO) with similar aims, focus on quasars and AGN. Launch of SIM is currently scheduled for 2009, and we expect our scientific results to emerge early in the mission life. A preliminary indication of the reference frame stability between SIM and ICRF (International Celestial Reference Frame) will be answered within the first year (question 2 above).

2 Astrometry of Quasars

With the prospect of precision astrometry in the optical waveband becoming available within a decade, a number of fundamental questions about the nature of AGN can be attacked in a new way. Currently, VLBI provides by far the most accurate astrometry of AGN (Ma et al. 1998) with positional accuracies around 100 microarcsec (μas). The fringe spacing of connected-element optical interferometers such as SIM is $\approx$10 milliarcseconds (mas), so most AGN cores will be unresolved. However, with global astrometry, radio (ICRF) and optical (SIM) catalogues can be compared at the sub-milliarcsecond level, and changes in the optical positions will be resolvable by SIM at the few μas level.

In addition to absolute astrometry, SIM will allow differential astrometry — colour-dependent position shifts — across the optical waveband. This will prove to be

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a powerful diagnostic tool for AGN structure on scales of a few μas. Below we discuss the physical origins of the astrometric shifts we expect to detect using precision astrometry.

2.1 Spatial Distribution of AGN Optical Emission

Thermal emission. Our knowledge of the inner accretion disk system comes mainly from theoretical models; one of the more popular ones is depicted in Figure 1. The disk itself contains at least two possible regions that produce optical continuum emission. When the accretion rate is high (near the Eddington limit, as is suspected in quasars, Seyfert galaxies, and broad-line radio galaxies), the disk is optically thick to free–free absorption, and a 'Big Blue Bump' is seen in the optical–UV spectrum (Band & Malkan 1989). For reasonable physical parameters, the diameter of this portion of the disk is ∼0.01 pc. At 15 Mpc, this region would subtend an angular size of ∼160 μas, while at $z = 0.5$ it would be only ∼2 μas, and not detectable by SIM.

Non-thermal emission. The 'Big Blue Bump' is probably not the dominant source of photoionising radiation in quasars. Instead, a steep power law source extends from the infrared to well into the UV (Osterbrock & Matthews 1986), due to optical synchrotron or perhaps Compton scattered emission from a radio or sub-millimetre source. This central source may be a magnetised corona or wind from the inner parts of the accretion disk, emitting optical synchrotron and thermal and Comptonised X-rays.

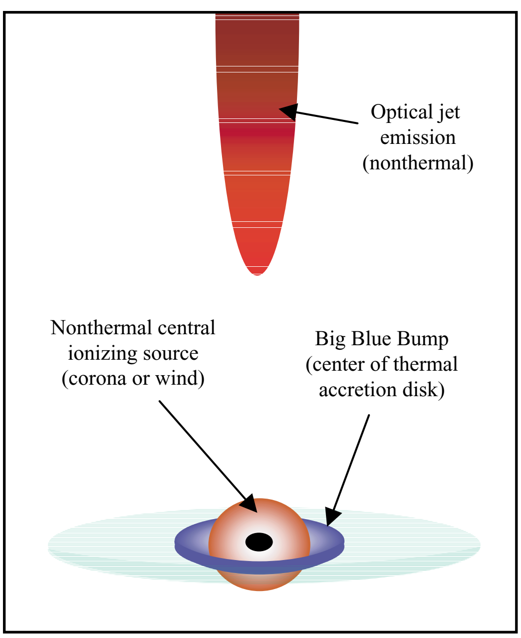

Figure 1 Schematic model of the central ionising source (after Band & Malkan 1989) and jet (after Königl 1981) for a typical AGN. Size of the central disk/corona structure is ∼70–120 R_{Sch} (∼100–160 μas for M87, or only 1–2 μas for a typical quasar at a redshift of 0.5). The offset between the optical jet and disk emission for 3C 345 at $z = 0.6$, based on the Königl model, is expected to be ∼0.4 pc or 80 μas.

Models of the corona region (Band & Malkan 1989) indicate a size of only ∼70 R_{Sch}. On larger scales, optical *beamed* radiation from a relativistic jet may be significant in radio-loud quasars, although the available evidence is indirect (Telfer et al. 2001).

The Beamed Relativistic Jet. Most radio-loud active galaxies contain a relativistic jet, which emerges perpendicular to the accretion disk (Figure 1). Centrifugal and magnetic pressure forces drive the outflow and magnetic pinch forces collimate it. Powerful jets appear to require the central black hole to be spinning rapidly (Wilson & Colbert 1995; Blandford 1999; Meier 1999). If an AGN is radio-loud, *and* viewed at a small angle to the jet axis (a 'blazar'), then optical continuum emission from the relativistic jet itself may be significant. As in the radio, this emission would be strongly beamed toward the observer, and the observed structure seen to be one-sided, perhaps dominating over processes with symmetrical distributions around the central black hole. The Königl (1981) model for relativistic jets predicts that, in the optical, the majority of the emission comes not from synchrotron emission from the central portion of the jet but rather from synchrotron–self-Compton emission in the region of the jet where the synchrotron emission peaks in the radio or millimetre (Hutter & Mufson 1986).

Binary Black Holes. Do the cores of galaxies harbour binary supermassive black holes remaining from galaxy mergers? How commonly does this occur? This is a question of central importance to understanding the onset and evolution of non-thermal activity in galactic nuclei.

An entire AGN black hole system may be in orbit about another similar system, as might occur near the end of a galactic merger, when the two galactic nuclei themselves merge, with a characteristic timescale of a few hundred million years. There is evidence that the process 'stalls out', due to scattering of stars out of the innermost regions of the potential well (Milosavljevic & Merritt 2000; Gould & Rix 2000). If this is so, then merger remnants may not be unusual. If massive binary black holes can be detected via their astrometric signatures over a significant fraction of an orbit, we can directly measure their orbit radii and masses, and thereby estimate the coalescence timescale of the binary.

How large is the astrometric signature? Rough estimates, based on the circumstantial evidence currently available, indicate that displacements of 10 μas or more (readily detectable with SIM) may be present in a number of AGN. The best candidate is probably OJ 287 (Lehto & Valtonen 1996; Kidger 2000), with an inferred period of 24 years from variability monitoring, and a mass of 10^9 solar masses. During 5 years of SIM monitoring, the expected orbital displacement is about 15 μas. Another example is 3C 390.3 (Gaskell 1996). In this radio galaxy, the evidence comes from moving features in the optical spectrum. The projected orbit size of ∼300 μas and period of ∼300 years are poorly constrained, but if correct, would yield a detectable signature with SIM.

2.2 Testing AGN Models using Astrometry

SIM should be able to distinguish which of the AGN emission regions (sketched in Figure 1, for the size scales relevant to SIM) dominates, in a variety of different classes of object. We identify two distinct possible locations for the photocentre of the red light relative to the blue. In both cases, most of the blue light is thermal emission from the optically thick part of the accretion disk — the 'Big Blue Bump'.

Case 1. Most of the red light is power law synchrotron emission along the relativistic jet.

Case 2. The red light comes from synchrotron or inverse Compton emission from a hot, magnetised corona or wind above the accretion disk.

The discriminators between these cases are simple: is there an offset between red and blue photocentres? And, if so, in what direction on the sky? Is the optical photocentre offset from the VLBI core position, and in what direction on the sky?

In Case 1, red light comes from the jet, so its photocentre will be offset (along the jet direction — obtained by VLBI imaging) from the blue photocentre associated with the accretion disk. In Case 2, red light comes from a disk corona or wind, so the red and blue photocentres should be coincident.

Comparing astrometric positions over different wavebands, including the radio, provides an important test of models for relativistic radio jets in AGN. Standard models such as those developed by Blandford & Königl (1979) and Königl (1981) predict significant shifts in the position of emission in different wavebands. These offsets should be readily detectable.

Currently, few direct measurements have been made. Most notable is the double quasar 1038+528 A & B (Marcaide & Shapiro 1984). For this (unrelated) close pair, the VLBI position of A relative to B shifted by about 700 μas between 2.3 and 8.4 GHz, presumably due to optical depth effects. This pair would be a faint target for SIM ($V = 17.5$ and 18.5), but the fact that large shifts have already been detected in the radio indicates that a shift of at least comparable magnitude between VLBI and SIM positions should be detectable in many AGN.

3 Space Interferometry Mission

SIM will be the first long baseline optical interferometer capable of detecting very faint targets, primarily because in space the fringes can be stabilised to long integration times. This will open up the study of active galaxies and quasars with astrometry.

The following is a brief description of SIM. More information is available on the project web site, at http://sim.jpl.nasa.gov. Figure 2 shows a sketch of the SIM design. SIM's design effectively provides an inertially stable platform for interferometric measurements across relatively wide fields. This stabilisation is achieved by using three interferometers simultaneously — two lock onto bright guide stars, while the third observes science targets. A laser metrology system monitors changes on the positions of the key optical components, effectively defining a rigid 3D 'truss', and allowing control of systematic errors equivalent to much less than a degree of fringe phase. For targets fainter than about $R \sim 14$, photon counting statistics begin to dominate over residual systematic errors.

While the spacecraft is stabilised, the science interferometer articulates over a 15° diameter, measuring the shift in the white light fringe positions of targets in the field, or 'tile'. In order to cover the whole sky, SIM will observe overlapping fields, with a carefully chosen 'grid' of stars, nominally ~1500 metal-poor K giants, to tie the tiles together. Astrometric parameters for science targets, the grid, and instrument parameters for each tile, will be derived in a global least squares fit.

SIM will also be able to measure any shift in the optical photocentre of AGN emission as a function of colour. With an octave of bandwidth available (400–1000 nm) SIM can make a very precise measurement of the angular separation between regions emitting different coloured light within the same source. Since this is a differential measurement, it is not subject to most of the systematic errors which potentially limit the absolute astrometric accuracy (depending on details of the observing mode, only faint SIM targets will be purely in the regime where photon statistics dominate). However, the colour shift measurement is expected to be photon limited, even for relatively bright objects. This is an example of an astrometric measurement which could be done very early in SIM operations. The simplest operating mode would be to divide the band into 'red' and 'blue' (averaged) bins, and detect the phase shift between them.

In a similar way, it will be possible to detect a phase shift in a strong spectral line such as Hα against the nearby continuum. Detailed simulations of a resolved AGN disk

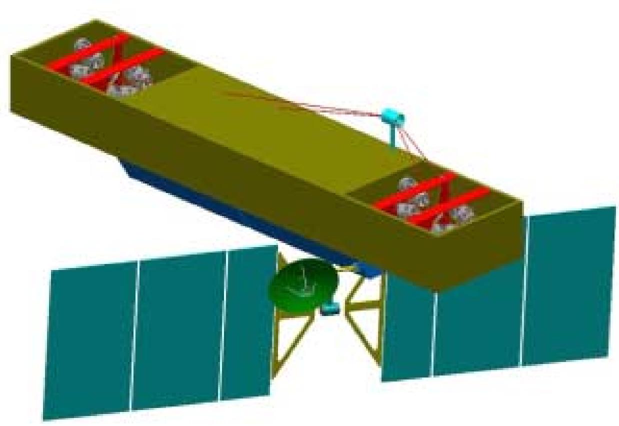

Figure 2 Layout of the main components of SIM, in its deployed configuration. Visible are the main 10 m structure housing all of the optics, the solar panels, and communications antenna. The short post houses a double cube-corner reflector which is part of the laser metrology system, which measures changes in the positions of the major optical elements. Four beams are shown linking the siderostats to the cube-corner.

at the distance of M87 by Böker & Allen (1999) have shown that a target which is *spatially* resolved, as well as spectrally resolved, can be imaged in a bright spectral line. For an AGN at a moderate redshift, no change in visibility amplitude is expected, but a phase shift should be readily detectable. By repeating the tile observations during the mission, we can learn whether this location is stable over time.

Although SIM will be inertially stable to allow microarcsecond precision measurements, it has no absolute reference, and the grid could have a net rotation. SIM will observe a number of carefully chosen quasars to serve as zero proper motion anchors. Fortunately, most of SIM's science program does not depend on an inertial frame, because selecting quasars stable on microarcsecond scales is a significant challenge. Indeed, as shown above, for selected objects astrometric variability will be readily detectable by SIM, and will form an important probe of quasar structure.

3.1 Distinguishing AGN Models using SIM

We consider two representative SIM targets: a nearby AGN such as M87, and a moderate redshift quasar such as 3C 345.

Nearby radio galaxy M87. We expect the optical emission to be dominated by the accretion disk region because its jets are not pointing within a few degrees to our line of sight (Biretta, Stern, & Harris 1991). There should be no colour shift between the red and blue SIM bands, because the corona and accretion disk are axisymmetric (Figure 1). However, we expect a relatively large offset (as large as several 100 μas) between the optical photocentre and radio photocentre (which is dominated by emission from the optically thick base of the radio jet).

Quasar 3C 345. If the non-thermal optical continuum from 3C 345 comes from the base of the relativistic jet, that signature should be detectable with SIM. The Königl (1981) inhomogeneous jet model predicts that optical jet emission should be roughly coincident with the 22 GHz radio emission, but offset about 80 μas from the black hole. Relative astrometry between SIM and VLBI should readily detect a shift this large, and the position angle of the shift should align with the VLBI jet. Colour-dependent position shifts may be observable across the SIM band analogous to the frequency-dependent separation effect well-known in VLBI observations (Unwin et al. 1994). The Königl (1981) model predicts a shift of 30 μas from the red to the blue end of the SIM band, and similar offsets are expected for a broad range of parameters for inhomogeneous jet models of quasars.

4 The Radio–Optical Frame Tie

How well can quasars perform as anchors for a reference frame based on stars? SIM will produce a very precise reference frame, using halo K giants, with positional accuracy of 4 μas. However, this frame may have an offset and a residual rotation rate. To be most useful for the astronomy community, and in particular for comparisons between images in different wavebands, e.g. VLBI imaging, this frame must be tied to the ICRF (Fey et al. 2001). In addition, some of the Galactic dynamics problems that SIM will address are sensitive to a net rotation of the frame.

As discussed above, there are good reasons for expecting astrometric variations in the optical band. In a sense, the most scientifically interesting targets for SIM may be the poorest choice for reference objects; the same problem is well-known in the ICRF itself. The ICRF radio sources are very compact, but many of these are flat spectrum and strongly variable at radio and optical wavelengths. Radio flux variability is correlated with changes in structure on milliarcsecond scales, but we have no optical images with resolution comparable to VLBI. However, Perlman et al. (1999) have shown how polarised optical and radio ‘knots’ in M87 (using HST and NRAO VLA data) are correlated on sub-arcsecond scales.

In the years before SIM launch, we will develop a list of suitable quasars to serve as reference objects for SIM, by applying selection criteria that have yet to be fully developed. Part of the strategy will be to observe about 50 frame tie quasars with SIM on the expectation that several will show significant residuals in their fitted astrometric parameters, and will be eliminated from the astrometric grid solution.

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