White Paper for the Decadal Survey:

Exploring the Most Compact Regions of Relativistic Jets with the Ultra-high Angular Resolution of Space VLBI

Decadal Survey thematic science area 4: Galaxies across Cosmic Time (GCT)

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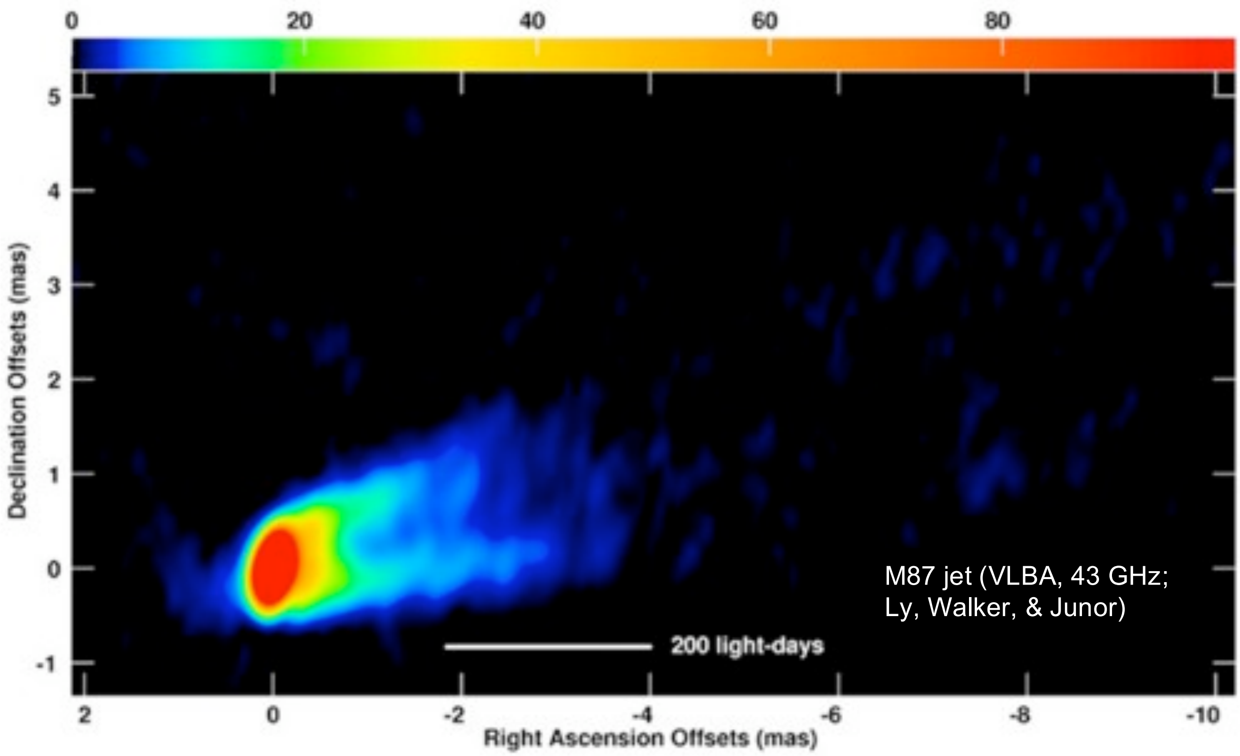

Decadal Survey thematic science area: 4: Galaxies across Cosmic Time (GCT)
Goal: to understand how super-massive black holes (SMBHs) generate ultra-relativistic jets and powerful gamma-ray emission in active galactic nuclei (AGNs)
Instrumentation: add a space-based antenna to ground-based arrays of radio telescopes, operating up to 43 GHz, to provide images with angular resolution as high as 38 microarcseconds
Technique: combine information from time sequences of images with light curves at higher frequencies to probe the emission and magnetic field structure of jets to compare with theories.
Opportunity in the next decade: join with the Japanese space agency, JAXA, to collaborate on the VSOP-2 mission that will launch a 9-meter VLBI antenna into an elliptical Earth orbit.

Introduction

Powered by accretion onto black holes with masses up to $\sim 10^{10}$ $M_{\odot}$, AGNs represent the most energetic long-lived phenomenon in the universe. In ~10% of these objects, a substantial fraction (as much as tens of percent) of the energy of accretion is converted into kinetic energy of outflows in the form of relativistic, highly collimated jets of energetic plasma and magnetic fields. The jets emit highly variable nonthermal radiation across the electromagnetic spectrum that can greatly exceed the thermal emission from the accretion disk and host galaxy in blazars, AGNs in which one of the jets points in our direction. In some cases, the bulk of the observed flux emerges in γ-ray photons in the GeV or even TeV energy range. One of the most intriguing and challenging quests of current astrophysics is to understand the physical conditions and processes that give rise to the formation of these relativistic jets, production of high-energy particles, and emission of γ rays. Of particular interest is the question of how accretion onto SMBHs generates such high-powered directed outflows.

The Power of Ultra-high Resolution Imaging

A scientific corollary to the cliché "a picture is worth a thousand words" might be "an image is worth a thousand inferences." The only current technique capable of viewing directly the parsec- and subparsec-scale regions of jets in AGNs is very long baseline interferometry (VLBI). Past breakthroughs in AGN research made possible by VLBI include, among many other findings, the discovery of apparent superluminal motions in parsec-scale jet, and the conclusion that the brightest γ-ray emission is associated with the fastest apparent speeds in blazars (Jorstad et al. 2001a; Kellermann et al. 2004).

The Very Long Baseline Array (VLBA) currently provides angular resolution of ~100 μarcsec at a frequency of 43 GHz (λ=7 mm). This is close to the frequency at which the overall nonthermal spectrum becomes optically thin, a circumstance that allows a view of the innermost portions of the jet. In some objects (e.g., BL Lac; Marscher et al. 2008), features upstream of the core[1] are seen as they move down the jet. Such observations suggest that sufficiently high-resolution observations could image the acceleration and collimation zone of the flow, which currently can be explored only in an indirect manner through time variability of flux and polarization. However, the spacings of the antennas of the VLBA are limited by the size of the Earth. Obtaining higher resolution while maintaining high dynamic range[2] requires an antenna in space.

Opportunity to Obtain Ultra-high Resolution Imaging: VSOP-2

The previous Decadal Survey included a recommendation for NASA to engage in a mission (named ARISE) to construct, launch into orbit, and operate a space-based VLBI antenna. While NASA has not yet moved forward on such a mission, the Japanese space agency JAXA is pro-

[1] The "core" is a term given to the essentially stationary, bright, compact feature at the narrow end of the jet seen in VLBI images. Although traditionally thought to be the point where the jet becomes opaque at the wavelength of the VLBI observation, the core in many blazars appears instead to be a physical structure such as a standing shock (D'Arcangelo et al. 2007; Marscher et al. 2008).
[2] Ground-based VLBI at shorter millimeter wavelengths can also provide higher resolution, but at the expense of much lower dynamic range owing to the smaller antennas, lower source fluxes, and more severe atmospheric effects.

ceeding with a similar mission, VLBI Space Observatory Programme-2, or VSOP-2. The planned observing frequencies are 43, 22, and 8 GHz (λ=7 mm, 1.3 cm, and 3.8 cm). At 43 GHz, the angular resolution will be as fine as 38 μarcsec.

VSOP-2 will consist of a 9-meter diameter millimeter-wave antenna in an elliptical Earth orbit with 25000 km apogee height and 1000 km perigee height. This enables, in conjunction with arrays of radio telescopes on Earth, creation of an effective aperture 3 times larger than is achievable from the ground. **This is turn allows the highest resolution imaging ever obtained (1000 times finer than HST)**. VSOP-2 was competitively selected in Japan, is currently in phase B, and has a scheduled launch date in early 2013. It is a second-generation mission that follows up the VSOP-1 mission (1997-2003) that operated successfully at lower frequencies (5 and 1.6 GHz) and consequently coarser resolution. It offers an order-of-magnitude improvement in both sensitivity and angular resolution over VSOP-1, and operates at higher frequencies.

VSOP-2 provides a relatively low-cost opportunity for the US to provide access to ultra-high angular resolution astronomy for studies of the most compact regions of jets in AGNs. The exquisite resolution of VSOP-2 plus ground-based antennas will create an interferometer array that will open a wide swath of new parameter space. This will essentially guarantee discovery of features of AGN jets that have escaped theorists' imaginations. Since we cannot anticipate such surprise discoveries, what we discuss below is necessarily an extrapolation of what we already know or suspect. What we actually find will overlap with current models as well as take us in unexpected directions. **VSOP-2's highest observing frequency (43 GHz) is able to avoid opacity in many of the most exciting AGNs, so that the extra resolution will allow us to image the cores of jets, which are essentially unresolved with ground-based arrays.** This will undoubtedly be revolutionary in our field: the core is a key structure in a jet and has already been implicated as the main site of steady optical synchrotron emission (D'Arcangelo et al. 2007).

Exploration of AGN Jets

The discovery of quasars in the 1960s eventually led to the inference that accreting SMBHs power the prodigious radiated luminosity from AGNs. Soon thereafter, VLBI observations showed conclusively that the centers of many AGNs contain jets of material flowing outward at speeds more than 99% that of light, generated close to the SMBH. High-resolution optical spectroscopy with the Hubble Space Telescope subsequently provided mass measurements of compact nuclei in both active and “normal” galaxies, showing that nearly every galaxy of substantial mass harbors a SMBH, with masses ranging from millions to billions times that of the Sun.

In the 1990s, the EGRET instrument aboard NASA's Compton Gamma Ray Observatory carried out the first significant survey of the γ-ray sky, detecting copious and highly variable γ-ray emission preferentially from those AGNs with the most highly relativistic radio jets pointing in our direction — blazars. The *Fermi* Gamma-ray Space Telescope, launched in 2008, is detecting many more blazars and gathering well-sampled γ-ray light curves for many of these. Together with data from X-ray telescopes, these observations have established that the universe at high energies is bathed in the diffuse radiation from millions of distant AGN jets. In addition, recent results have shown that SMBH-powered jets, which in some objects extend to 100s of kiloparsecs from the nucleus, profoundly influence the structures of — and growth of galaxies in — clusters of galaxies and energize the hot gas that pervades these clusters.

We have thus been led to a state of affairs that was unimaginable fifty years ago:

1. Most galaxies contain SMBHs at their centers, which in many cases power ultra-relativistic jets of material streaming outward at over 99.9% the speed of light.
2. These SMBHs energize the most powerful persistent γ-ray emitters in the universe.

These striking discoveries have left us with numerous challenges that push the current boundaries of astrophysical research.

VLBI is a premier tool for addressing these challenges, since centimeter and millimeter wavelengths are able to pierce the vast quantities of dust and gas surrounding the central engines, giving us a clear view of the jet. The hard limit to the angular resolution of ground-based VLBI, imposed by the Earth's physical size, drives the need for placing antennas in orbit. The factor-of-3 increase in achievable baseline length for VSOP-2 enables an order of magnitude improvement in areal resolution, offering the opportunity to image jets in unprecedented detail. **This aspect of VSOP-2 is central to the advancement of our understanding of jet physics, since the crucial processes of acceleration and collimation take place within a parsec of the central SMBH. This is below the resolution threshold of ground-based VLBI but resolvable with VSOP-2.**

The following subsections describe an approach to answering three key questions about ultra-relativistic jets and SMBHs that will be addressed by VSOP-2.

Key Question 1: How Are Ultra-Relativistic Jets Generated by SMBHs?

Jets emanating from AGNs are among the largest and most spectacular structures in nature, often remaining collimated for several million light years before dispersing into massive plumes of high-energy plasma emitting synchrotron radiation. Figure 1 shows a schematic of such a jet and its primary characteristics, over a range of nine orders of magnitude in size. From an astronomical standpoint, these AGN jets represent the most extreme members of a wide family of jet-powered phenomena, including γ-ray bursts, X-ray binary systems, and young stellar outflows. In the leading scenario for launching jets, the twisting, by differential rotation, of the magnetic field in the SMBH's accretion disk and/or ergosphere drives an energetic jet outflow along the poles (e.g.,Blandford & Znajek 1977; Blandford & Payne 1982; Lovelace et al. 1991; Begelman 1995; Meier et al. 2001; Hawley & Krolik 2006; McKinney & Narayan 2007). Figure 2 shows a recent model of a sub-parsec MHD jet propagating out from an AGN nucleus developing a kink instability similar to what VSOP-2 could observe (Nakamura and Meier 2004).

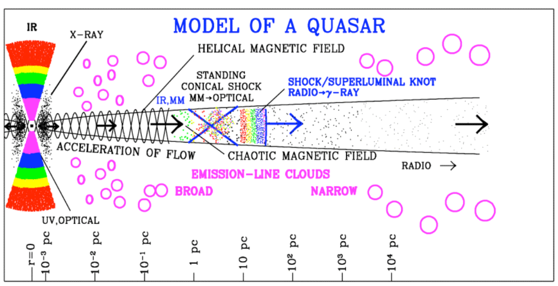

Figure 1: Schematic of an ultra-relativistic AGN jet, illustrating approximate locations of the jet acceleration region and gamma ray production. The distance scale is logarithmic in order to accommodate both small- and large-scale features on the same diagram.

Shock waves as well as fluid/plasma turbulence accelerate individual electrons in the jet to ultra-relativistic energies. These electrons spiral in the magnetic fields to produce synchrotron radiation at radio, infrared, optical, and, in some cases, UV and X-ray frequencies. They also scatter photons from within or outside the jet to X-ray and gamma-ray energies. While this scenario seems quite plausible, past confrontations of theories with AGN observations suggest that it is at best only partly correct. In particular, considerable uncertainty remains regarding how and where the outflow transforms from purely electromagnetic to kinetic energy-dominated, and the relative roles played by velocity shear, turbulence, shocks, and plasma instabilities in the flow.

Observations of ultra-relativistic jets are also affected by Doppler shortening of their variability timescales and aberration of their intrinsic radiation patterns. Jets viewed nearly end-on therefore tend to be the brightest, most compact jets in the sky. Their speeds in the sky plane can appear superluminal, since the emitting material closely follows its own previously emitted radio signals; current ground-only VLBI observations have shown apparent speeds up to ~50 times that of light in AGN jets. Multi-epoch imaging with VSOP-2 will track jet evolution at

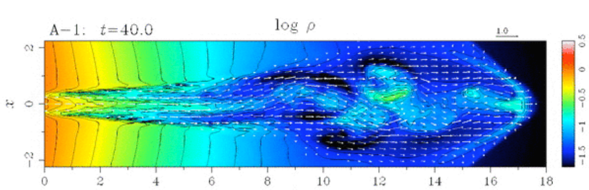

Figure 2: Snapshot of 3-D evolution of a sub-parsec scale AGN jet undergoing helical kink development due to twisted magnetic field lines; Nakamura and Meier (2004).

three times higher resolution than previously possible. Since any radio flux-limited sample of AGNs includes the most highly beamed sources in the sky, usually referred to as blazars, this will set a firm limit on the highest attainable Lorentz factors in AGN jets, a crucial parameter for accurate modeling of the jet acceleration process and the true distribution of jet speeds.

A major impediment in the study of AGN jet physics has been obtaining reliable measurements of the jet Doppler and Lorentz factors, which requires knowledge of both their intrinsic speed and viewing angle. VSOP-2 will determine all of these quantities using a new technique (Jorstad et al. 2005) that compares the flux decay times of individual moving knots, as measured with VLBI, to their light-crossing times. VSOP-2 images at 43 GHz will also provide the high resolution essential for accurate calculations of physical jet parameters, such as the expected X-ray and γ-ray flux spectrum.

A key observational test of the jet-launching models, best studied at high resolution, is the stability of the jet nozzle. It is believed that wobbling of the accretion disk and/or spin axis of the compact object causes the nozzle to slowly precess, so that material travels outward on a variety of ballistic trajectories. This effect has also been seen on decade-long timescales in AGN jets with the VLBA. In some cases, the wobbling has been ascribed to orbital motions of a binary SMBH; for others, helical Kelvin-Helmholtz or magnetic instability models have been developed. By observing the innermost jet regions of many AGNs at high resolution, VSOP-2 will aid in distinguishing between these various models, and indirectly probe the angular momentum properties of SMBH and the role of the jet in transporting this angular momentum.

Plan for answering key question 1:

1. Use VSOP-2 plus the VLBA to image (in full polarization at 43 GHz) a sample of the most highly variable AGNs with bright jets, each observed approximately once per month to determine the maximum values for apparent jet speeds, the stability of the jet nozzles, and the magnetic field structures in the jet-launching regions.
2. Measure physical sizes and timescales of flux decline of emission knots in the sub-milliarcsecond jet regions at 43 GHz where they are optically thin. From these values one can derive separately the true jet speed and viewing angle using the method of Jorstad et al. (2005).
3. Measure the degree of ordering and mean direction of the magnetic field, both with distance from the SMBH and between the flow axis and jet boundary.
4. Apply the newly measured jet properties, including their evolution over time, to test extant models of relativistic AGN jet generation near their parent SMBHs.

Key Question 2: Where & How Are Gamma-Rays Produced in Jets Near SMBHs?

An exciting discovery made by space-borne instruments and ground-based Cherenkov telescopes is the detection of high-energy GeV γ rays from over 100 AGN jets. There are currently several competing models for the source of this radiation, which include upscattering of synchrotron photons from either the jet (e.g., Bloom & Marscher 1996), accretion disk (Dermer & Schlickeiser 1994), or broad emission-line region (Begelman et al. 1994) by relativistic electrons, and high-energy particle cascades (Mannheim et al. 1991). A feature common to all models, however, is that the γ rays are expected to be associated with the compact regions of relativistic jets energized by the central SMBHs. High angular resolution observations from the VSOP-2 program, combined with γ-ray data from *Fermi*, offer an unparalleled opportunity to significantly increase our understanding of high-energy emission and particle acceleration mechanisms in AGNs, which in turn will probe the physical conditions of the jet near and upstream of the core. The *Fermi* Large Area Telescope (LAT) instrument is gathering well-sampled, *continuous* light curves for thousands of expected γ-ray blazars; VSOP-2 can focus on a subset of these objects with γ-ray signal/noise high enough to sample these light curves on timescales of weeks or less. Observations of rapid variability suggest that the bulk of blazar γ-ray emission comes from near the VLBI core of the jet where the required ingredients are available. High-resolution imaging of this region is therefore vital for understanding the mechanisms by which these high-energy photons are produced.

The location of the specific site of AGN γ-ray emission, and the correlation of the γ-ray time series with events imaged by the VSOP-2 program, are perhaps the most important factors by which we can distinguish among the competing models for the γ-ray production. The γ rays could either be generated mostly in the core, the region upstream of the core, or in the moving knots as they propagate downstream. [The last of these possibilities is supported by statistical correlations suggesting that superluminal ejections and mm-wave flares sometimes *precede* γ-ray flares (Valtaoja & Teräsranta 1995; Jorstad et al. 2001b).]

Since the VSOP-2 images will be made with both orthogonal polarizations, which sample different field components, even higher effective spatial resolution than the total intensity images will be obtained. For example, features emerging from the base of the jet with a different electric vector position angle will be apparent in the polarimetric images before they are resolved in the total intensity data. By tracking the evolution of these electric vectors alongside those observed at optical wavelengths, the site of the variable optical emission can be located on the VSOP-2 image. Observed time lags between the optical and γ-ray light curves will pinpoint the location of the gamma-ray emission region. This is the most fundamental information needed to specify the γ-ray production process (Blandford 2008). Furthermore, the derivation of the Doppler and Lorentz factors discussed above will supply the physical data required by theoretical models for computing the expected gamma-ray flux and spectral index.

Plan for answering key question 2:

1. Match events in the multi-epoch full-polarization VSOP-2 images of AGN jets, such as the emergence of a new superluminal knot, with γ-ray flares observed by Fermi to determine unambiguously the site of the gamma-ray emission within ultra-relativistic AGN jets.
2. Use the physical properties of jet knots derived from VSOP-2 imaging, including sizes, energy content, and magnetic fields (see Marscher 1983), to compute the expected γ-ray flux from each AGN for various models, and compare with the time-variable γ-ray fluxes measured by *Fermi*.

Key Question 3: How are Ultra-relativistic Jets Confined and Shaped as they Propagate away from SMBHs?

AGN jets have profound effects on the surrounding environment, e.g., in clusters of galaxies (McNamara et al. 2005). Energy and momentum exchange between jets and the intracluster medium between galaxies can regulate the formation and growth of galaxies and the SMBHs within them, as well as limit the rate of mergers and flows onto galaxies hosting SMBHs (Springel et al. 2005; Di Matteo et al. 2005). Moreover, radiation from the jets ionizes gas along a cone surrounding the channel of flow within the host galaxy. Shock waves form where jets ram into the external medium, inducing large bulk motion of gas and even triggering star formation. These effects are visible in AGNs today, but were even more prevalent at earlier epochs of the universe, when many galaxies were still in the formation phase and a greater proportion were strongly active. Understanding galaxy formation and the birth of the early generations of stars is therefore intimately tied to our understanding of how black holes grow by accretion and generate relativistic jets, and how the jets propagate from the center of a galaxy to its outskirts and beyond.

Beyond the zone where acceleration and collimation of the ultra-relativistic jet flow takes place, both observations and fully three-dimensional numerical simulations (e.g., Aloy et al. 2003) indicate that shocks, shear, turbulence, instabilities, and bends are all present. These processes change the direction and/or degree of magnetic field order, and energize electrons in different ways. For example, D'Arcangelo et al. (2007) found evidence, from variations in the 43 GHz and optical polarization, for a standing shock through which turbulent jet plasma flows in the core of the quasar 0420-014. VSOP-2 imaging of the linearly polarized intensity therefore will provide a valuable probe of the processes that govern the dynamics and state of the plasma in jets. High-resolution radio spectral imaging also provides important information on the geometry, magnetic field strength, relativistic electron density, and composition of AGN jet plasmas. In a number of cases VSOP-2 will measure the apparent shift of the optically thick core with frequency (Königl 1981), which provides estimates of magnetic field strength, total intrinsic luminosity and absolute geometry of the jet, and the mass of the central black hole (Lobanov 1998). Estimates of the total jet luminosity will be indispensable for multi-wavelength studies of broadband AGN spectra, as well as for statistical studies addressing the relation between AGN jet flow speed and overall power (e.g., Cohen et al. 2007).

Some of the most exciting recent discoveries in AGN jets have arisen from studies of their structure transverse to the flow direction. Observations of large scale AGN jets with the VLA (Laing and Bridle 2002) show distinct velocity gradients in which a fast central spine is surrounded by a slower sheath that interacts with the external medium. It is not yet clear to what extent these interactions serve to stabilize and/or decelerate the flow, and how they influence the overall evolution and structure of the jet. Our knowledge is more limited on small scales, due to the resolution limitations of ground-based VLBI. VSOP-2 will resolve the jets in the transverse direction, allowing us to observe phenomena such as limb brightening and changes in polarization that provide powerful probes of the flow properties.

In Figure 3 we compare the images of the blazer 3C345 that can be obtained with the VLBA-alone and with a VSOP-2 simulation. The increased resolution from using VSOP-2 will allow the innermost AGN jet region to be probed for the first time. VSOP-2 resolution of closer AGNs with similar jet structure corresponds to a linear resolution of 40, 300, & 400 gravitational radii in M87, 3C 111 and BL Lac, respectively, which allows probes of the core and region between the core and the acceleration and collimation zone of the jet with unprecedented detail.

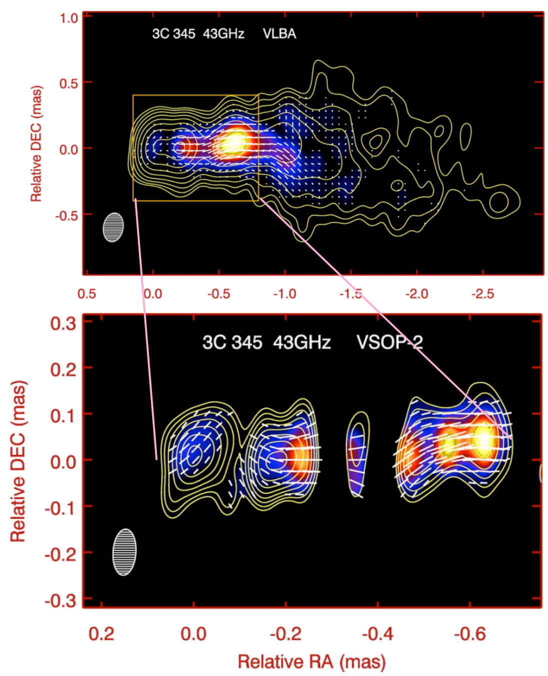

Figure 3: Image of a blazar jet at 43 GHz as observed with the resolution of the VLBA (top) and VSOP-2 (simulation, bottom). Supermassive black hole is to the left of the emission. Contours show total intensity, color polarized intensity with white sticks indicating direction of the electric vector. The VSOP-2 simulation includes only the features contained in the VLBA image; the actual VSOP-2 image is expected to show polarization and emission patterns that cannot be inferred from the VLBA data. Nevertheless, at the VSOP-2 resolution moving shocks (polarization parallel to jet, strongest at shock front), oblique standing shocks (polarization angled to the jet axis and strongest on the upstream edge), and turbulent regions (~zero polarization) are apparent; cf. cartoon in Figure 1.

Plan for answering key question 3:

1. Use ultra-high resolution linearly polarized intensity images from VSOP-2 to probe the transverse magnetic field structure on the smallest scales in jets.
2. Map the Faraday rotation in the jet to probe the magnetic field geometry inside the jet and in its surroundings.
3. Measure apparent shift of the jet core with frequency and consequently determine the jet's magnetic field strength, total intrinsic luminosity, and absolute geometry, as well as to estimate the mass of the SMBH.

Historical Perspective

A series of pioneering experiments involving NASA Tracking and Data Relay Satellite System (TDRSS) satellites (Levy et al. 1986, Linfield et al. 1989, 1990) provided the initial proof of concept for space-VLBI. These initial tests were successfully followed up by the Japanese-launched HALCA satellite mission (VSOP-1, 1997 – 2003; see Hirabayashi et al. 1998). VSOP-1 was an engineering mission from the Japanese MUSES (Mu-Series Engineering Satellite) program that solved a variety of complex issues involving deployment of a mesh antenna in space, phase transfer to the satellite, 128 Mbits/s real-time data downlink, data correlation, and space-VLBI imaging. This effort created a fully functional observatory that was ultimately made available to the astronomical community.

Following from the operational success of VSOP-1, a proposed U.S.-led successor mission called ARISE (Ulvestad, 1999, 2000) was recommended by the year-2000 Astronomy and Astrophysics Survey Committee. While costs preclude such a mission in the current tight fiscal environment, 7 of 9 ARISE science goals (see Table 3 of Ulvestad et al 1999) can be realized through the VSOP-2 science investigation.

US Contribution Needed by the VSOP-2 Project

The role that the US can play in the VSOP-2 project is threefold:

1. Provide funds to NRAO to support (a) the VLBA to serve as the main ground-based array to be used in conjunction with VSOP-2 and (b) the VLBA correlator to process the observations.
2. Construct and operate a dedicated two-way telemetry system for reference tone uplink and real-time 1 Gbits/s data downlink. Provide precision orbit determination (POD) using GPS and SLR data.
3. Fund US astronomers to carry out scientific investigations with VSOP-2.

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