Goals of the ARISE Space VLBI Mission$^{1,2}$

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Abstract

Supermassive black holes, with masses of $10^6M_\odot$ to more than $10^9M_\odot$, are among the most spectacular objects in the Universe, and are laboratories for physics in extreme conditions. The primary goal of ARISE (Advanced Radio Interferometry between Space and Earth) is to use the technique of Space VLBI to increase our understanding of black holes and their environments, by imaging the havoc produced in the near vicinity of the black holes by their enormous gravitational fields. The mission will be based on a 25-meter space-borne radio telescope operating at frequencies between 8 and 86 GHz, roughly equivalent to an orbiting element of the Very Long Baseline Array. In an elliptical orbit with an apogee height of 40,000–100,000 km, ARISE will provide resolution of 15 microarcseconds or better, 5–10 times better than that achievable on the ground. At frequencies of 43 and 86 GHz, the resolution of light weeks to light months in distant quasars will complement the gamma-ray and X-ray observations of high-energy photons, which come from the same regions near the massive black holes. At 22 GHz, ARISE will image the H$_2$O maser disks in active galaxies more than 15 Mpc from Earth, probing accretion physics and giving accurate measurements of black-hole masses. ARISE also will study gravitational lenses at resolutions of tens of microarcseconds, yielding important information on the dark-matter distribution and on the possible existence of compact objects with masses of $10^3M_\odot$ to $10^6M_\odot$.

Key words: black hole physics, masers, instrumentation: interferometers, telescopes, galaxies: active, gravitational lensing
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1 The ARISE Mission Concept

Supermassive black holes (SMBHs) are thought to be responsible for the astounding amount of energy released from the centers of many galaxies. The technique of Space VLBI ([Ulvestad, 1999]) is the only astronomical technique foreseen for the next 20 years that will have the capability of imaging the region dominated by the gravitational potential of the black hole, within light days to light months of the active galactic nucleus. ARISE (Advanced Radio Interferometry between Space and Earth) is a mission currently under active study in the U.S. that will orbit a 25-m telescope to work together with ground telescopes worldwide in order to investigate the spectacular astrophysics in the vicinity of SMBHs.

For ground-based VLBI operating at a frequency of 86 GHz on the longest baselines possible on Earth (~10,000 km), the best angular resolution is about 75 µas, a factor of ~500 better than that achievable with the Hubble Space Telescope. ARISE, in an elliptical orbit with a maximum altitude of 40,000-100,000 km, will work together with sensitive ground radio telescopes such as those in the Very Long Baseline Array (VLBA) and in the European VLBI Network (EVN), and will produce radio images of active galactic nuclei (AGNs) with angular resolution of 7–15 µas at the highest observing frequency of 86 GHz. Table 1 lists the basic mission parameters.

Table 1
ARISE Mission Parameters

| Parameter             | Value                      |
|-----------------------|----------------------------|
| Apogee Height         | 40,000–100,000 km          |
| Orbital Period        | 13–37 hr                   |
| Observing Bands       | 8, 22, 43, 86 GHz          |
| Antenna Diameter      | 25 meters                  |
| Maximum Data Rate     | 4–8 Gbit sec⁻¹             |
| Polarization          | Dual Circular or Linear    |
| Maximum Baseline      | 4–9 Earth Diameters        |

Table 2 lists the observation characteristics as a function of frequency. Detection thresholds for a baseline to the Effelsberg 100-m telescope (EB) are given, assuming no phase referencing and the maximum data rate. Because of angular momentum constraints, it is extremely unlikely that the space radio telescope can switch sources rapidly enough to do phase referencing, but this technique of calibrating the atmosphere may be enabled just by having the ground telescopes switch sources. At 43 and 86 GHz, millimeter-wave tele-
scopes such as SEST and the MMA/LSA will be important anchors that will significantly improve the fringe-detection threshold.

Table 2
Frequency-Dependent Observational Parameters for ARISE

| Parameter               | 8 GHz | 22 GHz | 43 GHz | 86 GHz |
|-------------------------|-------|--------|--------|--------|
| Aperture Efficiency     | 0.50  | 0.38   | 0.24   | 0.08   |
| System Temperature      | 12 K  | 16 K   | 24 K   | 45 K   |
| Resolution              | ≤ 150 μas | ≤ 60 μas | ≤ 30 μas | ≤ 15 μas |
| Detection Threshold to EB | 0.7 mJy | 1.9 mJy | 9.4 mJy | 150 mJy |

2 ARISE Science Goals

ARISE is a versatile, high-sensitivity instrument that will employ the technique of Space VLBI to image the environment of a variety of compact objects such as supermassive black holes (SMBHs). It will resolve details 5–10 times smaller than can be imaged using ground-based VLBI, and several orders of magnitude smaller than instruments observing in other wavebands. Table 3 summarizes the primary science goals of ARISE; a number of additional goals, such as imaging of young supernovae, are omitted due to lack of space.

Table 3
Primary Science Goals of ARISE

- Supermassive Black Holes and Radio Jets
  - AGN Fueling
  - Relativistic Jet Production
  - Generation of High-Energy Photons
- Accretion Disks and H₂O Megamasers
  - Masses of Supermassive Black Holes
  - Nature of Megamaser Disks
  - Accretion Processes
  - Geometric Distance Measurements
- Cosmology
  - Gravitational Lens Studies
- High-Redshift Radio Sources
The most important goals of ARISE focus on studies of SMBHs and their environments in active galactic nuclei, the most energetic power plants in the Universe. The popular treatment by Begelman & Rees (1996) discusses observed properties of AGNs over a variety of wavebands that are attributable to SMBHs. The current paradigm for an AGN includes, at its center, a SMBH that provides the power for the AGN. Surrounding the black hole is an accretion disk, that is roughly co-planar (except for disk warps) with a much more extensive “torus” of material that may extend for hundreds of parsecs. As material in the disk drifts toward the central black hole, energy is extracted from that material by the spinning black hole. A magnetized radio jet of highly relativistic particles is accelerated near the SMBH, and flows outward near the speed of light along the symmetry axis of the accretion disk. Flickering gamma-ray emission reveals the creation of large quantities of high-energy particles in the inner light months of the radio jet.

With ARISE, two critical classes of observations can be made. First, imaging of the inner light months of active galaxies in their continuum radio emission reveals the birthplace of the relativistic jets, the generation of shocks near that birthplace, and the key physical parameters in the regions of gamma-ray production. Second, imaging of molecular line (H$_2$O maser) emission from the inner light months of the accretion disks in AGN directly samples the dynamics of material in the vicinity of the SMBH. Such studies lead to direct measurement of SMBH masses and of the physical characteristics of the accretion process (Moran et al., 1995). VLBI in general, and ARISE in particular, provide important information, and actual images, that can be supplied by no other technique in modern astrophysics. The ARISE resolution at 86 GHz will correspond to $\leq 0.1$ pc for a blazar at $z = 0.5$, enabling resolution on a scale similar to that of the gamma-ray emission. In an H$_2$O megamaser galaxy at 50 Mpc distance, the 22-GHz resolution will be $\leq 0.05$ pc, enabling imaging of the vertical and velocity structures in the disk. Observations on such important physical scales in these objects are not possible with VLBI baselines whose length is limited by the size of the Earth.

Beyond the studies of SMBHs and their environment, ARISE can use AGNs for a variety of important cosmological studies. In particular, ARISE will permit investigation of radio sources with an otherwise unreachable combination of sensitivity and angular resolution, which is crucial for conclusive cosmological tests measuring the dependence of angular size and separation on redshift. Of special interest are the novel investigations that can be made using gravitational lenses (Kochanek & Hewitt, 1996). ARISE imaging of lensed AGNs will improve the modeling of the mass distribution, currently the largest uncertainty in the determination of the Hubble Constant by this direct method. A gravitational lens also acts as a “cosmic telescope” in magnifying the background source by a factor of 10 or more, effectively increasing the angular resolution of ARISE to near 1 $\mu$as, which will provide resolution of light days.
even for the most distant AGNs. Finally, the sensitivity of ARISE to structures on the scale of tens to hundreds of microarcseconds will enable detection of compact lenses having masses of $10^3$–$10^6 M_\odot$; such objects are among the leading candidates for the “missing” baryonic dark matter.

3 European Contributions to ARISE

ARISE is currently part of the long-term roadmap in NASA’s Structure and Evolution of the Universe theme; if ARISE is funded in its current incarnation, it will likely be as a U.S.-led mission. However, ARISE also has many of the elements of a “descendant” of two other Space VLBI concepts, QUASAT and the International VLBI Satellite, which were proposed to the European Space Agency (ESA), but ultimately were not funded. Thus, concepts developed in Europe already have played a key role in ARISE, and several members of the ARISE Science Advisory Group are based at European institutions. The newly formed Joint Institute for VLBI in Europe (JIVE) provides an excellent vehicle for the participation of European ground facilities in ARISE; the European development of millimeter-wave telescopes will be especially useful at the higher frequencies. The capabilities of ESA, including equipment that will be flown aboard Planck/FIRST, also could provide important contributions to the space element of ARISE. Table 4 lists some areas in which European participation could contribute significantly to ARISE.

Table 4
Possible European Participation in ARISE

| Science planning          |
|----------------------------|
| Ground radio telescopes    |
| Recording systems          |
| JIVE correlator            |
| Tracking station           |
| On-board VLBI equipment    |
| Space cryo-cooler or amplifiers |

4 ARISE Timeliness

The VLBI Space Observatory Programme (VSOP), is the first dedicated Space VLBI mission, in operation since early 1997 (Hirabayashi et al., 1998). VSOP, under the leadership of the Institute for Space and Astronautical Science in
Japan, has demonstrated the capability for routine Space VLBI imaging by observing strong sources at 1.6 and 5 GHz. A much more sensitive mission using this technique will be timely, because it provides an imaging capability in the compact regions that will be investigated by several upcoming high-energy satellites such as GLAST and ASTRO-E. ARISE will take advantage of space technologies currently under active development. The most crucial technology is that connected with the deployable 25-m reflector that must work at frequencies as high as 43 and 86 GHz. The current baseline selection for ARISE is an inflatable antenna, under development for several other applications in communications and remote sensing. The other “new” technologies are those aimed at achieving a very high sensitivity, and should be well in hand by the potential ARISE launch date of 2008. These include low-noise amplifiers (developed for MAP and Planck/FIRST) and cryogenic cooling to an ambient temperature of 20 K (tested aboard the Space Shuttle and required for Planck/FIRST).

Required ground systems include a number of sensitive ground telescopes. The EVN and the VLBA already provide a suite of ground telescopes as well as the entire operational infrastructure necessary for a VLBI mission. Completion of the Green Bank Telescope, the MMA/LSA, and the VLA upgrade will provide major new capabilities at the highest ARISE observing frequencies. Finally multi-gigabit per second data-recording and correlation capability will be required, and is under active development by several groups, notably in the Mark 4 and S3/S4 systems. Within the U.S., ARISE provides a unique opportunity for cooperation between space assets funded by NASA and an extensive ground infrastructure already developed under funding by the National Science Foundation. Thus, ARISE is a timely mission because it can take advantage of the large investments already made in ground facilities in both the U.S. and Europe.

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