ARISE

Advanced Radio Interferometry between Space and Earth

Zooming in on Black Holes

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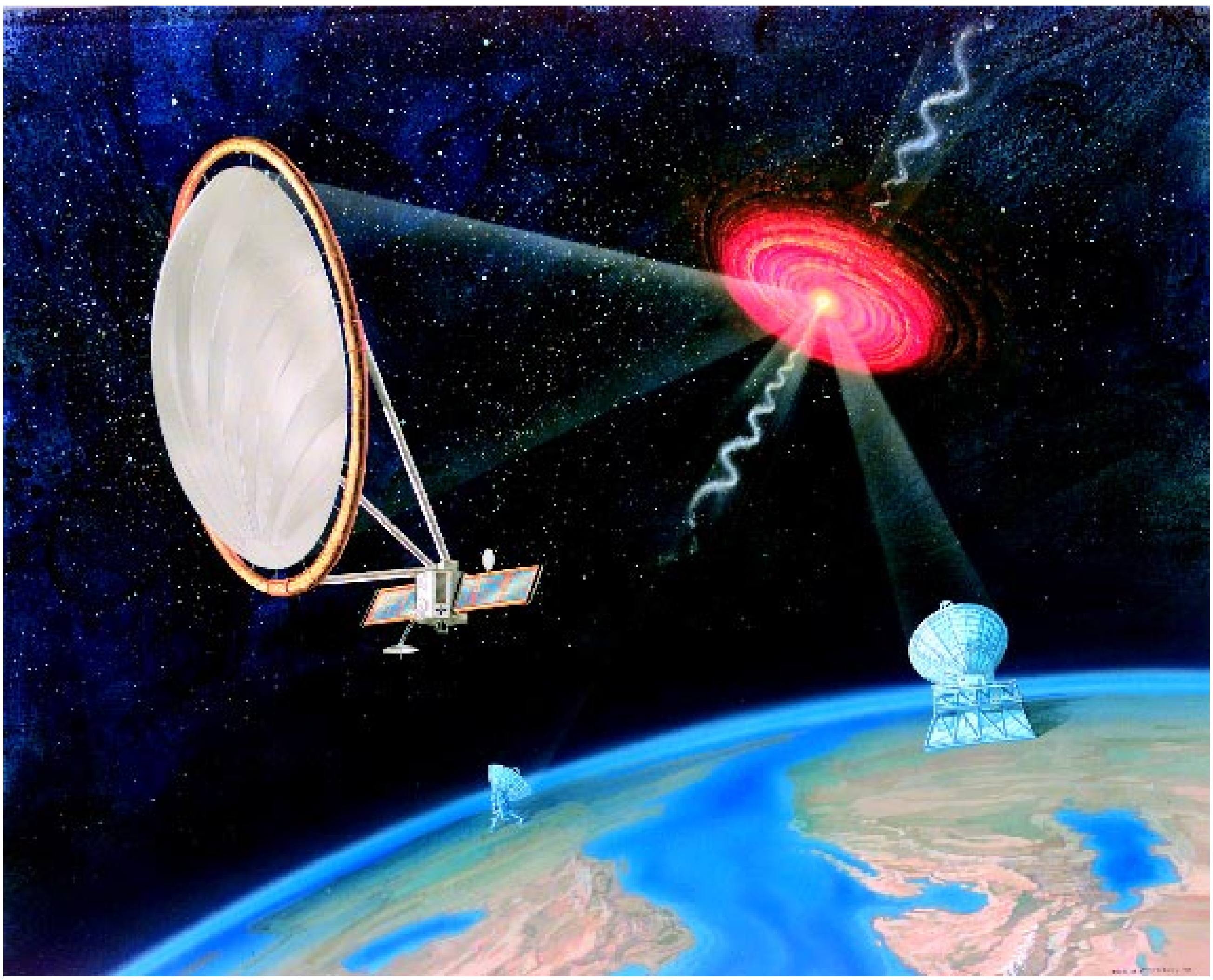

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ARISE Science Goals

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Editor
James Ulvestad
National Radio Astronomy Observatory

ARISE Science Advisory Group
Alan Marscher (Chair), Boston University
Moshe Elitzur, University of Kentucky
Denise Gabuzda, Lebedev Physical Institute
Michael Garrett, Joint Institute for VLBI in Europe
Lincoln Greenhill, Harvard-Smithsonian Center for Astrophysics
Leonid Gurvits, Joint Institute for VLBI in Europe
Jacqueline Hewitt, Massachusetts Institute of Technology
Hisashi Hirabayashi, Institute of Space and Astronautical Science
Arieh Königl, University of Chicago
Julian Krolik, Johns Hopkins University
Roger Linfield, California Institute of Technology
Christoper Moore, Kapteyn Astronomical Institute
David Murphy, Jet Propulsion Laboratory
Robert Mutel, University of Iowa
Susan Neff, Goddard Space Flight Center
Robert Preston, Jet Propulsion Laboratory
Jonathan Romney, National Radio Astronomy Observatory
Russell Taylor, University of Calgary
Esko Valtaoja, Tuorla Observatory
Ann Wehrle, California Institute of Technology
Anton Zensus, Max-Planck Institut für Radioastronomie

Other Contributors
Artur Chmielewski, Jet Propulsion Laboratory
Muriel Noca, Jet Propulsion Laboratory

ABSTRACT

Supermassive black holes, with masses of $10^6 M_\odot$ to more than $10^9 M_\odot$, are among the most spectacular objects in the Universe, and are laboratories for physics in extreme conditions. Understanding the physics of massive black holes and related phenomena is one of the key goals of modern astrophysics. This goal involves many theoretical disciplines, such as general relativity, high-energy physics, cosmology, and magnetohydrodynamics, and can be addressed by observations spanning the entire range of the electromagnetic spectrum. The primary goal of ARISE (Advanced Radio Interferometry between Space and Earth) is 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 images, of unprecedented angular resolution, will be made using the technique of Space Very Long Baseline Interferometry (Space VLBI).

ARISE will take advantage of the existing infrastructure in ground radio telescopes and systems used around the world for VLBI, including new instruments such as the Millimeter Array, and will explore a domain different from that studied by ground radio observatories. Since Space VLBI depends on both the space and ground elements, ARISE exemplifies the potential scientific gain from close cooperation between NASA and the National Science Foundation. 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_2O maser disks in active galaxies more than 15 Mpc from Earth; those disks are not adequately resolved from the ground. Gas motions in the disks will be measured on scales of light months, several orders of magnitude smaller than the velocity fields sampled by optical telescopes, 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 $10^3 M_\odot$ to $10^6 M_\odot$.

The critical technology for ARISE is the 25-meter aperture. Inflatable structures technology, under development for a variety of users, is the current strawman choice for the main reflector, although other concepts also are being explored. On-board low-noise amplifiers and cryogenic coolers are being produced for missions such as MAP, Planck, and FIRST; MAP will be launched in 2000, carrying amplifiers in the same frequency range needed for ARISE. Advances in recording and correlation systems, to increase the VLBI data rate to gigabits per second, are under development. Given sufficient funding for the antenna and data systems technology, ARISE could be ready for launch by 2008 for a cost in the range of \$300–\$400 million. It is anticipated that ARISE would be the forerunner of a future mission that would improve the resolution and imaging capability by orbiting multiple spacecraft simultaneously.

1. Executive Summary

1.1. Background

Supermassive black holes (SMBHs) are thought to be responsible for the astounding amount of energy released from the centers of many galaxies. In fact, there is growing evidence that giant black holes may exist not only at the centers of galaxies containing active galactic nuclei (AGNs), but also in many (or even all!) relatively quiescent galaxies, such as our own Milky Way. A supermassive black hole is a spectacular concentration of mass, with as much as several billion times the mass of the Sun contained within the "event horizon," an area no larger than the size of the solar system. This event horizon is the region from which no radiation or information can escape, so that all we may observe about the black hole itself is its mass and angular momentum. These properties dominate the physical behavior of material near the black hole. ARISE is the only astronomical instrument 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. For comparison, a schematic diagram of the resolution available to ARISE, compared to other classes of instruments, is shown in Figure 1.

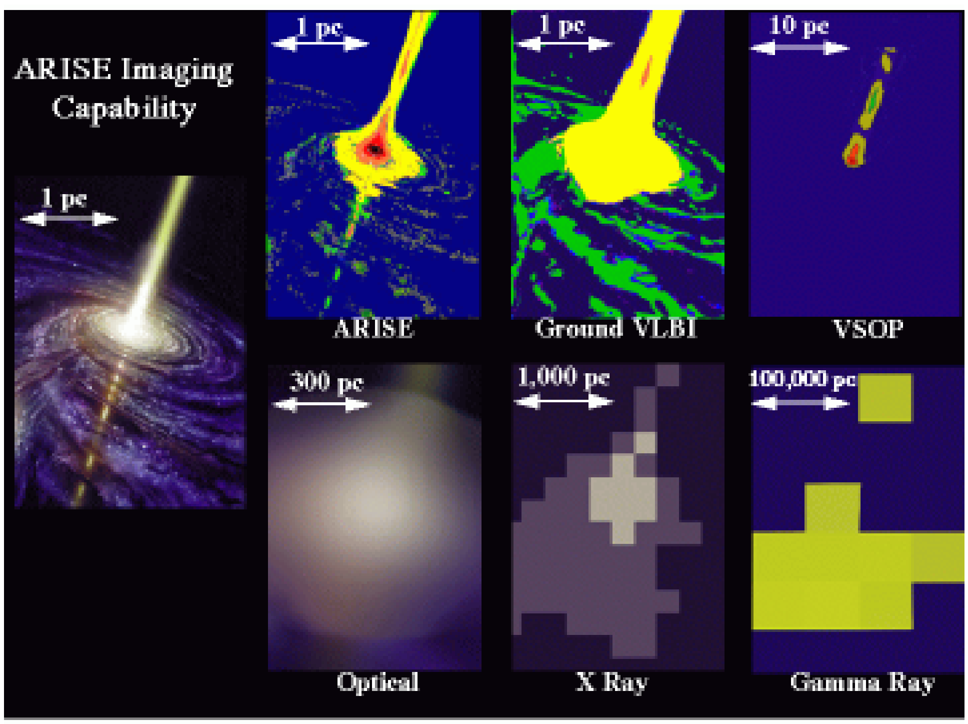


Fig. 1.— Schematic diagram of the resolution of ARISE and other instruments, for imaging of the environments of supermassive black holes. Note the dramatic change in scales for the instruments operating in different wavebands.

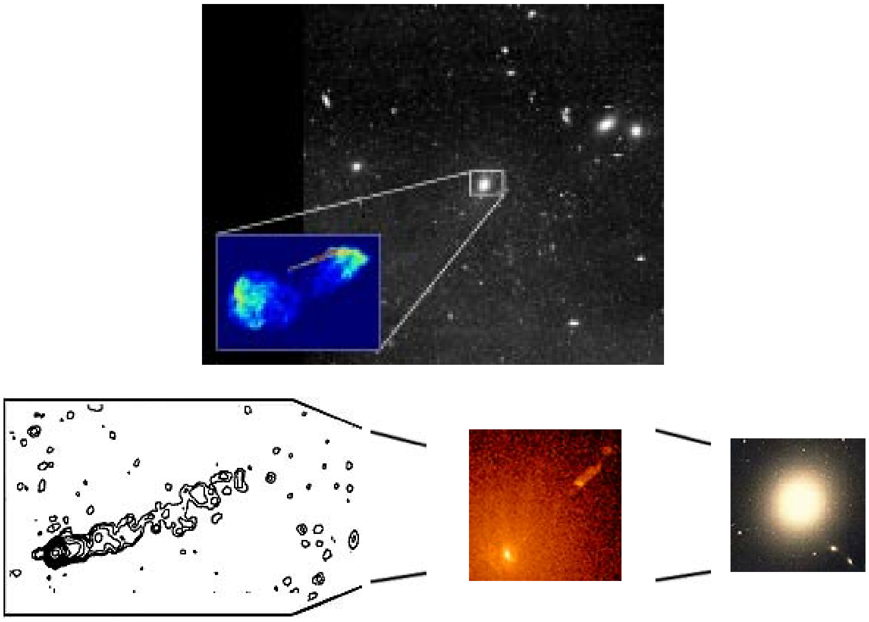


Fig. 2.— Radio and optical images of Virgo A (M87) at varying resolutions. **Top panel.** Optical image of the center of the Virgo cluster of galaxies, showing the dominant elliptical galaxy M87 at its center. Inset is a Very Large Array image of the large-scale radio emission that extends beyond the visible galaxy. **Bottom panel.** *Right:* Optical image of the galaxy M87. *Center:* Hubble Space Telescope optical image of the radio/optical jet. *Left:* VLBI image of the innermost jet, found within the unresolved active galactic nucleus in the lower-left corner of the optical jet image, and located within light months of the central $10^9 M_\odot$ black hole.

Radio telescopes such as ARISE provide a view of the Universe that is quite different from that emerging in other wavebands. Nearby stars are the apparently brightest optical objects viewed from the Earth, usually located no more than 300–600 pc (1000–2000 light years) away. In contrast, most of the brightest radio sources seen from Earth are AGNs, typically located far across the observable Universe, often at more than a million times the distance of the brightest stars. The jets emerging from the vicinity of the black holes in AGNs are observed and imaged almost exclusively at radio wavelengths. Figure 2 shows the different radio and optical views of the dominant elliptical galaxy in the Virgo cluster, M87, at a distance of 15 Mpc ($\sim$ 50 million light years). In this case, the radio emission extends beyond the visible galaxy, and also shows structure with resolution much finer than can be discerned at optical wavelengths.

For many galaxies, the central black holes produce more power than the entire output of the hundreds of billions of stars that comprise the galaxies. Together with their surrounding accretion disks, the black holes are responsible for producing the observed properties of objects like "quasars," spectacular beacons at the centers of extremely distant galaxies. The black holes power narrow jets of relativistic material that speed away from them at more than 99% of the speed of light ($0.99c$), and that have *apparent* motions as fast as $10c$.[1] Within galaxies, these jets can generate strong shock waves that compress gas and may thus be related to episodes of rapid star formation. They often extend well beyond the visible galaxies, supplying energy to the hot diffuse medium between galaxies. Thus, the black holes may hold the key to the origin and evolution of galaxies; were they "seed nuclei" around which the galaxies condensed? How have they grown as the galaxies evolved, and as galaxies have collided? Perhaps most galaxies went through a quasar phase, possibly related to galaxy mergers, at some point in their evolution.

Supermassive black holes in galaxies and quasars are the most spectacular physics laboratories in the Universe. They can produce energy with efficiencies ~ 50 times greater (per unit mass) than nuclear fusion, and are the only known way to power quasars and related AGNs. In fact, it is possible that much of the energy produced in the Universe over its lifetime is generated by these enormously powerful black-hole engines at the centers of galaxies. The energy production and related processes are direct consequences of the physics described by general relativity and high-energy particle physics, realms far beyond those we can investigate in any laboratory on Earth. Indeed, in many ways, black-hole physics provides us a glimpse of the physical processes in the very early Universe, when matter was packed much more densely than today, and when energetic particles abounded. Only Very Long Baseline Interferometry (VLBI) has the capability of directly imaging the environments of massive black holes in AGNs, on scales comparable to the sizes of their accretion disks and (in nearby objects) within factors of 10–100 of the event horizons themselves.

Table 1. Highest Resolution of Astronomical Imaging Techniques

Technique	Angular Resolution (arcsec)
Gamma-ray telescope	1800
X-ray telescope	1
Ground optical telescope	0.1–1
Space optical/infrared telescope	0.05
Radio VLA at 43 GHz	0.05
Expanded VLA at 43 GHz	0.01
Millimeter Array at 850 GHz	0.01
Optical interferometer, 100-m baseline	10^{-3}
Ground VLBI at 86 GHz	10^{-4}
ARISE at 86 GHz	$\leq 1.5 \times 10^{-5}$

[1] Apparent *superluminal* motion is actually an optical illusion of special relativity, caused by motion at nearly the speed of light along a direction close to the observer's line of sight.

Table 1 summarizes the typical resolution of a variety of astronomical imaging instruments; Figure 3 shows the same information graphically. The ARISE resolution of better than 15 μas will provide imaging on scales 10 to 10,000 times the event horizons of SMBHs in most AGNs, exactly the region where the local physics is dominated by the gravitational pull of the central objects. No other astronomical techniques except VLBI and Space VLBI, including optical interferometry on the ground or in space, can produce images of this region. The unique capability to make images at such high resolution is the basis for the scientific rationale for ARISE.

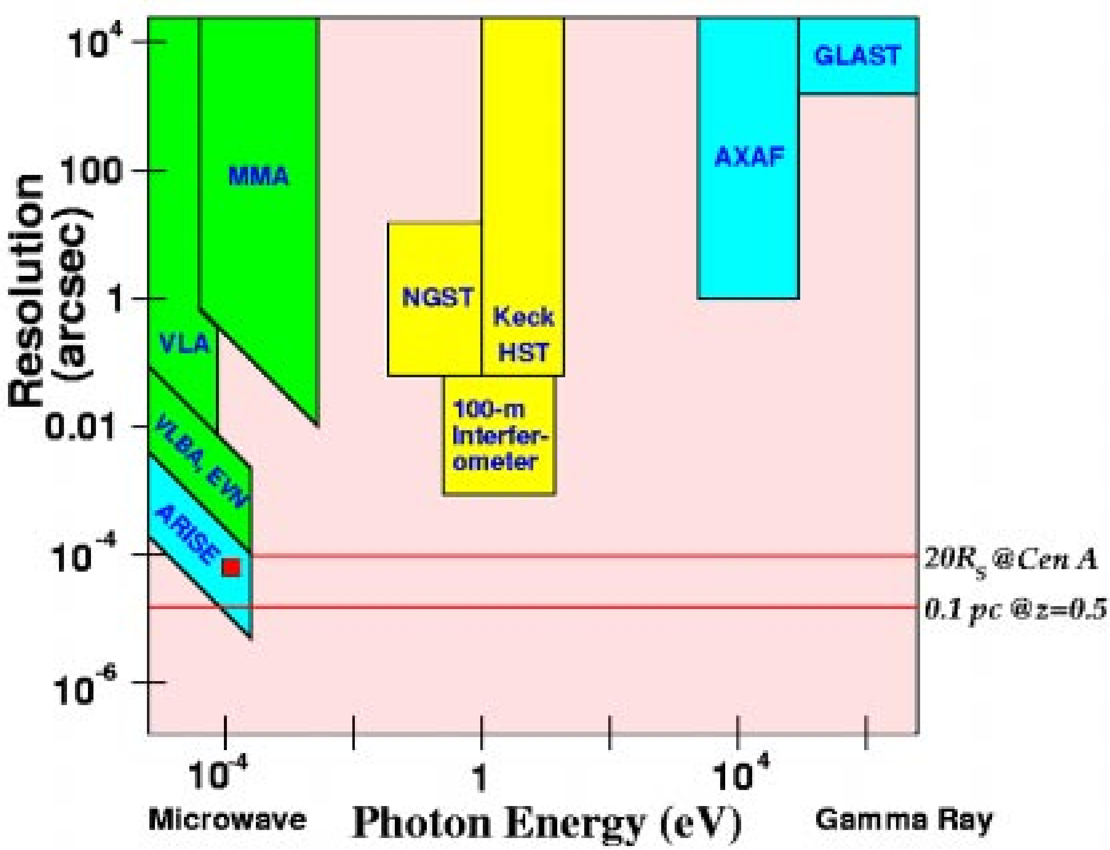


Fig. 3.— Spatial and energy/frequency coverage, on a logarithmic scale, for a variety of existing and proposed astronomical observatories, ranging from radio (microwave) to gamma-ray energies. Lines correspond to 20 Schwarzschild radii for a $10^9 M_\odot$ black hole at Cen A, and to 0.1 pc at a redshift $z = 0.5$. The red square indicates the ARISE resolution for an H_2O megamaser at 22 GHz, corresponding to 0.05 pc at a distance of 50 Mpc. Microwave and high-energy instruments in opposite corners (colored in blue), often are used to investigate different aspects of similar nonthermal phenomena. The instruments in the middle of the diagram, colored in yellow, usually observe the thermal emission from objects such as stars and galaxies. Some ground radio-telescope arrays that will be used with ARISE are indicated by green regions in the diagram.

1.2. Overview of ARISE Science

ARISE is a versatile, high-sensitivity instrument that will employ the technique of Space VLBI (Section 1.3) to image 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 2 summarizes the main science goals of ARISE.

Table 2. Science Goals of ARISE
Primary Goals
Supermassive Black Holes and Radio Jets
AGN Fueling
Relativistic Jet Production
Generation of High-Energy Photons
Accretion Disks and H_2O Megamasers
Masses of Supermassive Black Holes
Nature of Megamaser Disks
Accretion Processes
Geometric Distance Measurements
Cosmology
Gravitational Lens Studies
High-Redshift Radio Sources
Additional Goals
Stellar Astrophysics: coronae of active stars
High-energy Astrophysics: hypernovae
Jet Astrophysics: jet physics at light months from SMBHs
Shocks and Turbulence: supernovae and galactic masers

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, *Gravity's Fatal Attraction,* Scientific American Library) discusses observed properties of AGNs over a variety of wavebands that are attributable to SMBHs. A sketch of the currently accepted model for an AGN can be found in Figure 4. This model includes, at its center, a SMBH that provides the power for the AGN. Surrounding the black hole is an accretion disk, formed when rotating gas is pulled in by the gravitational field of the black hole. The accretion disk 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, it loses gravitational potential energy, which, in turn, can power energetic phenomena such as the production of copious quantities of gamma rays and X-rays. 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 and torus. Flickering gamma-ray emission reveals the creation of large quantities of high-energy particles in the inner light months of the radio jet. In many cases, this jet can continue far outside the visible galaxy.

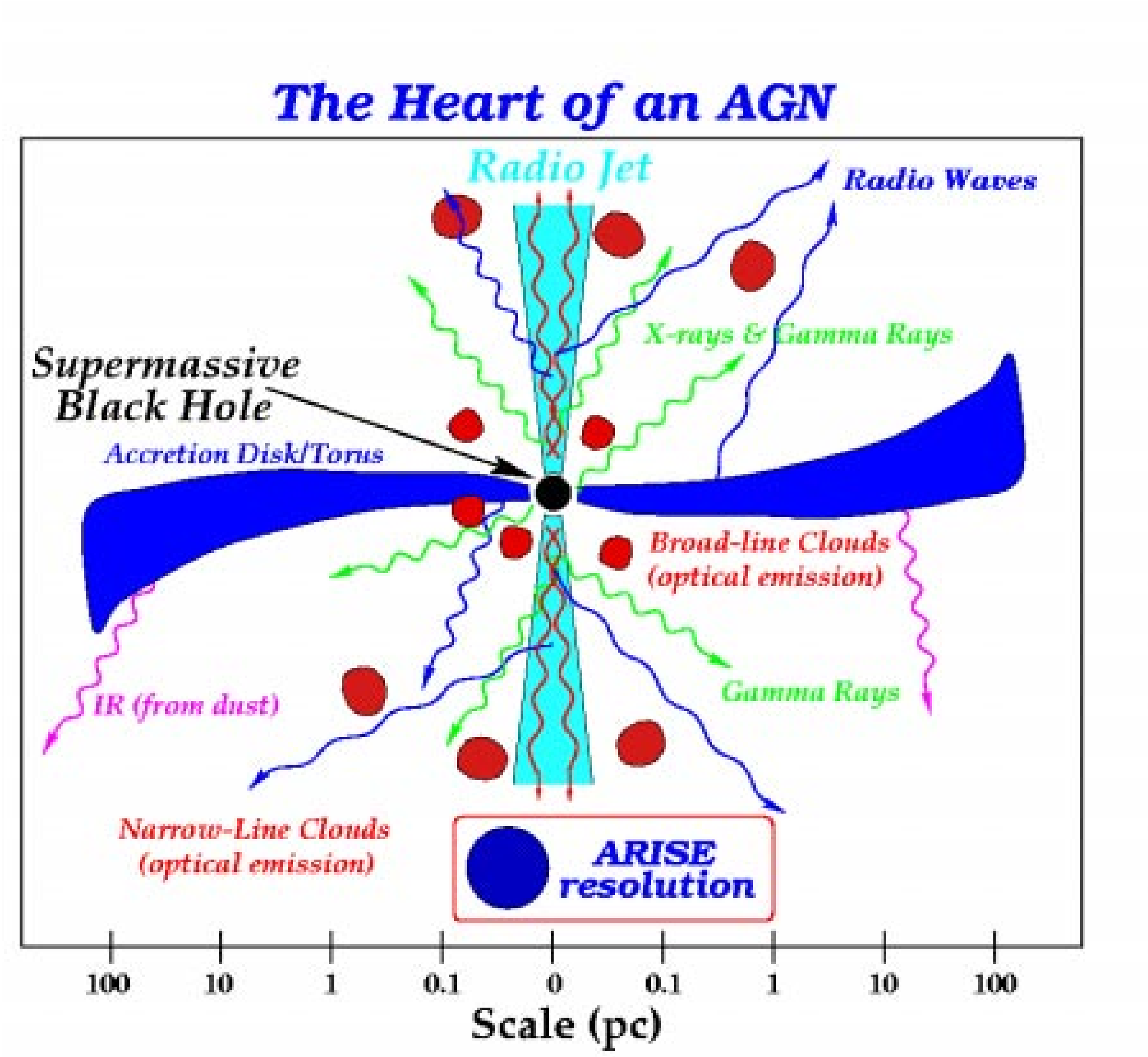


Fig. 4.— Schematic view of the central 100 parsecs (330 light years) of an AGN, including sketches of the regions that emit in various wavebands. (Note the logarithmic scale.) The typical linear resolution of ARISE, 0.05–0.1 pc (50–100 light days), is indicated on the bottom. This resolution corresponds to an 86-GHz continuum observation at $z \approx 0.5$ or to a 22-GHz H_2O maser observation at a distance of 50–100 Mpc. For a more nearby AGN, such as Cen A, the resolution can be orders of magnitude smaller, a few light days or better.

In AGNs, VLBI and other radio observations generally detect emission from nonthermal processes, both in the radio continuum (e.g., in the form of relativistic radio jets) and in discrete spectral lines (generated in disks that rotate around the central black holes), that are rarely seen in optical and infrared wavelengths. These jets and disks are excellent probes of the central energy source of an AGN and its surrounding environment. In addition, the radiation in other wavebands is often obscured and cannot in any case (due to insufficient angular resolution) be directly imaged on the scale of light weeks to light months. Observations of highly variable radiation, with time scales of months to shorter than one day in all wavebands, imply the presence of substantial energy production on the exact scales imaged by ARISE. For example, the variable gamma-ray emission is thought to come from the inner parts of the relativistic jets; imaging the total and polarized intensity in the jets can help distinguish between competing models for the gamma-ray production.

The gravitational pull of the SMBH results in high velocities in stars and gas clouds near the core of the AGN. In only a few nearby, unobscured systems, these motions can be studied by the Hubble Space Telescope at distances of $\sim$10–100 pc from the AGN. In contrast, VLBI observations reveal the actual velocity structures in the accretion disk within a parsec of the SMBH, even in galaxies whose centers are completely obscured at optical wavelengths.

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_2O 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. VLBI in general, and ARISE in particular, provide important information, and actual images, that can be supplied by no other technique in modern astrophysics. As Figures 3 and 4 show, the improvement in resolution over ground VLBI enables imaging of relativistic jets on the scale of the gamma-ray emission, and also enables superior resolution in the H_2O maser disks in AGNs.

Figure 5 shows the VLBI image of the H_2O maser and radio continuum emission from the inner light months of the Seyfert galaxy NGC 4258, at a distance of 7.1 Mpc, where VLBI imaging reveals an almost perfectly Keplerian disk of material orbiting a black hole with a mass of $3.9 \times 10^7 M_\odot$. Most known H_2O maser disks are in galaxies several times more distant, and weaker H_2O emission in galaxies at distances of 50–100 Mpc is expected to be discovered over the next few years. Only ARISE will have the resolution to measure the gas motions (velocity and centripetal acceleration) in the disks, and resolve the disk thickness, in such objects at distances greater than $\sim$ 15 Mpc.

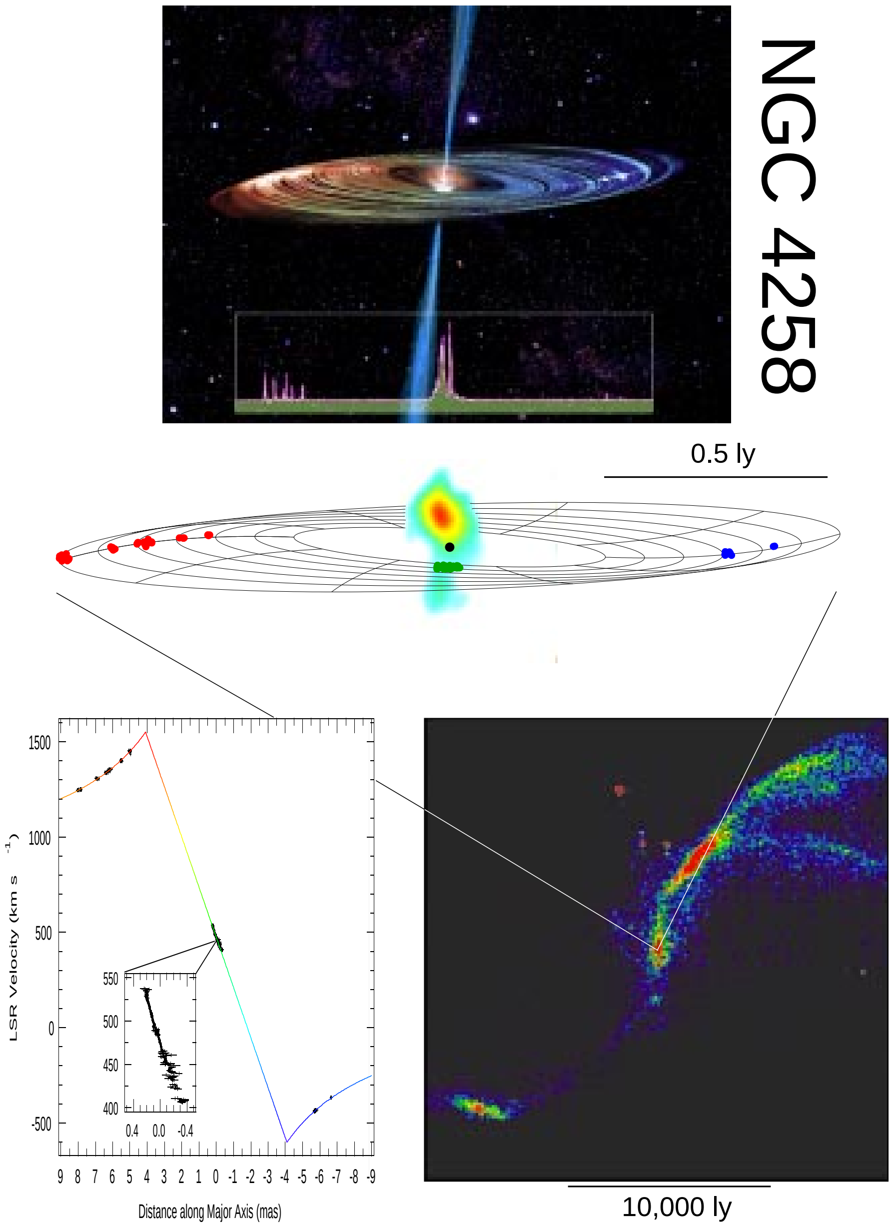


Fig. 5.— Very Long Baseline Array (VLBA) imaging of a disk orbiting the massive black hole at the center of the galaxy NGC 4258, at a distance of 7.1 Mpc. **Top Panel.** Artist's conception of the rotating disk, together with the measured radio spectrum showing redshifted and blueshifted H_2O maser emission at a frequency of 22 GHz. **Middle Panel.** Dots show the actual location of the Doppler-shifted H_2O maser emission imaged by the VLBA, outlining a slightly warped disk about 0.6 pc (2 light years) in extent, while the false color image is the radio jet emerging at a distance of about 4000 Schwarzschild radii from the central black hole. **Bottom Panel.** *Left:* VLBA measurements of the velocity structure (relative to the Local Standard of Rest) of the H_2O maser spots as a function of distance along the major axis of the disk, showing the Keplerian rotation that is used to determine a black hole mass of $3.9 \times 10^7 M_\odot$, with an error of only a few percent. *Right:* Very Large Array (VLA) 20-cm radio image of the inner spiral arms of NGC 4258, on a scale 20,000 times larger than the VLBA image.

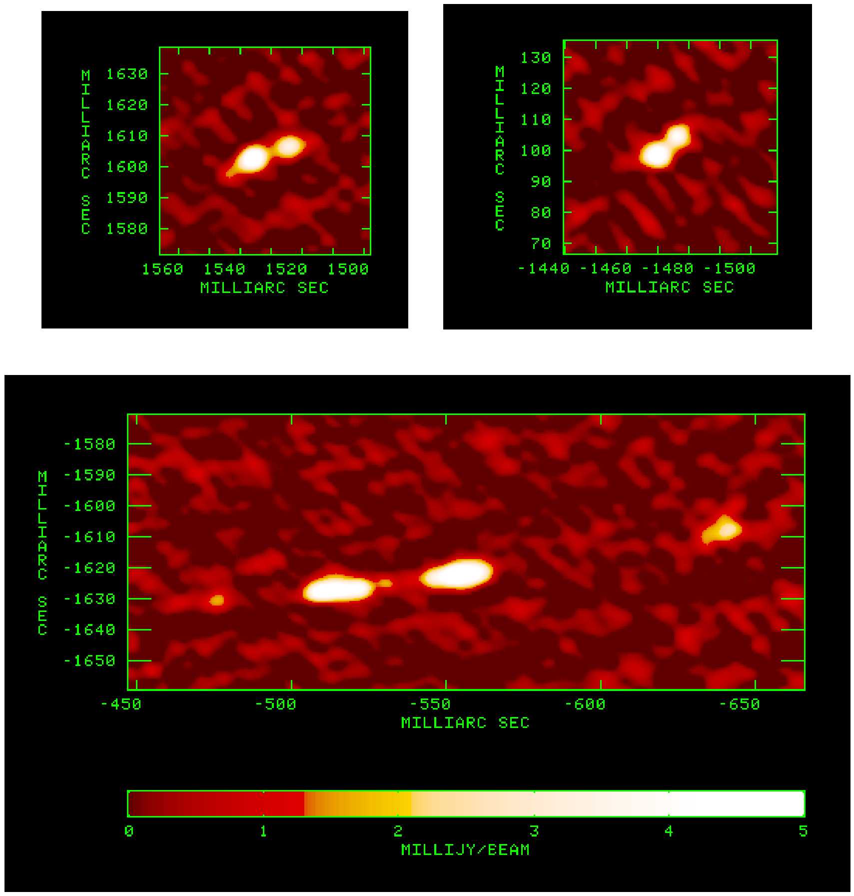


Fig. 6.— European VLBI Network 5-GHz map of the gravitational lens system 2016+112. Core-jet structure is revealed in each of the four images of the background object (one image in each of the upper boxes, and two more near the center of the lower box). The lower box shows two very extended, merging images, suggesting that the distant background radio source (at $z = 3.27$) straddles a region of high magnification (known as a caustic). Indeed, lens models predict that for these merging images, the magnification of the background source is ~ 40. Without the natural magnification provided by the lens, this source would have appeared unresolved.

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. These are systems in which a distant AGN shows multiple images at radio and optical wavelengths due to the gravitational influence of an intervening galaxy or cluster of galaxies. As an example, a ground VLBI map of four images in the gravitational lens system 2016+112, a very distant quasar lensed by intervening galaxies, is shown in Figure 6.

In a gravitational lens system, the distant AGN will vary at radio wavelengths; if a model of the intervening mass is available, the time delay between variations seen in the different images enables a direct determination of the distance between the Earth and the lens. Knowledge of the distance can yield an estimate of the Hubble Constant, H_0, which characterizes the overall scale of the Universe. ARISE imaging of lensed AGNs will provide a high resolution probe of the dark matter in the intervening masses, and will improve the modeling of the mass distribution, currently the largest uncertainty in the determination of H_0 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 μas, 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 candidates for the "missing" baryonic dark matter that may contribute significantly to the density of the Universe.

In addition to the primary goals of studying the environment of supermassive black holes and making unique contributions to cosmology, the versatility of ARISE will enable exploration of a number of additional areas of astrophysics, as summarized in Table 2. ARISE will contribute to **(1) stellar astrophysics,** through resolution of the coronae of active stars and their rapid time evolution, on scales smaller than a solar diameter; **(2) high-energy astrophysics,** via observations of the "hypernovae" that may be responsible for at least some gamma-ray bursts; **(3) jet astrophysics,** by studies of the jet structures and interactions at distances of a few light years from the SMBHs (and possibly in a few galactic sources spawned by X-ray binary systems); and **(4) the astrophysics of shocks and turbulence,** which may be constrained through studies of the fine-scale angular structure of supernovae as well as galactic maser sources in star-forming regions and in late-type stellar envelopes. Thus ARISE will be a very versatile user facility that will attract investigators studying a broad range of energetic astrophysical phenomena in addition to its most important goal of imaging and exploring the regions near supermassive black holes.

1.3. Description of ARISE

The technique of VLBI requires that widely separated radio telescopes simultaneously observe the same radio source at the same frequency. Over the course of an observation, Earth rotation changes the projected separation of each pair of telescopes, as seen from the radio source. In Space VLBI, an additional radio telescope is located aboard an orbiting spacecraft, and the orbital motion of that telescope causes a rapid change in the projected separations between Earth-bound and orbiting telescopes. Taken together, the data gathered from all the interferometer pairs synthesize an aperture as large as the orbit of the spacecraft (see Figure 7). Since the angular resolution depends on the ratio of the observing wavelength to the distance between telescopes, Space VLBI can provide higher resolution than is possible from the surface of the Earth.

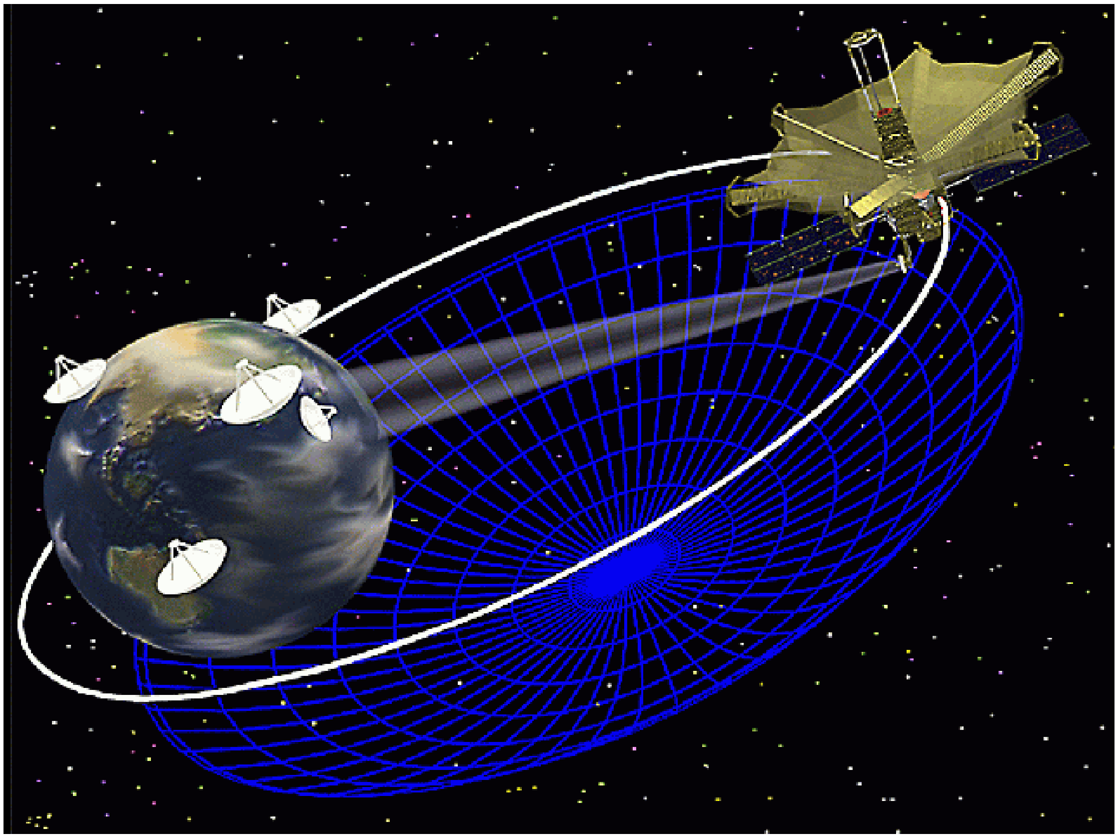


Fig. 7.— Schematic drawing of the Space VLBI concept, with the orbit of the HALCA spacecraft (VSOP mission) used to synthesize an aperture larger than the diameter of the Earth.

The VLBI Space Observatory Programme (VSOP), based on the HALCA (Highly Advanced Laboratory for Communications and Astronomy) satellite launched in early 1997, is the first dedicated Space VLBI mission. VSOP originated as an engineering experiment that also has the capability to do some science. It has routinely imaged strong radio sources at observing frequencies of 1.6 and 5 GHz, demonstrating many of the technologies required in the Space VLBI technique. Those technologies include (1) a high-rate digital data downlink (128 Mbit sec^{-1}); (2) generation of an on-board clock of hydrogen-maser quality by uplinking a tone from a ground tracking station and correcting for transmission errors at correlation; (3) implementation of spacecraft ephemerides and time corrections from the two-way link at ground VLBI correlators; and (4) calibration and imaging of the combination of data from space and ground radio telescopes. A sample 5-GHz image from VSOP, compared to the ground-only image on the same scale, is shown in Figure 8. In this case, the modest improvement of a factor of 1.5–2 in resolution was sufficient to cleanly separate the two main radio components in the center of a distant gamma-ray blazar. Images sampling higher portions of HALCA's orbit have resolution a factor of 2–3 better, and demonstrate that the techniques are well in hand to increase the angular resolution further by using a Space VLBI mission such as ARISE.

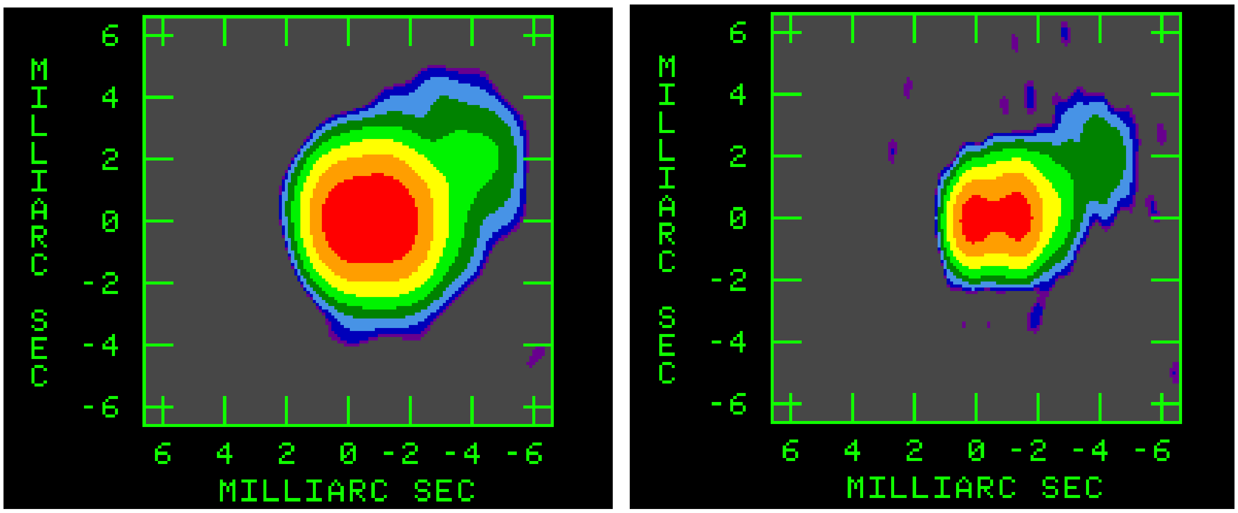


Fig. 8.— VLBI images, at identical scales, of the distant gamma-ray blazar 1633+382 (z = 1.81) at an observing frequency of 5 GHz. **Left Panel.** Ground-only image using the VLBA. **Right Panel.** Space VLBI image made by combining the data from the HALCA satellite with the VLBA data.

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, employing a 25-m radio telescope orbiting the Earth with an apogee height of 40,000–100,000 km, and working together with sensitive ground radio telescopes, will produce radio images of AGNs with angular resolution of 7–15 μas at the highest observing frequency of 86 GHz. This additional factor of 5–10 in resolution (a factor of 25–100 more pixels per given angular area) will provide imaging capability within 5–10 Schwarzschild radii for $10^8 M_\odot$ to $10^9 M_\odot$ SMBHs in some nearby active galaxies, as well as on the light-month scale of gamma-ray emitting regions anywhere in the Universe.

Table 3. 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

ARISE will have observing capability at several standard VLBI frequencies, including 43 and 86 GHz, in order to achieve the desired resolution. The space telescope also will have extremely high sensitivity at 22 GHz, enabling imaging of accretion disks using the H_2O maser emission that occurs about 10^4 Schwarzschild radii from the SMBHs in nearby AGNs. Finally, the 8-GHz observing frequency, when combined with large ground telescopes, will provide the most sensitive high-resolution images available for AGN jets, gravitational lenses, and other energetic phenomena. Receivers with noise temperatures within a factor of 5 of the quantum limit are easily achievable, and will combine with a large bandwidth to provide sensitivity 100 times better than that available with VSOP in 1997 and 1998. Basic mission parameters of ARISE are provided in Table 3, and the observing parameters at each frequency are given in Table 4. The listed ranges of detection thresholds correspond to observations with a single 25-m telescope of the VLBA (higher threshold) or with the 100-m Green Bank Telescope (lower threshold).

Table 4. 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	$\leq 150\ \mu$as	$\leq 60\ \mu$as	$\leq 30\ \mu$as	$\leq 15\ \mu$as
Detection Threshold	0.4–1.9 mJy	0.8–4.5 mJy	2.5–15 mJy	26–120 mJy

ARISE can be ready for launch by the year 2008, given adequate funding, at a total cost of $300 to $400 million (in 1999 dollars, including the launch vehicle and ground systems). Several technologies currently under active development will be used for ARISE, which could be the forerunner of future missions that orbit multiple telescopes simultaneously. 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 (see Figure 9), under development for several other applications in communications and remote sensing. Backup technologies that would be more massive and costly are also being investigated. Errors in the main reflector surface are expected to take the form of large-scale deformations rather than small-scale inaccuracies; active work is being carried out on a simple, mechanically deformable subreflector that would correct for such irregularities if the main reflector cannot reach the required surface accuracy of better than 0.25 mm. The other "new" technologies are those aimed at achieving a very high sensitivity. Space-qualified low-noise amplifiers in the required frequency range have already been built by the National Radio Astronomy Observatory for use aboard the Microwave Anisotropy Probe, scheduled for launch in 2000. Cryogenic coolers have been tested aboard the Space Shuttle, and will be developed further before the launches of Planck and the Far Infrared and Submillimetre Telescope in 2007. Data-recording and correlation systems will reach 1 Gbit $\sec^{-1}$ in the Mark 4 VLBI system before 2000, and extension to 4 or 8 Gbit $\sec^{-1}$ is currently under study.

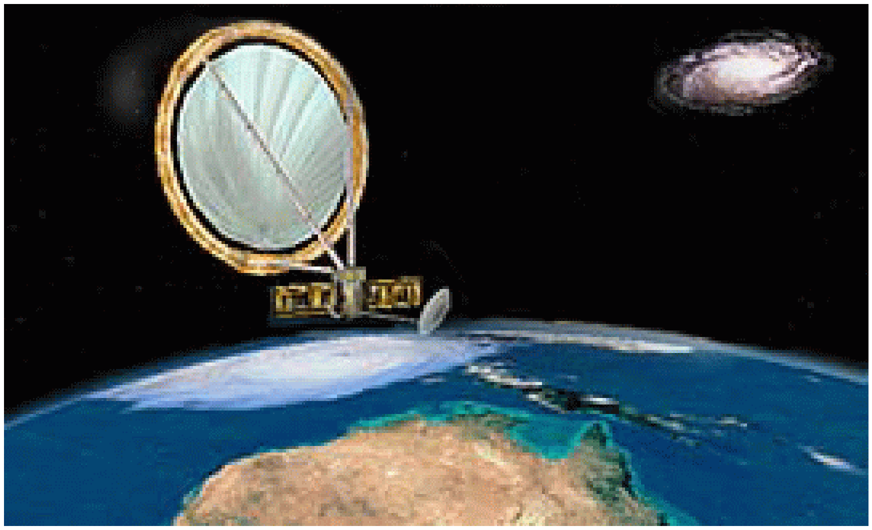


Fig. 9.— Current baseline configuration for ARISE, using an off-axis inflatable antenna and Gregorian optics. The antenna is kept inflated with a very low pressure, while the struts and torus supporting the antenna are inflated to a much higher pressure initially, then rigidized in orbit. The small dish evident in the lower right portion of the spacecraft is the subreflector.

ARISE is complementary to space-based observations in much higher frequency bands that will have much more limited imaging capabilities. A new generation of more sensitive gamma-ray satellites, such as the Gamma-ray Large Area Space Telescope (GLAST), will detect a larger number of AGNs by virtue of their gamma-ray emission; observations of gamma-ray luminosities and variability combined with ARISE imaging will provide key constraints on the physical processes at the bases of jets. X-ray spectroscopy from missions such as ASTRO-E and Constellation-X will explore the physical conditions in the plasmas within ~ 100 Schwarzschild radii of massive black holes. Imaging of H_2O masers with ARISE will supply complementary information on the disks $\sim 10^4$ Schwarzschild radii from the black holes, while imaging of the jets in nearby AGNs can probe scales comparable to those sampled by X-ray spectroscopy. The physics of the high-energy and radio emission clearly are closely related, and ARISE provides the only way to obtain images of the regions where the high-energy photons are produced.

ARISE will work together with the large networks of radio telescopes that currently are used for ground-based VLBI, such as the VLBA and the European VLBI Network. It will take advantage of the large worldwide infrastructure in hardware and operations that has enabled VLBI to become a routine observing technique, thus naturally lending itself to extensive international cooperation. Furthermore, ARISE will employ the same basic Space VLBI techniques already proven in the VSOP mission during 1997 and 1998. The addition of ARISE to the ground VLBI networks will provide sufficient resolution to image relativistic jets in distant blazars on the scale of the gamma-ray emission, and to resolve the disks in H_2O megamasers at distances of 50–100 Mpc; such resolution cannot be achieved from the ground, because the diameter of the Earth limits the VLBI resolution. New, very sensitive ground radio telescopes that will become operational in the

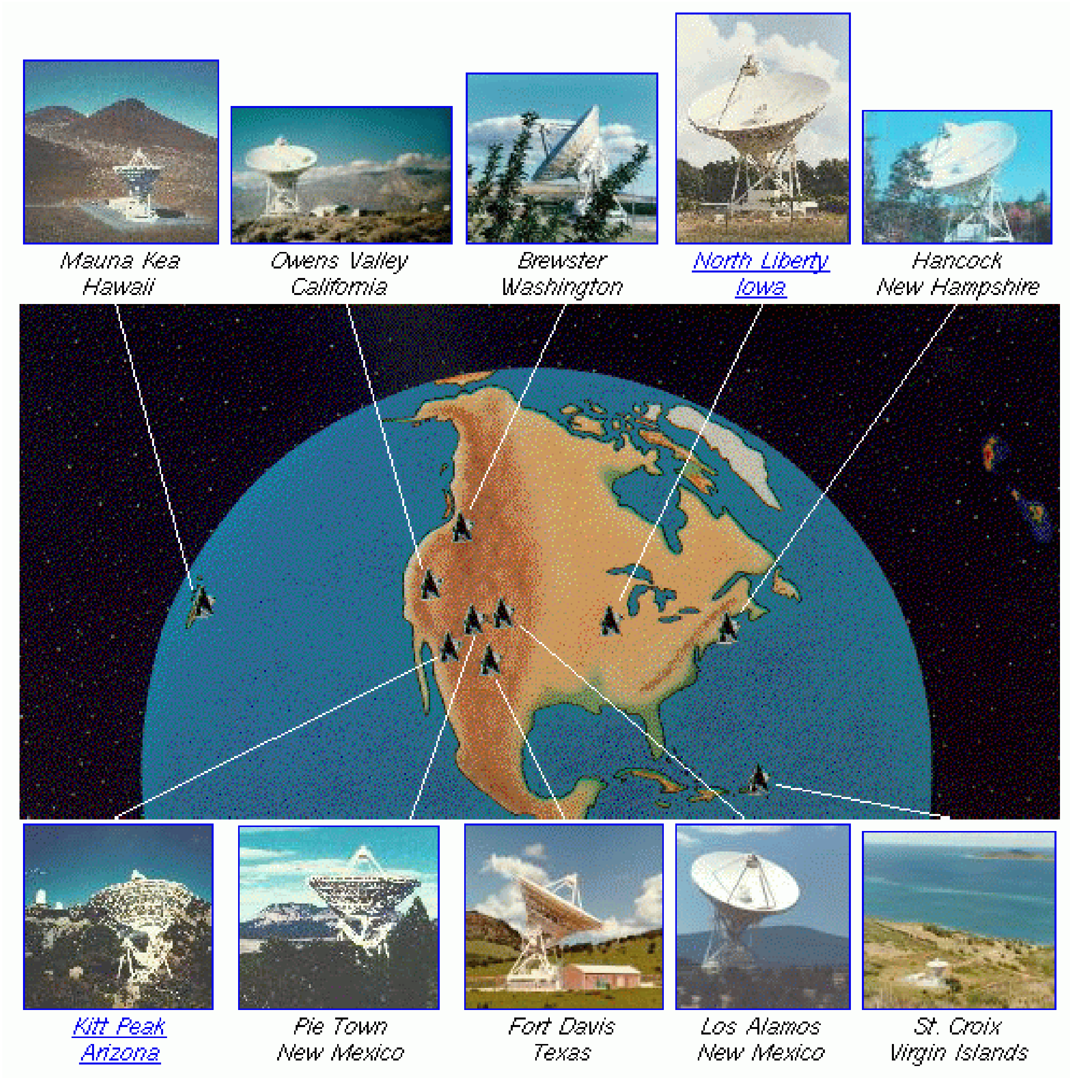


Fig. 10.— Images of the 10 VLBA telescopes, which will work with ARISE from 8 to 86 GHz.

next decade include the Green Bank Telescope, the Millimeter Array, and (probably) the upgraded Very Large Array. (The proposed Square Kilometer Array is much further in the future, and will not work at the high frequencies that are most critical for the ARISE science.) As stand-alone instruments, these telescopes will address important scientific problems, such as star formation in distant galaxies, at much lower resolution. However, they also will provide outstanding sensitivity as elements of the ground array observing with ARISE, particularly at the higher frequencies; this will result in greatly improved sensitivity at the highest resolutions. Thus, ARISE is a scientifically valuable mission that is well-timed to take advantage of decades of advances in radio astronomy, combining NSF ground assets with a NASA spacecraft, in order to study the astrophysics related to the massive black holes in the centers of galaxies.

2. Supermassive Black Holes and Radio Jets

2.1. Model of an Active Galactic Nucleus

Active galactic nuclei manifest themselves observationally in a number of ways. Some are radio galaxies, which often have strong radio emission far outside the visible parent galaxy. There are the point-like "quasars" that are found in the cores of some distant spiral and elliptical galaxies; a few percent of these are very strong radio emitters, though most are not. Close relatives of quasars are the BL Lacertae objects, particularly "blazars," which are apparently quasars ejecting relativistic jets of material almost directly toward the Earth. Less powerful types of AGN include objects such as Seyfert galaxies, which are weak quasars embedded in relatively nearby spiral galaxies. The currently accepted model of an AGN was summarized in the Executive Summary. At its heart is a supermassive black hole (SMBH), surrounded by a disk of accreting material; infall of material from the disk toward the black hole is thought to power the phenomena that we observe in AGN. High-resolution imaging of the compact radio emission from many types of AGN, all thought to be powered by central black holes, is a principal goal of ARISE.

2.2. Blazars and Jets

"Blazars" comprise a class of AGN defined as objects whose radiation across the electromagnetic spectrum is highly variable and comes mainly from nonthermal processes. Ground-based VLBI images have shown that most blazars have core-jet morphology, where the "core" is an unresolved bright feature at one end of the jet. The jet itself has a knotty structure, and many of these knots appear to travel away from the core at speeds exceeding that of light, as shown in Figure 11. Such apparent "superluminal" motion can be explained as an illusion of special relativity that occurs when the flow in the jet is at a speed very close to that of light, and the jet points almost along the observer's line of sight (see Pearson & Zensus 1987 for a summary). The effect is maximum when the viewing angle relative to the jet axis is $\sin^{-1}(1/\gamma)$, where γ is the knot's Lorentz factor (e.g. 5 when the knot's speed is $0.98c$, where c is the speed of light). Although only a small fraction of jets will point so closely toward the line of sight, these jets will appear very bright because they beam the radiation mostly into the forward direction. Such jets can therefore be detected from far away. Since the volume of space sampled increases with distance, most of the bright compact radio sources in the sky are distant objects with jets pointing almost directly at us.

During the 1990s, the EGRET high-energy gamma-ray detector on the Compton Gamma Ray Observatory found that many of the brightest blazars are sources of strong, highly variable, high-energy gamma rays (e.g., Mattox et al. 1997; Mukherjee et al. 1997). The ground-based Whipple Observatory has found that three relatively nearby blazars are highly variable sources of gamma rays with energies exceeding 3×10^{11} electron volts, or 0.3 TeV (Catanese et al. 1998). In

Fig. 11.— Motion of components in the radio jet of the gamma-ray blazar 3C 279, over five years. The apparent speed of the outermost component is $4.3h^{-1}c$, where h is Hubble's constant in units of 100 km s^{-1} Mpc^{-1}.

many blazars, the apparent luminosity in gamma rays exceeds that from all other frequency bands, by as much as three orders of magnitude. The brightness of the gamma rays has been observed to change by more than 100% over times of days to weeks in several blazars. These gamma-ray flares are thought to correspond to the generation of new relativistic shock waves in the jets; their time scales (after correction for relativistic effects that compress the apparent timescale) indicate that typical dimensions of the new shocks are on the order of light weeks to a few light months, corresponding to angular sizes of a few tens of μas, exactly the angular scale that can be probed by ARISE (see Figure 12). Radio "flares" in the jets are typically on the order of a jansky in strength (1 jansky = 1 Jy = 10^{-26} W m^{-2} Hz^{-1}); high-frequency (millimeter wavelength) radio flares are thought to be related to the gamma-ray flares, and probably represent the generation and ejection of new radio components. The strength of the radio emission often can be characterized by its observed "brightness temperature," the temperature that a thermal body of the same compactness would have in order to emit an equivalent amount of radio radiation. The strength of the flares, and the sizes indicated by their variability time scales, imply that the brightness temperature of the shock component is typically $\gtrsim 10^{12}$ K.

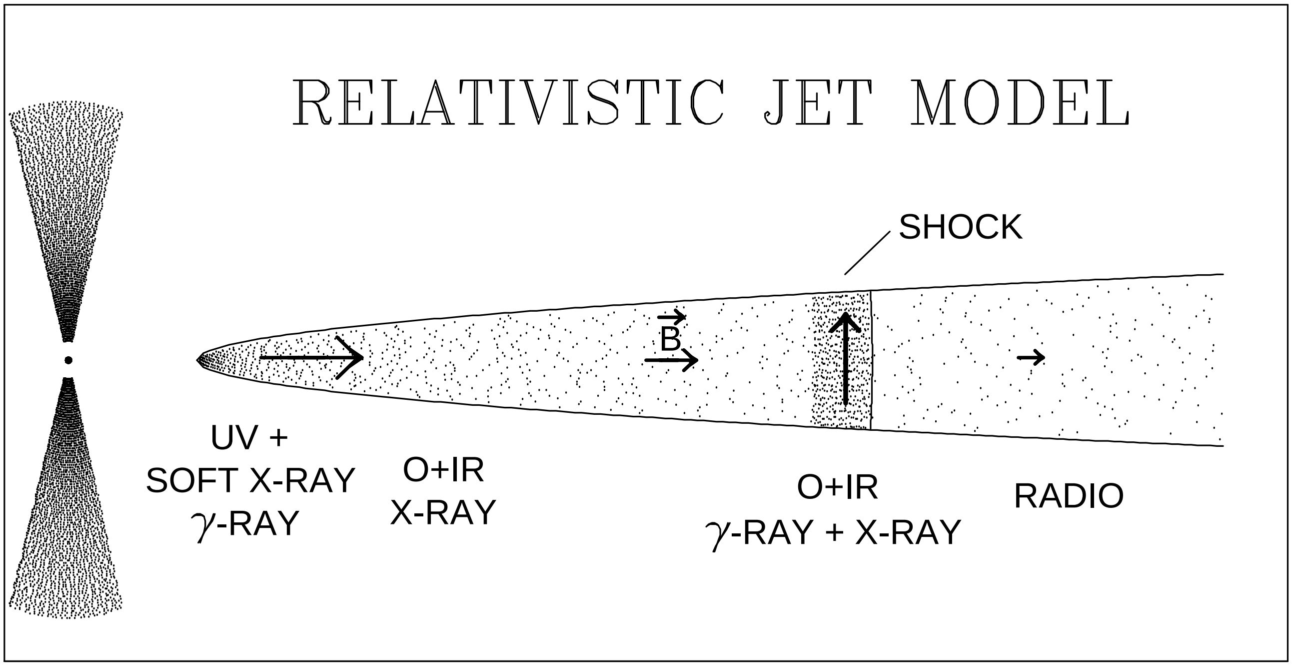


Fig. 12.— Cartoon model of the locations of emission in different parts of the electromagnetic spectrum, in the inner part of a relativistic jet.

Many astronomers world-wide have been puzzling over the following questions:

- **AGN Fueling.** What is the ultimate source of power that drives a blazar? The phenomenon seems to be related to similar, lower luminosity objects in our Galaxy that are thought to be powered by accretion of gas from one, usually large, star onto a very compact remnant of a star: a neutron star or a black hole. In the case of blazars, the compact object would need to be a SMBH, with mass as high as several billion times that of the Sun but with a size smaller than the solar system. Where does such a SMBH get its fuel? How does it convert the infall of gas into the ejection of relativistic jets?
- **Relativistic Jet Production.** How are relativistic jets made? (For example, see Begelman 1995 for current ideas.) Specifically, how is so much energy generated in the vicinity of a SMBH, then channeled into very narrow jets (containing ultrarelativistically hot, magnetized plasma) that flow out of the nucleus at speeds that can exceed $0.99c$? This requires extremely efficient acceleration of charged particles to very high energies, collimation of the ultra-hot plasma into cones of flow that have opening angles of only about 1 degree, and acceleration of the plasma as a whole such that it flows from the nucleus at a speed near that of light. What is the origin of the strong magnetic field that is indicated by the synchrotron radiation from the jet, and what role does it play in the dynamics of the outflow?

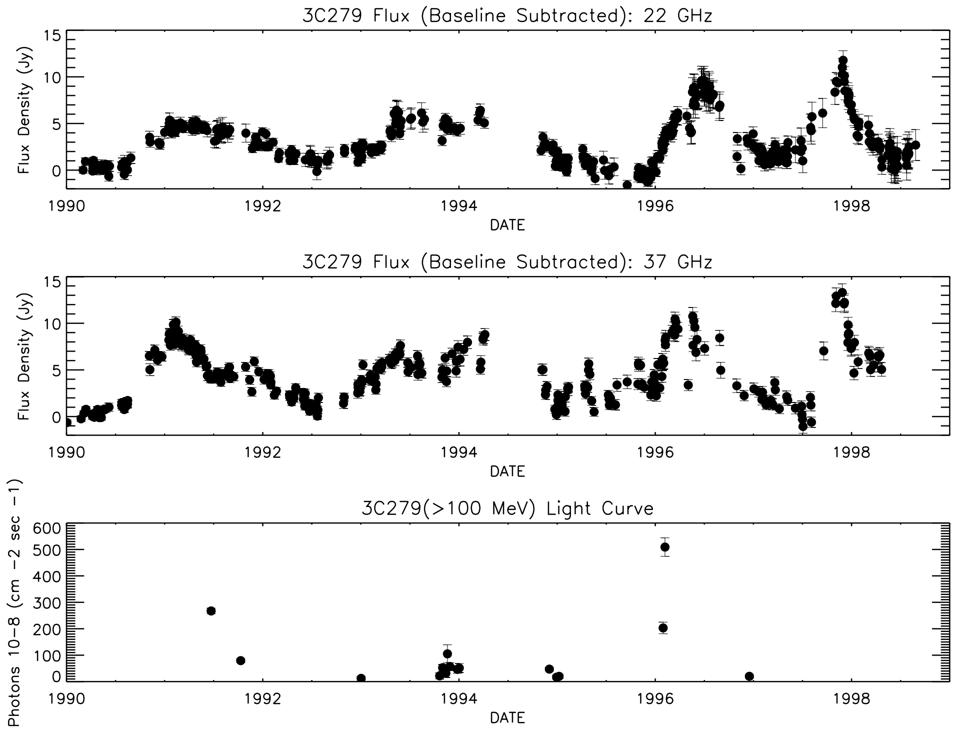


Fig. 13.— Radio variability in the blazar 3C 279 at frequencies of 22 GHz (1.3 cm wavelength) and 37 GHz (8 mm wavelength), compared to the strong gamma-ray variability sampled by EGRET. Note the onset of the strong millimeter-wavelength flare at the beginning of 1996, which roughly coincides with the (undersampled) flare seen by EGRET.

- **Generation of High-Energy Photons.** What is the mechanism by which the gamma rays (as well as X-rays) are created? The radio-to-infrared (and perhaps optical and even X-ray) emission apparently is generated by the incoherent synchrotron process, in which highly relativistic electrons emit radiation by virtue of their acceleration in a strong magnetic field. These low-energy photons may be scattered to X-ray and gamma-ray energies by collisions with the relativistic electrons themselves, the so-called "inverse Compton" process. Although most investigators consider inverse Compton scattering by the relativistic electrons as the main process by which the gamma rays are made, it is unclear which "seed" photons are being scattered, synchrotron photons already created by the jet electrons (synchrotron self-Compton mechanism) or photons from other regions such as the broad emission-line clouds (external Compton mechanism). In either case, the time scale of variability of the gamma rays is often too short to understand easily; the gamma rays and accompanying X-rays must come from a region large enough that the probability of their destruction by electron-positron pair production is small. For example, in the quasar 3C 279 (see Figure 13, this implies that the gamma-rays and X-rays come from a region whose size is of order 0.02–0.1 pc (e.g., Marscher 1995). This is similar to the resolution of the longest

ARISE-to-Earth baselines and to the size of the apparent radio core. Another important question is whether the gamma-ray flares are related to the ejection of superluminal knots in the radio jet. Typically, the gamma-ray flares occur during the first few months of a millimeter-wave flare in the core, so they may be related to new shocks that have propagated just a few tens of microarcseconds from the core. ARISE will have the resolution to see the effects on the jet soon after any such gamma-ray event observed by a future gamma-ray mission such as GLAST, and to measure the proper motions of the features associated with the gamma-ray emission.

2.3. Potential Impact of ARISE

The key to answering the questions described above lies in a combination of direct imaging and multiwavelength monitoring observations of the emission in the most compact regions in blazars. Attempts to do this were made for a number of gamma-ray blazars, with multiwavelength monitoring campaigns (e.g., Wehrle et al. 1998) and 22- or 43-GHz ground-based VLBA (Very Long Baseline Array) monitoring of changes in the structure of the jet (e.g., Marchenko et al. 1998). While these campaigns greatly increased our knowledge of blazar emission mechanisms, one of the disappointments was that, even at 43 GHz (wavelength of 7 mm), most of the cores of the blazars remained unresolved (e.g., Figure 14). In addition, the cores of many of the blazars are opaque at 43 GHz, because the relativistic particle density is so high that radio photons emitted at this frequency and below by high-energy electrons will be absorbed by lower energy relativistic electrons, and thus will not escape from the emitting region and make their way to our telescopes. Therefore the underlying structure of the core region cannot be imaged, even in principle. At 86 GHz, where the radio spectra show that the cores in most sources are not opaque (i.e., they are "optically thin"), and the resolution is potentially twice as fine as at 43 GHz, ground-based VLBI still can provide resolution of only 75–100 μas, corresponding to 0.4–0.5 pc at a distance of 10^9 pc (compared to the desired resolution of ≤ 0.1 pc). It is therefore clear that only 86-GHz Space VLBI is adequate to directly image the region inside the core, where most of the high-energy X-ray and gamma-ray emission is produced. With ARISE, the core region will be resolved if the maximum baseline exceeds about 50,000 km, and the core will be transparent at 86 GHz for most blazars and at 43 GHz for some. For the 50,000-km baseline, the nominal imaging resolution will be 15 μas at 86 GHz, while source sizes as small as 2 μas will be measurable by detecting a 10% loss in fringe visibility on the longest baseline.

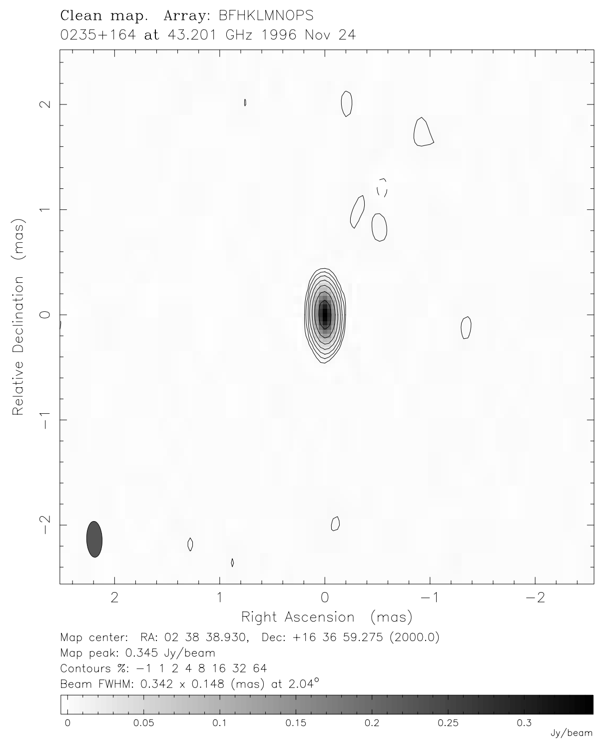


Fig. 14.— VLBA image of the blazar 0235+164 at 43 GHz. The source is apparently unresolved at 43 GHz on ground baselines; the combination of doubling the observing frequency and increasing the baseline length by a factor of 5 or more will provide 10 times better resolution of the inner jet and gamma-ray-emitting region.

A plot of the imaging resolution available with ARISE, for 38 confirmed EGRET detections of blazars with known distances (Mattox et al. 1997) is shown in the left-hand panel of Figure 15. Most of these objects are quite strong at 86 GHz, and should be detectable easily with ARISE. Source flux counts indicate that about 300 blazars have total 86-GHz flux densities above 0.5 Jy; nearly all of these should be detectable on long baselines with the nominal ARISE mission. The right-hand panel of Figure 15 shows a histogram of the linear resolution for 179 of these sources having known distances, indicating that the ARISE imaging resolution will be better than 100 light days (0.1 pc) for about 25% of them. It is expected that all of these sources will be detected by the next-generation gamma-ray mission, the Gamma-ray Large Area Space Telescope (GLAST), scheduled for launch in about 2005.

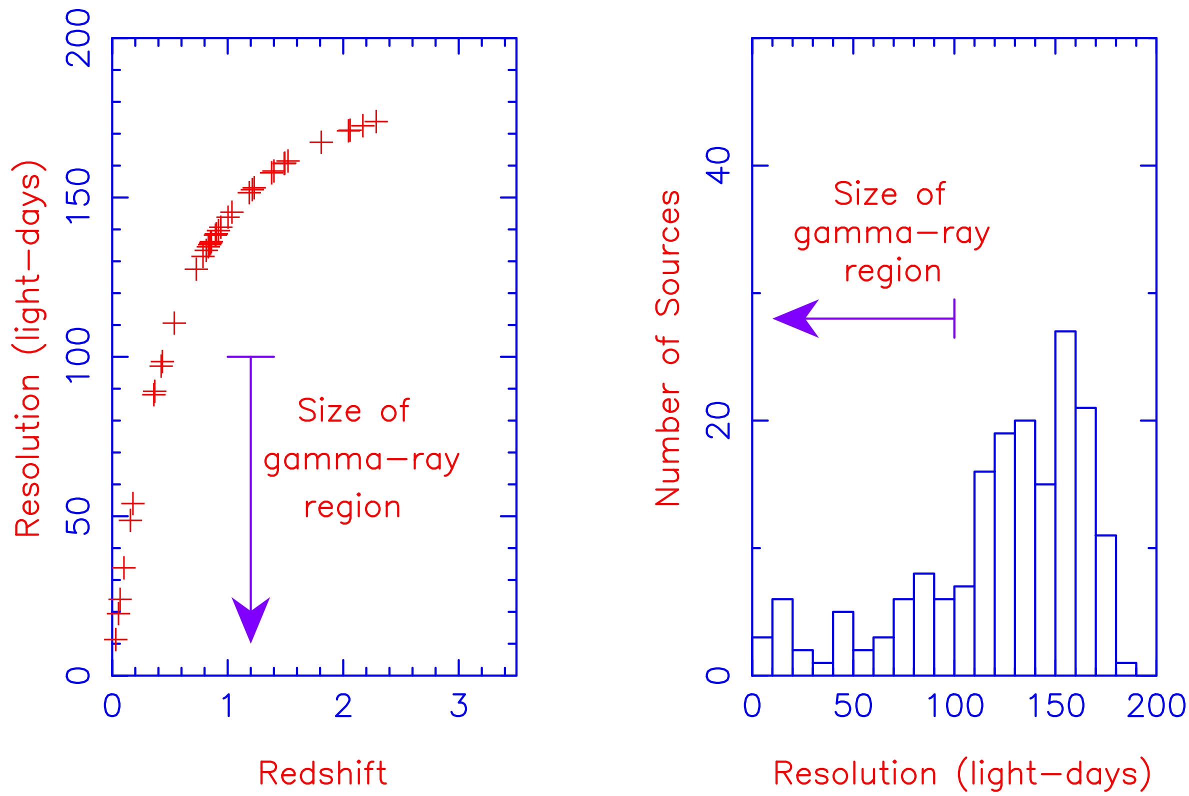


Fig. 15.— Linear resolution available at 86 GHz for ARISE (50,000-km baseline) observing two samples of blazars. **Left Panel.** Resolution for 38 blazars of known redshift z (i.e., known distance) detected by EGRET. **Right Panel.** Histogram of the resolutions for 179 blazars with measured redshifts and with 86-GHz flux densities greater than 0.5 Jy.

Direct imaging of the core region of blazars enables exploration of the following physical phenomena:

1. Formation of the jet near the SMBH
2. Ejection of plasma flowing at speeds near that of light
3. Particle acceleration at shock fronts and in the ambient jet
4. Jet magnetic fields
5. Production of shock waves and radio-emtting knots through variations in the jet flow

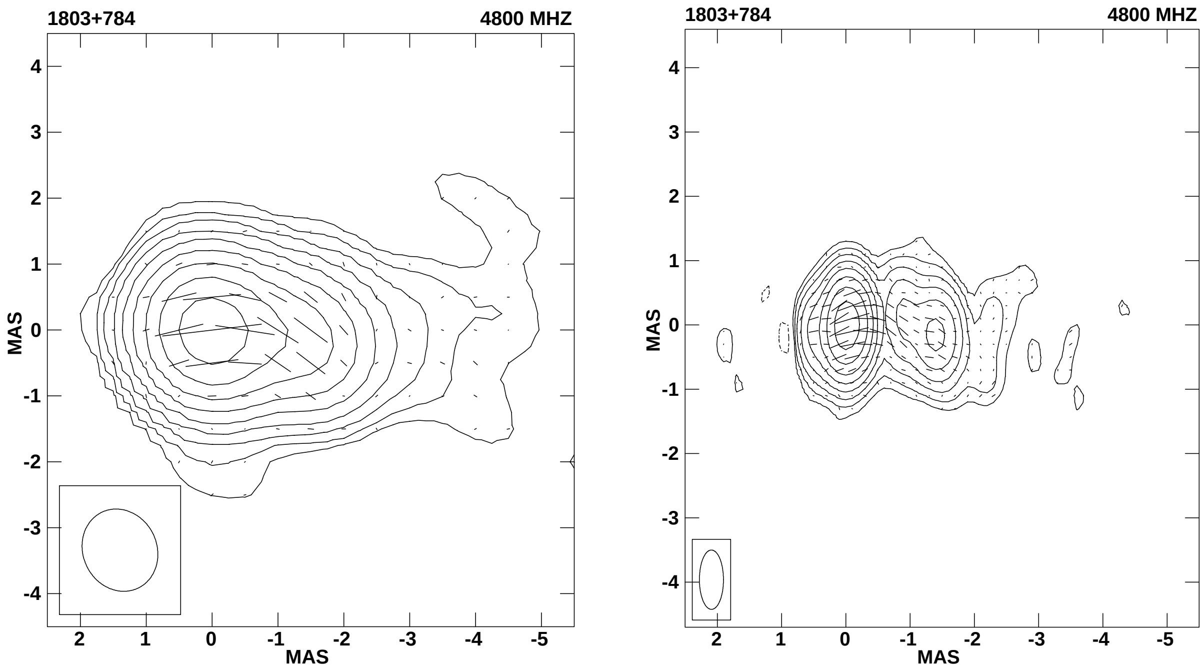
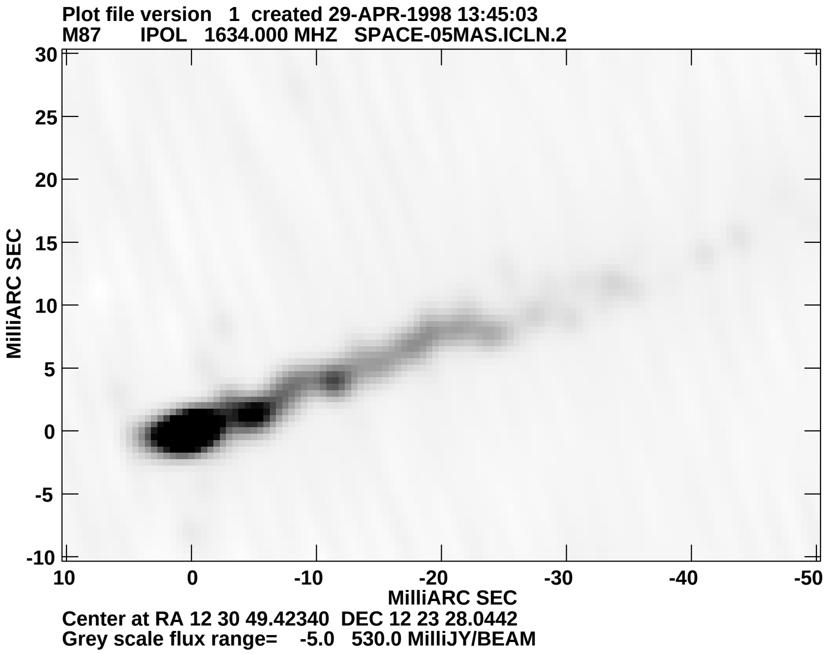


Fig. 16.— VLBI polarimetric images of the blazar 1803+784 at 5 GHz, showing the total intensity, indicated by contours, and the direction of the electric field vectors, indicated by the straight lines plotted over the images. **Left Panel.** Ground-only image from a VSOP observation, showing polarization at an oblique angle to the radio jet. **Right Panel.** Higher-resolution image from the same observation, but including the HALCA spacecraft along with the ground telescopes, of the same region displayed in the ground image. This shows that the electric vectors actually follow a curving inner jet very well, indicating that the magnetic field remains perpendicular to the jet rather than being offset at an oblique position angle.

Direct imaging of the core region of blazars enables exploration The structure of the magnetic field, as revealed by radio polarimetry, provides important clues about the physics of the inner jets. Figure 16 is a Space VLBI image of a blazar made by VSOP. The left-hand panel, a ground-only image, shows electric vectors that appear to be at an oblique angle to the radio jet, difficult to explain in standard models. However, the Space VLBI image in the right-hand panel shows that the jet actually bends to the north and then back to the south, with the electric vectors following this curvature perfectly. This indicates that the magnetic field in the jet is, in fact, perpendicular to the jet, probably because of compression of the field lines in a shock. The higher resolution of ARISE for imaging such phenomena on smaller scales will prove to be especially powerful when combined with multiwavelength monitoring of the variability of brightness and polarization in the jets.

There are other important aspects of jets that higher resolution imaging will explore. Jets are known to bend; possible reasons include illusions of bending caused by ribbons of emission appearing inside the jets, pressure gradients in a confining external medium (which result in oblique shocks that deflect the flow), collision with ambient gas clouds, erratically variable ejection direction at the jet nozzle, and precession of the jet nozzle (perhaps related to binary black holes in some cases). Each of these represents very interesting physics. Figure 17 is a Space VLBI image of the twisting of the jet in the active elliptical galaxy M87, indicating that the wavelength of this twisting increases with increasing distance from the core. The bending in this case may be due to instabilities in the jet, to precession of the spinning SMBH, or a combination of these and other effects. Jet bending can be explored much closer to the nozzle with higher resolution high-frequency observations, which should reveal the cause of the twisting appearance.

Particle acceleration is a long-standing mystery in astrophysics: nature seems to be able to do it efficiently and up to astonishingly high energies. Particle acceleration in jets can be explored via the synchrotron radiation emitted by the relativistic electrons. Recent VLBA imaging of circularly polarized emission from radio jets in blazars indicates that their relativistic particles are primarily electrons and positrons, rather than electrons and protons (Wardle et al. 1998), possibly resolving a key uncertainty about jet composition. This implies that the acceleration process may act on particles that are pair-produced by energetic photons in the vicinity of the central SMBH. Primary unknowns are how close to the central engine these electron-positron pairs are produced, and at what sites these electrons (and positrons) are accelerated to high energies. Circularly polarized images from ARISE will allow an estimation of the positron/proton fraction closer to the central engine, and linearly polarized intensity images from ARISE will provide the magnetic field geometry and how it relates to the acceleration of the electrons.



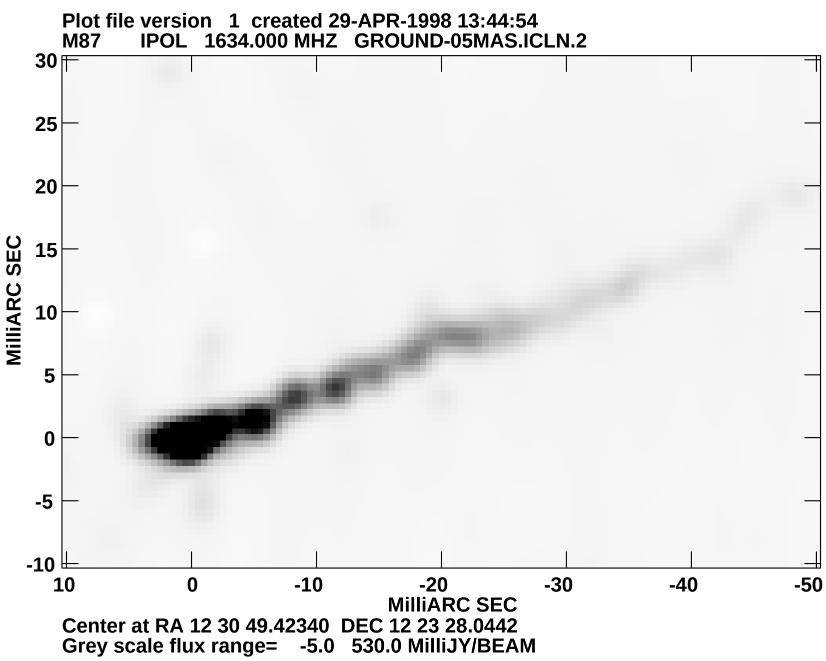


Fig. 17.— **Upper Panel.** Nuclear jet of M87 imaged with VSOP, with a 2-mas restoring beam. This image reveals details of the wiggles in the nuclear jet much better than is possible with ground arrays. **Bottom Panel.** Image using only the *ground-station data*, super-resolved by a factor of two, to give the same beam as for the VSOP image. Note the falsely lumpy appearance of the jet in this image, which if believed, could lead to spurious interpretations of jet motions and bending.

A number of radio sources vary by tens of percent on timescales less than a day ("intra-day" variability) at centimeter wavelengths. If the variations are intrinsic to the source, this creates a problem, because regions as compact as light-days (or even light-months) should be opaque at these wavelengths, and the inferred brightness temperatures may be as high as 10^{20} K, about nine orders of magnitude higher than expectations for incoherent synchrotron radiation.[2] One solution is that some of the emission is coherent, high-brightness temperature radiation; however, the other characteristics of the source (e.g., the spectrum and polarization) seem normal, implying that incoherent synchrotron emission supplies the observed radio waves. Refractive interstellar scattering can produce the observed flux-density variations, but for one source, correlated variations occur also at millimeter and optical wavelengths, too high for scattering to play a role. In addition, in another blazar, PKS 0405−385, even interstellar scattering requires an angular size so small that the brightness temperature of $\sim 10^{14}$ K inferred from the variability time scale far exceeds (by nearly three orders of magnitude) what is expected for incoherent radiation (Kedziora-Chudczer et al. 1998). A brightness temperature this high seems to be the exception rather than the rule; the variability time scales of most intra-day variables imply $T_b \approx 10^{13}$ K, if explained by interstellar scintillation. Observed brightness temperatures near 10^{13} K could be caused by the relativistic boosting of synchrotron emission discussed previously, if the enhancement of the emission is near a factor of ~ 20. ARISE will be able to directly measure brightness temperatures of $\gtrsim 10^{13}$ K, higher by a factor of 5–25 than has been possible previously, so the mystery of intra-day variables might then be solved - or deepened!

Theoretical simulations of relativistic jets by several groups are now revealing rich structure that can be compared with high-resolution observations. Over the next decade, advances in computer technology will allow the current two-dimensional gas dynamical calculations to be extended to 3-D magnetohydrodynamical simulations. Very-high-resolution images will be needed in order to compare with the detailed structure that will be revealed by the simulations. Only in this way can we determine whether our general ideas about blazar jets as relativistic flows of magnetized, relativistically hot plasmas, have merit. For example, some simulations currently indicate that the highly collimated, powerful jets in blazars and related objects can be generated only in the vicinity of rapidly spinning black holes (e.g., Meier 1998). The black-hole spin enhances the poloidal magnetic field, increasing the energy available to "launch" the relativistic particles in the jet. In the nearby galaxy M87, with a measured SMBH mass of $3 \times 10^9 M_\odot$, the hot inner accretion disk will be imaged on a scale of a few times the Schwarzschild radius, near the last stable orbit for material circling a black hole. Thus, imaging of nearby AGN with ARISE can provide direct tests of the various jet models that predict collimation on scales of 10–100 times the Schwarzschild radius. The imaging will help answer the question about whether the collimation process is primarily a matter of "heredity," related to the intrinsic properties of the central engine, or "environment," related to the surroundings in the center of the host galaxy.

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[2]At intrinsic brightness temperatures much higher than $\sim 5 \times 10^{11}$ K, the emission is quickly quenched by scattering of the photons off the parent population of electrons, the so-called "inverse Compton catastrophe."

3. Accretion Disks and H_2O Megamasers

3.1. What are Megamasers?

The high luminosities and relativistic jets observed in AGNs are fueled by mass accretion through disks that are gravitationally bound to SMBH. The disks consist of hot, ionized material close to the black holes, which joins warm, dusty, molecular material at somewhat larger radii. The detailed structure of the circumnuclear material is fundamentally important to the physics of the galactic nuclei, but is difficult to observe directly, because it typically subtends a small angle on the sky and is obscured by a large column of dust and gas which make it invisible to optical telescopes. High-resolution imaging of this circumnuclear material provides critical information about black-hole masses, the structure of the surrounding disk, and the detailed physics of the accretion process. Such imaging is possible only using VLBI techniques at radio wavelengths; as discussed below, the high resolution of Space VLBI is required to derive the most important physical parameters of a significant number of systems.

Within the molecular disk material, densities (10^8 – 10^{10} cm^{-3}) and temperatures (400 – 1000 K) can be conducive to a population inversion of the energy levels of H_2O molecules, which are present in trace amounts. When the disks are close to edge-on, a well-ordered rotational velocity field can support strong maser action, and radiation is beamed anisotropically, in roughly the plane of the disk, at a frequency of 22.235 GHz (see Figure 18). Very strong H_2O maser emission was first observed from a number of AGNs during the 1980s; this radiation was dubbed "megamaser" emission, because of apparent luminosities more than a million times greater than the luminosity of such emission from star-forming regions in our own Galaxy. Ground-based VLBI observation of the nearest megamasers has shown that some trace linear structures with the dynamical signatures of relatively edge-on differentially rotating disk. The hypothesis that the H_2O megamaser emission comes from galaxies in which a disk is seen edge-on is also supported by optical/UV and X-ray spectroscopy and optical/UV spectropolarimetry. Within such a disk, at any particular line-of-sight velocity, the respective spectral-line emitting regions are virtually point-like, as seen on the sky, because of steep gradients in the local line-of-sight velocity field. Hence, these maser "spots" can be used to trace unseen underlying molecular structures in detail. For the rest frequency of H_2O, the velocity resolution of existing VLBI correlators is well-matched to the typical line width of 1 km s^{-1}, and the angular resolution of intercontinental VLBI arrays yields 10 resolution elements across 0.1 pc structures at distances of 7 Mpc.

In the classical AGN paradigm, dusty neutral material occupies a vertically thick circumnuclear torus that obscures the central black holes. Type-2 AGNs (e.g., Type 2 Seyfert galaxies) are those in which our line-of-sight to the black hole intersects this thick torus, while our view of the galaxy nucleus is "above" the torus in type-1 AGNs (e.g., Antonucci 1993). A cartoon of the different lines of sight is shown in Figure 19. The radio interferometric studies of the H_2O masers that lie in the neutral circumnuclear media of several galaxies have demonstrated the presence of substantial but very thin disks that may be extensions of the hot inner disks. Ground-based studies of H_2O

Fig. 18.— Plot of H_2O maser line emission at 22.235 GHz, from the megamaser galaxy NGC 4258.

masers have led to significant insights about the structure of nearby AGNs. The H_2O masers are found within 0.1–1 pc of the centers of their parent galaxies, a factor of 10^5 smaller than the radius of the galaxy, but near the outskirts of the region where the AGN dominates the local physics, on the order of 10^4–10^5 Schwarzschild radii. Because the maser emission occurs in discrete "spots" with well-defined velocities, which may last for years, it is possible to image the distribution of spots, to trace the radial-velocity structure, and with images obtained at multiple epochs spread over years, to measure proper motions in the sky plane. Water masers are known to exist at distances as great as 120 Mpc from Earth. High angular resolution VLBI observations using a space platform such as ARISE are imperative for the measurement of critical physical elements in a large number of nuclei such as rotation curves, proper motions, central engine masses, disk vertical structure, and geometric distances that are independent of the sources of calibration uncertainty that affect conventional distance indicators. Only the gross properties of a handful of the closest sources can be studied from the ground.

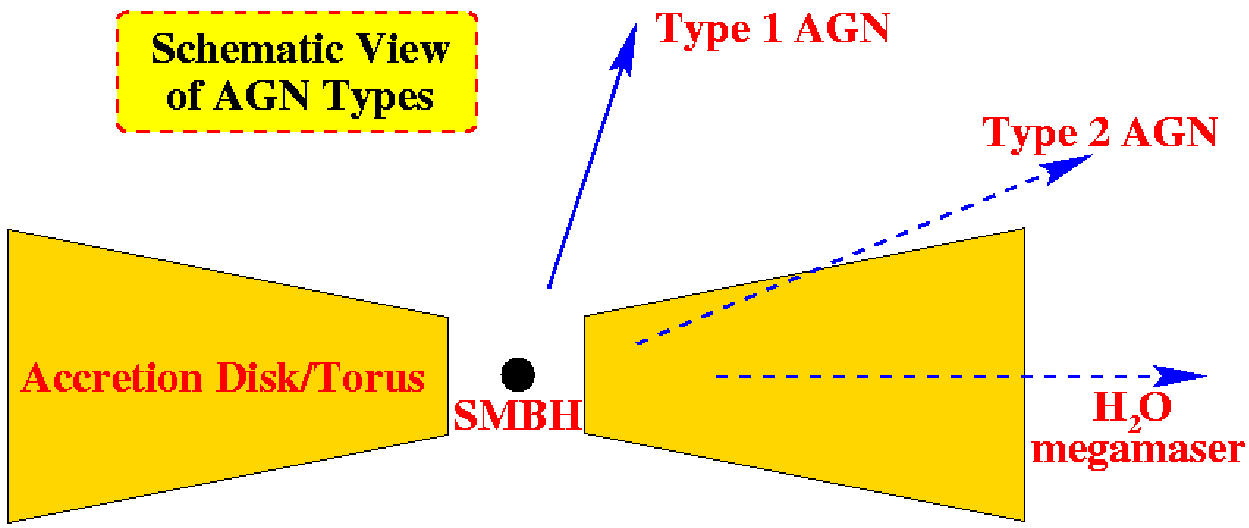

Fig. 19.— Schematic view of the lines of sight that give the appearance of different types of active galactic nucleus. A line of sight very close to the plane of the accretion disk/torus is necessary for the detection of water maser emission, since this enables long path lengths for the amplification of the maser emission.

3.2. Scientific Goals of ARISE Studies of H_2O Megamasers

There are a number of fundamental scientific questions that can be addressed using ARISE observations of 22-GHz H_2O megamasers in AGNs, such as the following:

- Masses of Supermassive Black Holes. The mass of the SMBH can be measured, sometimes with uncertainty of only a few percent, from the angular distributions of maser spots and their velocities. When combined with a measure of the bolometric luminosity of the AGN, this defines a fundamental accretion parameter, the ratio of the luminosity to the Eddington luminosity (proportional to black hole mass). This is a theoretical limit to the maximum luminosity available before accretion is suppressed due to radiation pressure. Measurements of SMBH mass in a number of galaxies can help build a statistical sample of the mass distribution of such black holes at the centers of active galaxies. Known maser accretion disks are associated with SMBHs less than about $10^8 M_\odot$, while known accretion disks detected with optical and infrared techniques in high luminosity AGNs, such as M87, seem to be bound by central engines more massive than $10^8 M_\odot$. There are recent indications that the mass of the black hole is strongly related to the mass of the spheroidal component of the galaxy ($M_{\rm BH} \sim 0.006 M_{\rm sph}$; e.g., Magorrian et al. 1998), and accurate black-hole masses for a number of relatively nearby megamaser galaxies would be an excellent test of this possible relationship.

- **Accretion Disk Structure.** The molecular portions of the accretion disks bound to SMBHs are unlikely to be smooth and continuous. In the presence of the intense radiation associated with SMBHs, the disks may be warped (e.g., Neufeld & Maloney 1995) and susceptible to wind or radiation driven ablation. The angular distribution of maser-emitting regions within disks and their variability may be indicative of some degree of clumpiness (e.g., Kartje, Königl, & Elitzur 1999). Clarification of the relationship between the maser-emitting gas and the underlying accretion disk is crucial if masers are to be utilized for detailed accretion-disk diagnostics. In principle, conditions conducive to maser action may exist throughout the vertical height of a disk, or possibly only near the surface, where the maser material may be up-lifted into the large-scale wind. The vertical structures of the masers and disks, degree of clumpiness, and interaction between disks and their surroundings can be investigated only with the high-angular resolution imaging afforded by Space VLBI. These observations will also help answer the question of whether the masers are excited by X-ray irradiation induced heating of accretion disks (e.g., Neufeld, Maloney, & Conger 1994), or by spiral and stochastic shock waves that propagate inside accretion disks (e.g., Maoz & McKee 1998).

- **Accretion Processes.** Masers trace accretion flows and may be used to estimate mass accretion rates onto SMBHs. Although inward drift velocities are probably too small to detect in most systems, observables such as disk thickness are related directly to accretion rate, for baseline models of viscously heated disks. Traditionally, accretion rates are inferred from spectroscopic data and from tracers that exist at much larger or much smaller radii from SMBHs. Notably, for nuclei that radiate much less than the inferred Eddington luminosities, energy may be advected into the SMBHs rather than being converted to radiation, in which case the accretion rates through the molecular portion of the accretion disks are orders of magnitude larger than in non-advective systems, signaling an entirely distinct mode of accretion (i.e., "Advection-Dominated Accretion Flows" — e.g., Lasota et al. 1996).

- **Geometric Distance Measurements.** The proper motions of maser spots, their positions, and line-of-sight velocities, provide a direct geometric measure of distance roughly analogous to the classical Statistical Parallax method of optical astronomy. VLBI imaging of H_2O masers is one of only two methods that can be used to make geometric measurements of extragalactic distances. (Supernova expansion is the other.) Herrnstein et al. (1997b) demonstrate that for a well-parameterized disk model, the accuracy of the distance measurements can be as small as a few percent, sidestepping numerous rungs on the classical cosmic distance ladder. Distances to four known H_2O megamasers within 15 Mpc can be measured using observations with ARISE. In fact, a recent ground-VLBI measurement of a distance of 7.2 Mpc to NGC 4258 (Herrnstein et al. 1999) is forcing a complete recalibration of the Cepheid distance scale being used in the *Hubble Space Telescope* key project on the cosmic distance scale, since the indirectly measured Cepheid distances *must* be consistent with the distance measured geometrically by means of VLBI. If suitable megamasers are detected at distances beyond approximately 50 Mpc, so that their recession velocities are dominated by the expansion of the Universe (the "Hubble flow"), then they may provide a direct and accurate measurement of the Hubble Constant, the fundamental parameter relating recession velocity to distance in the current Universe.

3.3. Results of Ground-Based Observations of H_2O Megamasers

For many of the AGNs that host H_2O masers, VLBI observations provide the richest data collected so far on structures within 1 pc of the central engine. The investigations are unique because the observations can resolve accretion disk structure and kinematics very well, given adequately large VLBI baselines. Specifically, studies of extragalactic H_2O maser emission have greatly strengthened the case for AGN unification schemes by conclusively demonstrating the existence of thin edge-on accretion disk systems bound by large central masses in type-2 AGNs.

At distances of up to 15 Mpc, important first-order physical characteristics of accretion disk-black hole systems, such as disk radii, black hole masses, and Eddington luminosities, have been measured in ground-based VLBI studies. The best studied system lies in the Seyfert galaxy NGC 4258, at a distance of 7 Mpc (see Figure 5 in the Executive Summary). It is one of the most convincing examples of a SMBH in any AGN, as well as the best evidence for a warped, thin accretion disk therein. The rotation curve of the disk is Keplerian ($v \propto r^{-0.5}$) to better than 1% ($\frac{\Delta v}{v}$) over a range of radii from 0.15 to 0.29 pc, which provides a central mass estimate of $4.0 \times 10^7 M_\odot$ (Miyoshi et al. 1995; Herrnstein et al. 1998). This result demonstrates that NGC 4258 radiates several orders of magnitude less power than the Eddington luminosity, either because of a low accretion rate or because of low efficiency in the conversion of mass accretion to energy.

The orbital motion of the NGC 4258 disk is observed directly in the detectable proper motions of masers, at a rate of about 30 μas yr^{-1}, and in the centripetal acceleration of the maser material at about 8–10 km s^{-1} yr^{-1} (e.g., Greenhill et al. 1995). Maser positions, velocities, and motions yield an unprecedented, geometric distance to NGC 4258 that has an uncertainty of less than 5%, including systematic sources of error (Herrnstein et al. 1997b). The model disk pinpoints the otherwise "invisible" black hole and dynamical center with unusual precision, from which the angular offset of the core of the 22-GHz continuum radio jet,[3] along the disk rotation axis, is measured to be 4000 Schwarzschild radii (Herrnstein et al. 1997a).

Accretion disks traced by maser emission have also been discerned in the higher-luminosity

[3]The continuum source is detected because the H_2O line plays the role of an adaptive optics guide star. For a ground array, the atmosphere is coherent for on the order of 1 minute. If the "guide star" can be detected in this time, then the deleterious effects of atmospheric fluctuations may be rectified and much fainter maser lines and continuum emission may be imaged.

Seyfert galaxies NGC 1068 at a distance of 15 Mpc, the Circinus galaxy at a distance of 4 Mpc (Figure 20), and NGC 4945 at 4 Mpc. Including NGC 4258, these disks have orbital velocities of 200–1100 km s^{-1} and radii of 0.1–1 pc, and they are bound by central masses of $1 \times 10^6 M_\odot$ to $4 \times 10^7 M_\odot$. The apparent detection of warps in several maser disks, on scales of less than 1 pc, suggests that with a larger statistical sample, direct tests might be possible for the provocative hypothesis that warped accretion disks, rather than vertically thick circumnuclear tori, are responsible for the obscuring X-ray column in type-2 AGNs (e.g., Phinney 1998).

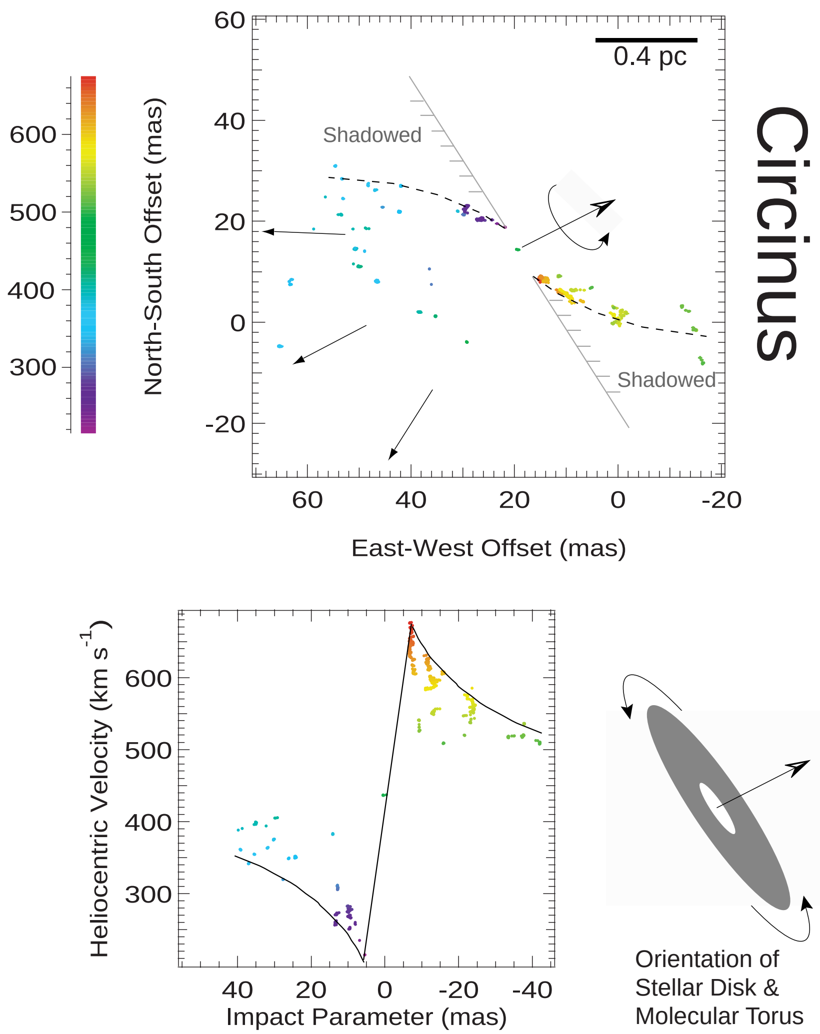

Fig. 20.— **Top Panel.** Plot of the maser-spot locations and radial velocities in the nearby Circinus galaxy. **Bottom Panel.** Disk rotation curve, modeled by including both Keplerian rotation and an outflowing wind from the nucleus, together with a schematic diagram of the orientation of the disk/torus.

Twenty-two H_2O masers in AGNs are known at distances of up to 120 Mpc and apparent luminosities of up to 6000 $L_\odot$, at least 10 times that of NGC 4258. Beyond the four already discussed, approximately 10 more masers that are suspected accretion disk-black hole systems are being investigated with available ground-based VLBI instruments. At the same time, surveys meant to detect more maser sources in accretion disks are ongoing. However, ground-based VLBI investigations are resolution-limited and can neither resolve adequately disk structures in AGNs beyond several tens of Mpc nor measure important physical parameters even in nearby systems. Only ARISE can achieve the necessary angular resolution; Figure 21 shows the resolution that ARISE will yield for the 22 known megamaser galaxies.

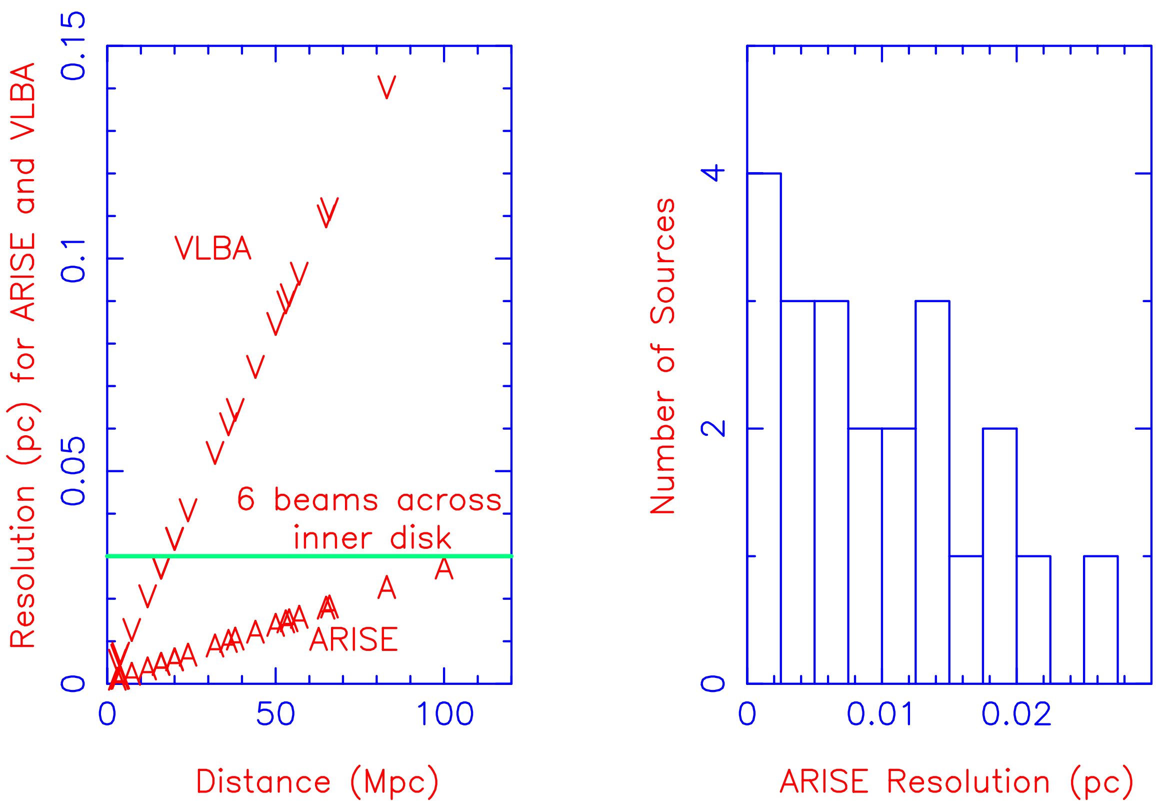

Fig. 21.— **Left Panel.** Comparison of the resolutions available for ARISE (50,000-km baseline) and the VLBA, for the 22 currently known H_2O megamaser galaxies. The resolution requirement of having six beams across the inner diameter of the maser disk is indicated (see Section 3.5 for further discussion). **Right Panel.** Histogram of linear resolutions for the currently known megamasers.

Twenty-two H_2O masers in AGNs are known at distances of up to 120 Mpc and apparent luminosities of up to 6000 $L_\odot$, at least 10 times that of NGC 4258. Beyond the four already discussed, approximately 10 more masers Though disk-borne masers are valuable targets in part because they seem to trace a relatively simple underlying geometry, it is notable that at least one known maser, in the radio galaxy NGC 1052 (Figure 22), is seen toward a relativistic jet (Claussen et al. 1998). Weak jet-borne maser emission may also exist in some other galaxies (e.g., NGC 1068). In NGC 1052, the angular structure of the maser emitting regions is poorly resolved by ground-based observations. With ARISE, masers may ultimately provide data on shocked and entrained molecular material on sub-parsec scales, which are not now available. Limited angular resolution also afflicts observations of the most apparently luminous and most distant known H_2O megamaser, in TXFS22265−1826 at 120 Mpc, for which the dichotomous classification of disk and jet features is difficult to apply.

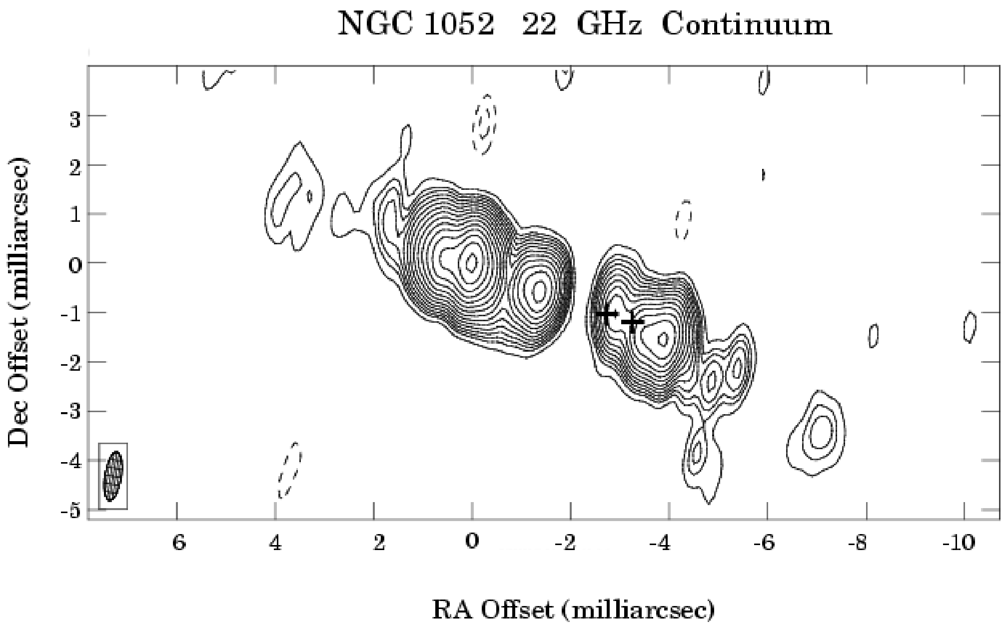

Fig. 22.— NGC 1052 VLBI jet seen in 22-GHz continuum emission. The locations of the H_2O megamasers are marked by crosses; in this case, the masers lie along the jet, rather than in the accretion disk perpendicular to the jet.

3.4. Searches for New Megamasers

Following the first generation of maser surveys, 22 sources are known to lie in AGNs within 120 Mpc. The maser strengths, which are time variable by factors of a few, are 0.05–40 Jy, and the host galaxies are distributed over the whole sky at distances of 4–120 Mpc. A new generation of surveys for maser sources is expected to at least double the number of detections within AGNs closer than 120 Mpc. Surveys of intermediate and high-redshift AGNs have also begun. The discovery of even one observable H_2O maser at cosmological distances would be significant. In such a case, the high angular resolution possible with ARISE is absolutely critical to the measurement of geometric distance, since ground-based VLBI would have inadequate resolution to separate maser spots and measure their motions.

Most maser surveys to date have concentrated on nearby, weakly active objects such as Seyfert galaxies and LINERs (galaxies with Low-Ionization Nuclear Emission Regions). About 500 galaxies have been studied. Of the LINER and Seyfert 2 galaxies observed at recession velocities less than 4500 $km\,s^{-1}$ (distances less than about 70 Mpc), about 10% contain detectable radio emission from H_2O megamasers; for recession velocities less than 7000 $km\,s^{-1}$ (distances less than about 110 Mpc), about 7% contain detectable H_2O emission. There is some preference for galaxies that have nearly edge-on stellar disks and nuclei with high ($> 10^{23}$ cm^{-2}) X-ray absorbing columns (Braatz et al. 1996; Greenhill et al. 1997). Conversely, no masers are known to lie in Seyfert 1 objects, as expected from the unified scheme for AGNs, which posits that our line of sight to these objects does not intersect the nuclear torus.

Past surveys concentrated on optically identified AGNs and have been bandwidth- and sensitivity-limited. Only relatively narrow band spectrometers were available, and efficient surveys were possible only within about ±200–300 $km\,s^{-1}$ of the galactic systemic velocities. The H_2O maser emission in an AGN typically can occur close to the systemic velocity of a galaxy (from the front side of an accretion disk) or at "high" velocities offset by plus and minus the orbital speed of the disk (from positions where the orbital motion is parallel to the line of sight). Therefore, the first surveys were largely insensitive to accretion disks whose strongest emission could be offset by > 300 $km\,s^{-1}$, which would be expected for the most massive black holes. Moreover, of the known megamaser galaxies with both high-velocity and systemic emission, only one has systemic emission that is the stronger of the two.

The latest generation of surveys emphasizes (1) greater simultaneous bandwidths, up to 6000 $km\,s^{-1}$, (2) higher sensitivity, and (3) more broadly defined source lists of AGNs. First, expanded bandwidth should enlarge the number of known masers because previous surveys have been biased in favor of detecting sources with strong systemic emission. Second, average survey sensitivity should improve by a factor of about two, which should at least double the known number of maser sources. The improvements stem from new receivers and spectrometers, and from the increased availability of large apertures, 70–100 meters in diameter (e.g., the Green Bank Telescope). Hence, almost three times the volume of space may be efficiently surveyed with the same luminosity sensitivity. Third, the addition of heavily reddened and low-luminosity objects that have not previously been identified as AGNs will expand the number of masers discovered. In light of these three factors, the canonical detection rate of 5–10% among Seyfert-2 galaxies and LINERS is presumably a lower limit. It is reasonable to expect that a total of at least 50 H_2O megamasers will be known among the existing samples of galaxies within about 200 Mpc.

3.5. Critical Value of ARISE to Studies of H_2O Megamasers

To illustrate the value of ARISE to observations of H_2O masers in AGNs, we compare the capabilities of ground-based and Space VLBI in the study of a $10^7 M_\odot$ black hole and associated accretion disk at a distance of 100 Mpc. We assume that the AGN radiates about 20% of the Eddington luminosity that corresponds to this mass, $L = 2 \times 10^{44}$ erg s^{-1}, for which the inner radius of the accretion disk, defined by the sublimation of silicate dust grains is on the order of 0.2 pc or 400 μas ($r_{\rm sub} \propto L^{\frac{1}{2}}$). For purposes of analysis, we assume an orbital apogee of 50,000 km for ARISE. The longest high-sensitivity ground-based baseline in common use for observations of H_2O emission is about 8000 km.

For the model disk, ground-based observations only marginally resolve the radial source structure and measurement of the mass of the central SMBH is impractical. The inner disk radius corresponds to about one ground-based resolution element ($\frac{\lambda}{B} \sim 500$ μas) and six resolution elements with ARISE (e.g., see left-hand panel of Figure 21). The outer radius of the source is only barely resolved in the absence of Space VLBI, assuming a 2:1 ratio of outer and inner radii, as is measured in several maser sources (see Figure 23). The fractional uncertainty in the mass of the central black hole is approximately the fractional uncertainty in the measurement of the disk radius. (Uncertainties in measured Doppler velocities contribute relatively little.) For a 50,000-km satellite apogee, the uncertainty in mass is less than about 20%; estimates from ground-based data would be problematic.

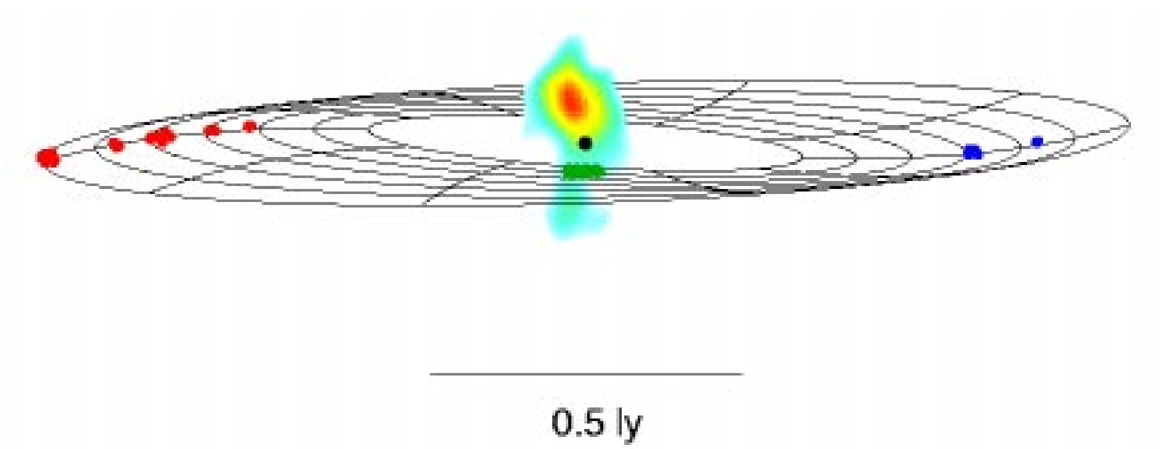

Fig. 23.— NGC 4258 megamaser disk observed with the VLBA, showing the approximate 2:1 ratio between the outer and inner radii. The inner radius is apparently determined by the sublimation of dust grains at a radius of 0.1–0.2 pc. The weak radio jet perpendicular to the disk is represented by the false-color part of the image.

The expected angular proper motion for the model accretion disk-black hole system is about 3 μas in 3 years for clumps near the inner edge and on the near side of the disk, where the orbital motion is transverse to the line of sight ($\dot{\theta} \propto {M_{\rm BH}}^{\frac{1}{4}} D^{-1}$, where $M_{\rm BH}$ is black-hole mass and D is distance). Such minute motions can be detected with ARISE if the centroid of the emission for individual maser features can be measured with a signal-to-noise ratio of about 10, only a factor of two above the detection limit. Ground-based observation has only detected proper motions for NGC 4258 (1000 km s^{-1} at a distance of 7 Mpc), and marginal measurements may be possible for one or two other nearby maser galaxies. The fractional uncertainties in the geometric distances that can be obtained once proper motions are measured are on the order of the uncertainty in black hole mass, probably less than about 20%. Among the H_2O maser sources that are known now to exhibit emission from clumps with orbital velocities parallel and perpendicular to the line of sight (i.e., systemic emission that will exhibit measurable proper motions with respect to high-velocity emission), proper motions and distances may be measured with ARISE for six sources at distances up to about 50 Mpc.

Vertical structure in the portions of accretion disks delineated by maser emission is difficult to resolve, since the axial ratios (height vs. radius) are typically at least 100. However, for a disk heated internally by viscosity, which is relatively large in radius (1 pc) and slow in rotation speed (less than about 300 km s^{-1}), a thickness of between one and a few ARISE resolution elements is reasonable. Somewhat larger thicknesses are predicted by disk-wind models (e.g., Kartje, Königl, & Elitzur 1999). In contrast, ground-based observations must rely on estimates of the scatter of emission centroids, over a range of Doppler velocities, about the local plane of the disk.

Based on flux density levels and line widths at the epoch of discovery all the H_2O maser sources detected in past H_2O maser surveys are strong enough to be observed with ARISE, in conjunction with a ground array that includes several large aperture antennas (e.g., 70-100 m diameter), though relatively new techniques to enhance the coherence of the ground-array may be required. The sensitivity limit is about 50 mJy in a several km s^{-1} wide spectral-line. This is the requisite flux density for the strongest single maser spectral feature; as noted before, this line may be used as a "guide star" that permits detection of potentially much weaker spectral lines. The sensitivity limits of future large-scale searches for new maser sources will probably be relatively well matched to the VLBI detection limit, because large numbers of sources must be surveyed and especially long integration times are not practical. More importantly, many of the sources that these surveys will detect will be notable for their broad spectra, featuring lines offset by at least several hundred km s^{-1}, and their relatively recent classifications as AGNs, rather than for their weak flux densities.

The above example of a megamaser galaxy at 100 Mpc, a number of which should be found in the new surveys over the next few years, shows several unique capabilities that require ARISE. The radial disk structure cannot be resolved from the ground, and the angular proper motion of maser clumps in the disk cannot be measured. ARISE, on the other hand, would resolve the disk (with ~ 10 pixels across its radius) and would be able to measure the black-hole mass and geometric distance with an accuracy better than 20%. Various models for the disk heating, warping, and accretion rate make different predictions about the vertical thickness of the disk; all (most???) predict a disk whose height is not resolvable from the ground, but could be imaged with ARISE. The high sensitivity and resolution of ARISE are well matched to the surveys that are expected to find a number of new megamaser AGNs at distances between 20 and 100 Mpc. In addition to the studies of the detailed physics of individual objects, this will permit the construction of a large enough sample to derive the distribution of properties of AGN accretion disks, perhaps allowing extrapolation to much more distant sources in which the disks cannot be detected or (if detected) resolved.

4. Cosmology

ARISE, by virtue of its capability of producing very high resolution images of astronomical objects far across the observable Universe, can make a number of contributions to cosmology. One such contribution was discussed in Section 3, associated with the geometric distance measurements to H_2O megamaser disks in AGN. ARISE imaging of gravitationally lensed objects, and the improved modeling that this will provide, also can be an important probe of dark matter and the distribution of mass in galaxies and galaxy clusters. In addition, the high-resolution images of very distant quasars can provide important input to some of the standard cosmological tests that attempt to reveal the curvature and ultimate fate of the Universe.

4.1. Gravitational Lenses

4.1.1. Basic Concepts

The idea that distant sources might be distorted and even multiply imaged by the gravitational potentials of intervening objects is one of the earliest predictions of general relativity. Since the discovery in 1979 of the first gravitational lens system, 0957+561 A,B (Walsh, Carswell, & Weymann 1979), this area of astrophysics has expanded rapidly. During the last 5–10 years lensing has emerged as a powerful new tool with which to attack some of the most challenging and fundamental problems of our time. In particular, known lens systems (both individually and collectively) have been used to estimate, and place limits on, global cosmological parameters viz. the expansion rate of the Universe, H_0; the matter density of the Universe, Ω; and the vacuum contribution to the energy content of the Universe, Λ. In addition, lenses have also been employed as sensitive and direct probes of dark matter, investigating its nature and its distribution on many different scales (see Narayan & Bartelmann 1996 for a comprehensive review).

Gravitational lensing occurs when radiation from a distant object (e.g. a quasar) is deflected by the gravitational field of an intervening body (e.g. a galaxy) lying close to the observer-source line-of-sight. The radiation from the distant source can therefore arrive at the observer via multiple paths, thus producing multiple (usually 3 or 5) images of the original, background source.[4] A sample radio image of a four-component gravitational lens, spread over a total size of a few arcseconds, is shown in Figure 24. Since the deflection at the lens depends only on its gravitational potential, lensing is sensitive to all forms of matter: luminous or dark. Gravitational lensing is achromatic, so systems are easily identified by the fact that lensed images have identical spectral (and polarization) properties. Since the radiation associated with particular images travels different geometrical paths and samples different gravitational potentials within the lens, the light travel time associated with each image can be different. Therefore, one observes a "time

[4]Typically, one image in a lens is highly demagnified, so an even number of lensed images, usually 2 or 4, is seen.

delay" between the arrival of radiation in one image and its appearance in another. For systems in which the mass distribution of the lens is well constrained, a measure of this time delay between 2 images provides a direct estimate of the differential path lengths associated with the images, which is sufficient to determine the linear scale at the redshift of the lens. Measurements of this type in a number of lenses with differing lens redshifts will allow the measurement of the change of this scale as a function of redshift and thus the derivation of H_0, Ω, and Λ.

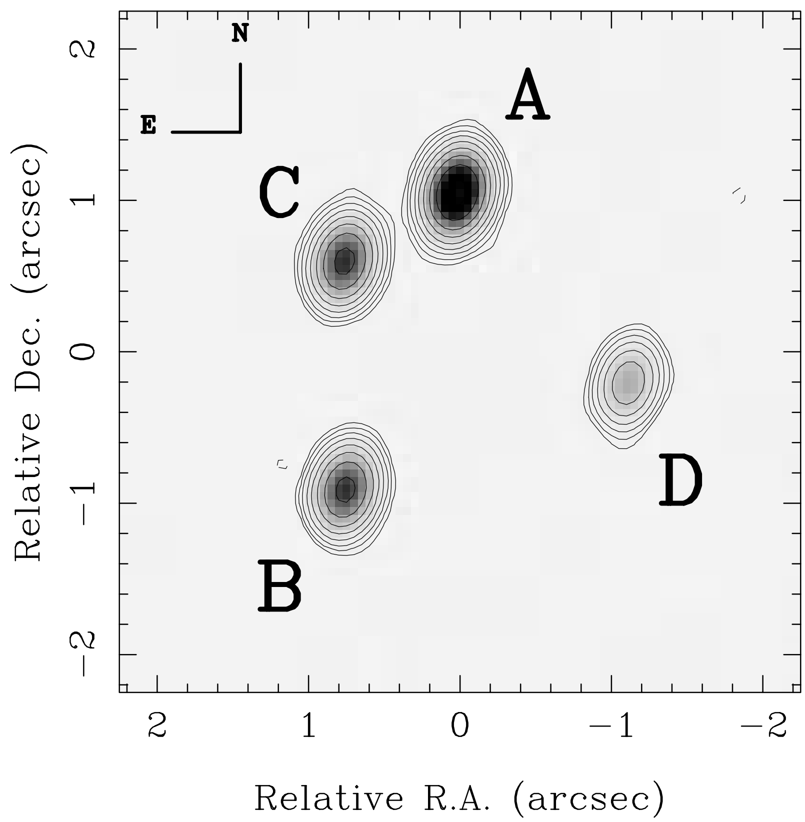

Fig. 24.— VLA 8-GHz radio image of the four-component gravitational lens 1608+656, discovered as part of the "Cosmic Lens All-Sky Survey" conducted at the VLA in the late 1990s. The four images span a total distance of about 3 arcseconds.

4.1.2. Weighing Galaxies and Determining the Hubble Constant

Ongoing radio searches for gravitational lens systems, have been remarkably successful: more than half of the strongly lensed quasars discovered to date are radio sources (e.g., Hewitt 1995; Keeton & Kochanek 1996), and 4 of the 6 known high-redshift sources of millimeter-wave molecular lines are also gravitationally lensed (e.g., Antonucci 1999). By 2008, the current generation of radio lens surveys will have furnished a list of at least 50–100 confirmed lens systems which can be detected by ARISE. Since the majority of these systems are likely to be fairly faint radio sources ($\sim$ 10–100 mJy), the high sensitivity of ARISE will be critical.

VLBI observations of gravitational lens systems are particularly important because their high spatial resolution often resolves radio images into various sub-components. The sub-scomponents in one image are related to those in another image by a simple, four parameter linear transformation known as the "magnification matrix." A sample ground-VLBI image of a gravitational lens is shown in Figure 25. The angular resolution of ARISE will enable the relative positions of VLBI components to be determined with higher accuracy than ever before. This will permit the derivation of more accurate magnification matrices and thus lens mass distributions. A comparison of matrices derived by ARISE on the sub-milliarcsecond scale, with those determined at scales of tens or hundreds of milliarcseconds by other radio instruments, will also allow the spatial derivatives of the magnification matrix to be derived (Garrett et al. 1994). Such measurements lead to tightly constrained lens models, a pre-requisite for reliable determinations of cosmological parameters (see Grogin & Narayan 1996).

Fig. 25.— VLBA 43-GHz images of the two main components of the gravitational lens 1830−211 at a resolution of 0.33 mas; these two components are separated by about 1 arcsecond, and are actually the peaks in a nearly complete Einstein ring. **Left Panel.** Image of the northeastern lensed component on 14 July 1996. **Right Panel.** Image of the southwestern lensed component on 14 July 1996. Note the different structure between the two, which places new constraints on the magnification matrix.

A comparison of galaxy masses found via lens mass distributions, with the observed distribution of light, can reveal the distribution of sub-luminous, dark matter in the lens galaxy. This dark-matter distribution has direct implications for the density of the Universe relative to its closure density and for theories of formation of galaxies and other baryon-dominated objects in the early Universe. Thus lenses offer a way of determining accurate galaxy masses using methods which are completely independent of traditional dynamical methods. If the mass distribution of a lens system is well constrained, and the time-delay between the images can be measured, estimates of the cosmological parameters can be made, in particular Hubble's constant, H_0. Such determinations are of crucial interest since they use methods which are independent of conventional bootstrapping distance-scale techniques. Determinations of H_0 from gravitational lenses are currently limited by systematic errors in the modeling of the systems. ARISE data can provide a new set of constraints to reduce these systematic errors.

4.1.3. Using Lens Systems as Natural Cosmic Telescopes

A fundamental property of gravitational lensing is that for a given lens system at least one image is magnified with respect to the original source. Typical image magnifications of ~ 10 are not uncommon, but factors of ~ 100 are also possible (Blandford & Hogg 1996). For magnified images observed by ARISE, the array's effective baseline length is scaled up by the lens magnification, thus boosting the resolution towards the unprecedented 1-μas scale.

Only a few of the known gravitational lenses have been observed with ground-based VLBI arrays at mm wavelengths (e.g. Garrett et al. 1997). Observations of bright lens systems, such as the blazar 1830−211, with ARISE at the highest observing frequencies, will provide a unique opportunity: the ability to image active radio sources within a few light days of the AGN core, a feat that would otherwise be impossible with un-lensed radio sources at cosmological distances. This tantalizing "inside view" should permit any evolving radio structure to be monitored. At these magnification-enhanced resolutions, significant changes may be expected on the accelerated time scale of a few days. Such changes, when compared between different images, may also permit a novel determination of the image time-delay, one of the crucial parameters required to determine cosmological parameters and traditionally one of the most difficult measurements to make accurately with conventional monitoring methods.

Making use of the fact that lensed images are all observed within the same individual telescope beam, ARISE 86-GHz observations should allow relative position measurements with an accuracy better than < 0.15 μas (in the *source* plane) to be made. On a time-scale of days to months, a search for position "jitter" between the radio cores (the base of the relativistic jets) can be made. This effect might be expected on the microarcsecond and sub-microarcsecond scale due to instabilities in the region at which the jet first forms - near the SMBH and its accretion disk. Frequent measurements of this "jitter," particularly in combination with gamma-ray observations, could be used to infer the sizes of jet formation regions and their temporal stability, thus providing useful constraints on the physical processes involved.

Accurate relative position measurements would also significantly increase the chances of observing relative proper motions between magnified lensed images on time scales of a few years. Only VLBI has sufficient resolution to detect cosmic proper motions, but even here the best relative position accuracies of $\sim 10\ \mu$as are such that only the motions of masers in nearby galaxies or of radio components in superluminal jets can be detected without resorting to time-scales much greater than the human life expectancy. ARISE observations of lens systems make the detection of relative proper motion in extragalactic sources a practical certainty on reasonable time scales of only a few years. Such measurements for an ensemble of lenses ($n \approx 10$) can set limits on the the deviation of the inertial reference frame defined by the lenses from that defined by the cosmic microwave background and enable an estimate of the Hubble constant (Kochanek, Kolatt, & Bartelmann 1996). In addition, residual proper motions relative to the microwave background probe the evolution of peculiar velocities with (lens) redshift and can be used to estimate the deceleration of the expansion of the Universe.

4.1.4. A Search for 10^3–$10^6 M_\odot$ *Black Holes in the Universe*

What is the nature of the dark matter that dominates the total mass of the observable Universe? This is one of the fundamental, but unanswered questions of modern astronomy. Primordial nucleosynthesis calculations predict that at least some of the dark matter (1–10%) must be baryonic in nature. If so, baryonic dark matter may adequately account for dark galactic halos, whose existence is suggested by galaxy rotation curves. The most likely baryonic dark matter candidates (Maoz 1994) are segregated into two main mass ranges: (i) sub-solar-mass dwarf stars and (ii) a population of massive compact objects ($\sim 10^4$–$10^6 M_\odot$). Recent detections of gravitational microlensing events (e.g., Alcock et al. 1993) toward the LMC suggest that some (but not all) of the Galactic dark matter may be in the form of low-mass baryonic objects. However, 10^3–$10^6 M_\odot$ objects remain attractive DM candidates since this mass range is close to the Jeans mass at recombination, which may be have been the preferred mass scale for the first bound objects that formed in the early Univese (Carr & Rees 1984).

For gravitational lenses located at cosmological distances, if the image separation θ is given in microarcseconds and the lens mass M is given in solar masses, $\theta \approx \sqrt{M}$. Ground-based VLBI maps of over 300 compact radio sources (Henstock 1996) have been examined for evidence of gravitational lensing with image separations on the scale of 2 to 40 milliarcseconds (corresponding to lens masses of 10^6–$10^8 M_\odot$) but produced no convincing lensing candidates. However, the mass range of prime interest for cosmologically distributed black holes is 10^3–$10^6 M_\odot$. This area is almost entirely unexplored, since its study is impossible from the ground, due to limits in resolution at centimeter wavelengths, and poor sensitivity at millimeter wavelengths. ARISE, with its combination of high angular resolution and superb sensitivity, can have a unique and significant impact in this field, as shown in Figure 26.

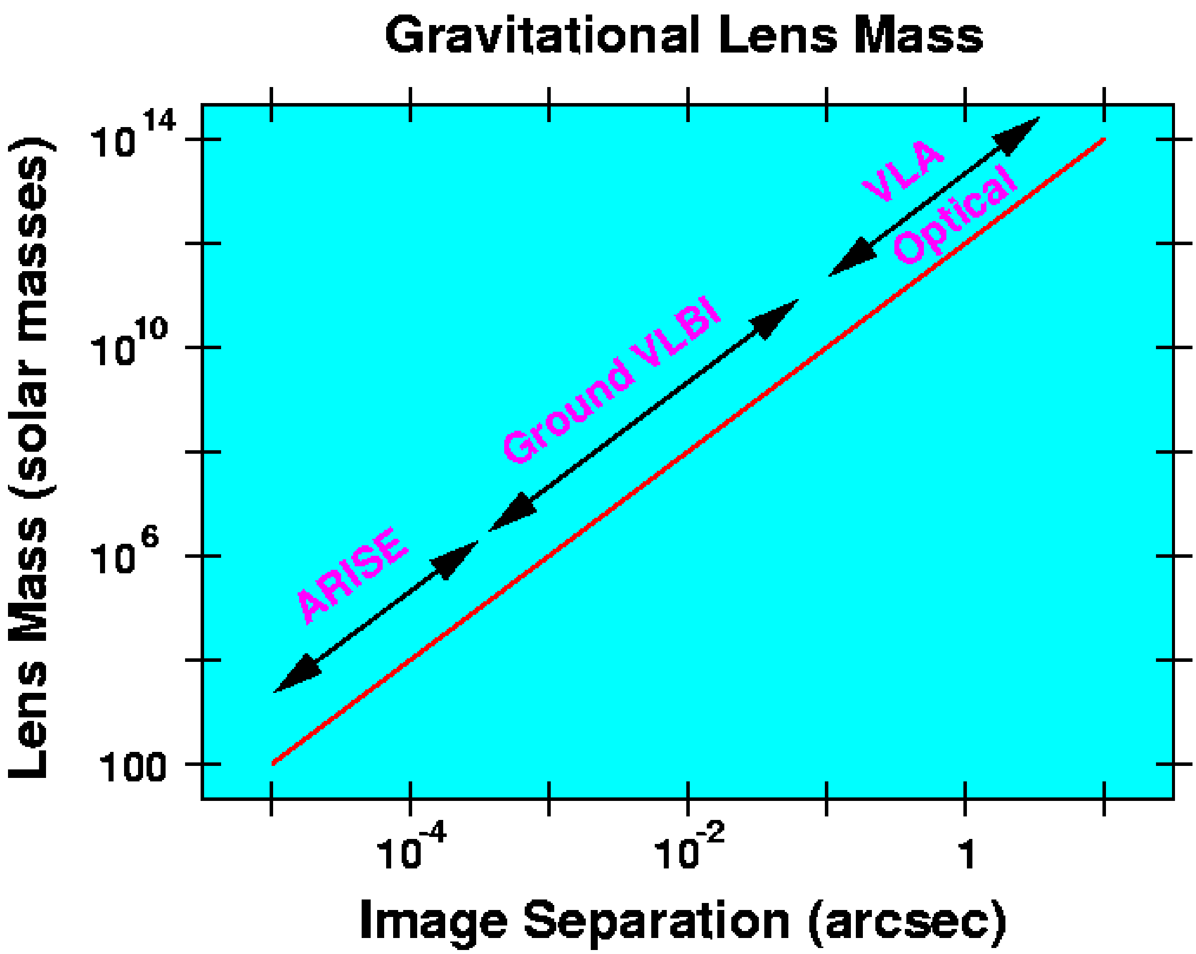

Fig. 26.— Sensitivity to lensing masses ranging from $100M_\odot$ to $10^{14}M_\odot$ as a function of image separation from 10 μas to 10 arcsec. Parameter space covered by various techniques and instruments is indicated.

A comparison of galaxy masses found via lens mass distributions, with Between 8 and 22 GHz, the resolution of ARISE will be a few tens to several hundred microarcseconds; this corresponds to image splitting by lens masses of $3\text{–}1000\times10^3M_\odot$, allowing an entirely new mass scale to be explored directly. The detection of compact objects in this mass range would be a spectacular result, but even a null result is of interest; a careful, multi-frequency survey of several hundred extragalactic radio sources with ARISE can limit the cosmological density of compact objects in this mass range to less than a few percent of the closure density of the Universe (Kassiola, Kovner, & Blandford 1991).

The relatively flat rotation curves seen in the outer parts of nearby galaxies strongly suggest that these galaxies are embedded within halos of dark, sub-luminous matter. With the sub-milliarcsecond resolution of ARISE, sub-structure in the halos may become observable as sub-milliarcsecond distortions in individual lensed images (Wambsganss & Paczynski 1992). This "granularity" within the lens will affect different images independently, since the radiation associated with each image encounters very different local conditions on its route through the lens galaxy. The expected distortions include further image splitting of the most compact radio emission and the presence of rings and holes in the more extended emission. Because of its high angular resolution, ARISE will be sensitive to sub-structure in lens galaxies having masses of 10^3–$10^6 M_\odot$.

4.2. Cosmology Using Distant AGN

Compact radio sources associated with AGN can act as cosmological "light-houses" which are visible anywhere in the Universe. This latter property makes them suitable objects for cosmological tests. If the compact radio source sizes are "standard rods," the observed dependence of apparent angular size as a function of redshift (the θ-z relation) can be used to constrain values of the deceleration parameter, q_0, as well as other cosmological quantities. While the background principles of using parsec-scale sources as cosmological standard rods are simple, a practical implementation of such tests faces serious difficulties, most of which are imposed by various selection and masking effects (e.g.. Wilkinson et al. 1998). In particular, two major characteristics, the angular resolution and VLBI imaging sensitivity, must be improved in order to make θ-z tests cosmologically conclusive.

As shown by Gurvits, Kellermann, & Frey (1999), a considerable number of sources remain unresolved with ground-based VLBI systems at ν = 5 GHz, particularly at cosmologically meaningful high redshifts (see Figure 27). An increase in angular resolution by a factor of 5 to 10 will eliminate the uncertainty arising from the unresolved radio structures, particularly at high redshifts. Furthermore, due to the flux density limitations of currently accessible VLBI samples, luminosities of low- and high-redshift sources available for θ-z tests are mismatched by several orders of magnitude, as shown in Figure 28. Although one can try to use such the luminosity-mismatched samples for cosmological tests, a much better result will be achieved by composing a luminosity-matched sample. To do so one needs to make VLBI images of AGN at higher redshifts ($z > 1$), with total flux densities 10–1000 times lower than those imaged to date (roughly at a level of $\sim$ 10 mJy and lower at centimeter wavelengths). Therefore, a useful contribution to the θ-z tests can be made by a VLBI system with angular resolution up to an order of magnitude higher than that of the global ground-based VLBI network, and with sensitivity about two orders of magnitude more sensitive than VSOP; both of these requirements will be met by ARISE.

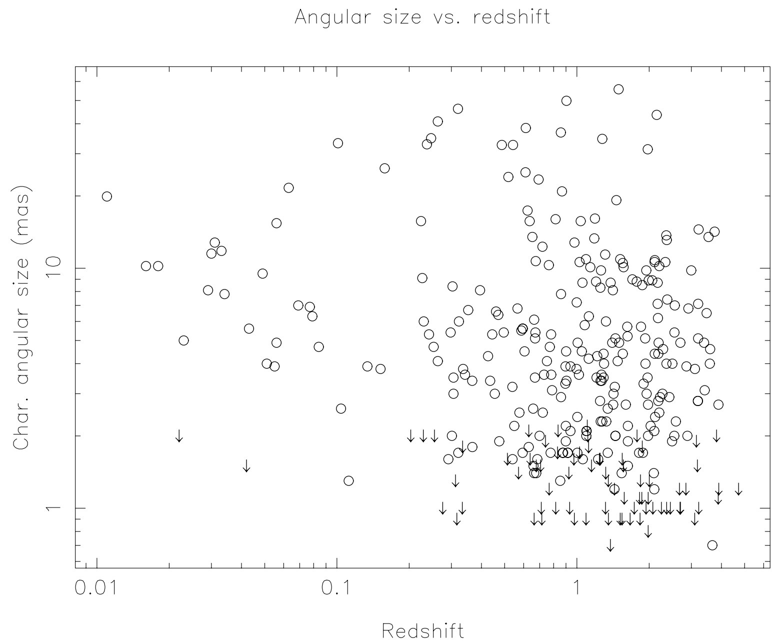

Fig. 27.— Measured angular size *vs.* redshift for a sample of 330 radio sources observed with ground VLBI. A large number of size upper limits exist for sources that cannot be resolved from the ground.

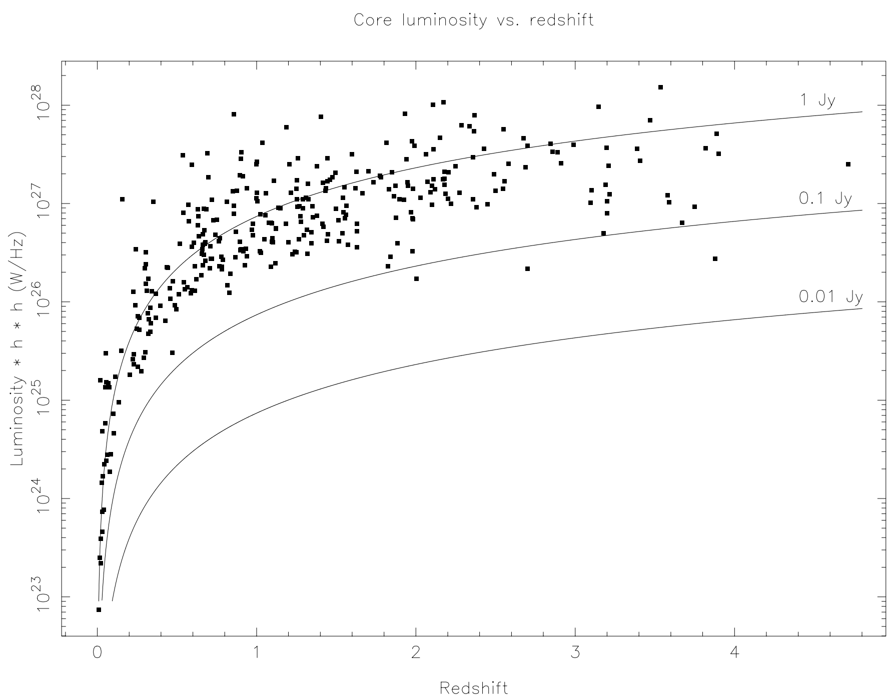

Fig. 28.— Radio luminosity as a function of redshift for the same sample of 330 radio sources that is plotted in Figure 27. The lack of low-luminosity sources at high redshift indicates a region of unexplored parameter space that will be investigated by ARISE.

5. Other Science Targets for ARISE

5.1. Stellar Coronae

The thermal radio emission from stars is far below the detection threshold of either ground or Space VLBI. However, many stars undergo energetic events that cause them to emit radio emission by nonthermal processes, raising their brightness temperatures into the range detectable by a Space VLBI mission such as ARISE. These phenomena are a direct analog of the flares and mass-ejection events that we see on our own Sun. However, for the other stars within our own Galaxy, the energetic phenomena are often unresolved on terrestrial VLBI baselines. At its lower frequencies, particularly at 8 GHz, ARISE will provide a combination of resolution and sensitivity that will address significant scientific questions regarding the events occurring in stellar coronae.

The evolution of coronal mass ejection events can be followed on a timescale of several hours by using snapshot imaging and phase referencing, should the latter technique be possible at the lowest ARISE frequencies. The 8-GHz resolution of about 150 μas corresponds to only 300,000 km for a star at 10 pc distance, less than 1/4 of the Sun's diameter. Therefore, the motion of the emission region can be resolved and followed over a region significantly smaller than a stellar radius. Producing the first images of mass-ejection events will provide a direct comparison to the Sun, giving new constraints on modeling of solar and stellar activity.

Many flaring stellar systems are binary stars. In these cases, the coronal radio emission can be related directly to the component stars and their magnetospheric structures. Figure 29 shows a VLBI radio map of the Algol binary star system, and the inferred location of the radio emission relative to the two stars (Mutel et al. 1998).

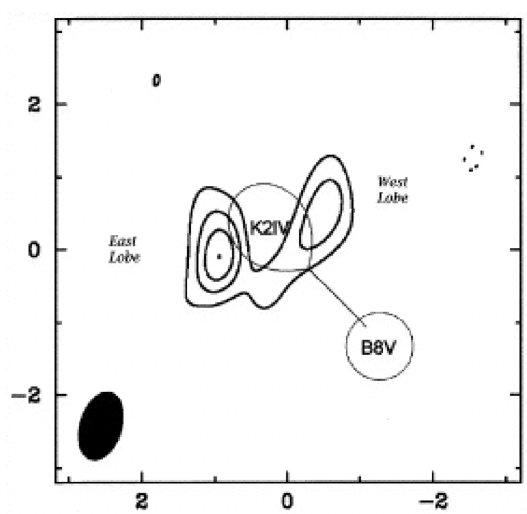

Fig. 29.— VLBA image of the radio emission from the corona of the Algol binary star system, over a scale of $\sim$ 2 mas. The orientation of the radio source and the binary star system are known, but the actual registration of the radio emission on the stellar system is conjectural.

Highly polarized stellar radio flares are often unresolved on terrestrial baselines, and are thought to result from a coherent emission process. This emission process is suggested by the presence of strong circular polarization, on the order of 20%, in some flaring objects. For these weak sources, only baselines using a space-based telescope can unambiguously probe brightness temperatures in excess of the limit of $\sim 5 \times 10^{11}$ K for incoherent synchrotron emission, allowing us to verify the coherent nature of these flares, and probe their plasma properties and motions in the stellar corona.

5.2. Gamma-Ray Bursters and Hypernovae

Gamma-Ray Bursters (GRBs) have been one of the greatest puzzles in astrophysics over the past decade, a puzzle that is now on the verge of being solved. Most GRBs appear to be at great distance and are unresolved in ground-based VLBI imaging at gigahertz frequencies; interstellar scintillation implies that their initial sizes are smaller than 10 μas (Frail et al. 1997; Taylor et al. 1997); a ground-based image of the burster GRB970508 is shown in Figure 30. These "garden-variety" GRBs typically have flux densities less than 1 mJy in their early stages, and will be accessible to a mission such as ARISE only on baselines to a very sensitive ground radio telescope, such as the nearly-completed Green Bank Telescope or the upgraded VLA.

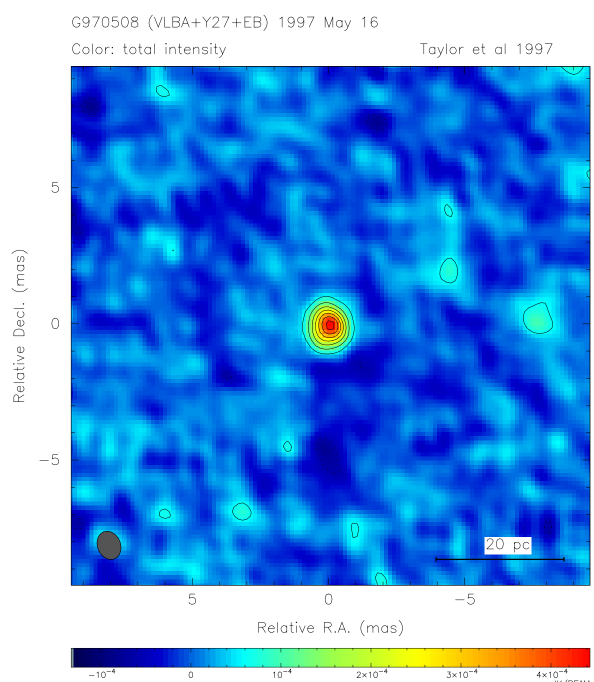

Fig. 30.— Ground VLBI image of the gamma-ray burster GRB970508 at 8 GHz, showing an unresolved source thought to be $\sim 10\ \mu$as in diameter.

There may be another, less common class of GRBs caused by extreme supernovae, or "hypernovae," such as GRB 980425 (Bloom et al. 1998; Kulkarni et al. 1998). This supernova had a peak flux density near 50 mJy at gigahertz frequencies and appears to have expanded relativistically, based on the lack of observed scintillation in the first few weeks after the supernova explosion. Thus, its size was in the vicinity of tens to hundreds of microarcseconds in the first two months after the explosion, perfect for imaging with ARISE. The origin of the gamma rays appears to be in the relativistic shocks generated by the supernova ejecta; models of the gamma-ray production will be greatly aided by resolution of the hypernova blast as soon as possible after the stellar explosion.

5.3. Supernovae

VLBI images of more common "classical" radio supernovae have been used to trace the expansion of the supernova shells in the first few years after their explosions (e.g., Rupen et al. 1998). A sequence of VLBI images of the expansion of Supernova 1993j in the spiral galaxy M81 is shown in Figure 31. Such images provide information about the expansion rate and deceleration, the distance to the host galaxy, and the density profiles of the ejecta and the circumstellar medium. At their peaks, the supernovae reach flux densities of tens of millijansky, easily accessible to ARISE. In general, they "break out" in the radio regime after they have expanded to a size of $\sim 10^{16}$ cm, which typically takes about a month. At a distance of 5 Mpc, this size corresponds to 130 μas, within reach of ARISE at 8 and 22 GHz, but not accessible to ground VLBI observations. In order to image the young supernovae at this early time at 8 GHz, a resolution nearer to 50 μas is desirable, implying an orbit altitude near 100,000 km. A sequence of observations at 1-wk intervals will enable the construction of a complete picture of its emergence from the "cocoon" generated by the progenitor star just before its death, allowing reconstruction of the rate and geometry of the mass loss of a star in its death throes.

Fig. 31.— Sequence of ground VLBI images of Supernova 1993j in M81, over several years, following its "breakout" in the radio regime. This source was not resolved until six months after the stellar explosion, but would have been resolved by ARISE at the initial onset of its radio emission.

5.4. Galactic Superluminal Sources

An important discovery of the last several years has been the emergence of a class of galactic superluminal radio sources (Rodriguez & Mirabel 1996). These objects, generally associated with black-hole X-ray (and soft-gamma-ray) sources in binary star systems in our own Galaxy, show physical phenomena similar to the more powerful extragalactic radio sources, including the ejection of relativistic jets with speeds very close to that of light. However, the motions in these objects are typically 5–50 mas per day, so Space VLBI will greatly over-resolve them; a ground image of the source GRO 1655−40 is shown in Figure 32. The main use of ARISE will be to image these sources during quiescent times, when their weak cores are not resolvable by ground-based VLBI. This requires extremely high sensitivity at 8 and 22 GHz.

Fig. 32.— Images of radio jet in the black-hole X-ray binary GRO 1655−40. ARISE would over-resolve the jet, but could be used to image the accretion disk surrounding the binary-star system.

5.5. Star-Forming Regions

Galactic star-formation regions exhibit maser emission from a wide variety of molecular species, such as H_2O, SiO, and methanol. The brightest masers typically are the H_2O masers at 22 GHz, which have brightness temperatures in the range of 10^{11}–10^{14} K, putting them well within reach of ARISE. In particular, there is a long history of observations of jets and outflows in a variety of wavebands in low-mass (roughly solar mass) star-formation regions. A beautiful example of the ground VLBI observations of such a region is shown in Figure 33, where the H_2O masers outline a bow shock on a scale of approximately 1 AU. At the distance of the Galactic Center, the typical speeds of 50 km s^{-1} for these masers correspond to a proper motion of 120 μas per month, about 1.5 times the nominal resolution of ARISE. In low-mass-star forming regions, the maser spots sometimes vary on quite short time scales; monitoring them more often than once per month may be necessary to connect the same spots at multiple epochs, but ground VLBI has inadequate resolution to measure the motions on such short time scales. ARISE, on the other hand, has a resolution well-matched to the studies of the low-mass-star formation regions throughout the Galaxy. In high-mass-star forming regions, maser spot lifetimes can be months and years. Space VLBI is suited to the measurement of proper motions in such regions in external galaxies, specifically in M33 and the Large Magellanic Cloud, and therefore to geometric distance determinations in these two systems. The conventionally measured distance to these two galaxies is important to calibration of many other extragalactic distance indicators.

In several young stellar objects the H_2O masers appear to trace a rotating circumstellar disk. A good example is provided by NGC 2071, where VLA measurements have indicated an apparent disk of radius ~ 50 mas (≈ 20 AU) whose plane is nearly perpendicular to the axis of the associated radio jet (Torrelles et al. 1998). In this case, ARISE will image structures that are a fraction $\sim 10^{-3}$ of the size of the maser-emitting region, which is about an order of magnitude better than the fractional resolution that can be achieved in images of megamaser disks in nearby AGN (see Section 3). This may enable studies of the internal structure of the individual maser spots. The observations of H_2O masers in star-forming regions, besides providing valuable clues to the structure of protoplanetary disks and stellar jets, thus will be useful also for guiding the study of maser-traced disks and outflows in AGN.

Fig. 33.— Young stellar object VLBA image.

5.6. SiO Masers in Evolved Stars

VLBI observations of SiO masers at 43 GHz in the immediate circumstellar environments of evolved stars such as Mira variables can provide direct imaging of the magnetic fields in their extended atmospheres (e.g., Kemball & Diamond 1997). Multi-epoch imaging (Figure 34) also shows the motions of the masers within the circumstellar shells as the stars pulsate, providing a unique picture of the entire cycle (e.g., Diamond & Kemball 1998). The stellar shells themselves are well resolved on the longest Earth baselines, and will be over-resolved by Space VLBI. However, the clean separation of maser spots by the higher Space VLBI resolution will make possible studies of the internal structure of individual maser spots, which will be a diagnostic for the small-scale shocks and turbulence that are believed to drive maser emission.

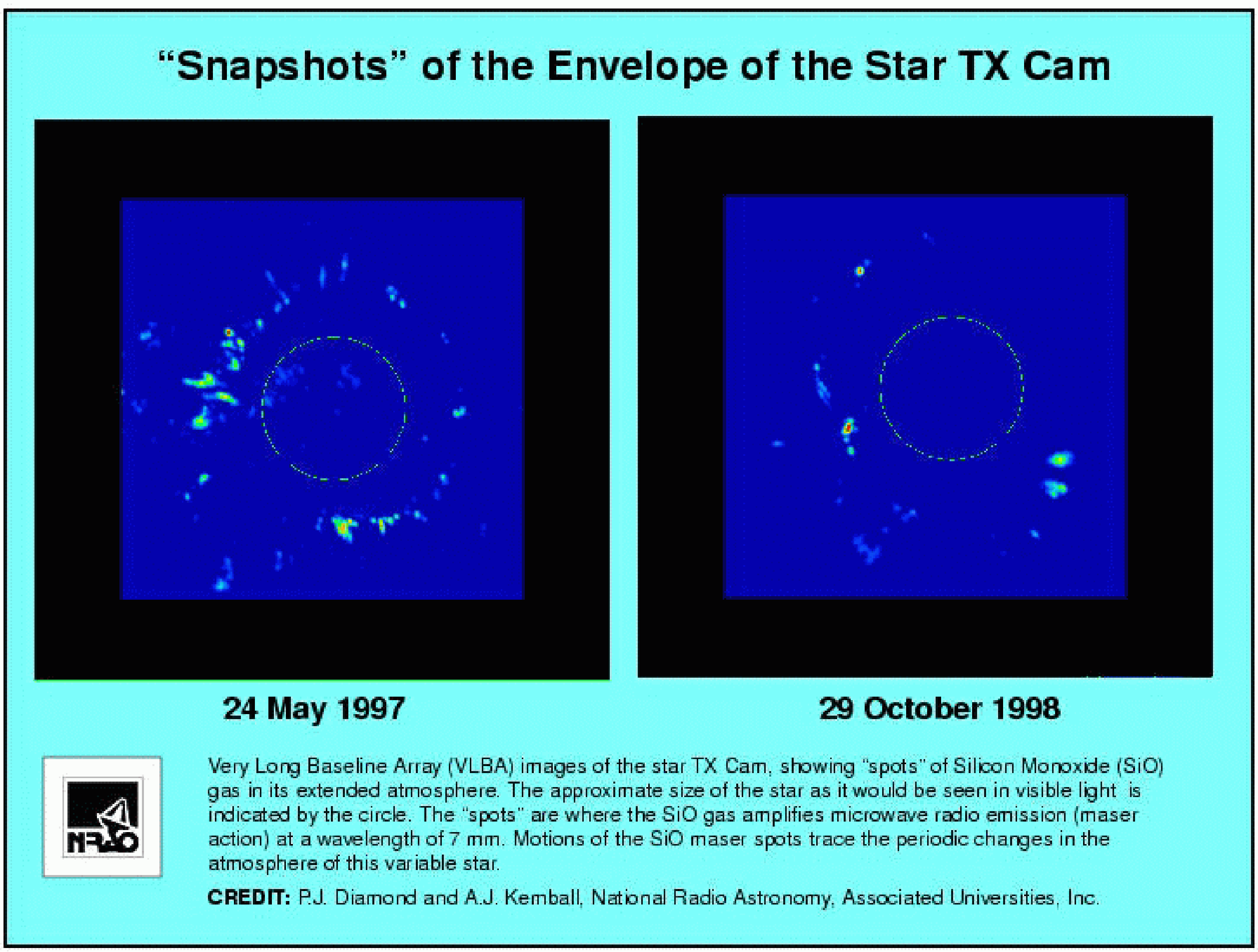

Fig. 34.— Two of many epochs of 43-GHz VLBA images of the SiO maser emission in the evolved star TX Cam. The inscribed circle gives the approximate location of the stellar photosphere.

6. What is ARISE?

6.1. What is Space VLBI?

As described in the Executive Summary, VLBI is a technique in which a compact radio source is simultaneously observed by an array of radio telescopes spread over a substantial fraction of the Earth's diameter. This enables synthesis of an aperture whose resolution is equal to a single telescope of a size equal to the longest spacing between individual antennas. Space VLBI is a modification of the VLBI technique in which at least one of the telescopes in the array is aboard a spacecraft orbiting the Earth; the longest baseline then can be somewhat longer than the apogee radius of the spacecraft orbit, enabling considerably higher resolution than that achievable with an Earth-bound VLBI array. Figure 7 in the Executive Summary nshows a conceptual drawing of the Space VLBI technique, which is described in much more detail by Ulvestad (1999).

The first dedicated Space VLBI mission, VSOP, began operation with the launch of the HALCA (High Altitude Laboratory for Communications and Astronomy) spacecraft in February 1997. HALCA carries an 8-meter radio telescope in space, to an apogee height of over 21,000 km, for the purpose of making VLBI observations in conjunction with networks of ground radio telescopes. The VSOP mission has demonstrated the capability of enhancing the resolution of the VLBI technique over that available with Earth-bound radio telescopes, by making frequent observations leading to images of radio sources at 1.6 and 5 GHz. Further details about VSOP can be found in Hirabayashi et al. (1998).

ARISE is conceived as a successor to VSOP that extends its capability by more than an order of magnitude in resolution, frequency coverage, and sensitivity. The ARISE mission is currently one of the candidates specified in the long-term roadmap of the Structure and Evolution of the Universe theme within NASA. A 25-meter radio telescope would be launched in approximately 2008, into an orbit with an apogee height of at least 40,000 km. The spacecraft will carry cooled receivers and have observing capability at frequencies ranging from 8 to 86 GHz. Therefore, ARISE can be thought of in many regards as a spaceborne extension of the VLBA (Napier et al. 1994), the world's only dedicated VLBI array. At the highest frequency, the angular resolution will be 15 μas or better, corresponding to the diameter of the event horizon of a $10^9 M_\odot$ black hole at the distance of Centaurus A, or to 2 light months for an AGN at a distance of 10^9 pc. Details of the ARISE mission concept have evolved to their current form over the last several years, based on scientific and technical discussions in the astronomical and engineering communities; that evolution can be seen in a number of publications (e.g., Gurvits, Ulvestad, & Linfield 1996; Ulvestad, Gurvits, & Linfield 1997; Ulvestad & Linfield 1998).

6.2. ARISE Frequency Coverage

The primary reason to launch a Space VLBI radio telescope far above the Earth is to enhance the resolution over that achievable with ground VLBI arrays. The orbiting telescope must observe at frequencies that are within the Earth's atmospheric window, because ground telescopes must observe simultaneously in order to form the necessary VLBI baselines. Since the finest resolution achievable depends linearly on the ratio of the observing wavelength to the size of the longest baseline, it is therefore sensible to develop a space telescope that observes at the shortest radio wavelengths (highest frequencies) also visible from the ground. For this reason, the 43- and 86-GHz frequencies have been selected for ARISE. The critical spectral line from compact objects is the H_2O line at 22.235 GHz, so a 22-GHz receiver also is included. Finally, to address the scientific issues that can be attacked with the highest possible VLBI sensitivity, it is desirable to have the spacecraft operate at the most sensitive VLBI frequency available on the ground, leading to a decision to put an 8-GHz receiver on board ARISE. Similar sensitivity is available at 5 GHz, and including this frequency aboard the spacecraft is still an option if mass and volume permit.

6.3. ARISE Sensitivity

As in any astronomical instrument, the highest possible sensitivity is desired. For radio telescopes, the sensitivity of an individual telescope often is expressed as the "System Equivalent Flux Density" (SEFD):

$$\mathrm{SEFD} = k_B T_{\mathrm{sys}} / 2A_e \ , \tag{1}$$

where A_e is the effective area of the radio telescope, T_{sys} is the system temperature, and k_B is Boltzmann's constant. The r.m.s. noise for the baseline between a ground telescope (g) and ARISE (A) is then given by

$$\Delta S_{gA} \ = \ \frac{\sqrt{\mathrm{SEFD}_g \ \mathrm{SEFD}_A}}{C\eta\sqrt{2 \ \Delta\nu \ \tau_{\mathrm{acc}}}} \ . \tag{2}$$

Here, C is the coherence in the accumulation time τ_{acc}, $\Delta\nu$ is the bandwidth, and η is an efficiency factor ($\eta = 0.88$ for the VLBA correlator and 2-bit sampling). Normally, the detection threshold for interference "fringes" is given by

$$S_{\mathrm{min}} \approx 7\Delta S_{gA} \ . \tag{3}$$

The astrophysical goals discussed in this document lead to a desire for fringe-detection thresholds in the 1–10 mJy range for continuum radio sources at the frequencies between 8 and 43 GHz. At 86 GHz, ARISE will predominantly observe strong, core-dominated radio sources ("blazars") with typical unresolved cores of $\sim$ 1 Jy. This fact (and the necessary limits related to declining telescope efficiencies, increasing system temperatures, and decreasing integration times) leads to a goal of 100 mJy for the fringe-detection threshold at 86 GHz. Finally, for spectral-line observations at 22 GHz, the observations of H_2O megamasers lead to a desired detection threshold near 100 mJy for a 1-km-s^{-1} spectral line.

Table 5. ARISE Fringe-Detection on Baseline to 1 VLBA Telescope

Parameter	8 GHz	22 GHz	43 GHz	86 GHz
ARISE Diameter	25 m	25 m	25 m	25 m
ARISE Efficiency	0.5	0.38	0.24	0.08
ARISE $T_{\rm sys}$	12 K	16 K	24 K	45 K
ARISE SEFD	130 Jy	240 Jy	560 Jy	3200 Jy
VLBA Diameter	25 m	25 m	25 m	25 m
VLBA Efficiency	0.72	0.52	0.36	0.15
VLBA $T_{\rm sys}$	30 K	60 K	80 K	100 K
VLBA SEFD	230 Jy	650 Jy	1250 Jy	3750 Jy
Coherence Time ($C = 0.9$)	350 sec	150 sec	60 sec	15 sec
Data Rate	4 Gbit sec^{-1}	8 Gbit sec^{-1}	8 Gbit sec^{-1}	8 Gbit sec^{-1}
Continuum Threshold $S_{\rm min}$	1.9 mJy	4.5 mJy	15 mJy	120 mJy
Image r.m.s. in 8 hr	$\sim$ 35 μJy/beam	$\sim$ 50 μJy/beam	$\sim$ 100 μJy/beam	$\sim$ 400 μJy/beam
Line (1 km s^{-1}) Threshold	0.2 Jy/ch	0.5 Jy/ch	1.3 Jy/ch	7.0 Jy/ch

Tables 5 and 6 summarize the detection thresholds for continuum and spectral-line observations on baselines to a single 25-meter VLBA telescope and to the 100-meter Green Bank Telescope (GBT); Figure 35 shows the continuum thresholds graphically, as a function of observing frequency.[5] The continuum image noise is estimated based simply on the number of baselines and integration time; the quoted values may not be achievable in total-intensity images of strong sources due to dynamic-range limitations. However, noise-limited imaging in polarized flux will provide measurements of very weakly polarized components in the VLBI cores and jets. For spectral-line sensitivities, line widths and channel widths of 1 km sec^{-1} are assumed; the sensitivities can be scaled with the square root of the channel width for wider or narrower lines. These line sensitivities include an extra factor of $\sqrt{2}$ reduction in the single-channel noise due to the use of dual-polarization observations.

For an array of N similar ground antennas such as the VLBA, the minimum detectable flux density may be reduced by a factor somewhat less than $\sqrt{N}$ (but more than unity!) by using the technique of global fringe-fitting, which has been shown to give a factor of 1.5–2 improvement for VSOP. In addition, it may be possible to increase the effective coherent integration time by using a variety of techniques to calibrate the atmosphere above the ground telescopes (e.g., phase referencing or water vapor radiometry). Therefore, the detection thresholds listed in Tables 4 and 5 are likely to be rather conservative estimates.

[5]The GBT is scheduled for completion in 1999, with 86-GHz operation planned well before the earliest ARISE launch date, and the VLBA is expected to be completely equipped at 86 GHz well before the ARISE launch.

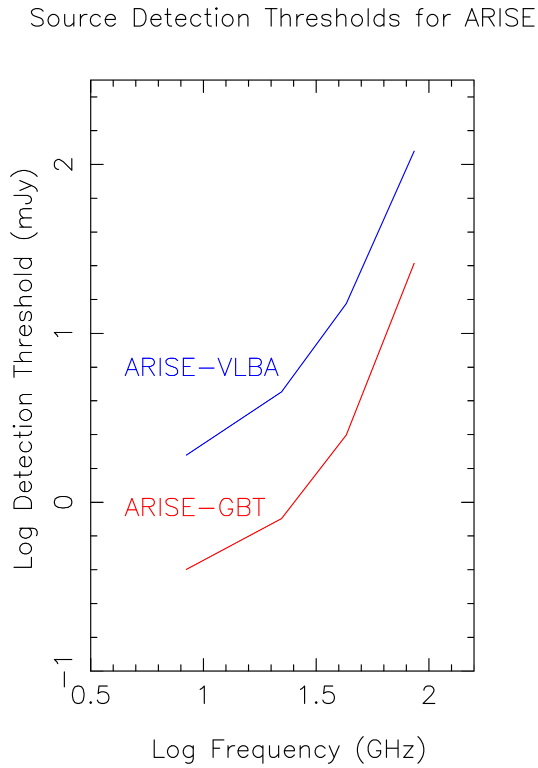

Fig. 35.— Continuum fringe-detection threshold for ARISE, as a function of observing frequency, using either a single VLBA antenna or the Green Bank Telescope as the ground element of the space-ground interferometer.

Table 6. ARISE Fringe-Detection on Baseline to GBT

Parameter	8 GHz	22 GHz	43 GHz	86 GHz
ARISE Diameter	25 m	25 m	25 m	25 m
ARISE Efficiency	0.5	0.38	0.24	0.08
ARISE $T_{\rm sys}$	12 K	16 K	24 K	45 K
ARISE SEFD	130 Jy	240 Jy	560 Jy	3200 Jy
GBT Diameter	100 m	100 m	100 m	100 m
GBT Efficiency	0.70	0.65	0.50	0.20
GBT $T_{\rm sys}$	25 K	38 K	60 K	100 K
GBT SEFD	13 Jy	21 Jy	36 Jy	175 Jy
Coherence Time ($C = 0.9$)	350 sec	150 sec	60 sec	15 sec
Data Rate	4 Gbit sec^{-1}	8 Gbit sec^{-1}	8 Gbit sec^{-1}	8 Gbit sec^{-1}
Continuum Threshold, $S_{\rm min}$	0.4 mJy	0.8 mJy	2.5 mJy	26 mJy
Line (1 km s^{-1}) Threshold	0.04 Jy/ch	0.07 Jy/ch	0.2 Jy/ch	1.6 Jy/ch

6.4. ARISE Orbit Selection

It is necessary to have a longest baseline of at least 50,000 km in order to achieve the desired resolutions of ≤ 15 μas for blazar observations at 86 GHz, and ≤ 60 μas for 22-GHz imaging of H_2O megamasers in nearby AGN. Higher orbits produce better resolution, but at the expense of imaging fidelity, due to large "holes" in the synthesized aperture of the interferometer. The nominal choice for the ARISE apogee height, 40,000 km, will produce a maximum baseline length of 50,000 km, and is a compromise between resolution and imaging fidelity. A final orbit selection will be made later in the evolution of the project, according to the scientific and technical information available at that time.

The orientation of the orbit plane determines the direction of the sources for which the best imaging can be done; the best two-dimensional imaging capability will occur for objects that are located in directions close to the normal to that orbit plane. It is desirable to observe sources in a wide range of directions during the mission lifetime of 3–5 yr, which can be enabled if the orbit plane precesses significantly during that time. At the nominal apogee height of 40,000 km and an inclination of 30° with respect to the Earth's equator, the orbit plane and the location of perigee both will precess with periods of a few years if the perigee height is below about 2000 km. If a larger apogee height is ultimately selected, a perigee height of ~ 1000 km is required in order to produce the desired precession.

6.5. ARISE Brightness Temperature Sensitivity

A Space VLBI mission such as ARISE is well-suited to probe regions of intense, compact, radio emission generated by nonthermal processes, rather than thermal emission from objects such as stars and gas clouds. The intensity of compact emission often is characterized by its brightness temperature (T_b), where the brightness temperature is defined as the temperature of a thermal body that would emit an equal amount of radiation from the observed area. The sensitivity to sources of a given brightness temperature depends both on the flux-density limit (see Section 6.3) and the telescope separation (and resolution) created by the orbit (see Section 6.4). Using the Rayleigh-Jeans approximation to Planck's blackbody law, the brightness temperature thus is defined as

$$T_b \;=\; \frac{S\ c^2}{2k_B\nu^2\theta^2}\ , \tag{4}$$

where S is the source flux density and θ the angular size of the source. If S_J is S in units of jansky, ν_9 is ν in units of 10^9 Hz, and θ_1 and θ_2 are the full widths at half maximum (in milliarcseconds) of the intensity for an elliptical Gaussian source model, the observed brightness temperature of that source can be written as

$$T_b \;=\; 1.2\times 10^{12}\ \mathrm{K}\ \frac{S_J}{{\nu_9}^2\ \theta_1\ \theta_2}\ . \tag{5}$$

For an AGN at redshift z, the brightness temperature in the source rest frame is higher by a factor of $(1 + z)$, at a rest frequency a factor of $(1 + z)$ higher than the observed frequency.

The upper limit to the intrinsic brightness temperature, due to inverse Compton losses for an incoherent synchrotron source that is not relativistically beamed, is $\sim 5 \times 10^{11}$ K. Since source brightness temperatures in excess of 10^{13} K have been inferred from the variability time scales of intra-day variable sources, it is desirable for ARISE to have the capability of measuring such high values of T_b. Brightness temperatures of $\gtrsim 10^{13}$ K can be measured directly at all the ARISE frequencies, provided the projected baseline length is at least 40,000 km. The minimum detectable brightness temperature between ARISE and a single VLBA antenna is approximately 10^{10} K. However, if a large telescope such as the Green Bank Telescope or the upgraded VLA is included, this threshold will be reduced by another factor of 4 or more. With some form of tropospheric calibration, the detection threshold can be reduced below 10^9 K, which will open up a whole set of radio-weak active galactic nuclei for observation. At the lower frequencies, using telescopes of the European VLBI Network (EVN), which tend to be larger than the VLBA antennas, also will be of great benefit in reducing the lower limit to the brightness temperature.

One of the mission requirements is to be able to detect at least ~ 100 blazars at 86 GHz on a baseline to a VLBA telescope. Figure 36 shows the estimated number of detectable blazars at 86 GHz as a function of the data rate for the space and ground telescopes, for observed brightness temperatures of 5×10^{11} K and 1×10^{12} K.[6] The blazar brightness temperatures are enhanced above the inverse Compton limit by relativistic beaming, and are typically $\gtrsim 1 \times 10^{12}$ K in the source frame (or $\gtrsim 5 \times 10^{11}$ K in the observer's frame). Therefore, Figure 36 indicates that the data rate required to detect ~ 100 blazars at 86 GHz is either 4 or 8 Gbit sec^{-1}, depending on the exact assumptions that are made.

[6]Observed brightness temperatures are used in Figure 36; for an object at a redshift of $z = 1$, the brightness temperature in the source's co-moving frame is twice as high as the value we observe.

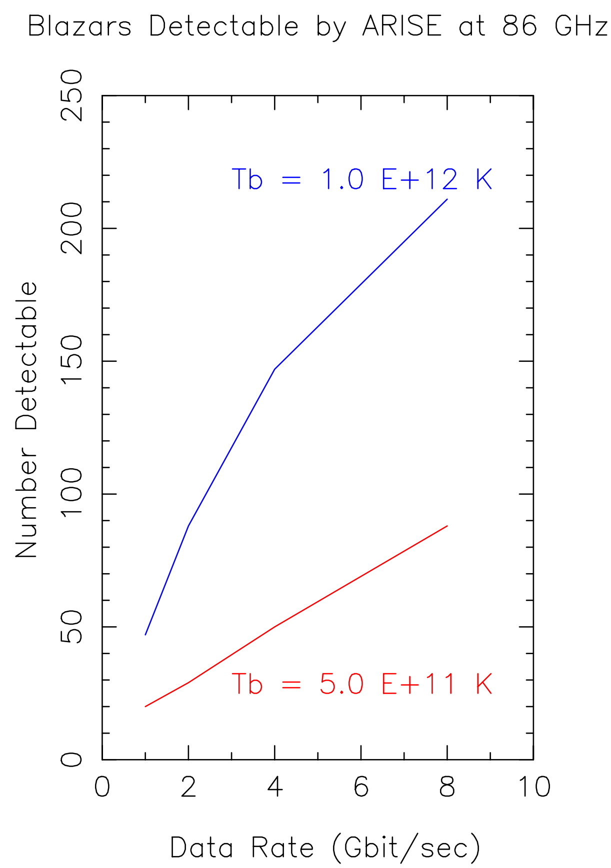

Fig. 36.— Estimated number of blazars detectable at 86-GHz on an ARISE-VLBA baseline, as a function of data rate, for two different values of the observed brightness temperatures.

6.6. ARISE Spacecraft and Mission Design

The design of the ARISE spacecraft has focused on satisfaction of the key science goals, as described previously. This section summarizes the key points of that design that are related to the VLBI observing system; many more details of the strawman design can be found in Chmielewski et al. (1999).

After extensive consideration of the possibilities, an offset Gregorian design was settled on for the orbiting radio telescope. The Gregorian system offers less blockage of the spacecraft and solar arrays by the large radio telescope, and provides the possibility of a simple correcting subreflector, at the expense of increased solar torques due to the asymmetric design. This tradeoff will continue to be reviewed carefully during future development of the more detailed spacecraft design.

The current design has provision for array feeds at the higher frequencies of 43 and 86 GHz, as well as a simple mechanically deformable subreflector, in case the primary antenna surface alone does not provide adequate performance at these frequencies. The low-noise amplifiers will be similar to those developed for the Microwave Anisotropy Probe (scheduled for launch in 2000). They will be cooled to ambient temperatures of 20 K, using the same technologies that will be used in the Planck and FIRST missions, enabling receiver noise temperatures of a factor of 3–5 times the quantum limit. Since the system noise will not be affected by ground and atmospheric pickup as is the case for ground radio telescopes, the receiver noise will be a much larger fraction of the total system temperature, and the space antenna can be considerably more sensitive than a comparable ground telescope.

Accurate timing is needed for any VLBI telescope, in space or on the ground. The on-board time and frequency reference will be generated by means of a reference tone sent from a ground tracking station; that tone will be transponded back to the ground, and measurement of the two-way Doppler shift will be used to correct time tags at the VLBI correlator. Spaceborne hydrogen-maser frequency standards will be thoroughly demonstrated before ARISE launch, but are not currently in the baseline plan, since VSOP has demonstrated very high coherence for the time transfer link between a tracking station and a Space VLBI satellite.

Orbit determination with an accuracy of tens of meters is adequate for VLBI correlation and provides coherence times at least as good as the limits placed on ground telescopes by atmospheric propagation effects. However, much more precise orbit determination offers the possibility of extending the coherent integration times and improving the sensitivity threshold, provided the propagation effects for the ground radio telescopes can be calibrated. A Global Positioning Satellite receiver will be flown aboard ARISE; studies show that a reconstructed orbit accuracy of better than 10 cm can be accomplished for orbits as high as 50,000 km, with degradation by less than a factor of two for higher orbits. This will be sufficient for coherence times up to an hour; longer coherent integrations would not be feasible because of the rapid changes in the synthesized aperture due to the spacecraft's orbital motion.

The wideband data link to the ground, up to 8 Gbit s^{-1}, will be achieved by radio-frequency transmission in the 37–38 GHz band. Use of dual polarization and advanced data modulation techniques will enable the high data rate to be downlinked in this 1-GHz band. Optical communication techniques are currently being considered as a backup possibility, but are not envisioned as the baseline system because of the current immaturity of the technology and infrastructure for their use.

Data recording and correlation systems are important aspects of the ARISE system; recorders having data rates up to 8 Gbit s^{-1} are required not only for the spacecraft tracking stations, but for every participating ground radio telescope. The current Mark 4 VLBI system is capable of recording 1 Gbit s^{-1} with expansion to 2 Gbit s^{-1}, but requires frequent tape changes at that high rate. An alternative candidate for data recording is the more advanced version of the 128 Mbit s^{-1} S2 system developed in Canada in the 1990s; a straightforward development path is seen for the

S3 and S4 systems, which would provide up to 4 Gbit s^{-1} by roughly 2005. The latter systems offer the distinct advantage that they are based on commercial, front-loading cassette recorders, which should easily lend themselves to robotic tape-changing, thus lowering operations costs for large arrays of ground antennas.

6.7. Unique Attributes of ARISE

A number of other sensitive radio telescopes are in operation or under active development. The Very Large Array (current or upgraded) and the Millimeter Array are connected-element interferometers that study problems related to stars and star formation, starburst galaxies, and large-scale phenomena related to AGN. They are very useful ground radio telescopes for the "other end" of baselines to ARISE, because of their high sensitivity; as stand-alone instruments, they explore completely different types of science at much lower resolution. The crucial ground VLBI telescopes are the EVN and the VLBA. Because Europe is rather smaller than North America, and most of the EVN telescopes operate only at frequencies up to 22 GHz, the resolution of the EVN is a factor of ~ 20 poorer than ARISE, while the resolution of the VLBA or of an intercontinental array using both the VLBA and EVN telescopes is a factor of 6–8 poorer. As described in the detailed science discussion, the highest resolution and highest frequencies are crucial to the primary scientific goals of ARISE, and cannot be achieved with any ground array now or in the foreseeable future. However, the ground telescopes in both VLBI arrays are critical components of the ARISE mission, in that they will form the other end of all the ground-space baselines and help fill in the aperture plane. In addition, they will provide an enormous amount of infrastructure on which ARISE can build during its development and operation.

Radio telescopes that are not yet approved include the Square Kilometer Array (SKA) and the VSOP-2 Space VLBI mission. The SKA will be a very sensitive telescope if it is built, but there is not yet an agreed-upon concept for this telescope, and it is clear that operation at frequencies higher than a few gigahertz will be difficult and extremely expensive. If it is built, with a large patch of the telescope in a single location, it will be a useful adjunct to ARISE at its lowest frequency. However, it seems unlikely that the SKA will be built until well after 2010. The VSOP-2 mission is likely to be launched in the 2007 time frame, and will consist of a 10-meter telescope operating up to 22 (or possibly 43) GHz, with a data rate of 1 Gbit s^{-1} and an apogee altitude of 20,000 km. Thus, its resolution will be about a factor of 6–10 poorer than ARISE obtains at 86 GHz, and 2–5 times poorer at the same frequenciesr; the sensitivity of VSOP-2 also will be about an order of magnitude less. Therefore, VSOP-2 will be unable to address the key science goals of ARISE, since it will have neither the resolution nor the high frequencies necessary to image the gamma-ray-emission regions in blazars, and also will not have the sensitivity for imaging of extragalactic H_2O megamasers. However, if VSOP-2 and ARISE operate concurrently for part of their lifetimes, the aperture-plane coverage and image fidelity for observations at the lower ARISE frequencies will be enhanced for projects requiring resolution intermediate between

Earth-only and Earth-ARISE arrays on moderately strong radio sources.

There are a number of other planned or proposed telescopes that would investigate some of the same types of astrophysical problems as ARISE. For instance, the Next Generation Space Telescope (like HST) can image the outer parts of the disks surrounding massive black holes in nearby galaxies, but the resolution several orders of magnitude poorer than ARISE would not enable these telescopes to approach the Schwarzschild radii of the black holes. Gamma-ray telescopes such as GLAST will provide extremely important information on blazars, including the time scale of variability (which reflect the critical size scales and physical properties of the inner jets) and the distribution of gamma-ray luminosities. Launch of ARISE during the lifetime of GLAST will enable contemporaneous VLBI and gamma-ray observations of blazars, so that the VLBI imaging can give an actual picture of the region where the gamma-ray emission is occurring. The motions of the actual gamma-ray-emitting regions also can be measured directly by ARISE. Even non-simultaneous observations can make an important contribution, although the deductions would be more statistical in nature. X-ray imaging or spectroscopy missions (e.g., Astro-E and Constellation-X) also can provide information about the plasma near massive black holes, or in the inner accretion disks surrounding them. However, once again, only ARISE can provide true images of these regions rather than inferences based on information such as variability time scales.

6.8. ARISE Technology Development and Readiness

Still needs writing

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For copies of the above documents, or for other information about ARISE, please contact James Ulvestad (julvesta@nrao.edu, 505-835-7298) or Artur Chmielewski (abc@jpl.nasa.gov, 818-354-0255).

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