Galaxies and Their Constituents at the Highest Angular Resolutions
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The VSOP Project: Space VLBI Imaging of AGN at 1.6 and 5 GHz

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Abstract. The VLBI Space Observatory Programme (VSOP) combines an orbiting radiotelescope with arrays of ground radio telescopes to extend the Very Long Baseline Interferometry (VLBI) technique to baselines up to almost three Earth diameters. In this paper, we present results from VSOP observations of active galactic nuclei (AGN) at 1.6 and 5 GHz from the first 3.5 years of the mission.

1. The VSOP misson

The VSOP mission started from the launch of the HALCA (Highly Advanced Laboratory for Communications and Astronomy) satellite on February 12, 1997. Observations started in May 1997, and were soon followed by the detection of the first fringes between HALCA and ground radio-telescopes. Although HALCA has experienced some troubles (such as the low gain of 22 GHz receiver and failure of one reaction wheel), VSOP observations have continued for well over three years. It is expected that the solar battery power, which was thought would be the deciding factor in HALCA's lifetime, is sufficient to continue observing for 2–3 more years (Murata et al. 2000). If there are no unexpected on-board failures, Space VLBI observations will be able to continue for at least the nominal 5 year mission lifetime.

The VLBI Space Observatory Programme is a very international mission (Hirabayashi et al. 1998, 2000a). The HALCA satellite was built and launched in Japan, and is supported by five tracking stations and one commanding station in four countries, three correlators in three countries, and 32 telescopes in 14 countries! Thanks to the efforts of those operating these many critical elements, a wealth of scientific results have been possible from VSOP observations. Proceedings from the COSPAR meeting in July 1998, and VSOP Symposium in January 2000 illustrate the variety of science being undertaken with VSOP observations. We focus here on VSOP observations of active galactic nuclei.

2. VSOP and HALCA properties

HALCA is effectively an 8 m diameter antenna in an orbit with a 21400 km apogee height and 560 km perigee height. It has three observing bands: from 1.60–1.73 GHz (L-band), 4.7–5.0 GHz (C-band) and 22.0–22.3 GHz (K-band). The 22 GHz band was found after launch to have an unexpectedly low gain and so is not used for routine scientific observing. The 1.6 and 5.0 GHz bands have typical system noise temperatures of 75±30 K and 95±30 K, respectively (Kobayashi et al. 2000).

Baseline sensitivities of 80 mJy at L-band and 100 mJy at C band are achievable, for a 7σ detection with a VLBA 25 m antenna. Typical resolutions for VSOP observations at 1.6 and 5.0 GHz are 0.75 mas and 0.25 mas, respectively. The 5.0 GHz band resolution is almost equivalent with that for 15 GHz observations with the VLBA. Thus we can study the appearance of astronomical objects with similar resolutions at two different frequencies and can determine the spectral index variation over the source. Such observations are a powerful tool to understanding the physical properties of the source observed.

3. Scientific Results

3.1. Polarization Observation

Although HALCA has only one polarization receiver system (LCP only), with dual polarisation ground observations VSOP can make polarisation observations to make high resolution studies of spatial variations in magnetic field structures. VSOP polarization observations (Gabuzda, 1999) revealed a twisted jet in the AGN 1803+784, with the magnetic field remaining perpendicular to the jet direction all along the bent structure. A detailed study of VSOP polarization observations is made in Kemball et al. (2000).

3.2. Monitoring Observation

Multi-epoch observations have been made of a number of key sources. For most sources, however, because of HALCA's sun-angle constraints, there are periods when observations are not possible. However, sources near the ecliptic poles are visible all year round and so can be monitored at regular intervals. An example is 1928+783, for which changes in the milli-arcsecond–scale structure have been studied by Murphy et al. (2000).

3.3. High Linear Resolution Studies

For low redshift sources, VSOP's high angular resolution translates into high linear resolution. For M87, the VSOP beam at 5 GHz is ~300 times the Schwarzschild radius of the super-massive black hole revealed by HST spectral studies. VSOP observations of M87 are enabling quantitative studies of how jet sub-structure evolves with time. The first VSOP image at 1.6 GHz showed a helical structure (Reid et al. 2000). A more recent, higher sensitivity, 1.6 GHz observation made in March 2000 (Reid et al. private communication) shows limb-brightened structure of the jet. VSOP monitoring observations at 5 GHz do not show the $6c$ movement which is seen in the outer jets by the HST (Junor et al. 2000).

3.4. Spectral Index Mapping and Free-Free Absorption

VSOP has the same resolution as ground VLBI with three times higher frequency. Spectral mapping with matched resolution allows information on the optical thickness, spectral aging, etc. to be determined. The sources studied with this technique include 3C 279 (Piner et al. 2000), 3C 84 (Asada et al. 2000) and Mkn 501 (Edwards et al. 2000).

Free-free absorption of radiation from the counter-jet of NGC 4261 in the sub-parsec accretion disk was clearly seen with the use of a 4.9 GHz VSOP image and ground-based VLBI images (Jones et al. 2000). Similar studies have been made of a number of GPS sources also (Snellen et al. 2000; Kameno et al. 2000a, 2000b, Sutou et al. 2000).

3.5. X-ray Jets

The synchrotron photons at radio wavelengths are intimately related to X- and gamma-rays by the inverse-Compton effect. A second-epoch VSOP observation of PKS 0637−752 was made in August 1999, coordinated with a calibration observation of the just-launched Chandra satellite. The Chandra observation revealed an X-ray jet consistent with the ATCA radio images (Schwartz et al. 2000). The VSOP observations were used to establish an $\sim 11c$ super-luminal motion in the parsec-scale jet, placing strong constraints on the angle between the parsec-scale jet and our line of sight to the quasar (Tingay et al. 2000, Lovell et al. 2000).

3.6. Quasars at High Redshift

Imaging of high-redshift quasars at the VSOP frequencies of 1.6 and 5 GHz enables their milli-arcsecond radio structures to be studied at emitted frequencies of 6.5–8.0 and 20–27 GHz respectively. Over 20 VSOP observations of high-z quasars have been conducted to date. Highlights include the detection of extremely violent bending in the quasar 1351-017 (z=3.71) and the discovery of the most distant rich "core-jet" structure in the quasar 2215+020 at z=3.55 (Gurvits et al. 2000).

3.7. High Brightness Temperature Sources

There is a brightness temperature limit of $\sim 10^{12}$ K for incoherent synchrotron emission in the rest frame of the emitting plasma due to inverse Compton scattering loss of the emitting particles (Kellermann and Pauliny-Toth 1969). The brightness temperature observed in our reference frame differs from its value in the emitted frame by the factor $\delta/(1+z)$, where δ is the Doppler factor of the component in the rest frame of the radio source core. VSOP is a unique instrument for the measurement of brightness temperature, as the brightness temperature is directly proportional to the maximum baseline length sampled in the observation. Brightness temperatures in excess of 10^{12} K have been measured for a number of sources implying large Doppler boosting factors for material in the jets (e.g., Bower & Backer 1998, Shen et al. 1999, Preston et al. 2000).

3.8. The VSOP Survey Program

The VSOP Survey Program is providing a large complete sample of homogeneous data on the sub-milli-arcsecond radio structures of 289 AGN, which is essential for studying cosmology and statistics of AGN, planning future VLBI observations, and for designing future Space VLBI missions (Hirabayashi et al. 2000b).

4. Summary and the Future

VSOP observations have produced the highest resolution 5 and 1.6 GHz images, advancing our understanding of AGN on a number of fronts. Space VLBI observations at 22 GHz and higher frequencies with the future missions hold a great deal of promise.

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