Astrophysical Phenomena Revealed by Space VLBI
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Masers from Space: A Review and a Preview of Space VLBI Maser Observations

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Abstract

A review is presented of the current state of spectral line observations performed with VSOP. The historical context is discussed and the limitations due to sensitivity, intrinsic size and the effects of interstellar scattering are described. A preview of what might be possible with proposed future space VLBI missions, VSOP-2 and ARISE, is also presented. The principal conclusions are that SiO masers are probably not a viable target due to their intrinsic sizes but that H_2O megamasers and H_2O masers in regions of star formation will be a prime target for the future.

1 Introduction

Prior to the launch of HALCA, there was much excitement at the prospect of space VLBI observations of maser sources. Unlike continuum interferometry, the fixed observing frequency of a line limits the resolution possible with ground-based VLBI. The only way to increase the spatial resolution is to fly a radio telescope. HALCA is equipped with three receivers; it is useful to examine what molecular masers or absorption lines might have been detected with those systems.

HALCA's L-band receiver can observe between 1.60 and 1.73 GHz, this means that all four ground-state transitions of OH can be observed. Such masers are to be found in regions of star formation (SFR), circumstellar envelopes (CSE), in the shock-excited regions around supernova remnants (SNR), in the thin atmospheres of comets and as megamasers in the inner regions of other galaxies. OH is also seen in absorption towards the nuclei of active galactic nuclei.

The C-band system covers the frequency range 4.7 to 5.0 GHz. Maser emission also exists in this band; Jy-level excited-state OH masers and H_2CO are observed in SFR, both molecules are also observed in absorption against the continuum emission of some galaxies. Potentially, the K-band system at 22 GHz had the greatest prospects of yielding new and exciting results since strong, compact masers are known to exist in SFR, CSE and the nuclei of galaxies. Unfortunately, as we are all aware, the K-band system was damaged, possibly through vibration during the launch and was rendered almost inoperable.

Although there are many possible types of maser accessible to HALCA, observations of the sometimes weak emission are not possible due to the severe sensitivity limitations imposed by the constraints of the spacecraft. Table 1 lists the pre-launch estimates of the 7σ noise in a 1 minute integration for each observing band on a HALCA-VLBA baseline, apart from the degradation of the K-band system these estimates were remarkably accurate.

Table 1: Pre-launch estimates of 7σ noise in 1 minute integration on HALCA-VLBA 25m baseline.

Observing band	16 MHz (mJy)	15kHz (mJy)	Comment
L	131	4200	
C	147	4700	No C-band masers detectable
K	400	12000	K-band sensitivity degraded

The limitations apparent in Table 1 meant that, on sensitivity grounds alone, only OH masers in SFR, CSEs and SNR and the various types of H_2O maser would be accessible to HALCA.

However, there are other limitations. Masers resident in different types of object appear to have a wide variety of intrinsic sizes. OH masers in the envelopes of evolved stars appear, in general, to have sizes $>$ 20 milliarcsec (Bowers et al. 1980) and would not therefore be detectable on space-ground baselines. There are some exceptions to this, Norris et al. (1984) showed that the most-blue shifted peak of the 1612 MHz OH maser emission towards the OH/IR star OH127.8-0.0 was compact on trans-Atlantic baselines. This phenomenon has since been observed in several other stars (Sivagnanam et al. 1988; van Langevelde et al. 2000) and is attributed to the special location of the blue-shifted masers, they appear to lie directly along the line-of-sight to the star and probably amplify the compact thermal emission originating in the stellar photosphere (see Figure 1).

In the complex gaseous structures surrounding SNR shock-excited 1720 MHz OH masers are known to be reasonably common. However, recent MERLIN and VLBA results by Claussen et al. (1999) show that they have large intrinsic sizes ranging from 50 ⟶ 180 milliarcsec.

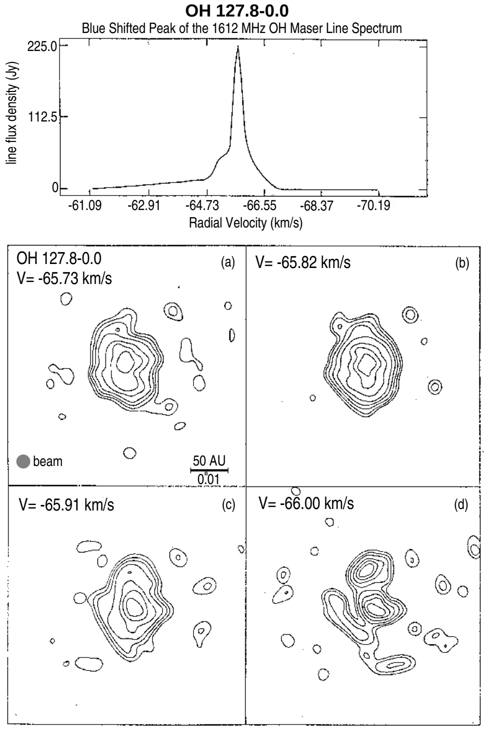

Figure 1: Single-dish spectrum and global VLBI images of OH 1612 MHz maser emission in four velocity channels around the blue-shifted peak of OH127.8-0.0 (Diamond et al., in preparation).

All four transitions of the ground-state of OH are to be found towards SFR, however, the intrinsic sizes of such masers are difficult to determine. Some appear to be dominated by scattering (see below), while maser physics also appears to play a role. For example, Reid et al. (1980) have shown the 1665 MHz OH masers in W3(OH) to be $\sim$ 5 milliarcsec in size, while Masheder et al. (1994) determined the sizes of the 1720 MHz masers in the same source to be $<$ 1.2 milliarcsec. This latter measurement implies that, for W3(OH) at least, the measured size of the 1665 MHz masers must be intrinsic.

Most H_2O maser sources have compact emission detectable on the long ground-space baselines except for those in CSEs. Several groups have shown that such masers have sizes ranging from 0.2 ⟶ 1.2 milliarcsec (Spencer et al. 1979; Diamond et al. 1987).

2 The Bane of Spectral Line VLBI: Scattering

Radio waves from distant sources propagate through the interstellar medium (ISM) and are affected by their passage. Free electrons in the ISM have a number density $\delta \mathrm{n}_e$ that varies over scales from 100km to 1 kpc. This results in variations in the refractive index of the medium ($\delta \mathrm{n}_r \sim (-r_e\lambda^2/\ 2\pi)\delta \mathrm{n}_e$) which in turn result in a phase perturbation that manifests itself in a variety of observable phenomena; namely: angular broadening, angular wander, pulsar pulse broadening, pulse time fluctuations and intensity scintillations. For the study of masers with long-baseline interferometers the principal problem is the angular broadening of the maser spots.

The angular diameter resulting from scattering is related to the scattering measure:

$$SM = \int_0^D C_N^2 ds \tag{1}$$

where C_N^2 denotes the power in the fluctuation spectrum along the line of sight. Taylor and Cordes (1993) provide a relationship between the scattered angular diameter and the scattering measure valid for galactic sources:

$$SM = (\frac{\Theta}{71mas})^{5/3}\nu_{GHz}^{11/3} \tag{2}$$

Numerous studies of pulsars, masers and extragalactic sources have demonstrated the reality of the scattering process. In some cases the scattering can be extreme, Frail et al. (1994) showed that the angular diameter of some OH masers in OH/IR stars close to the Galactic Centre exceeded 1000 milliarcsec. Diamond et al. (1988) showed, from a global VLBI survey of some 60 OH sources, that there was a tendency for angular sizes of masers to increase with distance implying that, in general, interstellar scattering determines the angular size and therefore the brightness temperatures.

However, once again there are exceptions. Kemball et al. (1988) performed a single-baseline VLBI survey with Medicina and Hartebeesthoek of 16 strong 1665 MHz OH masers in SFR. Surprisingly, they detected three sources, all with sizes ~ 1 milliarcsec; the size predicted by our understanding of scattering was 20 milliarcsec. This result implied that there may be holes in the scattering screen.

3 HALCA and OH Masers

As the above discussion makes clear the potential spectral line targets available to HALCA are somewhat limited. However, successful observations of OH masers in SFR OH34.26+0.15, one of the sources detected by Kemball et al. (1988), have recently been reported by Slysh et al. (2000). Using a ground array of ATNF, Mopra, Tidbinbilla, Usuda, Shanghai and Bear Lakes co-observing with HALCA they successfully detected fringes to the spacecraft. The maser spots were only partially resolved with the major and minor axes of the strongest peak estimated at 2.6 ± 0.5 and 0.3 ± 0.3 milliarcsec respectively. It is possible that the masers spots are composed of still smaller, unresolved features. A lower limit to the brightness temperature of 6×10^{12}K results from these measurements. Such a value exceeds the maximum values of T_B predicted by some maser models by an order of magnitude. In order to accommodate such high values it is probable that the maser emission is not isotropic but is highly beamed.

Slysh et al. point out that a distant pulsar (14.5 kpc) and an extragalactic source which lie within $10'$ and 0.76 degrees of OH34.26+0.15 respectively are both very heavily scattered, having angular sizes > 200 milliarcsec when scaled to 1665 MHz. OH34.26+0.15 lies at a distance of 3.8 kpc and so the obvious conclusion is that the source of the heavy scattering lies beyond the maser source. Slysh et al. therefore suggest that their space VLBI results suggest a large scale deviation in the distribution of the scattering material in the Galaxy.

4 HALCA and H_2O Masers

Due to the degradation of the K-band system it was not expected that any celestial source could be observed by HALCA, however, nature provided a surprise in the form of a massive outburst of an H_2O maser in Orion-KL. Such outbursts have been observed before. Between 1979

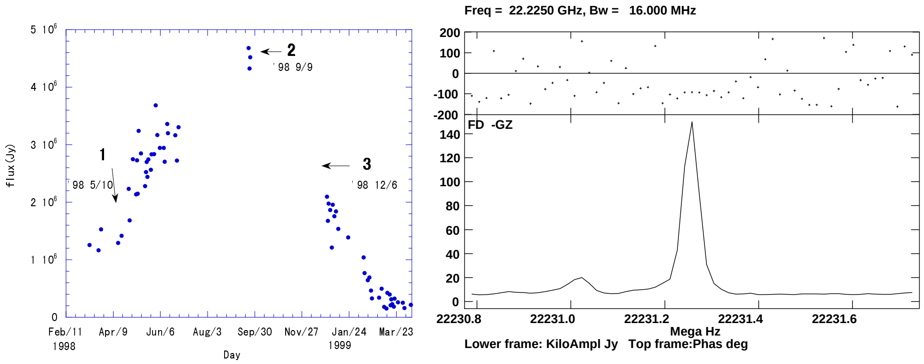

Figure 2: a) Time evolution of the peak flux density of the 8 km/s feature in Orion-KL, data taken with the Kagoshima 6-m telescope; b) Scalar averaged spectrum of the H_2O maser emission in Orion-KL on the baseline FD–HALCA.

and 1988 a maser at a velocity of 8 km/s flared to a flux density of 7 MJy. During that time a global VLBI observation by Matveyenko et al. (1988) revealed the burst region to have a linear structure with a clear velocity gradient along it indicative of rotation. Matveyenko et al. (1988) proposed a model in which the individual masers denoted long coherent paths in a structure similar to the rings around Saturn.

In the early Spring of 1998 the same region flared again, eventually reaching a flux density of $\sim$ 5 MJy. Fig 2a shows the time evolution of the burst as seen from the 6-m radio telescope in Kagoshima. On March 3, 1998 an observation was performed using the VLBA and HALCA, fringes were found at the VLBA correlator on April 9, 1998. Fig 2b shows the scalar-averaged amplitude and phase spectrum for a minute interval on the baseline Fort Davis–HALCA. Kobayashi et al. (these proceedings) discuss the nature of the peculiar linear structure of the maser region as determined from VLBA monitoring.

5 The Future

There are two proposed space missions of interest to spectral line observers: VSOP-2 and ARISE. Currently, it is planned to equip VSOP-2 at 5 (or 8) GHz, 22 GHz and 43 GHz; ARISE would be similarly equipped but with an additional receiver at 86 GHz. The sensitivities are such that both antennas would be able to detect hundreds if not thousands of H_2O and SiO masers if compact structure is present. The apogee for each spacecraft is planned to be $\sim 40,000$ km, the resultant resolution at 22, 43 and 86 GHz will be 60, 30 and 15 μarcsec respectively. Such a high apogee will, in all likelihood, preclude observations of SiO masers. Numerous VLBA observations of v=1, J=1-0 SiO masers at 43 GHz have demonstrated that fringes are rarely detected on the long 8000 km baselines of the array, implying that the intrinsic sizes of such masers is $> 200\mu$arcsec. Despite several attempts, no transatlantic fringes towards 43 GHz SiO maser sources have yet been detected. 86 GHz observations of the v=1, J=2-1 transition appear to generate the same result. Although such observations are still in their infancy, CMVA observations of several sources have not detected compact emission on intra-USA baselines.

The principal target of future space VLBI missions will be H_2O masers, in particular megamasers in the nuclei of other galaxies and masers in SFR. Since the discovery of the Keplerian rotating disc of gas traced by H_2O maser emission by Miyoshi et al. (1995) a cottage industry has developed attempting to determine the detailed structures of the known megamaser sources and also to detect new sources.

There appear to be two types of megamaser source; the first is of the class exemplified by NGC4258 (Miyoshi et al. 1995) which contains a sub-parsec scale disc of gas in Keplerian rotation about a $39 \times 10^6 M_\odot$ black-hole. A continuum jet is known to be emerging along the rotation axis of the system (Herrnstein et al. 1997). Other similar sources are NGC1068, NGC4945, Circinus, NGC3079 and IC2560. A second type of galaxy (e.g. NGC1052: Claussen et al. 1998) exhibits maser emission that appears to lie along the continuum jets. The detailed study of these objects at the high resolution available to space-VLBI will enable astronomers to measure the masses of the supermassive black holes that lurk in the centre of these galaxies, to probe the accretion disc structure, to measure the distances using proper motion studies (e.g. Herrnstein et al. 1999) and to study the jet physics.

Another prime target will be the study and monitoring of the H_2O

masers in regions of star formation. Gwinn (1994) and others have demonstrated that scattering in the ISM affects H_2O masers as well as OH, though to a lesser extent since the angular broadening varies approximately as λ^2. So, some masers will be resolved on the longest space VLBI baselines. However, Migenes et al. (1999) in a pre-VSOP survey have observed several 10s of sources with compact structures on long ground baselines suggesting that there will be many accessible targets.

Astronomers will be able to study the detailed structure of the maser regions, the small-scale structure and shapes of the masers themselves but above all they will be able to perform frequent monitoring of the changing structures in such objects. Long-term proper motion studies have revealed the distances and overall dynamics of some masers; for example Gwinn et al. (1992) have determined the distance to the H_2O maser in W49(N) to be 11.4 ± 1.2 kpc and have shown that the masers are expanding in a bipolar manner from a common point presumed to be a newly born star.

However, space VLBI observations could perform such measurements much more quickly, more accurately and enable studies of the complex motions that probably exist in such regions. Observations with VSOP-2 or ARISE would be able to watch a typical H_2O maser in W49N move its own diameter in 3-4 weeks. One can imagine that ‘movies’ analogous to the SiO movie of TX Cam (Diamond & Kemball, in preparation) could be produced in this manner.

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