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2mm Wavelength VLBI of SiO Masers and AGN

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Abstract. In April 2002 an array of antennas operating at 129GHz successfully detected VLBI fringes on both continuum AGN and SiO spectral line sources. The 129GHz fringes represent the highest frequency spectral line VLBI detections to date. The array consisted of the University of Arizona Kitt Peak 12m antenna, the Sub Millimeter Telescope Observatory 10m (HHT), and the IRAM 30m dish on Pico Veleta. These observations are the first fringes at any frequency at the SMTO and we discuss the technical challenges involved.
At 129GHz, a number of evolved stars and several young stellar objects exhibit strong SiO maser emission in the v=1 J=3-2 transition. Preliminary cross power spectra of VYCMa on the HHT-Kitt Peak baseline (∼190km) are consistent with multiple spatially separate maser spots associated with the star. We discuss phase mapping this emission and the implications for constraining the SiO maser pumping mechanisms and circumstellar dynamics around these objects. Future observations will include continuum observations of the radio source at the Galactic Center, SgrA*, and higher frequency maser lines including HCN and methanol.

1. Introduction

A compelling case can be made for extending the VLBI technique to high frequencies. First and foremost, angular resolution improves linearly with frequency allowing more detailed imaging of sources. This is the only avenue available for better resolution given Earth-based arrays: VLBI at 3mm wavelength already approaches 80μas fringe spacing which is very near the limit imposed by the Earth's diameter. Plasma effects which can mask small scale structure at lower frequencies also decrease in severity as λ^2. Faraday Rotation (and therefore depolarization) is a prime example, and studies of jet formation and propagation in AGN, which depend on teasing out the fine structure of B-fields, require high frequency VLBI. Scatter broadening due to ionized components of the ISM is another example, one which prevents imaging the intrinsic structure of Sgr A*, the massive black hole candidate in our Galaxy. In addition, radio spectra of AGN generally turn over in the mm wavelength range, so high frequency VLBI arrays can peer more deeply into AGN cores that are Synchrotron Self Absorbed at lower frequencies. And, finally, by opening new spectral windows, previously inaccessible maser transitions become available for VLBI study.

With many new large aperture antennas planned in the mm and sub-mm bands, it is not so much a question of *if*, but of *when* VLBI at frequencies higher than 86 GHz will deliver on the promise outlined above. Within the next decade, CARMA (a combination of the current BIMA and OVRO arrays), ALMA and the LMT will combine with existing mm wave dishes, including the IRAM 30m, to enable Earth-sized high frequency VLBI arrays with enough sensitivity to image AGN at useful dynamic ranges. Current arrays are limited at high frequencies in both sensitivity and baseline coverage, but they provide crucial test beds for developing techniques and exploring future scientific drivers.

We report here on a successful VLBI experiment at 129GHz in April 2002 on a triangle of stations including the IRAM 30m (Spain), the Heinrich Hertz Telescope of the SMTO (Mt. Graham, Arizona) and the University of Arizona 12m (Kitt Peak, Arizona). On the long baselines to IRAM, 3C279 was detected with fringe spacings of 56μas. Such detections are useful in estimating AGN core sizes, but this sparse array does not permit true imaging. The main targets of the 129GHz experiment were not AGN but SiO J=3→2 maser sources around both evolved stars and the Orion star forming region. Because different spectral features of masers can correspond to distinct regions of emission in the circumstellar environment, even sparse VLBI arrays can often map the maser structure. Here we describe the technical work at both the Kitt Peak and HHT sites that enabled this experiment and discuss the preliminary results and prospects for imaging.

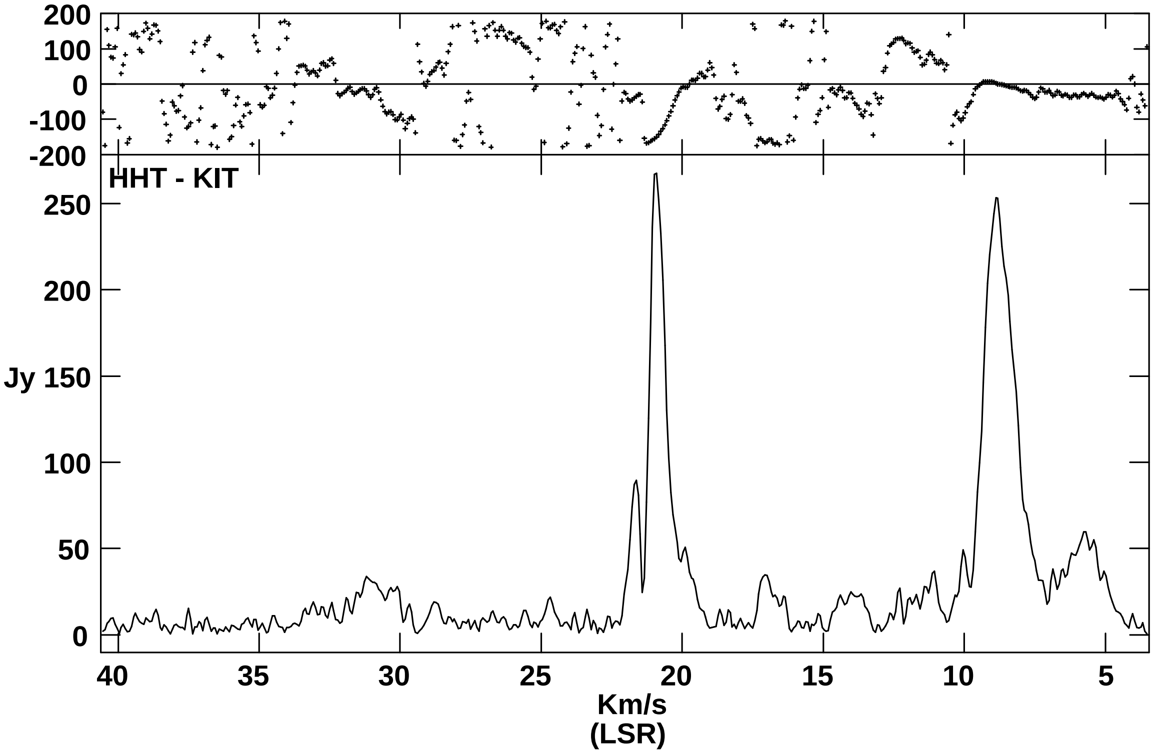

Fig. 1. Cross power spectra of the v=1 J=3→2 (129 GHz) SiO maser toward the evolved star VYCMa. Top panel shows interferometric phase, bottom panel the amplitude. Spectral features with distinct phases are most likely spatially separated maser features in the circumstellar envelope. The data are calibrated in Jy assuming gains at both HHT and Kitt Peak sites of 0.02K/Jy and $T_{\rm sys}$ of 300K and 400K respectively.

2. Technical Aspects

A number of technical tasks had to be accomplished to carry out the 2mm VLBI. Key technical aspects are briefly described below.

A previous 230GHz VLBI attempt using the HHT revealed that the Hydrogen maser used at that site may not have been sufficiently stable. This unit was shipped back to the CfA in Cambridge, MA. where it was found to have a stability characterized by: $\sigma_y(\tau) = 4\times10^{-13}\tau^{-1} + 8\times10^{-14}\tau^{-0.5}$. The coherence loss at this level of maser stability can be expressed as Loss $= 1 - \exp(-\sigma(\tau)^2/2)$ where $\sigma(\tau) = 2\pi\nu\tau\sigma_y(\tau)$. So for $\tau = 10$ seconds, the coherence loss would be $\sim 36\%$, an unacceptably high value. A newer H-maser was refurbished, tested and shipped out to the HHT in preparation for observations at 129GHz and 147GHz (the 147 GHz observations are covered elsewhere in these proceedings).

To search for VLBI fringes, the exact position of the HHT was required. A geodetic differential GPS antenna was mounted on the back side of the HHT sub-reflector and the position refined over a 24 hour period. The same measurement was performed at the Kitt Peak 12m whose VLBI position was known, and the resulting position difference yielded the HHT position to within $\sim$ 10cm.

The decision to attempt the VLBI in the 2mm band as opposed to the 1mm band was motivated by the decrease in sensitivity to maser stability, atmospheric turbulence and instrumental phase noise. Accordingly, a 2mm receiver had to be constructed for use at the HHT - the Kitt Peak 12m and IRAM 30m were already so equipped.

VLBI backends including data acquisition racks and magnetic tape recorders were shipped to both HHT and Kitt Peak sites for this experiment. Both sites used Mark4 VLBI formatters and recorded total bit rates of 224Mb/s using 2-bit samples to increase sensitivity on spectral line sources.

Broadband $\frac{1}{4}\lambda$ plates were fabricated at IRAM for use at the two Arizona sites. These plates were sufficiently broadband that they could be used at both 129 GHz and 147GHz to convert LCP to linear polarization.

Local oscillators at all sites were tested by injecting a tone directly into the receiver feeds and mixing down to IF frequencies. Comparison of this tone with one derived from the H-maser frequency standard can expose potential coherence losses due to LO impurity. At Kitt Peak, for example, a high frequency ($\nu > 1$MHz) noise pedestal on the LO caused $\sim$ 10% of the signal power to be moved outside the VLBI fringe rate window.

3. SiO Masers

Silicon Monoxide (SiO) masers, excited by a combination of radiative and collisional pumps, arise in some atmospheres of both evolved stars and YSOs. Masers are observed in many ro-vibrational transitions of this simple rotor molecule, giving rise to very compact and very bright features that trace long gain paths through stellar environments. The excitation energy of the v=1 SiO vibrational state is 1800K which places these masers, due to pumping considerations, very close to the stellar photosphere. VLBI observations place the masers within $\sim$ 4 stellar radii of evolved stars (Diamond et al 1994, Doeleman et al 1998, Phillips et al 2001). SiO masers can be excellent dynamical probes providing evidence for rotation in evolved stars (Boboltz et al 2000, Hollis et al 2001) and for outflow from protostars (Greenhill et al 1998, Doeleman et al 1999). In most cases, VLBI of SiO masers provides the most detailed pictures of the envelopes around these stellar objects which are opaque in the optical and IR.

Recent VLBI studies reveal that the relationship between different SiO maser transitions around individual objects is complex. Towards the Red Giant R Cassiopeiae, for example, the v=1 J=1→0 (43 GHz) and J=2→1 (86 GHz) masers appear to be largely co-spatial (Phillips et al, these proceedings). In the Orion-BN/KL region, however, these same transitions are offset from each other and likely occur in different regions of a shocked bipolar outflow (Doeleman et al 2002). The HHT-Kitt Peak baseline is unique in its capacity to observe SiO masers in the J=3→2 (129 GHz), J=4→3 (172 GHz) and J=5→4 (215 GHz) SiO transitions with angular resolutions comparable to known maser structures. Given the results on lower frequency maser lines, VLBI exploration of SiO masers in the 1-2mm band will likely reveal unforeseen relationships among newly imaged transitions.

In contrast with the case of mapping continuum sources, maser emission can be imaged with a single baseline, and the peculiarities of doing so are well understood (Doeleman et al 1998). It is essential that an isolated spectral feature be found that is very closely approximated by a point source. To do this, one must examine the calibrated visibility amplitudes at each frequency channel. Once a point-like feature is found, the rest of the data set is spectrally phase referenced to this feature and mapping can proceed.

During the April 2002 observations, we observed a total of six SiO maser sources selected for their flux density. These sources are highly variable with the SiO maser maximum typically lagging the IR/Optical maximum by 0.25 of a stellar cycle. The sources were: Orion-BN/KL, WHya, VYCMa, RLeo, RCas, χCyg.

The data reduction at this point is preliminary and we have only detected one source, VYCMa, so far. The cross-power spectrum of VYCMa (Figure 1) reveals strong compact emission at multiple velocities. The associated phases (top panel) show that after fringe rate correction, there are significant phase offsets between spectral features. These data have not yet been corrected for phase delay across the passband, but it is likely, given the phase signatures, that we are seeing individual maser features which are spatially distinct. It remains to be seen if we can isolate a point-like feature and produce a real map of the emission. The ability, though, of the Mark4 correlator to produce

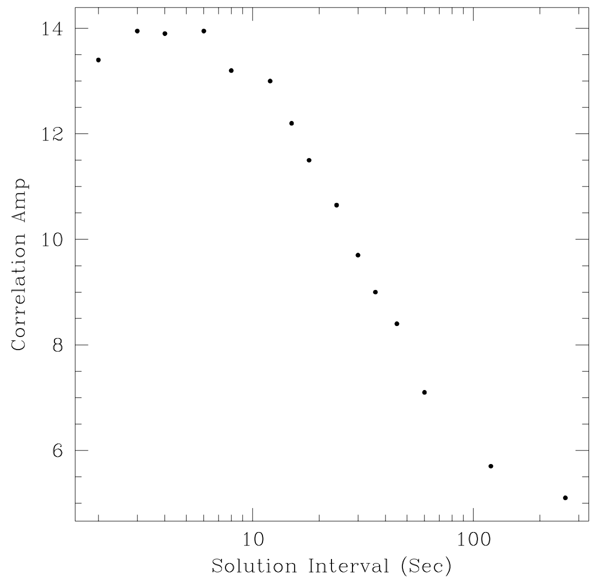

Fig. 2. Coherence of the HHT-Kitt Peak baseline was determined for a sample scan by plotting the vector averaged amplitude of the spectral feature at 8.5 km/s as a function of fringe solution interval. The plateau below intervals of $\sim$ 8 seconds sets the coherence time.

512 point cross power spectra increases the chances that such a component can be found.

The SiO masers in VYCMa are bright enough that fringe rate solutions can be found on time scales below 3 seconds. This allows us to empirically determine the coherence time of the HHT-Kitt Peak baseline at 129GHz by comparing the strength of spectral features at different solution intervals. Figure 2 shows the resulting plot in which a clear "plateau" forms at solution intervals below 8 seconds. This occurs because the solution interval falls below the coherence time of the interferometer. If we take the coherence time to be that solution interval at which the amplitude of the spectrum falls to 95% of this "plateau" value, then this baseline has a $\sim$ 10sec coherence time. This is almost certainly due to atmospheric turbulence.

4. AGN and Sgr A*

The AGN 3C279 served as a calibrator for the spectral line targets, but was also detected at 129GHz on intercontinental baselines from Arizona to the IRAM 30m in Spain. If we assume that 3C279 must be approximately half the size of the 56μas fringe spacing, then its linear size must be less than 0.2 pc ($H_\circ$=100km/s/Mpc, $q_\circ$=0.5, z=0.538). This size corresponds to 2000 Shwarzschild Radii of a $10^9 M_\odot$ Black Hole.

By segmenting and incoherently averaging the 3C279 visibilities, we find that during these observations the coherence times on the HHT-KTPK, HHT-IRAM, KTPK-IRAM baselines were 2 seconds, 8 seconds and 3 seconds respectively. Comparison with the $\sim$ 10 seconds coherence time in Fig 2 implies that poor weather at the Kitt peak site is responsible. After correcting for the effects of short

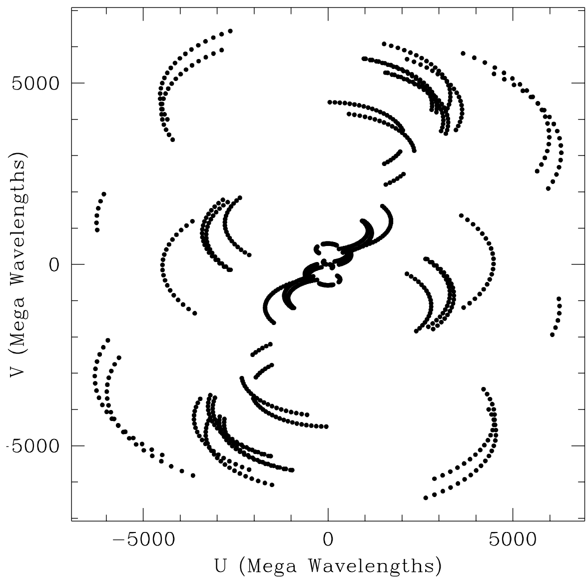

Fig. 3. 230GHz-VLBI baseline coverage on the Galactic Center source Sgr A* on an array including: CARMA, LMT, ALMA, Kitt Peak, HHT, IRAM 30m, SEST, JCMT.

Table 1. 3C279 Calibrated Flux Densities.

Baseline	$S_{corr}(Jy)$	$Baseline(M\lambda)$
HHT-IRAM	2.9	3600
KTPK-IRAM	2.9	3670
HHT-KTPK	11.6	73

coherence time, we find correlation amplitude values for 3C279 of Amp(KTPK-IRAM)=3.5x10^{-4}, Amp(KTPK-HHT)=5.2x10^{-4} and Amp(HHT-IRAM)=5.2x10^{-4}.

We attempted to calibrate these data assuming SEFD(HHT)=15000Jy, SEFD(IRAM)=2600Jy. By further assuming that the correlated flux density on both Arizona-Spain baselines must be identical, we find that SEFD(KTPK)=33000Jy. This calibration gives the correlated flux densities in Table 1.

During the observations, the total flux density of 3C279 was measured to be $\sim 21Jy$ at 129GHz. If we assume that most of the 129GHz flux is compact on ∼2mas scales, then the measured short baseline S_{corr} is unreasonable and may be due to any of a number of calibration uncertainties: 1. there is some source of undiagnosed phase noise in the signal path; 2. coherence times are actually smaller than we are measuring; 3. the calibration (T_{sys}) is faulty; or 4. some problem we do not yet understand. In any event, VLBI calibration at these frequencies remains a difficult problem and will likely be solvable only with the inclusion of more telescopes so that closure quantities can be used. Even with the calibration uncertainty, it appears that 3C279 is resolved on the long baselines.

Sgr A*, the compact radio source at the Galactic Center is thought to mark the position of a $2.5 \times 10^6 M_\odot$ Black Hole. While it is tantalizingly close to Earth and holds the promise of helping us understand the physics of its more massive extragalactic cousins, it is shrouded by an ionized plasma that broadens VLBI images. High frequency VLBI is the only means available to pierce the scattering screen and image the intrinsic structure of Sgr A*. Doeleman et al (2001) have shown that it is possible to use closure quantities to calibrate a high frequency (86 GHz) VLBI array and iteratively solve for structural models of Sgr A*. But this requires of order 6 telescopes to ensure that enough phase and amplitude data can be recovered using closure. At frequencies above 86 GHz, current VLBI arrays become sparse and the sensitivity of individual antenna are relatively low.

Two factors will alter the future VLBI landscape and permit 1mm and 2mm observations of Sgr A*. In the near future, the Mark5 VLBI system (see A. Whitney, these proceedings) will boost recording capability from the standard 256 Mb/s to over 1Gb/s thereby increasing baseline sensitivity by over a factor of 2. This enhancement puts Sgr A* within reach at 230GHz on today's longest and most sensitive baselines. Sgr A* has already been detected with 215GHz VLBI (Krichbaum et al 1998, Greve et al 1995) on moderate length baselines, but it is difficult to make size estimates due to calibration uncertainty.

The second factor is that a number of large aperture mm wave dishes and arrays are planned for construction over the next decade. These sensitive dishes combined with wide-band recording should be able to definitively map the structure of Sgr A*. Figure 3 shows the (u, v) coverage possible with such an array.

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