mm VLBI: World Record Resolution and Study of SiO Masers

S.S. Doeleman, R.B. Phillips, A.E.E. Rogers, J.M. Attridge, M.A. Titus, D.L. Smythe, R.J. Cappallo, T.A. Buretta, A.R. Whitney (MIT Haystack Observatory), T Krichbaum, D.A. Graham, W. Alef, A. Polatidis, U. Bach, A. Witzel, J.A. Zensus (MPIfR-Bonn), A. Greve, M. Grewing (IRAM), R. Freund (NRAO), P. Strittmatter, L. Ziurys, T. Wilson, H. Fagg (Steward Observatory)

I. Why push the VLBI technique to shorter wavelengths?

a. Better resolution (λ/D).
b. Faraday rotation and, thus, depolarization in quasar cores decreases as λ^2.
c. Scatter broadening through ionized media decreases as λ^2.
d. "Flat spectrum" radio-loud AGN tend to become optically thin at λ~1mm.
e. New spectral windows make previously inaccessible maser transitions available to high resolution study.

II. 2mm VLBI Observations:

In April 2002, a VLBI array of 5 radio telescopes observed AGN on both long (intercontinental) and short (~150 km) baselines at frequencies of 129GHz and 147GHz. Detections of the AGN 3C279 achieved angular resolutions of 49μas, an astronomical record. On the short Kitt Peak – SMTO baseline, bright SiO masers in the J=3? 2 rotational transition were detected by VLBI for the first time.

The 2mm band was chosen because it led to a record angular resolution on the array baselines, it was not so high in frequency that weather had to be excellent at all sites, and it allowed observations of bright SiO maser transitions near 129 GHz. Coherence times of the array (the time over which the VLBI signal can be integrated) ranged from seconds to one minute (see Fig 2).

In preparation for the April 2002 experiment, a 2mm band receiver was constructed for the SMTO, a Hydrogen maser and VLBI recording system transported to the SMTO. A separate VLBI system sent to the Kitt Peak site used a Hydrogen maser signal provided from the nearby VLBA antenna courtesy of NRAO. Interferometric fringes were detected at 147GHz on the Pico Veleta – Kitt Peak – SMTO triangle and also on the Pico Veleta – Metsahovi baseline. At 129GHz, fringes were obtained on the Pico Veleta – Kitt Peak – SMTO triangle.

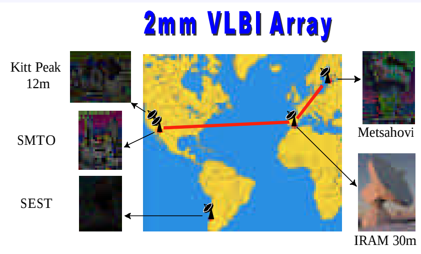

Figure 1: Array used for VLBI at both 129 and 147 GHz. Red lines connecting telescopes show baselines which detected the AGN 3C279. On the baselines from Arizona to Spain, fringe spacing (λ/D) was 49 μas, an angular resolution record in astronomy.

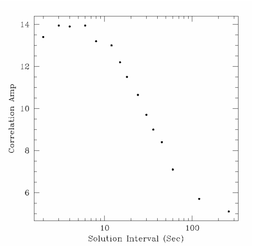

Figure 2: Coherence of the HHT-Kitt Peak baseline was determined for a sample scan on VY CMa by plotting the vector averaged amplitude of the spectral feature at 8.5 km/s as a function of fringe solution interval. The plateau below intervals of ~8 seconds sets the coherence time of the baseline.

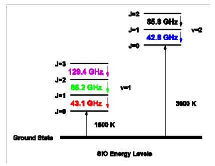

Figure 3: Ro-Vibrational energy levels for SiO maser transitions.

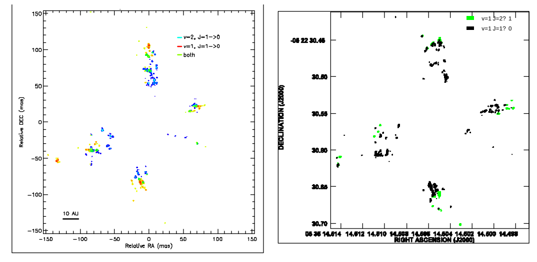

Figure 4: Examples that underscore the fact that SiO masers in different transitions can trace distinct regions and physical conditions in their host environments. On the left, registered maps of the v=1 and v=2 J=1? 0 maser transitions showing the vibrationally excited v=2 transition forming much closer to a central protostar in the Orion BN/KL nebula. On the right, registered maps of the v=1 J=1? 0 and J=2? 1 maser transitions, this time with the J=2? 1 masers located further from the Orion BN/KL protostar.

III. SiO Masers

Silicon Monoxide (SiO) masers, excited by a combination of radiative and collisional pumps, can arise in the atmospheres of both evolved stars and YSOs. Masers are observed in many ro-vibrational transitions of this simple rotor molecule (Fig 3), giving rise to very compact and very bright features that trace long gain paths through stellar environments. VLBI observations place the masers within ~4 stellar radii of evolved stars (e.g. Diamond et al 1994), making them excellent dynamical probes of rotation in evolved stars (Boboltz et al 2000) and for outflow from protostars (Greenhill et al 1998, Doeleman et al 1999).

Recent VLBI studies reveal that the relationship between different SiO maser transitions around individual objects is complex. In some cases, for example, the v=1 J=1? 0 (43 GHz) and J=2? 1 (86 GHz) masers are largely co-spatial (see Phillips et al – poster 115.10U), but in the case of SiO masers in the Orion BN/KL region, these same transitions are offset from each other and likely occur in different regions of a shocked bipolar outflow (Fig 4).

The HHT-KittPeak 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. VLBI comparison of multiple SiO maser transitions holds the key to understanding the chemistry of the environments in which they form.

IV. VY CMa: An Asymmetrical Envelope

VY CMa is a luminous (5×10^5 $L_\odot$) red hypergiant with an asymmetric reflection nebula fueled by a high mass loss rate (3×10^{-4} $M_\odot$). The stellar radius is ~12 AU, well past the orbit of Saturn in our solar system. SiO masers in this source are well documented, but no VLBI study has yet been made to determine their structure. Optical images made by the HST (Smith et al 2001) show the reflection nebula extending to the SW with almost no emission to the NE of the star (Fig 5). The faint optical emission that is seen to the NE is highly reddened, a fact which forms the basis for a model in which a stellar disk obscures nebula emission to the NE.

The VY CMa SiO masers are arranged in a rough line (Fig 6), not in a "ring" encircling the star as is seen in some other sources. In VY CMa we may be observing a partial "ring". Alternatively, the masers may be forming in a circumstellar disk oriented nearly perpendicularly to the NE-SW reflection nebula. Future proper motion studies of the masers as well as simultaneous imaging of multiple maser transitions should help discriminate between these possibilities.

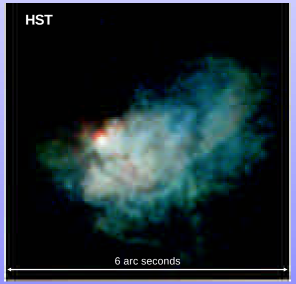

Figure 5: Optical HST image of the VY CMa reflection nebula

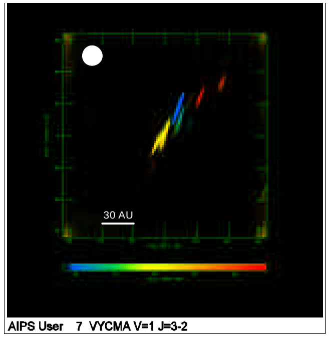

Figure 6: Velocity color coded map of the v=1 J=3? 2 (129 GHz) SiO masers towards the evolved hypergiant star VY CMa. The white disk shows the estimated size of the stellar photosphere. The masers cannot be registered to the stellar position, but their quasi-linear morphology suggests they form either in an incomplete ring around the star or in a circumstellar disk.

V. Ongoing Work:

We are extending this work to higher frequencies (230GHz) where angular resolution on the longest baselines can reach 29μas. In the Galactic Center, where a $3\times10^6 M_\odot$ black hole is thought to exist, this resolution corresponds to ~5 Schwarzschild radii. New observations at this frequency on an array including PicoVeleta, Plateau de Bure, SMTO, Kittpeak(12m) were made in April 2003 and await processing.

New 2mm observations of SiO targets in April 2003 were combined with VLBA observations at 3mm and 7mm. Preliminary results show detections in all three wavebands for at least two sources: VY CMa and the evolved star RCas.

References:

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