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Comments

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COMPARISONS OF SiO MASER AND LONG-PERIOD VARIABLE POSITIONS IN THE R AQUARII AND OMICRON CETI BINARY SYSTEMS

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ABSTRACT

We have determined that the absolute position of the centroid of SiO maser–emitting spots toward both R Aqr and *o* Cet are coincident with the position of the long-period variables (LPVs) in these binary systems to within the errors of measurement. The SiO positions were determined with the Hat Creek interferometer, while the LPV positions were determined with the 8 inch (20 cm) transit circle of the US Naval Observatory. These results contradict an earlier report of a circumbinary SiO maser far removed from the LPV in the R Aqr binary system, and we suggest statistical reasons for the discrepancy. We present high-resolution spectra of both sources and discuss possible models.

Subject headings: astrometry — interferometry — masers — nebulae: H II regions — stars: individual (R Aquarii, Omicron Ceti) — stars: long-period variables

I. INTRODUCTION

At 250 pc (Whitelock 1987), R Aqr is the nearest dust-type symbiotic binary system and the stronger of only two such objects displaying SiO maser emission (Allen *et al.* 1989). Continuum observations of R Aqr with the VLA in its high-resolution A-configuration at 2 cm wavelength previously revealed the presence of two emitting regions designated C1 and C2 by Hollis *et al.* (1986). The stronger, spatially resolved C1 H II region (∼100 AU in diameter) was assumed to engulf the entire binary system (orbital semimajor axis ∼17 AU). Observations of R Aqr with the Hat Creek interferometer were performed by Hollis *et al.* (1986) to determine the position of the SiO maser in the belief that its position would pinpoint the position of the 387 day Mira-like variable with respect to C1. The assumption of coincidence of the LPV envelope and SiO maser emission was based on the fact that the maser involves vibrational states which are at least 1750 K above the ground state and the fact that the maser velocities are found to be at or near the stellar radial velocity; both circumstances argue for the maser emission to be located in or near the stellar photosphere. Thus, it came as a surprise that the SiO maser emission was far removed ∼250 AU (∼1″) southeast of the C1 emission peak. Independently, through transit circle observations, Michalitsianos *et al.* (1988) determined that the R Aqr LPV optical position was just outside of the western ionization front associated with C1. Subsequently, with the VLA in its A/B-configuration, Kafatos *et al.* (1989) searched for and found 2 cm continuum emission knots which were coincident in position with the SiO maser position reported earlier (Hollis *et al.* 1986); however, at the same time these authors failed to find such features at 6 cm. Kafatos *et al.* interpreted these results as evidence for thermal and optically thick density-enhanced regions due to shock wave heating of the circumbinary nebulosity which could give rise to a collisionally pumped circumbinary SiO maser by shock waves emanating from the hot companion's accretion disk. In parallel with these efforts, we decided to repeat the Hat Creek interferometer SiO measurements for R Aqr and also perform similar observations on the *o* Cet binary system, containing a 332 day variable (Mira itself) which displays similarities with symbiotic Mira-like variables (Whitelock 1987), as well as observe several other singly evolving LPVs (see Wright *et al.* 1990). We wanted to confirm our previous results and test the hypothesis that there may well be something unique about LPVs in symbiotic-like systems which affords the formation of circumbinary masers.

II. OBSERVATIONS

a) Radio Astrometry

Vibrationally excited SiO emission ($v = 1$, $J = 2$–1 transition at 86243.37 MHz) toward R Aqr and *o* Cet was observed in left-circular polarization with the millimeter interferometer at the Hat Creek Radio Observatory. R Aqr was observed on 1988 February 3 and 14 with a resultant mean epoch of

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[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc, under cooperative agreement with the National Science Foundation.

1988.12 and *o* Cet was observed on 1988 February 6 and 1988 May 9 with a resultant mean epoch of 1988.23. For the February run, the three 6.1 m diameter antennas were located 122 m east, 145 m west, and 177 m north of the midpoint of the interferometer track, giving one long E–W and two long diagonal baselines. Additional observations of *o* Cet were made in May with the antennas located 73 m west, 79 m north, and 116 m north in order to resolve lobe ambiguities which arise due to this source's declination. Data were obtained with a 512-channel cross-correlation spectrometer (Urry, Thornton, and Hudson 1985). The correlator bandwidth was set to 320 MHz for phase calibrator sources and 5.0 MHz for observations of the SiO maser sources. Single-sideband system temperatures, scaled to outside the atmosphere, were 240–350 K at the zenith. The position for *o* Cet was measured with respect to quasars 0106+013, 0234+285, and 0420−014 and the position for R Aqr, similarly, with respect to 2223−052 and 2251+158; quasar positions were determined at a mean epoch of 1979.9 (Perley 1982) and were taken from the VLA calibrator list. The flux density was calibrated against those of the quasars, which in turn were calibrated against the fluxes of Venus, Uranus, and Mars. The instrumental frequency response was measured from observations of 3C 84. Maps were made from the calibrated data, and CLEANed (a particular method of sidelobe removal; see Clark 1980) over the central few arcseconds. Omicron Cet data produced a synthesized beam of $\alpha \times \delta = 1''.8 \times 2''.5$ and, similarly, R Aqr data yielded $\alpha \times \delta = 1''.4 \times 2''.9$. The maser position was measured from these maps by means of a least-squares Gaussian-fitting routine. The measured positions and estimated errors are given in Table 1. Potential sources of error in these measurements are discussed in detail by Wright *et al.* (1990).

b) Optical Astrometry

Astrometric observations of *o* Cet and 10 FK 4 reference stars, with well-known positions lying within ±1 hour of right ascension and ±15° declination of *o* Cet, were obtained using the 8 inch transit circle of the US Naval Observatory at Flagstaff, Arizona, between 1988 September 27 and 1988 October 22; the mean epoch of the observations is 1988.77. The instrument has been previously described by Holdenried and Crull (1986). For each observing session, reference stars were observed and the position of *o* Cet reduced differentially to the FK 4 system in the manner of Dick and Holdenried (1982). The resultant *o* Cet position was determined from six observations in right ascension and six observations in declination and is tabulated with our similarly determined position for R Aqr (see Michalitsianos *et al.* 1988) in Table 1.

III. DISCUSSION

Astronomical SiO masers are exclusively stellar phenomena, and it is not certain whether the pumping mechanism is due to collisional or radiative processes (Langer and Watson 1984), although observational evidence is currently pointing toward radiative pumping (e.g., Bujarrabal, Planesas, and del Romero 1987). With VLBI techniques, Lane (1982, 1984) observed a few SiO stars and demonstrated that an SiO maser ensemble consists of bright unresolved spots distributed spatially over a region of characteristic size (few times 10^{14} cm) in the direction of a given object. Presumably, the collection of individual maser spots are clustered about the stellar position. We use "presumably" since absolute positions of both the maser and the star are difficult to measure. Actually, since maser spectra often contain multiple velocity components or emission peaks due to maser coherence paths that grow and decay with time and/or period of the long-period variable (see Clark *et al.* 1984), it is not to be expected that the maser spots will always be in the same locations. In any case, due to the stellar distances involved, the determination of the absolute position of an SiO maser will be the centroid of the maser spot distribution when employing the Hat Creek interferometer for such work.

Table 1 indicates that the optically determined positions of the LPVs in both the R Aqr and *o* Cet binary systems cannot, within the errors quoted, be distinguished from the corresponding SiO maser positions now determined from the Hat Creek interferometry. It is reasonable to conclude that such maser emission originates close to the stellar photosphere as expected since the high excitation of the maser virtually demands it. Moreover, the distribution of maser spots, for all

TABLE 1

SiO MASER AND LONG-PERIOD VARIABLE POSITIONS

Source	Feature	α(1950)[a]	δ(1950)[a]	Mean[a] Epoch	α(1950)[b]	δ(1950)[b]	Common[b] Epoch	Notes
R Aqr	SiO	$23^h41^m14^s.252$(10)	−15°33′43″.26(20)	1988.12	$23^h41^m14^s.252$(10)	−15°33′43″.26(20)	1988.12	c, d
R Aqr	LPV	23 41 14.263(07)	−15 33 43.23(22)	1987.06	23 41 14.265(07)	−15 33′43.25(22)	1988.12	e, f
R Aqr	LPV	23 41 14.256(04)	−15 33 43.10(05)	1986.68	23 41 14.259(04)	−15 33 43.13(05)	1988.12	g, f
R Aqr	C1	23 41 14.266(03)	−15 33 43.00(05)	1985.03	23 41 14.272(03)	−15 33 43.06(05)	1988.12	h, f
o Cet	SiO	02 16 49.076(10)	−03 12 22.60(20)	1988.23	02 16 49.076(10)	−03 12 22.60(20)	1988.23	d
o Cet	LPV	02 16 49.081(10)	−03 12 22.29(15)	1986.81	02 16 49.080(10)	−03 12 22.62(15)	1988.23	e, i
o Cet	LPV	02 16 49.067(06)	−03 12 22.54(09)	1988.77	02 16 49.067(06)	−03 12 22.41(09)	1988.23	d, i

[a] Positions (1 σ errors in parentheses) reflect inherent source proper motion accumulated at the mean epoch of the observations.

[b] Positions (1 σ errors in parentheses) for a given source's features have been corrected for source proper motion to a common epoch.

[c] The centroid position of the SiO maser toward R Aqr was previously measured with the Hat Creek interferometer (Hollis *et al.* 1986). The 1986 position is 0″.74 south and 0″.36 east of the position reported here. The 1986 and 1988 spectra are similar, but the 1986 maser emission region was somewhat larger than the synthesized beam due probably to poor atmospheric seeing. We have more confidence in the position reported here because of a smaller synthesized beam, an improved signal-to-noise ratio, and because we derive consistent positions from data sets obtained on two different days in 1988 (see text).

[d] Positions obtained from present work (i.e., SiO with Hat Creek interferometer and LPV with USNO 8-inch transit circle).

[e] The J2000.0 position was obtained from Baudry *et al.* (1990) and converted to the B1950.0 position shown.

[f] R Aquarii proper motion annual correction rates used are $+0^s.0020$ and −0″.021 (SAO 1966).

[g] Position obtained from Michalitsianos *et al.* 1988.

[h] Position of the central H II region C1 obtained from Hollis *et al.* 1986.

[i] Omicron Cet proper motion annual correction rates used are $-0^s.0008$ and −0″.233 (SAO 1966).

late-type stars so far probed via VLBI techniques, cluster within regions less than ~0″.1 on the sky since these objects typically have distances in the range of 100–2000 pc. The 1 σ errors on the SiO positions quoted in Table 1 totally encompass such a region for each of the two sources we have investigated. This lends further support to the contention that our maser centroid positions are accurate determinations of the LPV positions.

Our results for the binary systems R Aqr and *o* Cet are consistent with a near-photospheric interpretation for the SiO maser phenomenon; however, Orion's IRc2 is clearly another matter. The spectrum of IRc2 shows emission extended over ~30 km s^{-1} with two prominent peaks analogous to that of R Aqr (see Fig. 1). Because the signal-to-noise for IRc2 is so large, Plambeck, Wright, and Carlstrom (1990) were able to produce relative position maps of all the spectral channels with relative errors of ~0″.105. Many of the systematic errors drop out of the relative position maps. Moreover, Plambeck *et al.* found an ellipsoidal ring of maser emission with a diameter of ~0″.15. A model of maser emission in a rotating expanding disk reproduces both the spatial distribution and the spectrum, with the emission arising from an annular region extending from 40 to 80 AU from the central ~25 $M_\odot$ star (Vogel *et al.* 1985) which is embedded in heavy nebulosity. The diameter of such a disk is 160 AU and would subtend ~0″.3 at the distance of Orion. The R Aqr maser is much weaker, and a comparison of the positions of the two peaks in its spectrum shows no positional difference, with an upper limit of ~0″.1. The peaks in the *o* Cet spectrum are also coincident to within ~0″.1. Thus, if an SiO disk model for R Aqr is appropriate, the disk is clearly smaller than that of IRc2 and we cannot determine its size from our present data. R Aqr and IRc2 could be more rigorously observationally tested for conformance to an SiO disk model by determining the maser spot distributions by means of VLBI. Certainly in the case of IRc2, it should reveal a greater spatial range for such distributions which have yet been observed in any source as predicted by the model of Plambeck, Wright, and Carlstrom (1990). In the case of R Aqr, this sytem should be probed with baselines sensitive to scale sizes from ~0″.008, which corresponds to the 2 AU diameter of the infrared photosphere (see Hinkle *et al.* 1989), to ~0″.2, which is a factor of 2 beyond the spatial limits established by this work.

The earlier determination of the R Aqr SiO maser position derived from the Hat Creek interferometer (Hollis *et al.* 1986) does not agree with the present work (see note c of Table 1). The difference could be due either to systematic errors or effects of signal-to-noise, and we believe it is the latter. The basic interferometer observation and calibration procedures at Hat Creek have not changed since the absolute measurement of the Orion IRc2 SiO maser position was originally reported by Wright and Plambeck (1983). The most recent determination of that position by Plambeck, Wright, and Carlstrom (1990) agrees with the previous determination within the uncertainties of about ~0″.2, showing the telescope systems to be stable. Another useful check of the system is provided by comparison between maps of H II regions made at Hat Creek and at the VLA. For example, a 6 cm VLA map of the core of W49, obtained with 0″.3 resolution, has two small (less than ~0″.5 diameter), well-isolated H II regions that are also visible on a Hat Creek 3 mm map which has 2″.5 resolution (Welch *et al.* 1987). The W49 feature positions agree between the two maps to within ~0″.3. The 3 mm W49 map was made during the

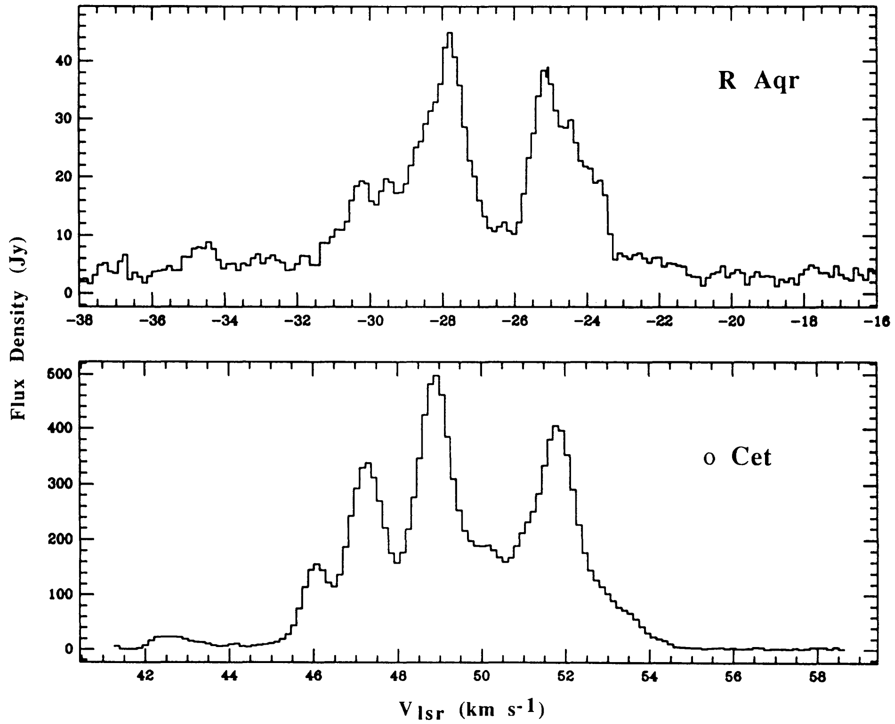

FIG. 1.—Spectra of the $v = 1, J = 2$–1 transition of SiO masers with 0.136 km s^{-1} velocity resolution toward *o* Cet observed at optical phases 0.09 and 0.36 (mean observational epoch 1988.23) and R Aqr at optical phase 0.39 (mean observational epoch 1988.12). The R Aqr spectrum here compares to that of Hollis *et al.* (1986) taken at optical phase ~0.5 (mean observational epoch of 1986.1); both R Aqr spectra are dominantly bimodal with emission peaks at −25 and −28 km s^{-1} but the relative intensities of the peaks have reversed in the intervening years.

same time period as the Hollis *et al.* (1986) R Aqr SiO maser position determination. Since the observing procedures were the same during both sets of R Aqr maser observations, and the above discussion shows the system to be stable and reliable, we do not believe that the difference in the R Aqr SiO maser results is due to systematic errors. On the other hand, the visibility phase fluctations, presumably due to the atmosphere, were substantially smaller during the more recent set of R Aqr observations. Whereas the unCLEANed map of the maser in the recent R Aqr observations was the same as the " dirty beam," the maser map was noticeably broadened in the previous determination, as noted in Hollis *et al.* (1986). Although one expects that the phase errors should average out, it is not certain that such will be the case for a source as weak as R Aqr. The lower visibility phase noise in the present R Aqr observations gives us confidence that these data provide a more reliable positional determination for the SiO maser.

In summary, as Table 1 shows, our new 1988 SiO position is coincident with the R Aqr optical positions measured by Michalitsianos *et al.* (1988) and by Baudry *et al.* (1990), and with component C1 on the 2 cm VLA map presented by Hollis *et al.* (1986). In the cases of the binary *o* Cet, which is devoid of nebulosity, and the symbiotic binary R Aqr, embedded in heavy nebulosity, the maser emission spots are most likely near-photospheric phenomena as expected. This work illustrates the difficulties in obtaining astrometric positions of weak sources of SiO maser emission. We favor the new R Aqr position because of better observing conditions which resulted in lower visibility phase noise, because we obtained similar results on *o* Cet, and because of the difficulty in understanding how the earlier results of R Aqr could be physically correct. We have exhaustively pursued alternative explanations and conclude that the R Aqr positional discrepancy is likely due to statistical considerations.

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