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SUB–ARC SECOND 2 CENTIMETER CONTINUUM AND SiO SPECTRAL LINE OBSERVATIONS OF R AQUARII

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ABSTRACT

Sub–arc second (~ 0″.15) VLA observations at 2 cm have resolved the previously reported 6 cm H II region, which engulfs the R Aquarii binary system, into two components. The stronger 2 cm component is itself partially resolved (distorted in shape), which may be a consequence of the long-period variable (LPV) wind being subjected to the intense ionizing radiation field of the hot companion's accretion disk, which we suspect is precessing. The distorted radio contours of the central H II region may also suggest that one hemisphere of the extended LPV envelope is directly illuminated by the intense radiation field of the accretion disk, owing to the orientation of the disk. The accretion disk can be formed by tidal mass exchange between the LPV and hot companion, which results in blobs of material periodically being expelled primarily in the northeast direction. Together with the VLA results, we report SiO observations obtained with the Hat Creek interferometer that suggest maser action occurs in the circumbinary nebulosity far removed from the LPV photosphere.

Subject headings: stars: accretion — stars: binary — stars: circumstellar shells — stars: radio radiation — stars: symbiotics

I. INTRODUCTION

A review of literature on R Aquarii suggests that the distance to it is uncertain but within the range 180–300 pc (cf. Solf and Ulrich 1985; Wallerstein and Greenstein 1980; Lepine, Le Squeren, and Scalise 1978; Gregory and Seaquist 1974). In any case, R Aquarii is the nearest symbiotic star system and has been well studied at X-ray, ultraviolet, optical, and radio wavelengths. Until now, the highest spatial resolution observations of the R Aquarii system were reported by Hollis *et al.* (1985). These authors used the VLA to determine morphology with ~ 1″ spatial resolution at 6 cm, and the features detected include (1) an optically thick, thermal, and unresolved H II region which presumably engulfs the binary system, or at least surrounds the hot ionizing companion of the cool, ~ 387 day, LPV; (2) an optically thin, thermal, and partially resolved jet (feature B) which is centered ~ 6″ away and at a position angle of ~ 29° with respect to the binary system; (3) an unresolved feature A which is centered ~ 2″.7 away and at a position angle of ~ 45° with respect to the binary system; (4) a weak and unresolved feature A′ which appears counter to feature A on the opposite side of the binary system. These 6 cm observations enabled a determination of the mass-loss rate of $2.7 \times 10^{-7}\ M_{\odot}\ \mathrm{yr}^{-1}$ from the system which probably originates from the LPV wind (cf. Hollis *et al.* 1985, 1986), forming the central H II region. Owing to the proximity of the binary system to Earth, VLA 2 cm observations in the A configuration should in principle permit resolving the LPV wind which is distorted by the photoionization due to the hot companion's accretion disk. Hence, VLA observations with a limiting spatial resolution of ~ 0″.15 were attempted along with complementary observations of SiO emission using the three-element Hat Creek interferometer to determine an accurate position of the LPV, assuming such emission is masing in proximity to the LPV photosphere (Elitzur 1980). The surprising results of these observations are presented and discussed with regard to possible models of the R Aquarii system.

II. OBSERVATIONS

a) *Very Large Array*

The NRAO[1] VLA observations, centered on feature A (see Table 1), were made on 1985 January 11 from (1900 LST to 0300 LST. The A antenna configuration with 26 antennas was employed at 2 cm (14,940 MHz), utilizing an intermediate frequency (IF) bandwidth of 50 MHz and two IF pairs. The spacing between antenna pairs varied between 0.8 and 36.6

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

TABLE 1

OBSERVATIONAL SUMMARY OF POSITIONS[a] AND FLUXES

R Aqr Feature (1)	α(1950) (2)	δ(1950) (3)	Integrated Flux (4)
C1	$23^{\rm h}41^{\rm m}14\overset{\rm s}{.}266(3)$	$-15°33'43\overset{''}{.}00(5)$	$8.52(22)^{\rm b}$ mJy
C2	23 41 14.293(3)	−15 33 42.65(5)	$1.37(20)^{\rm b}$ mJy
A[c]	23 41 14.398(7)	−15 33 40.85(10)	$< 0.67^{\rm b}$ mJy
SiO[d]	23 41 14.277(10)	−15 33 44.0 (2)	46.5×10^{-20} W m^{-2}

[a] The positions shown for VLA and Hat Creek observations reflect proper motion. Note that the time interval separating the 2 cm (1985 Jan 11) and SiO (1986 Jan–Apr) observations is ~ 15 months, and the correction for proper motion during that interval is at most ~ $+0\overset{\rm s}{.}003$ and ~ $-0\overset{''}{.}026$; these corrections are estimated from tabulations in the *Smithsonian Astrophysical Observatory Star Catalog.*

[b] The 1σ error on the background field of the VLA 2 cm map in Fig. 1 is ~ 0.05 mJy per beam; the corresponding integrated flux error for a given map feature is the product of 0.05 mJy times the square root of the number of beam areas encompassing the feature. The 2 cm limit for feature A is 3 σ.

[c] The position (including effects of proper motion) of feature A was determined by Kafatos, Hollis, and Michalitsianos 1983 with the VLA at 6 cm on 1982 Sep 26.

[d] The integrated spectrum of SiO at the position of peak emission (Fig. 2) has been determined from data obtained during the period 1986 Jan–Apr and yields a flux of ~ 3×10^{42} photons s^{-1} if R Aquarii is 180 pc distant or ~ 9×10^{42} photons s^{-1} if 300 pc distant.

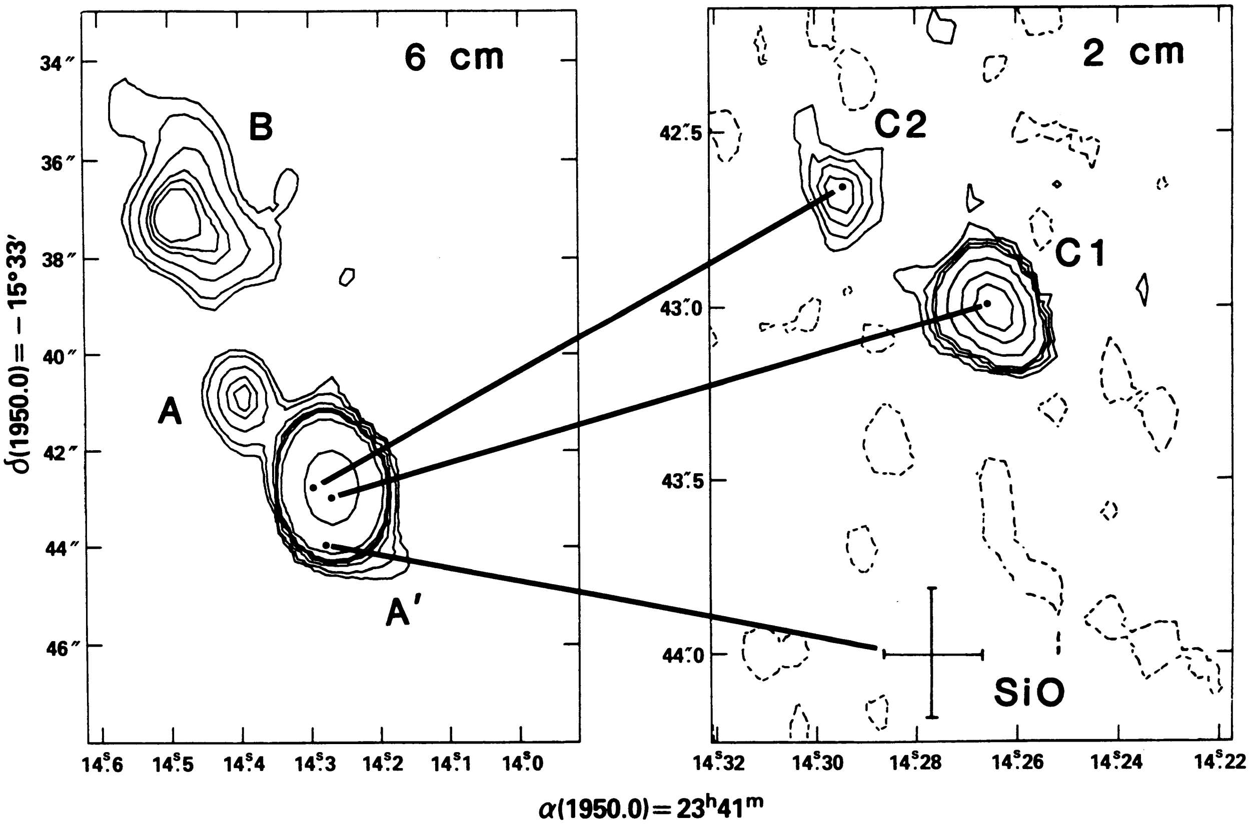

FIG. 1.—(*left*) The 6 cm VLA map of R Aquarii as published by Hollis *et al.* 1985; peak 6 cm flux is ~ 7.5 mJy per beam with contour levels of 0.15, 0.20, 0.30, 0.40, 0.45, 0.50, 0.75, and 3.70 mJy. (*right*) This work's 2 cm VLA map showing the unexpected division of the 6 cm central H II region into components C1 and C2; peak 2 cm flux is 4.00 mJy per beam with contour levels of −0.1, 0.2, 0.3, 0.4, 0.5, 1.0, 2.0, and 3.0 mJy. The plotted cross is the SiO maser position as determined by interferometry at Hat Creek; the extent of the cross in east-west and north-sourth directions is 2 σ.

km which yielded a restoring beam of 0''.157 × 0''.106 with a position angle of 1°.87. Each 12.5 minute observation of R Aquarii was followed by a 2.5 minute observation of 2345 − 167 which was used as the calibrator for amplitudes and phases; total time dedicated to each object was ~ 5.9 and ~ 0.9 hr, respectively, exclusive of array move time. The flux density scale was established by assuming 2345 − 167 to have a flux density of 1.15 Jy at a wavelength of 2 cm for the observational epoch. Moreover, 3C 48 and 3C 138 were also observed during the run and, under the preceding assumption, measured fluxes obtained were 1.699 ± 0.075 Jy for 3C 48 and 1.271 ± 0.069 for 3C 138. Both 3C 48 and 3C 138 are probably resolved for the VLA in the A configuration and were, therefore, not used for flux scale determinations. A summary of positions and integrated flux levels for R Aquarii 2 cm features is given in Table 1, and detected features are shown in Figure 1. Although our 2 cm observations were centered on feature A, we did not detect this feature which is ≤ 1 mJy at 6 cm (Hollis *et al.* 1985). Insufficient map signal (see Table 1) precluded self-calibration; therefore, map tapering was attempted but failed to detect feature A. Most probably poor phase stability precluded a 2 cm detection of feature A which is thought to be thermal (Kafatos, Michalitsianos, and Hollis 1986).

b) *Hat Creek Interferometry*

Vibrationally excited SiO emission (J = 2–1, v = 1, at 86,243.37 MHz) toward R Aquarii was observed at six configurations of the three-element Hat Creek Interferometer (Welch and Thornton 1985) in the period 1986 January to 1986 April. Spectral data were obtained using a digital correlation receiver with simultaneous measurements in a 5 and 10 MHz bandwidth, each with 128 channels, giving spectral resolutions of 39 and 78 kHz, respectively. A total integration of 32 hr was obtained on-source with phase calibration against quasi-stellar sources: 3C 454.3, 0007 + 106, and 2345 − 167. The flux scale was determined from observations of Venus using brightness temperatures given by Ulich (1981). The data were calibrated and reduced using standard Radio Astronomy Laboratory routines, and no significant changes in the spectrum were observed during the observational period (cf. Lane 1982; Nyman and Olofsson 1986). These data produced a synthesized beamwidth of 2''.6 in right ascension and 3''.6 in declination. The sidelobe response of the synthesized beam was removed using both the CLEAN and Maximum Entropy routines. The SiO emission is unresolved and consistent with a maser emitting source. The signal-to-noise ratio on the resultant maps can be improved by setting the amplitudes constant and using only the visibility phase which contains the position information. Maps were made of individual and averaged frequency channels. SiO positions were determined both from the maps and by fitting the visibility phase in the manner of Wright and Plambeck (1983). The relative positions of the three velocity features evident in the spectrum (Fig. 2) agree to within ±0''.2 in both right ascension and declination. The average position of the integrated maser emission from −32 to −20 km s^{-1} is given in Table 1. Figure 2 shows the spectrum centered at the peak of emission and integrated within a 5'' aperture which contains essentially all the SiO emission. The emission region is somewhat larger than the synthesized beam because of atmospheric "seeing." Systematic position errors were estimated by measuring positions from maps made using subsets of the data. An observed map position derived for 2345 − 167 (calibrated against 3C 454.3 and 0007 + 106) was compared to its well-known position and found consistent with these errors.

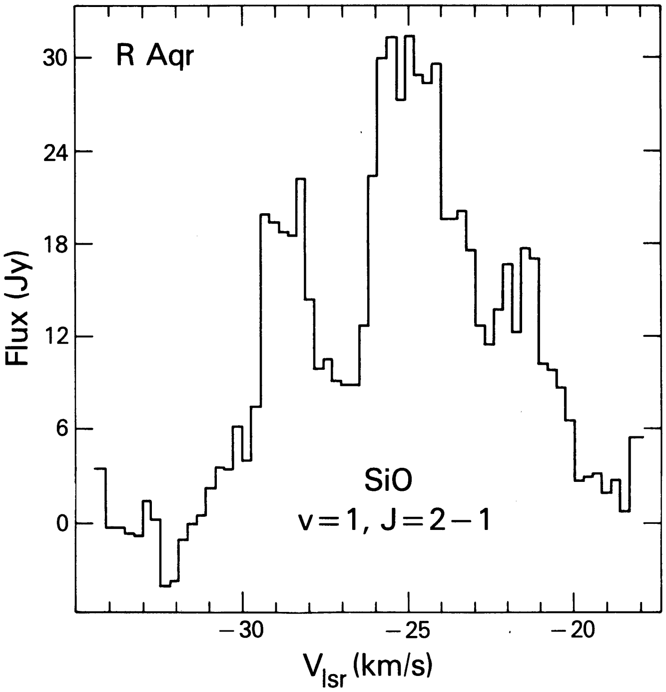

FIG. 2.—The v = 1, J = 2–1 SiO maser profile toward R Aquarii at a resolution of 78 kHz or 0.27 km s^{-1} for observations obtained from 1986 January to 1986 April (see text).

III. DISCUSSION

Figure 1 shows the present VLA observations in the form of a CLEAN, untapered, 2 cm map in relation to the CLEAN, untapered, 6 cm map previously published by Hollis *et al.* (1985). Unexpectedly, the 6 cm central H II region has divided into two components when observed with higher resolution and frequency. The brighter of the two components is designated C1 and the fainter (by a factor of ~ 6), C2. Relative to C1, feature C2 is ~ 0''.5 away and at a position angle ~ 55°. It is tempting to assume that C1 corresponds to the position of the LPV–hot subdwarf binary since (1) the semimajor axis of the binary orbit is ~ 2.5 × 10^{14} cm, which subtends < 0''.1 for distances > 180 pc to R Aquarii, and (2) the stronger flux emanating from C1 probably indicates the presence of the hot ionizing companion. Clearly, optical confirmation of the LPV position is needed.

Morphologically there are two aspects to these new VLA observations which are likely to provide important clues concerning the dynamics and physical conditions within the immediate environs of the binary system. First, there is a regular progression of position angle with distance for the various discrete features in the system relative to

C1: C2(~ 55°, ~ 0″.5), A(~ 45°, ~ 2″.7), and B(~ 29°, ~ 6″). This may indicate precession (seen in projection) of the object which is responsible for the expulsion of discrete blobs of material. The relation between position angle and distance for each of these features is difficult to reconcile with models that invoke shadowing effects to explain the sudden appearance of random condensations in the LPV wind (Spergel, Giuliani, and Knapp 1983). Second, the egg shape of C1 as seen in Figure 1 is certainly not that of the elliptical Gaussian beam. Moreover, C1 has an axis of symmetry with a position angle of ~ 45° which is far removed from the beam position angle of 1°.87. If, in fact, the hot ionizing companion star is contained within C1, the partially resolved C1 feature may indicate that the extended envelope of the LPV is not illuminated uniformly. This follows if the accretion disk in the system is inclined with respect to the orbital plane owing to precession. Thus, the tenuous atmosphere/envelope of the LPV more directly exposed to the intense radiation field of the accretion disk would become distorted, resulting in a wind or stream which is accelerated along an axis normal to the plane of the disk. This may explain why the R Aquarii jet appears one-sided.

Kafatos, Michalitsianos, and Hollis (1986) have recently proposed a new accretion disk model for the R Aquarii system to explain their spatial/spectral observations in the ultraviolet in context with X-ray, optical, and radio observations. In this model a thick accretion disk is formed around the hot ionizing companion, primarily by Roche lobe overflow at periastron, and discrete blobs of gas and dust are expelled by radiation pressure from the outer extremities of the accretion disk at characteristically low expansion velocities. Such velocities (e.g., ~ 50–100 km s^{-1}) are, in fact, observed in the system (Solf and Ulrich 1985). The model further predicts that two oppositely directed ionizing cones of radiation, whose opening angles of ~ 150° are determined by the accretion disk, account for the observed features in the system. Hence, thermally expanding discrete blobs are expelled at moderate velocities consistent with the observed kinematics and the morphology of our VLA maps. The problem of symmetrical jet action in such a model remains to be explained. If precession is occurring as our radio results suggest, the total inferred precession angle is at least ~ 26°; such an angle may be significant enough to influence the apparent one-way flow of discrete blobs, the result of nonuniform illumination of the extended LPV envelope and/or atmosphere, which is in proximity to the source of ionizing radiation. At periastron, mass exchange between the LPV and hot secondary would increase substantially, thus greatly intensifying the radiation field of the accretion disk and further ionizing blobs of material which were expelled during previous outbursts, in addition to leading to the expulsion of new parcels of material.

Figure 2 displays the $v = 1$, $J = 2$–1 SiO spectrum for R Aquarii obtained from our Hat Creek observations at the position of peak emission (see Table 1). Although the assumption that C1 engulfs the orbit of the system seems reasonable, our SiO observations unexpectedly determine a maser source position which is ~ 1″ or ~ 2.7×10^{15} to ~ 4.5×10^{15} cm south of C1 for distances of 180 and 300 pc, respectively. The maser position and 1σ uncertainties in both coordinates are plotted in Figure 1. Since the LPV is a red giant, Mira-like variable and $M \approx 2\ M_{\odot}$ (Kafatos, Michalitsianos, and Hollis 1986), the diameter of the star would be ~ 6×10^{13} cm with an individual maser spot size diameter of ~ 10^{14} cm (Bertschinger and Chevalier 1985). By means of VLBI observations, Lane (1982, 1984) has shown that the SiO ($v = 1$, $J = 1$–0) emission in a red giant envelope is comprised of clusters of individual maser sources which extend some ~ 4–6 r_* from the star's center. In the case of R Aquarii, this would translate to ~ 1×10^{14} to ~ 2×10^{14} cm which is not consistent with the observed ~ 2.7×10^{15} to ~ 4.5×10^{15} cm separation, assuming the position of the LPV itself is coincident with C1. However, the largest individual maser position separation measured by Lane is ~ 1.6×10^{15} cm for the red supergiant VX Sgr with the $v = 1$, $J = 1$–0 transition of SiO. Moreover, the maser spot distribution for VX Sgr was modeled by an expanding circumstellar shell, assuming the star at the center. The derived radius of this shell is ~ 8×10^{14} (Lane 1982, 1984). Hence, our $v = 1$, $J = 2$–1, observations would be more characteristic of a red supergiant envelope even though the R Aquarii LPV is presumably a red giant. We point out that the Lane (1982) SiO maser VLBI observations were of single red giant and supergiant envelopes while we have observed a unique binary system containing a red giant; as such the separation distance between the R Aquarii LPV and the maser is ~ 3.4 to ~ 5.6 times the shell radius that Lane obtained for the VX Sgr envelope. On the other hand, the presence of the hot companion star of the LPV would provide a means to populate the high energy levels of the SiO maser and, thus, probably permits the maser to form anomalously far from the LPV in the circumbinary nebulosity. With future improvements in telescope system sensitivity, the R Aquarii binary system should be probed with spectral line VLBI techniques to determine individual maser positions, utilizing the relatively strong $v = 1$, $J = 1$–0 transition (cf. Lane 1982; Spencer *et al.* 1981).

In summary, our 2 cm VLA continuum observations indicate that we have (1) partially resolved the LPV wind as it is distorted by the photoionization of the hot companion's accretion disk; and (2) determined that precession of the accretion disk is possibly occurring as suggested by the morphology associated with the apparent ejection of features C2, A, and B. Moreover, in conjunction with our VLA observations, our Hat Creek interferometry of SiO suggests that (3) the $v = 1$, $J = 2$–1 transition emanates from a circumbinary layer far removed from the position of the LPV itself (~ 2.7×10^{15} to ~ 4.5×10^{15} cm). We note that our original motivation for obtaining the SiO observations was the belief that the line emission would be near the LPV photosphere as suggested by collisionally pumped SiO maser models (notably, the convective cell model by Elitzur 1980), and, as such, a position determined for the maser would be an effective determination of the LPV position itself. Our assumption was probably incorrect, and our observations and those of Lane (1982) underscore that the question of pumping mechanisms for SiO emission in red giants and supergiants is still open.

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