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R AQUARI: THE LARGE-SCALE OPTICAL NEBULA AND THE MIRA VARIABLE POSITION

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ABSTRACT

The R Aquarii symbiotic star system is surrounded by a large-scale optical nebula. We present observations of the nebular [O III] structure and discuss its morphological significance in context with previously observed small-scale radio-continuum features, which may be related. We suggest that a precessing accretion disk may explain the global features of both the large-scale optical emission and the small-scale radio emission. Moreover, we have determined an accurate position of the system's Mira, which suggests that a recent theoretical model, yielding an egg-shaped central H II region for symbiotic systems with certain physical parameters, may apply to R Aquarii. The optical position of the 387^d period Mira variable is consistent with our previous findings in the radio, that SiO maser emission is far removed from the Mira photosphere.

I. INTRODUCTION

R Aquarii is at the center of a very complex system of large-scale nebulosity, which extends $\sim 2'$ in the east-west (EW) direction and $\sim 1'$ in the north-south (NS) direction (e.g., see broadband optical imagery shown in Sopka *et al.* 1982). The "S"-shaped filaments of the NS nebula and the two intersecting arcs of the EW nebula are nearly perpendicular. Since the early observations of Hubble (1943) and Baade (1944), the nebula was shown to be slowly expanding with velocities of 50–100 km s⁻¹. Based on expansion age, Merrill (1935, 1950) suggested that a single nova outburst about 600 yr ago could account for the nebulosity.

Recently, Solf and Ulrich (1985) proposed that the morphology of the EW nebula suggests a "bipolar, hourglass-like expanding shell," in which the emission, originating in a thin surface layer of the shell, is most prominent in an equatorial "ring zone," and becomes fainter at higher latitude angles. Solf and Ulrich proposed that the EW nebular ring was formed in a single novalike outburst about 640 yr ago, while the NS nebula was created in a more recent event about 185 yr ago. This model is supported, in part, by the kinematical properties of the nebula, deduced from moderate resolution coude spectra of the [N II], [S II], H α , and He I emission lines, which Solf and Ulrich interpret in context with the broadband UG1 and RG1 filter images obtained by Herbig in 1980 and published in Sopka *et al.* (1982).

R Aquarii also has small-scale nebular features, as shown in the high-spatial-resolution radio-continuum maps (Fig. 1) obtained with the Very Large Array (VLA). Figure 1 clearly shows that the small-scale jetlike structure is composed of at least four discrete emission knots whose position angles (P.A.), relative to R Aquarii, suggest an ordered and sequential geometry of ejecta (Kafatos *et al.* 1983; Hollis *et al.* 1985, 1986). The most prominent component of the jet is feature B (a Fig. 1 radio feature, which has an optical coun-

terpart), which suddenly appeared in the late 1970s (Herbig 1980), and is approximately 6'.5 northeast of R Aquarii. Solf and Ulrich (1985) argue that feature B is a density enhancement associated with the outburst that formed the NS nebula and was only seen recently (1977) due to its interaction with other NS nebular material (i.e., brightening due to the rapid deceleration). On the other hand, ultraviolet observations of feature B indicate high-excitation emission lines of N V, He II, and C IV have increased by a factor ~ 5 between 1982 and 1985, compared with the essentially constant absolute flux of lower-excitation UV lines observed in the central H II region surrounding R Aquarii (Kafatos *et al.* 1986). The absence of N V, and comparatively weak He II emission in the H II region, indicates that the gas in the immediate vicinity of the LPV/hot subdwarf binary is lower in thermal excitation compared with feature B (Kafatos *et al.* 1986). This further suggests that soft x rays recently detected with EXOSAT in the 0.25–1 keV energy range in 1985 (Viotti *et al.* 1987) are probably more intense in feature B, where N V and He II are present (Kafatos *et al.* 1986).

R Aquarii is also the only known symbiotic nova to exhibit SiO maser activity (Lepine *et al.* 1978); this is a surprising result given the presence of a strong ionizing radiation field. However, a further complication, shown in Fig. 1, concerns the location of the SiO maser in relation to the radio-continuum morphology (Hollis *et al.* 1986), and, in particular, in relation to the central H II region, which must be nearly coincident in position with the 387^d period Mira. This follows because collisionally pumped models for the vibrationally excited $J = 2-1$, $v = 1$ transition predict SiO masering in the extended atmospheres of M giants and M supergiants (Elitzur 1980). However, for R Aquarii the position of the SiO maser is far removed ($\gtrsim 1''$ or $\gtrsim 10^{15}$ cm) from the central H II region and, hence, the Mira's photosphere (Hollis *et al.* 1986).

Here we have attempted to probe the R Aquarii complex on two fronts: (i) discern the morphology of the filamentary

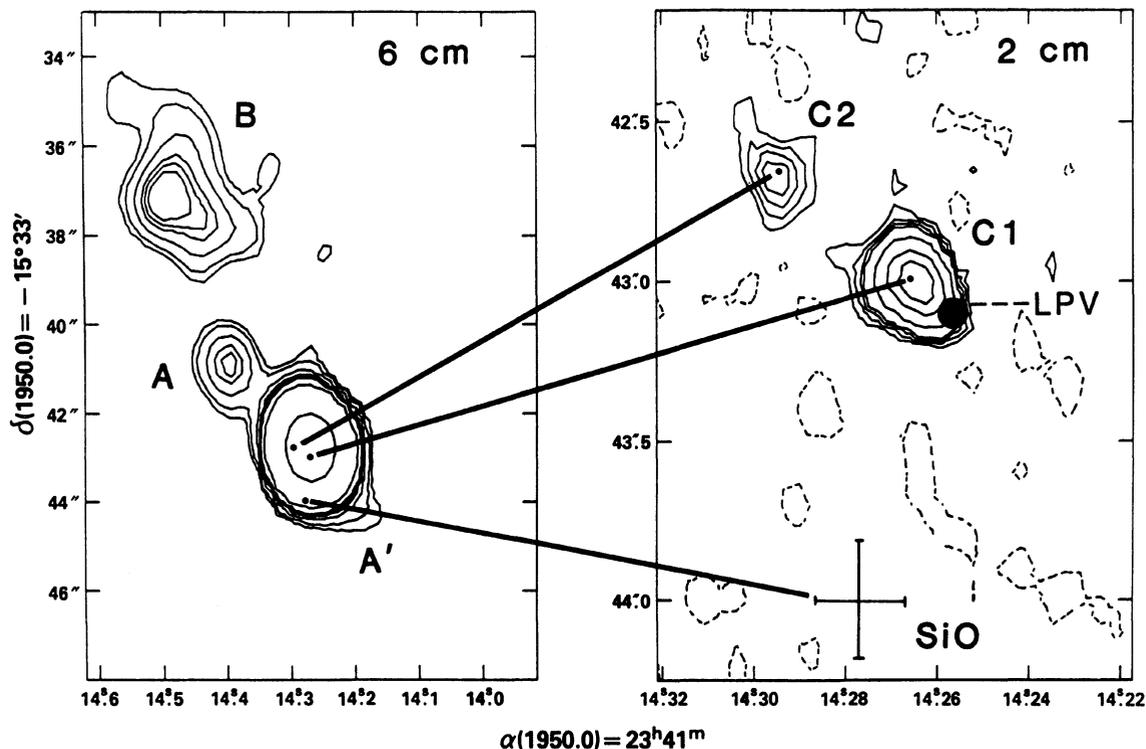


FIG. 1. (left) The 6 cm VLA map of R Aquarii (Hollis *et al.* 1985); the peak 6 cm flux is ~ 7.5 mJy per beam with contour levels 0.15, 0.20, 0.30, 0.40, 0.45, 0.50, 0.75, and 3.70 mJy. Relative to the central H II region C1, feature C2 is $0''.5$ at P.A. = 55° , feature A is $2''.5$ at P.A. = 45° , and feature B is $6''.5$ at P.A. = 29° . (right) The 2 cm VLA radio map (Hollis *et al.* 1985) in which the central H II region is resolved into feature C1 and C2; the peak 2 cm flux is 4.00 mJy per beam, with contour levels — 0.1, 0.2, 0.3, 0.4, 0.5, 1.0, 2.0, and 3.0 mJy. The 1950.0 position of these radio features reflects 1985.03 epoch proper motion. The 1950.0 position of the SiO maser ($J = 2-1$, $v = 1$ at 86 243.37 MHz) reflects 1986.13 epoch proper motion as determined from the Hat Creek three-element interferometer (each leg of the cross is the 1σ positional error). The 1950.0 position of the LPV determined in this work is plotted with a 1σ positional error radius (see text) and reflects 1986.68 epoch proper motion.

large-scale structure in [O III] of the NS and EW nebulae, and (ii) determine an accurate optical position for the Mira or long-period variable (LPV). By studying the nebular structure, we hope to investigate the mass-ejection mechanism. By determining the optical position of the LPV, we hoped to test a recent model that predicts the ionization structure of radio-emitting material in the vicinity of the binary, as well as determine the conditions under which the SiO maser is pumped.

II. OBSERVATIONS

Narrowband interference-filter images of R Aquarii in the emission lines of [O III] λ 5007, [O III] λ 4363, and H α were obtained with the RCA #3 CCD camera on the NOAO* #1 0.9 m telescope at Kitt Peak on 1986 October 1. The [O III] images at λ 5007 and λ 4363 were taken as a series of 10 min exposures, for a total integration of 120 and 60 min, respectively. The 10 min [O III] exposure limit was chosen to avoid saturating the CCD in the region around the star (AAVSO m_v (1986.75) ~ 7.5 , Mattei (1987)) and its associated 'blooming' along the east-west direction of the CCD. However, several pixels at the core of the LPV in the [O III] images did saturate the analog-to-digital converter in the

CCD electronics. One H α image was taken with an integration time of 5 min. However, the higher measured signal of the LPV through the H α filter saturated the region around the star and produced a large extended stellar halo which dominated the H α emission. Also, the RCA #3 CCD chip has a high susceptibility to particle 'hits,' and the short exposures minimized any confusion problems between faint diffuse sources and these background hits.

The sky conditions were good and afforded a photometric reproducibility of $\pm 3\%$. The absolute intensity calibration was based on observations of NGC 6210 and Feige 110 (a NOAO IRS flux standard) taken at a similar airmass. Each image was bias-frame subtracted and flatfielded. Finally, to improve the signal-to-noise, and especially to eliminate the particle hits, a 3×3 median smoothing was applied (Fig. 2). The resultant effect on the spatial resolution is minimal since the image scale of 0.86 arcsec per pixel is less than the $\sim 1.8''$ seeing.

The stellar contamination of the extended faint nebosity surrounding R Aquarii is observed to extend to $\sim 20''$ from the LPV. This is evident by the agreement with the predicted ratio of stellar fluxes through the λ 4363 and λ 5007 filters along the SE-NW directions where there are no obvious [O III] λ 5007 emission 'knots.' Thus, the only [O III] λ 4363 emission detected is in the SW-NE direction and within $10''$ of the LPV. The faint extended wings of the stellar profile are due to atmospheric and instrumental scattering.

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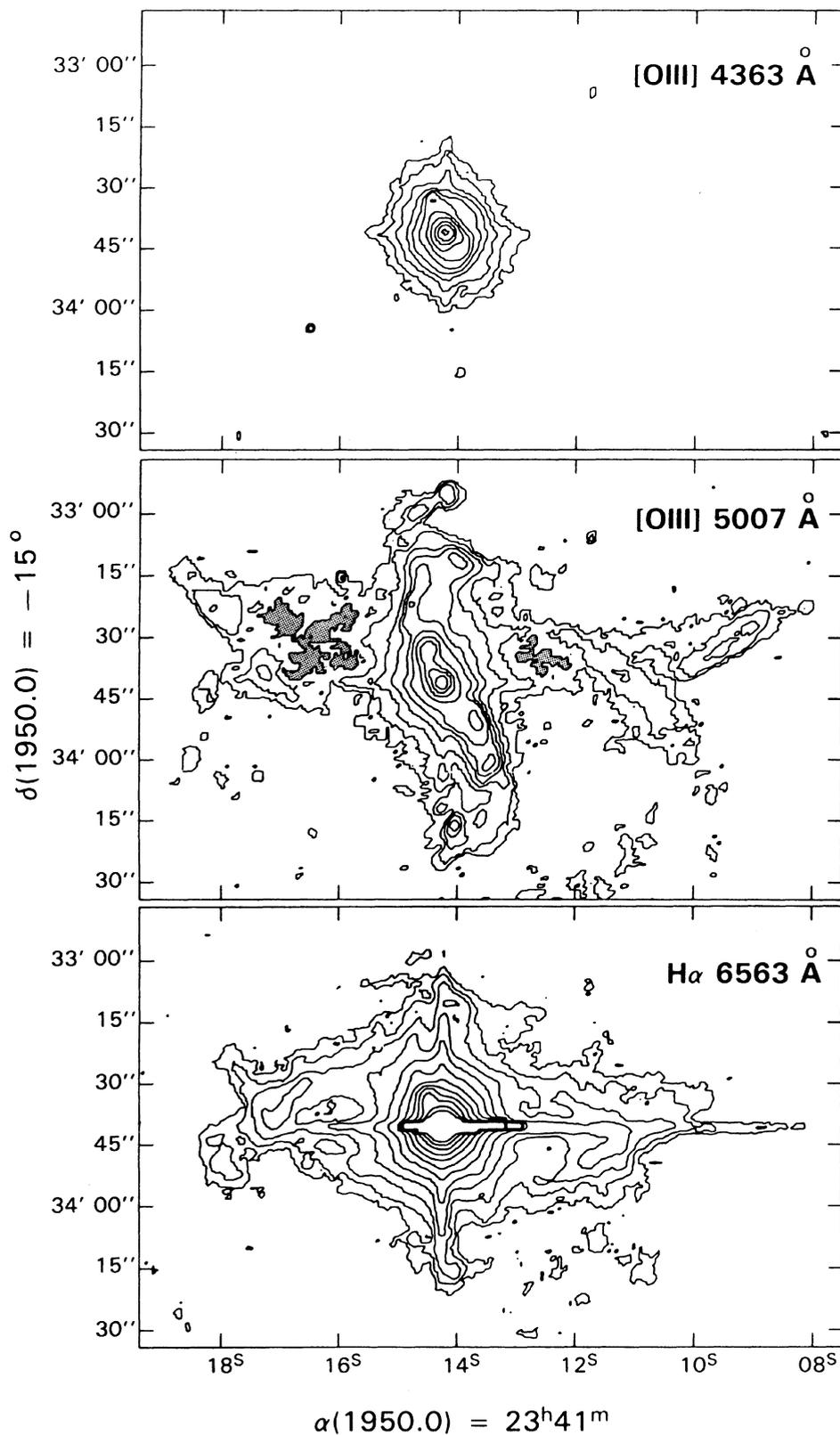


FIG. 2. (top) Shown is a contour image of R Aquarii through an interference filter with a FWHM passband of 18 Å centered at the [O III] 4363 Å emission line. The dominant contribution to the measured signal in all regions is from the LPV (i.e., scattered starlight), except for structure in the SW-NE direction. The diffraction spikes are noticeable along the NS and EW directions. These data represent an effective 1 hr exposure (see text). Contour intensity levels are 31 (3σ), 62, 124, 248, 496, 992, 1980, 3970, 15 900, 63 500, and 254 000 Rayleighs; the lowest contour level is 3σ above sky background. Note that 1 Rayleigh = $10^6 \times (4\pi)^{-1}$ photons $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$. (middle) Shown is a contour image of R Aquarii nebulosity in [O III] line emission centered at 5007 Å with a FWHM passband of 15 Å. These data represent an effective 2 hr exposure (see text). There is stellar contamination within 20" of the LPV, but the [O III] 5007 Å emission 'knots' generally dominate. Contour intensity levels are 14 (3σ), 28, 56, 112, 224, 448, 1792, 7168, 28 670, and 114 700 Rayleighs. Note that the shaded areas in this image represent values less than the lowest contour level. Such extended spatial mapping of [O III] line emission structure has not been reported previously. (bottom) Shown is a contour image of R Aquarii nebulosity in H α line emission centered at 6563 Å with a FWHM passband of 38 Å. These data represent a 5 min exposure. The stellar contamination is severe with the LPV signal saturating the CCD and produces a halo which everywhere dominates the H α emission. Contour intensity levels are 113 (3σ), 225, 450, 900, 1800, 3600, 7200, 14 400, 28 800, 57 600, 115 200, and 230 400 Rayleighs.

Astrometric observations of the LPV light of R Aquarii and ten FK4 reference stars, with well-known positions lying within ± 1 hr right ascension and $\pm 15^\circ$ declination of R Aquarii, were obtained using the 8 in. transit circle of the U.S. Naval Observatory at Flagstaff, Arizona, between 1986 August 14 and 1986 September 29. The instrument has been previously described by Holdenried and Crull (1986). For each observing session, reference stars were observed and the position of R Aquarii was reduced differentially to the FK4 system in the manner of Dick and Holdenried (1982). The resultant R Aquarii LPV position was determined from 11 observations in right ascension and 12 observations in declination: $\alpha(1950.0) = 23^{\text{h}}41^{\text{m}}14^{\text{s}}.256(4)$ and $\delta(1950.0) = -15^\circ 33' 43".101(45)$, where the uncertainties are 1σ on the mean position; the mean epoch of the observations is 1986.68, with no correction for proper motion. Hence, the 1950.0 position reported here can be directly compared with the recent radio-continuum features obtained with the VLA (Hollis *et al.* 1986).

III. RESULTS AND DISCUSSION

The large-scale [O III] λ 5007 images shown in Fig. 2 convey a clear impression of symmetric NS bipolar flow. The curvature of the NS arcs suggests a counterclockwise rotation of the central object, which repeatedly expels material. Likewise, the small-scale radio jet features (C2, A, and B) shown in Fig. 1 define an arc of similar curvature. There is a linear relation between the distances and position angles of C2, A, and B relative to C1 (central H II region), which also suggests an ordered geometry. If parcels are ejected in successive outbursts, each parcel will expand as it cools (Kafatos *et al.* 1986). This is consistent with the 'older' feature B being more spatially extended compared with the closer, 'younger,' and more compact radio knots A and C2.

The foregoing comparison between the extended large-scale bipolar structure seen in [O III] and the small-scale radio features is noteworthy, but there are no prominent radio features to the southwest of the central H II region as one would expect if the small-scale radio features were also bipolar. In terms of this 'missing' small-scale bipolar structure, only the extended contours associated with radio feature A', which are elongated SW of feature C1 (Fig. 1), indicate counterjet symmetry with feature A. Similar arguments have been made by Mauron *et al.* (1985) from near-UV optical images. The general one-sidedness of the radio-jetlike structure could be possibly explained by the hot star's hypothetical precessing accretion disk (Kafatos *et al.* 1986), which periodically interacts with the LPV envelope, expelling material away and toward the LPV.

Three-body precession can only occur if the accretion disk is sufficiently massive. However, a massive disk cannot form by the capture of the Mira wind alone, because this would imply an unreasonably large mass-loss rate for the late-type giant, if only $\sim 10\%$ of the stellar wind was captured. Kafatos *et al.* (1986) have proposed that a thick accretion disk could form by Roche lobe overflow, at or near periastron of a highly elliptical 44 yr orbit. During this orbital phase, substantial mass could be drawn from the envelope of the Mira, creating the disk; more material could be accreted by the disk by capturing a fraction of the Mira wind, or by tidal mass exchange at periastron in successive orbital encounters. The Roche lobe overflow would correspond to outbursts in the system, similar to the spectroscopic outburst that was observed in the 1920s (Kafatos *et al.* 1986). If par-

cels are ejected mainly perpendicular to the axis of the disk during these tidal events, and have an average velocity of $\sim 50 \text{ km s}^{-1}$, we can estimate the precession period for two cases, given the distance to the system of 180–300 pc: (i) assume the precession axis of the accretion disk is along the line of sight. We find that the rotation axis moves 26° (i.e., the P.A. difference between C2 and B) in 185 yr (typical expansion age for feature B). The total precession period would be ~ 2500 yr. (ii) assume that the precession axis of the accretion disk is in the plane of the sky. Further assuming that any one of the S-shaped structures shown in the Fig. 2 [O III] image is due to the expulsion of material while the accretion disk precesses about an axis tangential to the center of the S, the oldest ejecta would then lie at the ends of the S, while the newest ejecta would originate from the S center. For such a geometry, this would define one-quarter of the precessional period, which is estimated to be $\lesssim 2100$ yr for a typical ejection velocity of $\sim 50 \text{ km s}^{-1}$, if R Aquarii is 180 pc distant.

A thick accretion disk is consistent with the relative excitation of jet features C2, A, and B compared with the central H II region (feature C1). If the broad, intense cone of ionizing accretion-disk radiation photoexcites the jet features (Kafatos *et al.* 1986) with a disk luminosity $L_{\text{disk}} \sim 10L_{\odot}$, then the ionized parcels which are ejected primarily normal to the disk plane slowly accelerate due to radiation pressure acting on grains. The parcels achieve modest terminal velocities of $\lesssim 100 \text{ km s}^{-1}$, which are consistent with the radial-velocity differences observed between the jet features and central nebula (Solf and Ulrich 1985). If the disk is presently seen nearly edge-on, consistent with the system being eclipsing (Wallerstein 1986), most of the ionizing radiation from the inner disk is obscured. However, the ejecta are exposed directly to the radiation field of the disk and hot subdwarf, which explains why the jet parcels are higher in excitation compared with the central H II region (Kafatos *et al.* 1986). However, we make note that the existence of thick accretion disks in astrophysics is controversial and has yet to be demonstrated by observations.

On the other hand, twisted ejection, which leads to the formation of the filamentary arcs that characterize the outer nebula, could result as a consequence of binary motion. Because ejection of material occurs primarily normal to the disk plane, orbital-motion effects would tend to complicate the geometry of the disk wind by twisting the flow. The wind from the Mira would also tend to exert a force on the disk wind away from the late-type giant. For the purposes of this paper, it is not necessary to dwell on these, admittedly speculative, ideas.

We make note that other mechanisms for explaining outbursts in symbiotic stars have been proposed. For example, novalike outbursts can initiate expulsion from thermonuclear detonation at the surface of the accreting star. However, the relatively small velocities of $\lesssim 100 \text{ km s}^{-1}$ observed in the R Aquarii nebula and radio/optical/UV jet indicate that mass expulsion cannot originate close to the hot star. Kafatos *et al.* (1986) have proposed that the radiatively driven mass expulsion takes place in the outer regions of an extended thick accretion disk that encircles the hot star. In the outer disk region, the escape velocities are $\lesssim 200 \text{ km s}^{-1}$, consistent with the characteristic velocities found in nebular features (cf. Solf and Ulrich 1985).

Within the large-scale nebula, the excitation can be obtained from the [O III] $I(\lambda 5007)/I(\lambda 4363)$ intensity ratio.

The intensity of the [O III] λ 4363 line becomes greater as the upper level (1S_0) is increasingly populated. This occurs as the electron temperature (T_e) increases, and/or as the electron density (n_e) increases. The [O III] intensity ratio affords an estimate of T_e from the ionization models of Kafatos and Lynch (1980). For $I(\lambda 5007)/I(\lambda 4363)$ values in the range 10–100, we obtain $T_e = 66\,000$ – $11\,000$ K, respectively, if $n_e \lesssim 10^4$ cm $^{-3}$. At these densities, there is little dependence of the [O III] ratio on n_e (Kafatos and Lynch 1980). Thus, the high-excitation [O III] λ 4363 line is detected in generally hotter regions, (i.e., the H II region and in features A, A', and B). On the other hand, [O III] λ 5007 emission is more ubiquitous (see Fig. 2), and in the outer nebula the n_e is 100–800 cm $^{-3}$ (Solf and Ulrich 1985). From UV-line intensity ratios (Kafatos *et al.* 1986) n_e is $\sim 3 \times 10^4$ cm $^{-3}$ in the higher-density region of the jet (primarily feature A), and $\sim 10^4$ cm $^{-3}$ in feature B. The [O III] intensity ratio of ~ 15 to ~ 20 found in feature B implies that T_e is $\sim 35\,000$ to $\sim 27\,000$ K, with an uncertainty in temperature of ± 5000 K. These temperatures are somewhat higher compared with values obtained from optical or UV-line spectra of $T_e \sim 20\,000$ K (Kafatos *et al.* 1986), and could be explained if the λ 4363 emitting gas is clumpy, and higher in density compared with the more ubiquitous λ 5007 regions. For example, if $T_e \sim 20\,000$ K in the jet, then $I(\lambda 5007)/I(\lambda 4363) \sim 10$, for $n_e \sim 10^6$ cm $^{-3}$. Our observations do not indicate that feature B is composed of knots of emitting material. However, near-UV images of H. Sol (private communication) clearly indicate that feature B itself is composed of at least four distinct clumps, which are evident on the UG1 plates but are not as conspicuous in published contour plots of the same data (Mauron *et al.* 1986). Finally, Fig. 2 shows that the H α contours are less extended in the EW direction compared with the [O III] λ 5007 contours. This would indicate that higher electron temperatures prevail outside of the region determined by the H α emission and, therefore, the H α emission cannot simply be the result of a purely photoionized H II region.

Figure 1 shows that our optical determination of the LPV position is near or on the ionization front to the west and south of C1 and may provide clues concerning the ionization structure of the C1 H II region. Taylor and Seaquist (1984) find that the geometry of the central ionized region in symbiotic stars is dependent on (1) the separation of the cool giant and hot companion, (2) the effective temperature T_{eff} of the hot companion, and (3) the mass-loss rate of \dot{M} of the cool giant. For sufficiently high mass-loss of $\dot{M} \sim 3 \times 10^{-6} M_{\odot}$

yr $^{-1}$, the ionization region formed around the hot companion takes the shape of an ellipsoid, and the cool giant is located in the neutral region just outside of the ionization front (cf. Nussbaumer and Vogel 1986). Even though the mass-loss rate of the Mira in R Aquarii is estimated at $\dot{M} \sim 2.7 \times 10^{-7} M_{\odot}$ yr $^{-1}$ (Hollis *et al.* 1986) and is small compared with the cases considered by Nussbaumer and Vogel, the lower effective temperature of the hot companion $T_{\text{eff}} \sim 27\,000$ K may compensate for the small \dot{M} and result in an egg-shaped H II region, rather than an expected hyperboloid-shaped ionization front. The overall mass-loss rate from the system in R Aquarii may, however, be substantially greater than a few times $10^{-7} M_{\odot}$ yr $^{-1}$, which we deduced from radio data.

Although the morphology of the H II region (feature C1) is similar to what the Nussbaumer and Vogel model predicts, the presence of an intense radiation field associated with a thick accretion disk, which could be precessing, will introduce important complications. This will make direct application of Nussbaumer and Vogel's model difficult in the case of the R Aquarii radio morphology.

While the Mira position from optical observations and the 2 cm peak continuum emission from A array VLA radio observations have nearly the same uncertainties (i.e., 0".05) and absolute positions, the SiO maser position has a larger uncertainty (i.e., $\sim 0".2$) as determined by the methodology of Wright and Plambeck (1983). However, the separation of the Mira and SiO maser is $\sim 1''$, which, in the most conservative case, corresponds to an $\sim 5\sigma$ positional separation (Hollis *et al.* 1986). Hence, the physical separation of the Mira and the SiO maser is $\gtrsim 100$ stellar radii, and is inconsistent with the convective cell model (Elitzur 1980), which explains the SiO emission-pumping mechanism by collisions that require the high column densities in extended atmospheres of M giants and M supergiants evolving singly. In fact, the SiO maser is far removed from the entire binary system since the semimajor orbit axis is $\gtrsim 10^{14}$ cm (Kafatos *et al.* 1986) and the Mira is $\sim 2.7 \times 10^{15}$ to $\sim 4.5 \times 10^{15}$ cm from the SiO maser, for distances to R Aquarii of 180 to 300 pc, respectively. Clearly, the R Aquarii binary system, its circumbinary nebulosity, and the presence of SiO maser emission may require shocks to obtain the densities necessary to collisionally pump the maser.

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