

1989

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Recommended Citation

Hollis, J.M., Yusef-Zadeh, F., Cornwell, T.J., Oliverson, R.J., Michalitsianos, A.G., Kafatos, M. (1989) RX Puppis: Detection of Asymmetrical Radio Structure, *The Astrophysical Journal*, 337:514-519. doi: 10.1086/167119

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This article was originally published in *Astrophysical Journal*, volume number, in year. DOI: [10.1086/167119](https://doi.org/10.1086/167119)

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RX PUPPIS: DETECTION OF ASYMMETRICAL RADIO STRUCTURE

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Received 1987 December 28; accepted 1988 July 11

ABSTRACT

Subarcsecond ($\sim 0''.3 \times \sim 0''.1$) observations of the RX Puppis symbiotic system with the Very Large Array (VLA) have resolved 2 cm continuum emission which deviates from a previously reported circularly symmetric radio distribution. The radio structure is comprised of at least three nearly colinear components. Under the assumption that the strongest feature is coincident with the hot star, the other two features lie 230 and 590 AU distant. These radio features are reminiscent of small-scale radio structure detected toward R Aquarii, another symbiotic star system, and probably represents material ejected from the RX Puppis system at an earlier epoch.

Subject headings: stars: binaries — stars: individual (RX Pup) — stars: radio radiation — stars: symbiotic

I. INTRODUCTION

Symbiotic stars comprise a class of interacting binary systems whose composite spectra indicate both a late-type red giant and a hot companion. They are further divided into two subclasses: stellar-type ("normal" cool star infrared continuum emission) and dust-type (thermal infrared radiation from dust prominent). The prevailing theory is that the compact, hot star accretes material from the red giant, either through Roche lobe overflow or capture from a wind, thus giving rise to an accretion disk surrounding the hot star. To date, ~ 10 such systems have been observed with sufficient spatial resolution and sensitivity to enable spatial mapping of the extended radio continuum structure with the VLA (Taylor 1988).

Among the known symbiotic stars, one of the nearer, stronger, and putatively variable radio emitters is RX Puppis, a dust-type system with a Mira-like long period variable (LPV) of 580 days and a hot subdwarf companion with $T_{\text{eff}} \sim 10^5$ K (Kafatos, Michalitsianos, and Feibelman 1982). Reports of radio emission from RX Puppis have always been intriguing. For example, Seaquist (1977) first detected radio continuum emission at centimeter wavelengths from RX Puppis in 1975 January and February which suggested that the emission was variable on an hourly timescale and that it possessed a flat radio continuum spectrum² indicative of free-free emission from an optically thin gas. Subsequently Wright and Allen (1978) confirmed that $\alpha \sim 0$ and source flux variations were noted. Rapid flux variations would not be consistent with any simple model of thermal radiation and could be suggestive of a nonthermal source of radiation in RX Puppis. Since these

early measurements, the source has completely changed its radio signature. As recently as 1985 March–April the spectral index in the range 1.4–110 GHz was measured to be $+0.80 \pm 0.06$ (Hollis *et al.* 1986) and $+0.72 \pm 0.04$ (Seaquist and Taylor 1987). Additionally, Hollis *et al.* (1986) found no hourly RX Puppis flux variations in an analysis of 6 cm VLA data obtained with the maximal hour angle coverage possible on three successive days (i.e., 1985 March 29–31) and no linear polarization was observed which would have indicated a non-thermal source.

Recently, Hollis *et al.* (1986) suggested that the RX Puppis system possesses extended 6 cm continuum emission; their evidence was obtained with the VLA in the hybrid A/B configuration and was deduced from a plot of visibility amplitude versus increasing projected baseline and also a comparison of observed total flux to the peak flux of the single radio feature observed. Moreover, these authors indicated that double extended source structure was weakly suggested at longer projected baselines and predicted that a full A configuration at 2 cm would probably resolve features within the system.

The only similar system closer to Earth than RX Puppis is R Aquarii (~ 250 pc; see Whitelock 1987), a dust-type symbiotic star containing a Mira-like LPV. It, too, had been previously reported as a variable radio emitter (Bowers and Kundu 1979; Gregory and Seaquist 1974). However, monitoring with the VLA from 1982 to 1984 yielded no measurable 6 cm flux variations of the central source (Hollis *et al.* 1985). Moreover, we probed R Aquarii extensively in high resolution and found small-scale (arc seconds), jet-like features emanating from one side of a relatively bright central H II region which is nearly coincident with the Mira position (Michalitsianos *et al.* 1988b). Thus, we were motivated to conduct a search of RX Puppis to determine the differences between the two seem-

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² The power-law spectrum convention used here is of the form $S_\nu \propto \nu^\alpha$, where S_ν is the flux, ν is the observation frequency and α is the index.

TABLE 1
RX PUPPIS OBSERVATIONAL AND GAUSSIAN FITTING RESULTS

PARAMETER	GAUSSIAN FITTING				OBSERVED
	Component A	Component B	Component C	A + B + C	
1986 May 19 (14.94 GHz)					
Peak Flux (mJy beam ⁻¹)	22.22 ± 0.37	17.00 ± 0.38	1.62 ± 0.21	...	23.60 ± 0.12
Integrated Flux (mJy)	45.85 ± 0.94	33.21 ± 0.81	2.24 ± 0.25	81.30 ± 1.27	83.41 ± 3.67
Size ^a	0".15 × 0".13	0".16 × 0".12	< 0".18 × 0".11	...	0".32 × 0".09
Position Angle	31°6	153°0	0	...	-1°
α(1950.0)	08 : 12 : 28.179	08 : 12 : 28.192	08 : 12 : 28.214	...	08 : 12 : 28.18
δ(1950.0)	-41 : 33 : 18.20	-41 : 33 : 18.25	-41 : 33 : 18.24	...	-41 : 33 : 18.24
1985 March 29 + 30 + 31 (4.86 GHz)					
Peak Flux (mJy beam ⁻¹)	...	...	...	23.38 ± 0.69	23.17 ± 0.03
Integrated Flux (mJy)	...	...	...	28.11 ± 2.27	29.71 ± 0.75
Size ^a	...	...	...	0".48 × 0".41	1".22 × 0".82
Position Angle	...	...	...	145°	12°
α(1950.0)	...	...	...	08 : 12 : 28.20	08 : 12 : 28.20
δ(1950.0)	...	...	...	-41 : 33 : 17.93	-41 : 33 : 18.00

^a Under *Gaussian Fitting*, size refers to the source (deconvolution of the synthesized beam from the fitted component); size of the synthesized beam is tabulated under column headed "Observed."

ingly similar systems and confirm our previous suggestion that extended structure could be observed with the VLA in the A configuration at 2 cm.

II. OBSERVATIONS

The observations of RX Puppis, under excellent weather conditions, were made between 0600 and 1000 LST on 1986 May 19 at 2 cm with the NRAO³ VLA in the A configuration. Twenty-seven antennas were employed at 2 cm (nominally 14,940 MHz), utilizing an intermediate frequency (IF) bandwidth of 50 MHz and two IF pairs separated by 50 MHz. Spacing between antennas varied between 0.8 and 36.6 km. The phase center of these observations was at the nominal position of RX Puppis which for epoch 1950.0 in equatorial coordinates is $\alpha = 08^{\text{h}}12^{\text{m}}28^{\text{s}}.2$ and $\delta = -41^{\circ}33'18''.0$ or in galactic coordinates is $l = 258^{\circ}.5$ and $b = -3^{\circ}.9$. Observations of RX Puppis were interleaved with observations of 0826-373 for phase calibration purposes and to ensure maximum u, v coverage. On-source integration time (exclusive of array move time) for RX Puppis and 0826-373 totaled 182 and 24 minutes, respectively. Observations of 3C 286 were made to establish the flux calibration scale for RX Puppis and 0826-373 by assuming that 3C 286 has constant flux densities of 3.45/3.46 Jy for the IF pairs at 2 cm. For the observational epoch, the IF pair bootstrapped fluxes of 0826-373 were $1.728 \pm 0.019/1.732 \pm 0.021$ Jy at 2 cm. The calibrated amplitudes and phases for the two IF pairs for the RX Puppis observations were combined to achieve a $2^{1/2}$ enhancement in signal to noise, were self-calibrated in order to minimize the antenna-based phase errors, and were then Fourier-transformed before CLEANing (a particular method of sidelobe removal; see Clark 1980) the spatial maps. The resultant synthesized 2 cm beam is $0".32 \times 0".09$ at position angle $\sim -1^{\circ}$.

On 1986 May 20, similar extensive VLA observations were undertaken at 1.3 cm but the weather was very poor. We made elaborate attempts to process the 1.3 cm data using radio-interferometric imaging techniques for weak objects under

conditions of poor phase stability (see Cornwell 1987); these efforts revealed that the 1.3 cm data were not salvagable.

For comparison with excellent 2 cm results, we also reprocessed our earlier 6 cm (nominally 4,860 MHz) A/B configuration VLA observations of 1985 March 29, 30, and 31 (Hollis *et al.* 1986). Since each day's data was indistinguishable from any other day's data (i.e., no continuum flux changes were observed), we self-calibrated each data set in turn as we successively combined all three data sets into one final self-calibrated data set in order to improve signal to noise. The total on-source integration time was 570 minutes and the resultant synthesized 6 cm beam is $1".22 \times 0".82$ at position angle $\sim 12^{\circ}$.

III. ANALYSIS AND DISCUSSION

The most interesting result of our observations is the detection of discrete parcels of radio emission emanating from the central H II region at 2 cm. Additionally, we detected a statistically significant (> 3 times the RMS noise level) northern protrusion in the combined 6 cm data. Figure 1 shows the resultant spatial mapping at 6 cm (1985 March) and 2 cm (1986 May). In each contour plot it is obvious that the total radio emission region is larger than the beam size as indicated in the lower right. Moreover, the 2 cm emission region is very much smaller than the 6 cm emission region and is comprised of at least two sources. Figure 2 shows, however, that an east to west intensity profile slice through the central portion of the 2 cm map strongly suggests that three features make up the extended spatial emission. Table 1 summarizes the fitting results for both the resolved 2 cm data and the partially resolved 6 cm data.

The 6 cm data suggests that, relative to the 2 cm data, larger scale radio structure is present in RX Puppis. A similar result is obtained for R Aquarii (e.g., Hollis *et al.* 1985). Relative to the strongest 2 cm component A, 2 cm components B and C lie to the east at position angles of $\sim 109^{\circ}$ and $\sim 96^{\circ}$, respectively, suggesting that the system must somehow largely block expansion in a counter direction since comparable bipolar morphology is theoretically expected in close, interacting binary systems (see Livio 1982).

³ The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

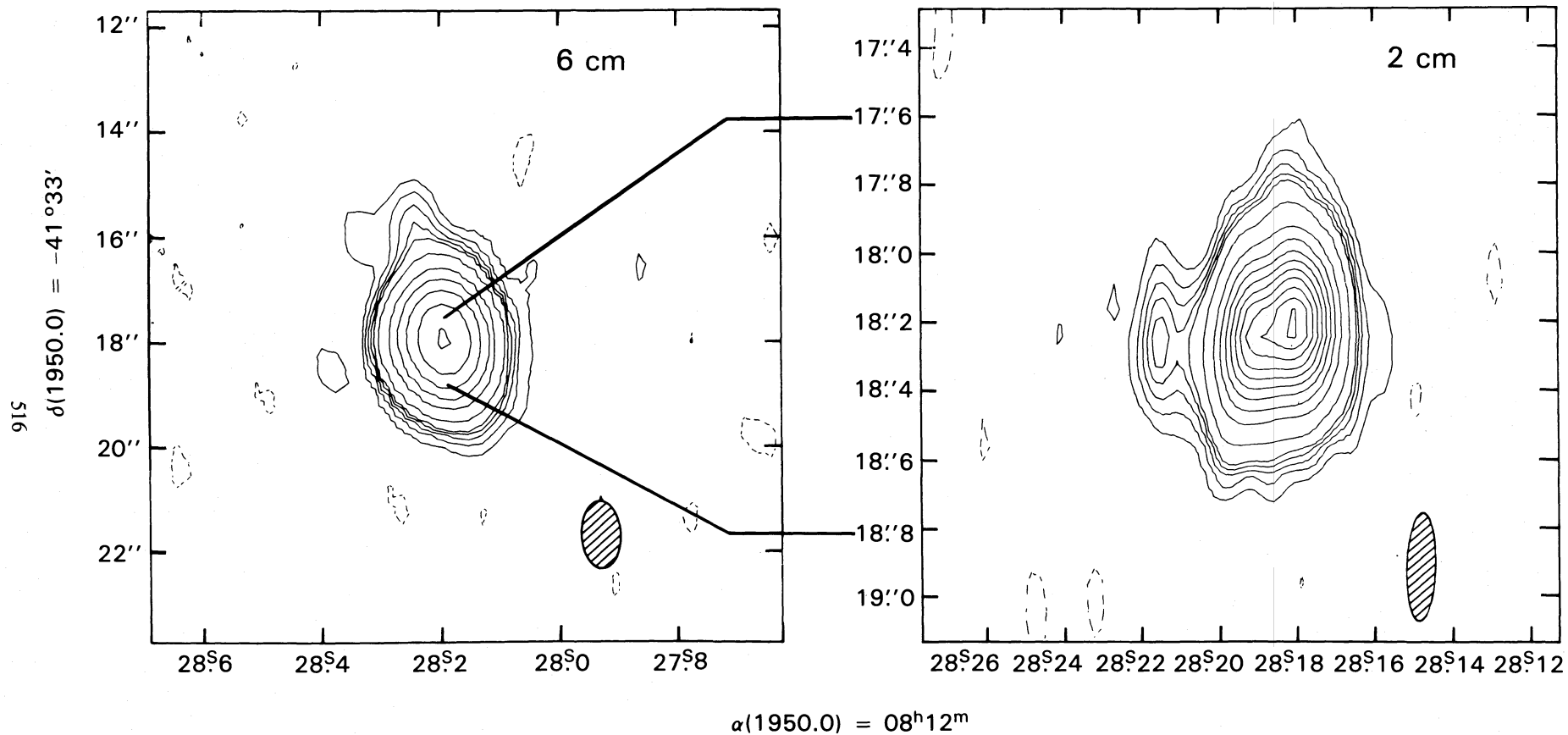


FIG. 1.—(left) The 6 cm VLA hybrid A/B configuration map of RX Puppis; peak flux is ~ 23.17 mJy per beam with contour levels of $-2, 3, 5, 7, 9, 11, 20, 50, 100, 200, 400,$ and 800 multiples of the rms noise level which is $27 \mu\text{Jy}$ per beam. The FWHM 6 cm synthesized beam shown in the lower right corner is $1''.22 \times 0''.82$ with position angle $+12^\circ$. (right) The 2 cm VLA A configuration map shows RX Puppis resolved; peak flux is ~ 23.60 mJy per beam with contour levels of $-2, 3, 5, 7, 9, 11, 20, 40, 60, 80, 100, 120, 140, 160, 180,$ and 200 multiples of the rms noise level which is $117 \mu\text{Jy}$ per beam. The FWHM 2 cm synthesized beam shown in the lower right corner is $0''.32 \times 0''.09$ with position angle -1° . The lines drawn from the central region of the 6 cm map to the ordinate of the 2 cm map show the scale differences between the maps.

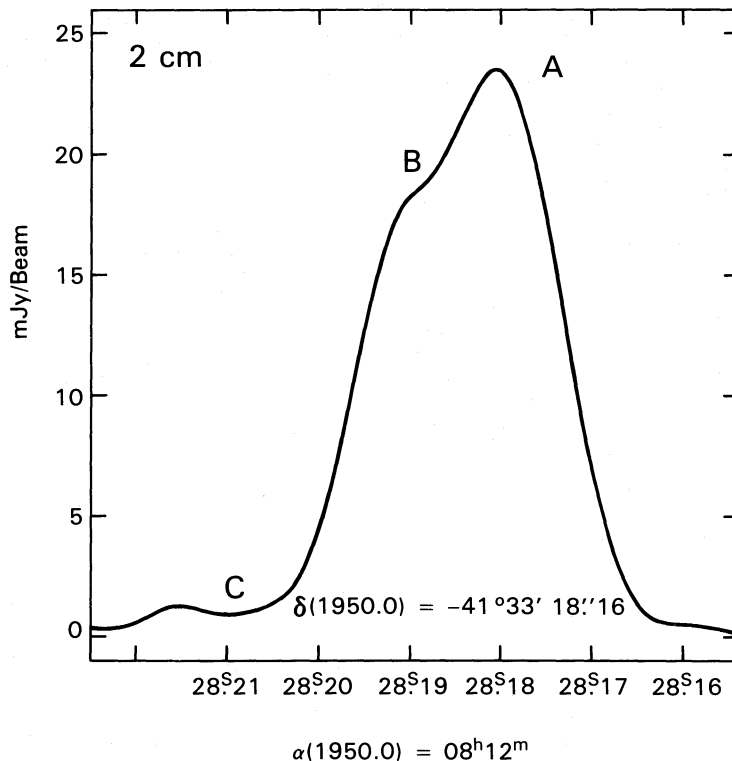


FIG. 2.—Shown is an east-west intensity profile slice through the central region of the 2 cm data displayed in Fig. 1. The linear slice suggests that three Gaussians may well represent the spatial data; the two-dimensional fitted Gaussian results for the components A, B, and C are shown in Table 1.

Figure 1 and Table 1 clearly indicate that circularly symmetric radio emission is ruled out. Seaquist and Taylor (1987), using the VLA in the A/B configuration, probed the RX Puppis system at 20, 6, 2, and 1.3 cm and concluded no discernible departure from circular symmetry when modeling their radio visibility data. In reviewing their observations we find no inconsistency since they had neither the resolution nor the sensitivity of the observations presented herein.

Unfortunately, no estimate of spectral indices is possible for components A, B, and C since they are only resolved at 2 cm. However, none of the 2 cm or 6 cm map features show any measurable linear polarization ($<1\%$). This strongly suggests that there is no significant nonthermal source of emission in the RX Puppis system at either observational epoch. Furthermore, the 1985 composite (unresolved) spectral index of $\sim +0.8$ may not be a significant departure from *partially* optically thick thermal bremsstrahlung due to a spherically symmetric steady stellar wind model (hereafter S^4 ; see Wright and Barlow 1975; Panagia and Felli 1975; Olton 1975) for the central H II region; the model predicts that the spectral index should be $+0.6$ and $+0.95$ for density laws of r^{-2} and $r^{-2.5}$, respectively. Moreover, neutral condensations in the wind from the RX Puppis system could tend to increase the spectral index above the canonical value of $+0.6$, if a density law of r^{-2} prevails.

There are at least three different models which could yield asymmetrical radio continuum emission similar to the morphology seen in Figure 1: (1) the colliding wind model (see Kwok 1982); (2) the symbiotic cool wind model (Taylor and Seaquist 1984); and (3) an ionized conical jet of unknown origin (Reynolds 1986). The competing winds from both the cool and hot star could produce double spectral line profiles as

seen in optical and ultraviolet spectra of RX Puppis, as would any nonspherical model composed of rings, shells, or jets. Such double profiles are also seen in semiforbidden lines (Kafatos *et al.* 1982, 1985). However, the colliding wind model does not account for the complex line structure seen in permitted lines of He II and particularly C IV (Kafatos, Michalitsianos, and Fahey 1985). The RX Puppis symbiotic cool wind model also encounters difficulty because the Taylor and Seaquist ionization parameter, $X > 3$, corresponds to a density-bound morphology (see Fig. 2 of Taylor and Seaquist 1984) which is not supported by our observed Figure 1 morphology. Additionally the Taylor and Seaquist model predicts a spectral index of $+0.6$ for the optically thick regime which is not consistent with the measured spectral index of $+0.8$.

The jet model of Reynolds (1986) seems to account for the observed morphology but avoids the question of the jet's origin. More importantly, Reynolds has shown that a conical jet wind may produce spectral indices in the range of 0 to $+2$. Figure 1 observations clearly show that we are not dealing with a spherical wind but, more probably, directional flow. Reynolds (1986) points out that a conical jet can have the same radio spectral index as an S^4 wind, leaving no spectral clue to indicate highly collimated flow. Furthermore, the Reynolds jet model with ~ 0.1 times the mass-loss rate of an S^4 wind model produces the same radio brightness because the jet is channeled into a small solid angle. Reynolds shows that the total integrated radio flux (e.g., $\alpha \sim +0.8$) could, for example, be composed of a core ($\alpha \sim +2$), and an inner, more confined jet ($\alpha \sim +0.2$), and an outer, more freely expanding jet ($\alpha \sim +0.6$). Considering the morphology of Figure 1, this model seems a promising candidate at this stage. Future nearly simultaneous observations at 1.3 and 2 cm in the A array con-

figuration with the VLA could provide A, B, and C spectral indices if, and only if, good atmospheric observing conditions prevail. In such an instance, the jet wind model can be observationally tested for the first time.

At present little is observationally known of the orbital parameters for symbiotic systems containing Miras, but Whitelock (1987) has inferred that the range of orbital periods for such systems is ~ 20 to ~ 200 yr; the corresponding orbital separation would vary between ~ 10 and ~ 45 AU, assuming that the total system mass is $\sim 2 M_{\odot}$. The lower limits to the period and separation seem to be more typical of Mira-like symbiotics. The upper limit to the period derives from the α Ceti (Mira) binary system which Whitelock suggests is "mildly" symbiotic because of its relatively large orbital separation estimated to be ~ 45 AU. In the case of RX Puppis at a distance of ~ 1500 pc (Whitelock 1987), we calculate that features B and C are, respectively, 230 and 590 AU away from the strongest central feature A. Hence, if feature A represents the central H II region in proximity to the hot companion, then features B and C are far removed from the binary system itself. On the other hand, Allen and Wright (1988) have advocated a binary separation for RX Puppis of ~ 1000 AU; if this controversial proposal is correct, then the radio structure we see could be the effect of binary interaction similar to that reported for H1-36 (Taylor 1988). It is of interest to note that Klutz and Swings (1981) reported 1979 December spectrograms in various optical lines which showed spectacular changes from those taken at earlier epochs; these authors concluded that RX Puppis was returning to a high-excitation phase after a quiescent phase which lasted ~ 20 years. Perhaps we are seeing the radio counterpart to this earlier optical report as recently suggested by Seaquist and Taylor (1987).

For radio continuum observations, three potentially observable quantities determine the mass-loss rate: the radio flux due to the mass loss, the wind terminal velocity (v_{∞}), and the stellar distance (e.g., Wright and Barlow 1975; Panagia and Felli 1975; Olton 1975; and Reynolds 1986). In the case of RX Puppis the most significant problem is the determination the wind velocity associated with the radio features now observed. The RX Puppis ultraviolet and optical spectroscopy obtained to date probes regions ≤ 1 AU (e.g., Kafatos *et al.* 1985) and ≤ 30 AU (e.g., Klutz, Simonetto, and Swings 1978) with respect to the hot companion, while the mass loss observed by radio continuum observations herein imply distances ≥ 230 AU. The diverse spectroscopic observations have yielded complex P Cygni profiles with a whole range of velocities, with the simplest spectral interpretation that a high-velocity (≥ 800 km s $^{-1}$) wind emanates from the hot star, or inner region of a disk, which is also surrounded by stationary rings or shells of gas and dust (Kafatos *et al.* 1985). However, the presence of the Mira and its associated cool wind complicates the line formation situation because hot and cool winds of the two stars must interact at some level in the RX Puppis system (Allen and Wright 1988). In any event, previous radio estimates of the mass loss, by employing the S 4 wind formalism, have varied from greater than $4.2 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ (Seaquist and Taylor 1987, favoring a lower-limit $v_{\infty} > 60$ km s $^{-1}$ for the cool star wind) to $\sim 5 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ (Hollis *et al.* 1986, suggesting a $v_{\infty} \sim 800$ km s $^{-1}$ hot star wind). However, these calculations did not reflect the effects of the spatially extended radio features which we are reporting in this work.

It is clear that the terminal velocity is highly uncertain.

TABLE 2
PHYSICAL PARAMETERS OF 2 CENTIMETER RADIO FEATURES

Parameter	Feature A	Feature B	Feature C
Distance (AU) ^a .....	...	230 ^b	590 ^b
Position Angle (deg) ^a .....	...	109	96
T_e (K) ^c	$\sim 10^4$	$\sim 10^4$	$\sim 10^4$
n_e (cm $^{-3}$) ^d	$> 6.0 \times 10^6$	$> 6.0 \times 10^6$	...
Mass (M_{\odot}) ^d	$> 8.2 \times 10^{-5}$	$> 8.2 \times 10^{-5}$	...
\dot{M}/v_{∞} ($M_{\odot} \text{ yr}^{-1}$)/(km s $^{-1}$):			
S 4 Wind ^e .....	...	$\sim 6.3 \times 10^{-8}$	
Conical Jet ^f .....	...	$\sim 1.1 \times 10^{-8}$	

^a Relative to the central H II region (assumed to be feature A).

^b Assumes RX Puppis is 1500 pc distant from Earth (Whitelock 1987).

^c Determined by Seaquist and Taylor (1987) as an average over the entire region.

^d Assumes spherical volume of radius $\sim 1.57 \times 10^{15}$ cm (see Table 1 source sizes).

^e See text for model explanation; derived using Wright and Barlow 1975 or Panagia and Felli 1975.

^f Derived using Reynolds 1986.

Hence, the least ambiguous mass-loss rate parameter we can tabulate is (\dot{M}/v_{∞}) for the RX Puppis system based on flux values of B and C, using the S 4 wind model or the jet wind model of Reynolds (1986). This parameter is given in Table 2 along with estimates of the temperature and lower limits to the density and mass of each 2 cm component. In our limit calculations we find the optical depth, τ , for features A, B, and C to be optically thick but if we assume that $\tau \geq 1$ at 110 GHz (Hollis *et al.* 1986) then we calculate that $\tau \geq 66$ at 2 cm (15 GHz). Moreover, we assume that the distance to RX Puppis is exactly 1500 pc but caution that parameters derived for the radio sources are critically dependent on the assumed distance.

The generally accepted explanation for mass loss for early O and B type stars involves radiatively driven winds, a consequence of high optical depth in strong resonance lines (cf. Castor, Abbott, and Klein 1975). Abbott (1982) has shown that this acceleration is constant over the temperature range of $50,000 \geq T_{\text{eff}} \geq 10,000$ K in O and B type giants, but drops off sharply for cooler stars. Hence, even if the Mira is the source of the ejecta, the RX Puppis hot companion ($T_{\text{eff}} \sim 10^5$ K) in proximity to the cool star would radiatively drive this material from the system.

Kafatos *et al.* (1985) and Michalitsianos *et al.* (1988a) have shown that an ~ 800 km s $^{-1}$ wind emanates from the hot companion star. Assuming this velocity, and using mass lower limits from Table 2, the kinetic energy associated with either features B or C would be greater than 5.2×10^{44} ergs. This energy is on the order of nova-like outburst energies, is indeed too high, and provides an upper limit for the velocities of features B and C. On the other hand, Kafatos *et al.* (1985) have developed a model of a series of gaseous rings encircling the RX Puppis hot companion to explain ultraviolet line profile structure of the C IV doublet. If one assumes that the gas pressure of the outer ring (total mass $\sim 10^{-7} M_{\odot}$), which is $\sim 10^{13}$ cm distant from the hot star, just equals the pressure of the high-temperature, low-density 800 km s $^{-1}$ wind at the same distance, then the wind could gently move material outward. In such an instance, mass conservation suggests that the velocity at 230 AU is ~ 0.01 km s $^{-1}$ while the escape velocity at this distance is ~ 4 km s $^{-1}$, assuming a $\sim 2 M_{\odot}$ binary system. Using the mass-loss parameter tabulated in Table 2, it

can be seen that any velocity $\leq 1 \text{ km s}^{-1}$ would be consistent with the Kafatos *et al.* (1985) model in which the outer ring is quasi-stable and provides the departure point for the system's mass loss. If such is the case, then features B and C would essentially be stationary. This hypothesis is difficult to check observationally but it may be worthwhile to further analyze line profile information of low excitation lines which may emanate from components B and C.

In summary, we have resolved the RX Puppis system in 2 cm continuum emission and have shown that the system's radio morphology is similar to that of the R Aquarii system. Moreover, both systems are suspected to have an accretion disk surrounding the hot companion. The ionizing cone of radiation from the accretion disk could beam material in two directions but, in the case of RX Puppis, we only see evidence of material expulsion in one direction. Similarly a sensitive search for an R Aquarii counterjet has not yielded definitive

results. On the other hand, the two symbiotic systems have important differences. For example, the RX Puppis hot companion temperature is ~ 4 times hotter than that of the R Aquarii hot companion. Further, R Aquarii has an optically thin jet while optically thick radio features prevail in the RX Puppis case. Even so, the ultimate source of ejection material in both systems is almost certainly the cool star's wind which probably gives rise to a wind from the outer regions of an accretion disk.

We are grateful to Peggy Perley of the VLA staff for help during the data calibration phase and to Nancy Oliverson for a critical reading of the manuscript. We also appreciate the helpful comments of Russ Taylor and Ernie Seaquist. J. M. H., A. G. M., and R. J. O. acknowledge the support of NASA RTOP 188-41-55 Task 12 for this work.

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