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EVIDENCE FOR EXTENDED RADIO EMISSION SURROUNDING RX PUPPIS

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ABSTRACT

We report evidence for $\sim 1''$ extended structure in 6 cm continuum emission emanating from the symbiotic star system RX Puppis. We did not detect hourly continuum flux changes as suggested in previous radio experiments by others. Our observations indicate that the predominant nature of the radio emission is thermal and consistent with an optically thick stellar wind emanating from the symbiotic star system. Our results are discussed with regard to other similar stellar binary systems.

Subject headings: stars: individual — stars: radio radiation — stars: symbiotic

I. INTRODUCTION

Anisotropic mass ejection has been detected in a variety of galactic objects which include SS 433, symbiotic stars, T Tauri stars, and Herbig-Haro objects. In the case of R Aquarii, a symbiotic star system, the observed collimated structure is probably a clue to understanding the mechanism responsible for mass ejection. The generally accepted model for a dust-type symbiotic star system is a Mira variable and a nearby hot companion (e.g., hot subdwarf) which periodically accretes material from the extended Mira atmospheric envelope and undergoes outbursts; several of these systems have become slow novae. Similar to R Aquarii, the peculiar emission object RX Puppis, at a distance of 1000 pc (Kafatos, Michalitsianos, and Feibelman 1982) to 3000 pc (Whitelock *et al.* 1983) with a 580 day Mira variable, is also a member of dust-type symbiotic stars which are distinguished by strong infrared emission. Seaquist (1977) suggested hourly continuum flux variations in RX Puppis at 8.7 GHz. Moreover, Kafatos, Michalitsianos, and Fahey (1985) have shown ultraviolet spectral line structure variations in RX Puppis on time scales of, at most, months; these observations of multiple-component spectral lines also suggest an extended RX Puppis ring system.

Inspired by these previous RX Puppis investigations, we obtained 6 cm Very Large Array (VLA) and 3 mm NRAO[2] 12 m telescope observations of this object to probe for possible extended structure, temporal flux changes, and the nature of the continuum emission itself.

II. OBSERVATIONS

The observations of RX Puppis were made between 0600 and 1030 LST on 1985 March 29, 30, and 31 with the NRAO VLA in an A/B hybrid configuration (i.e., north arm configured for the A array; east and west arms in the B array). Twenty-seven antennas were employed at 6 cm (nominally 4860 MHz), utilizing an intermediate frequency (IF) bandwidth of 50 MHz and two IF pairs centered at 4885 and 4835 MHz. Spacing between antenna pairs varied between 0.3 and 22.8 km which yielded a synthesized CLEAN beam of $1''.3 \times 0''.9$ with a position angle of $\sim 15°$. Observations of RX Puppis were interleaved with observations of 0826−373 for phase calibration purposes. Data averaging time was 30 s for all observations; on-source integration time (exclusive of array move time) for RX Puppis and 0826−373 totalled 190 and 27 minutes, respectively, for each of the 3 days. Observations of 3C 48 were made to establish the flux calibration scale for RX Puppis and 0826−373 by assuming that 3C 48 has constant flux densities of 5.36/5.41 Jy at frequencies of 4885/4835 MHz which correspond to the two IF pairs. For the 1985 epochs of observation, the bootstrapped fluxes of 0826−373 were 2.452(16)/2.479(50) Jy on March 29, 2.443(12)/2.452(6) Jy on March 30, and 2.436(13)/2.451(6) Jy on March 31. The calibrated amplitude 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 ratio and were then transformed to produce two-dimensional CLEANed maps for each day's observations.

In order to estimate a spectral index for RX Puppis, complementary continuum observations at 110 GHz were made on 1985 July 2 and 6 with the 12 m NRAO Cassegrain telescope on Kitt Peak with a cooled two-channel mixer radiometer which had system temperatures of ~ 560 K and ~ 440 K and an effective bandwidth of 600 MHz. The beam switching observing mode was accomplished by nutating a subreflector $\pm 1'$. The antenna beamwidth was measured to be $\sim 60''$ at 110 GHz. Measurements were of the "OFF-ON-ON-OFF" type. Flux calibration was accomplished by observations of Mars (17.3 Jy) on July 2 and Venus (834 Jy) on July 6.

III. DATA ANALYSIS

The position of RX Puppis is $\alpha(1950) = 08^h12^m28^s.2$ and $\delta(1950) = -41°33'18''$ and, hence, VLA observations were effected between elevations of 8° (VLA telescope constraint) and 14°.3 (source transit). Poor atmospheric conditions at such observational elevations can produce phase errors (and to a lesser extent, gain errors) which are difficult to remove by data

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TABLE 1

RX Puppis Observed Flux and Gaussian Fit Results

Date	Gauss Fit[a]	Observed Flux[b]
March 29 (4.86 GHz):		
Peak flux (mJy per beam)	21.42(4)	21.34(5)
Integrated flux (mJy)	26.00(13)	27.77(1.8)
Major axis position angle (degrees)	13.06(20)	...
Size (arcsec)	1.393(3) × 0.953(2)	...
March 30 (4.86 GHz):		
Peak flux (mJy per beam)	24.06(3)	24.26(5)
Integrated flux (mJy)	28.67(10)	30.05(1.8)
Major axis position angle (degrees)	12.75(16)	...
Size (arcsec)	1.371(2) × 0.964(1)	...
March 31 (4.86 GHz):		
Peak flux (mJy per beam)	24.12(3)	23.42(5)
Integrated flux (mJy)	28.74(9)	30.09(1.8)
Major axis position angle (degrees)	11.38(16)	...
Size (arcsec)	1.392(2) × 1.000(1)	...
June 2 and 6 (110 GHz):		
Total flux (mJy)	...	505(46)

[a] Quantities in parentheses are 1 σ formal Gaussian fit errors.

[b] Quantities in parentheses are 1 σ errors; VLA errors are estimated from $\sim$ 0.05 mJy per beam map noise times the number of beam areas encompassing the emission feature.

editing. However, using repetitive self-calibrations for phase (i.e., routine ASCAL on the NRAO image processing system) each day's 6 cm data set was improved to the extent that the sidelobe pattern was removed from the final CLEANed map which had a nominal map error of $\sim$0.05 mJy per beam. The input model to each successive use of the ASCAL routine consisted of the previously CLEANed image, excluding all CLEAN components found after the first negative component. Moreover, the ASCAL averaging time employed was 3 minutes since atmospheric phase variations occur on a time scale of $\sim$10 minutes. The resultant maps for March 29, 30, and 31 showed no apparent features which could be easily interpreted as extended structure. However, each map was fitted with a single Gaussian model, and these results are presented in Table 1. Table 1 clearly shows that the fit to each day's data yields a source size and position angle which is very similar to the beam; hence, it is necessary to analyze these data for structure by methods other than map morphology. For example, a Gaussian model (NRAO JMFIT routine) approximates RX Puppis data as is evident from a comparison of the fitted total and peak flux and the observed total and peak flux (see Table 1) on each day. Since the fitted peak to total flux for RX Puppis observations is $\sim$0.83, we interpret this as evidence for extended structure because a point source should yield unity. Moreover, as an independent observational check, the point source 0826−373 yielded a fitted peak to total flux of $\sim$0.95; this phase calibrator is a point source for all configurations of the VLA.

Further evidence for extended structure about RX Puppis is shown in Figure 1 which represents the coherent vector

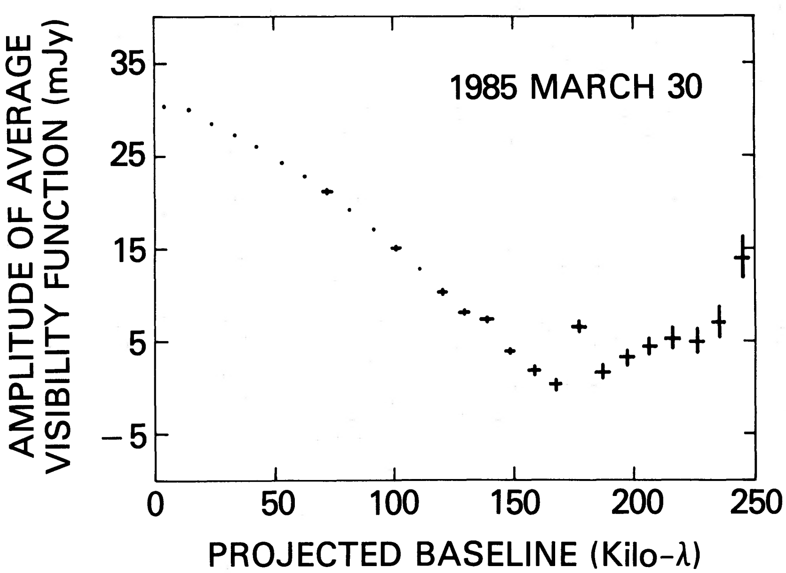

Fig. 1.—Shown is the average visibility function for observations on 1985 March 30. The amplitude of the average complex number in each bin with respect to projected baseline is plotted. When significant enough to show above the resolution of the plot symbol, the 1 σ error on an amplitude is indicated by the vertical extent of the plotted cross. The profile can be modeled as a single extended Gaussian source whose half-power diameter is $\sim 1''$. Moreover, double extended source structure is weakly suggested at longer projected baselines, but these baselines are undersampled.

average of the visibility function amplitude versus increasing projected baseline (i.e., regardless of direction on the sky) for the 1985 March 30 self-calibrated visibility data set which seemed to have the least phase calibration problems; a similar plot for visibility function phase for these same data yielded essentially zero at all projected baselines and, therefore, is not shown. Kwok (1985) has demonstrated that plots similar to Figure 1 are quite useful in determining source size and properties when such sources appear pointlike in the intensity maps but are, in fact, resolved. Figure 1 shows the profile of an extended source (cf. Fomalont and Wright 1974; Kraus 1966) and, assuming a Gaussian brightness distribution, yields a half-power diameter of $\sim 1''$ for the source. Hence, we conclude that the VLA in the A configuration at 2 cm would resolve the extended structure present in the RX Puppis system.

We also analyzed each of the self-calibrated visibility data sets for possible hourly time variations in the flux from RX Puppis as suggested by Seaquist (1977). This was accomplished by simply breaking up each daily data base into quarters with respect to time and generating plots similar to those in Figure 1; such plots show variations at the longer baselines as one would expect for differences in hour-angle coverage and under-sampling. However, at the shorter baselines, no significant variations were seen to within the errors on the plots. Hence, we conclude that no hourly 4.8 GHz flux variations were present in RX Puppis during the course of our observations.

Although we also observed 3C 286 as a potential polarization calibrator, this proved unnecessary since uncalibrated Stokes parameter Q, U, and V maps of RX Puppis showed no significant flux levels (i.e., $< 1\%$ of the corresponding intensity, I, map flux levels). Therefore, we conclude that the 6 cm emission from the RX Puppis system is predominantly thermal in nature.

Our 12 m telescope continuum observations at 110 GHz yield a flux of 505 ± 46 mJy (see Table 1) which, when combined with the 4.86 GHz flux determinations from Table 1, produce a spectral index of $+0.9 \pm 0.1$. Although a ~ 0 spectral index for RX Puppis was determined by Wright and Allen (1978), simultaneous multifrequency VLA observations in 1985 May by Seaquist and Taylor (1985) yield an index of $+0.72 \pm 0.04$ based on a least-squares fit of 1.49, 4.86, 14.94, and 22.46 GHz data; these authors note that the 22.46 GHz result may be 25% in error. Hence, the RX Puppis spectral index would be better determined by combining the Seaquist and Taylor data with our 110 GHz result, and, in this instance a least-squares fit yields an index of $+0.80 \pm 0.06$ for RX Puppis with the regression line passing through all 1 σ error bars on the data. Thus, the RX Puppis spectrum is essentially linear from 1.49 GHz to 110 GHz and consistent with an optically thick wind emanating from the system as we subsequently discuss.

IV. DISCUSSION

Regarding radio continuum observations, few stars are detectable, and fewer still show extended structure. RX Puppis is one such stellar system with a total 6 cm flux of ~ 30 mJy. The characteristic $\sim 1''$ size of the extended 6 cm emission from RX Puppis produces linear dimensions of $\sim 1.5 \times 10^{16}$ to $\sim 4.5 \times 10^{16}$ cm at RX Puppis distances corresponding to 1000–3000 pc, respectively. These linear dimensions for RX Puppis extended emission are factors of 3 to 9 times the size of the R Aquarii jet–like feature B (Hollis *et al.* 1985) which, at 3 mJy, is the dominant extended 6 cm emission feature in this similar star system. However, from present RX Puppis observations, we cannot determine if the extended emission has multicomponent structure as is the case for the R Aquarii binary system. RX Puppis is 4–10 times further away than R Aquarii but has ~ 3 times the total 6 cm flux from all features in the R Aquarii system. Recently Hjellming (1985) has detected a jetlike protrusion at 6 cm emanating from the compact H II region surrounding AG Pegasi, another symbiotic (albeit stellar-type) system at a distance of ~ 600 pc. Similarly Taylor and Seaquist (1985) report radio observations of the CH Cygni symbiotic (nova) system which indicate high-velocity jet activity. Hence, such radio emission features may be common to symbiotics and certainly must be related to the evolution of such interactive binary systems.

Our recent 110 GHz observations of RX Puppis indicate that the spectral index is $\sim +0.8$ when combined with 1.49, 4.86, 14.94, and 22.46 GHz data from Seaquist and Taylor (1985). This index departs from the canonical value of $+0.6$ expected for an ionized, spherically symmetric, steady mass outflow stellar wind at constant speed (Wright and Barlow 1975) but is similar to the value of $+0.78$ obtained by Wright and Barlow (1975) for V1016 Cygni, another symbiotic system. On the other hand, the composite spectral index for R Aquarii is $+0.36$ (Hollis *et al.* 1985) even though individual resolved features have indices that depart from this overall value (e.g., the R Aquarii jet has an index of ~ -0.1 and R Aquarii itself has an index of $\sim +0.6$). If the RX Puppis radio emission is interpreted as due to an ionized wind and if we further assume that there is no multicomponent emission in RX Puppis (unlike R Aquarii), then either the RX Puppis wind emanates predominantly from either the cool star or the hot companion since a colliding wind model (competing winds from both the cool and hot stars; cf. Kwok 1982; Willson *et al.* 1984) has been shown not to be applicable for RX Puppis (Kafatos, Michalitsianos, and Fahey 1985).

First, let us take the case in which a ~ 50 km s^{-1} wind comes from the cool component of the binary system which we assume is 1000 pc distant. From the formalism of Taylor and Seaquist (1984), we find that the minimum values of the parameters of the system are a mass loss rate $\dot{M} \approx 2 \times 10^{-5}\ M_\odot$ yr^{-1}, an orbital semimajor axis $a \sim 8 \times 10^{14}$ cm, and a hot star emitting photons at a rate of $L_{\rm ph} \approx 2 \times 10^{47}$ s^{-1}. Considering these parametric values, we are at a loss to explain why the mass loss rate from the cool star would be in excess of a few times $10^{-5}\ M_\odot$ yr^{-1} since the hot secondary star would have minimal effect on the atmospheric envelope of the cool star at such a large implied separation. If we assume that the total mass of the RX Puppis system is $\sim 3\ M_\odot$ (cf. Kafatos, Michalitsianos, and Fiebelman 1983), then the orbital period is at least 200 yr. With a larger binary separation and period than the R Aquarii stellar system, we would expect that the cool star in the RX Puppis system to have a mass-loss rate on the order of a few times $10^{-7}\ M_\odot$ yr^{-1} since application of the Taylor and Seaquist (1984) model yields $\sim 3 \times 10^{-7}$ for R Aquarii (Hollis *et al.* 1985). In fact the mass loss rate for R Aquarii is typical for single Mira variables. Hence, we must conclude that the wind from the RX Puppis system must come from the hot star since the mass loss rate is two orders of magnitude larger than expected if the wind originates with the cool star.

Therefore, let us take the case in which a ~ 800 km s^{-1} wind (Kafatos, Michalitsianos, and Fahey 1985) comes from the hot component of the RX Puppis binary system which we assume is 1000 pc distant. Application of the model of Wright and

Barlow (1975) yields a hot star mass-loss rate of $5 \times 10^{-5}\ M_{\odot}$ yr^{-1}. We note that the value of $\dot{M}$ deduced from this formalism is only approximate since the observed spectral index of $\sim +0.8$ departs from the canonical value of $+0.6$. However, RX Puppis has been shown to be a strong infrared dust emitter (Whitelock *et al.* 1983) and dust can provide shielding for neutral condensations in the wind of the RX Puppis system. Such neutral condensations would tend to increase the spectral index above the canonical value (Wright and Barlow 1975).

It may well be that mass loss from dust-type symbiotic stellar systems is driven primarily by a wind from the cool star (e.g., R Aquarii) or from the hot star (e.g., RX Puppis), but in either case the ejection probably results from the close interaction of the two stars at periastron (Kafatos and Michalitsianos 1982; Kafatos, Michalitsianos, and Fahey 1985). Thus, in the case of RX Puppis, the ultimate source of material for the wind may still be the cool star which feeds the hot star's wind. Such a wind may be collimated by an accretion disk about the hot star and would almost certainly impede the accretion of orbital plane rings of material hypothesized for the RX Puppis system by ultraviolet spectroscopic observations (Kafatos, Michalitsianos, and Fahey 1985).

With regard to the hourly RX Puppis radio continuum flux variations reported at 8.7 GHz by Seaquist (1977) our observations at 4.8 GHz do not confirm such phenomena. Moreover, if the extended structure we have determined to be surrounding RX Puppis was undergoing any such flux variations, explanations invoking light travel time would be inadequate. If a pointlike radio component of the RX Puppis exists, it could potentially undergo some unknown repetitive cataclysmic activity on hourly time scales; however, our temporal analysis of the three RX Puppis data bases suggests no flux level changes.

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REFERENCES

Fomalont, E. B., and Wright, M. C. H. 1974, in *Galactic and Extra-Galactic Radio Astronomy*, ed. G. L. Verschuur and K. I. Kellerman (New York: Springer-Verlag), p. 287.
Hjellming, R. M. 1985, in *Radio Stars*, ed. R. M. Hjellming and D. M. Gibson (Dordrecht: Reidel), p. 97.
Hollis, J. M., Kafatos, M., Michalitsianos, A. G., and McAlister, H. A. 1985, *Ap. J.*, **289**, 765.
Kafatos, M., and Michalitsianos, A. G. 1982, *Nature*, **298**, 540.
Kafatos, M., Michalitsianos, A. G., and Fahey, R. P. 1985, *Ap. J. Suppl.*, **59**, 785.
Kafatos, M., Michalitsianos, A. G., and Feibelman, W. A. 1982, *Ap. J.*, **257**, 204.
Kraus, J. D. 1966, *Radio Astronomy* (New York: McGraw-Hill), p. 180.
Kwok, S. 1982, in *The Nature of Symbiotic Stars*, ed. M. Friedjung and R. Viotti (Dordrecht: Reidel), p. 17.
Kwok, S. 1985, in *Radio Stars*, ed. R. M. Hjellming and D. M. Gibson (Dordrecht: Reidel), p. 79.
Seaquist, E. R. 1977, *Ap. J.*, **211**, 547.
Seaquist, E. R., and Taylor, A. R. 1985, private communication.
Taylor, A. R., and Seaquist, E. R. 1984, *Ap. J.*, **286**, 263.
———. 1985, *IAU Circ.*, 4055.
Whitelock, P. A., Catchpole, R. M., Feast, M. W., Roberts, G., and Carter, B. S. 1983, *M.N.R.A.S.*, **203**, 363.
Willson, L. A., Wallerstein, G., Brugel, E. W., and Stencel, R. E. 1984, *Astr. Ap.*, **133**, 154.
Wright, A. E., and Allen, D. A. 1978, *M.N.R.A.S.*, **184**, 893.
Wright, A. E., and Barlow, M. J. 1975, *M.N.R.A.S.*, **170**, 41.

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