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THE LARGE-SCALE RADIO STRUCTURE OF R AQUARII

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ABSTRACT

Radio continuum observations of the R Aquarii symbiotic star system, using the compact D configuration of the VLA at 6 cm wavelength, reveal a large-scale $\sim 2'$ structure engulfing the binary which has long been known to have a similar optical nebula. This optical/radio nebula possesses $\sim 4 \times 10^{42}$ ergs of kinetic energy which is typical of a recurrent nova outburst. Moreover, a cluster of a dozen additional 6 cm radio sources were observed in proximity to R Aquarii; most of these discrete sources lie $\sim 3'$ south and/or west of R Aquarii and, coupled with previous 20 cm data, spectral indices limits suggest a thermal nature for some of these sources. If the thermal members of the cluster are associated with R Aquarii, it may indicate a prehistoric eruption of the system's suspected recurrent nova. The nonthermal cluster members may be extragalactic background radio sources.

Subject headings: radio sources: general — radio sources: spectra — stars: symbiotic

I. INTRODUCTION

R Aquarii is a symbiotic binary star system which contains a ~ 387 day Mira variable and a hot subdwarf companion whose presence is inferred spectroscopically from nebular line emission but hidden from direct view because it is of sufficiently low stellar luminosity (Michalitsianos, Kafatos, and Hobbs 1980) and/or is occulted by a thick accretion disk (Kafatos, Michalitsianos, and Hollis 1986). The system has long been known to be surrounded by complex optical emission nebulosity with an intense, small-scale, inner component and a more diffuse, large-scale, outer component. The inner nebulosity of the system has been probed in depth with the VLA at various wavelengths and extended antenna spacing configurations (e.g., Sopka *et al.* 1982 in the C configuration at 6 cm; Kafatos, Hollis, and Michalitsianos 1983 in the B configuration at 6 cm; Hollis *et al.* 1985 in the B configuration at 2, 6, and 20 cm; Hollis *et al.* 1986 in the A configuration at 2 cm), and these observations have determined the spectral indices of the central H II region and several jetlike radio features whose morphological details are on the subarcsecond to $\sim 10''$ scale. Due to the small-scale structure of the inner nebulosity and the inherent problems of observing faint nebular structure next to a bright star through Earth's atmosphere, much of the spatial optical work has dealt with the large-scale structure of the outer nebula (a notable exception is the near-UV morphology by Mauron *et al.* 1984). In fact, the large-scale $\sim 2'$ nebular structure has been reported only in optical atomic emission lines (e.g., Sopka *et al.* 1982; Solf and Ulrich 1985; Michalitsianos *et al.* 1987). Based on a ~ 600 yr expansion age (Baade 1944), presumably a long-lived optical structure is observed which may have a radio counterpart whose detection could provide important clues to the nature of the R Aquarii system. Since the approximate largest scale 6 cm structure visible to the VLA is $7''$, $25''$, $80''$, and $240''$ in configurations A, B, C, and D, respectively, it is necessary to use the D configuration (comprised of the shortest baselines) to conduct a high-sensitivity search for large scale structure. This *Letter* reports the first successful radio detection of a large-scale nebula surrounding R Aquarii in 6 cm continuum emission and discusses its implications.

II. OBSERVATIONS

The observations of R Aquarii were made between 2000 and 0400 LST on 1987 April 11 at 6 cm with the NRAO[1] VLA in the D configuration. Spacing between antennas varied between 40 m and ~ 1 km. The phase center of these observations was at the nominal position of R Aquarii which for epoch 1950.0 in equatorial coordinates is $\alpha = 23^h41^m14\overset{s}{.}269$ and $\delta = -15°33'42\overset{''}{.}890$ or in galactic coordinates is $l = 66\overset{\circ}{.}5$ and $b = -70\overset{\circ}{.}3$. Twenty-seven antennas were employed at 6 cm ($\sim 4{,}860$ MHz), utilizing an intermediate frequency (IF) bandwidth of 50 MHz and two IF pairs separated by 50 MHz. The 6 cm primary beam has a $\sim 9'$ full width at half-maximum. Observations of R Aquarii (12.5 minutes) were interleaved with observations of 2345−167 (2.5 minutes) for phase calibration purposes and to

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

ensure complete *u*, *v* coverage. On-source integration time (exclusive of array move time) for R Aquarii and 2345−167 totalled 359 and 53 minutes, respectively. Observations of 3C 48 were made to establish the flux calibration scale of R Aquarii and 2345−167 by assuming that 3C 48 has constant flux densities of 5.36/5.41 Jy for the IF pairs. For the observational epoch, the IF pair bootstrapped fluxes of 2345 −167 and 3C 138 (polarization calibrator source) were 1.631(6)/1.640(3) Jy and 3.734(10)/3.757(10) Jy, respectively. The calibrated amplitudes and phases for the two IF pairs for the R Aquarii observations were combined to achieve a $\sqrt{2}$ enhancement in signal-to-noise ratio, 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 1981) the spatial maps. For untapered maps, the 6 cm synthesized beam is 15″67 × 11″06 at position angle ~ −2°8.

III. RESULTS AND DISCUSSION

a) *Large-Scale Radio Structure*

The most interesting result of our observation is the detection of a radio counterpart to the optical emission arising from the circumbinary region of R Aquarii. Comparison between the radio and optical nebulosity is seen in Figure 1 which shows a contour plot of the large-scale 6 cm radio structure of R Aquarii superposed on an [O III] 5007 Å narrow-band (15 Å) image (Michalitsianos *et al.* 1987). For easy comparison, the optical image seen in Figure 1 has been convolved with the 6 cm radio beam (see § II). Moreover, Table 1 contains the integrated flux values for the eastern (E) and western (W) radio lobes whose peak intensities are slightly interior to the corresponding [O III] optical features. This displacement may be attributed to an [O III] excitation effect. Moreover, the integrated flux of W is greater than that of E in both optical and radio images. A more remarkable comparison between optical and radio is afforded by comparing radio contours of Figure 1 with a contour image (Fig. 1 of Solf and Ulrich 1985) which correspond to a direct Lick 3 m reflector photograph obtained by G. Herbig on 1980 October 18 in the red (6000–8000 Å) and represents predominantly Hα line emission (6563 Å). Michalitsianos *et al.* (1987) first pointed out that the extended nebulosity in [O III] at 5007 Å was morphologically quite different from Hα results; here we see that the radio continuum and Hα optical results are curiously very similar. Not only is the morphology of the individual components nearly identical in the Hα optical/radio continuum comparison, but the angular distance from peak E intensity to peak W intensity is ~ 76″ in the radio and ~ 78″5 in the optical. Hence, we conclude that these optical and radio data taken ~ 7 yr apart support our contention that the optical/radio nebula is quite stable and long-lived. Similarly, Hollis *et al.* (1985) have shown that morphologically the inner radio jetlike feature B, which is optically thin and thermal, appears nearly identical to its optical counterpart and exhibits a stable integrated radio flux over time scales of at least a few years.

Reprocessing of 20 cm data taken with the VLA in the B configuration (Hollis *et al.* 1985) was necessary to directly compare these 20 cm results with the new 6 cm D configuration untapered results. The 20 cm reprocessing consisted correcting for antenna phases derived through a self-calibration procedure followed by giving more weight to the shorter baseline data points (i.e., tapering). This failed to reveal an outer 20 cm extended structure, and, moreover, no polarization intensity was detected above an rms noise level of ~ 20

TABLE 1

SUMMARY OF RADIO SOURCES DETECTED

Source[a]	α(1950.0)	δ(1950.0)	6 cm Flux[b] (μJy)	20 cm Flux[c] (μJy)	α[d]
E R Aqr lobe	...	...	450	...	...
W R Aqr lobe ...	...	...	650	...	...
CDRS	23^h41^m20^s	−15°30′51″	3,560	8,330	−0.72
F................	23 41 31	−15 36 39	307	< 402	> −0.23
G	23 41 19	−15 37 04	390	1,050	−0.84
H	23 41 16	−15 37 11	262	< 402	> −0.36
I................	23 41 09	−15 36 51	440	< 402	> +0.08
J................	23 41 05	−15 36 28	433	< 402	> +0.06
K	23 41 03	−15 35 25	344	< 402	> −0.13
L................	23 41 04	−15 33 53	212	< 402	> −0.54
M	23 40 57	−15 33 46	1,426	898	+0.39
N	23 41 05	−15 31 51	182	< 402	> −0.67
X................	23 41 34	−15 31 21	1,268	2,008	−0.39
Y................	23 41 17	−15 27 04	8,800	22,980	−0.81

[a] Source names are keyed to radio features shown in the Fig. 2 tapered map.

[b] All 6 cm fluxes are peak except the integrated fluxes for the east and west radio lobes of R Aquarii. The 6 cm rms untapered-map noise from which these fluxes were taken is 29 μJy per beam.

[c] All 20 cm fluxes are peak or upper limits equivalent to 3 times the rms noise level (134 μJy) from reprocessed data (Hollis *et al.* 1985). The 20 cm map was tapered to have the same beam size as the untapered 6 cm map.

[d] Spectral indices or lower limits were obtained from $S_\nu \propto \nu^\alpha$.

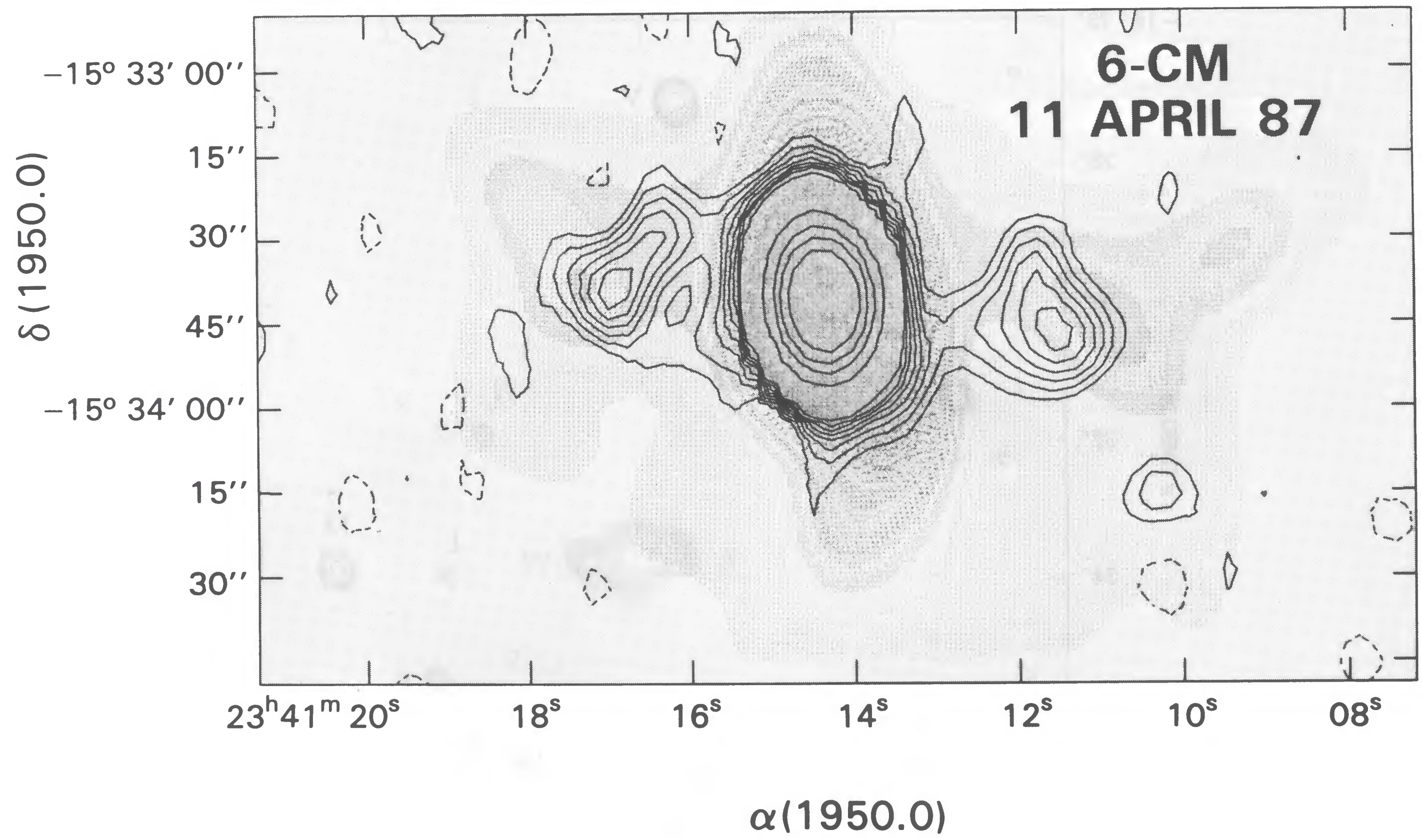

FIG. 1.—The 6 cm VLA contour map of the large-scale radio nebulosity surrounding R Aquarii. Contour levels are −2, 2, 3, 4, 5, 6, 7, 8, 10, 50, 90, 130, and 190 multiples of the rms noise level which is 29 μJy per beam. This untapered map reflects the synthesized beam of 15″.67 × 11″.06 which is approximately equivalent to the 190 rms contour level. The figure background is an [O III] 5007 Å image (Michalitsianos *et al.* 1987) convolved with the aforementioned radio beam for comparison.

μJy from either 6 cm radio lobe; both these results are consistent with the assumption that the extended radio structure is probably optically thin and thermal. Using this assumption, we calculate that the E and W radio lobes have an electron density range of $\sim 1.5 \times 10^2$ to $\sim 1.2 \times 10^2$ cm^{-3} and a combined mass of $\sim 7.9 \times 10^{-5}$ to $\sim 2.5 \times 10^{-4}$ $M_\odot$ for an R Aquarii distance $d = 180$–300 pc, respectively. Moreover, these densities are in agreement with the Solf and Ulrich (1985) estimate based on [S II] line ratios, and we calculate that this low-density nebulosity, once ionized, would remain hot and ionized for at least 200 yr. In our calculations, we have simply assumed that the radio lobes are approximately spherical with $\sim 15''$ radii; however, the actual geometry is not certain since we may be seeing some edge-brightening effect. Using ~ 50 km s^{-1} as a typical expansion velocity within the extended nebulosity (Kafatos and Michalitsianos 1982; Solf and Ulrich 1985), we find that the combined kinetic energy in the E and W radio lobes is $\sim 2 \times 10^{42}$ to $\sim 6 \times 10^{42}$ ergs for $d = 180$–300 pc, respectively. Such energy output is typical of a recurrent nova outburst (see Allen 1973).

b) *Compact Sources*

Unexpectedly, a map of the 6 cm primary beam (Fig. 2) revealed a dozen additional sources (see Table 1) in proximity to R Aquarii which lies well out of the galactic plane (see § II); eight of these sources are $\sim 3'$ south and/or west of R Aquarii. In Table 1, a compact double radio source (CDRS) was previously observed (Hollis *et al.* 1985), while all the remaining sources represent new detections with no known optical counterparts. Reprocessing of 20 cm data (Hollis *et al.* 1985), as previously discussed, was successful in obtaining complementary peak 20 cm fluxes or 3 × rms upper limits and are useful to estimate spectral indices (see Table 1) on these new 6 cm radio sources.

Clearly sources CDRS, G, X, and Y have steep negative spectral indices which are typical of extragalactic background objects. In fact we had previously reported the well-studied CDRS as a probable extragalactic source based on its nonthermal spectral index, strong linear polarization (~ 10% at 6 cm), and absence of an optical counterpart (Hollis *et al.* 1985). Although sources L and N have steep negative spectral index lower limits, these limits are not severe and, hence, such emission could either be thermal or nonthermal.

Source M has an index of +0.39 which is remarkably similar to the combined +0.36 spectral index of the optically thick, thermal inner H II region and the optically thin, thermal jetlike features within $\sim 10''$ of R Aquarii (Hollis *et al.* 1985). Thus, if similar to the R Aquarii small-scale radio structure, source M could be an unresolved combination of

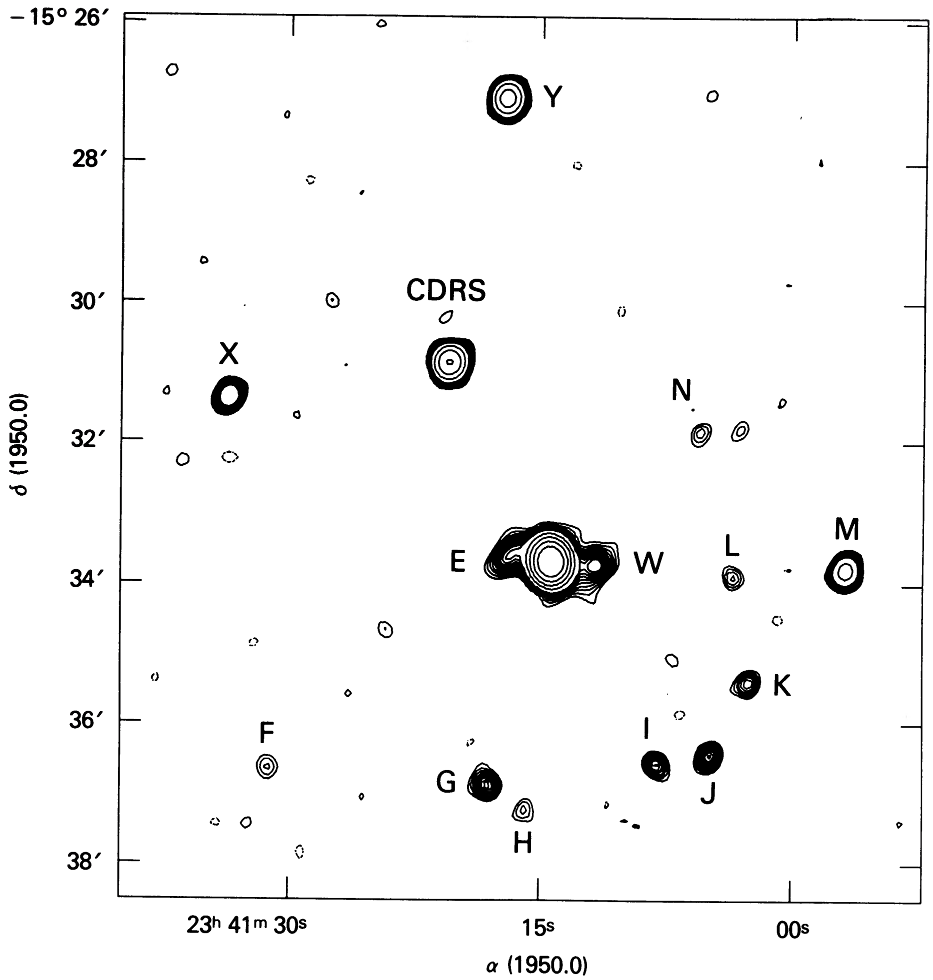

FIG. 2.—The 6 cm VLA contour map of the ~ 9′ FWHM primary beam centered on R Aquarii. Contour levels are −3, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 24, 48, 96, and 192 multiples of the rms noise level which is 25 μJy per beam. This naturally weighted (tapered) map enhances the low-level sources to the south and/or west and, hence, reflects the resultant synthesized beam of 19″.9 by 17″.8. The peak fluxes of the sources shown in this figure are listed in Table 1.

optically thin and thick, thermal emitting regions. Moreover, source M may well be associated with R Aquarii since it appears in line with the extended nebular protrusion to the west.

Lower limits to the spectral indices of sources F, H, I, J, and K suggest that each source probably has a flat radio spectrum consistent with thermal emission. From the observations to date, we cannot determine if these weak sources are associated with R Aquarii since their spectral indices and spatial density are consistent with those observed for weak, low-luminosity, nearby extragalactic objects (Fomalont *et al.* 1984). However, most of sources listed in Table 1 seem to be clustered near R Aquarii, and it is tempting to speculate that F, H, I, J, and K may be some past optically thin knotty relic of this complex binary system. Such knots or condensations would undoubtedly be enhancements in some larger distribution of extended material which is now too weak in its surface brightness to be detected. If this is the case, we estimate a total combined mass of $\leq 4.9 \times 10^{-5}$ to $\leq 1.8 \times 10^{-4}$ $M_{\odot}$ for d = 180–300 pc, respectively, based on 6 cm fluxes in Table 1. Interestingly enough, these mass limits are comparable to the mass estimate of the combined E and W lobes. If sources F, H, I, J, and K were ejected at ~ 50 km s^{-1}, the ejection occurred ~ 3300 to ~ 5600 yr ago for d = 180–300 pc, respectively. Hence, these observations may be evidence for a prehistoric nova-like outburst. Similarly, the ~ 2′ extended nebulosity may represent a more recent outburst ~ 650 to ~ 1100 yr ago. Kafatos and Michalitsianos (1982) first suggested that there may be Far Eastern historical records of such an outburst, and this was confirmed by Li (1985). The ejection that may have formed F, H, I, J, and K would not be expected to be found in such records unless the ejection occurred with a velocity of ≥ 100 km s^{-1}.

We must point out that the inner, small-scale, less-massive, jetlike features are more consistent with a precessing accretion disk ejection mechanism (Kafatos, Michalitsianos, and Hollis 1986). Since the escaping cone of radiation from the accretion disk is very broad (Kafatos, Michalitsianos, and Hollis 1986), the source of ionization of the E and W lobes could be radiation from the inner disk. It remains to be shown, however, whether this radiation can ionize the more remote sources. We find that $\geq 4\ L_{\odot}$ of ionizing radiation is needed to keep ionizing each of the sources such as F, H, I, J, and K. Since the accretion disk provides a total ionizing radiation of 20 $L_{\odot}$ (Kafatos, Michalitsianos, and Hollis 1986), photoionization from the inner disk is marginal. Alternatively, sources F, H, I, J, and K may be ionized by shock heating as they plow into the interstellar medium. The amount of energy radiated by each source is $\sim 5 \times 10^{40}$ ergs yr^{-1}, and the kinetic energy of expansion would be adequate enough to provide this rate.

c) *Summary*

We have (1) detected a large-scale $\sim 2'$ radio nebula which engulfs the R Aquarii symbiotic system; (2) shown that this radio nebula is morphologically similar to the Hα optical nebula; (3) calculated that the kinetic energy of the extended radio nebulosity is consistent with a recurrent nova outburst; (4) observationally shown that the $\sim 2'$ radio/optical nebula must be stable on a time scale > 7 yr; (5) unexpectedly detected 11 new radio sources in proximity to R Aquarii; (6) speculated that at least six of these new sources may be associated with the binary system which would suggest that R Aquarii underwent a nova-like outburst in prehistoric times.

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