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HIGH SPATIAL RESOLUTION VLA OBSERVATIONS OF THE R AQUARII JET

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ABSTRACT

High spatial resolution observations (~ 1″) of the jet feature associated with the symbiotic variable R Aquarii were obtained with the Very Large Array (VLA). The peak radio intensity of the jet lies at a 29°.3 P.A. with respect to the radio emission from R Aquarii itself. If the line defined by the jet and star is extended ~ 196″, it intercepts a previously reported and heretofore unresolved radio source. In our high spatial resolution 6 cm map, this feature is resolved into a compact double radio source, whose peak intensity lies on an axis defined by the jet and star. The possible association of this feature with R Aquarii or with the extended filamentary nebula that surrounds the system cannot be determined from these radio morphology studies alone. If this feature is associated with R Aquarii, it may represent ejecta from the system which occurred previously. Moreover, a new unresolved radio feature has been detected ~ 2″.7 from the central star at ~ 45° P.A. It may represent material recently ejected from the system, perhaps as the object precesses. Weak evidence for a counter-jet is suggested from radio contours centered on R Aquarii.

Subject headings: stars: accretion — stars: circumstellar shells — stars: long period variables — stars: mass loss — stars: radio radiation

I. INTRODUCTION

R Aquarii (M7e + pec) is a symbiotic star suspected of being a binary stellar system which consists of a 387 day period Mira variable with a hot subdwarf. This stellar region is characterized by an extended diffuse filamentary nebula that encircles an inner compact ionized region. A jetlike feature of the inner compact nebula appeared between 1970 and 1977. The jet has been observed in the optical (Wallerstein and Greenstein 1980; Herbig 1980), in the radio at 6 and 2 cm with the VLA (Sopka *et al.* 1982), and in the far-ultraviolet with the *International Ultraviolet Explorer* (*IUE*) (Michalitsianos and Kafatos 1982). A theoretical interpretation (Kafatos and Michalitsianos 1982) for the formation of the jet proposes that it involves supercritical accretion onto the hot companion star and occurs during periastron in a highly elliptical 27–44 year orbit.

Optical spectra obtained by G. Herbig (see Sopka *et al.* 1982) suggest radial velocity differences between the jet and adjacent nebular emission knots are substantial; the mean heliocentric radial velocity of the jet is ~ -70 km s^{-1}, while the mean radial velocity centered on the star is -44 ± 2 km s^{-1}. Enhanced microdensitometer images of Lick 3 m direct plates obtained by Herbig (1980) suggest the jet feature is detached from the star. Previously obtained radio continuum integrated flux measurements at 6 cm by Sopka *et al.* indicated the jet is weaker by a factor of ~ 4 compared with the star. These initial VLA observations, obtained with the C antenna configuration, lacked sufficient spatial resolution (~ 5″) to discern structure in the jet; however, they did show the radio emission was coincident with the optical jet feature photographed by Herbig (see Sopka *et al.*). These radio observations also reported an unresolved radio spot approximately 3′ from the R Aquarii radio source toward the NE along the 29°.3 P.A. line. It is not clear whether this radio source is associated with R Aquarii or is a background extragalactic radio source.

Michalitsianos and Kafatos (1982) obtained UV-spectra of the jet and the inner compact ionized region. The jet's far-UV continuum flux between 1200 and 2000 Å rises steadily with decreasing wavelength and is significantly different in appearance than the continuum flux distribution exhibited by the stellar ionized region. The compact inner region exhibits UV continuum emission which is flat or independent with wavelength over this spectral range. Moreover, prominent emission lines of Si II λ1815 and Si III] λ1892 seen in the central region are absent in the jet. These observations suggest the material in the jet is comparatively cooler and less dense than the central region. This has been confirmed by

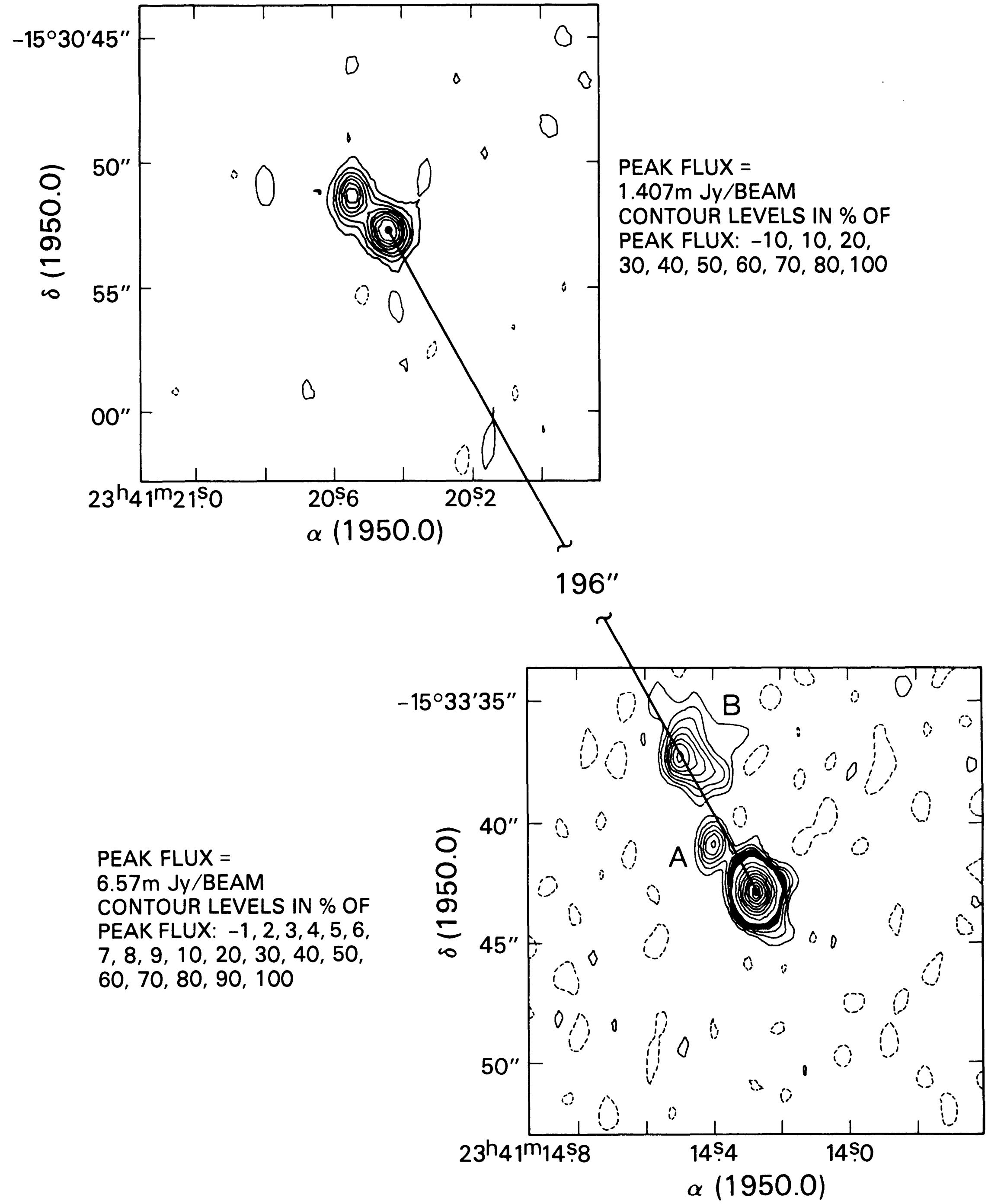

FIG. 1.—(*lower*) This 6 cm map shows structure extending from R Aquarii along a position angle of ~ 29°.3; contour levels and the peak flux for this map are shown to the left. Note the unresolved nature of the nearby point source (A) to the NE of R Aquarii and R Aquarii itself. The jetlike feature (B) farther to the NE shows some structure. (*upper*) This 6 cm map shows the CDRS with contour levels and its peak flux to the right. The double nature of this source is clearly resolved, but each component remains pointlike, reflecting the approximate shape of the synthesized beam (see text). The peak flux of the jetlike feature falls along the superposed position angle line, whose length is not to scale of the maps, from the peak flux of R Aquarii to the peak flux of the stronger CDRS component. The integrated flux of the CDRS and the jetlike feature are approximately the same (see Table 1). Caution is advised in drawing conclusions from any apparent complementary map morphology shown here between the CDRS and the R Aquarii environment until confirming observations of a different nature (e.g., spectrographic) are available.

TABLE 1

Observational Summary of Positions and Fluxes

Source (1)	α(1950) (2)	δ(1950) (3)	Integrated Flux[a] (mJy) (4)	Date (1982 Sep) (5)
Fig. 1, R Aquarii Map:	...	...	11.793[b]	26
R Aquarii	$23^h41^m14^s.270(1)$	$-15°33'42''.76(1)$	7.746[c]	26
Nearby point (feature A) ...	23 41 14.398(7)	−15 33 40. 85(10)	0.614[c]	26
Jet (feature B)	23 41 14.493(7)	−15 33 37. 23(10)	3.433[d]	26
Fig. 1, CDRS Map:	...	...	4.034[b, e]	27
Stronger feature	23 41 20.444(1)	−15 30 51. 66(2)	1.926[c]	27
Weaker feature	23 41 20.548(3)	−15 30 51. 29(4)	1.282[c]	27
Calibration Sources:				
3C 48	01 34 49.832	+32 54 20. 52	5360[f]/5360[f]	26–27
3C 138	05 18 16.532	+16 35 26. 92	3095(20)/3018(13)	26–27
2345−167	23 45 27.687	−16 47 52. 59	4198(33)/4055(29)	26–27

[a] The 1 σ error on the background field of all maps was ~ 0.05 mJy per beam.

[b] Total map flux.

[c] Flux under a fitted elliptical Gaussian.

[d] Flux resulting from subtraction of the contribution of R Aquarii and the nearby point feature from the total flux of the R Aquarii map.

[e] Note that the total flux of the CDRS map is more than the sum of the fluxes under the two fitted Gaussians which approximate this source (see text).

[f] Assumed known (Baars *et al.* 1977); flux density errors in this column reflect the uncertainty in determining flux calibration ratios from observations relative to 3C 48 (see text).

recent optical spectra of the forbidden O II and O III emission lines (R. Fesen, private communication) obtained of the jet feature.

II. OBSERVATIONS

The observations, centered on R Aquarii and the compact double radio source (CDRS), were made on 1982 September 26 and 27, respectively, with the NRAO[1] VLA. The B antenna configuration with all 27 antennas was employed at 4885 MHz (λ6 cm). The intermediate frequency bandwidth was 50 MHz. The spacing between antenna pairs varied between 0.2 and 11.1 km which yielded a synthesized CLEAN beam of 1''.42 × 1''.04 with a position angle of −1°.64. The observations of R Aquarii were interleaved with observations of 2345−167 which was used as the calibration source; time dedicated to each object was 12.5 and 2.5 minutes, respectively, inclusive of array move time. This observational procedure for R Aquarii was followed for a period of 8 hours centered on 0^h LST. The flux density scale was established by assuming 3C 48 to have a flux density of 5.36 Jy (Baars *et al.* 1977). A single 3C 48 observation of at least 4 minutes was made to establish proper flux density ratios with 2345−167 and R Aquarii. Identical observing and calibration procedures were followed for the CDRS, using 2345−167 as the calibrator source.

The data were edited and 2345−167 observations were used to calibrate the correlated amplitude and phase data of R Aquarii and the CDRS. The standard programs at the VLA site were used. The calibrated amplitudes and phases were transformed to produce the CLEANed 6 cm maps with no taper applied as shown in Figure 1. The presentation of the maps demonstrates the relative orientation of the CDRS with respect to the R Aquarii environment. R Aquarii itself is largely unresolved but does display some structure on the side opposite the jetlike feature (B in Fig. 1) which is ~ 6''.4 toward the NE along the 29°.3 P.A. line. Moreover, an unresolved feature (A in Fig. 1) ~ 2''.7 away from R Aquarii toward the NE is readily apparent. The CDRS is resolved into two pointlike features, and it is curious that all five distinct features in Figure 1 lie along the position angle determined by the peak flux in the CDRS and R Aquarii. Table 1 is a compilation of the positions and integrated fluxes of the radio features mentioned above. The total integrated flux of the CDRS map is comparable to the integrated flux we attribute to the jetlike feature near R Aquarii. Source count statistics predict the brightest background source at a 2.3 mJy level within a 9′ beam at 6 cm (Hjellming and Basart 1982). Thus, with just the observed morphology and attendant flux levels, we are unable to determine unambiguously if the CDRS is associated with R Aquarii. Future spectrographic observations in either the optical or ultraviolet may be able to resolve this important issue.

III. DISCUSSION AND CONCLUSIONS

R Aquarii is known to undergo erratic outbursts in which the hot source dominates the visible light of the

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

cool Mira primary. The binary period of the system is believed to be 44 years (Willson, Garnavich, and Mattei 1981), although a shorter period is not ruled out by the observations (Kafatos and Michalitsianos 1982). Merrill (1950) suspected the orbital eccentricity, e, of the system to be large. If outbursts observed in the system are the result of tidal interaction between the Mira and hot subdwarf companion, an $e \geqslant 0.85$ is necessary in order for the cool primary to fill its Roche lobe, which can occur only at or near periastron (Kafatos and Michalitsianos 1982). We point out that the Mira would fail to fill its Roche lobe by at least a factor ~ 5 for a 44 year orbit if the orbit were perfectly circular. The high eccentricity ensures that mass transfer can occur in the system at or near periastron: such mass transfer would proceed at supercritical rates and form an accretion disk. According to this model, the jet formed during the previous periastron encounter, which accounts for its appearance in the mid-1970s, roughly one binary period after the 1928–1935 outburst.

Present VLA observations of the R Aquarii environment suggest that the integrated radio flux emission at 6 cm has not changed over approximately 1 year (cf. Sopka *et al.* 1982). However, owing to the lower spatial resolution of the earlier 6 cm maps of the jet feature, we cannot determine if any morphologic changes have occurred in radio features (Fig. 1). The nearby point feature A is $\sim 2''.7$ away from the star and could represent material more recently ejected from the system. If this is the case, taking a distance of 300 pc to R Aquarii (cf. Michalitsianos, Kafatos, and Hobbs 1980; and Whitelock *et al.* 1982), $1''$ corresponds to a linear separation of $\sim 4.5 \times 10^{15}$ cm. Feature A is, therefore, about 1.2×10^{16} cm from R Aquarii. Its dimensions are less than the beam size of our VLA map at 6 cm. On the other hand, the jet (feature B) is elongated and spatially resolved. Its peak radio emission is located $\sim 6''.4$ or $\sim 2.9 \times 10^{16}$ cm from R Aquarii at $29^\circ.3$ P.A.

The expansion rate is likely supersonic, where the sound speed, $c_s \sim 10$ km s^{-1}, corresponds to the prevailing electron temperatures in the jet ($T_e \sim 10^4$ K). Our VLA observations enable us to obtain a lower limit for the velocity of feature B: its distance from R Aquarii is ~ 4 times its size, i.e., it has moved 4 times farther than it has expanded. It follows that feature A is moving with an ejection velocity, $v_{\rm ej}$, of at least 40 km s^{-1}. The ejection velocity may be as high as 760–1800 km s^{-1}, if ejection took place between 1970 and 1977. Assuming that feature A was expelled with the same velocity as feature B, we find that it was ejected 3–7 years following the emergence of feature B. If this interpretation is correct, these observations suggest material may be ejected successively every few years from the system.

As the two stars are presently receding from one another, we expect that tidal interaction will subside and, therefore, less and less material will be ejected from the system. The kinetic energy of feature B could be quite high. Taking an electron density $n_e \sim 3 \times 10^6$ cm^{-3} as appropriate for the jet (Wallerstein and Greenstein 1980; Michalitsianos and Kafatos 1982), we find that the kinetic energy of feature B is $E_{\rm B} \sim 2.5 \times 10^{46}\ (n_{\rm B}/3 \times 10^6\ {\rm cm}^{-3})(v_{\rm ej}/700\ {\rm km\ s}^{-1})^2\ (R_{\rm B}/8 \times 10^{15}\ {\rm cm})^3$ ergs, where $n_{\rm B}$ and $R_{\rm B}$ are the density and spatial extent of the feature respectively. The corresponding upper limits to the kinetic energy of unresolved feature A would be $\sim 1/30$ that of feature B for similar densities. The energetics involved in mass expulsion would be sufficient to maintain the extended filamentary nebula that surrounds the R Aquarii system at moderate excitation temperatures, say $T_e \leqslant 10^4$ K (Kafatos and Michalitsianos 1982). Future observations in both the optical and radio will be undertaken in order to determine the kinematics of various features of the nebula.

At present we cannot unambiguously associate the CDRS with R Aquarii or with the nebulosity that surrounds the system. However, it is curious that the *peak* intensities of the CDRS, the jet B, and R Aquarii itself are collinear.

If the jet and the nearby point source (feature A) are ejecta, their difference in position angles could be interpreted as precession of the system while it expells material. The morphology of the outer $\sim 2'$ nebula perhaps could be accounted for in this manner, thus explaining the characteristic lens-shaped filamentary structure. Repeated high spatial resolution observations could confirm this suggestion. The proximity of R Aquarii makes this the closest known object exhibiting jet activity. Continued monitoring of this symbiotic system over a wide variety of wavelengths is important in the next several years in order to determine if episodic mass transfer in the suspected binary system accounts for its observed optical and radio properties.

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