A REVIEW OF THE R AQUARII SYSTEM

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ABSTRACT. The spatially resolved nebula that characterizes the D-type symbiotic R Aquarii has afforded investigators a unique opportunity to probe the extended emission line regions. Its extensive and complex radio morphology, that includes SiO emission from the only symbiotic associated with maser emission, has provided important clues concerning the mass expulsion process in interacting binary radio stars. Infrared, radio, optical, UV and X-ray observations of the system are discussed in context with models which have been proposed to explain the appearance of the brilliant jet.

1. INTRODUCTION

1.1 Early Spectroscopic Observations

Of the modest number of known D-type symbiotic systems, R Aquarii (M7e) is unique among the group, having been studied extensively over a wide range of wavelengths. Its relatively close distance of d = 180 to 300 pc has afforded investigators an opportunity to probe the emission properties of the circumstellar-meniscus nebula which characterizes the system at optical, and more recently, at radio continuum wavelengths (Hollis et al. 1987). Since the early observations of Lampland of the 1920's, R Aquarii is known to be associated with an extended filamentary nebula which surrounds a 387^d period Mira. The presence of nebular forbidden lines in optical spectra was identified by Merrill (1934,1940 and 1950), who measured their radial velocities and observed the rise of the continuum from the hot source of the system. Between 1922 to 1933, the continuum of the hot subdwarf actually dominated the strong TiO absorption features associated with the Mira; the hot companion achieved a visual magnitude $m_V \sim 8$, which rivaled the Mira even at maximum light. Merill also recorded the presence of P-Cygni structure in the Balmer lines during the spectroscopic outburst of the 1920. Since that time R Aqr has seemingly returned to a quiescent state, in which the

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nebular emission lines of [N I], [N II], [S II], [O II], [O III], [Fe II], [Fe III], He I, He II and the Balmer lines are superimposed on the strong TiO features of the cool M star. The possible cyclic nature of the blue continuum source in R Aqr proposed by Merrill (1950), in which the hot source would again brighten in the mid-1960's, was not observed (Jacobsen and Wallerstein 1975).

The extended nebula consists of a filamentary structure that is comprised of two broad, and almost symmetric arcs, whose intersecting points form a double meniscus-shaped nebula, that is ~90-arcsec in EW extent. Nearly perpendicular to the EW nebula, a NS nebula of approximately 1-arcmin extent is also present. Both NS and EW nebulae are centered on a spatially unresolved HII region which surrounds the Mira and hot companion. Based upon the expansion velocity of the EW filaments, Merrill (1950) deduced that the outer nebula was created during a nova outburst which he estimated took place about 600 years ago. However, from ancient chronicles it has been suggested that the nova may have actually taken place about 1000 years ago (Kafatos and Michalitsianos 1982), or more precisely as a "guest star" of 1073 AD, as noted by Li (1985). Alternatively, Solf and Ulrich (1985) propose the EW and NS nebulae were formed in two distinct ejection events, in which the EW "ring" was formed 640 years ago, while the NS nebula was created in a more recent outburst, about 185 years ago.

1.2 Radio Continuum and SiO Maser Emission

Gregory and Seaquist (1974) detected the first radio emission from R Aqr at 10.5 GHz. Their observations indicated the source was variable on a timescale of ~1 month, over which time the flux density varied by a factor ~5. In addition, they deduced an upper limit to the size of the radio emitting region of ~1 arcsec, while the radio flux densities obtained at 10.5, 8.085 and 2.695 GHz suggested a spectral index of $\alpha \sim -0.1$, ($S \propto \nu^{\alpha}$), consistent with optically-thin bremsstrahlung emission. Lepine, LeSqueren and Scalise (1978), Zuckerman (1979) found SiO maser emission in R Aqr from the collisionally pumped vibrationally excitated $J = 2 - 1$, $v = 1$ transition. Zuckerman (1979) finds that the SiO lines at 43.12203 and 86.24327 GHz indicate radial velocities -28 km s^{-1} (LSR), which is close to the radial velocities of the K I and Ca I lines obtained by Wallerstein and Greenstein (1980), but is not consistent with most of the absorption features associated with the Mira, which indicate -20 km s^{-1} as the most commonly measured systematic velocity for the star. Emission lines formed at lower densities, such as [O III] and [N III], indicate larger radial velocities, that range up to -60 km s^{-1}, and suggest the velocities in the nebula increase outwardly (Wallerstein and Greenstein 1980). The discrepancy between the SiO maser velocity and optical lines from the Mira may be quite important, because SiO maser emission associated with M giants and M supergiants is believed formed in the extended atmospheres of these stars, where column densities are sufficiently high that SiO can be

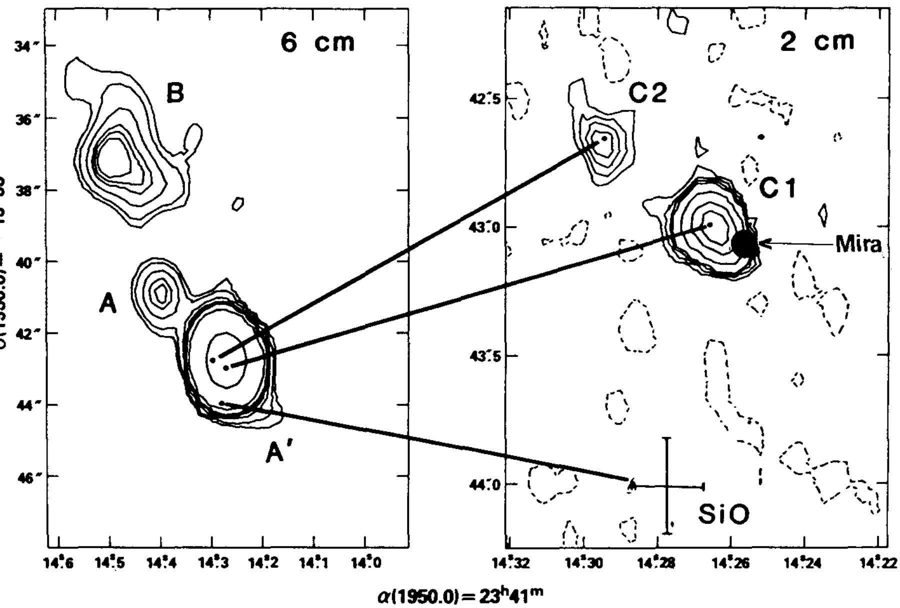

Figure 1: VLA 6 and 2-cm radio continuum maps showing position of the SiO Maser in R Aqr, and the astrometric optical Mira Position

efficiently pumped by collisions (Elitzur 1980). Accordingly, the SiO maser should be found in close proximity to the HII region, in which the Mira and hot subdwarf are embedded.

However, sub-arcseond radio continuum observations obtained with the Very Large Array (VLA) and SiO observations obtained with the Hat Creek Radio Interferometer demonstrate that the SiO maser is far removed from the HII region (Hollis et al. 1985). The centroid of SiO maser emission is ~ 1-arcsec south (4.5×10^{15}cm at d = 300 pc) of the HII region, which corresponds to the spatially resolved feature C1, one of the two radio features that comprise the central HII region. (Fig. 1). Moreover, astrometric observations indicate the Mira is located within feature C1 (Michalitsianos et al. 1987), consistent with the Hat Creek observations which indicate the maser is not in the near vicinity of the long period variable. This result will very likely impact models concerned with SiO maser emission in single late-type M giants as well. It may be that shocks formed several hundred Mira radii from a high velocity wind could achieve sufficient column densities that SiO maser emission can be excited through collisions (Elitzur, private communication). This question remains completely open for further investigation.

2. THE NATURE OF THE RADIO/OPTICAL/UV JET

2.1 Radio Continuum Observations

Wallerstein and Greenstein (1980) first noticed the appearance of a brilliant optical "spike" or "jet" in 1977 protruding about 6".5 - NE from the central star. From their spectra they concluded the "spike", as well as other points in the nebula are generally lower in density ($n_e \sim 10^2 - 10^3 cm^{-3}$) compared with the HII region, based upon the relative intensities of the [O II] and [S II] lines. Subsequently, RG1 and UG1 images of the jet from Lick 3-m direct plates obtained by Herbig (1980) indicated that the jet has probably brightened, and rivaled the Mira at minimum light ($m_V \sim 11$ mags.). A comparison of the 1980 plates with those obtained by Herbig in 1970 indicated that the jet had probably appeared within the decade. Radio maps obtained with the VLA at 6-cm (with ~4-5-arcsec spatial resolution; Sopka et al. 1982) closely matched the morphology of the Lick-UG1 images of the jet.

Higher spatial resolution (~ 1-arcsec) observations at 6-cm with the VLA (Kafatos et al. 1983) further resolved the jet and HII region in three discrete regions of emission, consisting of a spatially resolved feature B located about 6".5 from R Aqr at a position angle (p.a.) 29°, feature A, at 2".5 and p.a. = 45°, and emission from a compact HII region that corresponds to the position of the binary (Figure 2, VLA map). The extended contours SE of the R Aqr (labeled A') provide bipolar symmetry with feature A. Mauron et al. (1985) obtained high resolution optical images in near UV light confirming the radio structure, from which they concluded that features A and A' comprise the jet, while feature B is not dirtectly associated. However, given that features A and B have nearly the same p.a., and are relatively strong radio sources, it is unlikely that feature B not associated with physical processes that created A and A'. The spatial extent of feature B enabled Hollis et al. (1985) to obtain its spectral index $\alpha \sim -0.1$ from 20, 6 and 2-cm VLA maps. This index is consistent with optically-thin bremsstrahlung emission also found by Gregory and Seaquist (1974), but from the integrated radio emission of R Aqr at 10.5, 8.085 and 2.695 GHz. However, Hollis et al. (1986) also found that $\alpha \sim +0.6$ in the HII region, consistent with a spherically symmetric, optically-thick wind (Wright and Barlow 1975). The combined index of the jet and HII region is $\alpha \sim +0.3$, which cautions against surveys of unresolved stellar radio systems, in which the combined spectral indices of optically-thick and -thin emitting regions can introduce systematic errors (cf. Seaquist et al. 1984), if the jet nebulosity of R Aqr is typical of the contributions which extended radio structure can make in symbiotic stars. Additionally, a comparison of the 6-cm maps obtained between 20 Sept 1982 and 3 Feb 1984 indicate the integrated flux density of the map ~11.793 mJy had not changed over this period. If the radio flux from the system is highly variable (Gregory and Seaquist 1974), the system can have periods of prolonged radio quiescence as well.

Sub-arcsec 2-cm VLA maps of by Hollis et al. (1986) revealed the presence of another radio feature in the system C2 (Figure 1, right panel) at 0".5 and p.a. = 55°, whose flux density at 2-cm of 1.37 mJy is weaker compared with the HII region (feature C1), which is 8.52 mJy. In all, the radio components we associate with the jet, therefore, consists of features C2, A and B, with A' possibly indicating counterjet activity. The oblate contours that define feature C1 suggests a prolonagtion in the direction of C2, and indicates the HII region is spatially resolved. Astrometric observations of the luminous Mira indicate it is located within the contours of C1 (Michalitsianos et al. 1987), consistent with the model that the suspected ~44 year binary orbit (Willson et al. 1981) is surrounded by a compact HII region that is photoexcited by the intense radiation field of the hot subdwarf and/or accretion disk.

Finally, VLA observations obtained by Hollis et al. (1987) at 6-cm revealed radio emission from the outer ~2' - EW nebula. Typical electron densities derived from the radio emission of the extended EW nebulosity are $n_e \sim 10^2$ to $10^3 cm^{-3}$, consistent with estimates from optical nebular lines (cf. Wallerstein and Greenstein 1980; Solf and Ulrich 1985). Curiously, wide-field 6-cm maps also revealed a cluster of a dozen radio sources, most of which are ~3' south and/or west of R Aqr. Together with 20-cm data, these observations suggest limits of the index α, which indicate they are thermal, while other sources in the field with $\alpha < 0$ may be extragalactic background sources. If the cluster of sources is associated with R Aqr, they may provide the first direct evidence of a prehistoric outburst of the system (Hollis et al. 1987).

2.2 Far-UV, Optical Emission and Extinction in the System

The complex nature of the circumstellar extinction associated with R Aqr makes it difficult to obtain n_e and T_e from the emission measure. From optical spectra acquired in 1977, Wallerstein and Greenstein (1980) obtained an E(B-V) = 0.67 mags. for the inner nebula, while extinction in the vicinity of the jet appeared to be almost negligible. Similarly, Kaler (1981) obtained an E(B-V)=0.65 from the normalized fluxes of lines calculated from the recombination theory of Osterbrock (1974), approprite to $n_e \sim 10^6 cm^{-3}$, and $T_e \sim 10^4$K. Whitelock et al. (1983) found that the peculiar variability of Hα indicates that Wallerstein and Greenstein's value of 0.67 could be questionable. In order to explain these discrepancies, Whitelock et al. (1983) propose that an opaque dust cloud partially obscured the Mira between 1975 to 1978. From the Balmer lines, Hβ, Hγ, Hδ, and He I lines, (Brugel et al. 1984) have concluded that the extinction varied from E(B-V)=0.4 in 1979 to E(B-V)=0.05 in 1982, which together with Wallerstein and Greenstein's value of 0.67 in 1977, indicates that central star was partially obscured by a dust-cloud in 1977. Probably a combination of variable extinction and geometrical changes strongly affect the nature of the line and continuum emission from the source. The partial obscuration of R Aqr by an opaque dust cloud

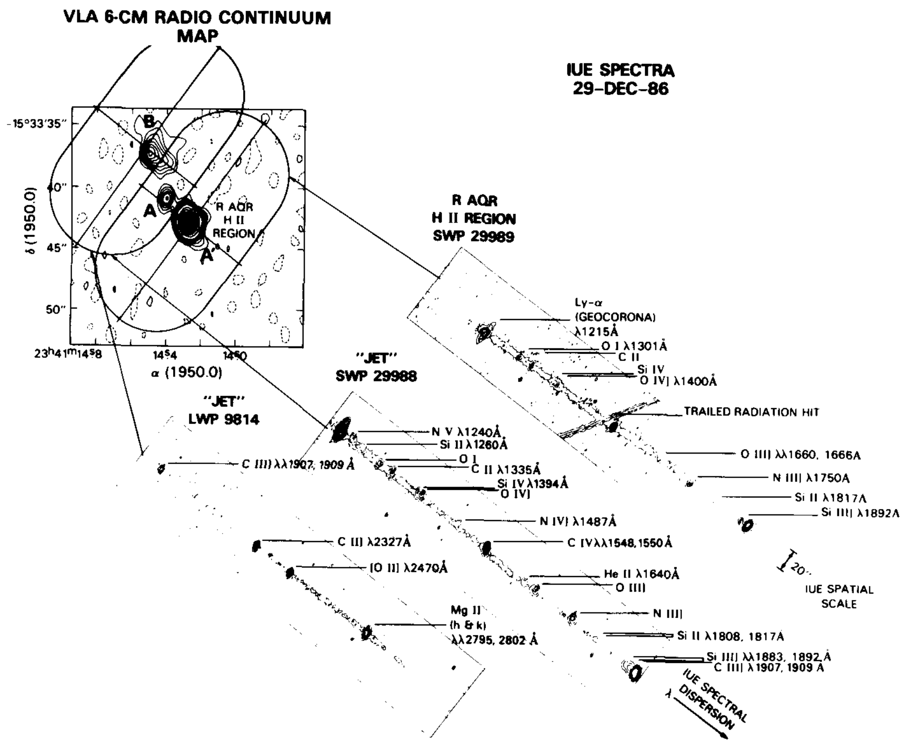

Figure 2: IUE 10x20" entrance slit shown on VLA 6-cm radio continuum map. Emission features are indicated for two slit positions; SWP 29988 & LWP 9814 centered on jet feature B, SWP 29989 on HII region.

is also suspected for another similar system, RX Puppis, that is based upon variations in J and V magnitudes over a timescale of ~2 years (Whitelock et al. 1984).

The spatial extent of the jet has afforded investigators an opportunity to examine the far-UV emission of the jet separately from the HII region. Low resolution IUE spectra (Δλ ~ 6Å resolution) indicate considerable differences exist in excitation between these regions (Kafatos et al. 1986). In addition to most of the resonance and intercombination lines of the jet exhibiting quasi-periodic variations in line strengths on timescales of $\gtrsim$1.5 years, a systematic increase in line intensity is observed over 4 to 5 years; while the line intensities appear essentially constant in the HII region. The appearance of N V λλ1238,1242, and strengthening of He II λ1640 emission in the jet, indicates that higher excitation conditions prevail at the jet offset position, compared with the HII region, where N V is absent, and He II emission is weak (Michalitsianos et al. 1986; Kafatos et al. 1986) (Fig. 2). The appearance of N V in the jet in 1985 is consistent with the first unambiguous detection of soft X-ray emission in the 0.25 to 1 KeV energy range with EXOSAT by Viotti et al. (1987). Because higher excitation conditions prevail in the jet, soft X-rays are likely to be more intense in the vicinity of features A and B, where N V and He II are prominent. EXOSAT does not have sufficient spatial resolution to determine where X-rays could be concentrated in the system.

Additionally, Paresce et al. (1987) obtained narrow band filter images with the ESO 2.2m coronograph telescope in Hα, and [N II], where they detected the appearance of a new feature, located at 8".4 and p.a. = 20^{o}. They suggest this new feature may be an extension of feature B, and provides evidence for shock excitation. The appearance of this new feature sometime between 1984 and 1986 is contemporaneous with the detection of N V at the jet offset position, and with the detection of soft X-rays from the system.

3.0 MODELING R AQUARII AND ITS JET

A number of models have been proposed to explain the nature of the complex nebulosity and temporal emission from this object. It seems reasonable that the emission line spectrum of the star can be explained by a compact HII region with characteristic densities and temperatures of $\gtrsim 10^{6}$cm^{-3} and T_e ~15,000K (Michalitsianos 1980). The intense radiation field emanating from the hot subdwarf and/or accretion disk, photoionizes the HII region (Kafatos et al. 1986), but also powers a stellar wind. Evidence for an optically-thick stellar wind in the system is indicated by the spectral index $\alpha \sim +0.6$ obtained by Hollis et al. (1985) in the radio, and from the first successful IUE SWP-HIRES spectrum of the central HII region, in which the anomalous C IV doublet intensity ratio of I(λ1548)/I(λ1550) ~ 0.6. This ratio being less than the optically-thick limit of unity can explained if a hot optically-thick wind, with an expanion velocity at least equal to the doublet separation of $\Delta\lambda$ = 2.6Å, or $\gtrsim$ 500 km s^{-1}, results in P-Cygni profile absorption of blue component photons by the red doublet component (Michalitsianos et al. 1987). This will enhance emission of the λ1550 line relative to λ1548 line, because the source function $S_{\nu,R}$ of the red doublet now depends on nonlocal values of $S_{\nu,B}$ of the blue doublet (cf. Castor and Lamers 1979; Olson 1982).

The appearance of the jet and the mechanism of its continued and sustained excitation is under dispute. Solf and Ulrich (1985) have shown that the velocities associated with features A and B (relative to the star) are characteristically $\lesssim$100 km s^{-1}. Solf and Ulrich (1985) suggest that feature B was part of the major outburst which formed the NS inner nebula about 185 years. The appearance of feature B in 1977 is the result of collisions with differentially moving material in the expanding nebula, which decelerates the parcel, resulting in shock heating and a sudden brightening of the parcel which took place in late 1970's.

The morphology of features A, B and C2 from high resolution VLA maps, however, suggests that the parcels which comprise the jet indicate systematic, organized flow from the system. As such, the radio features define an arc on the small-scale (up to ~7 arcsec from the central star) which is similar to the broad filamentary arcs that form the EW and NS nebula (on the 1-arcmin scale), as evident in narrow-band [O III] images (Michalitrsianos et al. 1987). This morphology could suggest that each parcel was ejected sequentially in repeated outbursts, while the central "cannon" precesses or rotates (Kafatos et al. 1986). Thus, there is evidence for an extended S-pattern in the NS bipolar nebula, which could reflect the historical sequence of outbursts from the system.

Also evident from IUE spectra, the continued increase in excitation at the jet offset position is not consistent with the cooling timescale of ~2-years for nebular material, if shock excitation were the only means of heating ejected parcels of gas in a low density gas, where $n_e \sim 10^2$ to $10^3 cm^{-3}$. Kafatos et al. (1986) suggest that the illumination of perviously ejected parcels by an intense cone of ionizing radiation created by a thick-accretion could explain morphology of the radio jet features, and the modulations of UV emission lines found in IUE spectra of feature B, if the broad radiation cone of the disk slowly precesses while also varying in intensity. This modulation could be the result of a variable mass accretion rate. A sufficient body of evidence is not presently available which favors either of these models. Quite probably, a combination of shock and photoionization models might eventually prove to be correct.

R Aqr could constitute a prototype of directed mass loss or jet activity in symbiotic systems. RX Pup and HM Sge also show similar structure in the C IV line profiles, indicating that these systems may also posses hot star winds. Moreover, the close proximity of R Aqr to earth affords us a unique opportunity to study the physics of jet formation. The suspected accretion disk in R Aqr could be visible with HST. The low velocities prevalent in the R Aqr jet have been explained as a result of ejection from the outer, cool regions of the giant accretion disk that surrounds the hot star. Grain opacity would be high in this region, resulting in efficient acceleration of gas parcels, even at luminosities much less than the Eddington limit (Kafatos et al. 1986). The existence of a hot stellar wind is only evident in the C IV profiles of the HII region, while the bulk of the ejected gas moves at much lower velocities ($\lesssim$100 km s^{-1}). The jet of CH Cyg may be related to jet activity in R Aqr, in the sense that high ejection velocities observed of $\gtrsim$1000 km s^{-1} are achieved because ejection takes place closer to the hot subdwarf (Taylor et al. 1986).

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