RADIO OBSERVATIONS OF SYMBIOTIC STARS

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I. INTRODUCTION

One of the defining characteristics of symbiotic stars is the presence of nebular emission lines, which indicates the existence of a circumstellar nebula. Since the excitation and ionization of atomic emission lines depend on the temperature and density of the emission region, line observations (optical or ultraviolet) therefore only selectively probe part of the circumstellar nebule. Radio observations being less sensitive to "hot spots", reflect the global character of the ionized region and are more suitable for determining the density structure of the nebula. Recent advances in the technique of aperture synthesis allow observations to be made with high resolution ($\sim 0\overset{''}{.}1$) and direct mapping of nebular structure is now a possibility. Since the circumstellar nebula is most likely to have originated from the stellar components of the symbiotic system, a better understanding of the nebula may provide important clues to the nature of symbiotic stars.

II. RADIO SURVEYS OF SYMBIOTIC STARS

The search for radio emission from symbiotic stars began in the early seventies. Early detection include V1329 Cygni (Altenhoff and Wendker 1973), V1016 Cygni (Purton, Feldman and Marsh 1973), and R Aqr (Gregory and Seaquist 1974). Systematic surveys have been carried out by Bath and Wallerstein (1976, 15 objects), Gregory and Seaquist (cf. Feldman and Kwok 1979, 17 objects), Wright and Allen (1978, 91 objects) and Kwok (1982, 41 objects). The emission line star survey by Purton *et al.* (1981) also contained a number of symbiotic objects.

Among the 112 stars catalogued by Allen (1979), approximately 10% are detected in radio wavelengths. The low detection rate is not entirely surprising. If we adopt a binary model for symbiotic stars where mass is being transferred from the cool to the hot component, it can be shown that the binary separation cannot exceed approximately twice the radius of the cool component (assuming a mass ratio of 3).

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This implies that the mass-transfer region is no greater than several $\times 10^{13}$ cm; or at a distance of 500 pc, an angular size of $\sim 10^{-2}$ arc seconds. No thermal radio emission can be expected to be detected using present-day instruments.

It is interesting to note that most of the detected objects are not "classical" symbiotic stars but more suitably described as slow novae. This, coincidentally, agrees with the separation of symbiotic stars into two classes as described by Paczynski and Rudak (1981), who distinguished between symbiotic stars with quasi-periodic variations (type I) and those with abrupt optical brightenings which last for years (type II). A difference in accretion rates is suggested to be responsible for the separation of the two types. Such distinctions were also noted by Allen (1979), who designated symbiotic stars with dust-like infrared excesses as type D and those without type S. Approximately 20% of the objects in Allen's (1979) catalogue is type D and these correlate well with the radio emitters. Webster and Allen (1975) also noted that [OIII] forbidden lines are stronger in type D objects and this is explained by Allen (1979) that type S object have denser envlopes and the forbidden lines are collisionally de-excited. Mira-like variability is also found to be more common in type D objects (Feast, Robertson and Catchpole 1977), suggesting that the cool component is a Mira. Most of the slow novae are classified as type D.

The brightest objects in the radio are all slow-novae which have undergone recent eruptions: RR Tel (1945), V1016 Cygni (1964), and HM Sge (1975). This seems to suggest that radio emissions are related to an ejection process, resembling the case of classical novae. For this reason, I shall briefly discuss the radio properties of novae and attempt to establish possible links between novae and symbiotics.

III. WIND MODEL OF NOVAE

Since the mechanism of radio emission is believed to be thermal free-free emission (with the exception of RX Pup, Seaquist 1977) radio-emitting slow novae must have circumstellar nebulae hundreds of times larger than those of symbiotic stars. Classical novae have long been known to be radio sources (Hjellming 1974) and one is tempted to seek a connection between novae and slow novae. In fact, Bath (1977) has suggested that symbiotic stars, slow novae and classical novae may all operate under similar physical mechanisms. Disc accretion by the compact companion at rates close to the Eddington limit produces an ultraviolet continuum source which produces a radiatively-driven wind. Variation in the wind mass-loss rate leads to a shifting optically-thick surface which could result in light variation observed in symbiotic stars. He suggests that the difference between novae and slow novae may just be the rate of the decrease in the mass-loss rate.

Bath and Shaviv (1976) and Gallagher and Starfield (1976) have already demonstrated that many observed properties of classical novae (including the visible light curves) can be explained by such a wind model. Since the free-free opacity is higher in radio wavelengths, the optically thick surface of the wind is in fact larger in the radio and the nova envelope can remain optically thick for a longer period of time than in the optical. It would be interesting to test the wind model of novae and compare its predictions with the observed radio "light curves". Furthermore, there is increasing evidence that fast stellar winds ($v \sim 2000$ km s^{-1}) are also present in slow novae (Andrillat and Swings 1982), suggesting that the wind model may also be applicable to slow novae.

Let us assume that after the optical outburst, mass loss rate from the hot companion decreases as a power law:

$$\dot{M}(t) = \dot{M}_o (t_o/t)^{\alpha} \tag{1}$$

Note that the $\alpha=0$ case corresponds to a pure stellar wind situation and $\alpha=\infty$ corresponds to a sudden ejection. For $\alpha>1$, the total mass of the nova envelope is finite:

$$\Delta M = \int_{t_o}^{\infty} \dot{M}(t) dt = \frac{\dot{M}_o t_o}{\alpha-1} \tag{2}$$

The density distribution in the nova envelope at any instant is given by:

$$\rho(r,t) = \frac{\dot{M}_o}{4\pi v r^2} \left(\frac{v t_o}{vt-r+r_o} \right)^{\alpha} \tag{3}$$

where v is the wind velocity and r_o the base radius of the wind. From equation (3), free-free emission from the nova envelope can be calculated at any epoch. Figure 1 shows the radio "light curves" of V1500 Cygni in 3 frequencies (Hjellming *et al.* 1979). Theoretical curves are fitted with the following parameters: $\Delta M = 5\times10^{-5} M_{\odot}$, $\alpha = 2$, $t_o = 1$yr and $r_o = 10^{11}$ cm. In the rising parts of the light curves where the whole envelope is optically thick the radio flux densities are those given by an expanding blackbody:

$$S_{\nu} = \frac{B_{\nu}}{D^2} \pi \, [v(t-t_o) + r_o]^2 \tag{4}$$

where B_{ν} is the Planck function. At later time intervals, the optically-thick surface will shrink from the physical edge of the envelope and the spectrum will have an intermediate spectral index (<2 but >0) until the whole envelope becomes optically thin and the declining stage begins.

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We can see that qualitative features of the radio light curves can be reproduced. Although the model and its associated parameters may not be unique, it offers a good physical explanation to the radio behavior of classical novae.

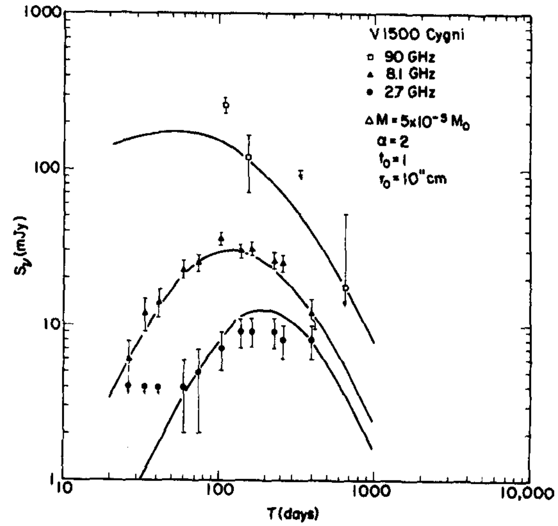

Figure 1. Model fitting to the radio light curves of V1500 Cygni. Radio data is taken from Hjellming et al. (1979).

IV. INDIVIDUAL OBJECTS

I shall now discuss the radio properties of individuals objects where spectral and/or temporal information is available. Attempts will also be made to interpret the observations in the framework of the above model.

A. V1016 Cygni

The radio spectrum of V1016 Cygni is probably the best measured among all symbiotic stars. The optically-thick part of the spectrum has a spectial index of 0.8 and shows no sign of variation over several years. The λ2.8 cm flux density has been monitored continuously since V1016 Cygni's initial detection in 1973 but only marginal evidence of variation is found (Purton *et al.* 1981). Since there is an 8-year gap between the optical outburst and the first radio measurement, we cannot completely rule out the possibility that it has undergone a rise and fall an is the case of classical novae. Nevertheless, it definitely demonstrates the existence of a quiescent component which is incompatible with a rapidly expanding blackbody. Also, the observed radio emission cannot be due to a fast wind from the compact component because the observed flux densities require a mass loss rate $>10^{-3} M_\odot$ yr^{-1} if v>1000 km s^{-1}.

The value of the spectral index, as well as the frequency dependence of the angular sizes (0".35 at λ6 cm and 0".19 at λ2 cm, Newell and Hjellming 1981), however, indicate that the optically-thick radio emission arise from a wind-like situation. There is evidence that the cool component of V1016 Cygni is an M giant and the presence of the

9.7 μm silicate feature suggests that mass is being lost by the M-giant. When the hot component was "turned on" in 1965, the M-giant wind would have become ionized. Assuming a mass loss rate of $\sim 10^{-5}$ $M_\odot$ yr^{-1} and an ejection velocity of ~ 10 km s^{-1}, the level of free-free emission from the ionized M-giant wind is comparable to the observed value.

Although the above picture adequately explains the quiescent radio emission from V1016 Cygni, the nebula of V1016 Cygni may have a more complicated structure, as evident by the high-resolution (HPBW$\sim$0ʺ07) λ1.3 cm VLA map obtained by Newell and Hjellming (1981). The map shows a bright rim of size 0ʺ3×0ʺ5 with a cavity inside. Weaker emissions (halo) can be seen outside the rim structure. One may identify the halo as the M-giant wind (optically thin at λ1.3 cm) and the bright rim as the result of the interaction between the M-giant wind and fast wind ($v \sim 1400$ km s^{-1}, Andrillat et al. 1982) from the hot component, similar to the interacting-winds model proposed for planetary nebulae by Kwok, Purton, and FitzGerald (1978). If this interpretation is correct then the radio emission should become optically thin at progressively lower frequencies (Kwok and Purton 1979). Newell and Hjellming suggest that this is in fact happening: the λ1.3 cm flux density they measured in 1981 is lower than earlier measurements reported by Purton *et al.* (1981) and the turn-over frequency might have moved to 20 GHz in 1981 from 40 GHz a few years ago.

In summary, there are probably two stellar winds in V1016 Cygni (one from each stellar component) and their interaction may result in the shell structure seen by Newell and Hjellming (1981). The shell is probably moving at relatively low velocity, for after 16 years from the initiation of the new fast wind, the M-giant wind is still the dominant contributor to the radio emissions below 10 GHz. Figure 2 shows a schematic diagram of the interacting-winds model.

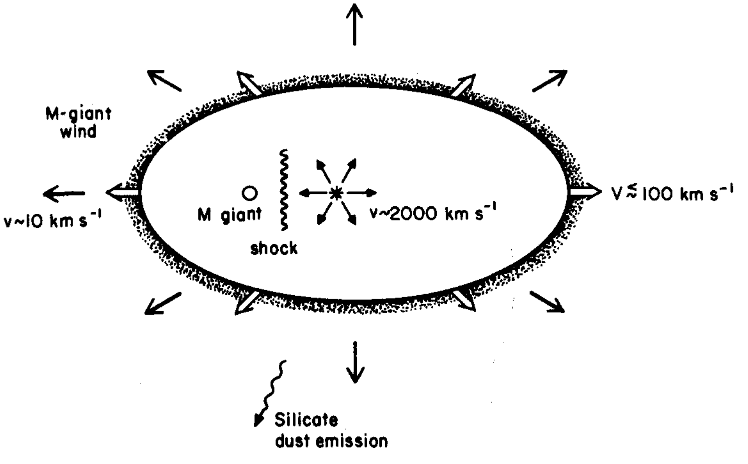

Figure 2. A schematic diagram of the interacting-winds model for slow novae.

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B. HM Sge

HM Sge had an optical outburst in 1975 and is in many respects similar to V1016 Cygni. Its infrared spectrum shows a strong silicate feature, suggesting the presence of an M-giant wind. A Wolf-Rayet feature of $\sim$2000 km s^{-1} (Wallerstein 1978, Allen 1980) has been seen, which can be attributed to a fast wind originating from the compact companion. HM Sge is easily resolved by the VLA. Observations made in May 1981 by Kwok, Bignell and Purton show the source to be elongated with a position angle of $\sim$40°. The angular sizes (1981) are also found to be dependent on frequency, with major axes of 1"5, 0"43 and 0"39 for 1.4, 5 and 15 GHz respectively.

In contrast to V1016 Cygni the radio spectrum of HM Sge has been undergoing rapid evolution. Figure 3 shows that the 10.6 GHz flux density has been increasing almost linearly at 15 mJy/yr since 1977. Figure 4 shows the spectra of HM Sge in 1977 and 1980. This continued brightening suggests a resemblance to the optically-thick phase of classical novae but the time scale is much longer. Since the spectrum is optically-thick to at least 15 GHz, the expansion velocity of the optically-thick surface can be estimated from the change in flux density. The derived value is of the order of 100 km s^{-1}, far less than the wind velocity of the hot component.

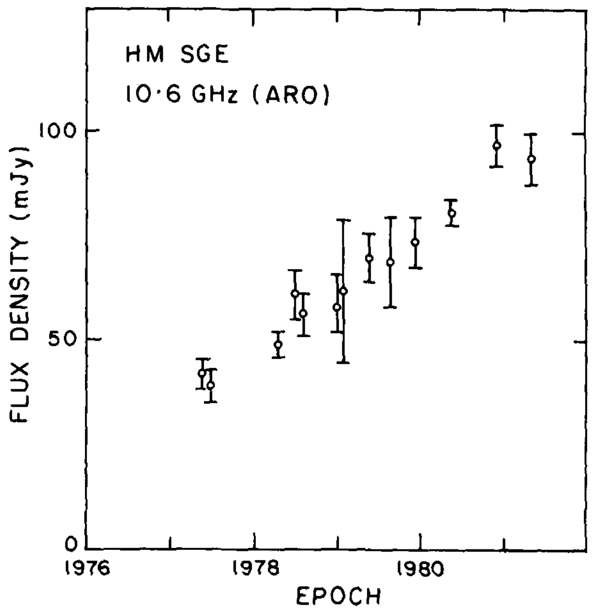

Figure 3. λ2.8 cm light curve of HM Sge (Purton, Kwok and Feldman 1982).

It is clear the nova model of §III cannot adequately explain the spectral evolution of HM Sge. If one takes into account the presence of the M-giant wind and adopts the interacting-winds picture of Figure 2, then the optically-thick emission could have originated from $\sim$100 km s^{-1} expanding shell, which is also increasing in mass as more material in the M-giant wind is being swept up. The observed elongated

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structure could also be explained by the asymmetric expansion predicted by the model.

C. V1329 Cygni

V1329 Cygni (HBV 475) had an outburst in 1966. Its [OIII] emission is much weaker than V1016 Cygni, indicating a denser nebula. Radio emission (12±4 mJy at 10.7 GHz) was first detected by Altenhoff and Wendker in 1973. Between 1973 and 1978, Purton *et al.* (1981) report an average flux density of 14±5 mJy at 10.6 GHz. In 1978, Hjellming (1981) measured a flux density of 5 mJy at 5 GHz using the VLA. However, a subsequent measurement by Kwok, Purton and Keenan (1981) found the source to have disappeared below an upper limit of 1 mJy. This suggests that V1329 Cygni is on its optically-thin decline phase (similar to novae) and a fast wind (Tamura 1981) from the compact companion may be responsible for the formation of the nebula.

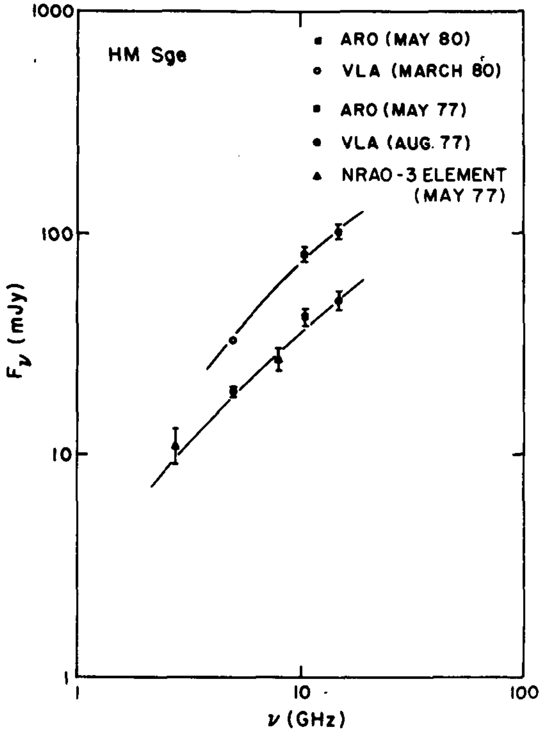

Figure 4. Spectra of HM Sge in 1977 and 1980.

D. AG Peg

AG Peg had an optical outburst in 1850 and has been on a steady visible decline since. Gallagher *et al.* (1979) suggest that the bolometric luminosity has remained constant and the visible light curve is best explained by a shrinking photosphere due to a very slowly decreasing wind. Evidence for a 2000 km s^{-1} wind has been found by Keyes and Plavec (1980). If the radio emission (13±2 mJy at 10.6 GHz) found by Gregory, Kwok and Seaquist (1977) arises from this wind then the mass loss rate is 1.4×10^{-5} $(D/kpc)^{3/2}$ $M_\odot$ yr^{-1}. Recent measurements by Ghigo and Cohen (1981) at 5 GHz are consistent with a wind-like spectrum.

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E. R Aqr

R Aqr is distinct from the other symbiotic stars for it possesses an extensive nebulosity. The nebula is expanding and is believed to have been ejected 630 years ago. Radio emission from R Aqr has been detected by Gregory and Seaquist (1974) and it is found to be variable on a short time scale, possibly associated with ejection events. VLA observations of R Aqr obtained by Spoka *et al.* (1981) show an angular size of $\sim 0\overset{''}{.}3$. Since this is much smaller than the optical nebula, the radio emission might have resulted from a recent ejection.

F. RR Tel

RR Tel is classified as a type D object and probably contains a Mira variable (Feast, Robertson and Catchpole 1977). Wright and Allen (1978) determine the radio spectral index to be $\sim$0.6. Unfortunately not enough temporal coverage is available to determine its possible variations.

V. SUMMARY

The fact that most symbiotic starts do not have detectable radio emission is consistent with the hypothesis that the mass transfer is via Roche lobe and the optical and ultraviolet emission lines originate from the mass transfer region. However, in a number of slow novae, stellar winds from either the cool or the hot components can generate an extended circumstellar envelope from which radio emission arises. It is interesting to note that when an M-giant wind is present, there is no need for the cool component to fill the Roche lobe, and accretion can occur via the M-giant wind. The evolution of the radio spectra of some slow novae is best explained by the interaction of two stellar winds, and this is supported by the line profile analysis by Willson and Wallerstein (1981). It is clear from radio observations that in classical novae the hot-star wind dominates and is normal symbiotic systems wind is not an important element. Slow novae, being intermediate objects, may have their origins tied to the presence of a stellar wind from the cool component.

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DISCUSSION ON RADIO OBSERVATIONS

Cassatella: There is no sign of such high velocities in the ultraviolet IUE spectra of V1016 Cyg and HM Sge or probably in the optical. This seems to be in contradiction with the high expansion velocity (about 1400 km s^{-1}) derived from the radio observations, unless these UV lines are not formed around the compact object.

Kwok: The 1400 km s^{-1} expansion velocity is taken from the H_α line width observed by Swings and Andrillat.

Friedjung: Firstly I object strongly to the term "slow novae" used for objects like V1016 Cyg that are rather different from ordinary novae. I also have a question. Can you give an upper limit to the mass loss rate from ordinary symbiotic stars, which do not show radio emission?
All normal red stars have winds, and it would be useful to have upper limits to the mass loss rate.

Kwok: Not all normal red stars have winds. From infrared data of Gehrz and Woolf (1971 Ap.J. 165, 285) only red giants with spectral type later than M2-3 show wind characteristics. However for a fully ionized wind to be detectable in the radio (1mJy at 5 GHz), $\dot{M}/v$ has to be $>10^{-8}$ $(M_\odot yr^{-1})/(km\ s^{-1})$ assuming $D \gtrsim 1$ kpc.

Kafatos: Is the shock arising from the colliding winds stationary, and what is the associated temperature? I would like also to comment that in the IUE range P Cygni profiles are generally not seen either in the hot lines or in the cool (e.g. MgII) lines of symbiotic spectra. Some exceptions are known (e.g. RX Pup), but they are rare.

Kwok: The equilibrium expansion velocity of the shock front depends on the relative strength of the two winds (see Kwok et al 1978 Ap.J. 219, L125).

Keyes: AG Peg is the exception to the correlation between radio emission and Allen D-type characteristics. Please comment on this.

Kwok: Radio emission from AG Peg is consistent with a wind of $\sim 10^{-8}$ $M_\odot yr^{-1}$ at a speed of ~ 2000 km s^{-1}. Therefore it can be explained by a nova-like decaying wind model. The radio emitting nebula is probably not formed by an M-giant wind.

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