MM/SUBMM OBSERVATIONS OF SYMBIOTIC BINARY STARS: IMPLICATIONS FOR THE MASS LOSS AND MASS EXCHANGE*

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ABSTRACT

We discuss mm/submm spectra of a sample of symbiotic binary systems, and compare them with popular models proposed to account for their radio emission. We find that radio emission from quiescent S-type systems originates from a conical region of the red giant wind ionized by the hot companion (the STB model), whereas more complicated models involving winds from both components and their interaction are required to account for radio emission of active systems. We also find that the giant mass-loss rates derived from our observations are systematically higher than those reported for single cool giants. This result is in agreement with conclusions derived from IRAS observations and with requirements of models for the hot components.

INTRODUCTION

Symbiotic stars are long-period interacting binaries composed of an evolved cool giant and a hot and luminous companion – in most cases a wind-accreting post-AGB star – surrounded by an ionized nebula. The nature of the cool giant plays a key role in the symbiotic phenomenon: it constrains the size of the binary, which must have enough room for a red giant, and yet allow the giant to transfer sufficient mass to its companion. As a result, we have two distinct classes of symbiotic binaries: the S-type (stellar) with normal red giants and orbital periods of about 1–15 yr, and the D-type (dusty) with Mira primaries usually surrounded by a warm dust shell and orbital periods generally longer than 15 yr. The hot star in most cases appears to be a white dwarf powered by thermonuclear burning of the material accreted from its companion wind. The presence of both the evolved giant, often heavily losing mass, and the hot companion copious in ionizing photons and in many cases possessing its own wind lends a large variety to the circumstellar environment of symbiotic stars. In particular, one can expect: ionized and neutral region; dust forming region(s); accretion/excretion disks; interacting winds; bipolar outflows and jets.

Such a complex multi-component structure makes symbiotic stars a very attractive laboratory to study evolution and interaction of binary systems, and excellent targets for both ground-based and space observations in practically any spectral range. The radio and far infrared studies are here of great importance as they can best probe the circumstellar envelopes of symbiotic binaries providing information about stellar winds and their interaction.

So far \( \sim 25\% \) of all symbiotic stars have been detected at cm radio range. In practically all cases, the radio emission is consistent with free-free radiation from ionised gas (Seaquist & Taylor 1990, hereafter ST90). Seaquist et al. (1984) proposed a simple binary model (the STB model) in which the radio emission originates from a conical region of the red giant wind ionized by the hot companion. The geometry of this region is governed by a single parameter, \( X \), which depends on the red giant mass-loss rate, the binary separation, and the Lyman continuum luminosity of the ionizing source. The predicted radio spectrum

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Fig. 1. The 1.3 mm flux density vs. the Hβ flux corrected for interstellar extinction. The solid and dashed lines correspond to optically thin case B emission for $T_e = 10^4$ and $2 \times 10^4$ K, respectively.

Fig. 2. The radio luminosity vs. K − [12] colour, which is believed to measure the circumstellar dust emission for cool giants.

turns over from optically thick to optically thin emission at a turnover frequency, $\nu_t$, which is related to the binary parameters. The observations of $\nu_t$ in quiescent S-type systems with known orbital parameters thus provides a critical test for the STB model. Unfortunately, the spectral turnovers have been thus far determined only in either D-type systems (where orbital periods are not known) or S-type systems – e.g. AG Peg – recovering from nova-type outbursts (Seaquist & Taylor 1992; Ivison et al. 1992, 1995).

In the following, we present and discuss preliminary results of mm/submm observations of a sample of quiescent S-type symbiotic systems. In particular, we show that they are in general consistent with the predictions of the STB model. We also estimate mass-loss rates for the cool giant and discuss relations between intensity of the mass loss and other parameters of these binary systems.

**OBSERVATIONS**

In February 1997, a sample of about 40 symbiotic stars was surveyed at 1.3 mm with the IRAM 30-m MRT. In 1997-98, 12 of these objects were also observed with the JMCT at 2, 1.3, 0.85 and 0.45 mm, respectively. We have combined our mm/submm flux densities with other published data to provide information about the continuum spectra in the radio/IR region for all of the symbiotic systems in our sample. In particular, cm-wave data were from Seaquist & Taylor (1990, hereafter ST90) and Seaquist et al. (1993, hereafter SKT93); *IRAS* fluxes were from Kenyon et al. (1988); near-IR photometric data were from Kenyon (1988) and Munari et al. (1992). We have ignored the possible effect of time variability on the interpretation of these spectra although we are aware of its importance, at least in some systems.

For the following analyses we have selected 20 S-type systems quiescent at the time of our observations. Most of these systems are also well-studied in the optical and UV; the appropriate binary periods are known for 14 of them, and for 7 systems we also have spectroscopic orbits (Belczyński et al. 2000). symbiotic binaries.

**TESTING THE STB MODEL**

Figure 1 shows the relation between the radio flux density at 1.3 mm plotted vs. the Hβ flux corrected for interstellar extinction. The diagonal lines represent optically thin case B emission for electron temperatures
Fig. 3. Continuum spectrum of RW Hya covering the radio, IR and visual bands. The spectrum is split into optically thick/thin ff emission (dashed and dotted curves, respectively) and the giant photospheric (solid curve) components.

Fig. 4. Comparison of the binary separations derived from the radio data, $a_{\text{radio}}$, with independently known values, $a_{\text{sp}}$. For AG Dra and RT Ser two values of distance have been considered.

appropriate for symbiotic nebulae. The systematic downward displacement with respect to the band shown suggests that the radio emission is optically thick at least up to $\sim 1.3$ mm (243 GHz) in agreement with the STB model which predicts the spectral turnover at $\sim 10^3$ GHz, i.e. at submm wavelengths, for typical quiescent S-type systems (SKT93). The mm radio emission shows also some correlation with the mid-IR flux, and the radio luminosity increases with the $K-[12]$ colour (Figure 2), which indicates that both the ionised gas and warm dust are involved in the mass flow, and suggest that the cool giant may be the source of this material. Similar results were obtained by SKT93 based on cm radio observations.

In fact, all stars in our sample but CI Cyg have continua that rise with increasing frequency in cm–mm range, and our IRAM and JMCT data together with other radio data show a single power law with slope $\geq +0.6$ over nearly 3 decades in frequency. In Figure 3, for example, we show the spectrum of RW Hya, which is typical for non-variable S-type systems, and eruptive systems in quiescence. To constrain the turnover frequency, $\nu_t$, for RW Hya, and other well-studied systems, we have estimated the optically thin ff emission in the mm range using the H I $ff+bff$ emission measure derived from the optical and UV data.

In the STB model, knowledge of $\nu_t$ allows to estimate the binary separation, $a$, which can then be compared with the independently known values. For a range in $X$ covering two orders of magnitude, the binary separation within a factor of 2 is (ST90; Mikolajewska & Ivison 2001)

$$a = 300 \left( \frac{T_e}{10^4 K} \right)^{-1/2} \left( \frac{\nu_t}{\text{GHz}} \right)^{-1} \left( \frac{S_t}{\text{mJy}} \right)^{1/2} \left( \frac{d}{\text{kpc}} \right) \text{ a.u.}$$

(1)

where $S_t$ is the optically thin flux near the turnover, and $d$ is the distance.

The comparison of binary separations predicted by Eq.(1) is shown in Figure 4, and it provides the strongest support for the STB model.

The only system for which the STB model does not work is CI Cyg, which shows flat continuum in mm/sub-mm range with a turnover at $\sim 27$ GHz. Both the relatively low turnover frequency (as compared with other quiet S-type systems in our sample) and optically thin flux density require parameters entirely inconsistent with the well-known binary parameters of CI Cyg (Mikolajewska & Ivison 2001). One possible cause of its low, optically thin radio emission (as compared with its very strong H I $bff$ and line emission in the optical and near UV) is that CI Cyg is one of the few symbiotic systems, in which the M giant shows strong tidal distortion, and losses mass via Roche-lobe overflow rather than via stellar wind.
IONIZATION GEOMETRY

Most systems in our sample have radio spectra with the optically thick spectral index $\alpha$ greater than 0.6, which implies an ionization geometry with $X < \pi/4$, and for these cases knowledge of both the turnover frequency, $\nu_t$, and $\alpha$ provides a measure of the value of $X$ which is related to the physical parameters of the system by the expression (ST90, STB)

$$X = 4.7 \times 10^{-17} (a/\text{a.u.})(L_{\text{ph}}/10^{46})[\dot{M}/v]/(M_\odot \text{yr}^{-1}/\text{km s}^{-1})]^{-2} \tag{2}$$

where $L_{\text{ph}}$ is the Lyman continuum photon luminosity of the hot component, while $\dot{M}$ and $v$ are the mass-loss rate the terminal wind velocity of the cool giant, respectively. The spectral index never exceeds 0.8, which implies $X \geq 0.2$ (STB).

This is consistent with results of numerical simulations of Raman scattered O vi $\lambda\lambda$ 6825, 7082 emission lines observed in many symbiotic stars which suggest that symbiotic systems have preferentially an ionization geometry with an $X$-parameter of about 1, which means that the 'average shape' of the ionization front does not differ significantly from the plane between the two stellar components (Schmid 1996). Moreover, the observed properties of the Raman scattered O vi lines in AG Dra, Z And, and few other systems suggest scattering geometry with $0.4 \geq X \geq 4$ (Schmid & Schild 1997a,b). Finally, recent study of optical spectra of 67 symbiotic systems shows that more than 50% of them have the O vi 6825 feature (Mikołajewska et al. 1997). The hot component luminosity in these systems is correlated with the luminosity in the O vi 6825 line, which can be qualitatively understood in terms of similar scattering geometry, and so similar efficiency of the scattering process, for all systems that show this feature. In our sample, 7 objects show the O vi lines, and it seems reasonable to assume that all of them have, within a factor of 4, $X \sim 1$.

**Fig. 5.** Comparison of $\dot{M}/v$ estimates for symbiotic binaries with those for single field giants (shaded area).

**Fig. 6.** $\dot{M}/v$ vs. $K - [12]$ colour (same symbols as in Fig.5).

MASS-LOSS RATES

To estimate mass-loss rates for symbiotic giants from radio data, Wright & Barlow’s (1975) relation is usually applied. This relation, however, underestimates $\dot{M}$ if the wind is only partially ionized, which seems to be the case for most if not all quiescent symbiotic systems. SKT93 estimated the magnitude of this underestimate from numerical models as a factor of 2, 1.5 and 1.15 for $X = 0.5, 1$, and 5, respectively.
Comparison of our estimates with $\dot{M}$’s for field giants (e.g. Dupree 1986) shows that symbiotic giants have systematically higher mass-loss rates than normal red giants do, and $\dot{M}/v$ is only weakly correlated with the spectral type of the giant (Figure 5).

Similar conclusion was reached by SKT93 based on analysis of radio emission at 3.6 cm, and Kenyon et al. (1988), who found that many symbiotic giants have large $[25] - [12]$ and $K - [12]$ colour excesses that are not caused by interstellar extinction. Figure 6 shows that our mass-loss rates are correlated with $K - [12]$ colour.

There are at least two possible explanation for the higher than average mass-loss rates for symbiotic giants. First, it can be a selection effect in the sense that only the very evolved giants, and so those with the highest mass-loss rates, can support symbiotic behaviour in widely separated binary systems. Second, it is possible that the mass-loss rate of the symbiotic giant is enhanced by its binary companion, which reduces the gravity at some points in the outflowing material due to illumination heating and/or causes tidal friction and perhaps enhanced dynamo activity. Tout & Eggleton (1988) argued that the tidal friction enhances mass loss by up to $\sim 2$ orders of magnitude in binary systems containing red giants. Tidal interactions are certainly important in symbiotic systems as suggested by practically circular orbits of all our target sample, as well as of most ($\sim 80\%$) other symbiotic systems with known orbital solutions (Belczyński et al. 2000).

On the other hand, Figure 7 shows that the giant mass-loss rate is apparently correlated with the hot component luminosity, $L_h$, which suggests importance of the illumination heating of the outer atmosphere of the red giant. Although one can naively interpret this correlation as a proof that in fact the radio emission originates from a wind emanating predominantly from the hot component, this is certainly not the case for our targets. The hot component wind with $\dot{M}/v \sim 10^{-8} M_\odot$ yr$^{-1}$ should produce prominent P-Cyg profiles in high-excitation emission lines which are not observed. Moreover, in such case the turnover frequency would be not related to the binary separation. On the contrary, the very good agreement between the binary separations derived from $\nu_k$ and the spectroscopic orbits (Figure 4) as well the correlation of $\dot{M}/v$ with $K - [12]$ colour provide strong evidence that the wind originates from the cool giant.

The correlation between the giant mass-loss rate and $L_h$ also has a natural interpretation in the frame of proposed models for the hot component. In general, the stronger is the cool giant wind the more material can be accreted by its hot companion. Most symbiotics interact by wind-driven accretion, and the expected
accretion rate is a few per cent of $\dot{M}_{\text{wind}}$, and in the case of our sample targets the corresponding accretion luminosity is of order of $10 - 100 L_\odot$. Although the hot component of a typical quiescent symbiotic system, with $L_h \sim 1000L_\odot$ and $T \sim 10^5$ K, cannot be powered solely by accretion, the situation improves radically if the white dwarfs burn H-rich material as they accrete it. For a typical $0.4 - 0.6 M_\odot$ symbiotic white dwarf (Mikolajewska 1997) the minimum accretion rate at which this happens is of order of $10^{-8}M_\odot$ yr$^{-1}$, while the maximum steady burning rate is set by the core mass-luminosity relation, and it is a few times higher. Thus depending on accretion rate (which is related to the giant mass-loss rate) the hot component luminosity is powered either by accretion or by thermonuclear burning of the accreted material, and in both cases its luminosity will be somehow related to the giant mass-loss rate. The mass-loss rates for symbiotic giants derived from our radio observations are thus sufficient to power via wind-accretion and thermonuclear burning the observed luminosities of their hot companions.

Finally, the giant-mass loss rates tend to increase with the orbital period (Figure 8). It is interesting that a correlation between the hot component luminosity and the orbital period was first find by Mikolajewska & Kenyon (1992), while M"urset & Schmid (1999) found a relation between the giant spectral type and the orbital period. Mikolajewska & Kenyon suggested that their result in fact implies a relation between the white dwarf mass and the binary period if the hot components lie on the plateau portion of white dwarf cooling curves and follow some standard core-mass luminosity relation. M"urset & Schmid noted that the limiting line from the spectral type – orbital period diagram is practically identical with the relation $l_1 = 2R_{\text{giant}}$ (where $l_1$ is the distance from the giant’s center to the Lagrangian point $L_1$), suggesting that this configuration is ideal for producing long-lived symbiotic phenomena.

CONCLUSIONS

We conclude that the radio emission in quiescent S-type systems except CI Cyg (and other systems containing Roche-lobe filling giants) originates from the red giant wind partially ionized by the hot component as proposed by STB. The mass-loss rates from symbiotic giants are systematically higher that in single field giants which suggest that only the giants with the highest mass-loss rates can support symbiotic behaviour in widely separated binary systems, in particular can power via wind-accretion and subsequent thermonuclear burning the observed luminosities of their hot companions.

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