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RADIO EMISSION FROM SYMBIOTIC STARS: A BINARY MODEL

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ABSTRACT

We examine a binary model for symbiotic stars to account for their radio properties. The system is comprised of a cool, mass-losing star and a hot companion. Radio emission arises in the portion of the stellar wind photoionized by the hot star. Computer simulations for the case of uniform mass loss at constant velocity show that when less than half the wind is ionized, optically thick spectral indices greater than +0.6 are produced. Model fits to radio spectra allow the binary separation, wind density, and ionizing photon luminosity to be calculated. We apply the model to the symbiotic star H1–36. Some predictions and further tests of the model are pointed out.

Subject headings: stars: binaries — stars: combination spectra — stars: radio radiation

I. INTRODUCTION

The class of symbiotic stars is defined by the basic characteristic of an optical spectrum containing both high excitation emission lines and absorption features of a cool, late-type star. To provide a more uniform criterion for the class, Allen (1979) has further stipulated that a symbiotic star must at one time have exhibited emission lines with excitation energy $E > 55$ eV (e.g., He II). A recent catalog by Allen (1981) contains 129 objects. Extensive infrared photometry of these stars (e.g., Swings and Allen 1972; Allen 1979; Kenyon and Gallagher 1983) has shown that the late-type spectral features arise from a red giant star, usually of spectral type M, but in some cases as early as K or G. About 25% of symbiotics show excess IR emission from dust, typically at a temperature of $\sim$700 K. *IUE* observations (e.g., Slovak and Lambert 1981; Michalitsianos *et al.* 1980) show that many symbiotics contain hot ($\sim 10^5$ K) continuum sources, which are undoubtedly the cause of the high energy ionization.

A few symbiotic stars have been known for some time to be radio sources. However, a recent, highly sensitive radio survey (Seaquist, Taylor and Button 1984; hereafter Paper I) has shown that greater than 25% of known symbiotic stars are radio sources at flux densities of $\sim$1 mJy. The spectral index, α ($S_\nu \propto \nu^\alpha$), at wavelengths of a few centimeters is invariably positive, ranging from 0 to 1.2. The emission mechanism is almost certainly thermal bremsstrahlung.

Radio emission from symbiotic stars has been previously modeled in terms of a single star with a totally ionized wind (Seaquist and Gregory 1973; Wright and Barlow 1975; Panagia and Felli 1975). For mass-loss rates of the order of 10^{-8} to 10^{-6} $M_\odot$ yr^{-1}, this model successfully accounts for the observed radio luminosities. However, the predicted radio spectral index is +0.6, at odds with the observed spectral index distribution for symbiotic stars which peaks instead at $\alpha \approx +1.0$ (Paper I). In this paper, we present a more detailed model for the radio properties in light of the mounting evidence for the binary nature of symbiotic stars. The model was introduced in Paper I. Here we discuss the characteristics of the model in more detail and apply the results to the symbiotic star H1–36.

II. THE MODEL

a) *Geometry of the Ionized Region*

We consider a cool star undergoing uniform spherically symmetric mass loss such that the gas number density is given by

$$n = A/r^2 \,, \tag{1}$$

where r is the radial distance from the mass losing star and

$$A = \frac{\dot{M}}{4\pi\mu m_{\rm H} v} \,. \tag{2}$$

Here $\dot{M}$ is the mass-loss rate and v is the constant wind velocity. Embedded in the wind at a radial distance, a, is a hot star emitting $L_{\rm ph}$ hydrogen ionizing photons per second. A schematic of the system is shown in Figure 1. The location of the surface of the resulting ionized nebula is determined by the balance of recombination and ionization rates inside the nebula and the flux of neutral hydrogen atoms across the surface. In Paper I, we showed that the effects of the wind flow can be ignored for symbiotic systems and that, under this condition, the location of the ionization front is given by the expression

$$f(u, \theta) = X \,, \tag{3}$$

where

$$X = \frac{4\pi\mu^2 m_{\rm H}^2}{\alpha} a L_{\rm ph} \left(\frac{\dot{M}}{v}\right)^{-2} \tag{4}$$

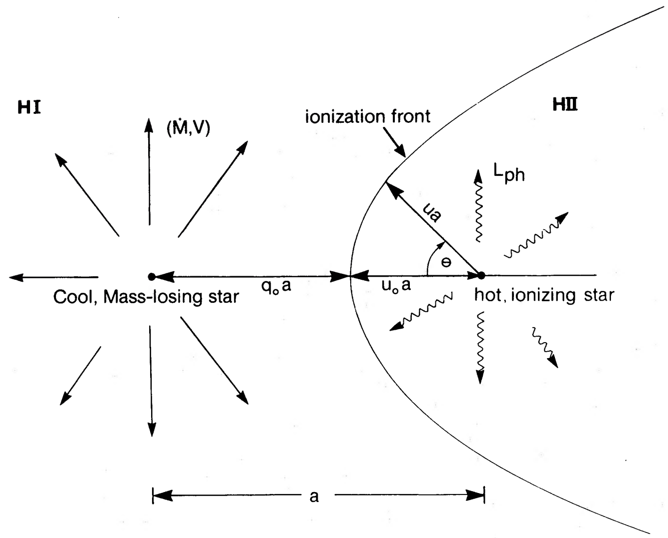

FIG. 1.—A schematic of the model

and α is the recombination coefficient to all but the ground state of hydrogen. The (u, θ) coordinate system is centered on the hot star, with u the radial distance normalized by the binary separation, a, and θ the angular measure from the axis joining the binary components. The function $f(u, \theta)$ is given in equation (5):

$$f(u, \theta) = \begin{cases} \dfrac{1}{3(1-u)^3} - \dfrac{u}{(1-u)^2} - \dfrac{1}{3} ; & \theta = 0 \\[2ex] \dfrac{(2\cos^2\theta - 1)u - \cos\theta}{2\sin^2\theta(u - \cos\theta)^2} + \dfrac{1}{2\sin^3\theta}\left[\tan^{-1}\left(\dfrac{u-\cos\theta}{\sin\theta}\right) + \tan^{-1}(\cot\theta)\right] + \dfrac{\cos\theta}{2\sin^2\theta} ; & \theta \neq 0, \pi . \\[2ex] \dfrac{1}{3} - \dfrac{u}{(1+u)^2} - \dfrac{1}{3(1+u)^3} ; & \theta = \pi \end{cases} \tag{5}$$

Because of the basic symmetry of the system, the ionized zone is cylindrically symmetric about the axis joining the binary components ($\theta = 0, \pi$). The closest point to the cool star lies on this axis at a distance $q_0 a = (1 - u_0)a$, with q_0 decreasing as X increases. An important property of the system is that for $\theta \neq 0°$, the limit of $f(u, \theta)$ as $u \rightarrow \infty$ is finite, and decreases as θ increases. At values of θ where this limit is less than X, the idealized stellar wind will be ionized to infinity. More realistically, for these values of θ the ionized nebula is density bounded.

There are two critical values of X about which the geometry of the ionized nebula undergoes a fundamental change. The three different geometries are illustrated in Figure 2. In the Figure, the system is viewed at an angle of 90° to the symmetry axis. When X is less than $\frac{1}{3}$ (see eq. [5]), the nebula is completely ionization bounded, surrounded on all sides by the neutral portion of the wind, At $X = \frac{1}{3}$, the wind is ionized to infinity at $\theta = \pi$, and, as X increases further, the ionized nebula becomes approximately cone shaped and density bounded in the outward direction. The nebula is still, however, primarily ionization bounded until $X = \pi/4$, at which point the wind is ionized to infinity at $\theta = \pi/2$. As X increases still further, the nebula becomes primarily density bounded, and the neutral portion of the wind consists of a conelike shadow zone, shielded by the dense region near the cool star.

In deriving the geometry of the ionized region we have ignored the effect of the orbital motion of the system. The resulting picture is justified if the recombination time scale at radii of a few times a is much shorter than the orbital period. At $r = a$, the ratio of the period to the recombination time is

$$\frac{P}{t_r} = 4 \times 10^3 \, \dot{M}_{-7} v_{10}^{-1} a_{14}^{-1/2} M_T^{-1/2} , \tag{6}$$

where $\dot{M}_{-7}$ is in units of $10^{-7}\, M_\odot\, \mathrm{yr}^{-1}$, v_{10} is in units of 10 km s^{-1}, a_{14} is in units of 10^{14} cm, and M_T is the total system mass in units of $M_\odot$. Known binary symbiotic stars have periods of ~ 2 yr, or $a \approx 5 \times 10^{13}$ cm for total mass of a few $M_\odot$. Thus, for typical late-type red giant mass-loss rates, the recombination time in the wind at $r \approx a$ will be a very small fraction ($\sim 10^{-3}$) of the orbital period.

b) Radio Spectra

We have carried out numerical integrations to calculate the emergent radio spectrum from the ionized nebula as a function of the parameter X. In Paper I, we presented schematic spectra for representative values of X in the range 0.1–10.0. Here we discuss what can be deduced about physical conditions from a knowledge of the radio spectrum, with a view to modeling of symbiotic star systems.

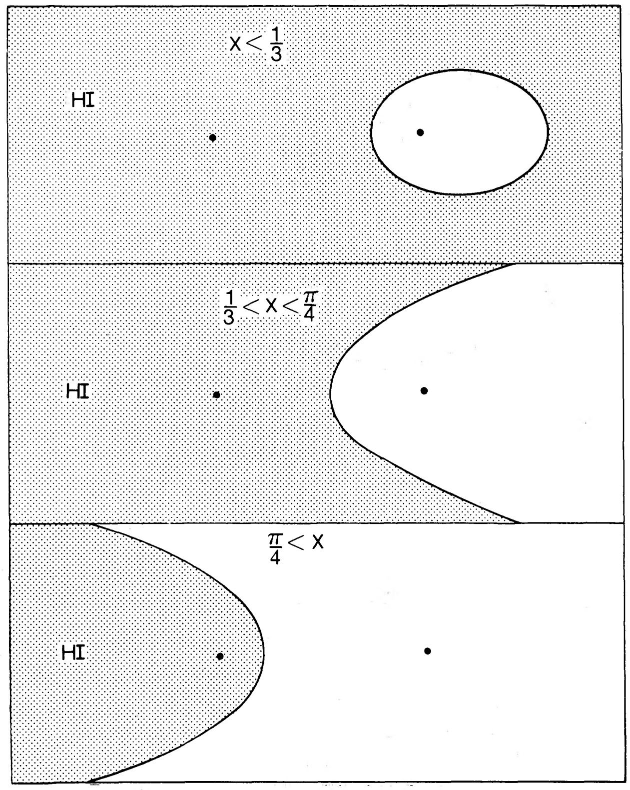

FIG. 2.—The characteristic shape of the ionized nebula for the three ranges of the parameter X

For all values of X there exists a finite inner or outer boundary to the ionized zone. Consequently, at frequencies above some critical value, the nebula will be totally optically thin, and the spectrum will become flat. The optical depth through the ionized region along the axis $\theta = 0$ is

$$\tau_\nu = 2.7 \times 10^{-20} \nu^{-2.1} T_e^{-1.35} a \int_{q_0}^{q_{max}} n_e^2 \, dq \,, \tag{7}$$

where ν is in gigahertz and a is in centimeters, and q_{max} is the position of the outer edge of the ionized zone at $\theta = \pi$. From equations (1) and (2) with $\mu = 1$, and assuming $q_0 \ll q_{max}$, the frequency at which $\tau = 1$ along the axis is given by

$$\nu_t^{2.1} = 8 \times 10^{66} T_e^{-1.35} (q_0 a)^{-3} \left(\frac{\dot{M}}{v}\right)^2 \text{ GHz} \,, \tag{8}$$

where $\dot{M}$ is in units of $M_\odot$ yr^{-1} and v is in kilometers per second. The spectrum turns over to a spectral index of -0.1 at a frequency of a few times ν_t.

The radio luminosity in the optically thin regime is

$$L_\nu = \int \epsilon(\nu) dV \,, \tag{9}$$

where $\epsilon(\nu)$ is the bremsstrahlung volume emission coefficient. For a fully ionized, pure hydrogen, Maxwellian plasma at temperature T_e the emission coefficient is

$$\epsilon(\nu) = 6.8 \times 10^{-38} n_e^2 T_e^{-1/2} g_{ff}(\nu, T_e) \text{ ergs cm}^{-3} \text{ s}^{-1} \,. \tag{10}$$

The flux density, at some frequency ν, in the optically thin portion of the spectrum is thus given by

$$S_\nu = 1.6 \times 10^{32} T_e^{-1/2} D^{-2} g_{ff}(\nu, T_e) \left(\frac{\dot{M}}{v}\right)^2 a^{-1} Q(X) \text{ mJy} \,, \tag{11}$$

where D is in kiloparsecs. The quantity $Q(X)$ is a volume integral, of order unity, that may be calculated numerically for a specific value of X.

In the optically thick regime, the shape of the spectrum is highly dependent upon the geometry of the ionized region and is, thus, a strong function of the parameter X. Moreover, since for $X < \pi/4$ the geometrical aspect presented to the observer changes markedly with the orientation of the system, the spectrum is also a function of the viewing angle. In cases where the geometry presented to the observer is that of a totally ionization bounded nebula, the spectral index at $\nu \ll \nu_t$ (totally optically thick) approaches $+2$. This

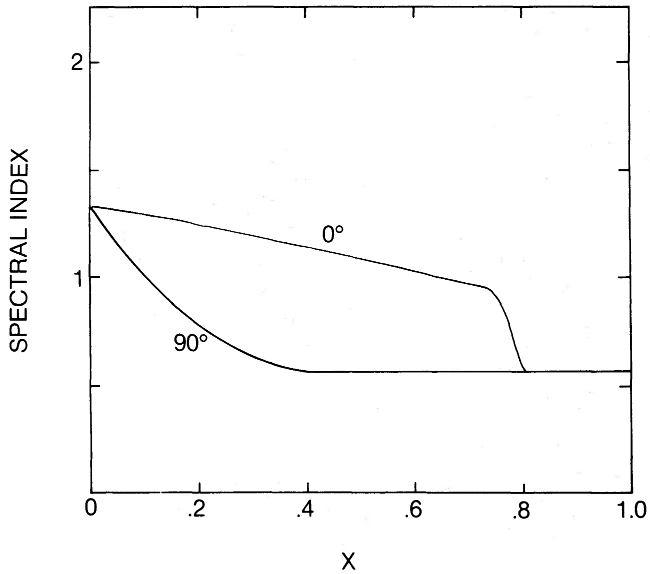

FIG. 3.—The model spectral index, as a function of the parameter X, at the point where the flux density is one-half the peak flux

effect is illustrated in Figure 3 where we show, as a function of X, the spectral index at the point in the spectrum where the flux density equals one-half the peak flux density. Separate curves are plotted for viewing angles of 0° (along the symmetry axis) and 90°. Indices for intermediate viewing angles will lie within the area enclosed by the two curves.

For very low values of X, the spectral index at both viewing angles converges to ~ 1.3. In this case the ionized zone is a small, ionization bounded region with an approximately spherical shape. As X increases, the index at 90° viewing angle decreases as the edge of the ionized zone moves rapidly outward in the $\theta = \pi$ direction, encompassing the less dense, optically thin gas at larger radii. At $X = \frac{1}{3}$, the wind is ionized to infinity, and the ionized region resembles a wedge cut out of the spherically symmetric wind. The spectral index reaches $+0.6$ at this point and is thereafter independent of X. For a viewing angle of 0°, the spectral index decreases more slowly as X increases from very low values. For $X < \pi/4$ the observer sees a circular, ionization bounded nebula with diameter slowly increasing with X. The transition to a density bounded nebula at $X = \pi/4$ (ionization to infinity at $\theta = \pi/2$) occurs over a very small range of X, producing a very abrupt drop of the spectral index to $+0.6$.

For $X > \pi/4$, the optically thick spectral index is $+0.6$ regardless of the viewing angle. In this case, the majority of the wind is ionized, and the ionized region approximates a spherically symmetric ionized wind. The formulation of Wright and Barlow (1975) is, therefore, a good approximation. An immediate result is that a spectral index greater than 0.6 implies $X < \pi/4$. For these cases, knowledge of both ν_t and the optically thick spectral index provides a measure of the value of X, which, from equation (4), is related to the physical parameters of the system by the expression

$$a\left(\frac{\dot{M}}{v}\right)^{-2} L_{\rm ph} = 2.8 \times 10^{75}\, X\,. \tag{12}$$

Equations (8), (11), and (12) constitute a set of three independent equations for the unknowns a, $(\dot{M}/v)$, and $L_{\rm ph}$. Detailed modeling of the radio spectra of symbiotic stars with $\alpha > 0.6$ can thus, in principle, provide a simultaneous, unique solution for the separation of the binary components, the density of the wind, and the ionizing photon luminosity of the hot star. In practice, since the derived values of ν_t and X depend upon the viewing angle of the system, fits to the radio spectra alone will yield a range of possible solutions.

It is noteworthy that the spectral index distribution for symbiotic stars (Paper I) exhibits a cutoff at $\alpha \approx 1.2$. Figure 3 shows a convergence at very low X to $\alpha \approx 1.3$ independent of viewing angle. The specific value of α at low X is dependent on the frequency at which the index is measured. For $\nu \ll \nu_t$, the index approaches $+2$. However, in the context of the model, the observed cutoff can be qualitatively understood in terms of the dependence of α on X and the limited sensitivity of radio surveys. At very low X, the size of the ionized nebula becomes very small (at $X = 0.05$, the linear diameter is $\sim a$). Thus, in general, sources with spectral index close to $+2$ will be faint, and therefore are not likely to be detectable.

III. THE SYMBIOTIC STAR H1–36

The star H1–36 is included in Allen's (1981) list of symbiotic stars. Recently, Allen (1983*a*) has carried out extensive optical and infrared spectrophotometry on H1–36 which provides conclusive evidence for the presence of an M giant. From fits to the IR continuum, Allen measures $A_K = 1.5$ mag, implying a visual extinction of ~ 20 mag. Analysis of the emission lines, however, yields $A_V = 2.2$ mag. Allen interprets the high extinction to the giant as arising from a circumstellar dust shell (seen in the IR continuum) and argues that the high excitation ionization must be produced by a hot binary companion exterior to the dust shell.

H1–36 is among the strongest radio sources associated with a symbiotic star. Multifrequency radio measurements over the period 1974–1977 were reported by Purton *et al.* (1977). The spectrum has a low-frequency spectral index of ~ 1.0 and a high-frequency turnover at ~ 10 GHz. No variability has been detected (Allen 1983*a*). In the context of a binary model, Allen (1983*b*) attributes the

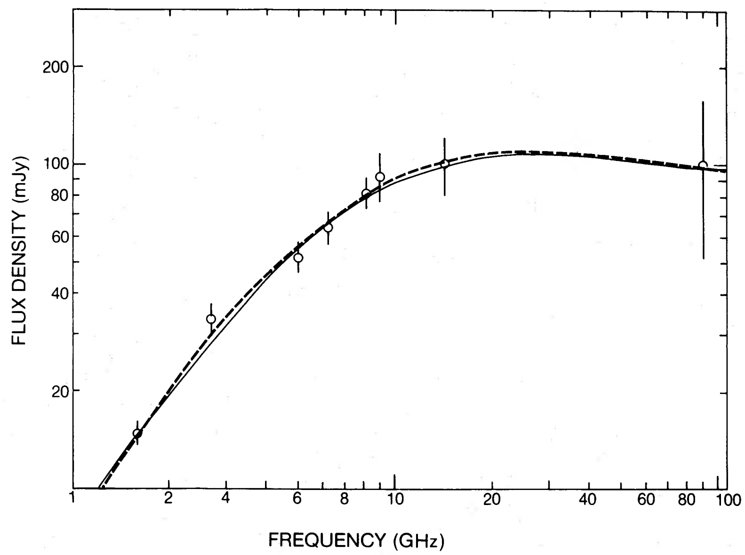

FIG. 4.—The radio spectrum of H1–36. Solid and dashed curves are model spectra for viewing angles of 0° and 90°, respectively.

spectral turnover to the presence of a neutral cavity about the *M* giant, as evidenced by the existence of the dust shell. However, no satisfactory explanation is presented for the optically thick spectral index in excess of +0.6.

Because of its well-measured radio spectrum and the independent evidence for binarity, H1–36 is a prime candidate for our model. We have fitted model spectra to the measurements of Purton *et al.* plus a recent measurement at 1.6 GHz by us with the NRAO[1] Very Large Array. The best fit to the data was established with a least-squares criterion as a function of the parameters X, ν_t and the flux density at frequency ν_t. Very nearly equally good fits were found for viewing angles of 0° and 90°. The best fit parameters are, for 0°, $X = 0.73 \pm 0.02$, $\nu_t = 8.7 \pm 0.5$ GHz, and $S(\nu_t) = 83 \pm 3$ mJy; and, for 90°, $X = 0.14 \pm 0.3$, $\nu_t = 2.9 \pm 0.5$, and $S(\nu_t) = 32 \pm 3$ mJy. Figure 4 shows the observed spectrum and the model spectra for both viewing angles. The model provides an excellent fit to the observations over the entire frequency range.

With equations (8), (11), and (12) and $T_e = 1.5 \times 10^4$ K (Allen 1983*a*), we have used the best fit model parameters to derive values for a, $\dot{M}/v$, and L_{ph} as a function of the distance to the star. The solution for each viewing angle is listed in Table 1. The physical conditions corresponding to the two solutions agree to within a factor of 4. We point out that based on our solutions, equation (6) yields $P/t_r \approx 10^5$. Orbital motion, thus, has negligible effect on the shape of the ionized region at $r \approx a$. The recombination time is comparable to the orbital period at $r \gtrsim 100a$. At these radii, the motion of the system will produce a residual, doughnut-shaped, optically thin emission region. The flux from this region may become important at $\nu \ll \nu_t$.

By assuming a typical bolometric magnitude for a late M giant to the late-type component of H1–36, Allen (1983*a*) suggests a rough distance of 4–5 kpc. Adopting a mean value for the model solutions yields, for a distance of 4.5 kpc, $a = 4 \times 10^{16}$ cm, $\dot{M} = 3 \times 10^{-6} v\, M_\odot$ yr^{-1}, and $L_{ph} = 2 \times 10^{47}$ photons s^{-1}. For a wind velocity of 10 km s^{-1} (typical, although slightly low, for red giant winds), the mass-loss rate is $3 \times 10^{-5}\, M_\odot$ yr^{-1}. This is significantly larger than the value of $5 \times 10^{-6}\, M_\odot$ yr^{-1} that results from using the 5 GHz flux density in the formula of Wright and Barlow (1975). The difference may be attributed to the smaller size of the emitting volume in our model.

We have calculated the expected Hβ flux from H1–36 under the assumption that the nebula is optically thin. Under this condition, the Hβ intensity is proportional to the optically thin radio flux density and is model independent. From equation (11) we may write

$$I_\beta = 1.4 \times 10^{18} \left(\frac{\dot{M}}{v}\right)^2 a^{-1} D^{-2} Q(X) , \quad (13)$$

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

TABLE 1

MODEL PARAMETERS FOR H1–36

Viewing Angle	X	q_0	a (cm)	$\dot{M}/v$[a]	L_{ph} (photons s^{-1})
0°	0.73	0.44	$3.3 \times 10^{15} D$	$1.3 \times 10^{-7} D^{3/2}$	$9.7 \times 10^{45} D^2$
90°	0.14	0.57	$1.4 \times 10^{16} D$	$5.2 \times 10^{-7} D^{3/2}$	$7.8 \times 10^{45} D^2$

[a] $\dot{M}$ in $M_\odot$ yr^{-1}, v in km s^{-1}, D in kpc.

yielding $I_\beta = 3 \times 10^{-11}$ ergs cm^{-2} s^{-1}. This agrees well with the de-reddened flux of 3.3×10^{-11} ergs cm^{-2} s^{-1} measured by Allen (1983*a*). It is thus evident that the radio and Hβ emission are produced in the same volume, and that, in the context of our model, the Hβ flux from H1–36 is not dominated by radiation from an accretion disk.

The solution for a viewing angle of 90° implies an ionization bounded nebula with dimension of a few times *a* that is embedded in the neutral portion of the wind. With a $1/r^2$ dust density law, the implied extinction of ~ 20 mag to the surface of the red giant suggests that this region, which lies at a radial distance of order, *a*, should also experience substantial visual extinction. In fact, for a distance of 4–5 kpc, the 2.2 mag of extinction to the emission-line region will be almost entirely interstellar. The actual viewing angle is probably, therefore, closer to 0°.

Our model for H1–36 presents a quiescent, steady-state picture of the system. The high frequency turnover of the spectrum is a natural consequence of the bounded nebula. In single-star models for symbiotic stars such turnovers have been attributed to finite inner boundaries of shell-like emission regions caused by episodic mass loss. In this scenario, as the inner boundary moves outward the optically thin flux will decrease. However, Allen (1983*a*) points out that recent observations have ruled out any evolution of the radio spectrum.

IV. DISCUSSION

We have shown that the radio spectrum of H1–36 can be reproduced by a simple, steady-state model in which a portion of the stellar wind of a cool giant is photoionized by a hot companion. Recent evidence that many, if not all, symbiotic stars are binaries suggests that the high spectral indices of other symbiotics (e.g., V2416 Sgr, $\alpha = 1.01$; BF Cyg, $\alpha = 0.98$) may be explained in the same manner. Within this framework sources which exhibit the canonical spectral index of +0.6 are those in which the red giant wind is nearly completely ionized. This condition is satisfied when

$$L_{\rm ph} > 2.2 \times 10^{75} a^{-1} \left(\frac{\dot{M}}{v}\right)^2 . \qquad (14)$$

In the case of H1–36, the model fits indicate that less than one-half of the wind is ionized. The picture resulting from the model is that of a very wide binary system ($a \approx 10^{16}$ cm) with a very high mass-loss rate ($\dot{M}$ = a few times $10^{-5}\, M_\odot$ yr^{-1}). For a total mass of $\sim 5\, M_\odot$, the orbital period of H1–36 is a few times 10^3 yr. By comparison, symbiotic stars that are known binaries have typical orbital periods of 1–2 yr, and mass-loss rates of $\sim 10^{-8}$–$10^{-7}\, M_\odot$ yr^{-1} seem adequate to account for the radio flux in most cases. With the caveat that symbiotic stars are by no means a very homogeneous group, H1–36 appears to be a scaled-up version of a typical symbiotic star, with binary separation and wind mass-loss rate $\sim 10^2$ times greater than "normal."

With such a large separation, the red giant component lies well within its Roche lobe. Thus, accretion onto the hot star takes place only through the stellar wind. Using the Bondi-Hoyle formulation, for a 1 $M_\odot$ object the accretion rate is $\sim 10^{-10}\, M_\odot$ yr^{-1}, which implies, for a white dwarf, an accretion luminosity of $\sim 1\, L_\odot$. This is much too low to explain the derived photon luminosity of 2×10^{47} photons s^{-1}, which requires instead $L > 1000\, L_\odot$. The high luminosity can be accounted for by thermonuclear shell burning fed by the wind accretion. Paczyński and Zytkow (1975) have carried out computer simulations of shell burning on white dwarfs for a range of accretion rates. Their results suggests that for $\dot{M} \approx 10^{-10}\, M_\odot$ yr^{-1}, a nuclear flash will occur, having luminosity of $\sim 10^4\, L_\odot$ and lasting ~ 50 yr.

Because of its scaled-up properties, H1–36 is a valuable test case for symbiotic star models. In particular, high resolution radio mapping will provide a direct test of our model. At the distance of H1–36, the dimension, *a*, corresponds to an angular separation of 0″.5. Since the dimensions of the ionized nebula is a few times *a*, the radio source should subtend an angle of 1″–2″. Radio mapping at resolution of a fraction of an arc second will resolve the structure of the nebula.

Further tests of the model will require accurate measurements of the radio spectra of other symbiotic stars with $\alpha > 0.6$. The model fit provides an independent estimate of the binary separation; therefore, such programs should be carried out on stars with known distance and binary period. One good candidate is BF Cyg ($p = 750^{\rm d}$, $D = 4$ kpc). Since the UV photon flux is a critical parameter of our model, *IUE* observations are also valuable.

Another interesting prediction of the model is, for $X < \pi/4$, a variation in the spectral index with orbital phase (see Fig. 3). Spectral monitoring of appropriate systems may provide evidence of this effect.

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