Eccentric orbits of close companions to asymptotic giant branch stars

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Abstract. I propose that the relatively high eccentricity $0.1 \lesssim e \lesssim 0.4$ found in some tidally strongly interacting binary systems, where the mass-losing star is an evolved giant star, e.g., an asymptotic giant branch star, is caused by an enhanced mass loss rate during periastron passages. Tidal interaction by itself will circularize the orbits of these systems in a relatively short time, hence a mechanism which increases the eccentricity on a shorter time scale is required. The proposed scenario predicts that the nebula formed by the mass loss process possesses a prominent departure from axisymmetrical structure. Such a departure is observed in the Red Rectangle, which has a central binary system, HD 44179, with an orbital period of $T_{\mathrm{orb}} = 318$ days, and an eccentricity of $e = 0.38$.

1. Introduction

In recent years it has been found that close binary companions to asymptotic giant branch (AGB) stars can influence the chemistry of the circumbinary shells (or disks) and of the post-AGB stars (e.g., Van Winckel et al. 1995), and the eccentricities of the orbits (e.g., Waelkens et al. 1996). (In this paper I refer by "close binary systems" to systems with orbital periods of $T_{\mathrm{orb}} \sim 1$ yr, i.e., there is a very strong tidal interaction between the AGB star and its companion. By wide systems I refer to systems where the tidal interaction is very weak.) Van Winckel et al. (1998) suggest that all post-AGB star with peculiar abundances are in close binaries. The peculiar abundances, i.e., depletion of Fe peak elements and some other elements (e.g., Waters et al. 1992; Van Winckel et al. 1999), is explained by accretion back from the circumbinary disk of gas depleted of dust (Waters et al. 1992), since the dust is expelled more efficiently from the disk by radiation pressure. The disk helps by providing a slow accretion rate and a low density to prevent an efficient drag between the gas and dust particles (Waters et al. 1992). It is not clear, though, that a Keplerian circumbinary disk is a necessary

condition for the separation of gas from dust. In an earlier paper (Soker 2000) I argued that a dense slowly expanding equatorial flow may have the same effect, while having the advantage that it does not require a huge amount of angular momentum as a Keplerian disk does.

Another peculiar property found among many of these binary systems is a high eccentricity (e.g., Van Winckel 1999, and references therein), despite the very strong tidal interaction between the AGB stars and their companions. Examples are: HD 44179, which is located at the center of the Red Rectangle, a bipolar proto planetary nebula (PN), has an orbital period of $T_{\mathrm{orb}} = 318$ days, a semimajor axis of $a \sin i = 0.32$ AU, and an eccentricity of $e = 0.38$ (Waelkens et al. 1996; Waters et al. 1998). AC Her, with $T_{\mathrm{orb}} = 1194$ days, $a \sin i = 1.39$ AU, and $e = 0.12$ (Van Winckel et al. 1998). 89 Herculis, with $T_{\mathrm{orb}} = 288$ days, and $e = 0.19$ (Waters et al. 1993). HR 4049, with $T_{\mathrm{orb}} = 429$ days, $a \sin i = 0.583$ AU, and $e = 0.31$ (Van Winckel et al. 1995).

Van Winckel et al. (1995) mention in one sentence in their discussion that "... the large eccentricities suggest that mass loss may have started at periastron only, thus increasing the eccentricity still." However, they did not carry out any quantitative study, but abandoned this explanation in favor of the "external disk" mechanism (Waelkens et al. 1996; Waters et al. 1998). What I term "external disk" mechanism is the tidal interaction between the binary system and the circumbinary disk, which is the model to explain eccentricities in young stellar binaries (Artymowicz et al. 1991; Artymowicz & Lubow 1994).

In the present paper I claim that a higher mass loss rate during periastron passage can indeed explain the high eccentricities observed in the systems mentioned above. I am motivated by earlier results that variation in the mass loss rate and the mass transfer rate with orbital phases in eccentric orbits can explain the formation of multiple shells in PNs (Harpaz et al. 1997; in that paper, though, the orbital periods are ~ 100 yrs rather than 1 yr), and the displacement of the the central stars from the centers of PNs (Soker et al. 1998). In the next section I describe the proposed model and the time scales involved, while in Sect. 3 the external disk mechanism proposed in other studies (e.g., Waelkens et al. 1996) is discussed. A short summary is in Sect. 4.

2. Eccentricity evolution due to mass loss

The eccentricity e is reduced by tidal forces on a time scale called the circularization time and is defined as $\tau_{\rm circ} \equiv -e/\dot{e}$. In the common tidal model in use, the equilibrium tide mechanism (Zahn 1977, 1989), the circularization time is given by (Verbunt & Phinney 1995)

$$
\begin{aligned}
\tau_{\rm circ} = 1.2 \times 10^4 \frac{1}{f} & \left(\frac{L}{2000 L_\odot} \right)^{-1/3} \left(\frac{R}{200 R_\odot} \right)^{2/3} \\
& \times \left(\frac{M_{\rm env}}{0.5 M_1} \right)^{-1} \left(\frac{M_{\rm env}}{0.5 M_\odot} \right)^{1/3} \left(\frac{M_2}{M_1} \right)^{-1} \\
& \times \left(1 + \frac{M_2}{M_1} \right)^{-1} \left(\frac{a}{3R} \right)^8 \ {\rm yr},
\end{aligned} \tag{1}
$$

where L, R and M_1 are the luminosity, radius, and total mass of the primary AGB star, $M_{\rm env}$ is the primary's envelope mass, and $f \simeq 1$ is a dimensionless parameter. The synchronization time is related to the circularization time by the expression $\tau_{\rm syn} \simeq (1 + M_2/M_1)(M_2/M_1)^{-1}(I/M_1 R^2)(R/a)^2 \tau_{\rm cir}$, where I is the primary's moment of inertia. Approximating the envelope density profile of stars on the upper RGB and AGB by $\rho \propto r^{-2}$, where r is the radial distance from the star's center, I find $I = (2/9) M_{\rm env} R^2$. Substituting this in the expression for the synchronization time I find

$$
\begin{aligned}
\tau_{\rm syn} = 150 \frac{1}{f} & \left(\frac{L}{2000 L_\odot} \right)^{-1/3} \left(\frac{R}{200 R_\odot} \right)^{2/3} \\
& \times \left(\frac{M_{\rm env}}{0.5 M_\odot} \right)^{1/3} \left(\frac{M_2}{M_1} \right)^{-2} \left(\frac{a}{3R} \right)^6 \ {\rm yr}.
\end{aligned} \tag{2}
$$

The short synchronization time means that the AGB star will spin with an angular velocity of $\omega \simeq (R/a)^{3/2} \omega_{\rm Kep}$, where $\omega_{\rm Kep}$ is the Keplerian velocity on the equatorial line of the primary. The high angular velocity and close companion will lead to an enhanced mass loss rate in the equatorial plane (Mastrodemos & Morris 1999).

The change in eccentricity due to an isotropic mass loss (the derivation is applicable for an axisymmetric mass loss as well; mass transfer will be discussed later) is given by (Eggleton 2000)

$$
\delta e = \frac{|\delta M|}{M}(e + \cos \theta), \tag{3}
$$

where δM is the mass lost from the binary in the stellar wind at the orbital phase θ (hence $\delta M < 0$), M is the total mass of the binary system, and θ is the polar angle, measured from periastron, of the position vector from the center of mass to the secondary. The derivation of Eq. (3) assumes that $\delta M(\theta) = \delta M(-\theta)$. To derive a time scale, I assume that in addition to its constant mass loss rate over the orbital motion $\dot{M}_w$, the primary AGB star loses an extra mass δM_p in a short time during the periastron passage, $\cos \theta = 1$. The total mass being lost in one orbital period $T_{\rm orb}$, is $\Delta M_o = \dot{M}_w T_{\rm orb} + \delta M_p$. I define the fraction of the mass being lost at periastron

$$
\beta \equiv \frac{\delta M_p}{\Delta M_o}. \tag{4}
$$

The constant mass loss rate $\dot{M}_w$ does not change the eccentricity. Hence, the change in the eccentricity in one orbital period is $\delta e = (1 + e)(|\delta M_p|/M)$. Over a time much longer than the orbital period we can write for the rate of change of the eccentricity

$$
\frac{de}{dt} = -(1 + e)\beta \frac{\dot{M}}{M} \tag{5}
$$

where the total mass loss rate is $\dot{M} = \Delta M_o/T_{\rm orb} = \dot{M}_w + \delta M_p/T_{\rm orb}$. I define the time scale for change in eccentricity due to enhanced periastron mass loss as

$$
\begin{aligned}
\tau_p \equiv \frac{e}{de/dt} = 4 \times 10^3 \beta^{-1} & \left[\frac{e}{0.2(1 + e)} \right] \left(\frac{M_1 + M_2}{2 M_\odot} \right) \\
& \times \left(\frac{|\dot{M}_o|}{10^{-4} M_\odot \, {\rm yr}^{-1}} \right)^{-1} \ {\rm yr}.
\end{aligned} \tag{6}
$$

Under the assumption that the fraction of mass lost at periastron passage β does not change during the evolution, we can integrate Eq. (5) to yield

$$
\frac{1 + e}{1 + e_i} = \left(\frac{M_i}{M} \right)^\beta, \tag{7}
$$

where e_i and M_i are the initial eccentricity and total mass, respectively. Both the initial over final mass and β can vary continuously among different systems. It is useful, however, to examine two extreme cases.

Systems with $\beta \simeq 1$: When most of the mass is being lost during a periastron passage, then $\beta \simeq 1$. Such can be the case for low mass AGB stars and/or stars not yet on the upper AGB, so that the mass loss rate is low, and the secondary, via direct gravitational effects, increases substantially the mass loss rate during periastron passages. For systems with $\beta \simeq 1$, a moderate amount of total mass loss can substantially increase the eccentricity. For example, for initial (initial means at the beginning of the interaction, not on the main sequence) masses of $M_{1i} = 1 M_\odot$ and $M_2 = 0.6 M_\odot$, and $e_i \ll 1$, if the primary loses its entire envelope of $0.4 M_\odot$, the eccentricity will be given by $1 + e \simeq 1.6/1.2 = 1.33$ or $e \simeq 0.3$. For $\beta = 0.5$ we get $e \simeq 0.15$ for the same mass loss evolution. The circumbinary wind (or nebula) is expected to have two prominent properties. First, since most of the mass, at least in the equatorial plane, is lost via a dynamical interaction between the two binary stars, and not by radiation pressure on dust, the wind expansion velocity in the equatorial plane will be very low (Soker 2000). Second, since most of the mass, or a substantial fraction of it, is lost during a periastron passage when the mass-losing star always moves in the same direction, the nebula is expected to possess a large degree of departure from axisymmetry (Soker et al. 1998). Such a process may explain the departure from axisymmetry observed in the Red Rectangle. The Red Rectangle has a close eccentric binary system, with $T_{\rm orb} = 318$ days and $e = 0.38$. The general structure of the Red Rectangle is highly axisymmetrical, up to $\sim 1'$ from the central star (e.g., Van Winckel 2000). However, the 10 μm map presented by

Waters et al. (1998; their Fig. 3) shows a clear departure from axisymmetry at scales of $\sim 5''$ from the central star. Their contour map shows that the equatorial matter is more extended in the west side.

Systems with $\beta \ll 1$: In these cases the total mass lost by the system should be larger, or only slightly smaller, than the total binary final mass in order for the eccentricity to be $e \gtrsim 0.1$. This is expected for systems where the mass-losing star reaches the upper AGB, hence has a strong wind. The rotation, because of synchronization with the orbital motion (Eq. (2)), can further increase the mass loss rate. Contrary to the previous case, the wind will have an expansion velocity typical for AGB stars, and the departure from axisymmetry will be small. Only in the equatorial plane might the flow be slower, since the mass lost at periastron via dynamical interaction may not be accelerated to high velocities (Soker 2000). The departure from axisymmetry might still be large enough to be detected by observations.

The tidal circularization time (Eq. (1)) and the time scale for the increase of eccentricity due to periastron mass loss (Eq. (6)) have a different dependence on the eccentricity, as well as on other parameters. We can find the conditions for the eccentricity to grow by requiring that the time scale given by Eq. (6) be shorter than the circularization time given by Eq. (1). For this purpose, we can neglect the dependence on the luminosity, radius, and envelope mass in Eq. (1). Neglecting the dependence on the envelope mass is justified since from Eq. (7) it emerges that for the eccentricity to change by $e \gtrsim 0.1$, the envelope mass to be lost should be $\gtrsim 0.2 M_\odot$. Using these approximations and $e \ll 1$, and taking $M_1 = M_2 = 1 M_\odot$, we find the condition for the eccentricity to grow

$$\left(\frac{a}{3R}\right)^8 \gtrsim \beta^{-1} \left(\frac{e}{0.2}\right) \left(\frac{|\dot{M}_o|}{10^{-4} M_\odot \ \mathrm{yr}^{-1}}\right)^{-1}. \tag{8}$$

In general, it is expected that $a \gtrsim 3R$. This is since for $e \simeq 0.3$ the periastron distance for $a = 3R$ is $a_p \simeq 2R$, and a Roche lobe over flow is likely to occur at these distances. The mass loss process increases the orbital separation, increasing further the ratio a/R. If the eccentricity does not grow much, and the continuous mass loss rate $\dot{M}_w$ increases as the AGB star's envelope mass decreases, then the system changes from a $\beta \simeq 1$ system into a $\beta \ll 1$ system.

Until now I have considered only mass loss, neglecting mass transfer. When the primary's radius to orbital separation ratio increases (as the primary expands along the AGB) to $(R/a) \gtrsim 0.5$, mass transfer, e.g., due to Roche lobe overflow, becomes important. The change in eccentricity due to a mass δM_{tran} transferred from the primary to the secondary is given by (Eggleton 2000)

$$\delta e = 2 \delta M_{\mathrm{tran}} \left(\frac{1}{M_1} - \frac{1}{M_2}\right) (e + \cos\theta). \tag{9}$$

Since enhanced mass transfer is expected during periastron passage, we see that the eccentricity will increase if $M_1 < M_2$, as is required for stable mass transfer and is found for these systems (e.g., HD 44179 in the Red Rectangle; Waelkens et al. 1996).

Because of the extended envelope of AGB stars, the mass transferred can be several times the mass lost in one orbital period. Therefore, the change in eccentricity due to mass transfer may become important when the mass-losing star becomes less massive than the accretor. The tidal interaction, though, will become stronger as well at these small orbital separations.

A final comment to this section is that because of their close companions, these post-AGB stars did not evolve on a canonical AGB track (H. Van Winckel, private communication). However, it is still expected that they had a high mass loss rate in their recent past.

3. Comparison with the external disk process

Waelkens et al. (1996) attributed the eccentricity of post-AGB close binaries to the external disk mechanism. In the external disk mechanism, which was developed for young binary systems (e.g., Artymowicz & Lubow 1994), there is a resonance interaction between the binary system and an external disk, mainly with the disk material closer than $\sim 6a$ to the binary system (e.g., Artymowicz et al. 1991). The eccentricity increases at a rate given by (e.g., Artymowicz et al. 1991)

$$\dot{e} \simeq 1.9 \times 10^{-3} \left(\frac{M_{\mathrm{disk}}}{M}\right) \left(\frac{2\pi}{T_{\mathrm{orb}}}\right), \tag{10}$$

where M_{disk} is the mass of the disk inner to $\sim 6a$.

The large uncertainty for post-AGB stars, or any post-main sequence mass-losing star, is the disk mass within $\sim 6a$. There is strong evidence for molecular disks in several AGB or post-AGB stars, but these disks have typical radii of several$\times 100$ AU (Jura & Kahane 1999). The inner boundaries of the disks can be much closer to the binary system, typically ~ 20 AU, or even $5-10$ AU in some cases (H. Van Winckel, private communication). In the Red Rectangle the inner boundary is modeled to be at ~ 15 AU (Waelkens et al. 1996), which is more than six times the semi-major axis of its central binary system HD 44179. In 89 Herculis the inner boundary of the circumbinary material, whether a disk or not, is at $r_i \sim 40$ AU (Waters et al. 1993). Waters et al. (1993) also estimated the disk mass to be $6 \times 10^{-4} M_\odot$. The circumbinary material extends to at least several tens of AU (Alcolea & Bujarrabal 1991), therefore the mass inside a radius of $6a$ will in any case be very small, $< 10^{-4} M_\odot$, so that the time scale for eccentricity increase will be very long.

The conclusion from this section seems to be that the disk's mass close to the binary systems, i.e., within $\sim 6a$, is too small in these systems to account for the high eccentricity via the external disk mechanism. Since these systems are post-AGB stars (or similar objects), it is still possible that during their AGB phase the disk mass was high enough for the external disk mechanism to be efficient. This possibility requires further examination.

4. Summary

In the present paper I propose that the relatively high eccentricity $e \lesssim 0.4$, of tidally strongly interacting binary systems

where the mass-losing star is an AGB star, a post-AGB star, or a similar object, is caused by an enhanced mass loss rate during periastron passages. Tidal interaction by itself will circularize the orbits of these systems in a relatively short time. Therefore, a mechanism which increases the eccentricity on a shorter time scale is required. Waelkens et al. (1996) suggested that the mechanism is an interaction with a circumbinary disk. The interaction occurs mainly with the inner regions of the disk, within ~ 6 times the binary orbital separation (e.g., Artymowicz et al. 1991). In Sect. 3 above I argued that such disks, if they exist, do not contain enough mass in their inner regions to explain the high eccentricity. Instead, I showed in Sect. 2 that an increase in the mass loss rate at periastron passages can explain these eccentricities.

Both the interaction with a circumbinary disk mechanism and the enhanced periastron mass loss rate mechanism predict much higher mass loss rate in the equatorial plane, via the strong binary interaction (Mastrodemos & Morris 1999), leading to the formation of a bipolar nebula, e.g., the Red Rectangle. But each has another strong prediction. The external disk mechanism predicts the presence of a relatively massive disk close to the binary system. So far there is evidence only for more extended disks. It remains to be shown, theoretically and observationally, that such disks exist (and the material is indeed in a disk and not in an outflow). The model proposed in the present paper predicts a prominent departure from axisymmetry, since the mass-losing star moves in the same direction at each enhanced mass loss phase during the periastron passage (Soker et al. 1998). The Red Rectangle possesses a clear departure from axisymmetry. This case was discussed in Sect. 2.

Another interesting object is the binary system AFGL 4106, which has a nebula with a clear departure from axisymmetry (Van Loon et al. 1999; Molster et al. 1999). However, this binary system is not a post-AGB system, but is composed of two massive stars (Molster et al. 1999), with an orbital period of less than 4500 days. Its eccentricity has not been determined yet, and according to the model presented here, it is very likely that the eccentricity of the binary system AFGL 4106 is $e > 0.1$.

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