Shaping the Outflows of Symbiotic Binaries

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Summary. Mass transfer in detached, symbiotic binaries is generally assumed to occur via Bondi Hoyle (B-H) accretion. However, in symbiotic Miras, wind material can fill the donor star’s Roche lobe and flow onto the companion through the inner Lagrangian point, similar to the case of standard Roche-lobe overflow (RLOF). In this paper, we present 3D hydrodynamical simulations of this new mass-transfer mode, “wind RLOF”. We show that the resulting wind structure is highly aspherical, with most of the wind material strongly concentrated in the binary plane, and that the mass-transfer rate can be 100 times larger than the equivalent B-H value. We discuss the implications of these results for the shaping of planetary nebulae and the formation of other systems related to symbiotic binaries, e.g. barium stars and Type Ia supernovae.

Key words: planetary nebulae: general - stars: binaries: symbiotic, accretion - stars: mass loss

1 Introduction

Symbiotic binaries consist of a hot compact star, typically a white dwarf, accreting wind material from a cool, evolved giant. Mira AB is the nearest and one of the best studied examples of such a system. The primary, Mira A, is an asymptotic giant branch (AGB) star losing \( \sim 10^{-7} \) M\(_{\odot}\) yr\(^{-1} \) via a slow wind [5]. The first pulsating variable to be discovered, it is the prototype long-period variable, with \( P_{\text{pul}} \sim 332 \) days. Mira B, its hot companion, is thought to be a white dwarf located \( \sim 70 \) AU (\( \sim 0.66 \)) away [14]. The orbit remains highly uncertain, with a period of at least 500 years [12, 21].

Most symbiotic Miras are surrounded by an ionized nebula. Similar to the case of planetary nebulae (PNe), the majority of these nebulae are structurally complex and highly aspherical. Although only mildly symbiotic, Mira’s circumbinary envelope also features strong deviations from spherical symmetry. In 1995 the binary was resolved in UV and optical wavelengths using HST, and an extended outflow from Mira A in the direction of Mira B was detected [13]. A similar bridge-like structure connecting the two stars was also apparent in the subsequent Chandra X-ray data.
In the mid-IR, circumbinary dust emission also showed a pronounced asymmetry in the direction of Mira B, but it revealed a north-south asymmetry as well [18]. The latter is present in CO observations of the molecular envelope of the binary and has been interpreted as evidence for a weakly collimated bipolar outflow [11].

One suggested cause of these asymmetries has been a strong wind interaction (of the kind associated with Roche-lobe filling stars) between Mira A and its companion. However, since Mira’s Roche lobe is at least an order of magnitude larger than its stellar radius, mass-transfer in the system has generally been assumed to occur via Bondi-Hoyle (B-H) accretion rather than Roche-lobe overflow (RLOF). In this paper we investigate a new mass-transfer mode inspired by the observations of Mira AB. In this mode, which we call “wind RLOF”, the Roche lobe of the primary is filled with material from the slow wind characteristic of Mira variables and not from the expansion of the star itself (as is the case in standard RLOF). This can occur if the region where wind is accelerated beyond the escape velocity (the dust forming regions in Miras) lies close to, or is a significant fraction of, the Roche-lobe radius.

The primary goal of this study is to determine the mass-loss geometry and the mass-transfer efficiency for binaries interacting via wind RLOF. Details of the numerical simulations, using smoothed particle hydrodynamics (SPH), are given in § 2. In § 3 we present some preliminary results. We conclude with a discussion of their implications for symbiotic binaries and other related systems, such as barium stars (Ba stars), Type Ia supernovae (SNe Ia) and bipolar PNe.

2 The Model

The binary is simulated using SPH, a Lagrangian method in which fluid is represented by a finite number of ‘particles’. Each fluid particle is assigned a position, density, velocity, temperature, etc., according to a set of desired initial conditions. These hydrodynamic characteristics are then evolved according to discretised SPH fluid equations and interpolation. As a result, this method is independent of grids and therefore particularly suited to simulating arbitrary geometries. Further details of SPH can be found in [20]. In this study, we utilize a modified version of the GADGET code [24].

The initial binary model consists of two point masses, a 1.4 $M_\odot$ Mira primary and a 0.6 $M_\odot$ white dwarf. We assume that the orbit is circular ($e = 0$) with separations of $a = 11, 12$ and 70 AU for models A-D, E and F, respectively. The primary’s radius, $R_0$, forms the equilibrium position of the inner boundary of our simulation, and is calculated using the period-mass-radius relation for Miras given by [29]. Assuming the pulsation period of Mira A, $R_0 = 271 R_\odot$.

Strong correlations between the mass-loss rates of gas and dust and the pulsation period [17, 36] suggest that both radial pulsations and radiation pressure on dust grains are key components of the Mira mass-loss mechanism. The former facilitate dust formation by creating cool, dense regions around the primary. We simulate radial pulsations using the piston method: the inner boundary oscillates radially with an amplitude of a few km s$^{-1}$ [4]. Wind particles are injected at this boundary with initial velocities that also vary sinusoidally, at an average mass-loss rate of $\dot{M}_{\text{gas}} \sim 10^{-6} M_\odot$ yr$^{-1}$.

The second component, radiation pressure on dust, mediates the transfer of linear momentum from the radiation field to the gas. This radiative force counteracts
the inward gravitational acceleration of the primary and is included in the momentum equation as an additional parameter, $\alpha$. Although detailed dynamical models with time-dependent dust formation and frequency-dependent radiative transfer have successfully reproduced the observed characteristics of carbon-rich Miras, 3D models for the winds of oxygen-rich Miras are still being developed [28, 9]. In our exploratory model, we assume that the acceleration will resemble that of carbon-rich Miras and parameterise $\alpha$ based on simulations by [7] and [10]. At the inner boundary, $\alpha = 0$ and slowly increases to its maximum value at the dust formation radius, typically $2 - 3$ R$_D$. We assume our fluid has a polytropic equation of state with $\gamma = 5/3$ and do not include effects due to radiative cooling, stellar rotation or tidal distortions of the primary.

Since we do not have sufficient resolution to model the white dwarf surface, we include a point sink term in the continuity equation and employ the method of [4] to simulate accretion. In this method a particle loses mass as it approaches the white dwarf and is removed from the simulation when its mass is reduced to 0.1% of its original mass. The accretion rate is then obtained by summing over the amount of material removed in a particular interval.

3 Results

Using the parameters and methods outlined in § 2, we generated four binary models (A-D) with terminal wind velocities (measured in the case of a single Mira) of $\sim 20$, $30$, $40$ and $50$ km s$^{-1}$, respectively. The orbital velocity of both stars is $v_{\text{orb}} = 12.7$ km s$^{-1}$, and the escape velocity from the surface of the Mira is $v_{\text{esc}} = 44$ km s$^{-1}$. Each simulation was evolved for at least one orbital period, during which more than $1 \times 10^5$ particles were injected in total.

The flow structure in the binary orbital plane for models A, B and D is shown in Fig. 1. For models B, D, (and C, not shown) the flow resembles that of a system where mass transfer is occurring primarily by wind accretion. In these cases, most of the wind material is lost from the binary and only a small fraction, $\sim 1\%$, is accreted by the secondary, comparable to the estimated amount from B-H accretion ($\sim 0.7\%$).

In contrast, the flow structure for model A demonstrates mass-transfer via wind RLOF. With the wind acceleration region located at $3$ R$_D$, the wind velocity within the primary’s Roche lobe ($R_L \sim 5$ AU outlined in white in Fig. 1) is sub-escape speed so that the wind is confined within $R_L$ and subsequently funneled through the inner Lagrangian point (L1) towards the white dwarf. Most of the wind material in this model is accreted by the secondary or remains bound to the system, and only a small fraction of the wind is tidally ejected to infinity. The resulting accretion rate for model A is $\sim 100$ times larger than the associated B-H value.

As well as a higher mass-transfer rate, the wind RLOF model also produces a highly aspherical mass-loss geometry. Meridional cuts for models A and D are included in Fig. 1. In model A, the wind material is strongly focused towards the binary orbital plane, whereas the wind in model D flows more freely in all directions. Similarly, for model E, with a slightly larger binary separation of 12 AU and a lower terminal wind velocity, $v_{\text{wind}} \sim 15$ km s$^{-1}$, the mass loss along the equatorial plane was enhanced by a factor of 50 compared to the poles. In Fig. 2, we plot the particles bound to the system in grey dots, those bound to the secondary in black dots, and
those unbound from the system in triangles. The unbound particles form a spiral shock (as also seen in [25, 19, 8]). While those particles bound to the secondary are likely to form an accretion disk, the bound particles within a radius of 20 AU from the primary, a much larger distance than the binary separation, are unlikely to form a circumbinary disk; instead they are tidally accelerated and later become unbound.

In Fig. 3 we show the variation of the anisotropy factor \( f \), which measures the deviation of mass-loss from spherical geometry \( (f = 1) \), and wind velocity with polar angle for model F. Here, we assumed that the dust forms in two shells, at 3 R\(_\odot\) and 10 R\(_\odot\), as proposed by [16] in their models of Mira's dust envelope, and a lower mass-loss rate of \( \dot{M}_{\text{loss}} \sim 10^{-7} M_{\odot} \text{yr}^{-1} \). The maximum wind acceleration was reduced to produce a wind with a terminal velocity of \( \sim 5 \text{ km s}^{-1} \) (estimates of Mira's wind velocity range between 2 – 8 km s\(^{-1}\) [5, 22, 11]). This simulation lasted
Fig. 2. The wind particles in the orbital plane for model E with $a = 12$ AU. Particles bound to the system, bound to the secondary and unbound are shown as grey dots, black dots and triangles, respectively.

for just under one orbital period and the resolution was much lower than in previous models; however, the mass-loss does appear to be enhanced in the equatorial plane by a factor of 12 relative to the poles. The wind velocity in the equatorial plane is twice that in the polar direction, similar to the ratio given by [11] for the velocities of Mira's bipolar outflow and expanding envelope.

4 Discussion

Symbiotic nebulae share many morphological and kinematical characteristics with PNe [6]. The bipolar nebulae of both classes are observationally very similar, and in some cases it is not easy to distinguish between these two phenomena, e.g. Mz 3
Fig. 3. Model F with $a = 70$ AU: The variations of the median velocity of the
wind (central curve), and the range of velocities that includes 50% of the material
(upper and lower curves) are shown as a function of polar angle. The broken line
traces the mass-loss anisotropy (left axis) with polar angle.

and M2-9 [23]. Indeed, this is not surprising, as binary interaction is currently one
of the favored mechanisms for the formation of bipolar outflows (e.g. GSW model
[15, 2]). If an equatorial density enhancement or even a circumstellar disk forms
from the slow wind lost by the AGB star, then the fast ionizing wind (emitted by
the white dwarf in symbiotics or by the newly exposed AGB core in PNe) will be
greatly impeded in the equatorial regions, resulting in the formation of a bipolar
nebula.

Previous wind accretion studies have shown that while it is possible to gravita-
tionally focus the winds in relatively close binaries, the same effect is weak or absent
in very wide binaries [8, 19]. However, the mass-loss geometry resulting from wind
RLOF, even in very detached systems, can produce the equatorial density enhance-
ments essential for shaping bipolar nebulae, which account for $\sim 15\%$ of all PNe.
and 50% of symbiotic Mira nebulae (e.g., [6]). Wind RLOF also has important consequences for the white dwarf’s wind which is thought to be powered by accretion. The high efficiency of mass-transfer may be able to account for the outbursts that occur in some symbiotic systems, and cause complex morphological changes to their nebulae, e.g., He 2-304.

The higher mass-transfer rates may also have implications for a wide range of related objects. For example, barium stars (Ba stars) are G or K type giants which have accreted s-process enriched material from a companion, most likely while the latter was on the AGB. Binary evolution models of these stars which currently include mass transfer by RLOF, B-H wind accretion and common-envelope evolution cannot fully reproduce the observed distribution of their orbital periods, overabundances and eccentricities [3]. The inclusion of wind RLOF might adequately address some of these discrepancies, as a large amount of s-process material can be transferred without orbital circularisation.

SNe Ia explosions are a further possible application for wind RLOF. In the single degenerate model, if a white dwarf accretes enough material from a non-degenerate companion to reach the critical Chandrasekhar mass, \( \sim 1.4 \, M_\odot \), a thermonuclear explosion will result. With the higher mass-transfer rates of wind RLOF, even relatively wide symbiotic binaries could become potential progenitors. While these symbiotic systems are probably not common enough to account for all SNe Ia, they may account for some “unusual” SNe, such as SN 2002ic, which showed evidence for a large amount of hydrogen which had been ejected in the progenitor’s recent past. Furthermore, polarization studies indicate that the geometry of this ejected material was highly asymmetric, perhaps in the form of a flattened disk [27].

5 Conclusion

We have demonstrated that a new mass-transfer mode, inspired by observations of Mira AB, is possible for wide symbiotic binaries. There are two major results of accretion via this mode. The first, a higher mass-transfer rate (compared to B-H accretion), has important implications for a wide range of accretion-dependent phenomena, e.g., Ba stars and SNe Ia. The second result is the creation of a highly aspherical mass-loss geometry, an important component in shaping bipolar symbiotic and planetary nebulae.

One of the largest uncertainties in models of interacting symbiotic binaries is the acceleration mechanism driving the Mira winds. Detailed observations of the dust forming regions in Miras, as well as laboratory studies of dust condensation and opacities, would facilitate improvements. The simulations presented here are very preliminary - we are currently developing a fully self-consistent, time-dependent dust model which includes 3D Monte Carlo radiative transfer. Our aim is to determine the effects of wind RLOF on the outflow geometry and mass-transfer rate for a wide range of symbiotic binary parameters, as well as to investigate the modified time-evolution of the binary itself.
References