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Wind Roche-Lobe Overflow: a New Mass-Transfer Mode for Wide Binaries

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Abstract. Most symbiotic binaries consist of an evolved giant star and a hot, accreting companion, typically a white dwarf. In wide symbiotic binaries, the companion may accrete part of the wind emitted by the giant by Bondi–Hoyle accretion. Here we present preliminary simulations of a new mass-transfer mode – wind Roche-lobe overflow (RLOF) – that can occur when the wind acceleration region of the evolved star occurs at several stellar radii (as, e.g., in Mira variables). If this region is relatively close to the Roche-lobe, wind material fills the giant's Roche-lobe and is transferred to the hot component through the inner Lagrangian point (similar to standard RLOF). We show that the accretion rate can be 100 times larger than the rate expected from standard Bondi–Hoyle accretion. Furthermore, mass loss from the system tends to be strongly concentrated towards the binary plane, producing an equatorial outflow. We discuss the implications of this study for the shaping of planetary nebulae, for symbiotic binaries as potential type Ia supernova progenitors and for the origin of barium stars.

1. Introduction

The binary Mira (*o* Ceti) is one of the best studied, and the only spatially and spectrally resolved, symbiotic binary. The system consists of a cool, pulsating asymptotic giant branch (AGB) star, Mira A, and a hot companion, Mira B, which is generally assumed to be a white dwarf (WD) with a separation of ~ 65 AU (Matthews & Karovska 2006). Observations in the last decade have indicated that, despite the large separation, the stars are strongly interacting. The first HST UV observations revealed a mass outflow from Mira A towards Mira B, providing unexpected evidence of direct mass transfer in this detached binary (Karovska et al. 2004). A highly aspherical circumbinary environment was also detected at mid-IR wavelengths (Marengo et al. 2001). The primary aim of this study is to investigate the nature of the mass-transfer process in Mira, which has important implications for similar types of wide binaries.

In most detached binaries, it is generally assumed that any mass transfer must occur by accretion from the wind rather than by Roche-lobe overflow (RLOF). However, in systems where one companion has a very slow wind, such as in binaries containing a Mira variable with a dust-driven wind (i.e. D-type symbiotics), mass transfer may resemble standard RLOF, which we shall refer to as "wind RLOF". In this case, the primary's Roche-lobe is not filled with material from the expansion of the star itself (as is the case in standard RLOF), but with the slow wind material which characterises Mira variables. In this study, we estimate the mass-transfer efficiency of this new mode as a function of the initial wind velocity.

Details of the simulations, using the smoothed particle hydrodynamics (SPH) method, are given in § 2. In § 3., some preliminary results are presented with a discussion of their implications for the origin of barium stars, the progenitors of type Ia supernovae and the shaping of planetary nebulae. We conclude with a summary of other physical processes that we plan to incorporate.

2. Numerical Method

As a first step in our investigation, we have produced a simple 1.4 $M_\odot$ Mira + 0.6 $M_\odot$ WD model to illustrate mass transfer by wind RLOF. The orbit is circular ($e = 0$) with a separation $a = 11$ AU and an orbital period $P_{\rm orb} \sim$ 9420 days. The binary is simulated using SPH, a Lagrangian method particularly suited to studying hydrodynamical flows with arbitrary geometries (Monaghan 1992). Throughout this study we use a modified version of the GADGET SPH code developed by Springel, Yoshida, & White (2001).

We include radial pulsations using the piston method in which the inner boundary, the surface of the primary, oscillates radially with an amplitude of a few km s^{-1} (Bowen 1988). The primary's average radius, 271 $R_\odot$, is derived from the period–mass–radius relation for Mira variables (Vassiliadis & Wood 1993), assuming the pulsation period of Mira A, $P_{\rm puls} \sim 332$ days. Wind particles are injected at the inner boundary with a velocity that also varies sinusoidally. An average mass-loss rate of $\dot{M}_{\rm loss} \sim 10^{-6}\ M_\odot {\rm yr}^{-1}$ is produced by setting the mass, number and frequency of the injected wind particles.

Radiation pressure on dust grains, an essential component for dust-driven mass loss, mediates the transfer of linear momentum from the radiation field to the gas. This radiative force on the wind particles counteracts the gravitational deceleration of the primary. In our model, this effect is mimicked by an acceleration parameter, α, in the momentum conservation equation for the wind particles (Theuns & Jorissen 1993). The parametrisation of α is based on models by Fleischer, Gauger, & Sedlmayr (1992), where $\alpha = 0$ at the inner boundary and slowly increases to its maximum value at the dust formation radius, typically $2 - 3$ stellar radii.

The WD surface is not resolved in our study. Instead we include a point sink term in the wind particles' continuity equation to represent the gravitational attraction of the WD. As particles approach the WD, they lose mass and are accreted (i.e., are removed from the simulation) when their mass is reduced to 0.1% of their original mass, as in Anzer, Börner, & Monaghan (1987).

3. Results and Discussion

We generated four models (A–D), in which the average wind outflow velocities were 20, 30, 40 and 50 km s^{-1}, respectively. Each simulation lasted for at least one orbital period with >100 000 particles injected during this time.

For models B, C, and D, the wind acceleration mechanism increased the particles' velocity above the escape velocity of the star ($v_{\rm esc} \sim 40$ kms^{-1} at the equilibrium radius) so that the flow structure resembles that of a system where

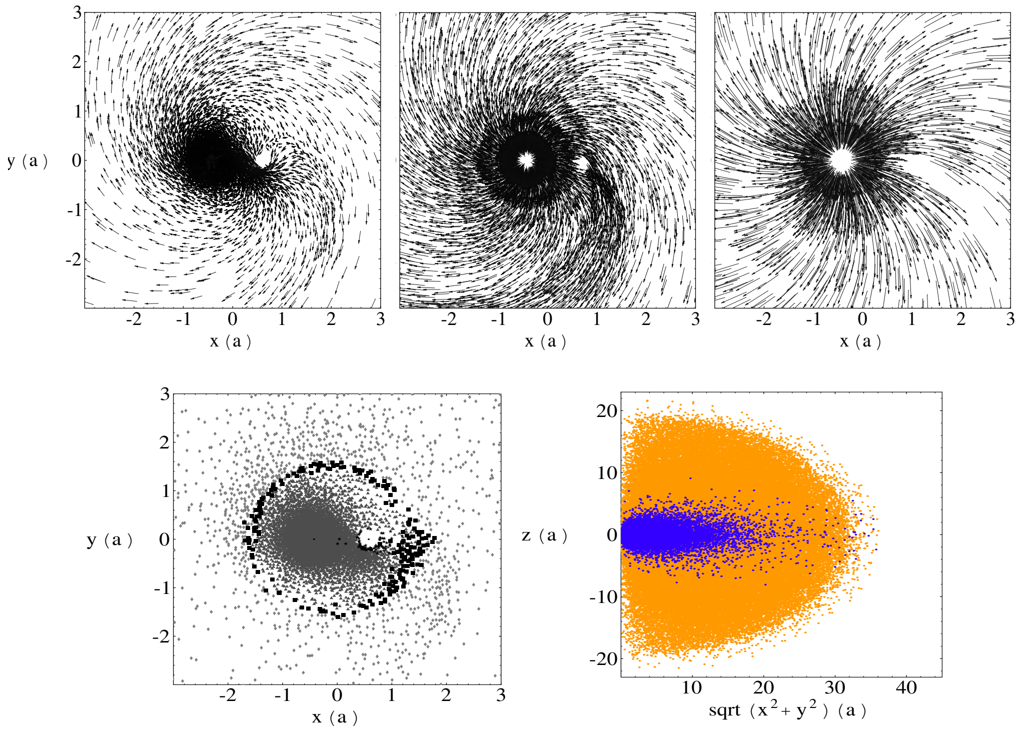

Figure 1. *Top:* The velocity field in the co-rotating centre of mass frame of model A (left), B (middle) and D (right) in the orbital plane. The Mira is at (−.57, 0) and the WD is at (0.42, 0). *Bottom (left):* The wind particles in the orbital plane for model A. The triangles are particles bound to the primary, the stars are bound to the secondary, the boxes are bound to the system and the diamonds are unbound. *Bottom (right):* Particle positions in the meridional plane for model A (dark) and model D (light).

the only mass transfer occurs by wind accretion (see Fig. 1). In this case the fraction of the material lost by the primary that is accreted by the secondary is ∼1.0 %, comparable to the estimate obtained from Bondi–Hoyle (B–H) accretion (∼0.7 %). In contrast, the wind in model A is confined to the Roche-lobe of the primary and flows through the inner Lagrangian point (L1) towards the WD. Most of the wind material in this model is accreted or remains bound to the system, and only a very small fraction of the wind is tidally ejected to infinity (see Fig. 1), i.e. the accretion rate is ∼ 100 times larger than the B–H value.

A possibly important implication of the much higher mass-transfer rates is that even relatively wide symbiotics could become potential type Ia supernova (SN Ia) progenitors. While these systems are probably not common enough to account for all SNe Ia, they may account for some "unusual" SNe, as for example SN 2002ic, which had a large amount of hydrogen in the immediate neighbourhood that had been ejected in the progenitor's recent past. It has also been suggested that the distribution of this material was highly asymmetric – perhaps in the form of a flattened disk (Wang et al. 2004).

As our simulations show, the mass loss from the system is strongly enhanced towards the orbital plane, producing essentially an equatorial outflow (see Fig. 1). Such equatorial enhancements are believed to be essential for the formation of bipolar planetary nebulae (PNe), which make up $\sim 10-20\,\%$ of all PNe (e.g. Corradi & Schwarz 1995) in the interacting wind model for the shaping of PNe (Kwok, Purton, & FitzGerald 1978). If an equatorial outflow or even a circumstellar disk forms from the slow wind, the fast wind from the hot, exposed white dwarf will be greatly impeded in the equatorial regions, resulting in strong polar outflows and the formation of a bipolar PN.

A further possible application for wind RLOF is the origin of post-AGB binaries, such as Ba + WD binaries. Barium (Ba) stars are G or K type giants that have accreted s-process enriched material from their AGB (now WD) companion. Binary evolution models which currently include RLOF, B–H accretion and common-envelope evolution cannot fully reproduce the distributions of the observed orbital periods, s-process abundances and eccentricities of these systems (Bonačić Marinović & Pols 2004). We plan to investigate the effect of wind RLOF on these important parameters and whether this mode can account for some of the discrepancies between the models and observations.

4. Conclusion

Wind RLOF is a new and relatively efficient mode of mass transfer for wide symbiotic binaries. The higher mass-transfer rates and aspherical wind structure may have strong implications for the progenitors of SNe Ia and the formation of Ba stars and bipolar PNe. It is important to note that these are only preliminary models – in our final model the approximation for α (see § 2.) will be replaced with fully self-consistent time-dependent dust formation equations and a 3D Monte Carlo radiation code. We will examine the importance of other binary parameters, e.g. eccentricity and separation, and study their time-evolution effects in order to improve our understanding of these enigmatic phenomena.

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