From Interacting Binaries to Exoplanets: Essential Modeling Tools
Proceedings IAU Symposium No. 282, 2011
Mercedes T. Richards & Ivan Hubeny, eds.

doi:10.1017/S1743921311028298

How Common Envelope Interactions Change the Lives of Stars and Planets

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Abstract. The common envelope interaction between a giant star and a stellar or substellar companion is at the origin of several compact binary classes, including the progenitors of Type Ia SN. A common envelope is also what will happen when the Sun expands and swallows its planets as far out as Jupiter. The basic idea and physics of the common envelope interaction has been known since the 1970s. However, the outcome of a common envelope interaction - what systems survive and what their parameters are - depends sensitively on the details of the engagement. To advance our knowledge of the common envelope interaction between stars and their stellar and substellar companions, we have carried out a series of simulations with Eulerian, grid-based and Lagrangian, smoothed particle hydrodynamics codes between a 0.88-$M_\odot$, 85-$R_\odot$, red giant branch star and companions in the mass range 0.1-0.9 $M_\odot$. In this contribution, we will discuss the reliability of the techniques, the physics that is not included in the codes but is likely important, the state of the ejected common envelope, and the final binary separation. We also carry out a comparison with the observations. Finally, we discuss the common envelope efficiency parameter, α and the survival of planets.

1. Introduction

Stars with initial mass from 1 to 8 $M_\odot$ go through two major phases of expansion during which interaction with stellar and planetary companions can occur.

Approximately 20% of F and G type stars have companions orbiting within 10 AU, so this type of interaction is not uncommon (Duquennoy & Mayor 1991). Common envelope interactions (Paczynski 1976) between stars and their stellar-mass companions are intensely studied because they give rise to about two dozen binary and single star (merged) classes, both at the low and high ends of the mass spectrum (e.g., cataclysmic variables [Warner 1995], close binary central stars of planetary nebula [De Marco 2009], low and high mass X-ray binaries [e.g., Verbunt 1993]). They are also supposedly at the origin of many stellar phenomena such as type Ia supernovae (e.g., Ruiter *et al.* 2011) and, possibly, gamma ray bursts (Fryer *et al.* 1999).

In addition, preliminary studies report that as many as ∼30% of common stars may have Jupiter-type planets within 3 AU (Lineweaver & Grether 2003, Bowler *et al.* 2010). This fraction may be even higher for more massive and more metal-rich stars (Fisher & Valenti 2005). Therefore, star-planet interactions may be common in the universe and, from studies of planets around subdwarf B stars (e.g., Setiawan *et al.* 2011), can affect the life of the star. For example, Soker (1998) suggested that giant-planet interactions are at the origin of subdwarf B stars.

CE interactions are complex physical phenomena to model because of the vast range of time and size scales that need to be resolved. The most modern simulations of star-star interactions are those of Sandquist *et al.* (1998), De Marco *et al.* (2003), Ricker & Taam (2008), Passy *et al.* (2012), and Ricker & Taam (2012). In this contribution, we discuss the simulations of Passy *et al.* (2012), which were carried out with two different modelling techniques.

2. Results

We here summarise the results of our common envelope binary interaction simulations and refer the reader to the paper by Passy *et al.* (2012) for more details. We have simulated the interaction between a 0.88-$M_\odot$, 85-$R_\odot$, non-rotating, RGB star and companions with masses 0.9, 0.6, 0.3, 0.15, and 0.1 $M_\odot$. We also present here, for the first time, a simulation with a 10-M_J-mass companion. The core of the giant had a mass of 0.39 $M_\odot$ and was represented by a point mass as was the companion. The giant star envelope physical parameters of density, temperature, pressure, internal energy, etc., were obtained by a 1-dimensional stellar structure calculation with the code EVOL (Herwig 2000) and relaxed into the computational domain. The companion was placed on the surface of the star and imparted a Keplerian orbital velocity (we also carried out simulations where the companion was given a larger velocity or was deposited 5% farther away, with a resulting small eccentricity of the initial orbit).

We have used two techniques in parallel. The grid technique implemented by the code *Enzo* (O'Shea *et al.* 2004), which we have modified to include an analytically-calculated potential for the point masses (this has resulted in higher degree of precision in the orbital calculation). *Enzo* is an adaptive mesh refinement technique, but we have for now used it in uni-grid mode with a resolution that was at best 256 cell on a side. Since the computational domain was 20 AU, this resulted in a resolution of 17 $R_\odot$. The second technique was the smooth particle hydrodynamic technique developed by Fryer, Rockefeller & Warren (2006) and known as SNSPH, using with 500,000 particles (for similar equivalent resolutions). The results obtained with these two techniques were very comparable.

The companion spirals rapidly inward in all cases and, after ~200 days, its orbit becomes stable with a much reduced orbital separation. All simulations last ~600 days (Figure 1). The halting of the in-spiral is due to the removal of mass from the space within the orbit. However, interestingly, while most of the mass is "lifted" to a substantial distance from the giant core (~100 $R_\odot$), most of it remains lightly bound. One energy source missing from our simulation and which may help unbind the envelope could be recombination energy (Han *et al.* 1995). In addition, a non-zero initial primary stellar spin may also help (Ricker & Taam 2008), although this idea was tested by Sandquist *et al.* (1998) and shown not to have much of an effect.

A second result was that the separation at the end of the dynamical in-spiral was relatively large and a strong function of $q = M_2/M_1$. This is expected from an energy conservation point of view, as more massive companions have more orbital energy to deliver and do not need to spiral in as much. However, a comparison with known post-common envelope systems (see for instance the compilations of De Marco *et al.* 2011, or Davis *et al.* 2012), reveals that most observed systems have homogeneously small final separations. There appears to be a mechanism by which most-to-all systems spiral in farther than predicted by our models. It is possible that if material is not unbound during the rapid in-fall phase, it may fall back towards the binary forming a circumbinary disk that can further reduce the binary separation (Kashi & Soker 2011).

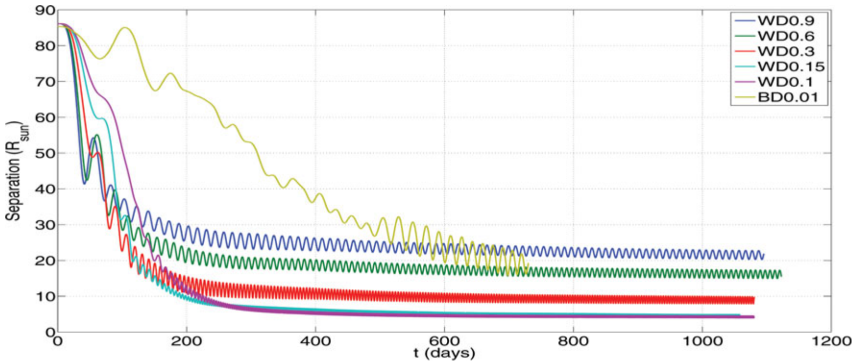

Figure 1. The orbital separation between the giant core and the companion for *Enzo* simulations. This figure is a modified version of the one presented by Passy *et al.* (2012), where we have added the orbital evolution of a 10-M_J companion. This simulation corroborates that smaller companions take longer to in-spiral, a thing that may contribute to their survival. For a colour version of this figure see Passy *et al.* (2012).

3. The common envelope efficiency and implications for low mass companions

The common envelope efficiency parameter, also known as α, allows one to determine the final separation of a post-common envelope system in population synthesis models (e.g., Politano & Weiler 2007). These models use, e.g., SN delay times to identify their progenitors. The common envelope efficiency is the ratio of the energy available to unbind the envelope (i.e., the orbital energy of the companion-primary system) to the work that needs to be done to unbind the envelope, (i.e., the binding energy of the primary's envelope). Energy sinks, which would make α small, are heating the gas and radiating this energy away, or affecting the kinetic energy of the ejected envelope. In our simulations, which do not lose heat, it is only the ejection speed that can make $\alpha < 1$. Since the envelopes of our simulated interactions are not fully unbound, it makes no sense to calculate the values of α.

In a semi-analytical study, De Marco *et al.* (2011) analysed a set of post common envelope systems for which primary and secondary masses, as well as orbital separations are known. Assuming that the post-common envelope primary mass is the same as the core mass of the giant primary at the time of the common envelope, and assuming the evolutionary stage of the primary at the time of the common envelope is known, one can reconstruct the stellar parameters at the time of the common envelope interaction. From this, the value of α can be calculated. By doing so, an inverse trend of increasing α with decreasing q emerged (albeit at low statistical significance, see also Davis *et al.* 2012), implying that higher mass companions sink similarly into the potential well as lower mass ones. This is in qualitative agreement with the observations but not with the simulations. A "cleaner" dataset, where fewer assumptions are made in the reconstruction would help answer the question of the relationship between q and α; such a dataset could be one where all systems are central stars of planetary nebula, guaranteeing an AGB common envelope (De Marco 2009).

Post-common envelope systems with low mass companions (including brown dwarfs [Qian *et al.* 2009] and planets) appear to have values of α larger than unity, indicating that their orbital energy is insufficient to eject the envelope of the primary. De Marco *et al.* (2011) suggested that low mass companions may take a longer time to spiral in towards the core of the primary and that this may favour a stellar reaction that aids in

https://doi.org/10.1017/S1743921311028298 Published online by Cambridge University Press

ejecting the envelope. We can corroborate this suggestion with our simulation of a 10-M_J companion (see Figure 1). De Marco *et al.* (2011) also suggested that the stellar response in question is a stellar expansion with the resulting reduction of the envelope binding energy. However, new results (Woods & Ivanova 2011) show this may not be the right explanation. The details of the interactions between stars and planets remain elusive.

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Discussion

V. Trimble: I am glad that you read my paper (Trimble & Ceja 2007; Astronomische Nachrichten, Vol. 328, p. 983) and even gladder that you chose to ignore it!

W. Kley: Very nice talk. You showed that all companions stop after a very short time (few hundred years). So, what made them stop? The loss of the envelope?

O. De Marco: Companions stop after a much shorter time than that, one to a few years! The reason why the companion stops its in-spiral in the simulations is that very little envelope mass remains within the orbit (approximately 10^{-2} $M_\odot$). As a result, the orbit becomes stable once again.

https://doi.org/10.1017/S1743921311028298 Published online by Cambridge University Press