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Stability of Mass Transfer in Eccentric Compact Binaries

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Compact binaries, which consist of a white dwarf and a neutron star, are interesting in several respects. Formed at the rate $10^{-4} - 10^{-5}\,\mathrm{yr}^{-1}$, most of them will come into contact in less than a Hubble time due to the emission of gravitational waves. If the subsequent mass transfer is unstable, their merger may possibly produce a gamma-ray burst without associated supernova or a supernova-like event. Furthermore, these binaries form with large eccentricities. Though gravitational wave emission tends to circularize the orbits, the binaries retain significant eccentricities when the mass transfer starts. The variation of binary separation per orbital period turns out to be of order of the scale height of the white dwarf, which leads to episodic, rather than steady, mass transfer. The necessity to resolve decently the small amounts of mass transferred in each episodic phase makes it non-trivial to simulate the system. We make use of a modified form of smoothed particle hydrodynamics, which enables us to model realistically-low mass transfer rates.

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1. Introduction

Binary systems, which consist of a white dwarf (WD) and a neutron star (NS) are promising candidates for a sub-population of long gamma-ray bursts. The evolution of such systems before the mass transfer is well-studied (see, for example, 2002 [1]). In particular, WD-NS systems are expected to have the birth rate of 10^{-4} – 10^{-5}, yr^{-1} per galaxy, as well as an observationally interesting merger rate. Most favoured formation scenarios (and two real observed WD-NS systems $\mathrm{J}1141+6545$ and $\mathrm{B}2303+46$) indicate that the NS in such systems is formed second. Peculiarly, when they come into contact, WD-NS binaries are still interestingly eccentric.

The mass transfer phase is less studied. According to [2], merger of WD-NS binaries may produce GRBs without associated supernovae, or supernova-like events. GRBs possibly originating from these systems have actually been observed [3]. Nuclear burning may be important during the merger [4], and finally WD-NS binaries make a promising source for gravitational waves (GWs). We study the stability of mass transfer in WD-NS binaries. That is, we identify whether or not WD-NS binaries merge dynamically during mass transfer, thus producing a GRB.

2. WD-NS Formation and Evolution Before the Mass Transfer

Newly formed WD-NS binaries eventually come into contact as a result of the energy loss through gravitational wave emission. The following scenario is commonly proposed as most plausible for describing, how the initial population of WD-NS binaries forms (see, e.g. [1]): 1. Initially the system consists of two sufficiently massive MS stars. 2. The primary expands, mass transfer to the secondary starts. 3. Only the He core is left from the primary. 4. The primary expands and mass transfer resumes. 5. The primary turns into a WD. 6. The secondary reaches the red giant phase, and fills its Roche lobe. 7. The common envelope phase starts, the system gets tight. 8. He secondary evolves, leading to either mass transfer to the primary or mass loss through winds: two populations form. 9. The secondary explodes as a supernova (assuming it has gained enough mass). 10. The newborn NS gets a mass loss kick and a natal kick – binary becomes eccentric.

Two classes of WD-NS binaries are produced by the scenario. If, before the SN explosion, there is a final mass transfer phase, the binaries are formed tight and eccentric ($a \sim 1\mathrm{AU}, e \lesssim 1$), like the system $\mathrm{J}1141+6545$. 95 percent of these WD-NS binaries subsequently merge due to the emission of GWs in less than a Hubble time. The case when no mass transfer phase happens, leads to much less tight binaries with $a \sim 10\mathrm{AU}, e \lesssim 1$, like $B2303+46$.

GW emission affects both a and e. Evolving the WD-NS population under the Peters equations [5], which describe the effects of GW emission on a and e, one arrives at another conclusion (see Figure 1). At the moment of coming into contact the binaries are still interestingly eccentric: the variation of the binary separation during its orbital period is of the order of the scale height of the WD. As a consequence, mass transfer is expected to be periodic, and the Roche lobe formalism is not applicable.

3. Modelling the Mass Transfer

Smoothed particle hydrodynamics (SPH), commonly used to simulate compact binary mergers, cannot be directly applied to simulate the onset of mass transfer in eccentric binaries. SPH

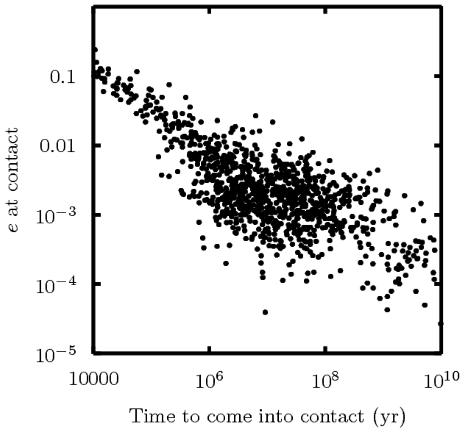

Figure 1: Population of J1141 + 6545-like WD-NS binaries from [8] evolved under the Peters equations. Residual eccentricity in the moment of coming into contact is plotted against the inspiral time.

replaces the bodies by sets of particles of *comparable masses*. If the binary were circular, the mass transfer rate would be of order $10^{-12} M_\odot$ per orbital period [6]. Hence one would need to utilize at least $\sim 10^{12}$ SPH particles to resolve the mass transfer, which is not feasible with modern computers. Instead, we involve a modified SPH scheme, called Oil-on-water [7]. The main idea of this scheme is to artificially separate the atmosphere and the body of the star. This allows one to use two types of SPH particles of *very different masses* in a single simulation and hence to resolve realistically-low mass transfer rates.

We present results from a simulation of a $\gamma = 5/3$ polytrope $0.6 M_\odot$ star orbiting a $1 M_\odot$ compact companion, with a resolved phase of episodic mass transfer happening between the stars (Figure 2). We use the units, in which $M_\odot = 1, R_\odot = 1, G = 1$ (the time unit is ~ 1400 sec). The binary separation at its minimum is $2.2 R_\odot$, the eccentricity is $e = 0.29$. Direct application of the method to realistic white dwarf stars remains the subject of our ongoing research.

4. Conclusions

Binary systems, containing a white dwarf and a neutron stars are interesting in two perspectives. From one hand, they may form an observationally significant class of long duration gamma-ray bursts. From the other hand, these systems present a challenge for simulations, as the SPH technique is not applicable to them. We have presented the results of the ongoing research, studying the stability of mass transfer in WD-NS systems. We have demonstrated the possibility to resolve the episodic mass transfer by applying a modified version of common SPH code.

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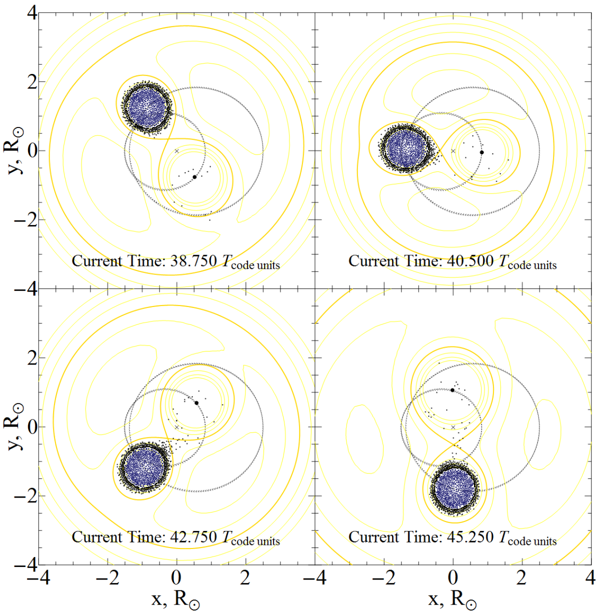

Figure 2: An example of simulation of a resolved mass transfer phase in a model polytrope-NS system. Water particles (blue) represent the body of the $0.6M_\odot$ star, and the $10^{-14}M_\odot$ oil particles (black) represent its atmosphere. Solid lines represent equipotential surfaces (thick ones correspond to the Roche lobe potential), the dotted lines represent the trajectories of the stars.

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