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Ultra-compact binaries: relevance and role of Utrecht

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Abstract. We present a short overview of the formation and evolution of ultra-compact binaries. They are relevant to a surprisingly large number of astrophysical phenomena (binary interactions, mass transfer stability, explosive phenomena such as type Ia supernovae and gravitational waves).

1. Introduction: what are ultra-compact binaries?

Ultra-compact binaries refer to double stars with orbital periods typically less than about one hour. They come in two general flavours: detached systems and interacting binaries in which mass is transferred from one star to the other. The limit of about one hour is derived from a very simple argument, dating back to Paczyński (1971, see also Verbunt 1997). Each component in a binary has a radius at most the size of its Roche lobe, which for a star of mass M and radius R with a companion of mass M_2 can be approximated as $R_{\rm L} = 0.46a\frac{M^{1/3}}{(M+M_2)^{1/3}} \geq R$ (Paczyński 1971). When combined with Kepler's third law to eliminate a (and M_2!) using the orbital period P this yields $M/R^3 \geq \mathrm{const}/P^2$. Therefore, the smaller the period, the higher the density of the objects and for periods smaller than one hour, the densities are too high for main sequence stars. Ultra-compact binaries therefore consist of evolved components: white dwarfs, neutron stars, He stars or black holes, which makes them a class apart.

2. Formation and evolution

Because both components in ultra-compact binaries are evolved stars, their formation is a probe of different uncertain processes in binary evolution: common-envelope evolution, magnetic braking, massive star evolution and NS/BH kicks. Three different formation channels have been proposed (see e.g. Nelemans & Jonker 2010):

In the WD channel the primary evolves to become a compact object that then is engulfed in a common envelope with the secondary. After the common envelope the secondary becomes a WD and gravitational wave (GW) radiation brings the WD into contact with the primary at a period of a few minutes. If the mass transfer is stable (see §3), the orbit will widen again (Fig. 1).

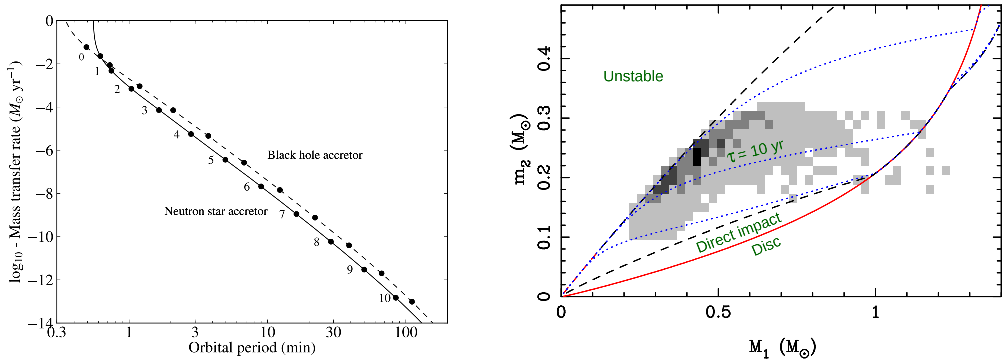

Figure 1. Left: Mass transfer evolution as a function of orbital period for UCXBs, the dots indicating the logarithm of the age of the system in years. From van Haaften et al. (2012b). Right: stability regions for the onset of mass transfer between two WD. For direct impact accretion (middle region with most expected systems) stability depends on tidal coupling. From Marsh et al. (2004).

In the He star channel the evolution is largely the same, except that the core of the secondary after the common envelope is a core He burning star that starts mass transfer to the primary at periods of several tens of minutes and first evolves to shorter periods, until a minimum of around 10 minutes is reached and then turns around.

In the evolved main-sequence channel the secondary fills its Roche lobe to the compact object when it just reaches the end of the main sequence. It first evolves as a normal low-mass X-ray binary or cataclysmic variable, until the H depleted core of the star becomes exposed. The system essentially merges onto the He star channel, although in many cases the transferred material still shows traces of H (e.g. Podsiadlowski et al. 2002). Work done in Utrecht showed that in order to get to very short orbital periods, fine tuning of the initial binary parameters as well as strong magnetic braking is needed (van der Sluys et al. 2005).

3. Stability at the onset mass transfer

The onset of mass transfer is an extremely interesting phase in the case of a WD donor. Because WD have an inverted mass-radius relation, the donor will always be the lower mass object. The stability criterion ($R = R_{\rm L}$ and $\dot{R} = \dot{R}_{\rm L}$ at all times) immediately gives an upper limit to the mass ratio of the system (see van Haaften et al. 2012b). But even if in principle the mass transfer can be stable, the time scales of the evolution due to GW emission are short and the mass transfer rates high (Fig. 1). For NS (and BH) accretors this means the mass transfer is highly super-Eddington. Assuming radiation liberated by accretion is used to expel the excess matter from the inner Lagrangian point (L1) one can derive a (likely) upper limit on the mass transfer that can still be stable (King & Ritter 1999). Because the mass transfer scales with the donor mass this puts an upper limit to the initial mass of a WD donor of 0.38 $M_\odot$. Therefore He core WD can survive the onset of mass transfer more easily.

For WD accretors another interesting issue arises: at these very short periods, the accretor is relatively big compared to the orbit and in many cases the mass stream from L1 will hit the surface of the accretor directly (so-called direct impact, see Fig. 1). This complicates the stability analysis of mass transfer, as the usual condition that the angular momentum that the donor loses to the stream is stored in the disk that forms and then via tides put back in the orbit (and thus can effectively be ignored, see Verbunt & Rappaport 1988) is not obvious anymore. This could seriously destabilise the mass transfer (see Fig. 1), unless there is strong tidal interaction between the orbit and the spinning accretor (which is unknown, Marsh et al. 2004).

4. Explosive phenomena

The evolution around the onset of mass transfer can give rise to various explosive phenomena: if the mass transfer is unstable the two stars will merge. In the case of two WDs with enough mass, this has been proposed as a possible origin of type Ia supernovae. For lower mass WD the outcomes are more likely R CrB or sdB stars (Webbink 1984). Less work has been done on the merger of a WD with a NS, but recently Metzger (2012) suggested they may produce sub-luminous supernovae.

Even if the mass transfer is stable, there may still be fire works. The two known classes of objects are ultra-compact X-ray binaries (UCXBs; a NS accreting He or a C/O mixture, see van Haaften et al. (2012b) and AM CVn stars (a WD accreting He, see Solheim 2010). The mass transfer is driven by GW emission and is characterised by rapidly dropping mass transfer rates (see Fig. 1). In AM CVn stars the mass transfer rate of He onto a WD in the early phase is high enough to produce He novae. At periods of around 10 min, the mass transfer rate has dropped enough that the ignition mass becomes so large that the layer is degenerate enough for the burning to proceed on a dynamical timescale, leading to a thermonuclear explosion, observable as a sub-luminous supernova, called .Ia supernova (Bildsten et al. 2007). With the advent of wide-field variability surveys such as Pan-Starrs and PFT, there are good chances of finding these supernovae. Indeed several new types have been found (e.g. Kasliwal et al. 2010), but it is (yet) unclear which observed types belong to which theories!

5. Late time evolution

If the systems survive the early violent evolution, the mass transfer rate continues to go down (Fig. 1). The mass ratio becomes very extreme (< 0.01), and the disk has to grow larger and larger to redistribute the angular momentum and it has been suggested that this would be impossible, leading to an instability. However, Priedhorsky & Verbunt (1988) already showed that that was likely not the case and recent SPH calculations indeed confirm that the disk becomes large and the system survives (see Fig. 2 and van Haaften et al. (2012b)), leading to a large pile up of systems at long orbital periods. For AM CVn systems indeed many long period systems are found (see Solheim 2010). However, this is not the case for UCXBs. We explored the options to explain this and conclude that either the systems are invisible most of the time (e.g. due to thermal instabilities in the disk), or the evolution is sped up by X-ray induced wind mass loss from the donor, which is also consistent with the average X-ray luminosity of the few long-period UCXBs and the idea that the millisecond radio pulsar system PSR

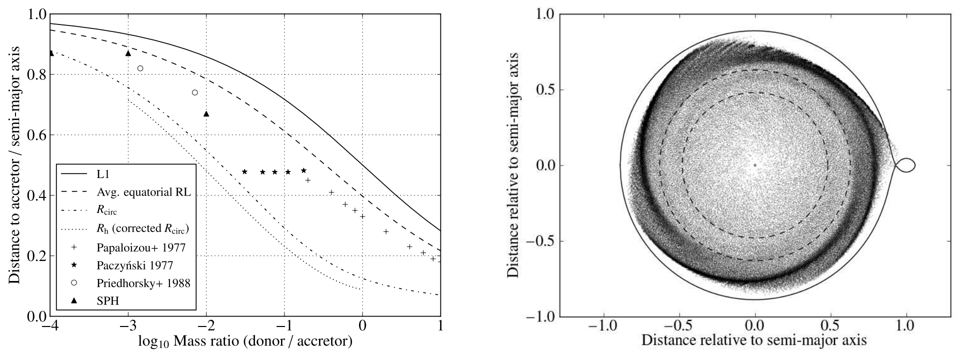

Figure 2. Left: radii of Roche lobe, circularisation radius (R_h) and outer edge of the disk according to several authors as function of mass ratio. Right: SPH calculation of a disk in an extreme mass ratio case. From van Haaften et al. (2012b).

J1719−1438 is a remnant of UCXB evolution (see Bailes et al. 2011; van Haaften et al. 2012a).

6. Gravitational waves

The evolution of ultra-compact binaries is largely driven by GW radiation. It is therefore maybe not unexpected that they are important GW sources. Indeed, space detectors such as the eLISA mission (Amaro-Seance et al. 2012) should be able to detect several of the known AM CVn stars and a detached double WD with a period of only 12 min (Brown et al. 2011). They thus are guaranteed or verification sources. More interesting, eLISA should detect several thousand new ultra-compact binaries most with periods shorter than 10 minutes! It should detect *all* NS star (and BH) binaries with periods shorter than 35 min in the whole Galaxy.

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