Astrophysics of white dwarf binaries

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Abstract. White dwarf binaries are the most common compact binaries in the Universe and are especially important for low-frequency gravitational wave detectors such as LISA. There are a number of open questions about binary evolution and the Galactic population of white dwarf binaries that can be solved using gravitational wave data and at the same time, our ever improving knowledge about these binaries will help to predict the signals that can be expected for LISA. In addition a number of white dwarf binaries will serve as verification sources for the instrument. I will discuss these issues and report recent, surprising, developments in this field. Finally I report calculations about the feasibility of complementary electro-magnetic observations which unfortunately cannot reproduce the optimistic results of Cooray et al. [1].

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INTRODUCTION: WHITE DWARF BINARIES

White dwarf binaries are the most common compact binaries in the Universe, simply because the vast majority of stars that evolve to become a compact object form a white dwarf. In addition, most stars (as far as we know) are formed in binary systems, roughly half of which have orbital periods short enough that the evolution of the two stars when they become giants is strongly influenced by the presence of a companion, either through indirect influence of tides – causing changes in rotation and possibly enhancing the stellar wind – or directly through mass exchange.

In particular it has become clear from observed close binaries, that a large fraction of binaries that interacted in the past must have lost considerable amounts of angular momentum, thus forming compact binaries, with compact stellar components [e.g. 2]. The details of the evolution leading to this loss of angular momentum are uncertain, but generally this is interpreted in the framework of the so called “common-envelope evolution”: the picture that in a mass-transfer phase between a giant and a more compact companion the companion quickly ends up inside the giant’s envelope, after which frictional processes slow down the companion and the core of the giant, causing the “common envelope” to be expelled, as well as the orbital separation to shrink dramatically [e.g. 3].

If we restrict ourselves to the most compact binaries know, often called ultra-compact binaries, in which both components of the binary are compact objects, we distinguish two types of binaries: detached binaries, in which the two components are relatively widely separated and interacting binaries, in which mass is transferred from one component to the other. In the detached class, we will be concentrating on double white dwarfs, while in the interacting class, there are two types: white dwarfs accreting from a white dwarf like object (the so called AM CVn systems, after the prototype of the class,
FIGURE 1. Period versus total mass of double white dwarfs. The points and arrows are observed systems [9], the grey shade a model for the Galactic population. Systems to the left of the dashed line will merge within a Hubble time, systems above the dotted line have a combined mass above the Chandrasekhar mass. The top left corner shows the region of possible type Ia supernova progenitors, where the grey shade has been darkened for better visibility.

the variable star AM CVn) and neutron stars accreting from a white dwarf like object, known as ultra-compact X-ray binaries (UCXBs) [e.g. 4, 5, 6].

ASTROPHYSICS WITH DOUBLE WHITE DWARFS

Ultra-compact binaries are interesting objects for a number of reasons. A very brief sketch of some of the most important astrophysical questions related to double white dwarfs follows.

**Binary evolution** Double white dwarfs are excellent tests of binary evolution. In particular the orbital shrinkage during the common-envelope phase can be tested using double white dwarfs. The reason is that for giants there is a direct relation between the mass of the core (which becomes a white dwarf and so its mass is still measurable today) and the radius of the giant. The latter carries information about the (minimal) separation between the two components in the binary before the common envelope, while the separation after the common envelope can be estimated from the current orbital period. This enables a detailed reconstruction of the evolution leading from a binary consisting of two main sequence stars to a close double white dwarf [7]. The interesting conclusion of this exercise is that the standard schematic description of the common envelope [2] – in which the envelope is expelled at the expense of the orbital energy – cannot be correct. An alternative scheme, based on the angular momentum, for the moment seems to be able to explain all the observations [8].
Type Ia supernovae  Type Ia supernovae have peak brightnesses that are well correlated with the shape of their light curve \[10\], making them ideal standard candles to determine distances. The measurement of the apparent brightness of far away supernovae as a function of redshift has led to the conclusion that the expansion of the universe is accelerating \[11, 12\]. This depends on the assumption that these far-away (and thus old) supernovae behave the same as their local cousins, which is a quite reasonable assumption. However, one of the problems is that we do not know what exactly explodes and why, so the likelihood of this assumption is difficult to assess [e.g. 13]. One of the proposed models for the progenitors of type Ia supernovae are massive close double white dwarfs that will explode when the two stars merge \[14\]. The SPY survey \[15\] is aimed at making an inventory of double white dwarfs to test this proposal, at least in terms of whether the expected number of mergers is compatible with the type Ia supernova rate. In Fig. 1 the observed double white dwarfs are compared to a model for the Galactic population of double white dwarfs \[16\], in which the merger rate of massive double white dwarfs is similar to the type Ia supernova rate. The grey shade in the relevant corner of the diagram is enhanced for visibility. The discovery of at least one system in this box confirms the viability of this model (in terms of event rates). See Tout \[17\] for a review of type Ia progenitor models.

Accretion physics  The fact that in AM CVn systems, as well as UCXBs the mass losing star is an evolved, hydrogen deficient star, gives rise to a unique astrophysical laboratory, in which accretion discs made of almost pure helium, or in the case of UCXBs, of almost pure carbon and oxygen are formed [e.g. 18, 19, 20, 21, 22, 23]. This opens the possibility to test the behaviour of accretion discs of different chemical composition.

RELEVANCE FOR/OE LISA

The compact binaries described above have a number important connections with LISA.

1. Firstly, there are a number of binaries known that should be detected by LISA, probably within a few weeks/months, the verification binaries \[24, 25\]. The LISA measurements will provide additional information to the already known parameters of these systems.

2. Current estimates of the Galactic population of these binaries predict tens of millions in the LISA frequency band, so many that they will form an unresolved background signal that can form an additional noise component in the instrument [e.g. 26, 27].

3. LISA is expected to individually detect thousands of compact binaries throughout the Galaxy [e.g. 26, 28], which will allow a completely new and complementary way to study Galactic populations of compact binaries and Galactic structure.

However, our knowledge on all these topics is fairly limited. This had led to a number of initiatives to try to come to a better understanding of the Galactic population of compact binaries in the Galaxy and the science that can be done with gravitational wave
Current developments include both theoretical investigations, new observations as well as studies to investigate the interplay between gravitational wave measurements and more traditional electro-magnetic observations. I will discuss a number of these issues.

**Verification binaries**

In the last year, the prototype of the interacting double white dwarfs, the variable star AM CVn, has been studied in detail using the William Herschel Telescope and the Hubble Space Telescope [30, 29]. AM CVn is one of the Verification sources [24, 25]. The new data yielded two surprises, the first is that the distance to the system is much larger than was expected: 606 pc, rather than the estimated 235 pc [29]. The second was the fact the the mass of the donor star and the mass ratio of the system are larger than expected: rather than fully degenerate, the donor turns out to be semi-degenerate [30]. Together these changes leave the expected signal strength as will be measure with LISA rather unchanged, but this expectation is now based on firm measurements and a realistic error bar can be given (see Fig. 2). Similar arguments for other systems (HP
FIGURE 3. Comparison of the backgrounds based on the population models of Nelemans et al. [37] (solid line) and 10% Hils et al. [27] (dotted line) and the Barack and Cutler [38] estimate. From Timpano et al. [39]

Lib, CR Boo, V803 Cen and GP Com) give results also plotted in Fig. 2, yielding a total of four definite verification binaries. The two shortest period systems, RX J0806.3+1527 and V407 Vul are still much debated and their periods are not yet confirmed as orbital and their masses are very uncertain [e.g. 31, 32, 33, 34, 35, 36]

Galactic white dwarf background

Another, rather amusing, “new result” concerns the Galactic gravitational wave background. The original Hils et al. [27] article (HBW90) presents the double white dwarf background in a rather generic way, which made it difficult to compare with more recent population synthesis based backgrounds such as my 2001 model [28]. The worrying aspect was always that the HWB90 background was comparable to my 2001 background, but seemingly contained much less sources. The recent detailed recalculation of the HBW90 population [39] allowed a direct comparison. This comparison, made last year at the Aspen conference, yielded the surprising result that the fact that indeed there are about a factor of 10 less sources (resulting in a $\sqrt{10}$ lower background) was almost exactly offset by the larger chirp masses in the HBW90 model compared to my 2001 model [see also 39, and Fig. 3]. The first is due to the, at that time, almost complete lack of observed close white dwarf binaries that led to the famous factor 10 reduction in the number of binaries advocated by HBW90. The higher chirp mass is due to the fact that HBW90 consider only one of the formation channels to the formation of close double white dwarfs [see 16, for a description of the formation channels] and modelled this in a simple way which led to binaries typically consisting of a low-mass white dwarf with a massive ($\sim 1M_\odot$) companion. The later models, and the currently known double white dwarfs, predominantly contain binaries with two low-mass white dwarfs [e.g. 40, 16, 9].
As the observational data now clearly confirm the dominance of low-mass systems, the reduction of the number of systems in HBW90 thus is a lucky “mistake”, yielding the right results for the wrong reason!

**Complementary electro-magnetic observations**

My final section is devoted to an issue which I think at the moment deserves much more attention than it receives: the investigation of the importance of complementary electro-magnetic observations. Cooray et al. [1] studied the feasibility of observing the resolved LISA sources with optical telescopes and concluded that “up to many tens of percent” of the resolved sources might be detectable with V-band magnitudes between 20 and 25 (see Fig. 4). This is a very promising result, but unfortunately I think it cannot be true. The simple reason being that typical white dwarfs have absolute magnitudes above 10 and the vast majority of the resolved systems will be close to the Galactic centre with a distance modulus of about 15, so the majority of the systems should have magnitudes above 25 even before absorption is taken into account. A histogram of the expected magnitudes for the resolved double white dwarf from my 2004 calculation [37] is shown in Fig. 5 and shows that after taking absorption into account only a tiny fraction of resolved LISA sources is expected to have a V-band magnitude below 25. Iben et al. [41] looked at the possible heating of double white dwarfs when their orbital periods become very short. The resolved LISA sources fall exactly in this class. Although the maximum tidal heating luminosity can be quite substantial, the increase in surface luminosity for the typically low-mass close white dwarf pairs is rather modest (see Fig. 6 of Iben et al. [41]), so tidal heating is likely not going to change this picture dramatically (see Fig. 5).
FIGURE 5. Histogram of expected V-band magnitudes of resolved LISA sources according to the model described in Nelemans et al. [37]. Tidal heating according to Fig. 6 of [41].

FIGURE 6. Sky position of the expected resolved LISA systems that can be observed with V < 25, in Galactic coordinates. The detached double white dwarfs are plotted as the large symbols, the AM CVn systems as the small dots. The area that will be covered by EGAPS-south is indicated.

The prospects of detecting the resolved interacting AM CVn systems with optical and/or X-ray instruments are more promising [37], due to the fact that the sort period AM CVn systems have high mass-transfer rates and thus are bright. In Fig. 6 I show the expected number of systems detectable (taken to be V < 25) plotted on the sky in
Galactic coordinates. The systems show a clear concentration in the Galactic plane. The area that will be observed using the ESO VST telescope as part of the European Galactic Plane Surveys (EGAPS) is indicated. A total of about 750 AM CVn systems and 50 double white dwarfs are expected.

CONCLUSIONS

Recent developments provide much improved estimates of the parameters of some verification binaries, with AM CVn, HP Lib, CR Boo and V803 Cen now all being definite verification binaries. A better understanding of the Hils et al. [27] calculation shows that their rather arbitrary reduction of the number of expected sources by a factor of 10 was a lucky move to offset the overestimate of the typical chirp mass of a double white dwarf by roughly a factor 2. Finally, the optimistic conclusion by Cooray et al. [1] that maybe tens of percent of the resolved LISA double white dwarfs can be observed optically seems literally too good to be true and unless I’m very much mistaken only several tens of resolved double white dwarfs will have V < 25. Several hundred resolved AM CVn systems are expected to be detectable optically. However, all these calculations are still very simple and determining reliable estimates of what can and should be done in terms of electro-magnetic preparation and follow-up of (resolved) LISA sources is one of the top priorities for the next years.

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