Ultra-Compact Binaries: *eLISA* Verification Sources

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Abstract.

There are numerous ultra-compact binary systems containing white dwarfs and neutron stars in the Galaxy. Many of these systems are weak gravitational wave emitters. However, there are eight known systems where the gravitational wave strain is strong enough to be detected by the proposed *eLISA* mission. These verification binaries are the strongest gravitational wave sources currently known, and *eLISA* will detect the gravitational waves from them within a few weeks to months. We review the properties of these eight sources including the observed rate of orbital decay. In addition, we present the recent results from the ELM Survey, which discovered the second best verification binary currently known. We also discuss the future prospects for increasing the number of verification binaries.

1. Introduction

The evolution of ultra-compact binaries involving white dwarfs (WDs), neutron stars, and stellar mass black holes is dominated by gravitational wave losses. Such systems evolve to shorter periods until they start interacting and possibly merge and create exotic phenomena, like Type Ia supernovae explosions from the mergers of two WDs. In the process, these systems emit gravitational waves. The sheer number of such sources in the Galaxy means that a fraction of them will be discovered at very short orbital periods, when they are strong gravitational wave sources.

The orbital period decay of several ultra-compact binary systems has already been detected from ground- and space-based observations, indicating that these systems must emit gravitational waves. The Hulse Taylor binary pulsar is such a system where the orbital period is shrinking by \(2.42 \times 10^{-12} \text{ s s}^{-1}\) (Weisberg et al. 2010), matching the predictions from general relativity. There are several other double pulsar, AM CVn, and double WD systems where the rate of orbital period decay has been measured from electromagnetic observations, providing additional indirect evidence for the existence of gravitational radiation.

The direct detection of gravitational waves is the final frontier in our exploration of the Universe. Instruments like *eLISA* will detect gravitational waves from thousands of systems, but the majority of these strong gravitational wave sources are currently unknown. On the other hand, there are eight known binary systems that *eLISA* must
detect within a few weeks of operation. This makes the eLISA project a unique mission compared to the other gravitational wave observatories. A working eLISA mission cannot fail to directly detect gravitational waves.

The eLISA measurements will provide information that is not available through electromagnetic observations. Gravitational wave detections will reveal the distances and inclinations of the observed binary systems, which will enable mapping the distribution of the compact binaries throughout the Galaxy. The frequency and phase evolution of individual systems will help us understand the physics of tides and mass transfer in extreme environments and strong gravitational fields.

Here we discuss different types of binaries that are potentially strong gravitational wave sources, including AM CVn systems, X-ray binaries, double pulsars, and double WDs. We present the latest results on the rate of orbital period decay in these systems in Section 2 and demonstrate that an eLISA-like mission ought to detect several of these binaries. We also discuss the current sample of verification binaries and the future prospects for increasing their numbers in Section 3.

2. Ultra-Compact Binaries

2.1. AM CVn Stars

AM CVn stars are interacting double stars with WD accretors and orbital periods less than about one hour. The prototype of this class, AM Canum Venaticorum, consists of a $0.71 M_\odot$ WD accreting from a $0.13 M_\odot$ companion in a 17 minute orbital period binary (Roelofs et al. 2007). The shortest period systems, HM Cnc and V407 Vul, show $\approx 100\%$ modulation in X-rays with 5.4 and 9.5 min periodicities. Until recently, it was unclear whether these periodicities match the orbital period or not. Optical spectroscopy observations of HM Cnc on the Keck telescope clearly demonstrate that HM Cnc has an orbital period of 5.4 min (Roelofs et al. 2010) and it contains a $0.55 M_\odot$ WD accreting from a $0.27 M_\odot$ donor star. Even though similar observations are not available for V407 Vul, the similarities between the two systems suggest that the 9.5 min periodicity is due to the orbital motion of the V407 Vul binary. These two objects are the shortest period compact systems currently known.

There are three formation scenarios for AM CVn systems involving three types of donor stars; WDs, helium stars, or evolved main-sequence stars. Studying the CNO and He abundances of known AM CVn systems, Nelemans et al. (2010) find evidence of WD donors in some systems, and evolved helium star donors in others. The WD channel requires a binary system with short enough orbital period that gravitational wave radiation drives the stars into contact. The low-mass WD fills its Roche lobe and transfers mass to the companion. Depending on the mass ratio of the binary system (if the mass ratio is extreme), the mass transfer is stable and the system evolves to longer periods (see Marsh et al. 2004; Nelemans et al. 2010).

Recent surveys have uncovered several binary WD systems with extreme mass ratios (Kilic et al. 2012). The important question is whether these systems will merge or if they will instead create AM CVn systems. The mass transfer between double WDs can be dynamically stable, unstable, or the intermediate case of either stability or instability depending on the degree of spin-orbit coupling. Motl et al. (2007) and Racine et al. (2007) demonstrate that the spin/orbit coupling is strong, raising the critical mass ratio to avoid merger from around 0.2 (no coupling) to 0.4-0.7. However, the SPH and
grid-based calculations of mergers of WDs disagree on the outcome of contact, and the prior evolution of AM CVn systems is still uncertain (see Marsh et al. 2004).

The stability of the mass transfer is important for both pre- and post-AM CVn evolution and the gravitational wave emission from such systems. Even though we expect all AM CVn systems to have stable mass transfer and evolve to longer periods, observations of orbital period decay in several AM CVn systems contradict this expectation. Strohmayer (2005) measure a rate of period change of $\dot{P} = -3.75 \times 10^{-11}$ s$^{-1}$ for HM Cnc. Similarly, Ramsay et al. (2005) find a spin-up rate of $\dot{P} = -3.17 \times 10^{-12}$ s$^{-1}$ for the 9.5 min system V407 Vul. The orbital periods of these two shortest period AM CVn systems known are decreasing at a rate consistent with orbital angular momentum loss through gravitational wave radiation. The orbital period of the next shortest period AM CVn system, ES Cet, does not show any evidence of a change so far (Copperwheat et al. 2011). The implication is that we really do not understand the mass transfer in short period double degenerate systems. Regardless of these issues, HM Cnc and V407 Vul, as well as the other known AM CVn systems are excellent gravitational wave sources.

2.2. X-ray Binaries

Interacting ultra-compact binaries with neutron star accretors are strong X-ray sources. There are several ultra-compact systems known with orbital periods less than 1 hour. The shortest period system, 4U 1820-30, includes a 1.4 $M_\odot$ neutron star accreting mass from a 0.06 $M_\odot$ helium WD companion with an orbital period of 685 s (11-min, Stella et al. 1987). Due to the extreme mass ratio of the two components, stellar evolution theory predicts conservative mass transfer from the Roche lobe filling secondary onto the neutron star and also an increase in orbital period. However, van der Klis et al. (1993) measure a decay in orbital period of $\dot{P} = -5.3 \pm 1.1 \times 10^{-8}$ yr$^{-1}$. As in AM CVn systems, we do not understand the orbital evolution of these systems, but several possibilities remain (van der Klis et al. 1993). In any case, the orbital shrinkage in 4U 1820-30 demonstrates that the system is emitting gravitational waves. Unfortunately, the lower secondary mass in these low-mass X-ray binary systems means that the chirp mass is also lower and the gravitational wave strain is significantly smaller than AM CVn systems with similar orbital periods. 4U 1820-30 can be detected by a LISA-like instrument with three arms, but it falls below the eLISA sensitivity limit.

The second shortest period ultra-compact X-ray binary known, 4U 0513-40, has an orbital period of 17 minutes (Zurek et al. 2009). 4U 0513-40 is located 12.1 kpc away and it contains a 1.4 $M_\odot$ neutron star and a 0.05 $M_\odot$ WD companion. The gravitational wave strain from 4U 0513-40, $h = 6 \times 10^{-24}$, is at the 1σ LISA detection limit after one year of integration. It would be challenging to detect this source with a LISA-like instrument since the detection also depends on the gravitational wave foreground at the same frequency. 4U 0513-40 falls below the sensitivity limit of eLISA.

As the two shortest period ultra-compact X-ray binaries discussed in this chapter demonstrate, due to the nature of the secondary stars, the gravitational wave strain of these binaries fall below the sensitivity limit of eLISA. Hence, there are currently no known eLISA verification binaries with a neutron star and a low-mass WD companion.

2.3. Double Pulsars

The Nobel Prize in Physics was awarded to R. Hulse and J. Taylor in 1993 “for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation”. The Hulse Taylor binary pulsar, PSR B1913+16, contains
two neutron stars with 1.44 and 1.39 \( M_\odot \) in a 7.8 hr orbit, which is decaying at a rate \( \dot{P} = -2.42 \times 10^{-12} \text{ s}^{-1} \) (Weisberg et al. 2010). The orbital decay rate is consistent with the predictions from general relativity. PSR B1534+12 is another double pulsar system, containing 1.33 and 1.35 \( M_\odot \) neutron stars in a 10 hr orbit. Stairs et al. (2002) measure \( \dot{P} = -1.4 \times 10^{-13} \text{ s}^{-1} \), which is consistent with the predictions from general relativity. Perhaps, the most interesting double pulsar system is PSR J0737-3039, a 2.4 hr orbital period system containing a 23-millisecond pulsar with a 2.8-second pulsar companion. The two neutron stars in this system have masses of 1.25 and 1.34 \( M_\odot \) (Lyne et al. 2004). Kramer et al. (2006) measure a decay rate of \( \dot{P} = -1.25 \times 10^{-12} \text{ s}^{-1} \), a value that is consistent with the general relativity predictions within an uncertainty of 0.05%. The gravitational wave strain from PSR J0737-3039 is above the \( \text{LISA} \) sensitivity limit after 1 year of observations. However, it falls below the \( \text{eLISA} \) sensitivity limit due to the loss of the third arm. Hence, there are currently no known double pulsar verification binaries for the \( \text{eLISA} \) mission.

2.4. Double White Dwarfs
The shortest period binary WDs are excellent gravitational wave sources. Double WDs in the Galaxy outnumber all other known types of gravitational wave sources and they form a gravitational wave foreground. Until recently, the shortest period double WD system known was WD 0957-666. This binary consists of two WDs with masses 0.32-0.37 \( M_\odot \) in a 1.46 hr period system (Moran et al. 1997). The merger time for the WD 0957-666 binary is about 200 Myr. Given its distance of 135 pc, the gravitational wave strain from WD 0957-666 is above the 5 \( \sigma \) detection limit of a \( \text{LISA} \)-like instrument. However, WD 0957-666 is another system that falls below the \( \text{eLISA} \) sensitivity limit. It is interesting that the two WDs in this system are low-mass helium-core objects. The Galaxy is not old enough to produce \( (M < 0.45 M_\odot) \) helium-core WDs. Low-mass helium-core WDs must therefore form when a companion strips the outer envelope from a post main-sequence star before the star reaches the tip of the red giant branch and ignites helium. They are usually found in close binaries, mostly double degenerate systems (Marsh 1995). However, about half of the low-mass WDs in the field do not show any radial velocity variations, indicating that they are single. Kilic et al. (2007) argue that these single low-mass WDs may come from old metal-rich stars that truncate their evolution prior to the helium flash from severe mass loss. They estimate a binary fraction of 50% for \( \sim 0.4 M_\odot \) WDs. However, they predict that the binary fraction rises to 100% for \( \sim 0.2 M_\odot \) extremely low-mass (ELM) WDs, since such extreme mass loss rates are not expected even for the most metal-rich stars in the Galaxy.

2.4.1. The ELM Survey
The ELM Survey (Kilic et al. 2010, 2011a; Brown et al. 2010, 2012) is opening a new window on short period binary WDs. After the discovery of four double WD systems with merger times shorter than 500 Myr (Kilic et al. 2010), radial velocity follow-up of the ELM WDs found in the Hypervelocity-star survey (Brown et al. 2006) and the SDSS Data Release 4 area led to the discovery of 12 merger systems, tripling the number of known merging WD systems (Brown et al. 2010; Kilic et al. 2011a). In 2011, the ELM Survey identified the three shortest period detached binary WDs known, a 12-min (Brown et al. 2011) and two 39-min orbital period systems (Kilic et al. 2011b,c). All three systems show flux variations due to the relativistic beaming effect and two
of the three also show ellipsoidal variations due to tidal distortions. These are the first two tidally distorted WDs ever found. The three systems with <1 h orbital periods are strong gravitational wave sources.

J0651 is the most interesting system found so far. It is the shortest period detached WD binary yet discovered. Brown et al. (2011) realized that J0651 is a compact binary system when back-to-back spectra separated by six minutes showed a ≈ 1300 km s\(^{-1}\) change in radial velocity. Figure 1 shows the observed radial velocities for J0651 (Hermes et al. 2012b). J0651 has a best-fit orbital period of 765 s and a corrected velocity semi-amplitude of 616.9 km s\(^{-1}\). It is very likely a Galactic disk object based on its small proper motion and systemic velocity. Its location 220 pc above the plane (for a distance of 1 kpc) is also consistent with a Galactic disk object.

In J0651, the orientation of the binary allows us to observe eclipses of each star by each other, leading to accurate measurement of the orbital parameters, masses, and WD radii. Its optical light curve obtained at the 8.1 m Gemini North telescope and the GTC 10.4 m telescope is shown in Figure 2. The lightcurve shows primary and secondary eclipses, ellipsoidal variations, and doppler boosting (the so-called relativistic beaming effect). J0651 contains a 0.26 \(M_\odot\) ELM WD and a 0.50 \(M_\odot\) secondary WD at an inclination angle of 84.4 degrees.

The two WDs in J0651 will come into contact in 0.9 Myr due to gravitational wave radiation. The system currently has a gravitational wave strain of \(10^{-22}\), about 10,000 times larger than the Hulse-Taylor pulsar; this system would be detected by the proposed eLISA mission in the first few weeks of operation. There is no evidence for mass transfer, thus J0651 is arguably one of the cleanest known strong gravitational wave sources. General relativity predicts that the system’s time-of-eclipse will shift.
by about 5.5 sec one year after its discovery in April 2011. Tidal interactions are also predicted to change the time-of-eclipse by an additional 0.3 s (Piro 2011; Benacquista 2011).

Recently, Hermes et al. (2012b) measured the rate of orbital decay in this system using 200 hr of observations. The observed decay rate of $\dot{P} = -9.8 \pm 2.8 \times 10^{-12}$ s s$^{-1}$ is consistent with the predictions from general relativity, $-8.2 \pm 1.7 \times 10^{-12}$ s s$^{-1}$, within the errors. This work establishes the feasibility of monitoring this system’s orbital period decay at optical wavelengths. The short period of J0651 makes it one of the loudest known sources of gravitational wave radiation, and continued monitoring of orbital decay in the system will provide strong constraints on the gravitational wave strain of J0651. We hope to one day compare this change with direct measurements of gravitational waves from an eLISA-like instrument and provide an unprecedented test of general relativity.

It is evident from the high-amplitude ellipsoidal variations of the primary that strong tidal forces are also present. These tides will act as a torque to spin-up the WDs if the system is synchronized, further robbing the orbit of angular momentum and increasing the rate of orbital period decay. The degree to which this tidal torquing influences the orbital evolution depends on the effective tidal locking, which is in many ways determined by the physical structure of the ELM WD. With just 13 months of monitoring, the current sensitivity in the observed rate of orbital decay is not yet sufficient to detect a significant deviation from pure gravitational wave losses. However, future observations should constrain this discrepancy, providing an excellent probe of the interior of ELM WDs.

Figure 3 shows the predicted gravitational wave strain amplitudes (Roelofs et al. 2007) and frequencies of the binary systems found in the ELM Survey so far (Kilic et al. 2012). There are three binaries, J0651, J0923, and J1630, that should clearly be
detected by a LISA-like mission within the first year of operation. There are also three more systems that are above the 1σ detection limit of LISA after one year of observations, but they will probably be lost in the Galactic foreground of unresolved double degenerate systems. Due to the slightly lower sensitivity of the eLISA mission, only one of these binaries, J0651, will clearly be detected by eLISA. It may be possible to identify several other ELM WD binaries, including J0923 and J1630, because we know their coordinates and physical parameters accurately from the optical observations. The remaining several dozen sources are important indicators of what the Galactic foreground may look like for gravitational wave detectors.

In addition to J0651, there are several other tidally distorted WDs found in the ELM survey (Hermes et al. 2012a). J1741 and J2119 are two such systems where the amplitude of the ellipsoidal variations is ≈1.5%. It is possible to use the time-of-minimum of the ellipsoidal variations in both objects to detect this orbital period decay. This rate of the orbital period change is sensitive to the mass of the unseen secondary, but for J1741, the orbital period is changing by at least $3.6 \times 10^{-13}$ s s$^{-1}$. This would cause the observed minimum to occur more than 8 s sooner within 15 years. For J2119, the orbital period is changing by at least $3.4 \times 10^{-13}$ s s$^{-1}$. The detection of orbital period change in these systems may be possible on a timescale of a decade or less. Such a detection would constrain the gravitational wave strain from these binaries,
which would be important for identifying these systems among numerous binaries that form the gravitational wave foreground.

3. Verification Binaries

Figure 4 presents the gravitational wave strain of known ultra-compact binaries compared to the NGO sensitivity limit. Currently, there are eight verification binaries, seven AM CVn systems and one binary WD system, for the eLISA mission. The best verification binary currently known is the 5.4 min period AM CVn system HM Cnc. The second best system is the detached 12-min binary WD system SDSS J0651. The 9-10 min orbital period AM CVn systems V407 Vul and ES Cet are also strong gravitational wave sources that should be detected by eLISA within a few weeks to months. The observed rapid orbital period decay in HM Cnc, J0651, and V407 Vul demonstrate that they are strong gravitational wave sources that are waiting to be detected by eLISA.

![Figure 4. Gravitational wave strain versus frequency for the verification binaries (green squares) and other known binaries (blue squares, G. Nelemans 2012, private communication). The solid line show the sensitivity of NGO.](image)

3.1. Future Prospects

With an orbital period of 27-min, the longest period verification binary currently known is the AM CVn system V803 Cen. The Galaxy must have thousands of similar sources that will be detected by eLISA, but the identification of these sources as verification binaries before eLISA flies requires large scale time resolved surveys. Five of the AM CVn systems that are also verification binaries were found as part of several different
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optical/ultraviolet surveys that obtained time series photometry or spectroscopy. The shortest period AM CVn systems, HM Cnc and V407 Vul, were discovered in ROSAT observations in the late nineties. The detached binary WD system J0651 was found as part of the ELM survey, a targeted spectroscopic survey of objects with the colors of ELM WD candidates.

Future wide-field synoptic surveys will lead to a gradual increase in the number of ultra-compact systems known. The SDSS and the Palomar Transient Factory (PTF) have found a few new AM CVn systems (Levitan et al. 2011; Rau et al. 2010). PanStarrs is another survey that obtains multi-epoch photometry of the same fields, which should lead to the discovery of a few more compact systems. The Large Synoptic Survey Telescope (LSST) is perhaps the most promising survey for ultra-compact binaries, as it will image the southern sky 1000 times over 10 years. The current sample of AM CVn and detached double WDs demonstrate that the majority of the systems found in these surveys will have orbital periods longer than 30 min, and they will be part of the gravitational wave foreground. However, follow-up observations of variable objects in PTF, Panstarrs, and the LSST have the potential to discover systems with shorter periods; eLISA verification binaries.

Interacting ultra-compact binaries with WD or neutron star accretors are strong X-ray sources. The discovery of HM Cnc and V407 Vul in ROSAT observations demonstrate that new AM CVn systems can be identified in future X-ray transient surveys. With RXTE and similar missions, more sources like HM Cnc and V407 Vul can be identified. The number of verification sources available for eLISA will likely increase slowly over the next decade, until the LSST comes online. Each LSST visit will have a limiting magnitude of 24.2 for a signal-to-noise ratio of 10. Scaling from the WDs found in the SDSS, this should lead to at least an order of magnitude increase in the sample size.

4. Conclusions

Ultra-compact binary systems containing WDs and neutron stars are numerous. The majority of these are double WD binaries in detached or interacting systems. There are several dozen detached WD and AM CVn systems known. However, the majority of these systems have orbital periods longer than 30 minutes. There are eight systems, seven AM CVn and one detached binary WD, that have periods in the range 5 min to 27 min. These are strong gravitational wave sources and they are eLISA verification binaries. The eLISA mission will detect these eight systems within the first few weeks to months of operation. Unlike the other gravitational wave detectors, eLISA has a unique advantage that it has these verification binaries. The number of verification binaries is likely to increase over the next decade thanks to large scale transient surveys like the PTF, Panstarrs, and the LSST.

References

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