

Galactic Binaries as Sources of Gravitational Waves

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Abstract. I review the expected Galactic sources of gravitational waves, concentrating on the low-frequency domain and summarise the current observational and theoretical knowledge we have. A model for the Galactic population of close binaries, which is tested against the observations is used to predict the expected signal for the future space based gravitational wave detector LISA. With a simple model for the electro-magnetic emission from the same binaries I argue that a fair number of the LISA systems have electro-magnetic counterparts, which can be used to improve in particular the distance and mass measurements of these systems by LISA. Furthermore, LISA will enable us to test some aspects of the theory of binary evolution that are very difficult to assess in different ways.

1. INTRODUCTION: GALACTIC SOURCES OF GWR

As for all astrophysical phenomena, if it is present in our own Galaxy it often can be studied in most detail, simply because of the proximity of the sources. This also holds in some sense for gravitational wave phenomena. Many Galactic sources are, or could be (strong) gravitational wave radiation (GWR) sources. In particular binary stars are obvious sources as has been realised long ago [e.g. 1].

The amplitude of the gravitational wave signal increases with the chirp mass of the binary and its gravitational wave frequency [e.g. 2], which means that more massive, equal mass, short period binaries are the most promising sources. The frequency range covered by the current and planned detectors is limited to frequencies between about 0.1 mHz and 1 Hz for the space based detector LISA and about 50 to 5000 Hz for ground based detectors. For binary objects this translates to orbital periods between 5.5 hr and 2 seconds and 40 and 0.4 milliseconds for space and ground based detectors respectively. These short periods imply small separations (or very high masses) through Kepler's law, thus for stellar mass objects this means that we have to concentrate on compact stars, in particular helium stars, white dwarfs, neutron stars and black holes.

The most important classes of binary stars as sources of gravitational waves are: helium star – white dwarf/neutron star binaries, double white dwarfs, white dwarf – neutron star/black hole binaries, and double neutron star/black hole binaries (see Fig. 1). If these objects form in binaries with orbital periods below ~ 10 hr, the angular momentum losses due to GWR will make them spiral together within a Hubble time, until the separations are small enough that mass transfer starts. Helium stars start mass transfer typically at periods of 30 – 60 min (GWR frequencies of 1 – 2 mHz), but evolve to shorter periods, before they reach a period minimum around 10 min [e.g. 3, 4]. Double white dwarfs and white dwarf – neutron star/black hole binaries start mass transfer at

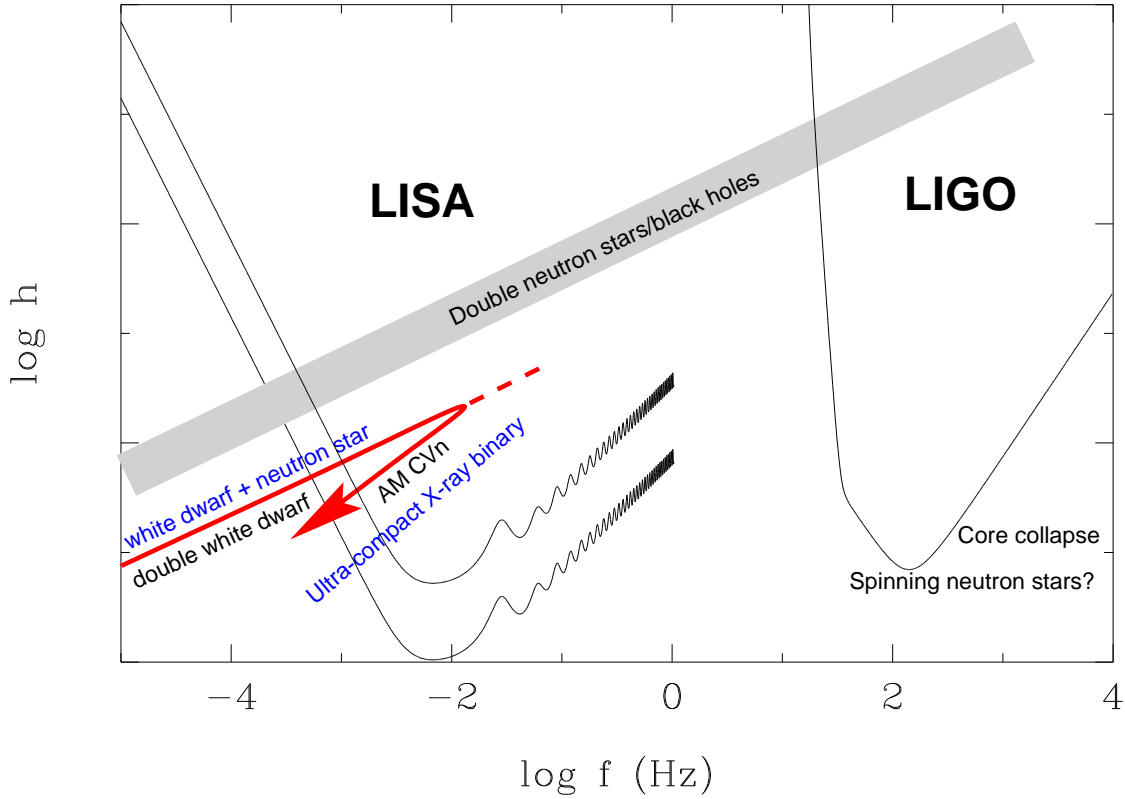


FIGURE 1. Schematic picture of the evolution of compact binaries in frequency – gravitational wave amplitude space. Plotted are the expected sensitivities of LISA and LIGO, and the evolution of different types of binaries, discussed in the text. The big arrow shows the evolution of binaries that start stable mass transfer, while the dashed extension in the middle of the plot represents binaries which have more massive white dwarfs, evolving to shorter periods, where they coalesce.

orbital periods of a few minutes (GWR frequencies around 20 mHz). The more massive the white dwarf in these binaries, the smaller it is and thus the shorter the period at which mass transfer starts.

Both the helium star as the white dwarf binaries might start *stable* mass transfer to their white dwarfs, or neutron star/black hole companion, causing these binaries to evolve back to longer periods (see Fig. 1). Such sort-period mass-transferring objects are observed and are called AM CVn systems and ultra-compact X-ray binaries (UCXB's) in the case of white dwarf and neutron star/black hole accretors respectively.

Finally binaries in which both components are neutron stars or black holes will continue decreasing their orbital until they reach stunning orbital periods of about 1 ms (GWR frequency about 2 kHz, see Fig. 1). These frequency ranges are also the ranges where non-binary Galactic sources, like rapidly rotating neutron stars and the rapidly rotating cores of collapsing stars in supernova explosions will emit GWR [e.g. 5, 6, 7]. For a discussion of these high frequency sources, I refer to contributions of Mezzacappa, Fryer, Heyl, Bulik in this volume. For the remainder of this article I will concentrate on Galactic sources of *low-frequency* GWR.

As our knowledge of these sources stems from a combination of observational facts and model extrapolations of these observations, I will first discuss the observations we have of the short period binary populations (Sect. 2), before discussing a model for the Galactic short period binaries (Sect. 3) and presenting the expected low-frequency signals that can be detected by LISA (Sect. 4). I will then discuss the importance of complementary electro-magnetic observations (Sect. 5) and the scope for “Galactic GWR astronomy”, i.e. testing our models and understanding (in this case of close binaries) with GWR measurements (Sect. 6).

2. SUMMARY OF CURRENT OBSERVATIONAL KNOWLEDGE

For a more comprehensive discussion of the observed short period binaries that are relevant for LISA see Verbunt [8], Verbunt and Nelemans [9]. In the last few years there have been quite some new discoveries of compact binaries, which will enable us to test the theoretic models in some more detail than was previously possible. I summarize these below.

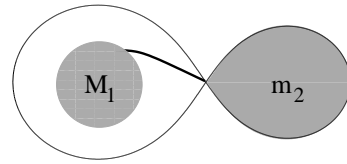


FIGURE 2. Schematic picture of the direct impact phase of accretion between two white dwarfs.

Double white dwarfs Up to the middle of the 1990s, about 200 white dwarf were checked for binarity, yielding 14 close double white dwarfs [see for a review 10]. The SPY project [11] is a survey on the ESO VLT 8m telescope, using the UVES spectrograph to check ~ 1000 white dwarfs for radial velocity variations indicating binarity. For each white dwarf, two spectra with high spectral resolution and high signal-to-noise are taken and compared. It will be, by far, the largest (fairly homogeneous) sample of white dwarf checked for binarity and is expected to discover $\sim 150 - 200$ new close binary white dwarfs. The current status is that 577 white dwarfs have been analysed and 123 are close binaries, 14 with an M dwarf companion, the rest with a white dwarf companion. For about ten systems follow-up observations to determine system parameters like orbital periods, masses etc. have been completed, yielding orbital periods between 0.3 and 5 days [e.g. 12, 13, 14]. In addition to the SPY discoveries, a double white dwarf with a relatively long period of 30 days was found by Maxted et al. [15].

AM CVn systems Very excitingly, there have been three AM CVn candidates found with extremely short periods: RX J1914.4+2456 [V407 Vul, 16, with a possible period of 9.5 minutes], KUV 01584-0939 [ES Cet, 17, with a period of 10.3 minutes] and RX J0806.3+1527 [18, 19, with a possible period of 5.3 minutes]. Not only does this bring the number of known AM CVn systems from 8 to 11, but it shows that the shortest period AM CVn systems, which are much less numerous than their longer period descendants because they evolve quickly, can be found. The two shortest period systems might also be in a so called “direct impact” phase of accretion, in which the accretion stream directly hits the surface of the accreting star rather than forming a disc [20, 21, see Fig. 2]. Based on a simple modelling

of the brightness of the systems we found that most of the systems in a magnitude limited sample would fall between roughly 20 and 40 minutes [20]. Indeed, two of the new candidates are found by their X-ray emission, different from the “normal” AM CVns that are found in the optical. The two shortest period systems await spectroscopic confirmation of their periods to be orbital, and some models suggest they are not AM CVns but either detached double white dwarfs [22] or longer period systems [23]. Recently another suspected supernova (SN2003aw) turned out to be an AM CVn system undergoing an outburst [24].

Ultra-compact X-ray binaries Another recent development, worth mentioning is the discovery of three new ultra-compact X-ray binaries (where with ultra-compact I mean orbital period below the period minimum for a main sequence mass donor (~ 60 min), bringing the total to 7 of which 2 reside in a globular cluster. In all systems the neutron star turned out to be an accreting millisecond X-ray pulsar: XTE J1751-305 [25, 26, 27], XTE J0929-314 [28, 29, 30] and XTE J1807-294 [31]. The systems have orbital periods of 42.4, 43.6 and 40.1 mins respectively. There are another six candidates, based on similarities with known ultra-compact X-ray binaries in either X-ray and/or optical spectra, or optical brightness [e.g. 32, 33].

3. A MODEL FOR THE GALACTIC POPULATION

To be able to predict the number of low-frequency GWR sources we have to construct a model for these binaries in the Galaxy, as the observations are too incomplete to estimate the total number of systems present in the Galaxy. As our knowledge of stellar and in particular binary evolution is rather limited, we have to construct this a model in such a way that we can use the observations to test some of the basic assumptions that go into the model. The basic ingredients of a Galactic binary population model are

- A description of stellar and binary evolution:
 - For single stars, we need their mass, radius, luminosity and core mass, as function of initial mass and time (and metallicity).
 - For binary stars a recipe for effects of stellar wind mass loss, mass transfer, supernova explosions etc on the orbit of the binary.
- Initial parameter distributions
 - Initial primary mass distribution, according to some initial mass function, the mass ratio distribution of the zero-age main sequence binaries, an initial separation distribution and initial eccentricity distribution of the binaries.
- Normalization and space distribution
 - Star formation history of the Galaxy
 - The initial binary fraction of objects in the Galaxy.
 - Galactic distribution, of stars (as function of time)

We use the binary star population synthesis code developed by Portegies Zwart and Verbunt [34], with some new ingredients like the initial mass function [for which we now use 35], and a self consistent model for the star formation rate as function of time

TABLE 1. Galactic merger rates and birth rates for binaries containing compact objects, with an (order of magnitude) estimate of the uncertainty and the number of systems that can be resolved by LISA (see Sect. 3 and 4).

Type	birth rate (yr^{-1})	merger rate (yr^{-1})	uncertainty factor	resolved systems
(wd, wd)	2.0×10^{-2}	8.3×10^{-3}	5	10658
AM CVn	1.3×10^{-3}		50	9831
UCXB	1.1×10^{-5}		20	22
(ns, wd)	6.8×10^{-5}	3.8×10^{-5}	20	8
(ns, ns)	5.2×10^{-5}	2.5×10^{-5}	50	7
(bh, wd)	7.2×10^{-5}	2.6×10^{-6}	50	0
(bh, ns)	3.5×10^{-5}	1.0×10^{-5}	50	0
(bh, bh)	1.7×10^{-4}	5.1×10^{-6}	50	0

and position in the Galaxy, based on Boissier and Prantzos [36]. For further details on the ingredients of the model presented here, we refer to Nelemans et al. [37]. In Table 1 I show the resulting birth and merger rates in the Galaxy for binaries containing compact objects. An order of magnitude estimate in the uncertainty in the quoted birth and merger rates is given in the table. For the double white dwarfs this number comes from the range we get in our own models [see 37, 38] plus the estimate of the fraction of white dwarfs that are close binaries [39]. For AM CVn systems the estimate is based on Nelemans et al. [20]. For the neutron star binaries the estimates are based on the range of birth rates published by Portegies Zwart and Yungelson [40], Belczynski et al. [41].

4. EXPECTED RESULTS FROM LISA

We now use the Galactic model described in the previous section to calculate the expected signals that are detectable by LISA as we did in Nelemans et al. [42], see also Evans et al. [2], Hils et al. [43], Webbink and Han [44], Postnov and Prokhorov [45], Hils and Bender [46]. In Table 1 we list the number of systems that LISA will be able to resolve individually in frequency.

Fig. 3 shows the expected signals detected by LISA in frequency space, i.e. neglecting any complications from the fact that LISA is actually moving in space. At the lowest frequencies the vast number of double white dwarfs in the Galaxy form an unresolved noise background. The average of the background is plotted as the solid line. Only at frequencies above ~ 2 mHz the background disappears and individual systems can be resolved. The distribution of GWR wave amplitude vs. frequency of the resolved double white dwarfs and AM CVn systems is plotted as the grey shades, while the 200 strongest sources, plus the resolved detached neutron stars binaries and ultra-compact X-ray binaries are shown individually.

The vast majority of the expected resolved sources are double white dwarfs and AM CVn systems, with only a handful of neutron star binaries and ultra-compact X-ray sources. See Nelemans et al. [37] for more details.

A few remarks must be made about these calculations. The number of resolvable

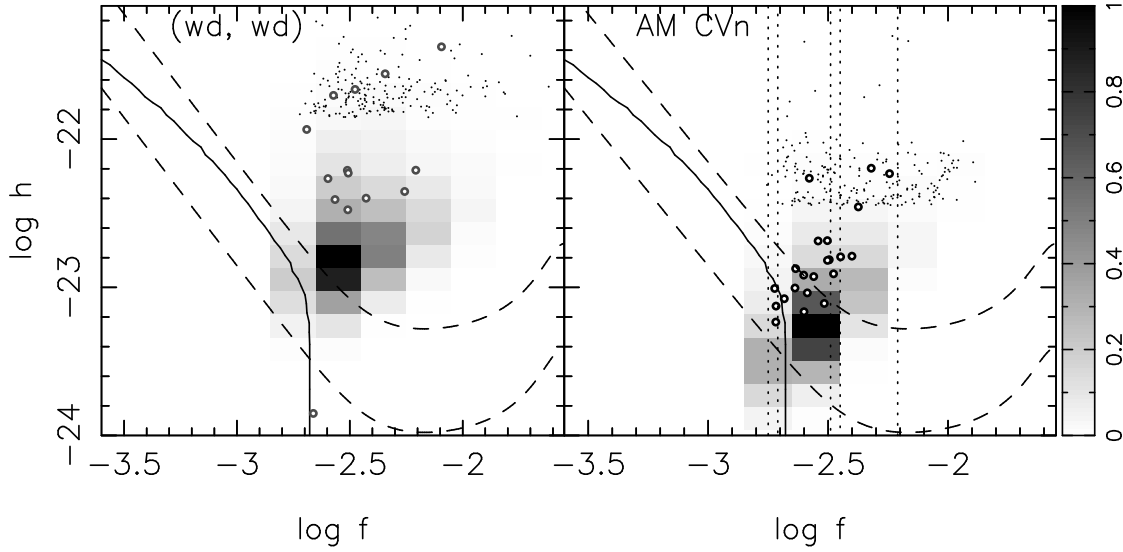


FIGURE 3. GWR wave amplitude h as function of the GWR frequency f for the expected low-frequency Galactic binaries, which are expected to be detectable by LISA. The left panel shows the (10658) double white dwarf systems as the grey shade, with the 200 strongest sources as points, to increase their visibility. The right panel shows the (9831) resolved AM CVn systems that are expected, again showing the 200 strongest sources as points. Over plotted with the large symbols are the neutron star binaries in the left panel and the ultra-compact X-ray sources in the left panel. The average double white dwarf background is plotted as the solid line, while the dashed curves show the LISA sensitivity for a integration time of 1 yr giving S/N of 1 and 5 respectively [47].

systems is determined in a simple way, just evaluating the number of systems present in each frequency bin, with fixed width, $\Delta f = 1/T$, where T is the integration time, for which we use 1 yr. That means that the exact response of the detector to the combined signals isn't taken into account, which on the one hand might complicate the actual detection of the sources. We also did not consider the possibility that sources could be detectable in the frequency range where the double white dwarf background noise dominates, either because of the large amplitude or possibly their position on the sky. For a discussion of the number of resolved systems for which the frequency change can be measured see e.g. Nelemans et al. [37, 42], Webbink and Han [44].

5. COMPLEMENTARY ELECTRO-MAGNETIC OBSERVATIONS

As briefly mentioned before, LISA will in fact measure the signals from the binaries convolved with the changing detector response due to its orbit in space. That means that the position of the source can be reconstructed [48], but it also means that the measured signal depends not only on the binary properties (period, and masses) and the distance, but also on the position in the sky (and the relative contributions of the two GWR polarization signals depend on the inclination of the binary). An interesting possibility is using electro-magnetic observations to determine some of the parameters (like position on the sky and orbital period) of the systems that can be resolved by LISA,

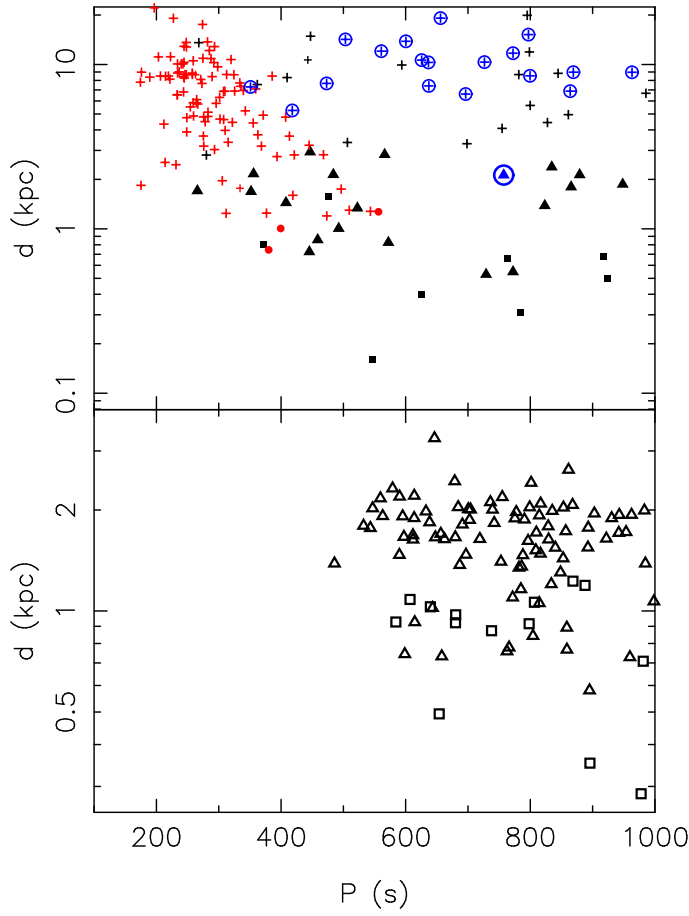


FIGURE 4. Period vs distance distribution of resolved systems detectable in the X-ray and/or optical band. **Top panel:** Systems detectable only in X-rays (pluses), and systems that are detectable in the optical and X-ray band (filled circles: direct impact systems with a bright donor, filled triangles: systems with an optically bright disc, filled squares: systems with bright disc + donor). The ultra-compact X-ray binaries are the circled symbols. **Bottom panel:** Systems only detectable in the optical band (circles: direct impact systems with a bright donor, triangles: bright discs, squares: bright disc + donor). From Nelemans et al. [37].

in order to use the GWR data to determine other parameters that are difficult to obtain otherwise (masses, inclinations and, if the frequency change of source can be measure, distance) to higher accuracy

We therefore use very simple models for the optical and X-ray emission from the mass transferring systems (AM CVn systems and ultra-compact X-ray binaries) to estimate the number of resolved system in our Galactic model that can also be detected with optical or X-ray detectors. The results are summarised in Fig. 4, where we plot the subset of the resolved systems that can also be observed with current X-ray (top panel) and optical (bottom panel) detectors. In total we expect some 330 of the ~ 10000 resolved AM CVn systems and almost all resolved ultra-compact X-ray sources to be detectable in electro-magnetic radiation. However, this estimate is based on the capabilities of current optical and X-ray instruments, so by the time LISA will be operational, this number will be higher.

These simple models only include X-ray emission from the direct impact spot and the boundary layer, while the optical emission is either from a single temperature disc, or from the donor star. We do not include any irradiation or (compressional) heating of the accreting object. For the interstellar absorption we use a very simple, symmetric, smooth model. For more details, see Nelemans et al. [37].

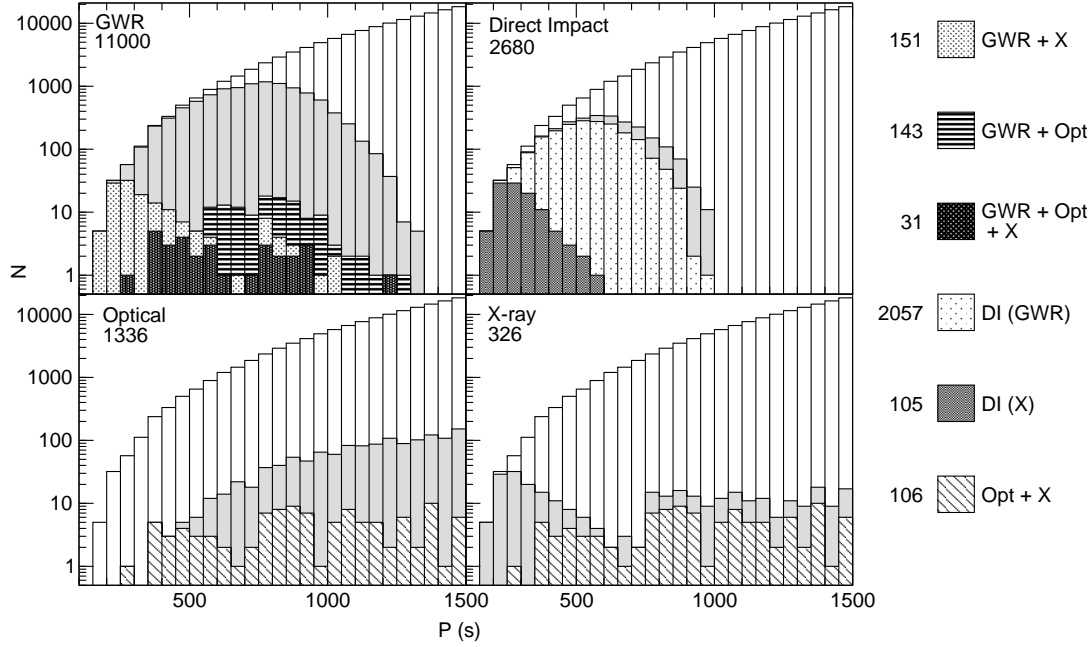


FIGURE 5. Histograms of the population of short-period AM CVn systems, subdivided in different types. In the top left panel we show the systems that can be resolved by *LISA* in grey and subdivide these in the ones that have optical counterparts (GWR + Opt), X-ray counterparts (GWR + X) and both (GWR + Opt + X). Similarly the top right panel shows the population that is in the direct impact phase of accretion in grey and we subdivide that population in GWR and X-ray sources. The bottom two panels show (again in grey) the populations that are detectable in the optical band (left panel) and the X-ray band (right panel). In both lower panels the distribution of sources detectable both in optical and x-ray band is shown by the hatched region (Opt + X), from Nelemans et al. [37]

6. GRAVITATIONAL WAVE ASTRONOMY: TESTING THE MODELS WITH LISA

As shown in the previous sections, *LISA* will be able to discover a very large number of short-period binaries in the Galaxy and will be especially sensitive to the shortest periods. These periods are exactly the ones that are most difficult to probe with classical techniques. The double white dwarfs with periods below half an hour are difficult to find, because the integration times used in spectroscopic binary searches are typically of the order of 10 minutes, resulting in strong orbital smearing of the absorption lines. Both for the detached systems and for the mass transferring systems the time scale on which the period changes increases with decreasing orbital period, so the number of systems at short periods is just much smaller than at longer periods [e.g. Fig. 2 of 42].

However, since *LISA* is sensitive mainly to the short period systems, it will provide an enormous amount of information about the shortest period range. In particular the phase directly before, and directly after the onset of mass transfer has a number of question that are almost impossible to answer with optical or X-ray observations. Just before the

mass transfer starts, the stars are so close together that the usual assumption, that the angular momentum in the two stars and the (tidal) interaction between the two stars can be neglected, probably doesn't hold anymore. In that case the period change reflects the combination of GWR losses and the other effects [e.g. 44].

At the onset of mass transfer almost all AM CVn systems will be in the already mentioned direct impact phase. The details of the evolution of the binaries, and indeed the stability of the mass transfer in this phase are very uncertain so that observations of these systems have to provide the necessary information to understand, or at least probe this phase [e.g. 20, 49]. To summarize our results we show in Fig. 5 histograms of the different subpopulations of short-period AM CVn systems [see 37, for more details].

A second aspect of the large number of detectable systems is that, if for enough systems the frequency change and thus the distance can be measured, the short-period binaries can be used as tracers of Galactic structure. In particular the mass distribution in the inner regions of the Galaxy, which is difficult to observe because of interstellar absorption, is a promising area of investigation.

7. CONCLUSIONS

I discussed our current knowledge of compact binaries in the Galaxy and showed that there are still large uncertainties. With sometimes rapidly increasing samples of observed systems some of the uncertainties in the models can be addressed. However some questions, especially related to the shortest period binaries are very difficult to answer. The best current models predict a very large number of (in particular) double white dwarf and AM CVn binaries that can be resolved by LISA. As these are predominantly very short-period systems this will provide invaluable information on some of the crucial open questions. I argued that complementary optical, X-ray and infra-red observations might be useful in constraining the parameters of the resolved binaries, although many will not be detectable with electro-magnetic detectors.

ACKNOWLEDGMENTS

I would like to thank Lev Yungelson, Simon Portegies Zwart, Frank Verbunt and Sterl Phinney for help and discussions and PPARC for financial support.

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