The Galactic Gravitational wave foreground

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Abstract. I present an overview of the Galactic binaries that form the foreground for the ESA/NASA Laser Interferometer Space Antenna (LISA). The currently known population is discussed, as well as current and near-future large-scale surveys that will find new systems. The astrophysics that can be done when the LISA data becomes available is presented, with particular attention to verification binaries, the overall Galactic populations, neutron star and black hole binaries and sources in globular clusters. I discuss the synergy with electro-magnetic observations and correct an error in the estimate of the number of LISA systems that can be found in the optical compared to Nelemans (2006a) and conclude that at least several hundreds of systems should be detectable.

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1. Introduction: Galactic gravitational wave binaries

Already in the 1980s, it was realised that compact binaries in the Galaxy are sources of low-frequency gravitational waves (e.g. Evans et al., 1987; Lipunov et al., 1987; Hils et al., 1990). In particular double white dwarf binaries dominate the signal at frequencies above 0.1 mHz, with a total Galactic population of ~30 million objects (Hils et al., 1990; Nelemans et al., 2004b; Timpano et al., 2006).

The binaries that are most relevant for LISA are the so-called ultra-compact binaries (Nelemans, 2006b), consisting of two compact evolved stars. We distinguish

(i) *Detached* binaries where both stars are well separated, of which the following classes are known

**Double white dwarfs** are the most common systems. They are the endpoints of many binary evolution scenario’s (see Webbink, 1984). They have been discovered observationally (e.g. Saffer et al., 1988; Marsh, 1995) and the largest project to find them, the ESO Supernova Ia Progenitor SuveY (SPY; Napiwotzki et al., 2001) has discovered several tens of them, although very few in the LISA frequency range (see Nelemans et al., 2005).

**White dwarf – neutron star binaries** are typically found as white dwarfs around radio pulsars (see Lorimer, 2005), with long-period orbits. No systems in the LISA frequency range are known, but several are expected (Nelemans et al., 2001; Nelemans, 2003).

**Double neutron stars** were the first to be discovered (Hulse and Taylor, 1975) but currently only 8 are known (see Lorimer, 2005), of which the shortest period is 2.4 hours.

(ii) *Interacting* binaries, in which mass is transferred from one star to the other, of which the following classes are known

**AM CVn stars**, in which a white dwarf is accreting (helium rich) material from a compact companion (e.g. Warner, 1995; Nelemans, 2005). Currently 22 are known with periods between 5.4 and 65 min (see Nelemans, 2005).

**Ultra-compact X-ray binaries**, which have neutron star accretors (no ultra-compact black hole systems have yet been found). Currently there are 27 (candidate) systems (in’t Zand et al., 2007), only 8 with well known periods between 11 and 50 minutes. From their X-ray and optical spectra it has been inferred that the donors stars can be either helium rich or carbon/oxygen rich (Schulz et al., 2001; Juett et al., 2001; Nelemans et al., 2004a, 2006) but from the properties of type I X-ray bursts it has been inferred that in most systems the matter accumulated on the neutron star is helium (see in’t Zand et al., 2005).

Ultra-compact binaries, especially when observed with LISA, are interesting objects from Astrophysical point of view in a number of areas.
**Binary star evolution** The ultra-compact binaries represent one of the most evolved stages in binary evolution and in order to get their ultra-short periods, they must have had extreme angular momentum loss in one or likely more common-envelope phases (e.g. Nather *et al.*, 1981; Webbink, 1984). The process of angular momentum loss in a common envelope is poorly understood (e.g. Taam and Sandquist, 2000; Nelemans and Tout, 2005) so detailed understanding of ultra-compact binaries will teach us something about binary evolution in general. At the short periods that these binaries have, angular momentum loss due to gravitational wave radiation becomes the most important driver of the binary evolution (e.g. Paczyński, 1967; Vila, 1971; Tutukov and Yungelson, 1979).

**Type Ia Supernovae progenitors** The use of type Ia supernovae as standard candles (Phillips, 1993) has led to the discovery of the accelerated expansion of the Universe (Riess *et al.*, 1998; Perlmutter *et al.*, 1999), but their progenitors are unknown. Directly observing the progenitors is difficult, as they are typically observable only nearby, where the occurrence rates are low (of the order of a few per millennium in our Galaxy, e.g. Botticella *et al.*, 2008; Sullivan *et al.*, 2006), except using archival Chandra X-ray or Hubble Space Telescope optical observations (Voss and Nelemans, 2008; Maoz and Mannucci, 2008; Roelofs *et al.*, 2008; Nelemans *et al.*, 2008). Therefore, studying the potential progenitor populations and determining their occurrence rates is a promising way forward (e.g. Yungelson, 2005; Förster *et al.*, 2006). As such, ultra-compact binaries are very relevant, as some of them may be progenitors (e.g. Solheim and Yungelson, 2005), but they certainly come from the same general population in which the supernovae originate.

**Galactic structure** When LISA will discover many thousands of ultra-compact binaries (e.g. Nelemans *et al.*, 2001, see Sect. 3.2), it opens up the possibility to chart their distribution throughout the Galaxy, in particular in the inner region, where most systems are expected. Thus, LISA measurements will contribute towards our understanding of the structure of the Galaxy.

**Binary interaction** Finally, during the evolution of ultra-compact binaries, there may be other processes except for gravitational wave radiation and mass transfer that determine the orbital evolution, in particular tidal dissipation in the white dwarfs (e.g. Racine *et al.*, 2007; Willems *et al.*, 2008). LISA observations will thus allow detailed study of the physics of mass transfer, tides and other interactions in these ultra-compact binaries.

2. Recent progress in Astrophysics: Surveys

One of the recent developments in astrophysics is the advent of digital large-scale surveys.

**SDSS** The Sloan Digital Sky Survey (SDSS/SEGUE York *et al.*, 2000), is a ~8 000
Figure 1. Area of the Galactic Bulge Survey in Galactic coordinates. The two boxes show the final area that will be observed, and have been chosen to avoid the largest extinction (shown as grey shade). The points indicate the population of expected X-ray sources, based on very simple estimates. The dashed box is the area of the Wang et al. (2002) X-ray survey for which optical follow-up is impossible due to extinction.

square degree survey, which was largely aimed at extra-galactic sources. The area is imaged in five optical bands (u,g,r,i,z) yielding more than 250 million objects and of a subset of about 1 million sources spectra were taken. From the SDSS database 7 AM CVn systems were found (Roelofs et al., 2005; Anderson et al., 2005, 2008). Extrapolating this to the full photometric database, another 40 systems should be in the SDSS area. Low-resolution identification spectroscopy of the candidates is currently underway (Roelofs et al., 2008). Comparing these numbers with the predictions of population models (Nelemans et al., 2004b) it was found that even pessimistic models likely overestimate the true number of AM CVn stars in the Galaxy (Roelofs et al., 2007b).

**RATS and OmegaWhite** The Rapid Temporal Survey RaTS (Ramsay and Hakala, 2005) and OmegaWhite‡ are variability surveys that specifically target short period (<1 hour) variability by taking time series photometry of large areas on the sky (40 and 400 square degrees respectively) for periods of 2 hours with points each few minutes. RaTS is currently underway on the Isaac Newton Telescope and the ESO 2.2m telescope. OmegaWhite will start in 2009 using OmegaCam (Iwert et al., 2006) on the ESO VLT Survey Telescope. Many new, short period ultra-compact binaries will be discovered.

GBS  The Galactic Bulge survey (GBS) uses the Chandra X-ray satellite and ground-based optical observations to chart the population of X-ray binaries (including ultra-compacts) in the inner part of the Galactic Bulge (Jonker et al., in preparation). Observations are made of two regions of 1 x 6 square degrees each, located directly above and below the Galactic Center at $1^\circ < |b| < 2^\circ$ (Fig. 1). Using this observing strategy it avoids the very strong dust absorption in both X-rays as well as red optical wavelengths that plague observations at the very Galactic Center. The same area has been imaged using the CTIO 4-m Blanco telescope in the optical red broad-band $r, i$ and narrow-band H$\alpha$ filters to a depth of $r \sim$23.5 and equivalent H$\alpha$ line flux. This depth is chosen such that a low-mass main-sequence companion to a neutron star or black hole accretor at the distance of the Galactic Center will be detected. H$\alpha$ observations have been included since many non-ultra-compact binaries will show H$\alpha$ emission in their spectra. All optical observations have been obtained and are reduced. Half of the X-ray observations are obtained and reduced and already have led to the identification of 1700 new X-ray sources. Due to the exquisite spatial resolution of Chandra many of these have unique counterparts in the optical data. The remaining X-ray observations will be obtained over the coming years. The number of X-ray sources is in line with our model calculations, giving confidence in the number of (ultra-)compact binaries to be detected from the GBS (30-60).

EGAPS  The European Galactic Plane Survey (EGAPS) is surveying the full Galactic Plane in a strip of 10x360 square degrees centered on the Galactic equator. It uses the broad-band optical $U, g, r, i$ bands and additionally the narrow-band H$\alpha$ and HeI 5875 (northern hemisphere only) bands, down to 21st magnitude or equivalent line flux. The survey has been described in Drew et al. (2005) and Groot et al. (submitted). The Northern survey has been running on the Isaac Newton Telescope on La Palma since summer 2003 and is currently 65% complete. The southern survey will start next year on the VST survey telescope of the European Southern Observatory as a 100-night ESO Public Survey.

GAIA  The ESA GAIA mission (Perryman et al., 2001) will image the whole sky down to magnitudes around V=20 with the aim to measure positions, spectral energy distributions and radial velocities (for the brighter stars) of upto one billion stars. The satellite will continuously map the sky while it rotates and thus build up an enormous set of very accurate relative position measurements. At the end these can be turned into absolute positions. As each position in the sky is visited many times (typically around 90 times) parallax and proper motion of all objects will be determined.
3. Astrophysics with LISA

3.1. Verification binaries

One of the uses of ultra-compact binaries is that some are known, guaranteed LISA sources and thus can be used as verification sources (e.g. Ströer and Vecchio, 2006) even though (much) stronger, but yet unknown, sources will likely be detected first. Important for the use of known sources as verification is of course to know their properties as accurately as possible before LISA flies. Recent progress here has been made by using the FGS instrument on board of the Hubble Space Telescope to measure accurate distances to a number of AM CVn stars (Roelofs et al., 2007a). Together with estimates for the component masses from the absolute magnitudes this has led to estimates of the expected LISA signal that are well determined with reliable error bars (Fig. 2 and Roelofs et al., 2007a). For the shortest periods systems the distances and component masses are not (yet) well determined enough to give well defined signal estimates.
3.2. (Un)resolved foregrounds

The number of ultra-compact binaries depends strongly on their orbital period as the evolutionary timescale decreases sharply towards shorter periods. At the same time the frequency resolution of LISA remains constant. Therefore there is a large difference in the properties of the ultra-compact binary population at low frequencies, where there are many objects in the Galaxy per frequency resolution element, and at high frequencies, where there are few, if any objects per resolution element (e.g. Evans et al., 1987).

At high frequencies many systems can in principle be individually detected and have their properties measured with high accuracy, depending on the signal-to-noise ratio. The current Mock LISA data challenges (e.g. Arnaud et al., 2007) show that indeed in more or less realistic data sets, the ultra-compact binaries can be detected. As these are a small subset of the population and the total population is probably strongly concentrated in the inner Galaxy, most of these systems will reside close to the Galactic center. For some fraction of these systems the frequency evolution can be detected (e.g. Ströer et al., 2005), although the details are still under investigation in the MLDC rounds.

A separate class of systems that will be individually detected are lower frequency systems that have such strong signals that they stick out above the local noise that is formed by the collective weaker signal sources. These are typically the intrinsically stronger sources (with high-mass components) and the nearby sources (e.g. Benacquista et al., 2007).

At lower frequencies the many systems together form what is often called the unresolved Galactic foreground (a better name than the previously used “background”). Although this is often depicted as an extra noise component that at low frequencies exceeds the instrumental noise, this is a bit misleading as it really is a signal and more importantly, it is variable over the year as the bulk of this foreground comes from systems that are located towards the Galactic center (e.g. Edlund et al., 2005). This opens the possibility to use its shape to learn about the distribution of the sources in the Galaxy. In particular the different Galactic components (thin disk, thick disk, halo) have a contribution that vary differently, although the contribution of thick disk and halo are very small compared to the thin disk (e.g. Ruiter et al. ApJ submitted).

3.3. Electro-magnetic counterparts

A very interesting possibility is to observe systems both individually with LISA, as well as with electro-magnetic means. The information that can be obtained from the gravitational-wave data is complementary to that which can be obtained from electro-magnetic data, in particular optical and/or near infrared. The question is how many of the systems that LISA will detect are also observable with optical or near infrared detectors. The problem is that most resolved binaries reside close to the Galactic center, where they suffer from heavy extinction. Cooray et al. (2004) estimated that a large fraction (several tens of percents) of the double white dwarf LISA sources would
be detectable electro-magnetically, but we showed (Nelemans, 2006a) that they likely overestimated the intrinsic brightness of the white dwarfs and that only several tens of systems would be detectable. However, we recently found that that estimate is too pessimistic due to an error in the Galactic distribution of the systems in Nelemans (2006a), which is too concentrated to the Galactic center. We redid the calculation and now find the much more optimistic result that several hundreds of double white dwarf LISA systems might be detectable electro-magnetically (Fig. 3). Note that for this estimate we use a very simplistic estimate of the number of systems that can be individually observed with LISA: all systems with frequencies above 2.1mHz or (barycentric) strain amplitudes larger with \( \log h > -28.152 - 1.9992 \log f \). This results in a 33 thousand systems of which \( \sim 2000 \) have \( V < 24 \) (\( \sim 6\% \)). This simple estimate for the number of individually resolved systems is likely an overestimate (e.g. Benacquista et al., 2007). We are currently investigating this in more detail (Finn & Nelemans, in preparation). Our new estimate is still lower than Cooray et al. (2004), because of their overestimate of the intrinsic brightness of white dwarfs.

In Fig. 3 we also show the I-band and K-band magnitudes of the LISA systems that suffer less from extinction. For apparent magnitudes fainter than 20 the number of systems is largest in the K-band. Current wide field surveys and instruments typically have limiting magnitudes of 22-24 in the V- and I-bands and 20-21 in the K-band.

As also mentioned by Cooray et al. (2004) one of the most interesting features of the double white dwarfs that can be detected electro-magnetically is that a large fraction of them will be very short period, with relatively large probability of showing eclipses. In this respect the GAIA measurements, which typically consist of \( \sim 90 \) photometric measurements are interesting, as eclipsers should show up in this data (Marsh & Nelemans, in preparation). Detecting eclipsers would allow to get detailed information about the absolute dimensions of the systems and might allow detection of period evolution even for the systems for which the LISA mission duration is too short to measure it.

3.4. Neutron star and black hole binaries

Not that much attention has been been given to ultra-compact binaries with neutron star and black hole components for LISA. They are typically considered for the ground based detectors as they are the only systems at the high frequencies accessible from Earth. And although the numbers are much smaller than those with white dwarf components, there are several tens of systems expected (e.g. Nelemans et al., 2001). This may be enough to link them to the, by the time LISA flies hopefully well determined, merger rates of neutron star and black hole binaries.

\( \S \) Due to an underestimate of the formation time of the systems in the Galaxy for which we use a star formation history that starts in the inner Galaxy
Figure 3. Histogram of apparent magnitudes of the double white dwarfs that are estimated to be individually detected by LISA (see text). The black-and-white line shows the distribution in the V-band, the black line the distribution in the I-band and the grey histogram the distribution in the K-band. Galactic absorption is taken into account. The zoom-in shows the bright-end tail of the V-band distribution.

3.5. Globular clusters

A special situation occurs in globular clusters: large assemblies of up to a million old stars in a relatively small volume forming very dense stellar systems. Binaries play in important role in the evolution and stability of the clusters (see Hut et al., 1992). From X-ray observations it has become clear that there is an overabundance of ultra-compact X-ray binaries in globular clusters, compared to the disc of the Galaxy. This could in principle be very interesting for gravitational wave detectors, that are particularly sensitive to ultra-short periods binaries (e.g. Benacquista et al., 2001). It would be even more interesting would be if also white dwarfs binaries would be overabundant in globular clusters. Indeed in some cluster simulations it has been found that there are more close double white dwarfs in a dense environment, in particular massive ones that have been proposed as possible type Ia supernova progenitors (Shara and Hurley, 2002; Hurley and Shara, 2003). However, Ivanova et al. (2006) do not find such enhancement. Interestingly, Bedin et al. (2008) find a puzzling white dwarf sequence in the globular cluster NGC 6791 which they propose is due to a large fraction (34%) of double white dwarfs. So if indeed double white dwarfs are formed more easily in globular clusters, LISA will see stronger signal from them and thus may contribute to the study of dynamical formation of binaries in dense stellar systems.
Another interesting aspect of dynamical interactions in globular clusters is the possibility of forming eccentric white dwarf binaries, while in the Galactic disc eccentricity typically is a clear sign of the presence of a neutron star in the binary. Willems et al. (2007) investigate this possibility and conclude that indeed eccentric binaries are formed and may very well be detected by LISA. If so, the strong interaction at periastron passage will give unique information on the internal structure of the white dwarf and the (tidal) interaction in the system (Willems et al., 2008).

4. Conclusions and Outlook

It is clear that there are many interesting developments in Astrophysics with consequences for LISA, in particular the advent of large-scale surveys, that will discover a lot of sources that are interesting for LISA and likely will lead to a much better understanding of the Galactic population of ultra-compact binaries before LISA flies. Already now for a number of systems the parameters are determined accurately enough that they can serve as verification binaries. However, LISA is particularly sensitive to many binaries that are difficult to observe with traditional instruments and will discover thousands of them. In particular these ultra-short period binaries are particularly interesting for the physics questions regarding the (tidal) interaction between compact objects.

Some special attention has been given to globular clusters as these large assemblies of stars may harbour some very interesting objects such as eccentric double white dwarf binaries. It may even be so that the formation of LISA sources in globular clusters is strongly enhanced, something that will be tested with the LISA measurements.

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