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 become 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 American Institute of Phys. Conf. Ser. vol 873) and conclude that at least several hundreds of systems should be detectable.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction: Galactic gravitational wave binaries

In the 1980s, it was already realized 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 Laser Interferometer Space Antenna (LISA) are the so-called ultra-compact binaries (Nelemans 2006b), consisting of two compact evolved stars. We distinguish the following.

(i) Detached binaries where both stars are well separated, of which the following classes are known.
(a) Double white dwarfs are the most common systems. They are the endpoints of many binary evolution scenarios (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 SurveY (SPY; Napiwotzki et al 2001), has discovered several tens of them, although very few in the LISA frequency range (see Nelemans et al (2005)).

(b) 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, 2003).

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

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

(a) AM CVn stars, in which a white dwarf accretes (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)).

(b) 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 eight with well-known periods between 11 and 50 min. From their x-ray and optical spectra, it has been inferred that the donor 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 the 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 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 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 2008b, Nelemans et al 2008). Therefore, studying the potential progenitor populations and determining their occurrence rates are 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
but they certainly come from the same general population in which the supernovae originate.

**Galactic structure.** When LISA discovers many thousands of ultra-compact binaries (e.g. Nelemans *et al* (2001) see section 3.2), it opens up the possibility of charting 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 a 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 an $\sim$8000 square degree survey, which was largely aimed at extra-galactic sources. The area is imaged in five optical bands ($u, g, r, i, z$) yielding more than 250 million objects, and spectra were taken of a subset of about one million sources. 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* (2008b)). 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*¹ are variability surveys that specifically target short-period ($\lesssim 1$ h) variability by taking time series photometry of large areas on the sky (40 and 400 square degrees respectively) for periods of 2 h with points each of few minutes. *RaTS* is currently underway on the Isaac Newton Telescope and the ESO 2.2 m 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 $1 \times 6$ square degrees each, located directly above and below the Galactic centre at $1^\circ < |b| < 2^\circ$ (figure 1). Using this observing strategy, it avoids the very strong dust absorption in both x-rays and red optical wavelengths that plague observations at the very Galactic centre. The same area has been imaged using the CTIO 4 m Blanco telescope in the optical red broadband $r, i$ and narrowband H$\alpha$ filters to a depth of $r \sim 23.5$ and an equivalent H$\alpha$ line flux. This depth is chosen such that a low-mass

¹ http://www.astro.ru.nl/omegawhite.
main-sequence companion to a neutron star or black hole accretor at the distance of the Galactic centre will be detected. Hα observations have been included since many non-ultra-compact binaries will show Hα emission in their spectra. All optical observations have been obtained and are reduced. Half of the x-ray observations are obtained and reduced and have already 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) surveys the full Galactic Plane in a strip of $10 \times 360$ square degrees centred on the Galactic equator. It uses the broadband optical $U, g, r, i$ bands and additionally the narrowband Hα and HeI 5875 (northern hemisphere only) bands, down to the 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 up to 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 can thus be used as verification sources (e.g. Ströer and Vecchio (2006)) even though (much) stronger, but yet unknown, sources will likely be detected first. What is 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 has been made here 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 (figure 2 and Roelofs et al. (2007a)). For the shortest period 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 centre. 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 centre (e.g. Edlund et al 2005). This opens the possibility of using 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 a thick disk and halo are very small compared to the thin disk (e.g. Ruiter et al (submitted))

3.3. Electro-magnetic counterparts

A very interesting possibility is observing systems both individually with LISA and 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 centre, 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 that 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 on the Galactic centre\(^2\). 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 (figure 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 2.1 mHz or (barycentric) strain amplitudes larger with \( \log \mathcal{h} > -28.152 \times -1.9992 \log f \). This results in 33 thousand systems of which \(~2000\) have \( V < 24 \) (\(~6\%)\). 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 and 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 figure 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.

\(^2\) Due to an underestimate of the formation time of the systems in the Galaxy, in combination with the use of a star formation history that starts in the inner Galaxy.
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 of a very short period, with relatively large probability of showing eclipses. In this respect the GAIA measurements, which typically consist of ~90 photometric measurements, are interesting, as eclipsers should show up in this data (Marsh and Nelemans, in preparation). Detecting eclipsers would allow us 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 much attention has 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. 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.

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 an 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 period binaries (e.g. Benacquista et al (2001)). It would be even more interesting if white dwarf binaries would also 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 a 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 the 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 will likely lead to a much better understanding of the Galactic population of ultra-compact binaries before LISA flies. For a number of systems, the parameters are now already determined accurately enough so 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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