Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
Proceedings IAU Symposium No. 363, 2023
E. Troja & M. G. Baring, eds.
doi:10.1017/S1743921322000618

Prospects for studying Galactic neutron stars in binaries with LISA

Valeriya Korol

Institute for Gravitational Wave Astronomy & School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, UK
email: korol@star.sr.bham.ac.uk

Abstract. So far detached compact binaries containing neutron stars have been observed either at intermediate stages of the evolution by radio telescopes or at merger by ground-based gravitational wave detectors. Sensitive to gravitational waves from binaries millions to thousands years prior to the merger, the future Laser Interferometer Space Antenna (LISA) will be crucial for bridging the gap between the currently accessible regimes. Depending on the binary type, LISA could potentially discover from a few to several hundreds in the entirely new regime throughout the Milky Way. Here we provide a concise summary of the current expectation for the detection of Galactic binaries containing neutron stars with LISA, focusing on double neutron stars and neutron star - white dwarf binaries. We outline a few examples of science investigations that LISA data will enable for these binaries.

Keywords. Gravitational waves, binaries: close, stars: neutron, white dwarfs

1. Introduction

Laser Interferometer Space Antenna (LISA) is the future ESA-led gravitational wave (GW) mission. Consisting of three identical drag-free spacecrafts in an equilateral triangle configuration distant 2.5 Mkm apart and connected by laser links, LISA will be sensitive to GWs of $10^{-4} - 10^{-1}$ Hz (Amaro-Seoane *et al.* 2017). This HHz frequency window is populated by a large variety of astrophysical GW sources ranging from stellar-mass compact objects binaries in the Milky Way, to extreme mass ratio binaries such as massive black holes with stellar-mass companions, to mergers between nascent massive black holes at high redshift. The mHz GW window offers a unique opportunity for studying Galactic stellar populations of stellar remnants, illusive or completely invisible to electromagnetic telescopes (e.g. Nelemans *et al.* 2001). In particular, LISA will detect Galactic binaries with a neutron star (NS) component: several 100s of white dwarf - neutron stars (WD-NS; Breivik *et al.* 2020), up to a 100 double neutron stars (DNSs; Andrews *et al.* 2020), and a handful of NSs with either black hole (NS-BH; Wagg *et al.* 2021) or Helium star companions (NS-He star; Götberg *et al.* 2020). LISA can follow their in-spiral up to millions years prior to merger, which corresponds to orbital periods of at most a few hours. Thus, it will fill in the lack of observations between intermediate (detached) evolutionary stages accessible with radio telescopes (but limited to our Galaxy) and later stages accessible either through observations of ultra-compact X-ray binary (UCXB) with X-ray telescopes or through GW radiation when they merge with ground-based GW detectors. Note, however, that ground-based GW detectors are sensitive to extra-galactic DNS and NS-BH mergers that may result from progenitor populations that differ from that in our Galaxy. The advantage of LISA is that it can observe Galactic DNSs, WD-NS, NS-BH and NS-He star binaries everywhere in the Milky Way, possibly, even

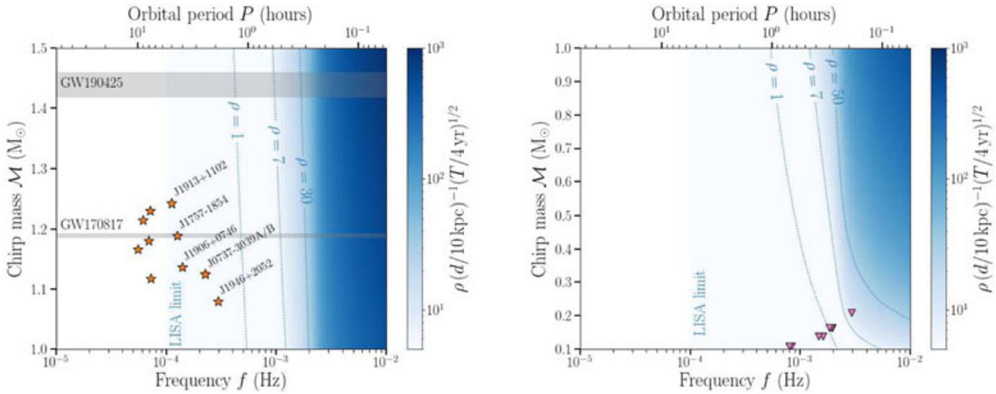

Figure 1. Known DNSs (orange stars) from radio observations and WD-NS (magenta triangles) from X-ray observations in the GW frequency f – chirp mass $\mathcal{M}$ parameter space. We aslo show in colour the sky-, inclination- and polarisation-averaged signal-to-noise ρ for a circular DNS at $d = 10$ kpc after nominal four years of LISA mission. Dotted contours show signal-to noise ratios of 1, 7 and 30. Grey horizontal bands represent chip masses of GW170817 and GW190425.

reaching the Andromeda galaxy. For orbital periods of less than 20 min, LISA will deliver a complete sample with well-understood selection effects (e.g. Korol *et al.* 2018).

2. LISA measurements

The detectability of Galactic binaries with LISA depends mainly on the GW frequency $f = 2/P$ (with P being binary's orbital period), chirp mass $\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$ (with m_1 and m_2 being the primary and secondary masses) that defines how fast the GW frequency changes during the in-spiral phase ($\dot{f}$), and the luminosity distance d. These three quantities define binary's GW amplitude

$$\mathcal{A} = \frac{2(G\mathcal{M})^{5/3}(\pi f)^{2/3}}{c^4 d}, \tag{2.1}$$

where G and c are respectively the gravitational constant and the speed of light. Given LISA's power spectral density $S_\mathrm{n}(f)$ and transfer function $R(f)$ (e.g. Korol *et al.* 2020), the angle-averaged signal-to-noise ratio can be defined as

$$\rho^2 = \frac{24}{25}|\mathcal{A}|^2 \frac{T}{S_\mathrm{n}(f)R(f)}. \tag{2.2}$$

Figure 1 shows the signal-to-noise ratio produced by a circular DNS at the distance of 10 kpc and observed over the nominal 4 years with LISA. For comparison, we show sub-samples of the known shortest period Galactic DNSs (orange stars) and UCXBs (magenta triangles). By plugging in their measured parameters in Eq. 2.2, we find that all of the known DNS (Farrow *et al.* 2019 and references therein) lay under the LISA detection threshold of $\rho = 7$ and only one UCXB exceeds this threshold.

Within the LISA band, for binaries with $f > 1.75$ mHz the chirp mass can be measured through the measurement of $\dot{f}$ (e.g. Korol & Safarzadeh 2021). At lower frequencies, binaries will be seen as monochromatic over the whole duration of the mission, meaning that only measurements of f and $\mathcal{A}$ will be possible, while their chirp mass measurement will be degenerate with that of the distance (cf. Eq. 2.1).

Unlike circular binaries, eccentric ones emit GWs at multiple harmonics. Each signal can be thought as a collection of n signals from circular binaries emitting at $f_n = nf/2$ and the amplitude $\mathcal{A}_n = \mathcal{A}(2/n)^{5/3} g(n,e)^{1/2}$, where $g(n,e)$ is given in Peters & Mathews (1963). The total signal-to-noise ratio can be estimated as the quadrature sum of the

https://doi.org/10.1017/S1743921322000618 Published online by Cambridge University Press

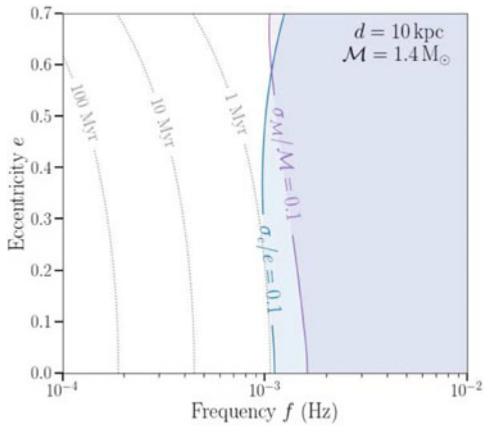

Figure 2. Fractional error of 0.1 on the chirp mass (in purple) and the eccentricity (in blue) for a DNS with the chirp mass of $\mathcal{M} = 1.4\,\mathrm{M}_\odot$ at the distance of $d = 10\,\mathrm{kpc}$ as measured by LISA. Contours of the merger times of 1, 10 and 100 Myr are marked by the grey dotted lines.

individual harmonics' signal-to-noise ratios. Thus, under the assumption of the optimal GW signal recovery, the signal-to-noise of an eccentric binary is always greater than that of a circular one. In the eccentric case, to measure the chirp mass, in addition to $\dot{f}$, one also needs to simultaneously measure the eccentricity, which is possible when at least two harmonics are detected (e.g. Seto 2016), otherwise only an upper limit on the chirp mass can be derived. To summarise, Figure 2 illustrate contours of fractional error of 0.1 on the chirp mass ($\sigma_\mathcal{M}/\mathcal{M}$ in purple) and the eccentricity (σ_e/e in blue) for a DNS with $\mathcal{M} = 1.4\,\mathrm{M}_\odot$ and $d = 10\,\mathrm{kpc}$. The overlapping region shows that both quantities can be measured for $f > 2\,\mathrm{mHz}$ regardless of the binary's eccentricity.

3. Science Investigations

Given measurements of the binary's frequency, chirp mass and eccentricity based on the LISA data, below we outline possible science investigations for WD-NSs and DNSs.

Stability of the Case BB RLO in eccentric DNSs. The orbit of an eccentric LISA DNS is characterised by the last mass transfer phase prior to the DNS formation - the so-called Case BB mass Roche Lobe Overflow (RLO) initiated by the expansion of the naked helium star after core-helium depletion (Haberts 1986). Simulations and the period distribution of observed Galactic DNSs indicate that this phase should to be predominantly stable (e.g. Tauris *et al.* 2015, Vigna-Gómez *et al.* 2018). Lau *et al.* (2020) shows that the biggest variations on the LISA DNS detection rate results from the assumption on the stability of the Case BB RLO phase. They find that the detection rate is the highest (35 DNS detected by LISA) when the case BB RLO is assumed to be stable, while the detection rate is the lowest (4 DNSs detected by LISA) when the case BB RLO is assumed to be unstable. This is because an unstable Case BB RLO leads to an additional common envelope phase, which produces DNSs with sub-hour periods that merge rapidly. In addition, Lau *et al.* (2020) find that the resulting eccentricity distributions arising from these two assumptions to be significantly different. Thus, eccentricities measured by LISA can help to learn about the stability of the last mass transfer experienced by DNSs.

GW190425-like DNSs in the Milky Way. Another interesting question is whether our Milky Way hosts GW190425-like binaries, a presumed DNS merger with estimated total mass of $3.4\,\mathrm{M}_\odot$ (LIGO/Virgo Collaboration 2020). Korol & Safarzadeh (2021) conducted a simple experiment assuming that the Galactic DNS population consists of two distinct

https://doi.org/10.1017/S1743921322000618 Published online by Cambridge University Press

sub-populations: a fraction w_1 that follows the observed Galactic DNS chirp mass distribution and a fraction w_2 that instead resembles the measured chirp mass of GW190425. They verified that LISA's measurement errors on the chirp mass allow the reconstruction of the 'true' chirp mass distribution and the 'true' relative fraction DNSs in the two sub-populations with no bias. Specifically, they demonstrated that LISA's accuracy on recovering the fraction of GW190425-like binaries depends on the DNS merger rate and ranges between 30 - 5%.

NS natal kics in NS-WD binaries. One of the most straightforward ways of learning about neutron star natal kicks is via WD-NSs that, compared to DNSs, experience only one kick and are expected to be an order of magnitude more numerous than DNSs in the LISA's sample (Breivik *et al.* 2020). By comparing two mock WD-NS populations detectable with LISA generated with and with no kick based on models of Toonen *et al.* (2018), we found that the detection rates, chirp mass and eccentricity distributions to be significantly different (Korol *et al.* in prep.). Thus, reconstructing these distributions from the LISA data offers an opportunity to learn about neutron star natal kics.

Multi-messenger synergies. LISA's sample of WD-NSs, DNSs, NS-BHs and NS-He star binaries will provide a number of multi-messenger synergies as illustrated in Fig. 1 of Tauris (2018) using the example of the UCXB evolution. A typical UCXB system evolves through a low-mass X-ray binary phase (observable at optical and X-rays wavelengths), followed by a detached phase (observable through radio waves and GWs) and followed by an UCXB phase (observable in optical, x-ray and GWs). Importantly, LISA can detect such a binary in both detached and accreting phases, thus overlapping with radio and X-ray/optical observations. Thus, data can be gathered from both messengers - GW and light - complementing one another. The multi-messenger approach will be crucial for constructing a complete picture of the evolution of Galactic binaries containing NSs.

References

Andrews, J. J., Breivik, K., Pankow, C., D'Orazio, D. J., Safarzadeh, M. (2020), *ApJL*, 892
Amaro-Seoane, P. *et al.* (2017), *arXiv*, 1702.00786
Breivik, K., Coughlin, S., Zevin, M. *et al.* (2020), *ApJ*, 898,
Götberg, Y., Korol, V., Lamberts, A. *et al.* (2020), *ApJ*, 904
Habets, G. M. H. J. (1986), *A&A*, 165, 95–109
Farrow, N., Zhu, X.-J., & Thrane, E. (2019), *ApJ*, 876
Korol, V., Koop, O., & Rossi, E. M. (2018), *ApJL*, 866
Korol, V., Toonen, S., Klein, A. *et al.* (2020), *A&A*, 638
Korol, V., & Safarzadeh, M. 2021, *MNRAS*, 502, 5576–5583
Lau, M. Y. M., Mandel, I., Vigna-Gómez, A. *et al.* (2020), *MNRAS*, 492, 3061–3072
LIGO & Virgo Collaborations (2020), *ApJL*, 892,
Nelemans, G., Yungelson, L. R., & Portegies Zwart, S. F. (2001), *A&A*, 375, 890–898
Peters, P. C., & Mathews, J. (1963), *Phys. Rev.*, 131, 435-440
Seto, N. (2016), *MNRAS*, 460, L1–L4
Tauris, T. M., Langer, N., & Podsiadlowski, P. (2015), *MNRAS*, 451, 2123–2144
Tauris, T. M. (2018), *Phys. Rev. Lett.*, 121
Toonen, S., Perets, H. B., Igoshev, A. P., Michaely, E., & Zenati, Y. (2018), *A&A*, 619,
Vigna-Gómez, A., Neijssel, C. J., Stevenson, S., Barrett *et al.* (2018), *MNRAS*, 481, 4009–4029
Wagg, T., Broekgaarden, F. S., de Mink, S. E., *et al.* (2021), *arXiv*, 2111.13704