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Detectability of Double White Dwarfs in the Local Group with LISA

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Abstract

Detached double white dwarf (DWD) binaries are one of the main science cases for the Laser Interferometer Space Antenna (LISA). As the most numerous LISA sources, they will provide important contributions toward understanding binary evolution, supernovae Type Ia (SNIa) formation channels, and the structure of the Milky Way. So far only detection prospects for the Milky Way have been predicted. In this Letter we show that LISA has the potential to detect DWDs in neighboring galaxies up to the border of the Local Group. In particular, we compute quantitative estimates for the number of detections in M31. We expect between a dozen to several tens of DWDs above the nominal detection threshold, for a mission duration between 4 and 10 years. We show that detectable extra-galactic DWDs include those with the shortest orbital periods ($P < 10$ minutes) and with the highest chirp masses ($\mathcal{M} > 0.6\,M_{\odot}$). This subgroup represents candidates for SNIa progenitors. These binaries are virtually undetectable at those distances in optical, implying that LISA could be the best instrument able to provide SNIa merger rates across the Local Group.

Key words: binaries: close – gravitational waves – Local Group – white dwarfs

1. Introduction

Detached double white dwarf (DWD) binaries with orbital periods <1 hr will be important gravitational wave (GW) sources for the Laser Interferometer Space Antenna (LISA) mission in many ways (Amaro-Seoane et al. 2017). First, DWDs are guaranteed LISA sources. A number of short-period DWDs have already been identified at optical wavelengths (e.g., Kupfer et al. 2018). Those with the strongest signals can be used as calibration sources as they will be detectable already after one week of observations; over time their signal will increase, thus improving the accuracy with which these sources can be used to monitor data quality as new data are acquired (Littenberg 2018). Second, DWDs will be the most numerous LISA sources. The total number of expected detections exceeds 10^5 (e.g., Nelemans et al. 2001; Ruiter et al. 2010; Marsh 2011; Korol et al. 2017). Thus, for the first time LISA will provide a sizeable sample of short-period DWD binaries to test binary formation theories and validate SNIa formation channels (e.g., Nelemans et al. 2001, 2004; Rebassa-Mansergas et al. 2018). Moreover, such a large number of individually resolved sources spread all over the Galaxy will allow us to map the Milky Way in GWs and precisely measure structural parameters such as the scale radii of the bulge and the disk (Adams et al. 2012; Korol et al. 2018). When combining GW and optical measurements for DWDs with optical counterparts we will also be able to derive the mass of the bulge and the disk component of the Galaxy (Korol et al. 2018). DWDs are so common in the Milky Way that their unresolved signals will form a background for the LISA mission (e.g., Robson & Cornish 2017). This background contains information on the overall stellar population in the Milky Way and can be also used to derive the Milky Way's parameters, such as the disk scale height (Benacquista & Holley-Bockelmann 2006). Finally, LISA will allow us to study the population of DWDs in the Milky Way's globular clusters, which is difficult to detect in the optical because of the intrinsic faintness and crowdedness of DWDs in such a dense environment (Benacquista et al. 2001; Willems et al. 2007; Kremer et al. 2018).

Previously, the detectability of DWDs has been exclusively assessed in the Milky Way, while extra-galactic DWDs were only considered to be a contribution to the background noise (e.g., Kosenko & Postnov 1998; Farmer & Phinney 2003). In this Letter we focus for the first time on the properties of extra-galactic DWDs that can be resolved by LISA in the Local Group, and especially in the Large and Small Magellanic Clouds (LMC and SMC), and M31 (the Andromeda galaxy). We show that LISA will detect binaries with the shortest periods and highest total masses, and therefore double-degenerate SNIa progenitors. As discussed in Rebassa-Mansergas et al. (2018), these are difficult to find with optical telescopes in the Milky Way. Essentially, they are too faint to be identified from Hα double-lined profiles in spectra and their eclipses are too short when considering the typical cadence of observations of optical sky surveys such as *Gaia*. Therefore, LISA might be the best tool to facilitate the statistical studies of these systems.

In this Letter, we forecast the parameter space of DWDs accessible through GW observation located at the distance of SMC, LMC, and M31 (Section 2). We use a synthetic population to quantify the number of detection for M31 (Section 3). In Section 4 we present our conclusions.

2. Maximal Distance

In this section we consider an illustrative example of a monochromatic DWD binary; i.e., a binary whose orbital period decay due to GW emission is too small to be measured during the mission lifetime. A monochromatic assumption is justified when interested in the signal-to-noise ratio (S/N) only, as was already tested in Korol et al. (2017).[1] Note, however, that the measurement of the orbital period decay is essential in order to recover the binary chirp mass and the distance from GW data. For a monochromatic source the S/N can be

[1] We also specifically tested the monochromatic assumption for the Andromeda population (Section 3). We find that the monochromatic assumption typically overestimates the S/N by 0.4.

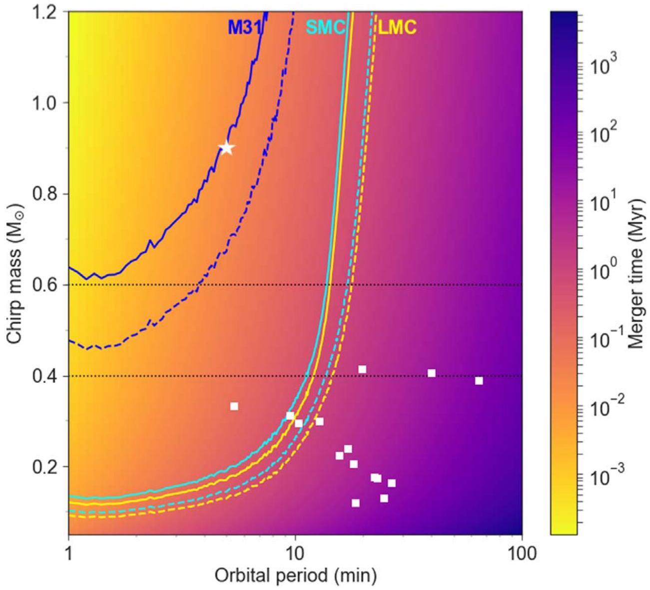

Figure 1. Curves of sky- and inclination-averaged $S/N = 7$ in orbital period-chirp mass space evaluated at the distances of the LMC, SMC, and M31 for 4 years (solid) and 10 years (dashed) mission lifetime. The color represents the merger time. White squares are known Galactic GW sources (DWDs and AM CVns), and the white star is our test binary.

estimated as (e.g., Maggiore 2008)

$$S/N = \mathcal{A}\, F(\iota, \theta, \phi, \psi) \sqrt{\frac{T_{\rm obs}}{S_{\rm n}(f)}}, \tag{1}$$

where $\mathcal{A}$ is the amplitude of the GW signal, $F(\iota, \theta, \phi, \psi)$ is a function that accounts for the instrument response to the binary inclination ι and sky position (θ, ϕ) with respect to the detector and polarization angle ψ averaged over one LISA orbit (Cornish & Larson 2003, Equation (42)), $T_{\rm obs}$ is the observation time, and $S_{\rm n}(f)$ is the total noise spectral density (instrument + Galactic background) at the binary frequency $f = 2/P$, with P being the binary orbital period. The amplitude can be computed using the quadrupole approximation as

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

where $\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$ is the chirp mass, and d is the distance (e.g., Maggiore 2008). We draw ψ randomly from a flat distribution between $[0, \pi]$. We adopt the sky- and inclination-averaged noise curve, $S_{\rm n}(f)$, corresponding to the LISA mission design accepted by ESA plus the Galactic background computed for the nominal (solid lines) and extended (dashed lines) mission duration of 4 years and 10 years, respectively (Amaro-Seoane et al. 2017). Finally, we average the S/N over the inclination angle ι and the position in the sky (θ, ϕ). Equation (2) shows that the strength of the signal mainly depends on three binary parameters: f (or P), $\mathcal{M}$, and d. Thus, we study the detectability of DWDs with LISA as a function of these parameters.

In Figure 1 we plot in $P - \mathcal{M}$ space the sky- and inclination-averaged curves of $S/N = 7$ at the distance of the LMC (yellow), SMC (cyan), and M31 (blue) for 4 years (solid) and 10 years (dashed) mission lifetimes. Thus, the areas above the curves delimit the parameter space detectable by LISA in these galaxies. At the distances of the LMC and SMC, LISA will be sensitive to DWDs with chirp masses $>0.1\,M_\odot$[2] when the orbital period $<$20 minutes, whereas at the distance of M31 LISA will be sensitive only to binaries with $\mathcal{M} > 0.5\,M_\odot$ and $P < 10$ minutes. The white star shows a typical binary detectable at the distance of M31 (Figure 3) with $\mathcal{M} = 0.9\,M_\odot$ and $P = 5$ minutes (hereafter our test binary). Although the binary population synthesis model by Korol et al. (2017) predicted only a few of such binaries in the Milky Way, they would certainly be detected by LISA with precise measurement of their chirp mass and distance (e.g., Rebassa-Mansergas et al. 2018). The color contour in Figure 1 shows the binary merger time:

$$\tau \simeq 1\ {\rm Myr} \left(\frac{P}{12\ {\rm minutes}}\right)^{8/3} \left(\frac{\mathcal{M}}{0.3\,M_\odot}\right)^{-5/3}. \tag{3}$$

Thus, Figure 1 reveals that DWDs accessible to LISA in the three considered galaxies will merge in $<$1 Myr. The two horizontal lines at $\mathcal{M} = 0.6, 0.4\,M_\odot$ correspond to binaries with a total mass (M) equal to the Chandrasekhar mass when adopting, respectively, equal mass and $m_2/m_1 = 0.18$. This value is the minimum mass ratio for binaries with $M > 1.38\,M_\odot$ in the Korol et al. (2017) catalog. Note that $\mathcal{M} = 0.6, 0.4\,M_\odot$ are the lower bounds of the parameter space corresponding to double-degenerate SNIa progenitors. Finally, the white squares are known Galactic GW sources (DWDs and AM CVns) from Kupfer et al. (2018), showing the part of parameter space explored so far at optical wavelengths. In particular, those with the shortest periods (HM Cnc, V407 Vul, ES Cet, and SDSS J0651) could be detected by LISA if placed at the distance of LMC and SMC. On the other hand, the parameter space accessible in M31 is currently unprobed.

Next, we consider a test binary (white star in Figure 1) to assess the maximal distance detectable by LISA. Figure 2 represents the sky- and inclination-averaged S/N in the distance-orbital period parameter space for fixed $\mathcal{M} = 0.9\,M_\odot$ (left panel) and in distance-chirp mass parameter space for fixed $P = 5$ minutes (right panel). As a reference we indicate the distances of LMC, SMC, M31, and the radius of the Local Group with dashed horizontal lines. The black solid line shows the LISA detection threshold of 7. The area below the curve represents the parameter space detectable by LISA and shows that LISA has the potential to detect DWDs with very short periods and high chirp masses, like our test source, almost up to the border of the Local Group.

3. DWD Detections in Andromeda

Here we address quantitative estimates for the number of detections in the Andromeda galaxy. Properties of extra-galactic DWDs are not known, as not a single DWD has been observed outside of our Galaxy. However, because M31 is a spiral galaxy similar to the Milky Way, we can extrapolate the properties of the Galactic population of DWDs to that of Andromeda. To obtain a mock population we use the binary population synthesis code SeBa (Portegies Zwart & Verbunt 1996; Toonen et al. 2012) that has been employed to forecast LISA detections in the Milky Way (Amaro-Seoane

[2] Note that in this Letter we do not consider AM CVn systems that typically have $\mathcal{M} < 0.1\,M_\odot$.

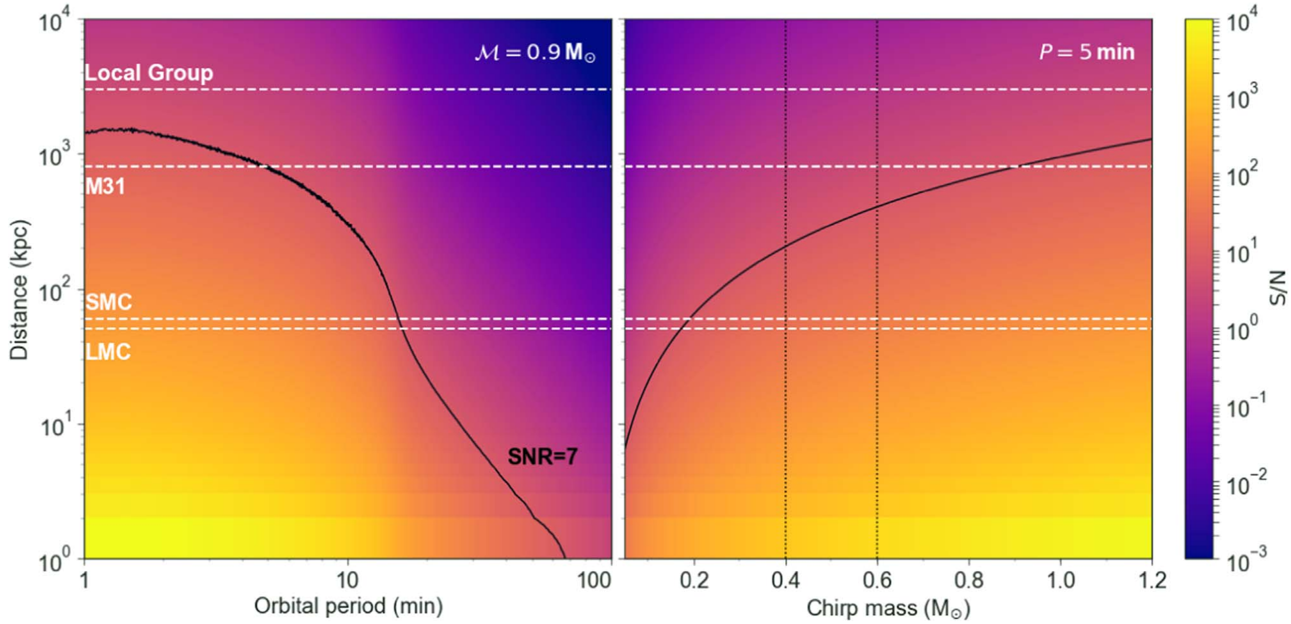

Figure 2. S/N for the test DWD in the distance-orbital period for $\mathcal{M} = 0.9\,M_\odot$ (left) and distance-chirp mass for $P = 5$ minutes (right) space after nominal 4 years of observations. The black solid line represents the iso-S/N contour of 7. Dashed horizontal lines mark the distance of the LMC, SMC, M31, and the border of the Local Group.

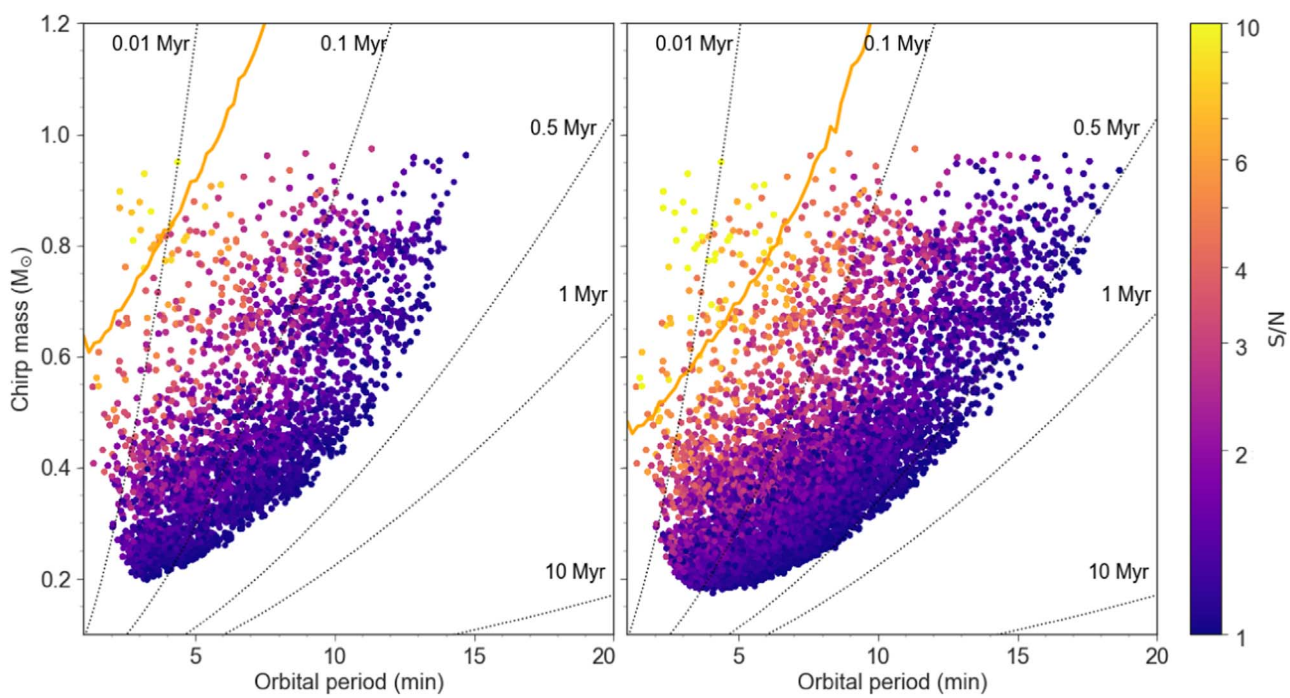

Figure 3. DWDs in M31: after 4 years (left panel) and after 10 years (right panel) observation time with LISA. The orange solid line represents the sky- and inclination-averaged LISA detection threshold of 7. Black dotted lines are iso-merger contours.

et al. 2017; Korol et al. 2017). The initial stellar population is obtained assuming the Kroupa initial mass function, a flat binary mass-ratio distribution, a log-flat distribution for the binary semimajor axis, a thermal distribution for the orbit eccentricity, an isotropic distribution for binary inclination angles, and a constant binary fraction of 50% (Kroupa et al. 1993; Raghavan et al. 2010; Duchêne & Kraus 2013). We use the $\gamma\alpha$ prescription for the common envelope phase, calibrated on observed DWDs in the Milky Way (Nelemans et al. 2001). The sensitivity of our model to these assumptions is addressed in Korol et al. (2017) and Toonen et al. (2017). Finally, we assume the total stellar mass of Andromeda to be twice that of the Milky Way (e.g., Sick et al. 2015). For all binaries we assign galactic coordinates $(l,\ b) = (121,\ -21)$, $d = 800$ kpc, and an inclination angle randomly drawn from a uniform distribution in $\cos\iota$. We compute the S/Ns as described in Section 2.

We find 17 (60) binaries with $\mathrm{S/N} \geqslant 7$ in 4 (10) years of the mission (see Figure 3). In particular, the majority are CO+CO and the small fraction are CO+ONe DWDs. These detections will clearly appear in the LISA sky as an over-density located at the position of M31, far from the Galactic disk. Once these sources are identified, a careful modeling of the waveform would yield an independent confirmation of their extra-galactic origin as well a novel determination of Andromeda distance. Specifically, for binaries in M31 the distance can be determined up to 20%, using Equation (29) from Takahashi & Seto (2002). All of the binaries detectable by LISA ($S/N > 7$) will merge in less than 0.1 Myr. We also find that the LISA sample is complete for $P < 3.5$ minutes and $\mathcal{M} > 0.7\,M_\odot$. The completeness is $\sim$50% for DWDs with $P < 4.5$ minutes and $\mathcal{M} > 0.6\,M_\odot$, and drops to $\sim$10% for $P < 10$ minutes and $\mathcal{M} > 0.6\,M_\odot$. Given the completeness and the merger time across the sample we will be directly able to estimate the DWD merger rate in M31. Note that here we implicitly assume that all DWDs with chirp mass $>0.6\,M_\odot$ merge (e.g., Shen 2015). However, it is also possible that at orbital periods of 2–3 minutes a DWD starts mass transfer, but how frequent this is depends on the uncertainties in mass transfer physics (Marsh et al. 2004).

Figure 3 shows that there are many more DWDs lying just below the detection threshold. A possible way of increasing the number of detections is to perform a targeted search for signals at the position and distance of M31. Specifically, the results of this study can be used to construct priors for the frequency and chirp mass. We also suggest that using optical measurements for M31 as priors on the coordinates and distance can be advantageous.

4. Conclusions

In this Letter we have explored the detectability of DWDs outside of the Milky Way. We proved that LISA has the potential to detect binaries in neighboring galaxies LMC, SMC, and M31. We find that, in the LMC and SMC, LISA can detect DWDs with $P < 20$ minutes and $\mathcal{M} > 0.1\,M_\odot$, while in M31 LISA will be sensitive to those with $P < 10$ minutes and $\mathcal{M} > 0.6\,M_\odot$. Using an example DWD with $P = 5$ minutes and $\mathcal{M} = 0.9\,M_\odot$, we showed that binaries with such characteristics can be detected up to 1 Mpc distance, i.e., within the large volume of the Local Group. In the Andromeda galaxy we found a dozen to several tens of DWDs above the LISA detection threshold for 4 and 10 years mission. This gives optimistic prospects for detecting other kinds of stellar-type GW sources such AM CVns and ultra-compact X-ray binaries, which will likely have an electromagnetic counterpart. A large fraction of extra-galactic DWDs detectable by LISA will have total mass exceeding the Chandrasekhar mass limit and will merge in less than 1 Myr, meaning that LISA has the potential to provide SNIa merger rates across the Local Group.

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