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PREPARING FOR LISA WITH CFH TELESCOPE: SYNERGIES BETWEEN GRAVITATIONAL WAVES AND ELECTROMAGNETIC OBSERVATIONS

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Abstract. Very short period double white dwarfs (DWDs) in our Milky Way (MW) will be one of the most numerous classes of sources detectable by the upcoming *Laser Interferometer Space Antenna (LISA)*, with its scientific return strongly enhanced by the availability of electromagnetic (EM) counterparts. This makes the present an ideal opportunity to chart the population of (potential) LISA sources across the MW, exploiting the deep u-band sensitivity of the Canada-France-Hawaii Telescope (CFHT). Our aim is to develop a strategy to identify *LISA* source candidates in multiband photometric surveys, in order to select targets for further follow-up and identification. Starting from a theoretical population of Galactic WDs, combined with a consistent cooling model for the evolution, we construct a synthetic EM catalogue of WD detections. We find that the resulting magnitude and colour distributions can help us distinguish *LISA* source candidates from the broader white dwarf population: the former populate a specific area in colour-colour diagram, with little contamination from single systems and wide binaries. This, in turn, can enable the definition of the optimal strategy for a new survey to be proposed to the CFHT community.

Keywords: gravitational waves – LISA – white dwarfs – binaries: close – techniques: photometric

1 Introduction

The *Laser Interferometer Space Antenna (LISA)* (Colpi et al. 2024), expected to launch in 2035, will detect gravitational waves (GWs) in the milliHz band, a range densely populated by inspiralling double white dwarfs (DWDs) with orbital periods lower than $\sim$ 90 minutes (Nelemans et al. 2001). *LISA* is predicted to detect thousands of these systems, opening the door to a complete view of close DWDs in the whole Milky Way (MW) (Amaro-Seoane et al. 2023). Despite their relatively low luminosity, these systems can also be observed through their electromagnetic (EM) emission, with major WD surveys as the spectroscopic Sloan Digital Sky Survey (SDSS) (Kepler et al. 2016) and the *Gaia* astrometric and spectroscopic survey (Gentile Fusillo et al. 2021). Identifying close binaries is more challenging because a deeper follow-up analysis is needed, either with spectroscopy, as done by the extremely low-mass (ELM) Survey (Brown et al. 2020), or with high-cadence photometry, such as the Zwicky Transient Factory (ZTF) (Graham et al. 2019).

Studying tight DWDs is crucial for understanding stellar and binary evolution processes and the scientific return could be substantially enhanced by combining GW and EM measurements. Indeed, EM data can improve the accuracy of GW parameters, enable the measurement of individual component masses (Shah & Nelemans 2014) and potentially infer the presence of tidal interactions (Leslie et al. 2025), thereby offering key insights into Type Ia supernova progenitors. In addition, a reliable set of well-characterised EM binaries would also provide significant benefits for *LISA* data analysis (Littenberg & Lali 2024).

With a scheduled launch in 2035, now is the time to prepare the systematic search for these systems. In preparation for *LISA*, our goal is to expand the list of *LISA* candidate systems that exhibit detectable EM signatures, using their characteristic nature of ultra-compact DWDs. We present a method for their identification in photometric data, paving the way for tailored EM surveys complemented by follow-up studies. We simulate a survey strategy for the Canada France Hawaii Telescope (CFHT), a 3.6-meter telescope in Maunakea that is particularly relevant for this science case, as its wide-field imager Megacam can observe deeply in the u-band.

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2 Methods

We investigate the EM signatures of WDs in the u, g, and r photometric bands by building a synthetic WD catalogue including single WDs, DWDs, and white dwarf-main sequence (WDMS) binaries with a faint MS star. Indeed, in the latter two cases, the fluxes combine, appearing as a single source in photometric surveys. We employ the binary population synthesis code COSMIC (Breivik et al. 2020) to generate a population of WDs in the MW, either as single stars or as DWDs or WDMS binaries. We maintain the default parameters of COSMIC for all the runs and vary the stellar metallicity across 25 distinct values. The simulated population provides the orbital period and formation time of DWDs and WDMS binaries along with the intrinsic properties of individual stars. Particularly relevant is the core composition of the WDs: the majority of them have a carbon–oxygen (CO) core, with a small fraction of oxygen–neon (ONe) WDs and helium-core (He) WDs. All of these physical features strongly influence the subsequent evolution up to the present time and the resulting EM signature.

We assign coordinates to each system following a three-component model of the MW, with a bulge, halo, and disc. We refer to the spatial distribution of Nelemans et al. (2001) for the disc, defining a scale height of 300 pc; to Ruiter et al. (2009) for the halo; and to Korol et al. (2017) for the bulge. For the disc and the bulge, we implement an overall star formation history derived from a cosmological hydrodynamic simulation of a MW-like galaxy, employed also in Lamberts et al. (2019), that accounts for the evolution in time of the mean metallicity. We assume a halo composed of stars born in the first ~ 1.5 Gyr with low metallicity.

We let the DWDs evolve through GW emission (Peters & Mathews 1963), assuming circular orbits, and we discard the ones that coalesced before the present time. We neglect DWD interactions but remark that strong tidal torques can significantly modify the final population by slowing the evolution and causing binaries to outspiral (Toubiana et al. 2024). The final population of systems in the MW at the present time comprises $\sim 8.7 \times 10^8$ DWDs, $\sim 2.5 \times 10^9$ WDMS binaries, and $\sim 5.3 \times 10^9$ single WDs.

The WD cooling time is highly multi-faceted and primarily governed by the core composition, the mass, and the luminosity (Althaus et al. 2010). In our work, we employ the cooling sequences for pure H atmosphere WDs from La Plata Stellar Evolution group and Pulsation Research group (2024), which cover the mass range 0.2 - 1.3 $M_\odot$, and the full cooling computations from Althaus et al. (2013) for extreme low-mass WDs. We acknowledge that there might be some discrepancy in treatment of the latter, as the absolute magnitude values are computed assuming $0.2 M_\odot$, but their fraction over the whole dataset is negligible. By interpolating these curves in a continuous range of mass and age, we extract the WD properties at the present time for all the WDs in our population.

The main sequence stars are approximated with a black body spectrum based on the effective temperature and stellar radius provided by COSMIC. We apply the filter response curve for SDSS (Doi et al. 2010) to obtain the absolute magnitudes in the u, g, and r bands and we includ in our population only the binaries in which the WD is at least 150% more luminous in absolute magnitude than the companion star. For these systems, together with all the DWDs, we compute the total absolute magnitude by summing the fluxes of the two components in different bands.

Finally, we obtain the observed emission of each WD by computing the apparent magnitude, $u_{\rm app}$, as

$$u_{\rm app} = u_{\rm abs} - 5 + 5 \log d + A_u, \tag{2.1}$$

where $u_{\rm abs}$ is the absolute magnitude in the u filter, d is the distance from the WD in parsecs, and A_u is the Galactic extinction in the u band. In order to estimate the latter, we rely on the three-dimensional map of MW dust reddening generated by Green et al. (2019), combined with the all-sky extinction map provided by Dharmawardena et al. (2024) to complete the sky coverage.

3 Results

As WDs are typically hot astrophysical objects, the u filter becomes particularly useful for studying their emission, together with g and r filters to have colour combinations. We construct a mock dataset of all-sky EM observations in these bands by assuming an observed magnitude limit of 24.54 in the u and r bands and 25.07 in the g filter, consistent with the capabilities of instruments such as MegaCam of CFHT. Within these magnitude limits, the simulated EM catalogue contains $\sim 1.51 \times 10^6$ DWDs, $\sim 1.19 \times 10^5$ WDMS binaries, and $\sim 6.65 \times 10^6$ single WDs.

We start investigating the properties of our synthetic catalogue by looking at the absolute u magnitude and the u–g colour. In the left panel of Fig. 1, we plot the density distribution of the sources, differentiating between possible LISA sources (in magenta) and the rest of the sample (in blue). We consider sources with GW emission between $[10^{-4} - 0.1]$ Hz to be possible LISA sources ($\sim 1.1 \times 10^5$ systems in our catalogue). The GW frequency of a circular binary system is twice the orbital frequency for a monochromatic signal. The total population also contains DWDs at frequencies lower than the LISA band, single WDs, and WDs in WDMS binaries. It is remarkable how the high frequency DWDs stand out from the broader population. This is because most of them have undergone binary interactions and stellar stripping and are characterised by lower mass values and larger radii, which directly lead to brighter observed emissions. In addition, LISA sources are found to be younger WDs and therefore are intrinsically more luminous (Lamberts et al. 2019). These distinctive traits can facilitate the identification of LISA candidates among all the EM observations, enabling a targeted analysis of a particular area in the magnitude-colour plot.

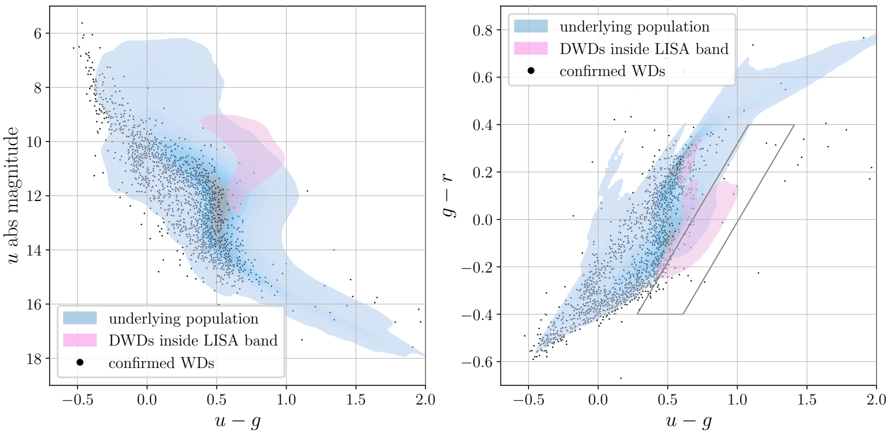

Fig. 1. Density distribution in magnitude-colour (left) and colour-colour space (right) of our synthetic catalogue highlighting potential LISA sources (magenta) with respect to the rest of the remaining systems (blue). The black points are confirmed WD observations.

We validate the simulated catalogue with WD candidates from *Gaia* Data Release 3 (Gentile Fusillo et al. 2021), selecting a highly reliable sample of WDs that have additional SDSS spectroscopy. The observations in the SDSS system are displayed in Fig. 1 as black dots. Their location in the u versus u–g diagram aligns with our synthetic population, supporting the validity of our theoretical framework.

In the broader context of photometric surveys, where distance measurements are not available, we turn our attention to colour-colour plots, which allow us to display data based only on their observed magnitudes. The right panel of Fig. 1 shows the density distribution of our synthetic population in the u–g versus g–r colour space, with LISA candidates emphasised as before. By applying specific colour cuts shown in Fig. 1 (-0.4 < g–r < 0.4 and -1.01 < g–r - u–g < - 0.68), we found that the major contribution in that region comes from LISA candidates (63%, $\sim$ 65000 systems), with a smaller contribution (31%, $\sim$ 32000 systems) from DWDs at GW frequencies from $\sim 10^{-7}$ Hz to $\sim 10^{-4}$ Hz, which are still relevant when studying the continuum of short-period DWDs. The LISA candidates inside the selected area are $\sim$ 57% of all the sample without colour selection. Only a minimal fraction comes from single WDs (5%), and even less is from ultra-wide DWDs (0.1%), while we have almost no contribution from WDMS binaries, as their colour distribution covers markedly different values. Between the high frequency DWDs, we estimate $\sim$ 2000 of them will be detectable by LISA in 10 years of observation time using the GBGPU package (Katz 2022).

Motivated by the prospect of a future survey with CFHT, we simulate an observing strategy for this instrument in order to provide realistic estimates of the expected detections. We account for the telescope's sky coverage by restricting to equatorial declinations within 10° and 80°. In addition, we define a surveyed region within $2.5° < |l| < 20°$ in Galactic latitude l, thereby excluding the halo, where the number density of WDs is low, and the thinner disk, where the dust extinction affects significantly the detection efficiency. The adopted magnitude limits ($u, r < 24.54$; $g < 25.07$) correspond to an exposure time of 600s per filter. By applying these conditions, we obtain an overall observing time of 340 nights and we find 470 detectable LISA sources inside our colour selection. We compare this set-up with an alternative strategy: we increase the thickness of the surveyed area around the Galactic disk ($2.5° < |l| < 45°$), and we tighten the magnitude limit to $u, r < 24.12$; $g < 24.67$, corresponding to a single exposure time of 300s. The observing time required is 380 nights, with around 510 detectable LISA sources within the colour cuts. Tab. 1 summarises the results. Since both strategies deliver comparable detection numbers, a more detailed analysis is necessary to optimise the survey design.

Magnitude limit	Sky area	Total time	Number of detections
$u, r < 24.54$; $g < 25.07$	$2.5^\circ < l < 20^\circ$	~ 340 nights	~ 470 LISA sources
$u, r < 24.12$; $g < 24.67$	$2.5^\circ < l < 45^\circ$	~ 380 nights	~ 510 LISA sources

Table 1. Summary of the simulated survey strategies.

4 Conclusions

We have generated a synthetic population of Galactic WDs, both as single stars and in binary systems and we have computed magnitudes and colours from full evolutionary models of WDs. From this sample, we have constructed a mock EM catalogue, while also accounting for dust extinction, in order to investigate the density distribution in magnitude-colour and colour-colour space, focusing on the u, g, and r filters. We find that high frequency DWDs, which are potential LISA sources, clearly separate from the underlying population of wider DWDs, single stars, and WDMS binaries and we applied a colour selection to maximise this separation. In this targeted area in the colour-colour diagram, we find that $\sim 63\%$ of all observations come from DWDs in the LISA band, with a smaller fraction from binaries with orbital frequencies down to 10^{-7} Hz and a negligible contamination from single systems, wide DWDs, or WDMS binaries. By simulating a survey with CFHT, we estimate ~ 500 observations of LISA sources within our colour selection, with a required observing time of $\sim$450-500 nights. These results pave the way for tailored strategies aimed at identifying potential LISA sources in photometric surveys, delivering targets for subsequent follow-up studies.

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