Prospects for observing ultra-compact binaries with space-based gravitational wave interferometers and optical telescopes.

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\section{INTRODUCTION}

A variety of detector concepts for space-based gravitational wave interferometers have been proposed, the most well studied concept being LISA\textsuperscript{[1]}. It was understood early on that the most numerous source class radiating in the band covered by LISA-like detectors will be the galactic population of ultra-compact binaries (UCBs) comprised of pairs of stellar remnants: white dwarfs, neutron stars or black holes. The gravitational radiation from these UCBs will be the dominant signal in the frequency band covered by LISA-like detectors.

Early estimates of the composite signal from the UCBs showed that the signals of the vast majority of the galactic binaries will overlap and be unresolvable from one another, forming a limiting foreground (or “confusion noise”) for space-based gravitational wave detectors. Later studies based on population synthesis demonstrated that the signals of the vast majority of the galactic binaries will overlap and be unresolvable from one another, forming a limiting foreground (or “confusion noise”) for space-based gravitational wave detectors. Later studies based on population synthesis showed that the signals of the vast majority of the galactic binaries will overlap and be unresolvable from one another, forming a limiting foreground (or “confusion noise”) for space-based gravitational wave detectors.

Detailed data analysis studies have shown that $\sim 10^4$ individual binaries could be resolved out of the foreground by a gravitational wave observatory like LISA\textsuperscript{[2,3]}. This builds on previous work\textsuperscript{[4]}. Demonstrating the feasibility of follow-up observations for high-frequency UCB sources, we estimate the total number of multi-messenger sources by beginning with a population synthesis model of the galaxy\textsuperscript{[5,6]}. Complete with optical magnitudes. From this we produce a magnitude limited source catalog, then estimate how well each system will be localized on the sky by different gravitational wave detector configurations. Using hundreds of Monte Carlo realizations over the spatial distribution of the galaxy and the UCB orientations, we find tens to hun-
dreds of sources that can be observed both electromagnetically and gravitationally.

The information encoded about the UCBs in each of the two spectrums is highly complementary, enabling tests of general relativity, full measurement of the physical parameters enabling constraints on binary synthesis channels, and new methods of probing the close interaction dynamics of the compact stars (Cutler et al. 2003; Stroeer et al. 2005).

## 2 DETECTORS

For a gravitational wave observatory, the limiting sensitivity as a function of frequency is dominated at low frequencies by acceleration noise $S_a$, while the “floor”, where the detector is most sensitive, is dominated by position measurement noise $S_p$. Table 1 contains the parameters used for the detector configurations in this study. These parameters can be used to compute the noise power spectral density

$$\begin{align*}
S_n(f) &= \frac{S_{gal}(f)}{f^2} + 4(3 + 2 \cos u + \cos 2u)S_a/(2\pi f)^4, \\
& \quad \text{where } u = 2\pi f/c, \quad S_{gal} \text{ is the contribution to the instrument noise from the unresolved UCB foreground (Timpano et al. 2006).}
\end{align*}$$

The configurations we will highlight correspond to the classic LISA design ($\ell = 5$ Gm), as well as two shorter arm-length configurations ($\ell = 2$ Gm and $\ell = 1$ Gm) in order to cover a variety of plausible mission configurations. The 1 Gm configuration is similar to the eLISA mission being considered by the European Space Agency (Amaro-Seoane et al. 2012). We use an observation time of two years for each configuration.

This suite of detectors provides a broad palette to illustrate the observational capabilities of these instruments with regards to the UCBs. A classic depiction of the performance for these interferometers is a plot of the average sensitivity curve in strain spectral density versus frequency (Larson et al. 2000), as shown in Fig. 1. The eLISA concept is the only one which uses a 4-link configuration. The doppler ranging between each spacecraft in the constellation is accomplished using two laser links. Thus the 4-link design is a single-vertex interferometer, while the 6-link designs allow for three (coupled) interferometers. This difference accounts for an additional improvement in the 6-link sensitivity curves by a factor of $\sim \sqrt{2}$ at frequencies where the UCBs are found.

### 3 DISCOVERING NEW VERIFICATION BINARIES

The focus of this work is to study the population of detectable UCBs in the context of multi-messenger astronomy. We will focus on the sources detected via GWs which could potentially be identified electromagnetically. There is a separate class of UCBs, the “verification binaries,” which are known low-frequency GW sources with AM CVn serving as the archetype. There are $\sim 30$ known verification binaries, $\sim 5 - 10$ of which could be identified by the GW detectors considered here, with sources still being discovered (Nelemans et al. 2011; Roelofs et al. 2007; Brown et al. 2011). This study does not include the known verification binaries in the galaxy catalogs. Furthermore, many of the AM CVn systems would not be localized well enough by the GW measurement alone to warrant simple electromagnetic follow-up observations.

### 3.1 Binary selection

The UCB population model is essentially identical to that found in Nelemans et al. (2004), so the positions and ages of the systems are based on the Boissier & Prantzos (1999) Galactic model. We use the white dwarf cooling tracks based on Hansen (1999) as shown in the Appendix of Nelemans et al. (2004). We convert the luminosities to V-band magnitudes using zero-temperature white dwarf radii and simple bolometric corrections based on the effective temperature. This should suffice for this initial estimate of the potentially detectable population, but can be improved using detailed WD cooling models in the future. We determine the absorption as in Nelemans et al. (2004) based on the Sandage (1972) model, but correcting for the fact that the dust is more concentrated than the stars, so we use 120 pc as scale height for the absorption.

To construct the magnitude limited catalog, we begin with the entire binary population in the synthesized galaxy. The limiting apparent magnitude of a telescope is a function

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**Table 1.** Gravitational wave detector configurations used in this study. Configuration 1 corresponds to eLISA. Configuration 5 is the classic LISA design. All simulations were for two year mission lifetimes.

<table>
<thead>
<tr>
<th>Config.</th>
<th>$\ell$ (m)</th>
<th>$\sqrt{S_n}$ (m/s$^2$/\sqrt{Hz})</th>
<th>$\sqrt{S_p}$ (m/$\sqrt{Hz}$)</th>
<th>Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$1 \times 10^9$</td>
<td>$4.5 \times 10^{-15}$</td>
<td>$11 \times 10^{-12}$</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>$2 \times 10^9$</td>
<td>$3.0 \times 10^{-15}$</td>
<td>$10 \times 10^{-12}$</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>$5 \times 10^9$</td>
<td>$3.0 \times 10^{-15}$</td>
<td>$18 \times 10^{-12}$</td>
<td>6</td>
</tr>
</tbody>
</table>

**Figure 1.** Sensitivity curve for each of the detector configurations in Table 1. The solid lines show the sensitivity set by the measurement noise while the dashed curves include an estimate of the UCB confusion-limited foreground. Over-plotted are the 1000 loudest binaries in our simulated catalog (green crosses), and the known verification binaries (blue stars).
of the aperture \( D \), the exposure time \( t \), and the properties of the detector used for imaging and photometry [Schaefter 1996; Howell 1989]. A rudimentary fit to the limiting magnitude \( m \) using a telescope of aperture \( D \) (in m) and for exposure time \( t \) (in seconds) is given by \( m = 19.6 D^{0.675} t^{0.025} \).

Using commercial CCD detectors, a \( D = 0.5 \) m telescope will reach a photometric magnitude \( m \approx 21 \) in \( t \approx 75 \) s, where as a \( D = 1.0 \) m telescope will reach the same magnitude in \( t \approx 20 \) s. This paper examines the role of small to large aperture telescopes by examining a broad range of limiting magnitudes; lower bounds of \( m = 18–24 \) were chosen as the electromagnetic cutoff. All sky survey instruments such as LSST could further improve the number of candidates. The single exposure limit for LSST is expected to be \( m \approx 24 \), whereas the magnitude limit of the final stacked image is expected to be around \( m \approx 27 \) [Ivezik et al. 2011].

### 3.2 Gravitational wave detector response

From the magnitude-limited catalog, we determine the number of “bright” UCBs that will be well measured by the GW detector. To do so we must first estimate the confusion noise for each configuration. The instrument response to the galactic foreground is constructed by generating and co-adding waveforms for each source in the full simulated galaxy catalogue using the fast-slow decomposition in Cornish & Littenberg (2007). The confusion noise, \( S_{\text{conf}} \), is empirically determined from the simulated data by iteratively removing sources brighter than a running estimate of the background. This procedure is first discussed in Timpano et al. (2006) with an improved implementation used here as in Nissanke et al. (2012).

With the confusion noise incorporated into the detector sensitivity curves, we determine how well the GW detector can measure the source parameters of a UCB waveform, using the well-worn Fisher Information Matrix \( \Gamma_{ij} \) (Cutler & Flanagan 1994), the inverse of which approximates the covariance matrix. There is no shortage of literature highlighting short-comings of the Fisher to approximate GW parameter errors e.g., Vallisneri (2008). However, given the scope of the problem we are addressing (hundreds of ground-based optical telescopes, we perform the analysis with \( \Gamma_{ij} \)).

For a binary to be considered “well localized” we require that the 63% confidence interval of the sky-location posterior distribution function subtends an area on the celestial sphere below some threshold \( d\Omega \). To bracket the capabilities of ground-based optical telescopes, we perform the analysis with \( d\Omega \leq 1 \) and \( \leq 10 \text{ deg}^2 \). We estimate the area of the sky-location error ellipse using the full covariance matrix found by inverting \( \Gamma_{ij} \) (Lang & Hughes 2008).

The number of well localized, bright binaries is computed for hundreds of realizations where we Monte Carlo over the orientation of each binary, as well their location within the Galaxy. For the orientation, we draw the inclination \( \iota \) from a uniform distribution \( \cos \iota = U[-1, 1] \), and the polarization angle \( \psi \) and initial phase \( \varphi \) from \( U[0, 2\pi] \). We find up to a several hundred GW sources will be viable candidates for electromagnetic follow-up searches, depending on the depth of EM survey and the GW detector characteristics (See the left-hand panel of Figs. 2 and 3).

### 3.3 EM detection strategies

We now consider how to select candidates for follow-up observations from the full GW catalog. Pointing telescopes at all of the GW sources localized within the adopted threshold would be inefficient, as we find between \( 10^3 \) and \( 10^4 \) GW sources in the full catalog will meet the \( d\Omega \leq 10 \text{ deg}^2 \) threshold, while \( \lesssim 10\% \) are likely to be brighter than \( m = 24 \), and only \( \lesssim 1\% \) pass the \( m \leq 20 \) cut.

Additional considerations need to be made to increase the efficiency of follow-up observing campaigns. We illustrate two simple ways to isolate the GW sources that may be electromagnetically observable. These suggestions are supported by calculations shown in Table 2.

First, the large majority of UCB sources are confined within the galactic plane. Conversely, the magnitude limited catalogs sample the local galaxy, which is much more uniformly distributed on the celestial sphere. Therefore, as a rough cut on the GW catalog, any binaries that are well localized but out of the galactic plane are good candidates. These are additionally attractive sources, as there will be less optical background and extinction against which the observing campaign will have to compete. We find between \( \sim 20\% \) and \( \sim 50\% \) of the well-localized binaries in the \( 20^\text{th} \) to \( 24^\text{th} \) magnitude-limited catalogs have galactic latitudes \( |b| \gtrsim 20^\circ \), while that fraction is reduced to \( \sim 1\% \) for the full GW catalog. A uniform distribution of stars on the celestial sphere would have 66% of the stars with \( |b| \gtrsim 20^\circ \).

The other strategy for identifying optical counterparts relies on estimates of the distance to the galactic binary. Typical UCB sources will undergo very little evolution of their orbital period during a space-borne GW detector’s lifetime. Without measurement of the rate of change of the gravitational wave frequency \( f \) the GW observation only constrains the overall amplitude of the signal without decoupling the chirp-mass and the luminosity distance \( d_L \) (Schutz 1986; Stroeer & Vecchio 2006). For \( \sim 10–20\% \) of the multi-messenger sources we sufficiently constrain \( f \) and \( A \) to measure \( d_L \) to within \( 20\% \), but astrophysical effects such as tides may impact the orbital evolution and thus bias the distance estimate. For the remaining systems in the GW catalog, we can use reasonable priors on the mass and mass ratio of white dwarf binaries to put meaningful constraints on \( d_L \) from the amplitude measurement alone.

Using only the amplitude, frequency and priors on the masses constructed from the population synthesis simulation, we find that the distribution of the most likely (ML) luminosity distances \( d_L^{\text{ML}} \) is strongly peaked between 0 and 8 kpc – the distance to the galactic center – for the magnitude limited catalogs. The \( d_L^{\text{ML}} \) distributions for the full well-localized catalog with no magnitude cut is more uniformly distributed over a larger range.

Our final consideration pertains to the expected optical light curves for UCB systems identified in the GW catalog. The population synthesis galaxy in our study is restricted to detached white dwarf binaries, as opposed to interacting
reduce the total number of candidates by a factor of \( \sim R \) (Cooray et al. 2003), the minimum inclination angle with respect to the other in the binary, photometric variability is not guaranteed. The systems in the GW catalog that are best constrained are typically those at the high-frequency end of the population. This is to our advantage, because the shorter period binaries have a higher probability of eclipsing one another during an orbital cycle.

We can put an additional cut on our EM/GW catalog by requiring the binaries to be eclipsing. (See the right-hand panel of Figs. 2 and 3). From simple geometrical arguments (Cooray et al. 2003) the minimum inclination angle with respect to our line of sight that will produce eclipsing light curves is

\[
\cos(t_{\text{min}}) \sim 0.3 (f/3.5 \text{ mHz})^{2/3}
\]

assuming all binaries have mass \( M_{\text{total}} \sim 0.5 \, M_\odot \) and radius \( R_{\text{WD}} \sim 10^3 \, \text{km} \). If we only consider binaries in the multi-messenger catalog with inclination angle less than \( t_{\text{min}} \), we reduce the total number of candidates by a factor of \( \sim 3 \).

Nevertheless, we still find upwards of \( \sim 100 \) candidates for the large GW detector configurations and deep, wide field, optical surveys. Requiring eclipsing light curves significantly degrades the multimessenger potential for the 1 Gm configuration using catalogs limited to 20th magnitude and dimmer – such EM follow-up surveys could come up empty.

4 DISCUSSION

We conclude that space-based gravitational wave detectors will be useful observatories for discovering new UCBs in the galaxy that could be observed electromagnetically, though deep, wide field, optical surveys may be required to produce large catalogs. We reach this verdict by considering a range of plausible near-future space-based gravitational wave detector concepts, and assess their measurement capabilities for magnitude limited catalogs of UCBs. Magnitudes for the constituents of each binary were derived from the population.
At the pessimistic end, we consider magnitude 18 limited catalogs, and single-vertex interferometers with 1 Gm arm-lengths. The best scenario considered the classic LISA design and an optical telescope limited at 24th magnitude. The number of multi-messenger candidates was anywhere from a few to several hundreds over that range of detector capabilities. If we put on the additional constraint that the sources must be eclipsing to allow for electromagnetic observation the counts were reduced by a factor of ~ 3.

While most of the known verification binaries are AM CVn type stars, our study only considered detached white dwarf binaries, thus providing a very complimentary catalog of UCB multi-messenger systems.

This work considered a conservative approach to finding multi-messenger UCBs, with competing criteria that strongly affect the expected population of systems detectable in both spectrums. Electromagnetic detections are most strongly affected by the magnitude limit of the detection survey, a function of telescope aperture. By contrast, the gravitational wave detection catalogs of UCBs are expected to have thousands of systems in them; most will be too faint to be detectable by any electromagnetic survey. However the gravitational wave localization criterion is a strong constraint on the multi-messenger catalog. We find that wide-field surveys ($\Delta \Omega < 10^{-2}$ deg$^2$) yield more candidates than more narrow fields of view ($\Delta \Omega 
lessapprox 1$ deg$^2$) by 50-100% for the full catalogs, and by a factor of 2-4 for the eclipsing binaries.

We have estimated the number of UCB multi-messenger candidates without considering what could be done with joint GW and EM observations. Our follow-on effort will consider the science yield from joint observations of both the known verification binaries — mostly mass-transferring systems — and the close, detached binaries that will be discovered by space-borne gravitational wave detectors.

### Table 2. Multi-messenger candidates will be a minority of the spatially well-resolved GW signals. Here we enumerate the fraction of binaries that will make good candidates for electromagnetic follow-up observations. Plain numbers in the table correspond to the sky-resolution requirements (column 2), and then the fraction which are significantly above the disk ($\Omega > 10$ deg$^2$, while those in parenthesis correspond to the 1 deg$^2$ threshold. We tabulate the average number of binaries $N$ that meet the sky-resolution requirements (column 2), and then the fraction which are significantly above the disk ($|b| > 20^\circ$ - column 3), or have $d_L$ measured to within 20% (column 4), the idea being that near-by binaries are more likely to be optically detectable — proximity can be inferred by $|b|$ and/or determined through $d_L$. The columns then repeat for the $m \leq 20$ and $m \leq 24$ magnitude-limited catalogs.

| Config | Full galaxy $N$ | $|b| > 20^\circ$ | $\Delta \Omega < 20\%$ | $m \leq 20$ | $|b| > 20^\circ$ | $\Delta \Omega < 20\%$ | $m \leq 24$ | $|b| > 20^\circ$ | $\Delta \Omega < 20\%$ |
|--------|----------------|------------------|---------------------|------------|------------------|---------------------|------------|------------------|---------------------|
| 1      | 1700 (370)     | 0.02 (0.03)      | 0.60 (0.93)         | 24 (9)     | 0.44 (0.49)      | 0.16 (0.43)         | 150 (48)   | 0.22 (0.25)      | 0.26 (0.67)         |
| 2      | 7500 (2400)    | 0.01 (0.01)      | 0.34 (0.75)         | 62 (28)    | 0.48 (0.48)      | 0.08 (0.17)         | 444 (197)  | 0.22 (0.22)      | 0.16 (0.34)         |
| 3      | 12000 (6100)   | 0.01 (0.01)      | 0.27 (0.60)         | 71 (35)    | 0.48 (0.40)      | 0.07 (0.15)         | 563 (293)  | 0.22 (0.21)      | 0.14 (0.26)         |

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G. Nelemans maintains a wiki with the most up-to-date list of verification binary parameters at <www.astro.ru.nl/~nelemans/dokuwiki/doku.php?id=lisa_wiki> cited 2 September 2011.

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