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

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ABSTRACT

Space-based gravitational wave interferometers are sensitive to the galactic population of ultra-compact binaries. An important subset of the ultra-compact binary population are those stars that can be individually resolved by both gravitational wave interferometers and electromagnetic telescopes. The aim of this paper is to quantify the multi-messenger potential of space-based interferometers with arm-lengths between 1 and 5 Gm. The Fisher Information Matrix is used to estimate the number of binaries from a model of the Milky Way which are localized on the sky by the gravitational wave detector to within 1 and 10 deg$^2$ and bright enough to be detected by a magnitude limited survey. We find, depending on the choice of GW detector characteristics, limiting magnitude, and observing strategy, that up to several hundred gravitational wave sources could be detected in electromagnetic follow-up observations.

Key words: galaxy: stellar content — gravitational waves — binaries: close — white dwarfs

1 INTRODUCTION

A variety of detector concepts for space-based gravitational wave interferometers have been proposed, the most well studied concept being LISA (Bender et al 1998). 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 (Evans et al 1987; Hills et al 1990; Hills & Bender 1997) 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 (Nelemans et al 2001; Benacquista et al 2003; Edlund et al 2003; Timpano et al 2004; Ruiter et al 2009) have borne this expectation out. 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 (Timpano et al 2006; Crowder & Cornish 2007; Littenberg 2011; Nissanke et al 2012).

A subset of the resolvable binaries will be detectable electromagnetically. The purpose of this work is to assess the multi-messenger potential for different space-based detectors spanning the trade-space of future mission designs. This builds on previous work (Cooray et al 2003; Nelemans 2004, 2009) 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 (Nelemans et al 2004), 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).

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.

| Config. | ℓ (m) | \( \sqrt{S_0} \) (m/s/\( \sqrt{\text{Hz}} \)) | \( \sqrt{S_x} \) (m/\( \sqrt{\text{Hz}} \)) | Links |
|---------|-------|-----------------------------------|-----------------|-------|
| 1       | \( 1 \times 10^9 \) | \( 4.5 \times 10^{-15} \) | \( 11 \times 10^{-12} \) | 4     |
| 2       | \( 2 \times 10^9 \) | \( 3.0 \times 10^{-15} \) | \( 10 \times 10^{-12} \) | 6     |
| 3       | \( 5 \times 10^9 \) | \( 3.0 \times 10^{-15} \) | \( 18 \times 10^{-12} \) | 6     |

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).

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 \(~ 30\) known verification binaries, \(~ 5 \sim 10\) of which could be identified by the GW detectors considered here, with sources still being discovered (Nelemans 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 Boisier & Prantsos (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 120pc 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...
of the aperture $D$, the exposure time $t$, and the properties of the detector used for imaging and photometry (Schaefer 1994; 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 $m = 19.6 D^{0.755} - 0.025$. Using commercial CCD detectors, a $D = 0.5$ m telescope will reach a photometric magnitude $m \simeq 21$ in $t \sim 75$ s, where as a $D = 1.0$ m telescope will reach the same magnitude in $t \sim 20$ 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 $m \simeq 24$, whereas the magnitude limit of the final stacked image is expected to be around $m \simeq 27$ (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-known 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 Monte Carlo’s of thousands of detectable binaries) more rigorous parameter estimation studies would be impractical (recently Vallisneri (2011) has proposed a way around this dilemma). On the other hand, the UCBs in which we are most interested – those that can be well localized on the sky – have atypically high signal to noise ratio, where the Fisher provides a good estimate of the true parameter errors (Crowder & Cornish 2005).

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 $i$ from a uniform distribution $\cos i = U[-1, 1]$, 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 20th to 24th magnitude-limited catalogs have galactic latitudes $|b| \geq 20^\circ$, 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 $|b| \geq 20^\circ$.

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 multimessenger 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...
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to our line of sight that will produce eclipsing light

(Granato et al. 2003) the minimum inclination angle with re-

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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

(Granato et al. 2003) the minimum inclination angle with re-

spect 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 $R_{\text{WD}} \sim 10^8$ km. If we only consider binaries in the mul-
ti-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 configu-
ration using catalogs limited to $20^\text{th}$ 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 de-
tector concepts, and assess their measurement capabilities
for magnitude limited catalogs of UCBs. Magnitudes for the
constituents of each binary were derived from the population

Figure 2. Number of binaries with sky-location resolved to within 1 deg$^2$ for each configuration as a function of limiting magnitudes. The left panel shows the total number of candidates, the right panel shows the subset of eclipsing binaries. The error bars represent the full range after Monte Carlo'ing over the location and orientation of each UCB system. Even the modest detection abilities (magnitudes $m \sim 19$) of small aperture telescopes can yield several electromagnetic counterparts; larger telescopes with deeper magnitude grasp will have significantly more sources that can be surveyed.

Figure 3. Same as Figure 2, except here we use an angular resolution threshold for the GW detector of $d\Omega \leq 10 \text{ deg}^2$. 

AM CVn systems. Without mass transferring from one star
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

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observing ultra-compact binaries with gravitational waves and optical telescopes.

| Config | Full galaxy | $N$ | $|b| > 20^\circ$ | $|m| < 20^\circ$ | $N$ | $|b| > 20^\circ$ | $|m| < 24^\circ$ | $N$ | $|b| > 20^\circ$ |
|--------|-------------|-----|----------------|-------------------|-----|----------------|-------------------|-----|----------------|
| 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) |

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 $\Omega < 10 \text{ deg}^2$, 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.

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