Mon. Not. R. Astron. Soc. **000**, 1–6 (2012) Printed 27 August 2012 (MN LaTeX style file v2.2)

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

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arXiv:1207.4848v2 [astro-ph.IM] 24 Aug 2012

Accepted — Received —; in original form —

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 2004; Edlund et al 2005; Timpano et al 2006; Ruiter et al 2006) 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 off previous work (Cooray et al 2003; Nelemans 2006, 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-

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Config.	ℓ (m)	$\sqrt{S_a}$ (m/s^2/$\sqrt{\mathrm{Hz}}$)	$\sqrt{S_x}$ (m/$\sqrt{\mathrm{Hz}}$)	Links
1	1×10^9	4.5×10^{-15}	11×10^{-12}	4
2	2×10^9	3.0×10^{-15}	10×10^{-12}	6
3	5×10^9	3.0×10^{-15}	18×10^{-12}	6

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.

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_x. 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

$$S_n(f) = S_{\rm gal}(f) + (4/3)\sin^2 u\,[(2+\cos u)S_x + 2(3+2\cos u+\cos 2u)S_a/(2\pi f)^4]\,, \quad (1)$$

where $u = 2\pi f\ell/c$ and $S_{\rm gal}$ is the contribution to the instrument noise from the unresolved UCB foreground (Timpano et al 2006).

The configurations we will highlight correspond to the classic LISA design ($\ell = 5$ Gm), as well as two shorter armlength 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.

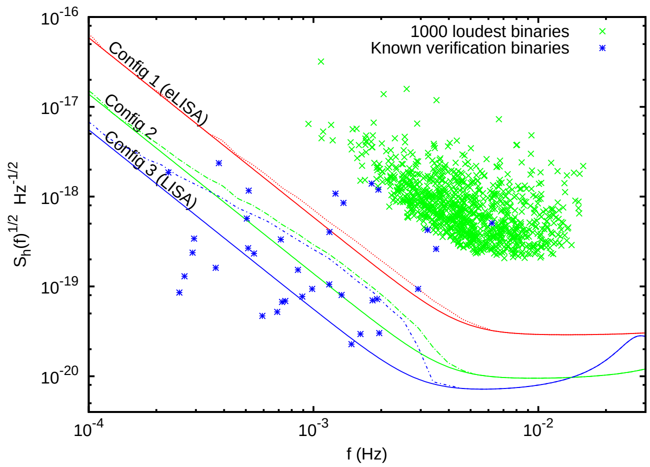

Figure 1. Sensitivity curve for each of the detector configurations in Table 1. The solid lines show the sensitivity set by the measurment noise while the dashed curves include an estimate of the UCB confusion-limited foreground. Over-plotted are the brightest UCBs in our simulated catalog (green crosses), 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 $\sim$ 30 known verification binaries, $\sim 5-10$ of which could be identified by the GW detectors considered here, with sources still being discovered (Nelemans 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 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 (Schaeffer 1990; 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 $m = 19.6\ D^{0.073}\ t^{0.025}$. 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_{gal}, 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 Γ_{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 2007).

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 $d\Omega \leqslant 1$ and $\leqslant 10$ deg^2. We estimate the area of the sky-location error ellipse using the full covariance matrix found by inverting Γ_{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 ι from a uniform distribution $\cos\iota = \mathrm{U}[-1, 1]$, and the polarization angle ψ and initial phase φ from $\mathrm{U}[0, 2\pi]$. 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 $d\Omega \leqslant 10$ deg^2 threshold, while $\lesssim 10\%$ are likely to be brighter than $m = 24$, and only $\lesssim 1\%$ pass the $m \leqslant 20$ 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^{th} to 24^{th} magnitude-limited catalogs have galactic latitudes $|b| \geqslant 20^\circ$, 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 $|b| \geqslant 20^\circ$

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 $\dot{f}$ 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 $\dot{f}$ and $\mathcal{A}$ 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 dL_{ML} is strongly peaked between 0 and 8 kpc – the distance to the galactic center – for the magnitude limited catalogs. The dL_{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

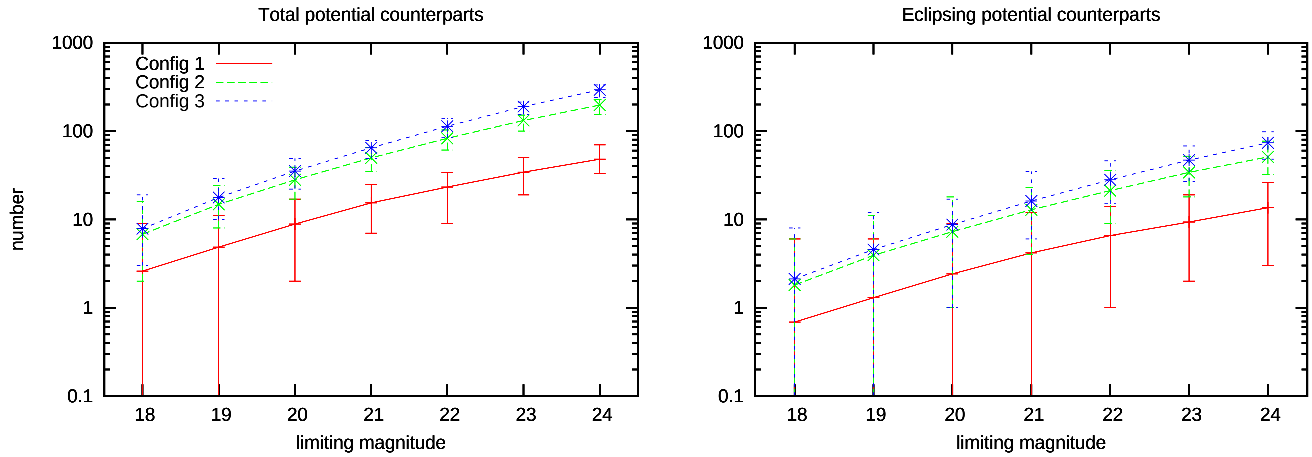

Figure 2. Number of binaries with sky-location resolved to within 1 deg^2 for each configuration as a function of limiting magnitudes. The left panel shows the total number of candidates, the right panel shows the subset of eclipsing binaries. The error bars represent the full range after Monte Carlo'ing 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.

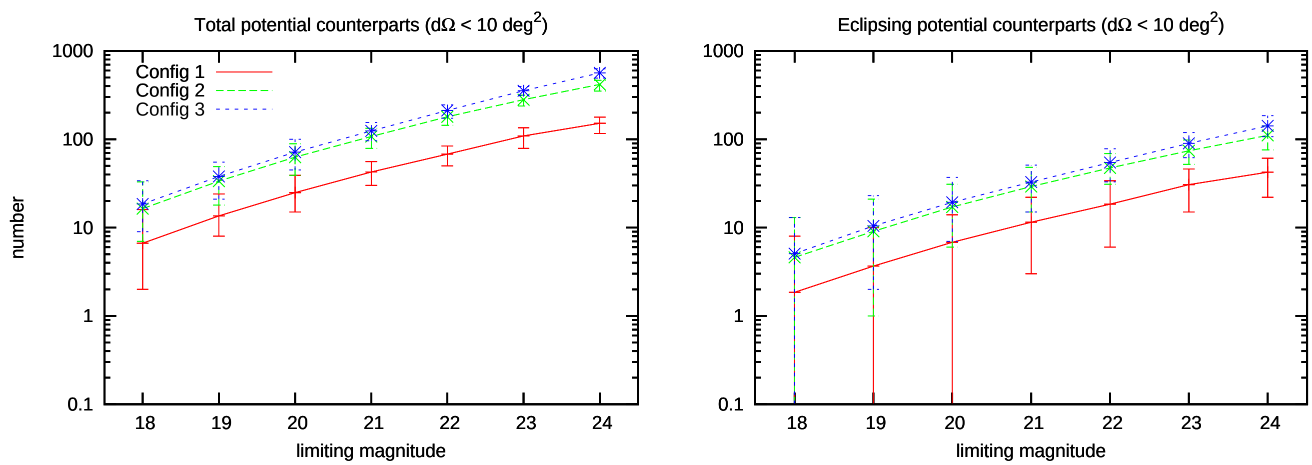

Figure 3. Same as Figure 2, except here we use an angular resolution threshold for the GW detector of $d\Omega \leqslant 10$ deg^2.

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 (Cooray et al 2003) the minimum inclination angle with respect to our line of sight that will produce eclipsing light curves is

$$\cos(\iota_{\rm min}) \sim 0.3 (f/3.5 \text{ mHz})^{2/3} \qquad (2)$$

assuming all binaries have mass $M_{\rm total} \sim 0.5$ M$_\odot$ and radius $R_{\rm WD} \sim 10^4$ km. If we only consider binaries in the multi-messenger catalog with inclination angle less than $\iota_{\rm min}$, we reduce the total number of candidates by a factor of ~ 3. Nevertheless, we still find upwards of ~ 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 20$^{\rm th}$ 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 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

Config	Full galaxy $\bar{N}$	$\|b\| > 20°$	$\frac{\Delta d_L}{d_L} < 20\%$	$m \leqslant 20$ $\bar{N}$	$\|b\| > 20°$	$\frac{\Delta d_L}{d_L} < 20\%$	$m \leqslant 24$ $\bar{N}$	$\|b\| > 20°$	$\frac{\Delta d_L}{d_L} < 20\%$
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)

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 $d\Omega \leqslant 10$ deg^2, while those in parenthesis correspond to the 1 deg^2 threshold. We tabulate the average number of binaries $\bar{N}$ that meet the sky-resolution requirements (column 2), and then the fraction which are significantly above the disk ($|b| > 20°$ – 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 $m \leqslant 20$ and $m \leqslant 24$ magnitude-limited catalogs.

synthesis simulations, and the gravitational wave measurement capabilities were estimated using the Fisher Information Matrix. Any UCBs that were brighter than our chosen magnitude limits (18-24) and located on the sky by the gravitational wave detector to within angular resolution $d\Omega$ were considered multi-messenger candidates. We estimated the multi-messenger catalog sizes for both $d\Omega \leqslant 1$ and 10 deg^2.

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 24$^{\text{th}}$ 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 ($d\Omega \leqslant 10$ deg^2) yield more candidates than more narrow fields of view ($d\Omega \leqslant 1$ 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.

ACKNOWLEDGMENTS

This work was supported by NASA Grants 08- ATFP08-0126 (TBL), NNX12AG30G (SLL), and NNX10AH15G (NJC). GN acknowledges support from the Dutch Foundation for Fundamental Research on Matter (FOM).

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