3-1-2009

The contribution of halo white dwarf binaries to the laser interferometer space antenna signal

Ashley J. Ruiter

Krzysztof Belczynski

Matthew Benacquista

Kelly Holley-Bockelmann

Recommended Citation

Ashley J. Ruiter, et. al., (2009) The contribution of halo white dwarf binaries to the laser interferometer space antenna signal.Astrophysical Journal693:1383. DOI: http://doi.org/10.1088/0004-637X/693/1/383

The Astrophysical Journal, 693:383–387, 2009 March 1 doi:10.1088/0004-637X/693/1/383

THE CONTRIBUTION OF HALO WHITE DWARF BINARIES TO THE *LASER INTERFEROMETER SPACE ANTENNA* SIGNAL

Ashley J. Ruiter[1,2,7], Krzysztof Belczynski[3,4], Matthew Benacquista[5], and Kelly Holley-Bockelmann[6,8]
[1] New Mexico State University, Department of Astronomy, 1320 Frenger Mall, Las Cruces, NM 88003, USA; aruiter@nmsu.edu, kbelczyn@nms.edu
[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA
[3] Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[4] J. Kepler Institute of Astronomy, University of Zielona Gora, Poland
[5] Center for Gravitational Wave Astronomy, The University of Texas at Brownsville, 80 Fort Brown, Brownsville, TX 78520, USA; benacquista@phys.utb.edu
[6] Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, USA; k.holley@vanderbilt.edu
Received 2007 November 28; accepted 2008 November 11; published 2009 March 2

ABSTRACT

Galactic double white dwarfs were postulated as a source of confusion limited noise for the *Laser Interferometer Space Antenna* (*LISA*), the future space-based gravitational wave observatory. Until very recently, the Galactic population consisted of a relatively well-studied disk population, a somewhat studied smaller bulge population and a mostly unknown, but potentially large halo population. It has been argued that the halo population may produce a signal that is much stronger (factor of $\sim$ 5 in spectral amplitude) than the disk population. However, this surprising result was not based on an actual calculation of a halo white dwarf population, but was derived on (1) the assumption that one can extrapolate the halo population properties from those of the disk population and (2) the postulated (unrealistically) high number of white dwarfs in the halo. We perform the first calculation of a halo white dwarf population using population synthesis models. Our comparison with the signal arising from double white dwarfs in the Galactic disk+bulge clearly shows that it is impossible for the double white dwarf halo signal to exceed that of the rest of the Galaxy. Using microlensing results to give an upper limit on the content of white dwarfs in the halo ($\sim$30% baryonic mass in white dwarfs), our predicted halo signal is a factor of 10 *lower* than the disk+bulge signal. Even in the implausible case, where all of the baryonic halo mass is found in white dwarfs, the halo signal does not become comparable to that of the disk+bulge, and thus would still have a negligible effect on the detection of other *LISA* sources.

Key words: binaries: close – Galaxy: halo – gravitational waves – white dwarfs

Online-only material: color figures

1. INTRODUCTION

The *Laser Interferometer Space Antenna* (*LISA*) is a proposed joint ESA/NASA mission that will be the first space-based gravitational radiation (GR) detector (see, e.g., Hughes 2006, and references therein). It has been known for some time (Hils et al. 1990) that Galactic double white dwarfs will be a prominent source of GR for *LISA*. Thousands of Galactic double white dwarfs are expected to be resolved well enough to yield their masses and orbital parameters (Nelemans et al. 2001, 2004; Ruiter et al. 2007), which will lead to an improved understanding of common envelope evolution scenarios and the origin of Type Ia Supernova and/or subdwarf B star progenitors (Livio 1989; Webbink 1984; Iben & Tutukov 1984; Han et al. 2003). However, a much larger number of double white dwarfs ($\sim 10^7$) will be detectable within the *LISA* sensitivity range but will be unresolved. In fact, close double white dwarfs are so numerous that they are expected to dominate the *LISA* GR signal at low frequencies,[9] their signal rising above that of the instrumental noise level and generating confusion-limited noise—a confusion "foreground." Thus, in order to attempt to uncover sources beneath the confusion noise, one must construct the expected total GR signal from these binaries and remove it from the *LISA* data stream. To do this, it is of considerable importance to determine a priori the characteristics, which will set the level of signal (e.g., masses, orbital periods, location in the Galaxy, etc.) of the double white dwarf population. In addition, the level of signal arising from Galactic double white dwarfs can be useful in constraining the structure and extent of the Galactic thick disk (Benacquista & Holley-Bockelmann 2006).

The contribution of low- and intermediate-mass extragalactic binaries to the *LISA* signal was shown to be rather insignificant in comparison with the Galactic populations (Farmer & Phinney 2003). The GR signal from Galactic and extragalactic black hole MACHO[10] binaries was investigated by Ioka et al. (1999), and it was in general found that black hole binaries at cosmological distances will have a higher impact on *LISA* than will the halo black hole MACHOs, although the foreground signal from Galactic double white dwarfs will still dominate.

The *LISA* GR signal arising from the Galactic population of double white dwarfs has been investigated by several groups (e.g., Hils et al. 1990; Postnov & Prokhorov 1998; Hils & Bender 2000; Nelemans et al. 2001, 2004; Benacquista et al. 2004; Edlund et al. 2005; Timpano et al. 2006; Ruiter et al. 2007). In most previous calculations, the Galactic GR signal was calculated for a single-component disk with the bulge excluded, until recently where a bulge component has been considered (Nelemans et al. 2004; Ruiter et al. 2007). We note that while the signal arising from the bulge should not be discounted, the Galactic disk is the major contributor to the *LISA* GR signal out of the two populations (see Section 3 for further explanation).

[7] SAO Predoctoral Fellow.
[8] Oppenheimer Fellow.
[9] $f_{\rm gr} = 2/P_{\rm orb}$ for circular binaries.
[10] Massive Astrophysical Compact Halo Object, or sometimes MAssive Compact Halo Object.

Up until now, a full calculation of the *LISA* GR signal due to the halo population of binaries has never been calculated. Hiscock et al. (2000) estimated that a Galactic halo white dwarf population will produce a GR signal significantly exceeding that of a disk population, though it was hypothesized by Nelemans et al. (2001) that such a strong GR signal from the halo is unlikely given the physical characteristics of a $\gtrsim 10$ Gyr halo stellar population. We demonstrate that the latter is indeed true, and argue against the existence of a strong halo GR signal with our detailed calculations Section 4.

In this study, we calculate the *LISA* GR signal arising from white dwarf binaries in the Galactic halo. We include in our signal calculation any double white dwarf within the *LISA* sensitivity range: $f_{\rm gr} = 0.0001$–1 Hz (orbital periods between ~ 5.6 hr and 2 s). We note here that this work is a follow-up study to our previous, more detailed study of the *LISA* signal arising from double white dwarfs in the Milky Way disk and bulge. Thus, for a thorough description of population synthesis modeling, signal calculations or binary evolutionary histories, we refer the reader to that study (Ruiter et al. 2007, which we will refer to from now on as RBBLW). The main objective of this work is to determine whether or not the halo population, omitted in most previous studies, will provide a significant contribution to the *LISA* GR signal. Since we do not know the contribution of white dwarfs, in number or in mass, to the Galactic halo, we use two extreme models to bracket our uncertainties. In one model, we set the halo contribution to zero (e.g., no white dwarfs in the halo and the halo white dwarf baryonic mass fraction $\eta_{\rm B} = 0$), while in the other, we assume that all of the baryonic halo mass is in white dwarfs ($\eta_{\rm B} = 1$). We then calculate models within these brackets to compare the various halo realizations to that of the Galactic disk+bulge population to determine if (and at what point) the GR signal from halo double white dwarfs becomes significant compared to that of the rest of the Galaxy. We discuss our results in context of recent microlensing experiments in order to constrain our intermediate models, and comment on the prospects for future *LISA* observations in Section 4. In Section 2, we describe our calculations, and in Section 3, we present our results of the halo gravitational wave signal juxtaposed with the Galactic (disk and bulge) gravitational foreground calculations of RBBLW and Nelemans et al. (2004).

2. MODEL DESCRIPTION

The Galactic baryonic halo mass, potential, and shape are all poorly constrained (Zinn 1985; Saha 1985; Morrison 1996; Majewski 1993; Morrison et al. 2003). In general, halo properties are estimated from star counts of thousands of intrinsically bright stars, such as red giants, blue horizontal branch stars, and RR Lyrae variables, with associated photometric or spectroscopic parallaxes. There is strong evidence that at least some of the halo was built by destroying satellite galaxies, resulting in a "stringy" halo structure (Johnston et al. 1999). Some obvious evidence for this may be found in the Magellanic Stream, a tidal arc of stars stretching over 100° of the sky (Putman et al. 1998; Morrison et al. 2000). Nonetheless, for this first attempt, we employ the canonical well-mixed spherically symmetric halo with a total baryonic mass of $10^9\,M_\odot$ and a density profile as follows (Zinn 1985; Morrison 1996; Morrison & Sarajedini 1996; Siegel et al. 2002):

$$\rho_{\rm halo} \propto (1 + r/a_{0,\rm halo})^{-3.5}, \qquad (1)$$

where $a_{0,\rm halo}$ is the scale radius of 3.5 kpc.

Once we have the mass model, we can populate the halo with our binaries. We use the `StarTrack` population synthesis code for single and binary evolution (Belczynski et al. 2008) to evolve our halo stellar population. We assume one metallicity and age for the entire halo, although we note that the halo has been observed to be comprised of two distinct components varying in metallicity (Carollo et al. 2007), and may very well have a triaxial shape (e.g., Helmi 2004). For the halo population, we use an evolution model, which incorporates: (i) low metallicity $Z = 0.0001$, (ii) a burst of star formation at $t = 0$ Gyr, and (iii) is evolved through 13 Gyr (e.g., Schuster et al. 2006). Our spatial distribution and evolutionary model parameters for the disk+bulge population are described in detail in Section 2 of RBBLW, but we summarize the differences here: (i) the disk and bulge stellar populations are evolved with near-solar ($Z = 0.02$) metallicity, (ii) the disk has a constant star-formation history for 10 Gyr, the bulge has a constant star-formation history for the first Gyr with none thereafter, and (iii) both disk and bulge populations are 10 Gyr old. The remaining evolutionary parameters for disk, bulge, and halo populations are the same.

Once the halo stellar population has been evolved, we record the physical properties of the close white dwarf binaries (orbital periods $\lesssim 5.6$ hours) and calibrate the results. We construct a grid of models in which we constrain the total mass of white dwarf stars in the present halo relative to the total baryonic halo mass. We choose four different realizations of the halo, keeping the halo mass constant, only varying the parameter which sets the fraction, by mass, of white dwarf stars (single and binary) within it ($\eta_{\rm B}$). Binarity of 50% is assumed. We choose mass fractions of 0% (no white dwarfs in the halo) and 100% as the extreme cases. For intermediate cases, we choose two models of 15% and 30% (based on microlensing results of Alcock et al. (2000)[11], Lasserre et al. (2000), and Brook et al. (2003)). We extract all double white dwarfs with GR frequencies within the *LISA* sensitivity range (10^{-4}–1 Hz) to calculate the spectral amplitudes, and compare the *LISA* halo spectra to that of the Galactic disk+bulge. We calculate the *LISA* timestream signals using the approach of Rubbo et al. (2004), which are added together yielding the total observatory data stream, which is then Fourier transformed in order to produce the frequency domain data (the spectra presented in Section 3). The actual *LISA* GR spectra are obtained using the Benacquista et al. (2004) simulation code. We note that all of our white dwarf binaries within the *LISA* sensitivity range have circular orbits. Eccentric white dwarf binaries are expected to arise from dynamical interactions in globular clusters (Benacquista 2001), where the phase-space densities are much higher than in the halo or the disk. These eccentric binaries, however, could provide a unique opportunity for learning about white dwarf structure with *LISA* (Willems et al. 2007).

3. RESULTS

For $\eta_{\rm B} = 1$ in a $10^9\,M_\odot$ halo, we obtain 1.5×10^9 white dwarfs (single and binary); 500×10^6 binary white dwarfs and out of these 27.5×10^6 *LISA* binary white dwarfs. Only 5.5% of double white dwarfs have periods shorter than 5.6 hr (GR frequencies in the *LISA* band: 10^{-4}–1 Hz). Obviously, the above numbers scale down linearly with $\eta_{\rm B}$. Chemo-dynamical simulations of the Milky Way (Brook et al. 2003) have demonstrated that a

[11] Alcock et al. (2000) suggest that a 20% (by mass) white dwarf halo is consistent with their microlensing results, although likely it is an overestimate if compared with chemical evolution models.

white dwarf-dominated halo, which is evolved from a white dwarf progenitor-dominated initial mass function (Chabrier et al. 1996) at early times, would lead to an overproduction of carbon and nitrogen when compared to observed abundances, so the $\eta_B = 1$ model is unrealistic. For a realistic upper limit on the white dwarf halo contribution, we choose $\eta_B = 0.3$ based on Lasserre et al. (2000, their Figure 2; also Brook et al. (2003) their Section 5), and this yields 8.3×10^6 *LISA* double white dwarfs in the halo. For a Galactic disk+bulge with a total stellar mass of $6 \times 10^{10}\, M_\odot$ for *all* stellar types (Klypin et al. 2002), we predict a total of $\sim 1.6 \times 10^9$ white dwarfs; 550×10^6 double white dwarfs, out of which only 8% are found within the *LISA* band: 44.5×10^6 (including all degenerate binaries; see RBBLW).

Note that the halo is presumed to include a specific fraction of mass in white dwarfs (η_B); therefore, the predicted numbers of white dwarfs are a direct result of the (i) adopted halo mass and (ii) calculated (with population synthesis) mass and period distributions for halo white dwarf binaries with the assumed binary fraction. For the rest of the Galaxy, in addition to the calculation of double white dwarf properties, we have computed the white dwarf mass fraction with the adopted Galactic field initial mass function (for details, see RBBLW). In other words, the disk+bulge model results in a true white dwarf formation efficiency per unit mass, while in the halo model this efficiency is imposed a priori (through the straightforward application of observational constraints, e.g., MACHOs).

The disk and halo double white dwarf populations differ significantly in numbers and physical properties due to the different environments under which stellar evolution proceeds (metallicity, age, star-formation history). For example, typical average double white dwarf chirp masses ($\mathcal{M} = (M_p M_s)^{3/5}/(M_p + M_s)^{1/5}$, where M_p and M_s represent the first-formed and second-formed white dwarf masses, respectively) of halo systems are $0.13\, M_\odot$ as compared to $0.19\, M_\odot$ for the disk. Also, there are relatively few short-period double white dwarfs in the halo (5.5% versus 8.0% for the disk+bulge), since this population is older and a larger number of short-period systems have merged. In particular, some double white dwarf systems form on rather short orbits (e.g., hybrid white dwarfs[12] with carbon–oxygen (CO) white dwarf companions), and none of these systems are found in our 13 Gyr old halo population (see below).

In Figure 1, we show the number density (per resolvable frequency bin) of *LISA* white dwarf binaries as a function of GR frequency for both the halo and the combined disk+bulge population of RBBLW. At nearly all frequencies, the disk+bulge population outnumbers the halo by nearly a factor of 2 ($\sim$ 45 versus $\sim$ 28 million *LISA* binaries). However, there is a relative increase in the number of halo systems between $\sim$ 0.0002 and 0.0004 Hz ($\sim$ 170–80 minute orbital periods). This is attributed to the fact that there is a relatively higher number of RLOF double white dwarfs with hydrogen white dwarf donors in the halo population. Double degenerate binaries with hydrogen white dwarfs take a long time to form; on the order of $\gtrsim 10^9$–10^{10} yr as opposed to $\sim 10^8$ for other, heavier double WD types (e.g., CO–CO, hybrid-CO) descended from more massive progenitors. Remnant binaries formed from progenitors with more massive stars are more common in the (younger) Galactic disk. Hydrogen white dwarfs are evolved from binary progenitors in which a white dwarf (e.g., carbon-oxygen or helium) is feeding from a low-mass main sequence star. At some stage

[12] Carbon–oxygen (CO) white dwarfs with a thick helium envelope.

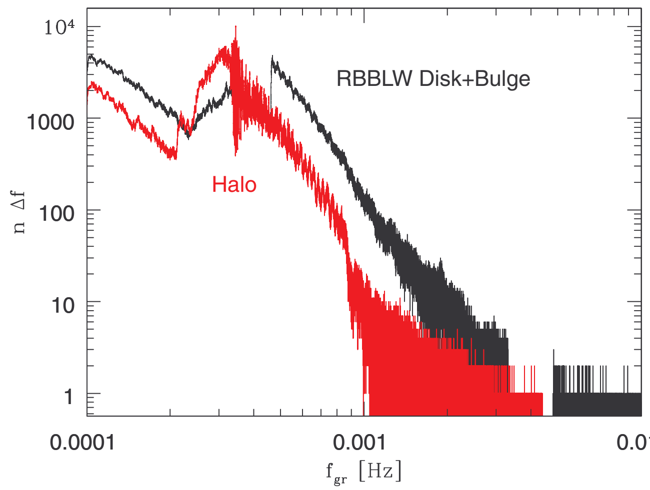

Figure 1. Number density ($n = (dN/df)$; δf is the size of a resolvable frequency bin for a 1 yr observation time, $1/T_{\rm obs} = 30$ nHz) for the 100% model halo population of *LISA* double white dwarfs, and the entire Milky Way disc+bulge population of *LISA* double white dwarfs presented in Ruiter et al. (2007). On average, the disc+bulge population is a factor of $\sim$ 2 greater in number than the 100% halo population.

(A color version of this figure is available in the online journal.)

during the mass transfer,[13] the main sequence donor becomes depleted of enough mass—to a mass below that of the hydrogen-burning limit—such that it is no longer capable of fusing hydrogen in its core and thus becomes degenerate (a hydrogen white dwarf is born). Because all of the binaries in the halo are 13 Gyr old, most systems have had time to reach contact, and many binaries which have evolved from more massive progenitors have since merged. Double white dwarfs involving hydrogen donors make up 75% of our *LISA* binary white dwarfs in the 13 Gyr old halo, spanning a frequency range from $\sim$ 0.0002 to 0.0009 Hz. By contrast, white dwarf binaries with hydrogen white dwarfs only make up 40% of the slightly younger bulge population (9–10 Gyr) and only 13% of the younger disk population. Additionally, only the disk population contains close white dwarf binaries with $f_{gr} > 4.4$ mHz (orbital periods less than 8 minutes), the majority of which are CO white dwarfs accreting from helium white dwarfs (a class of AM CVn binaries; Warner (1995)). Regarding massive white dwarfs, only 1.5% of *LISA* halo double white dwarfs are CO+CO systems, whereas this fraction is 12% for the disk. Out of the halo CO+CO systems, $\sim 2/3$ will merge within a Hubble time and have combined masses above $1.4\, M_\odot$, making them potential double degenerate scenario Type Ia supernovae (Iben & Tutukov 1984; Webbink 1984).

To obtain a better idea of the effect that location in the Milky Way has on the GR amplitude, in Figure 2 we show the number density distribution as a function of distance from the Sun for the three halo realizations, as well as the disk and bulge populations of RBBLW. It is immediately obvious that the halo signal is expected to be less than that of the rest of the Milky Way, given the extensive yet sparse stellar density distribution with respect to the bulge and disk. It becomes clear that even though the number of halo double white dwarfs are only about a factor of 1.6 in number below the disk+bulge combined, the GR amplitude is expected to be much weaker given the $1/D$ dependence (Rubbo et al. 2004), and the fact that the physical properties of the double white dwarfs (chirp masses, separations) in all three populations are not drastically different.

[13] Mass accretion rates are $\sim 10^{-11}\, M_\odot\ {\rm yr}^{-1}$.

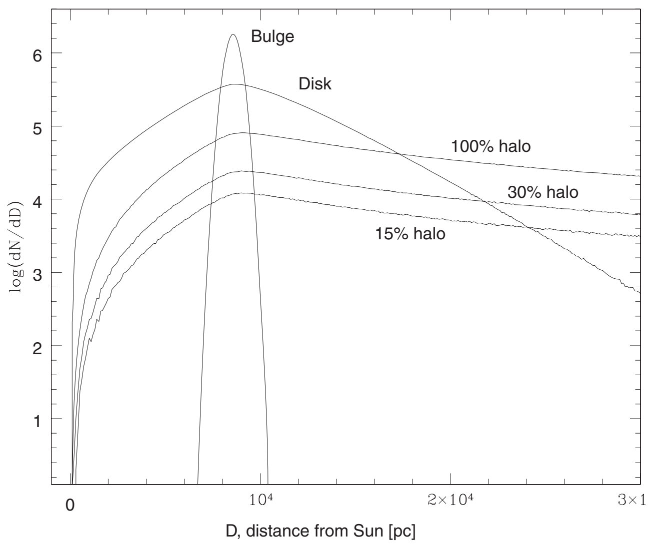

Figure 2. Number of *LISA* white dwarf binaries as a function of distance from the Sun in bin sizes of 100 pc. The Galactic bulge distance is concentrated around 8.5 kpc, and there are no more disc systems beyond $\sim$ 50 kpc. The 100% halo realization is nearly an order of magnitude below that of the disc distribution for the potentially strongest (closest) GR sources, until $>$ 1 kpc, where the disc begins to fall off more steeply.

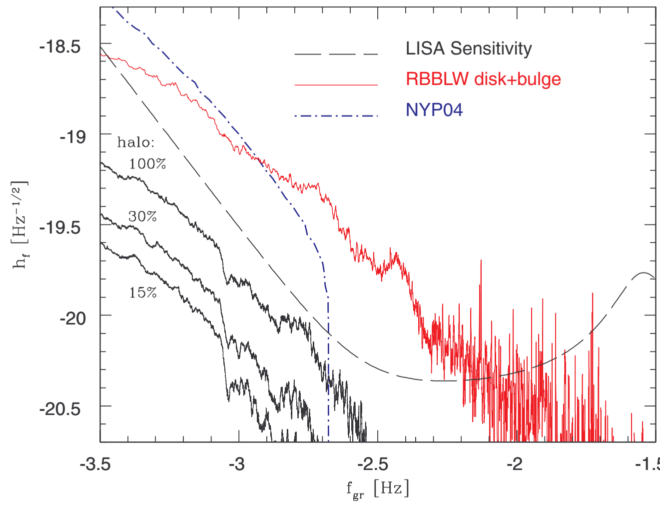

Figure 3. *LISA* gravitational wave spectra (amplitude densities). Shown are the gravitational wave signal for 15%, 30% and 100% (i.e., η_B = 0.15, 0.3 and 1, smoothed over 5000 resolvable frequency bins) realizations of the halo population of *LISA* double white dwarfs computed from our population synthesis models; Galactic double white dwarf signal from Ruiter et al. (2007) (red); smoothed Galactic disc foreground from Nelemans et al. (2004) truncated beyond $\sim$ 2 mHz where sources start to become resolved (blue dot-dash); and the *LISA* sensitivity curve for a signal to noise ratio of 1 (dashed line).

(A color version of this figure is available in the online journal.)

In Figure 3, we show spectral amplitude versus GR frequency of three Galactic halo double white dwarf realizations: 15%, 30%, and 100% halo models. In addition to our halo signals, we show the *LISA* sensitivity curve,[14] the median signal arising from the Galactic population from RBBLW, and the signal of the double white dwarf foreground of Nelemans et al. (2004). The shape of the *LISA* instrumental noise curve is a function of the acceleration noise (from *LISA*'s accelerometers), position noise, and the gravitational wave transfer function (see Larson et al. (2000) for a more detailed description of how the curve is calculated). The signal presented in Nelemans et al. (2004) is a measure of the barycentered double white dwarf *confusion foreground* amplitude h (rather than spectral amplitude h_f, see Timpano et al. (2006)), and is artificially truncated beyond $\sim$ 2 mHz, where individual binaries become resolved and the signal is no longer confusion limited in that study, whereas the signal from RBBLW is shown for a range of frequencies. We have scaled the amplitude of Nelemans et al. (2004) by $\sqrt{T_{\rm obs}} \times \sqrt{3/20}$, accounting for a 1 yr observation time for *LISA* and signal modulation due to the motion of *LISA*, respectively, to arrive at the root spectral density (spectral amplitude) h_f. We note that for even our most extreme (and unphysical) halo realization of $\eta_B = 1$, the halo signal is well below the signals of both Nelemans et al. (2004) and RBBLW, as well as the *LISA* sensitivity curve.

4. DISCUSSION

The amplitude of the GR signal from halo white dwarfs was previously estimated by Hiscock et al. (2000). In that study, Hiscock et al. (2000) used Hils et al. (1990) to estimate the number of disk white dwarfs, and arrived at the number (both single and binary) $N_{\rm disk} = 6.5 \times 10^8$. Hiscock et al. (2000) assumed that the properties of the halo white dwarfs were the same as those of the disk. Next they adopted the number of halo white dwarfs to be $N_{\rm halo} = 2 \times 10^{11}$. This was based on the mass of MACHOs (2×10^{11} halo objects with masses $\sim$ 0.1–1 $M_\odot$ derived by the MACHO collaboration (Alcock et al. 2000)), and the assumption that *all* MACHOs are white dwarfs. Note that this results in a halo mass of $\sim 10^{11}$ $M_\odot$; Hiscock et al. (2000) does not present the actual numbers of double white dwarfs that are within the *LISA* band for the halo nor for the disk populations. Naturally, Hiscock et al. (2000) obtain, due to a very high number of halo white dwarfs, a very strong GR signal from the halo population. In fact, they estimated that the level of signal from the halo could be a factor of $\sim$ 5 stronger than the one arising from the disk.

Comparison of predictions clearly shows that our number for the *entire* disk+bulge white dwarf population ($\sim 1.6 \times 10^9$) is rather similar to the disk prediction of Hiscock et al. (2000). However, their number for the entire halo white dwarf population is $\sim$ 2 orders of magnitude higher than we can presently use based on star-count data (Zinn 1985; Saha 1985; Morrison 1996; Morrison & Sarajedini 1996; Siegel et al. 2002). Even if we place the entire baryonic halo mass of 10^9 $M_\odot$ in white dwarfs, we obtain only 1.5×10^9 white dwarfs in the halo, while for a more realistic halo model ($\eta_B \sim 0.15$) our number is 2.25×10^8 (see Section 3). Such a large discrepancy in the estimate of the number of white dwarfs in the halo leads to a very different final result. In particular, our halo contribution is never higher than the Galactic disk+bulge signal. This marked difference stems from the fact that we employ a much smaller (baryonic) mass of the halo (10^9 $M_\odot$) than Hiscock et al. (2000) (10^{11} $M_\odot$).

The simple fact is that with a Milky Way virial mass of approximately 10^{12} $M_\odot$ (Klypin et al. 2002; Li & White 2008), the maximum baryonic mass in the *entire* Galaxy cannot be more than $\sim 8 \times 10^{10}$ $M_\odot$ without violating the strong constraint on Ω_B set by WMAP3 (Spergel et al. 2007). Given that the Milky Way disk and bulge itself is known to have a mass $\sim 6 \times 10^{10}$ $M_\odot$ (Klypin et al. 2002), it is extremely unlikely that the baryonic halo can be as massive as $O(10^{11})$ $M_\odot$. Even

[14] *Online Sensitivity Curve Generator*, based on Larson, Hiscock & Hellings, http://www.srl.caltech.edu/~shane/sensitivity/.

if there were significant play in the total baryonic mass of the halo, a white dwarf population of $O(10^{11})\,M_\odot$ would have had to have lost approximately $10^{10}\,M_\odot$ in gas during the planetary nebulae phase, and this much gas is likely to have been observed.

We have calculated the *LISA* gravitational radiation signal predicted to arise from double white dwarfs in the Galactic halo. In doing so, we have performed the first detailed calculation of the halo double white dwarf population and compared its signal to that of the disk+bulge population. Thus, for the first time there is a complete model Milky Way Galaxy (disk, bulge, halo) calculated self-consistently with the same binary evolution population synthesis code. The evolutionary calculations were done with the population synthesis code StarTrack (Belczynski et al. 2008), and the GR signal calculations were obtained with the detailed *LISA* simulation code of Benacquista et al. (2004). It was found that the GR signal arising from the halo population is significantly smaller than that of the rest of the Galaxy, and will not contribute substantially to the overall Galactic foreground signal. Further, if we use recent microlensing results in order to constrain the mass of the halo white dwarf population to 30% of the halo baryonic mass, we predict that the GR signal arising from the halo is at the level of $h_f \approx 7.1 \times 10^{-21}$ Hz$^{1/2}$ at 1 mHz (see Figure 3). The disk+bulge double white dwarf population generates a much larger noise level: $h_f \sim 10^{-19}$ Hz$^{1/2}$ at 1 mHz both for the StarTrack disk+bulge population (RBBLW) and for the previous prediction for the combined Galactic disk+bulge population obtained with a different population synthesis model (Nelemans et al. 2004).

Therefore, throughout the low-frequency region, where the disk+bulge signal is confusion limited, the halo signal is a factor of $\sim$ 10 lower than that of the disk+bulge. Since we have used an upper limit on the white dwarf contribution in the halo, and the actual halo white dwarf content is probably not higher than $\sim$ 10–20%, (Tisserand et al. (2007); see also Torres et al. (2002) for an estimate and the discussion of the number density of halo white dwarfs), we predict that the actual halo signal will be more than 10$\times$ lower than that of the disk and bulge combined. The reduced number of high-frequency halo systems compared with the disk population will result in a small number of potentially resolvable systems from the halo, since no halo systems are found with GR frequencies above 4.4 mHz (see Figure 1). A number of Galactic binaries predicted to be resolved with *LISA* have frequencies above this value ($\log(f) \approx -2.35$; Nelemans et al. (2004)). Even for an unrealistic halo model for which $\eta_B = 1$, the level of the average halo GR signal does not significantly approach that of the disk+bulge, and remains below the *LISA* sensitivity curve. It is clear that *LISA*'s ability to detect other sources will not be strongly curtailed by halo double white dwarfs, and that the GR signal from white dwarf binaries in the rest of the Galaxy (primarily the disk) will still constitute the prime limiting confusion foreground for *LISA*.

A.J.R. is thankful to S. Torres for informative discussion. M.J.B. acknowledges the support of NASA through grant NNG94GD52G and the Center for Gravitational Wave Astronomy (NAG5-13396). We also thank S. Larson for *LISA* sensitivity curve data, and G. Nelemans for the use of Nelemans et al. (2004) *LISA* amplitude data and helpful discussion. The StarTrack simulations were run at the Nicolaus Copernicus Astronomical Center and the Advanced Center for Computation, Research and Education.

REFERENCES

Alcock, C., et al. 2000, ApJ, 542, 281
Belczynski, K., Kalogera, V., Rasio, F. A., Taam, R. E., Zezas, A., Bulik, T., Maccarone, T. J., & Ivanova, N. 2008, ApJS, 174, 223
Benacquista, M. 2001, in 20th Texas Symp. Relat. Astrophys., 586, Detecting Eccentric Globular Cluster Binaries with LISA, ed. J.C. Wheeler & H. Martel (Melville, NY: AIP), 793
Benacquista, M. J., DeGoes, J., & Lunder, D. 2004, Class. Quantum Grav., 21, 509
Benacquista, M., & Holley-Bockelmann, K. 2006, ApJ, 645, 589
Brook, C. B., Kawata, D., & Gibson, B. K. 2003, MNRAS, 343, 913
Carollo, D., et al. 2007, Nature, 450, 1020
Chabrier, G., Segretain, L., & M'era, D. 1996, ApJ, 468, L21
Edlund, J. A., Tinto, M., Królak, A., & Nelemans, G. 2005, Class. Quantum Grav., 22, 913
Farmer, A. J., & Phinney, E. S. 2003, MNRAS, 346, 1197
Han, Z., Podsiadlowski, P., Maxted, P. F. L., & Marsh, T. R. 2003, MNRAS, 341, 669
Helmi, A. 2004, MNRAS, 351, 643
Hils, D., & Bender, P. L. 2000, ApJ, 537, 334
Hils, D., Bender, P. L., & Webbink, R. F. 1990, ApJ, 360, 75
Hiscock, W. A., Larson, S. L., Routzahn, J. R., & Kulick, B. 2000, ApJ, 540, L5
Hughes, S. A. 2006, in 6th Int. *LISA* Symp., 873, 13
Iben, I., & Tutukov, Jr, A. V. 1984, ApJS, 54, 335
Ioka, K., Tanaka, T., & Nakamura, T. 1999, Phys. Rev. D, 60, 083512
Johnston, K. V., Zhao, H., Spergel, D. N., & Hernquist, L. 1999, ApJ, 512, L109
Klypin, A., Zhao, H., & Somerville, R. S. 2002, ApJ, 573, 597
Larson, S. L., Hiscock, W. A., & Hellings, R. W. 2000, Phys. Rev. D, 62, 062001
Lasserre, T., et al. 2000, A&A, 355, L39
Li, Y. S., & White, S. D. M. 2008, MNRAS, 384, 1459
Livio, M. 1989, Space Sci. Rev., 50, 299
Majewski, S. R. 1993, ARA&A, 31, 575
Morrison, H. L., & Sarajedini, A. 1996 (ed.), Formation of the Galactic Halo . . . Inside and Out, Vol. 116 (San Francisco: ASP), 420
Morrison, H. L. 1996, in ASP Conf. Ser., 92, 453
Morrison, H. L., Mateo, M., Olszewski, E. W., Harding, P., Dohm-Palmer, R. C., Freeman, K. C., Norris, J. E., & Morita, M. 2000, AJ, 119, 2254
Morrison, H. L., et al. 2003, AJ, 125, 2502
Nelemans, G., Yungelson, L. R., & Portegies Zwart, S. F. 2001, A&A, 375, 890
Nelemans, G., Yungelson, L. R., & Portegies Zwart, S. F. 2004, MNRAS, 349, 181
Postnov, K. A., & Prokhorov, M. E. 1998, ApJ, 494, 674
Putman, M. E., et al. 1998, Nature, 394, 752
Rubbo, L. J., Cornish, N. J., & Poujade, O. 2004, Phys. Rev. D, 69, 082003
Ruiter, A. J., Belczynski, K., Benacquista, M., Larson, S. L., & Williams, G. 2007, arXiv:0705.3272
Saha, A. 1985, ApJ, 289, 310
Schuster, W. J., Moitinho, A., Márquez, A., Parrao, L., & Covarrubias, E. 2006, A&A, 445, 939
Siegel, M. H., Majewski, S. R., Reid, I. N., & Thompson, I. B. 2002, ApJ, 578, 151
Spergel, D. N., et al. 2007, ApJS, 170, 377
Timpano, S. E., Rubbo, L. J., & Cornish, N. J. 2006, Phys. Rev. D, 73, 122001
Tisserand, P., et al. 2007, A&A, 469, 387
Torres, S., García-Berro, E., Burkert, A., & Isern, J. 2002, MNRAS, 336, 971
Warner, B. 1995, Ap&SS, 225, 249
Webbink, R. F. 1984, ApJ, 277, 355
Willems, B., Kalogera, V., Vecchio, A., Ivanova, N., Rasio, F. A., Fregeau, J. M., & Belczynski, K. 2007, ApJ, 665, L59
Zinn, R. 1985, ApJ, 293, 424