The Astrophysical Journal, 540:L5–L8, 2000 September 1

LOW-FREQUENCY GRAVITATIONAL WAVES FROM WHITE DWARF MACHO BINARIES

William A. Hiscock, Shane L. Larson, and Joshua R. Routzahn
Department of Physics, Montana State University, Bozeman, Montana 59717
and
Ben Kulick
Department of Physics, California Institute of Technology, Pasadena, California 91125
Received 2000 May 31; accepted 2000 July 7; published 2000 August 23

ABSTRACT

The possibility that Galactic halo MACHOs are white dwarfs has recently attracted much attention. Using the known properties of white dwarf binaries in the Galactic disk as a model, we estimate the possible contribution of halo white dwarf binaries to the low-frequency (10^{-5} Hz $< f < 10^{-1}$ Hz) gravitational wave background. Assuming the fraction of white dwarfs in binaries is the same in the halo as in the disk, we find the confusion background from halo white dwarf binaries could be 5 times stronger than the expected contribution from Galactic disk binaries, dominating the response of the proposed space-based interferometer LISA. Low-frequency gravitational wave observations will be the key to discovering the nature of the dark MACHO binary population.

Subject headings: dark matter — gravitation — white dwarfs

1. INTRODUCTION

The MACHO project has detected 13–17 gravitational microlensing events in the direction of the Large Magellanic Cloud to date (Alcock et al. 2000), while the EROS collaboration has detected two (Lasserre et al. 1999). One result of the analysis of the observations (Alcock et al. 2000) is that, independent of the halo model assumed, there are of order 2×10^{11} MACHOs of mean mass 0.5 $M_\odot$ in the Galactic halo.[1]

While the microlensing observations have confirmed the existence of MACHOs (massive astrophysical compact halo objects) in the halo, the actual nature of these objects is still a matter of much debate. The mass suggests that these are main-sequence red dwarf stars, but these appear to be ruled out observationally (Bahcall et al. 1994; Graff & Freese 1996a, 1996b). Until recently, white dwarf (WD) stars also seemed to be highly unlikely MACHO candidates, since observations of the Galactic halo (see, e.g., Flynn, Gould, & Bahcall 1996) did not find a population of old, red, WD stars. Since conventional baryonic stars seemed to be ruled out, highly speculative candidate objects have been proposed as MACHO models, such as primordial black holes and boson stars.

Recently, however, new models of WD cooling processes indicate that old, cool, WD atmospheres form molecular hydrogen, which can strongly absorb red light. This implies that aging WDs will be blue objects rather than red as was previously believed (Saumon & Jacobson 1999; Hansen 1999). In light of these new cooling models, predictions have been made for the number of halo WDs that should be seen in deep field surveys (Richer 1999), and new analyses have detected candidate halo WDs with blue colors in the Hubble Deep Field (Ibata et al. 1999; Méndez & Minniti 2000). In addition, local blue WDs with large proper motions, indicating that they are members of the halo population, have been tentatively identified (Ibata et al. 2000).

In this Letter we assume that the halo MACHOs are WD stars and estimate the low-frequency (10^{-5} Hz $< f < 10^{-1}$ Hz) gravitational wave (GW) background that would be produced from a halo population of WD binaries. Such a background could be an important source for space-based laser interferometer GW detectors such as the proposed Laser Interferometer Space Antenna (LISA) mission (P. Bender et al. 1998, unpublished). GWs from halo WD binaries could be a very interesting signal (if one is interested in characterizing the binary population of MACHOs) or a serious confusion noise source (if one is concerned that this background is masking signals from other sources of interest, such as a cosmological background of GW). Estimates of the GW signal from a halo composed of primordial black holes has shown that the signal from binaries in the halo could dominate the output of an interferometer such as LISA (Hiscock 1998; Ioka, Tanaka, & Nakamura 1999).

In the absence of any observational evidence concerning the properties of a halo population of binary WDs, we make the assumption that WD binary properties in the halo mimic those of Galactic disk WD binaries (Hils, Bender, & Webbink 1990; Bender & Hils 1997). This assumption is almost certainly incorrect; the halo WD population is generally felt to be much older than the disk population and (based on the microlensing events) probably has a mass distribution that differs from the disk WD population. However, using the disk as a model is the best one can currently do.

2. DISK BINARIES AS GW SOURCES

The GW background generated by disk binaries (both Galactic and extragalactic) has been thoroughly studied by Hils et al. (1990; Bender & Hils 1997). They have made careful estimates of the GW signal due to Galactic disk WD binaries and also that due to extragalactic binaries. In recent work, they have combined these signal amplitudes with the planned properties of LISA to generate a simulation of LISA's response to the combined Galactic and extragalactic signals. The key factor in this analysis is the width of a frequency bin in the LISA data analysis for periodic sources. With a 1 yr integration time, each frequency bin will have a width $\Delta f = (1 \text{ yr})^{-1} \simeq 3 \times 10^{-8}$ Hz. At frequencies beginning at around 1×10^{-3} Hz and higher, the number of Galactic binaries per bin will begin to drop to order unity. At this point, the properties of individual Galactic binaries can be determined and their signal removed from the record, so that the weaker combined signal of extragalactic binaries will begin to be observable in the open bins.

[1] It is noteworthy that this number is similar in magnitude to the number of stars in the Galaxy.

Solving for a particular Galactic binary and removing it from the data record will typically require three bins of information (Hellings 1996). The effective spectral amplitude observed by LISA, h_f, after taking the finite bin width into account, is given by (Bender & Hils 1997)

$$h_f = \left\{ \frac{(h_f^e)^2 \left[(h_f^G)^2 + (h_f^e)^2(1 - e^{-3r})\right]}{e^{-3r}(h_f^G)^2 + (h_f^e)^2(1 - e^{-3r})} \right\}^{1/2}, \qquad (1)$$

where r is the number of Galactic binaries per frequency bin, h_f^G is the spectral amplitude of the Galactic binary background, and h_f^e is the spectral amplitude of the extragalactic binaries.

Using the relation between the spectral amplitude and the number of binaries per unit frequency dN/df, the GW luminosity of a binary $L(f)$, and the average inverse distance squared $\langle d^{-2} \rangle$,

$$h_f(f) = \frac{2}{\pi f} \left[\left\langle \frac{1}{d^2} \right\rangle L(f) \frac{dN}{df} \right]^{1/2}, \qquad (2)$$

it is possible to extract an estimate of dN/df from the Bender-Hils results along with an approximation to the spectral amplitudes of the backgrounds due to Galactic disk binaries and extragalactic binaries. We find that the Bender-Hils results are well approximated by

$$\frac{dN}{df} \simeq 4.47 \times 10^{-3} f^{-11/3}, \qquad (3)$$

$$\log (h_f^G) = -\left(\frac{7}{6}\right) \log (h_f) - 21.8, \qquad (4)$$

$$\log (h_f^e) = -\left(\frac{7}{6}\right) \log (h_f) - 23.0, \qquad (5)$$

where the frequency f is measured in hertz. The frequency dependence in these equations is characteristic of a population of circular binaries that is evolving solely as a result of gravitational radiation reaction.

3. RESCALING THE DISK TO THE HALO

A simple estimate of the GW background expected from binary WDs in the halo can be obtained by assuming that the WD binary population of the halo is similar in nature to that of the disk. One can estimate the halo GW background by rescaling the disk binary WD population, based on three factors:

1. the ratio of the total number of halo WD MACHOs to the total number of Galactic disk WDs, $N_{\rm halo}/N_{\rm disk}$;
2. the ratio of the average inverse distance squared of a halo MACHO to the average inverse distance squared of a disk WD, $\langle d^{-2} \rangle_{\rm halo}/\langle d^{-2} \rangle_{\rm disk}$; and
3. the ratio of the fraction of WDs in binaries in the halo to the fraction of WDs in binaries in the disk, α.

The number of WDs in the disk is computed by integrating over the standard cylindrical exponential model,

$$\rho = \rho_0 \exp\left(\frac{-r}{r_0}\right) \exp\left(\frac{-|z|}{z_0}\right), \qquad (6)$$

where $r_0 = 3.5$ kpc and $z_0 = 90$ pc are the exponential scale heights for the WD population in the disk (Hils et al. 1990) and $\rho_0 = 4.72 \times 10^{-2}$ pc^{-3} is the number density of WDs at the center of the galaxy (computed from the local density of WDs in the solar neighborhood, $\rho_\odot = 4.16 \times 10^{-3}$ pc^{-3} given in Knox, Hawkins, & Hambly 2000). Integrating the disk WD density using the distribution in equation (6) yields

$$N_{\rm disk} = 6.5 \times 10^8 \qquad (7)$$

for the disk population.

We assume that the number of MACHOs in a 50 kpc halo (to the LMC) is $N_{\rm halo}^{50\,{\rm kpc}} = 2 \times 10^{11}$, the halo model–independent result obtained by the MACHO collaboration (Alcock et al. 2000). For a larger halo, extending some 300 kpc (halfway to M31), this number can be scaled by assuming that the spatial distribution of WD MACHOs follows the standard spherical flat rotational halo model given by

$$\rho = \hat{\rho} \frac{R^2 + a^2}{r^2 + a^2}, \qquad (8)$$

where $\hat{\rho}$ is the local density of dark matter, r is the Galactocentric radius, $R = 8.5$ kpc is the Galactocentric radius of the Sun, and $a = 5.0$ kpc is the halo core radius. Integrating equation (8) out to 50 kpc and setting the number of MACHOs equal to 2×10^{11}, one obtains $\hat{\rho} = 0.0094\ M_\odot$ pc^{-3}. Using this value and integrating equation (8) out to 300 kpc gives

$$N_{\rm halo}^{300\,{\rm kpc}} = 1.3 \times 10^{12}. \qquad (9)$$

The average inverse distance squared between sources and the Sun $\langle d^{-2} \rangle$ may be found by integrating over the source distributions given in equations (8) and (6). Expressing the result as a distance, one finds that for the disk

$$\langle d^{-2} \rangle^{-1/2} = 4.85 \text{ kpc}, \qquad (10)$$

while

$$\langle d^{-2} \rangle^{-1/2} = 15.7 \text{ kpc} \qquad (11)$$

for a 50 kpc halo and

$$\langle d^{-2} \rangle^{-1/2} = 39.5 \text{ kpc} \qquad (12)$$

for a 300 kpc halo.

Nothing is presently known about the ratio of the fraction of WDs in binaries in the halo to the fraction of WDs in binaries in the disk α, so we leave this as a free parameter in our model and examine the consequences of different values for α.

In rescaling the disk background GW spectrum, there are two separate effects associated with the potentially larger number of WD binaries in the halo. First, the larger number tends to raise the overall level of the halo background relative to that of the disk. Second, since there are more halo binaries per unit frequency interval, this pushes the point in the spectrum where one first encounters open frequency bins (one or fewer Galactic halo binaries per bin) to higher frequencies than in the disk. Scaling the number of Galactic disk binaries by multiplying by the ratio of the total number of WDs in the halo to the number in the disk yields

$$\log\left(\frac{dN}{df}\right)_{\rm halo} = -\left(\frac{11}{3}\right)\log(f) - 2.35 + \log\left(\frac{\alpha N_{\rm halo}}{N_{\rm disk}}\right). \quad (13)$$

The overall level of the GW backgrounds from Galactic halo WD binaries and extragalactic halo binaries will scale according to

$$h_f^{\rm halo} = K(\alpha) h_f^{\rm disk}, \quad (14)$$

where the scaling factor $K(\alpha)$ is defined as

$$K(\alpha) = \left(\alpha \frac{N_{\rm halo}}{N_{\rm disk}} \frac{\langle d^{-2}\rangle_{\rm halo}}{\langle d^{-2}\rangle_{\rm disk}}\right)^{1/2}. \quad (15)$$

If one assumes that the halo population of WDs precisely mimics the disk population, then the same fraction of WDs will be in binaries in the halo as in the disk and $\alpha = 1$. In this case the scaling factor is given by

$$K(\alpha = 1) = \begin{cases} 5.42 & \text{for a 50 kpc halo,} \\ 5.49 & \text{for a 300 kpc halo.} \end{cases} \quad (16)$$

An estimate of the response of LISA to a background of GW from halo WD binaries can now be obtained by rescaling the Galactic and extragalactic disk spectral amplitudes (eqs. [4] and [5]) using equation (14) with equation (13) in equation (1). The resulting signal estimate for LISA is illustrated in Figure 1, along with the Bender-Hils estimate for disk binaries for comparison. The signal from the halo WD binaries is substantially stronger than that from the disk binaries. At lower frequencies, the predicted backgrounds for a 50 and 300 kpc halo are indistinguishable in the figure, owing to the similarity in the values of K in equation (16). The larger number of halo binaries compared to the disk fills the frequency bins to a substantially higher frequency before one encounters open bins, where weaker signals such as the extragalactic background may be observed. If only the disk background is present, then potential extragalactic sources can be detected above a critical frequency of about 2×10^{-3} Hz, where frequency bins cease to be cluttered with many Galactic binaries. With a 50 kpc halo, the greater number of Galactic binaries increases this critical frequency to about 1×10^{-2} Hz, while for a larger 300 kpc halo, the critical frequency is further increased to about 2×10^{-2} Hz. In the latter case, the frequency at which bins begin to open up and allow weaker extragalactic signals to be detected is roughly equal to where LISA's instrumental noise curve begins to rise.

Of course, it is presently unknown whether the fraction of WDs in binaries in the halo is comparable to that in the disk. A priori, it could be larger ($\alpha > 1$) or smaller ($\alpha < 1$). One question that can be posed within the present simple model is what value of α will result in the halo GW signal being similar in magnitude and shape to that of the disk. This determines a minimum value for α, above which the halo signal will dominate over that of the disk binaries. Reducing α in equations (13) and 14) one finds that the signal from a 50 kpc halo will be dominant if $\alpha > 10^{-2}$, while the signal strength from a 300 kpc halo would exceed that of the disk if $\alpha > 5 \times 10^{-3}$. This implies that even if the fraction of halo WDs in binaries is as low as 1% of the fraction of disk WDs in binaries, the WD MACHO binaries will be "bright" enough to stand out from the expected signal of the disk binaries. While the numbers here are highly sensitive to the specific details of the halo binary MACHO population, they illustrate that the halo will be a significant source of a low-frequency confusion background of GWs unless the fraction of MACHO WDs in binaries is orders of magnitude lower than in the disk.

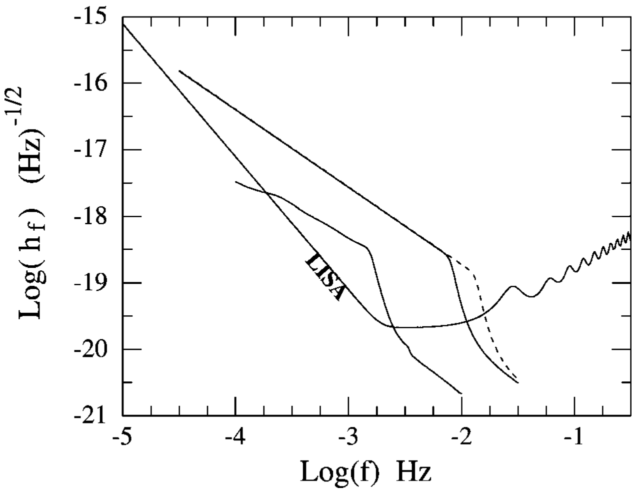

FIG. 1.—Expected response of LISA to the GW signal from a halo population of WD binaries shown for the case $\alpha = 1$. The upper solid curve represents a 50 kpc halo; the dashed curve represents a 300 kpc halo. The lower curve is the detailed spectrum predicted by Bender & Hils for disk binaries. The expected sensitivity of the LISA interferometer (signal-to-noise ratio = 1) is also shown.

4. DISCUSSION

While this simple scaled model is certainly not an accurate representation of the Galactic halo binaries, it does illustrate that the GW background from a halo population of WD binaries could easily dominate the signal in a space-based interferometer such as LISA. Furthermore, this result, together with other studies that have considered the GW signal from MACHOs if they were identified with primordial black holes (Nakamura et al. 1997; Hiscock 1998; Ioka et al. 1999, 2000), demonstrates that whatever the nature of MACHOs, if even a small fraction of them are in binary systems, then they will create a strong confusion noise background which could saturate the frequency range in which LISA is most sensitive (2×10^{-3} Hz $< f <$ 2×10^{-2} Hz).

Some may consider such a prospect discouraging, as the combined signal from abundant halo binaries could mask other weak signals and make them undetectable. This has previously been a serious concern with respect to the disk binaries—hence the name "confusion noise" for a signal that actually describes the short-period binary population of the Galaxy. There has been hope that the confusion noise from Galactic disk binaries could be extracted from the general stochastic (e.g., cosmological) background by utilizing the anisotropic nature of the disk signal (Giampieri & Polnarev 1997). If there is a substantial signal associated with halo binaries, however, then this scheme will not work. The solar position is sufficiently near the center of a spherical Galactic halo that it would seem difficult or impossible to be able to subtract out the halo confusion noise signal based on its very small anisotropy.

On the other hand, even our simple analysis shows that the GW signal from the halo binaries could be a powerful tool to determine the properties of the MACHO binary population as well as general properties of the halo itself, such as its size.

The authors wish to thank P. Bender and R. Hellings for helpful discussions. This work was supported in part by NSF grant PHY 97-34834 and NASA cooperative agreement NCC5-410.

REFERENCES

Alcock, C., et al. 2000, ApJ, submitted (astro-ph/0001272)
Bahcall, J. N., Flynn, C., Gould, A., & Kirhakos, S. 1994, ApJ, 435, L51
Bender, P. L., & Hils, D. 1997, Classical Quantum Gravity, 14, 1439
Flynn, C., Gould, A., & Bahcall, J. 1996, ApJ, 466, L55
Giampieri, G., & Polnarev, A. G. 1997, MNRAS, 291, 149
Graff, D. S., & Freese, K. 1996a, ApJ, 456, L49
———. 1996b, ApJ, 467, L65
Hansen, B. M. S. 1999, ApJ, 520, 680
Hellings, R. 1996, paper and comments presented at Int. Conf. on Gravitational Waves: Sources and Detectors
Hils, D. L., Bender, P., & Webbink, R. F. 1990, ApJ, 360, 75
Hiscock, W. A. 1998, ApJ, 509, L101
Ibata, R. A., Richer, H. B., Gilliland, R. L., & Scott, D. 1999, ApJ, 524, L95
Ibata, R. A., et al. 2000, ApJ, 532, L41
Ioka, K., Tanaka, T., & Nakamura, T. 1999, Phys. Rev. D, 60, 83512
———. 2000, ApJ, 528, 51
Knox, R. A., Hawkins, M. R. S., & Hambly, N. C. 2000, MNRAS, in press (astro-ph/9903345)
Lasserre, T., et al. 1999, preprint (astro-ph/9909505)
Méndez, R. A., & Minniti, D. 2000, ApJ, 529, 911
Nakamura, T., Sasaki, M., Tanaka, T., & Thorne, K. 1997, ApJ, 487, L139
Richer, H. B. 1999, preprint (astro-ph/9906424)
Saumon, D., & Jacobson, S. B. 1999, ApJ, 511, L107