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Can black-hole MACHO binaries be detected by the Brazilian spherical antenna?

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Abstract
Different studies show that dark matter of non-baryonic origin might exist. There is experimental evidence that at least one form of dark matter has been detected through microlensing effects. This form of dark matter is named MACHOs (massive astrophysical compact halo objects). The MACHO collaboration estimated that the masses of these objects are to be in the range 0.15–0.95$M_\odot$, where the most probable mass is of 0.5$M_\odot$. Some authors argue that MACHOs could be black holes, and that they could form binary systems, BHMACHO binaries. As is well known, binary systems are sources of gravitational waves. The Brazilian spherical antenna will operate in the frequency band of 3.0–3.4 kHz, sensitive to binaries of a pair of 0.5$M_\odot$ black holes just before coalescing. In the present work we study the detectability of these putative BHMACHO binaries by the Brazilian spherical antenna Mario Schenberg.

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1. Introduction

The issue of dark matter in astronomy has a long history. In the 1930s, for example, Oort claimed that the total amount of matter in the Galaxy is greater than the visible matter. In this very epoch, Zwicky found that the velocity dispersion of galaxies in a cluster exceeds that expected for a gravitationally bound stationary system if the only contribution comes from the galaxies themselves.

One could think that the invisible matter is made of ordinary matter, i.e., baryonic dark matter. There are, however, independent evidences that lead to the conclusion that the dark matter cannot be only made of baryons.

The big bang nucleosynthesis studies, for example, indicate that the amount of baryons in the universe is $\Omega_B h_{100}^2 = 0.020 \pm 0.002$ (95% confidence level; see, e.g., Burles *et al* (2001), where Ω_B is the baryonic density parameter and h_{100} is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}). This last figure takes into account, obviously, the luminous and the dark baryons.

On the other hand, several different studies of the cosmic background radiation, in particular those related to the primary anisotropies, indicate that non-baryonic dark matter exists. The WMAP results show, for example, that $\simeq$80% of the matter must be in the form of non-baryonic dark matter (Spergel *et al* 2003). It is, therefore, hard to avoid the conclusion that at least part of the dark matter present in galaxies and in the cluster of galaxies is in the non-baryonic form.

A question that still deserves to be properly answered has to do with the very nature of the dark matter, be it baryonic or non-baryonic. Generally speaking, it is argued in the literature (see, e.g., Peacock (1999) for a review, among others), to be conservative, that the dark matter could be in the form of the so-called brown dwarfs, if baryonic, and weakly interacting massive particle (WIMPs), if non-baryonic.

Paczyński (1986a) suggested that with the use of the lensing effect it would be possible to observe nonluminous matter in the form of brown dwarfs or Jupiter-like objects. He coined the term 'microlensing' to describe the gravitational lensing effect that can be detected by measuring the intensity variation of a macro-image of any number of unresolved micro-images. Also, the search of light variability among millions of stars in the large magellanic cloud (LMC) could be used to detect dark matter in the Galactic halo (Paczyński 1986b).

It is worth mentioning that Griest (1991) coined the acronym MACHO (massive astrophysical compact halo objects) to denote the objects responsible for gravitational microlensing. The name MACHO became very popular and is widely used to refer to any object responsible for the microlensing effect, whether these objects are located in the halo of the Galaxy or not, and regardless of their masses.

Paczyński's idea concerning the microlensing triggered many groups to search for MACHOs. Just to mention a couple of groups still active in this new field of astrophysics we have, for example: OGLE (Udalski *et al* 1992), EROS (Aubourg *et al* 1993), MACHO (Alcock *et al* 1993), among others. These various groups have been monitoring tens of millions of stars in the LMC, searching for light variability.

These various studies show that there are not enough MACHOs in the Galactic halo to account for its mass. Therefore, there should exist another kind of dark matter in the halo, most probably in the form of WIMPs.

Alcock *et al* (2000, MACHO Project), for example, based on a maximum-likelihood analysis, obtained a MACHO halo fraction of 20% for a typical halo model with a 95% confidence interval of 8%–50%. Moreover, they obtained that the most likely MACHO mass is between 0.15 and $0.9M_\odot$, with the most probable value being $0.5M_\odot$.

This MACHO mass is substantially higher than the fusion threshold of $0.08M_\odot$, and therefore should shine in some electromagnetic frequency band, but there is no evidence for that. We do not enter into a detailed discussion on this issue here, but refer the reader to the papers by Nakamura *et al* (1997), among others. We only remark that the MACHOs are least likely to be either white, red or brown dwarfs.

Nakamura *et al* (1997) argued that the MACHOs could well be primordial black holes. Obviously, it is not possible to form a black hole of $0.5M_\odot$ as a product of stellar evolution; it must have formed necessarily in the very early universe (see, e.g., Yokoyama 1997).

Here we are not concerned with the formation mechanism of this putative $0.5M_\odot$ black holes. In the present paper we consider that they exist, and as a result can form binary systems (the BHMACHO binaries) that, therefore, may generate gravitational waves (GWs).

The paper is organized as follows. In section 2, we consider the GWs from the spiralling BHMACHO binaries, in section 3 we consider the detectability of the BHMACHO binaries by the Brazilian spherical detector and finally in section 4 we present our conclusions.

2. Gravitational waves from spiralling BHMACHO binaries

Binary star systems are well-known sources of GWs that should be detected either by earth- or space-based GW detectors. Here we are interested in determining if the Brazilian spherical detector 'Mario Schenberg' is able to detect BHMACHO binaries.

Due to the fact that the Brazilian antenna will operate in the frequency band of 3.0–3.4 kHz, GWs emitted during the periodic or spiralling phase of the evolution of binary systems can only be detected if the components of the binaries are compact objects of sub-solar masses. Since the MACHOs could be black holes of $0.5M_\odot$, the BHMACHO binaries could in principle be detected by the Brazilian antenna.

Obviously the other GW detectors (the interferometers and the bars) will also see such putative BHMACHO binaries. As the interferometers are sensitive to GWs in the frequency band of 10 Hz–10 kHz, and the bars to $\sim$1 kHz, they will detect the BHMACHOs binaries before the Brazilian spherical detector. Note, however, that one spherical detector can determine the directions of the sources (see Forward (1971) and also Magalhães *et al* (1995, 1997) for details), while some bars and/or interferometers are necessary to do the same.

In figure 1 we present the frequency of the GW as a function of the coalescing time. We have used in this figure the well-known paper by Peters and Mathews (1963) for a pair of $0.5M_\odot$ BHMACHOs.

Note that when the BHMACHO binaries are emitting GW at 100 Hz they are about 10 s to coalescence . When these systems are emitting GW at the frequency band of the bars they are a few hundredths of second to coalescence. Finally, when the BHMACHO binaries are emitting at the frequency band of the Brazilian spherical detector they are $\sim$1 ms to coalescence.

It is worth stressing that the BHMACHO binaries are 'chirping' sources of GW when passing through the band of the interferometers, the bars and the spherical detectors such as the Brazilian one. In the following section, we consider the detectability of these binary systems by the Brazilian spherical detector.

3. Detectability of the BHMACHO binaries by the Brazilian spherical detector

The detectability of the GWs emitted by BHMACHO binaries, by either interferometers or resonant mass detectors, is easily discussed in terms of the waves' 'characteristic amplitude' h_c (see, e.g., Nakamura *et al* 1997, Thorne 1987):

$$h_c = 4 \times 10^{-21} \left(\frac{M_{\rm chirp}}{M_\odot}\right)^{5/6} \left(\frac{f_{\rm GW}}{100\,{\rm Hz}}\right)^{-1/6} \left(\frac{r}{20\,{\rm Mpc}}\right)^{-1}, \qquad (1)$$

where $M_{\rm chirp} = (M_1 M_2)^{3/5}/(M_1 + M_2)^{1/5}$ is the 'chirp mass' of the binary whose components have individual masses M_1 and M_2; and r is the source–earth distance. The h_c must be compared with a GW detector's 'sensitivity to bursts'.

A BHMACHO binary of $0.5M_\odot$ components, at 20 kpc to the earth, is emitting GW at the Brazilian spherical detector band with a characteristic amplitude of $h_c \sim 10^{-18}$. Since

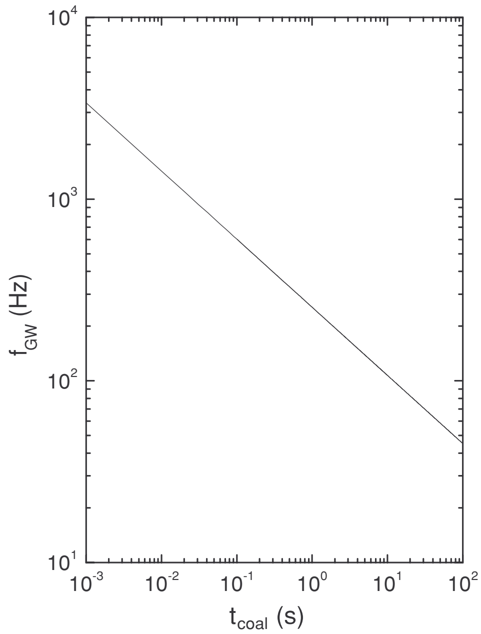

Figure 1. The frequency of the GW, f_{GW}, as a function of the coalescing time, t_{coal}, for a pair of $0.5M_{\odot}$ BHMACHOs.

the Brazilian spherical detector's sensitivity to burst is expected to be $h_s \sim 10^{-20}$, the signal-to-noise ratio gives SNR $\sim$ 100. Obviously the interferometers and the bars also detect such systems, in particular the Galactic ones, at high values of signal-to-noise ratios.

As seen, it would be very easy to detect BHMACHO binary systems, but the main question here is how many of them are expected to be detected, i.e., what is the event rate.

To assess the event rate related to the BHMACHO binary systems, we follow Nakamura *et al* (1997), who study the formation of such systems. They consider that the BHMACHOs are part of the cold dark matter, which is distributed throughout the universe.

Nakamura *et al* obtain, in particular, the probability distribution for the coalescence time for BHMACHO binaries. We refer the reader to their paper for a detailed discussion of this issue.

Although Nakamura *et al* derived the distribution function for the coalescence, and we are dealing with the spiralling phase, in particular the chirping phase, it is a good approximation to use their results since we are at most, in the case of interferometers, at 10 s of the coalescing phase.

For BHMACHOs in galaxies, such as our Galaxy, they find that the event rate is $\sim$0.05 events/yr. Although the SNR for Galactic BHMACHO binaries could be very high, it is not expected to detect them easily.

It is easy to show, using equation (1), that the Brazilian detector could be sensitive to BHMACHO binaries of the whole local group ($r \sim 1.5$ Mpc). But only M31 and M33 can give a significant contribution to the event rate. The Galaxy, M31 and M33 account for more then 90% of the local group mass. Considering that the contribution of M31 and M33 is similar to that of the Galaxy, one would expect to detect with the Brazilian detector 1 BHMACHO binary every 7 years.

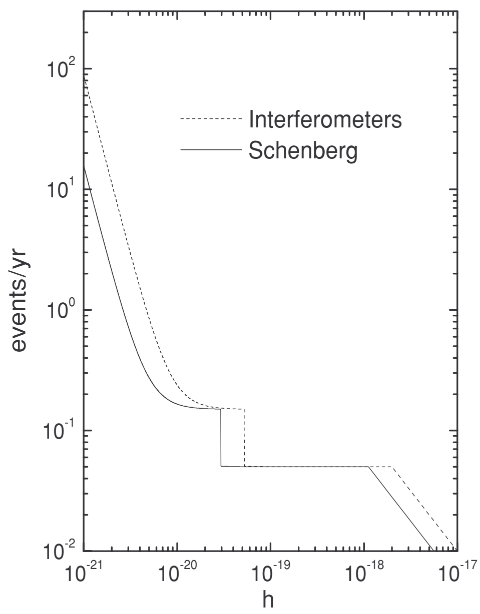

Figure 2. Event rate, in events per year, as a function of the sensitivity for interferometric detectors at 100 Hz, and for the Brazilian spherical detector at 3 kHz. We take into account the following contributions: the Galaxy, M31, M33 and the intergalactic BHMACHOs.

Let us now consider the contribution of the BHMACHO binaries distributed throughout the universe. Recall that the MACHO project estimate that 20% (with a 95% confidence interval of 8%–50%) of the Galactic halo could be in the form of BHMACHOs. We assume that the BHMACHOs are ∼20% of the dark matter too.

In figure 2 we show the event rate as a function of the sensitivity for interferometric detectors at 100 Hz, and for the Brazilian spherical detector. We consider a signal-to-noise ratio equal to unity. It is worth stressing that we are taking into account the following contributions: the Galaxy, M31, M33 and the intergalactic BHMACHOs, i.e., those distributed throughout the universe. Note that the curve for the resonant bar detectors, which is not plotted, would be located in between the curves for interferometers and the Brazilian detector. The event rate for the bars would be almost the same as the Brazilian detector.

Figure 2 has been constructed as follows. First of all, instead of using the event rate as a function of distance, we use equation (1) to obtain the event rate as a function of *h* for a given frequency and BHMACHO binaries' masses.

For distances below 20 kpc the event rate increases linearly from the centre to the border of the Galaxy, where the event rate is 0.05 events/yr. This corresponds to the linear segment on the right side of figure 2. From the border of the Galaxy up to just before reaching M31 and M32 the intergalactic BHMACHOs might be important, but since they follow the distribution of the dark matter their contribution is negligible. That is why there is a plateau in figure 2.

For a distance of 700–800 kpc, where M31 and M32 are located, there is an additional contribution of 0.05 events/yr from each of them. This corresponds to the step seen in figure 2.

For larger distances, say >1 Mpc, the background BHMACHOs' contribution to the event rate begins to be relevant and eventually the dominant contribution (see the left side of figure 2). Since the BHMACHO distribution is assumed to be homogeneous throughout the intergalactic medium its contribution to the event rate scales with the cubic power of the distance.

It is worth mentioning that, to calculate the event rate related to the intergalactic BHMACHO, it is necessary to take into account the BHMACHO coalescing rate, which has been calculated using equation (11) of the paper by Nakamura *et al* (1997).

Finally, note also that if the Brazilian spherical detector's sensitivity to bursts reaches $h_s \sim 10^{-20}$–10^{-21}, the prospect of detecting BHMACHO binaries can be several per year.

4. Conclusions

We consider in the present paper the detectability of the putative BHMACHO binaries by the Brazilian spherical detector.

We show that BHMACHO binaries of $0.5 M_\odot$ components can be detected by the Brazilian detector at a very high SNR for Galactic sources. However, the prospect of detecting such systems in the Galaxy is at most 1 every 20 years.

Considering that such systems are ubiquitous among the galaxies, and as a form of dark matter are distributed throughout the whole universe, the prospect of their detection can be significantly improved if the Brazilian spherical detector's sensitivity to bursts reaches $h_s \sim 10^{-20}$–10^{-21}.

Note that resonant bar detectors would see almost the same as the Brazilian spherical detector, while interferometers would see a higher event rate, since they have more sensitivity to this kind of signal than the other detectors.

Last, but not least, it is worth mentioning that one spherical detector can determine the direction of the BHMACHO binaries, while some bars and/or interferometers are necessary to do the same.

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References

Alcock C *et al* 1993 *Nature* **365** 621
Alcock C *et al* 2000 *Astrophys. J.* **542** 281
Aubourg E *et al* 1993 *Nature* **365** 623
Burles S, Nollett K M and Turner M S 2001 *Astrophys. J.* **552** L1
Forward R L 1971 *Gen. Rel. Grav.* **2** 149
Griest K 1991 *Astrophys. J.* **366** 412
Magalhães N S, Johnson W W, Frajuca C and Aguiar O D 1995 *Mon. Not. R. Astron. Soc.* **274** 670
Magalhães N S, Johnson W W, Frajuca C and Aguiar O D 1997 *Astrophys. J.* **475** 462
Nakamura T, Sasaki M, Tanaka T and Thorne K S 1997 *Astrophys. J.* **487** L139
Paczyński B 1986a *Astrophys. J.* **301** 503
Paczyński B 1986b *Astrophys. J.* **304** 1

Peacock J 1999 *Cosmological Physics* (Cambridge: Cambridge University Press)
Peters P C and Mathews J 1963 *Phys. Rev.* **131** 435
Spergel D N *et al* 2003 *Preprint* astro-ph/0302209
Thorne K S 1987 *300 Years of Gravitation* (Cambridge: Cambridge University Press) p 331
Udalski A, Szymański M, Kaluzny J, Kubiak M and Mateo M 1992 *Acta Astron.* **42** 253
Yokoyama J 1977 *Astron. Astrophys.* **318** 673