INSTITUTE OF PHYSICS PUBLISHING CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **22** (2005) S1021–S1026 doi:10.1088/0264-9381/22/18/S16

Searching for quasi-periodic gravitational waves from low mass x-ray binaries with AURIGA

A Mion[1], M J Benacquista[2], A Ortolan[3], M Cerdonio[4] and G A Prodi[1]

[1] Dipartimento di Fisica, Università di Trento and INFN, Gruppo Collegato di Trento, Sezione di Padova, I-38050, Povo, Trento, Italy
[2] Department of Biological and Physical Sciences, Montana State University-Billings, Billings, MT 59101, USA
[3] Laboratori Nazionali di Legnaro, Istituto Nazionale di Fisica Nucleare, 35020 Legnaro, Padova, Italy
[4] Dipartimento di Fisica, Università di Padova and INFN, Sezione di Padova, Via Marzolo 8, I-35131, Padova, Italy

E-mail: mion@science.unitn.it

Received 31 March 2005, in final form 10 June 2005
Published 6 September 2005
Online at stacks.iop.org/CQG/22/S1021

Abstract

Astrophysical models indicate that low mass x-ray binaries (LMXBs) are very promising as sources of continuous, quasi-periodic gravitational waves at high frequencies, such as those at which resonant bar detectors are operating. In this preliminary paper we quickly derive the expected amplitude of the gravitational wave signals. We show that it is likely that there may be some objects emitting in the AURIGA band. We are producing a database of possible sources and identifying the most promising ones. Our preliminary result indicates that we can achieve a good sensitivity with an observation time of about 10 days thanks to the improved sensitivity of the upgraded AURIGA detector. We also show what will be possible to perform with the advanced resonant detectors (DUAL). Finally, we briefly outline the general features of the analysis method we intend to apply postponing to a future paper the detailed discussion.

PACS numbers: 04.80.Nm, 95.85.Sz

1. Introduction

Low mass x-ray binaries (LMXBs) are systems composed of a low mass star (i.e. $M < 1\,\mathrm{M}_\odot$) and an old, recycled neutron star (NS) that is accreting matter from its companion [1]. The accretion should be able to spin up the NS to rotational frequencies that are higher than observed. The emission of gravitational waves (GW) has been proposed as a limiting mechanism to the spin-up process. The gravitational waves from some LMXBs may be detectable by resonant bar detectors.

2. Expected amplitudes

We want to obtain an estimate of the GW amplitude an LMXB can generate. We begin, for simplicity, by seeing what would occur if the star is not magnetized. Although this is not the case with LMXBs, we will apply these results later when we take into account the effect of the magnetosphere.

The Keplerian velocity at the NS surface is

$$\Omega_{\mathrm{K}}(R_{\mathrm{NS}}) = \left(\frac{GM_{\mathrm{NS}}}{R_{\mathrm{NS}}^3}\right)^{1/2} \simeq 13.6 \times 10^3 \ \mathrm{s}^{-1}, \tag{1}$$

where M_{NS} and R_{NS} are respectively the mass and radius of the NS. This corresponds to a period of $P_* \simeq 0.461$ ms. This is the value at which a non-magnetized NS cannot be spun up anymore by accretion. If $P > P_*$, and the star is not magnetized, then accretion will occur exactly at the surface, and the angular momentum transferred to the star by accretion will be

$$\tau = \dot{M}\Omega_{\mathrm{K}}^2 R_{\mathrm{NS}}, \tag{2}$$

since matter accreted at the rate $\dot{M}$ will have angular velocity exactly equal to Ω_{K} at the NS surface. If the star is a rigid body and the accretion disc strongly couples with the NS crust, then the angular acceleration will be $\alpha = \tau/I$, where I is the NS moment of inertia. Substituting numerical values, we get $\alpha \simeq 2 \times 10^{-12}$ s^{-2}, using the typical value $I = 10^{38}$ kg m^2 for a canonical NS. Given the angular acceleration α, the corresponding period derivative is

$$\dot{P} = \frac{2\pi\alpha}{\omega^2}. \tag{3}$$

For a rapidly rotating star, i.e. assuming $\nu = 500$ Hz, we find $\dot{P} \simeq 10^{-18}$. The energy derivative, still assuming the NS is a rigid body, will classically be

$$\dot{E} = 4\pi^2 \frac{I}{P^3}\dot{P} = 2 \times 10^{30} \ \mathrm{J\ s}^{-1}. \tag{4}$$

If we assume that the NS doesn't spin up because all of this energy is emitted via gravitational waves (GW), the corresponding strain amplitude at a distance r from the source to the Earth is

$$h = \left[G\frac{\dot{E}}{c^3\omega_{\mathrm{GW}}^2}\right]^{1/2} \frac{1}{r} \simeq 2 \times 10^{-26}, \tag{5}$$

with $\omega_{\mathrm{GW}} = 2\pi \cdot 1$ kHz and $r = 10$ kpc. This model, even with some modifications, has been considered viable, see, for example [2]. It has been improved, although the general idea remains the same, in [3]. In fact, in [2] the authors perform the calculations neglecting the possible presence of an elastic response of the crust, treating it as perfectly rigid. However, what is shown in [3] is that, for a reasonable model of the crust, the general results are still robust.

Now, we consider the case of a magnetized star. Following [4], we will assume the magnetic field B to be that of a dipole: $B(r) = (R_0/r)^3 B_0$, where B_0 is the field at the surface R_0 of the NS. We will also assume the accretion to be spherically symmetric. First, we have to calculate the distance from the NS at which matter will be accreted. A simple way to calculate an order of magnitude for the magnetosphere radius is to calculate the distance from the NS at which the pressure due to the magnetic field on the infalling accreted charged particles is equal to the internal pressure of the infalling gas [4]. The magnetic pressure can be written as

$$P_B = \frac{[B(r)]^2}{8\pi} = \frac{B_0^2 R_0^6}{8\pi} r^{-6}, \tag{6}$$

while for the internal pressure of the gas we can write, if the gas falls from rest at infinity,

$$P_g = \rho v^2 = \rho G M_{\rm NS} r^{-1}, \tag{7}$$

where ρ is the density and v the velocity, here approximated with that of a free-fall. The density can be easily written in terms of the mass transfer, in fact $\rho = \dot{M}/(4\pi r^2 v)$, and so $P_g = (\dot{M}v)/(4\pi r^2)$. The value of r at which the equilibrium is reached is an approximation of the magnetosphere radius R_* (see [4]):

$$R_* = G^{-1/7} B_0^{4/7} R_0^{12/7} M_{\rm NS}^{-1/7} \dot{M}^{-2/7}. \tag{8}$$

Substituting the values $B_0 = 10^8$ Gauss = 10^4 T, $R_0 \simeq 10$ km, $\dot{M} = 10^{-9}\ M_\odot\ {\rm yr}^{-1}$, we finally get $R_* \simeq 2R_0$: the magnetosphere radius, in these old, recycled NS, is only about twice the star's radius. This means that the angular momentum transferred to the star by accretion, and so the amount of gravitational waves, will be similar to the non-magnetized case. In fact, equations (2)–(5) show that there will be only a factor of $\sqrt{2}$ increase in h, and so we finally find

$$h \simeq 3 \times 10^{-26}. \tag{9}$$

For some years in the literature, the r-mode instability has been studied as an alternative mechanism to remove angular momentum from the NS. In principle, this instability can grow in all rapidly rotating NS. However, various dissipation mechanisms could damp the mode on a much shorter timescale, preventing its growth and thus eliminating it as a substantial source of gravitational waves. It now seems clear that steady r-modes are not likely to play an important role [2]. Because, as argued in [5], the equilibrium between spin-up due to accretion and spin-down due to gravitational radiation is unstable, an interesting situation occurs in which the star is characterized by a limit cycle: the star charges itself for several million years until the instability grows, and then the star slows down due to GW emission. The relative duration of these charging and emission cycles strongly depends on the amplitude at which the mode saturates. For our 'observational' point of view, it is important to have an idea of this relative duration. Unfortunately, this aspect is not well understood. The first estimation of these r-mode cycles can be found in [6]. Here the discussion takes into account the fact that, due to different viscosities in the NS fluid, the instability can arise only in a narrow window of the temperature of the NS core, which is expected to be about 1–4 × 10^8 K in LMXBs. They find that the r-mode is active only for a small fraction of the lifetime of the system, lasting about 1 month while the time required to turn the emission on is about 10^7 yr. However, given the fact that the total energy which is radiated at each cycle is constant, the smaller the duration of emission, the greater the GW amplitude. Calculations show that these signals could be seen from the distances of the galaxies in the Virgo cluster, so r-modes are still interesting if one performs a blind search for unknown sources. In 2000 Lindblom *et al* [7] showed that r-modes cannot become unstable (and thus emit GWs) if the crust is completely rigid because of the viscous dissipation in the boundary layer between the outer fluid and the inner crust. However, about this point, Levin showed that if the crust is not completely rigid and can 'adapt' itself to the motion of the undergoing fluid [5], the relative velocity between the outer fluid and the crust can be lower, and so the r-mode can grow before it is damped by viscosity. It's important to note that, in the case of LMXBs where accretion rates are probably sufficiently stable, it is sufficient to use the linearized equations of fluid dynamics, and so the frequency at which most of the signal is emitted is exactly $\Omega_{r\text{-mode}} = 4/3\,\Omega_{\rm NS}$. Current estimates show that GW emission probably lasts about 10^3–10^4 yr every 10^8 yr. If this is the case, we will have no more than about one emitting source every 10^4, and so for our purpose of a targeted search the probability of finding one of them in the emitting phase is too low,

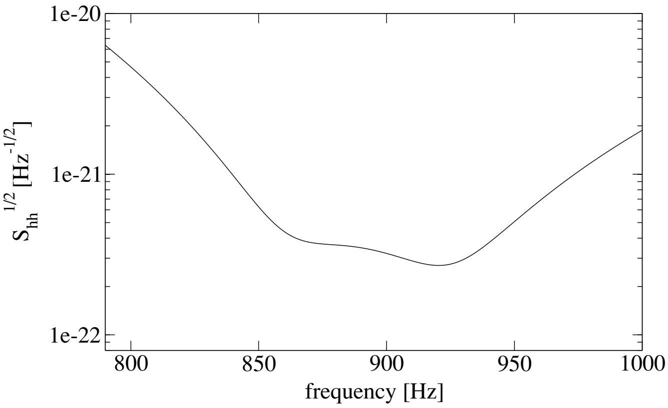

Figure 1. AURIGA run II goal sensitivity [11].

given the size of our database of sources to look at. We can conclude that, for our purpose, this second emission mechanism is not a likely source of measurable GWs.

3. Clustering of NS spins towards high frequencies

It has been observed (see, for example [8]) that spins of NS in accreted systems tend to be clustered at high frequencies. In support of this, there are both simulations of the dynamics of such systems and observations. Among the observations, good evidence of this has been found in globular clusters, in particular 47 Tuc [8]. Among the galactic LMXBs considered in this paper, there are some whose spin has been indirectly measured, using phenomena such as kHz QPOs or burst oscillations. Other demonstrations of this clustering, which is a very promising feature for resonant detectors, come from Monte Carlo simulations of accretion in LMXBs. We refer, in particular, to a simulation of [9] in which a population of old NS rotating at very low frequency begin to accrete matter. Under some assumptions about the average value of the magnetic field and the amount of transferred mass (values that are sufficiently well known from x-ray observations), and depending on the equation of state (EoS), the authors found that, in the case of a soft EoS, final rotation periods are clustered onto very small values, as low as 0.7 mHz. Considering the frequency of the fastest discovered radio pulsar, this allows us to conclude that the frequency range at which resonant detectors are operating is probably a very lucky choice. In the case of stiff EoS, final periods are found to be uniformly distributed between ~1–10 ms, and so the number of objects emitting in the band could be lower, but interesting nonetheless.

4. Discussion about reachable upper limits and their astrophysical implications

In this section, we show what observations could be done in two experimental cases: AURIGA at its goal sensitivity [11] and a DUAL SiC, also at the goal sensitivity [10]. Spectra are shown in figures 1 and 2.

Given the fact that, in the case of optimal filtering, the signal-to-noise ratio grows with the square root of the integration time, it is easy to calculate that the best upper limits that could be achieved with AURIGA and with DUAL SiC are on the order of $h_{\rm min} \simeq 3 \times 10^{-25}$ and $h_{\rm min} \simeq 2 \times 10^{-26}$, respectively. These values have been calculated with an effective integration time of 10 days. As can be seen, values for AURIGA are not too far from theoretical predictions

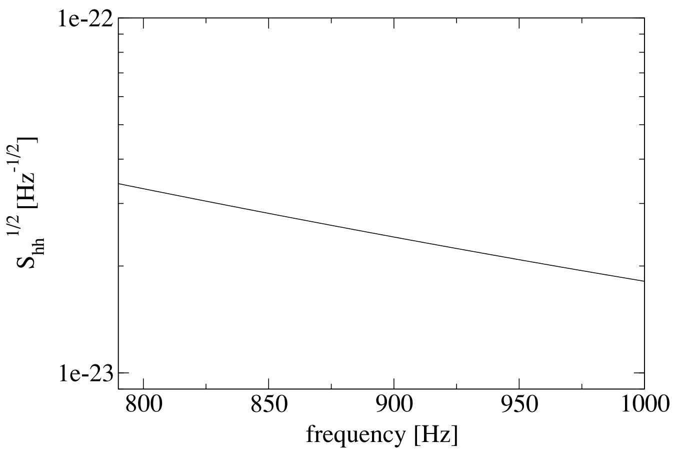

Figure 2. DUAL SiC goal sensitivity [10].

and are thus good to test physical parameters of these systems that are not well known, such as the true magnetosphere radius. The value for DUAL shows that an order of magnitude improvement in detection could also be possible.

5. General features about the data analysis

We are in the process of developing a database of targeted galactic LMXBs. Here we briefly underline some features of the data analysis. First, the intrinsic frequency of the signal is modulated by both terrestrial and source Doppler shifts. Sometimes the central frequency is known, sometimes it is not. Moreover, some orbital parameters are not known. In general, we will be able to infer how large the maximum Doppler shift could be, but we will not be able to analytically follow the non-linear phase evolution with the necessary precision. The signal is in the form

$$H(t) = \left[h_0^+ A^+(t) + h_0^\times A^\times(t)\right] \cos\left(\phi_0 + 2\pi\nu_{gw} t + \phi_D(t)\right), \qquad (10)$$

where h_0^+ and $h_0^\times$ are the signal amplitudes along two independent polarizations, $A^+(t)$ and $A^\times(t)$ are the antenna pattern factors, ϕ_0 is the (unknown) initial phase, ν_{gw} is the intrinsic frequency of the gravitational wave, ϕ_D is the amplitude of Doppler modulation, which depends on both the inclination of the orbital plane and the mass of the companion star. The analysis of the phase of the signal and the detection statistics does not differ from other analyses discussed in the literature [12, 13]. In cases in which the intrinsic central frequency is known, we will open a frequency window around the central frequency; in the other cases, we will need to cover all possible values of the central frequencies, by using partially overlapping windows, and suppose a very general time evolution of the phase, like a simple series expansion [12, 14]. The analysis we are implementing will give, in the case of detection, the values of coefficients in this expansion.

6. Conclusion

We have shown that LMXBs have the potential to be detected by resonant bar detectors such as AURIGA or DUAL. We have begun development of a data analysis strategy for extracting the signals from these sources.

References

[1] Van der Klis M 2000 *Ann. Rev. Astron. Astrophys.* **38** 717–60
[2] Ushomirsky G *et al* 2000 *Proc. 3rd Edoardo Amaldi conf. on Gravitational Waves*
[3] Ushomirsky G *et al* 2000 *Mon. Not. R. Astron. Soc.* **319** 902
[4] Padmanabhan T 2001 *Theoretical Astrophysics Volume II: Stars and Stellar Systems* (Cambridge: Cambridge University Press)
[5] Levin Y and Ushomirsky G 2001 *Mon. Not. R. Astron. Soc.* **324** 917
[6] Andersson N *et al* 2000 *Astrophys. J.* **534** L75
[7] Lindblom L *et al* 2000 *Phys. Rev.* D **62** 084030
[8] Bildsten L 1998 *Astrophys. J.* **501** L89
[9] Possenti A *et al* 2000 *Astrophys. J. Suppl.* **125** 463–78
[10] Bonaldi M *et al* 2003 *Phys. Rev.* D **68** 102004
[11] Zendri J *et al* 2002 *Class. Quantum Grav.* **19** 1925–33
[12] Jaranowski P *et al* 1998 *Phys. Rev.* D **58** 063001
[13] Allen B, Papa M A and Schutz B F *Phys. Rev.* D **66** 102003
[14] Astone P *et al* 2002 *Phys. Rev.* D **65** 042003