

Excitation of Neutron Star f-mode in Low Mass X-ray Binaries

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Abstract. Neutron Stars (NSs) present a host of pulsation modes. Only a few of them, however, is of relevance from the gravitational wave (GW) point of view. Among the various possible modes the pulsation energy is mostly stored in the f-mode in which the fluid parameters undergo the largest changes. An important question is how the pulsation modes are excited in NSs. Here we consider the excitation of the f-mode in the accreting NSs belonging to Low Mass X-ray Binaries (LMXBs), which may well be a recurrent source of GWs, since the NSs are continuously receiving matter from their companion stars. We also discuss the detectability of the GWs for the scenario considered here.

1. Introduction

Relativistic stars are known to have a host of pulsation modes. Only a few of them, however, is of relevance for gravitational wave (GW) detection. Concerning the GW point of view the most important modes are the fundamental (f) mode of fluid oscillation, the first few pressure (p) modes and the first GW (w) mode [1]. Among these three modes the pulsation energy is mostly stored in the f-mode in which the fluid parameters undergo the largest changes. It is worth mentioning that the r-mode can also be, under certain circumstances, a very important source of GWs for the neutron stars (NSs) [2].

An important question is how pulsation modes are excited in the NSs, which are of our concern here. There are many scenarios that could lead to significant asymmetries. Supernova explosions are expected to form a wildly pulsating NSs that emit GWs. A pessimistic estimate for the energy radiated as GWs indicates a total release equivalent to $< 10^{-6} M_{\odot}$. An optimistic estimate, when the NS is formed, for example, from strongly non-spherical collapse, suggests a release equivalent to $10^{-2} M_{\odot}$. (see, e.g., Ref. [3]).

Another possible excitation mechanism for NS pulsation is a starquake, which can be associated with a pulsar glitch. The energy released in this process may be of the order of the maximum mechanical energy stored in the crust of the NSs, which is estimated to be of $10^{-9} - 10^{-7} M_{\odot}$ [4, 5]. In a recent study [6] we consider the detectability of f-mode NSs in this scenario.

During the coalescence of two NSs several oscillation modes could in principle be generated. Stellar oscillations being excited by the tidal fields of the two stars, for example.

The NS may undergo a phase transition leading to a mini-collapse, which could lead to a sudden contraction during which part of the gravitational binding energy of the star would

be released, and, as a result, it could occur that part of this energy would be channelled into pulsations of the remnant. Similarly, the transformation of a NS into a strange star is likely to induce pulsations.

Excitation of f-mode in LMXBs is also possible, and in this case the GW could well be recurrently produced, since the NS is continuously receiving matter from its companion star.

Concerning the f-mode unstable NSs, we have recently studied their detectability by the Brazilian detector [6], the Schenberg antenna. However, we have only considered the isolated NSs that could be excited by starquakes, which can be associated with pulsar glitches. We showed that several events every year could be detectable by Schenberg. In the present paper we consider a scenario of f-mode excitation of NSs related to the LMXBs.

This paper is organized as follows. In section 2 we briefly discuss how the excitation of the f-mode can take place in NSs belonging to LMXBs, in section 3 we discuss the detectability of the GWs produced in this scenario, and finally in section 4 we present the main conclusions.

2. Neutron Stars in LMXBs: f mode excitation

The LMXBs are semi-detached binaries consisting of either a neutron star or a black hole primary, and a low-mass secondary which is filling its Roche lobe. There are known approximately 160 of these systems in the Galaxy.

The LMXBs usually presents disk, which is though to extend to stellar surface. The accretion rates are around $10^{-8} - 10^{-11} M_{\odot}/\text{yr}$. Since the NSs continuously accrete matter they turn the LMXBs potential sources of GWs.

An interesting characteristic of the LMXBs is the fact that the observed and inferred spin frequencies of the NSs are concentrated around 250-500 Hz. This means that in some way the NSs are losing the angular momentum they gain during the accretion process.

There are basically two alternative explanations to account for the emission of GWs in this case. The accretion process could generates a “mountain”, which turns the rotating star a time dependent mass quadrupole moment generating as a result GWs. The other alternative refers to the r-mode instability, which could make the NS liquid core emit GWs.

What we argue here is that during the accretion process the f-mode could be also excited, making the NSs emit GWs.

The excitation of the f-mode in the accretion process was recently studied by [7], who showed that the f-mode can be excited by accreted matter.

Since the accretion rate in the LMXBs is of $\sim 10^{-15} M_{\odot}/\text{s}$ or less, the excitation of the f-mode due to the accretion should be negligible.

However, the reader should recall that the NSs in LMXBs erupt in a thermonuclear process every few hours or days. This event is observed as a X-ray burst [8]. Of the approximately 160 known LMXBs about 70 are observed to produce bursts.

Since the nuclear energy release per baryon, in this case, is around 5 Mev [8] this X-ray burst does not yield enough energy to shake the NS exciting significantly its f-mode.

There is, however, a recently discovered kind of burst named superburst [9], whose observed energy is much greater than that produced in a normal burst. Cooper and Narayan [11] comment that all nine superbursts so far observed had energies of $\sim 10^{42}$ ergs and were detected in systems with accretion rates between 10% and 30% of the Eddington limit.

The superburst recurrence times are not well constrained, although three have been observed within 4.7 years from the system 4U 1636-536 [10, 11].

Because superburst is a relatively new phenomenon it is early to conclude how many LMXBs present this kind of burst and, therefore, what is superburst expected event rate. A very hough estimate, based simply only on the known superbursts, is an event rate of two superbursts every year.

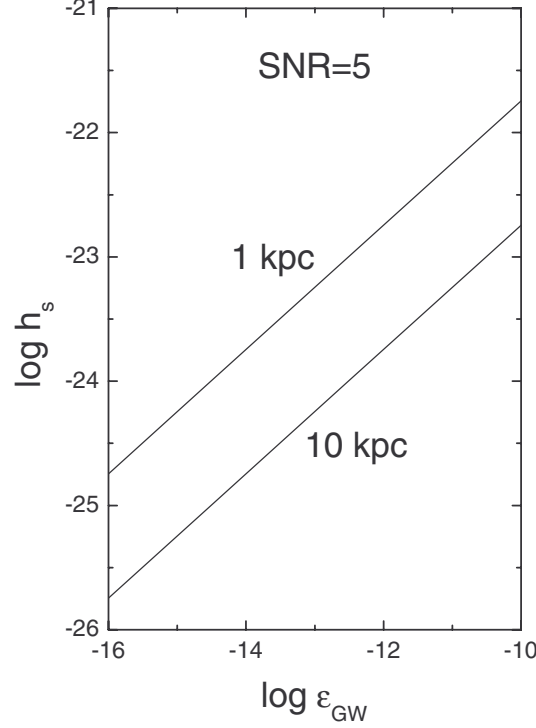


Figure 1. Sensibility h_s required to detect a source as a function of ϵ_{GW} for $\text{SNR} = 5$ and for sources located at 1 and 10 kpc.

Finally, it is worth mentioning that Strohmayer and Brown [12] proposed a model where the thermonuclear ignition of the material accreted by the NSs would account for the energy released in the superbursts. In their scenario an energy of $10^{43} - 10^{44}$ ergs would escape as neutrinos or would be conducted into the star, leaving 10^{42} ergs to emerge from the surface within a few hours.

We argue that the energy conducted into the NS could be channeled to excite the f-mode. In the following section we discuss the possible detection of the f-mode related to the superburst based on this scenario.

3. Detectability of f mode in LMXBs

It is worth recalling that the characteristic amplitude of GWs related to the f-mode instability is given by

$$h \simeq 2.2 \times 10^{-21} \left(\frac{\epsilon_{GW}}{10^{-6}} \right)^{1/2} \left(\frac{2 \text{ kHz}}{f_{GW}} \right)^{1/2} \left(\frac{50 \text{ kpc}}{r} \right), \quad (1)$$

(see, e.g., Ref. [13]) where ϵ_{GW} is the efficiency of generation of GWs, f_{GW} is the GW frequency, and r is the distance to the source.

Concerning f_{GW} , it is worth recalling that it depends on the equations of state (EOS) for the NS that, as is well known, is not completely established. We refer the reader to the paper by Kokkotas and Andersson [14], in particular its figure 2, where it is shown that, for a family

of EOSs, GWs of $\sim 2 - 4$ kHz may be produced by f-mode unstable neutron stars. In our calculation we assume a characteristic value of $f_{GW} = 3$ kHz.

A difficulty related to the calculation of the GW amplitude is because the distance for the LMXBs are known for only a couple of them. Since the LMXBs are found mostly towards the galactic center and in globular clusters, we assume for simplicity that most of them are at a distance of 10 kpc.

Last but not least, to evaluate h we need to know ε_{GW} . We are assuming that the energy available to excite the f-mode in accreting NSs is associated with the energy generated in superbursts.

As we have discussed in the preceding section, in the thermonuclear ignition model by Strohmayer and Brown [12] to account for the superbursts, an energy of $10^{43} - 10^{44}$ ergs would escape as neutrinos or would be conducted into the star. If all this energy is channeled to excite the f-mode, this would mean that $\varepsilon_{GW} \sim 10^{-11} - 10^{-10}$.

This efficiency is obviously an upper limit, since much probably only a small fraction of the energy associated with the superburst is channeled to the f-mode, this means that $\varepsilon_{GW} \ll 10^{-10}$.

To know the actual energy channeled to the f-mode one would need to model in detail the superburst energetics, which is a very complicated task. Here, therefore, we do not address our study to such an issue.

In figure 1 we present for a signal-to-noise ratio (SNR) of five and for sources located at 1 and 10 kpc, the sensibility h_s required to detect a source as a function of ε_{GW} .

Note that for $\varepsilon_{GW} \sim 10^{-11}$, $f_{GW} = 3$ kHz and $r = 10$ kpc, the sensitivity of a given detector to a burst source should be of a least of $h_s \sim 10^{-23}$. Such a sensitivity could be in principle achieved for the advanced LIGO operating as a narrowband interferometer (see, e.g., Ref. [15]).

On the other hand, for a lower GW efficiency generation, such as $\varepsilon_{GW} \sim 10^{-15}$, and also for $f_{GW} = 3$ kHz and $r = 10$ kpc, the sensitivity of a given detector to a burst source should be of the order of $h_s \sim 10^{-25}$. In such a case the detection could be very difficult.

Based on the superbursts observed in LMXBs, we argue that two events every year could be in principle detected with a detector with a sensitivity of $h_s \sim 10^{-23}$, if the efficiency of generation of GWs could achieve $\varepsilon_{GW} \sim 10^{-11}$.

4. Conclusions

We argue that it is worth paying attention to f-mode unstable NS, because it can be in principle one of the most important sources of high frequency GWs.

Since the f-mode unstable NSs in LMXBs could well be a recurrent source of GWs, this implies that a non negligible event rate could occur in this case. A rough estimate, based on the event rate of superbursts in LMXBs, indicates that two events every year could be detected if a sensitivity for burst sources of $h_s \sim 10^{-23}$ could be achieved, and also if the efficiency of generation of GWs could be of $\varepsilon_{GW} \sim 10^{-11}$.

Finally, it is worth mentioning that Kokkotas *et al* [16] show that detecting the f-mode, the EOS, the mass and the radius of the NSs will be strongly constrained. The reader should appreciate the reading of this paper by Kokkotas *et al* who show in detail how these above mentioned astrophysical information is obtained from the GW data.

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