Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
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Magnetic fields in galactic binaries and gravitational waves

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Abstract. The Laser Interferometer Space Antenna (LISA) mission will observe from space gravitational waves emitted by neutron stars and white dwarfs within galactic binaries. These compact stars can have intense magnetic fields. Therefore, the impact of the magnetic fields on the orbital and the spins evolution of binary systems can potentially be detected by LISA through the GW's strain. Within the magnetic dipole-dipole approximation, we found that magnetism generates a secular drift of the mean longitude which, in turn, shifts all the frequencies contained in the GW signal. For a quasi-circular orbit, the signal is mainly monochromatic and the magnetic shift is proportional to the product of the magnetic moments and is inversely proportional to the 7/2 power of the semi-major axis. Hence, for a highly magnetic binary system in compact orbit, a non-negligible amount of the frequency measured by LISA might have a magnetic origin.

Keywords. gravitation, gravitational waves, magnetic fields, neutron stars, white dwarfs

1. Introduction

The Laser Interferometer Space Antenna (LISA) mission will observe gravitational waves (GWs) in the bandwidth from below 10^{-4} Hz to above 10^{-1} Hz. In this frequency window, the main sources of GWs are the galactic binaries which are comprised primarily of white dwarfs (WDs) and neutron stars (NSs). It is expected that more than ten thousands of galactic binaries should be resolvable by LISA. Among these, tenth of them are of a particular interest since they are guaranteed sources for LISA, with an expected timescale of detection of the order of few weeks. Indeed, these "verification binaries" are already identified as GW sources with a high signal to noise ratio within LISA bandwidth. They will serve for calibrating the detector. Therefore any mis-modeling of the GW signal from verification binaries can potentially have an impact on the other extra-galactic scientific objectives of LISA.

Currently, galactic binaries are modeled as monochromatic sources, that is to say assuming a purely circular orbit within the Newtonian picture of two point-masses orbiting around each other. However, the situation can be slightly different e.g., if the orbit is eccentric, the GW strain is not expected to be monochromatic anymore. In addition, we could also could also expect a more complex signal that would result e.g. – from perturbations due to internal processes in WDs and NSs. As a matter of fact, WDs and NSs are among the most magnetized objects of the universe, with magnetic fields that can reach up to 10^9 G for WDs and up to 10^{15} G for NSs [Ferrario *et al.* (2020)]. Since then, the impact of magnetism on the dynamics of galactic binaries must be investigated.

2. Impact of magnetism on the orbital motion

We consider two compact and well-separated bodies that are forming a binary system. The total mass is $m = m_1 + m_2$ with m_1 and m_2 the masses of primary and secondary, respectively. We consider a relativistic description of the point-mass dynamics up to 2.5 post-Newtonian (2.5PN) approximation [Blanchet (2014)]. In that sense, we treat the dynamics of the binary system coherently with the fact that orbital energy is radiated away from the source by GWs. We also consider magnetic fields within the magnetostatic approximation which corresponds to the case of "fossil fields" that are frozen into the stars [Braithwaite & Spruit (2004)]. In addition, we consider that the magnetic fields of both stars are dominated by their dipole moments which is coherent with the fossil-field hypothesis. We assume for simplicity that the direction of the magnetic moments (called μ_1 for the primary and μ_2 for the secondary) are aligned with spin directions of the stars. Within this framework, we first derive the secular equations governing the evolution of the orientations of the magnetic moments and the orbit of the binary system. We adopt osculating elements within the method of variation of arbitrary constants to describe the orbital motion. We derive the first order solutions for the rotational and the orbital motion. This allows us to show that the magnetic dipole-dipole interaction generates a secular drift on the mean longitude (L) that is given by [Bourgoin *et al.* (2022)]

$$\dot{L}_{\mathrm{dip-dip}} = \frac{3\mu_0}{4\pi\sqrt{G}} \frac{\sqrt{m}}{m_1 m_2} \frac{\mu_1\mu_2}{a^{7/2}} \frac{(1+\sqrt{1-e^2})}{(1-e^2)^2} \cos\epsilon_1 \cos\epsilon_2, \tag{2.1}$$

where G is the gravitational constant, μ_0 is the permittivity of vacuum, a is the semi-major axis, e is the eccentricity, and ϵ_1 and ϵ_2 are the obliquities of the magnetic moments of primary and secondary respectively.

3. Impact of magnetism on GWs detected by LISA

At zeroth-order in eccentricity, namely the circular orbit, the GW signal emitted by a binary system is monochromatic. Then, the secular drift of the mean longitude due to the magnetic dipole-dipole interaction shifts the main frequency of the GW signal by the amount $2\dot{L}_{\mathrm{dip-dip}}$. Hence, if LISA is able to measure the main frequency Φ with an accuracy σ_Φ that is lower than the magnetic shift, namely

$$\begin{aligned}\frac{\sigma_\Phi}{\Phi} < 6.8\times10^{-7} &\left(\frac{\Phi}{10^{-1}\,\mathrm{Hz}}\right)^{4/3} \left(\frac{1.2\,\mathrm{M}_\odot}{m_1}\right) \left(\frac{0.3\,\mathrm{M}_\odot}{m_2}\right) \\ &\times \left(\frac{B_1}{10^9\,\mathrm{G}}\right) \left(\frac{B_2}{10^9\,\mathrm{G}}\right) \left(\frac{R_1}{6\times10^3\,\mathrm{km}}\right)^3 \left(\frac{R_2}{15\times10^3\,\mathrm{km}}\right)^3,\end{aligned} \tag{3.1}$$

then, one should be careful while attempting to interpret the measured frequency directly in term of binary's masses since the effect of magnetism may need to be considered. We have assumed here a binary made of highly magnetic WDs of radius R_1 and R_2.

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