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The importance of transient X-ray sources for gravitational wave physics

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The recent discovery of gravitational waves has opened a new window in observational astronomy. The X-ray sources are interesting targets of gravitational astronomy, among them X-ray binaries. Accreting neutron stars are candidates for continuous emission of gravitational waves in the sensitivity band of the advanced LIGO/Virgo interferometers. The X-ray binaries are also potential emitters of low frequency gravitational radiation in the frequency band of the forthcoming space based interferometer eLISA. The accurate knowledge of the orbital period of the X-ray binaries is necessary to estimate the gravitational emission at low frequency and to reduce the computational cost of searching the signal from accreting neutron stars. The systematic search for periodicities in the archives of X-ray missions can detect the required orbital periods and, in addition, superorbital periods. The preliminary results of a search for periodicities in the Swift/BAT and RXTE/ASM archives is presented, showing also how the estimated periodicities can provide information about the characteristics of the astrophysical sources.

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1. Introduction

The new born gravitational astronomy that started with the detection of the first mergers of binary black holes, GW150914 and GW151226 [5], [6], has a strong connection with X-ray astronomy. Several X-ray sources are potential gravitational wave emitters, among them accreting neutrons stars [46], [11]. In addition to X-ray sources that are candidate emitters of gravitational waves, the emission of X-rays is the signature of the electromagnetic counterpart of some promising sources of gravitational radiation for Advanced LIGO/Virgo, the mergers of neutron stars. The X-ray signal can be searched with X-ray observatories, such as Swift [29]. A preliminary search for transients in the horizon of advanced detectors has been performed by [30] using the data of the XMM Slew Survey, suggesting a non negligible contribution by variable objects and providing the identification of some of them. The first multiwavelength follow-up of candidate gravitational wave events selected by the first generation LIGO/Virgo interferometers has been performed by Swift [19]. An extensive electromagnetic follow-up of the GW150914 event has been performed over the whole electromagnetic spectrum [7], [8] and in the neutrino domain [9].

The X-ray sources are an extended realm that is being explored with a variety of space based experiments, since the discovery of the first extrasolar source, Sco X-1 [21]. The X-ray sources have been classified by [22], [23], [24], [25], [26], [27], who discussed their physical properties and their importance as multiwavelength laboratories in detail. Among them, the X-ray binaries play a strong role. The definition encompasses different astronomical sources whose main signature is the emission of X-rays, but that emit over the most part of the electromagnetic spectrum. The X-ray emission can be explained by the accretion of matter from a secondary star onto a compact object. The X-ray binary systems belong to two different classes. The High Mass X-ray Binary systems (HMXB) are made of a collapsed object, either a neutron star or a black hole, and a secondary star. Among the HMXBs, there are two subclasses: the Hard X-ray Binary Sources (HXTS) and the Permanent X-ray Sources (PXS). The common denominator of the two subclasses is the mechanism of mass transfer, through a stellar wind. The X-ray emission is modulated by the spin period of the compact objects, ranging from tens of milliseconds to thousands seconds. The member of the former subclass have orbits with a non negligible eccentricity, while the orbital period is in the range of a few days; the secondary is a Be star and the X-ray emission is harder than 17 keV and variable by two or three orders of magnitude in intensity during outbursts. The members of the latter subclass have orbits with negligible eccentricity and orbital periods smaller than a few days; the secondary is an OB star, while the X-ray emission is harder than 9 keV and nearly constant. The relation between the orbital period and the spin period of the X-ray pulsars shows a splitting of the HMXBs into separate subclasses: wind fed OB systems and Be systems (whose pulse periods behave as an increasing power of the orbital period) and disk fed systems (whose pulse periods behave as a decreasing power law of the orbital period) [24], [14]. The Low Mass X-ray Binary systems (LMXB) are also made of a collapsed object, either a neutron star or a black hole, and a secondary, a late type star. The mechanism of mass transfer is the Roche lobe overflow and the formation of an accretion disk. Among the LMXB objects, the Soft X-ray Transient Sources (SXTS) are identified by the soft X-ray emission, below 10 keV, and the presence of Quasi Periodic Oscillations (QPO) with periods that range from tens to thousands of milliseconds; these systems have orbital periods in the interval from hours to several days. The

HMXB and LMXB systems show remarkable differences in their spatial distribution: the former are more concentrated along the galactic plane.

The X-ray binary systems can emit gravitational waves due to their orbital motion [44]. Among them, accreting neutron stars can emit gravitational waves when the torque by accretion is balanced by the gravitational torque [46], [11]. In the following, the gravitational wave emission of X-ray binary systems will be presented, showing how these systems can act as multimessenger laboratories. The importance of an accurate knowledge of the orbital period and the preliminary results of a search for periodicities in the archives of X-ray observatories will be presented.

2. Gravitational wave emission of X-ray binaries

The ground based laser interferometers, Advanced LIGO/Virgo, are all sky monitor instruments searching for a variety of astrophysical events. Neutron stars that are accreting matter from an accretion disk can build up an angular momentum high enough to trigger the emission of gravitational radiation, achieving a steady state when the time scales of the viscous damping and the instability growth are equal [46]. The most part of the accreting neutron stars are rotating with spin frequencies of the order some hundreds Hz, within a narrow interval, suggesting that the angular momentum injected by the accretion is transformed into gravitational emission [11]. The mechanism provides a natural explanation for the the close value of the rotation frequencies, assuming that the neutron star has a net quadrupole moment, that can be produced by the deformation of the neutron star crust [45]. The expected gravitational wave signal is persistent and has a frequency that is twice the spin frequency of the neutron star. The gravitational wave strain is [46]:

$$h \sim 4 \times 10^{-27} \frac{R_6^{3/4}}{M_{1.4}^{1/4}} \left(\frac{F_x}{10^{-8}\ erg\ cm^{-2}\ s^{-1}} \right)^{\frac{1}{2}} \left(\frac{300Hz}{\nu_s} \right)^{\frac{1}{2}} \quad (2.1)$$

where F_X is the observed X-ray flux, ν_s the spin frequency, R_6 and $M_{1.4}$ are the radius and the frequency of the neutron star in units of 10^6 cm and 1.4 $M_\odot$, respectively. The estimated amplitude of the gravitational strain is in the range 10^{-26} to 10^{-27}, where Sco X-1 is the strongest sources [11]. The best candidates for gravitational wave emission are the sources that are brightest in the X-rays, the loudest one being Sco X-1. The spin frequency is measured by different techniques. Some sources show twin kHz quasi periodic oscillations (QPO), with a frequency separation almost constant in time and equal to the spin frequency. Other sources show oscillations at a frequency very close to the spin frequency during type I X-ray bursts. Accreting millisecond pulsars show intermittent pulsations. The distribution of spin periods is reported in Fig. 1. The periods range from tens of milliseconds to hundreds seconds. However, the periods are known only for less than 20% of the known low mass X-ray binaries.

The problem of searching for the continuous gravitational emission from low mass X-ray binaries has been discussed by [18]. The weakness of the predicted signal requires long observation times, of several months at least. The signal, initially monochromatic, undergoes Doppler modulation due to the Earth motion, with a spread of its energy. The measured signal must be corrected for the position of the source. The possible spindown of the source frequency produces an additional spread. The gravitational wave signal is searched using the matched filtering technique over the phase space of parameters, that includes the position of the source in the sky, the spin frequency

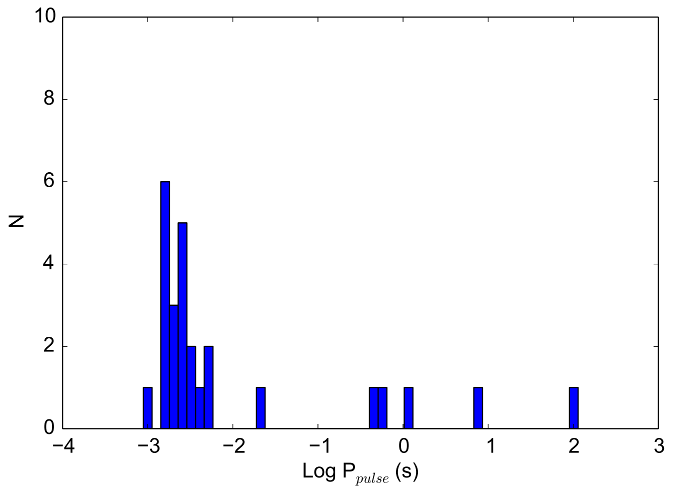

Figure 1: Distribution of the spin periods of the low mass X-ray binaries (data from [37])

and the orbital elements. The main problems to be faced in the detection of the gravitational signal of Sco X-1 and similar sources are the uncertainties on the gravitational wave frequency, related to the uncertainty on the spin frequency and the Doppler effect produced by the orbital motion of the system. A relevant part of the computational cost of the search for gravitational waves is due to the incomplete knowledge of the orbital parameters, that increases the number of required templates. The knowledge of the orbital period with high accuracy is of paramount importance to realize computationally fast pipelines for detection [18]. The orbital periods of low mass X-ray binaries are reported in Fig. 2; the period is known for less than one half of the detected systems.

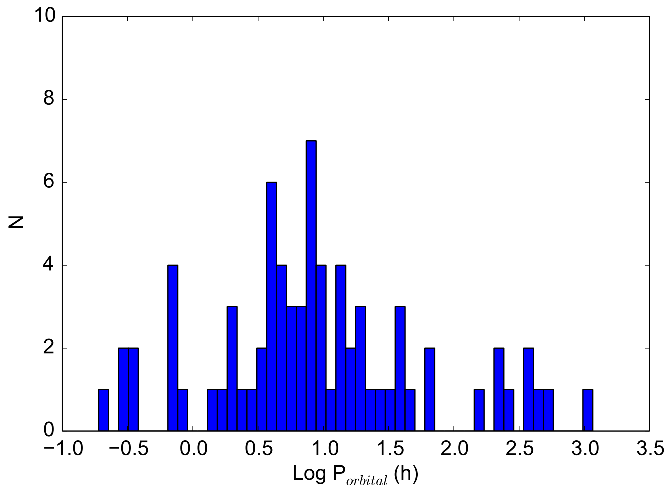

Figure 2: Distribution of the orbital periods of the low mass X-ray binaries (data from [37])

The detectability of the gravitational emission of low mass X-ray binaries in the initial and advanced interferometers has been discussed by [47]. The ground based interferometers can operate in broad band mode or in a narrow band mode, by tuning their sensitivity in a narrow frequency range at the expense of the broadband response [38]. Assuming an observation time of two years, some persistent and bright accreting neutron stars could be detected by the advanced LIGO/Virgo interferometers. The candidates are sources with QPOs in the kHz frequency range, that are more affected by uncertainties of the physical parameters than accreting millisecond pulsars and burst oscillation sources. The proposed search methods are a full coherent matched filter search with a demodulation of data and a power folding of data. The authors suggest to improve the accuracy of spin and orbital periods to decrease the number of templates.

The algorithms for the detection of the gravitational waves from the strong source Sco X-1 have been carefully investigated. A critical comparison of the search methods and the prospects for detection in advanced interferometers has been presented by [39]. Different pipelines of data analysis are discussed in detail.

The search for the gravitational wave emission of Sco X-1 has been performed in the first generation LIGO/Virgo interferometers, producing some upper limits in different frequency regions. The upper limit in the frequency bands 464-484 Hz and 604-624 Hz ranges from 1.7×10^{-23} to 1.3×10^{-21} [4]. The searches for continuous emission has set an upper limit of 7×10^{-25} in the region of maximum sensitivity around 160 Hz [3] and in the frequency range from 20 and 57.25 Hz [1]. A targeted search in the frequency band from 50 to 550 Hz has set an upper limit of the order of 1×10^{-24} around 150 Hz [2].

The X-ray binary systems can emit gravitational waves by a different mechanism linked to their orbital motion. The gravitational wave strain of a binary system is given by [44]:

$$h = 8.7\times10^{-21}\left(\frac{\mu}{M_\odot}\right)\left(\frac{M}{M_\odot}\right)^{\frac{2}{3}}\left(\frac{100\ pc}{r}\right)\left(\frac{f_{gw}}{10^{-3}\ Hz}\right)^{\frac{2}{3}} \tag{2.2}$$

where f_{gw} is the frequency of the gravitational wave, twice the orbital frequency, μ, M are the reduced and total mass of the binary, r the distance. The gravitational wave emission is in the sensitivity band of the forthcoming space based laser interferometer eLISA [10], with an arm length of 1 Million km, an evolution of the original LISA concept [36]. Among the X-ray binaries, we mention MWC 656, the first black hole/Be system [13], [28]. The source is a possible progenitor of a merging black hole-neutron star system [28].

The accurate measurement of the orbital period of the X-ray binaries is necessary for the estimation of their gravitational emission as binary systems and can decrease the computational load for the search of continuous emission from accreting neutron stars. A search for precision ephemerides of accreting neutron stars for the search of gravitational waves has been presented by [20], [41]. The orbital periods of Sco X-1 and Cyg X-2 have been determined by the optical spectroscopy of their optical counterparts. An alternative method is the systematic search of orbital periodicities in the archives of X-ray observatories [40], that will be presented in the next section.

3. Search for orbital periods in X-ray binaries

The systematic search for periodicities of X-ray binaries in archival data of X-ray observatories can detect their orbital periods, but also longer superorbital periods. The superorbital periods can be explained by the precession of a tilted accretion disk [42] or the occurring of outbursts according to the disk instability model [33]. There are a few systematic investigations of the periodicities of

X-ray binaries in the RXTE/ASM [48], [35], [31] and the Swift/BAT [17] archives. A systematic search has been started by [40] in the Swift/BAT (15-50 keV) [32] and RXTE/ASM (2-12 keV) [34] archives to discover new periodicities, to confirm and to improve known ones. The search has been performed with the SparSpec algorithm [12]. The data are modeled as the sum of the contributions of several frequencies, choosing the representation with the smallest number of non-zero amplitudes. The algorithm is suitable to analyze gapped and multiperiodic time series, as those of X-ray binaries, where both orbital and superorbital periodicities often appear. The data have been weighted taking into account the data error and the excess variability of the time series, following the procedure by [15], [16]. The periodicities detected in the complementary energy ranges of ASM and BAT are in agreement. For some sources, like the heavily obscured sources discovered by INTEGRAL/ISGRI, sometimes the periodicities are detected only in the high energy data of BAT. A sample of the results of the ongoing search for periodicities are reported in the Tables 1, 2, 3, 4. The periodicities are in agreement with the previous results [48], [35], [31], [17]. Some periodicities have been detected for the first time in Swift/BAT data.

Object	Period (days)
IGR J00370+6122	15.658
IGR J11215-5952	70.8
IGR J11435-6109	52.4
IGR J16320-4751	8.991
IGR J16393-4643	4.238
IGR J16418-4532	3.739
IGR J16465-4507	30.36
IGR J16479-4514	3.320
IGR J16493-4348	6.783
IGR J17252-3616	9.740
IGR J17354-3255	18.47
IGR J17391-3021	10.073
IGR J18027-2016	4.570
IGR J18483-0311	18.550
IGR J19140+0951	13.552

Table 1: Orbital periodicities of INTEGRAL sources

The Sparspec algorithm is efficient in detecting the presence of orbital and superorbital periodicities in several systems, such as 3A 0114+650, SS 433 and some obscured INTEGRAL sources, and the variation of the recurrence time of the outbursts in the Rapid Burster (X1730-333).

The values of the orbital periodicities estimated in the ongoing work allow to investigate the relation between the spin period and the orbital period discussed by [24], [14], using the known values of spin period [37]. The preliminary data reported in Fig. 3 show that high mass X-ray binaries with supergiant companions and with Be companions show an increase of the spin period with the orbital period. On the other hand, the low mass x-ray binaries show a decrease of the spin frequency with increasing orbital periods. The findings are in agreement with the discussion by

Object	Period (days)
LSI + 61 303	26.3
1A 0535+262	109.4
MXB 0656-072	104.1
4U 0728-25	34.55
4U 2206+54	19.13
Vela X-1	8.964
3A 0114+650	11.596
GX 301-2	41.47
SMC X-1	3.898
SS 433	13.079

Table 2: Orbital periodicities of some HMXB systems

Object	Period (days)
3A 0114+650	30.75
LMC X-4	30.37
IGR J16418-4532	14.72
IGR J16479-4514	11.88
IGR J11493-4348	20.06
SS 433	163.3
4U 1909+07	15.18

Table 3: Superorbital periodicities of some HMXB systems

Object	Period (days)
Cir X-1	16.54
Her X-1	34.87
Rapid Burster	116, 156, 87 in BAT, 103 and 208 in ASM
KS 1716-389	98.5
H 1820-303	168.2

Table 4: Orbital and superorbital periodicities of some LMXB systems

[24].

It has been suggested that the orbital and superorbital periods of X-ray binaries are correlated [49], [43], [17]. The preliminary data reported in Fig. 4 show the correlation reported by previous authors, but with a different behavior for the high mass X-ray binaries with Be secondaries and with supergiant secondaries.

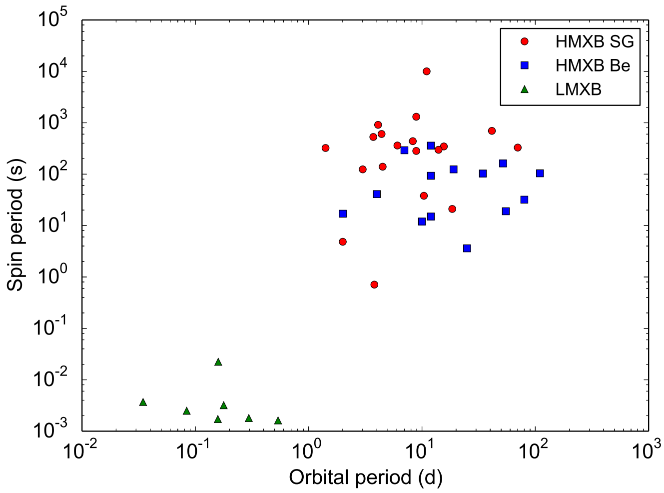

Figure 3: Dependence of the spin period on the orbital period of X-ray binaries, split by their type: HMXB systems with supergiant companion, with Be companion and LMXB systems

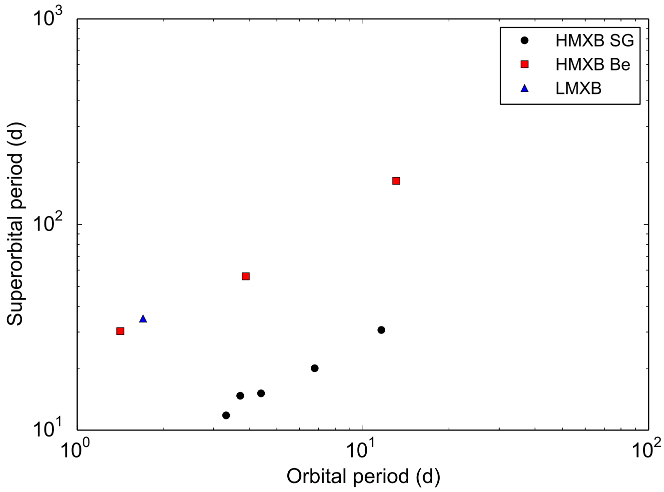

Figure 4: Dependence of the superorbital period on the orbital period for X-ray binary systems

4. Conclusions

The detection of the GW150914 has opened a new observational window for astronomy. The X-ray astrophysics will play a strong role in the new born gravitational astronomy, to understand the gravitational sources and in the context of follow up observations in the electromagnetic domain. X-ray binaries are of special interest for gravitational wave astronomy. Accreting neutron star systems are potential continuous emitters in the frequency band of the advanced LIGO/Virgo interferometers if the spin up torque by accretion is balanced by the spin down torque by the gravitational radiation. In addition, the X-ray binaries are potential sources of gravitational radiation in the low frequency band of the forthcoming space based interferometer eLISA. The accurate knowledge of the orbital period of the systems is necessary to estimate the gravitational emission at low frequency and to reduce the computational cost of searching the signal from accreting neutron stars. The systematic search for periodicities in the archives of X-ray missions can detect orbital periods and also superorbital periods. The preliminary results of a search in the Swift/BAT and RXTE/ASM archives have been presented. The estimated periodicities provide also information about the characteristics of the astrophysical sources.

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