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The search for continuous gravitational waves in LIGO and Virgo data

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Summary. — The detection of continuous gravitational waves is among the main targets of the LIGO and Virgo detectors. Such kind of signals, emitted *e.g.* by spinning neutron stars asymmetric with respect to the rotation axis, are very weak and their search poses challenging data analysis problems. In this review I will discuss the main issues regarding the search of continuous gravitational waves in the data of current interferometric detectors and some recently published results.

1. – Introduction

LIGO and Virgo Collaborations have reported in the past year the first direct detection of gravitational waves, produced by the coalescence of a binary black hole system [1]. There are, however, other possible sources of gravitational radiation which can produce detectable signals. Among these, there are spinning neutron stars, isolated or in a binary system. If a neutron star is asymmetric with respect to its rotation axis it will emit a continuous wave (CW) with frequency f_0 at a given ratio with respect to the rotation frequency f_{rot}, depending on the mechanism producing the asymmetry. Different mechanisms to produce an asymmetry in the mass distribution have been proposed: elastic stresses or magnetic field not aligned to the rotation axis ($f_0 = 2f_{rot}$), free precession around the rotation axis ($f_0 = k(f_{rot} + f_{prec})$, $k = 1, 2$, where f_{prec} is the precession frequency), excitation of long-lasting oscillations, *e.g.* r-modes ($f_0 \approx 4/3f_{rot}$), accretion of matter from a companion star, *e.g.* in low-mass x-ray binaries ($f_0 \simeq 2f_{rot}$).

CW signals are persistent and expected to be very weak. We can exploit their persistence by "integrating" the data over months or years in order to increase the signal-to-noise ratio. We know that potential sources of CW exist. About 2500 neutron stars are observed through their electromagnetic emission (mostly pulsars) but of the order of 10^8–10^9 should exist in the Galaxy. Then, we expect several neutron stars to emit CW signals in the sensitivity band of detectors, say between 20 Hz and 2 kHz. On the other hand, it is difficult to predict the amplitude of the signal, because it depends on the poorly known star degree of deformation (measured by the ellipticity), see eq. (1).

Although no detection of CW has been claimed so far, some interesting upper limits have been placed. In this paper I review the current status of the search of CW in the data of LIGO and Virgo interferometers. The paper is organized as follows. In sect. **2** the main features of CW signals are discussed. In sect. **3** I make a brief introduction to the data analysis problem, and describe some recently published results. Finally, sect. **4** is devoted to conclusions. See Mastrogiovanni's contribution to these Proceedings for a more specific discussion on the search of CW from Fermi sources.

2. – The signal

In general, the received signal from a spinning neutron star is a combination of the $+$ and $\times$ polarization components with time-dependent coefficients describing the detector sidereal response. In the prototypical case of a non-axisymmetric neutron star steadily spinning about one of its principal axes the signal has a frequency $f_0 = 2f_{rot}$, and its amplitude is

$$h_0 = \frac{4\pi^2 G}{c^4}\frac{I_{zz}\varepsilon f_0^2}{d}, \quad (1)$$

in which $\varepsilon = \frac{I_{xx}-I_{yy}}{I_{zz}}$ is the fiducial equatorial ellipticity expressed in terms of principal moments of inertia, and d is the star distance. The typical ellipticity of neutron stars is largely unknown, and according to theoretical computations, its maximum value can be in the range between $\sim 10^{-6}$ and $\sim 10^{-3}$, depending on the distortion mechanism and on the star equation of state, see *e.g.* [2-5].

The signal frequency at the detector is not constant; it varies in time because of the intrinsic star spin-down and the Doppler effect, caused by the detector motion (plus smaller relativistic modulations). For a source in a binary system the binary orbital motion too plays a relevant role. As a consequence, the power of a CW signal is spread across a range of frequencies, thereby reducing the signal detectability, if these effects are not properly taken into account.

For sources with known rotational parameters, assuming that all the observed spin-down is due to the emission of gravitational radiation, an absolute upper limit can be computed on the amplitude of the emitted signal, the so-called *spin-down limit*:

$$h_0^{\rm sd} = \left(\frac{5}{2}\frac{G I_{zz}\dot{f}_{rot}}{c^3 d^2 f_{rot}}\right)^{1/2} = 8.06\times 10^{-19}\frac{I_{38}^{1/2}}{d_{\rm kpc}}\sqrt{\frac{|\dot{f}_{rot}|}{f_{rot}}}, \quad (2)$$

where I_{38} is the star's moment of inertia in the units of $10^{38}\,{\rm kg\ m^2}$, $\dot{f}_{rot}$ is the time derivative of the star's rotation frequency, and $d_{\rm kpc}$ is the distance to the pulsar in kiloparsec. When rotational parameters are not known, by using the "characteristic" age of the source $\tau = \frac{f_{rot}}{4|\dot{f}_{rot}|}$, the limit can be written as [6] $h_{0,il} = 4.16\times 10^{-24}(\frac{1\ {\rm kpc}}{\rm d})(\frac{300\ {\rm yr}}{\tau})^{1/2}$. Setting a gravitational wave upper limit below the spin-down limit is an important achievement as it allows us to constrain the fraction of spin-down energy due to the emission of gravitational wave, which gives insight into the star energy budget.

3. – The search for CW

Typically, two main kinds of search are considered. One is the *targeted* search for CW signals from known neutron stars (*e.g.* pulsars) for which position and rotational parameters are known with high accuracy. In this case coherent methods, based on matched filtering, can be used to gain signal-to-noise ratio. The other is the *all-sky* search for CW signals emitted by neutron stars without electromagnetic counterpart. In this case a large volume of the source parameter space must be explored, and the analysis cannot be done with fully coherent methods due to the huge computer power that would be needed. As we will see in the following sections, intermediate cases also exist, like *narrow-band* and *directed* searches, in which some of the parameters are assumed to be well or partially known. In parallel, efforts have been started to develop analysis procedures for the search of non-standard CW, like long transient signals (with duration of hours-days) that could be emitted by, *e.g.*, young magnetars or due to r-modes excitation.

3˙1. *Targeted searches.* – Targeted searches are based on matched filtering, in which the data are cross-correlated with signal templates. In order to apply matched filtering, source position, spin frequency and frequency derivative(s) must be known with high accuracy. This allows to correct the Doppler effect, the spin-down and the other relativistic effects over long times, see *e.g.* [7, 8] for more details. Matched filtering is the most sensitive method (under the assumption of Gaussian noise), but its computational cost rapidly increases with the volume of the parameter space. This is why it can be used only for targeted searches, or over a very small range of parameter values. The sensitivity of a targeted search can be estimated as (at 1% false alarm probability, 90% detection probability)

$$h_{0,min}(f) \approx 10 \cdot \sqrt{\frac{S_n(f)}{T_{obs}}}, \tag{3}$$

where $S_n(f)$ is the detector noise power spectral density at the search frequency f, and T_{obs} is the observation time. The most recent fully coherent search for known pulsars has been conducted on Advanced LIGO O1 run, which spans the period between 2015 September 11 and 2016 January 19 [9]. The search was done for 11 "high value" pulsars using a Bayesian method [10], the F/G-statistic method [11], and the frequency-based 5-vector method [12], while other 189 targets were analyzed using only the Bayesian method. For 8 pulsars an upper limit on the signal strain amplitude below the spin-down limit has been obtained. The most stringent, in term of energy loss, has been set for the Crab pulsars, $h_{ul} \simeq 5 \cdot 10^{-26}$, corresponding to a constraint of about one per thousand on the fraction of rotational energy that can be emitted by this pulsar in gravitational waves.

On the Crab and Vela pulsars a narrow-band search has been done using Virgo VSR4 data, exploring a range of about 20 mHz around the central frequency. The expected sensitivity of narrow-band searches is a factor ∼2.5 worse with respect to that of targeted analysis [13, 14], but the search covers a larger parameter space. For the Crab the computed upper limit on this old data set was about 2 times below the spin-down limit [15].

3˙2. *All-sky searches.* – All-sky searches cannot be done with fully coherent methods because the number of points in the parameter space (which easily exceeds say 10^{31} for a few months of data), and then the number of templates that should be considered, is far too big for the available computing resources, see *e.g.* [16]. For this reason *hierarchical* approaches have been developed, with the aim of drastically reducing the computational load of the analysis at the cost of a sensitivity loss. The key idea is that of dividing the full data set into several shorter segments, analyzing them coherently, and then combining the results incoherently, that is losing information on the signal phase. In the incoherent step a relatively rough exploration of the parameter space is done and candidates, that is, interesting points in the parameter space, are selected and followed-up in a next stage of the analysis. The sensitivity of a blind search depends on the choice of several thresholds and parameters, but approximately it can be expressed as

$$h_{0,min}(f) \approx \frac{\Lambda}{N^{1/4}}\sqrt{\frac{S_n(f)}{T_{FFT}}}, \tag{4}$$

where $\Lambda \in [15,\ 30]$, N is the number of segments into which the data have been divided, and T_{FFT} is the duration in seconds of each segment. Recent all-sky searches have been based on different analysis pipelines, [17-21], using different algorithms, with segment lengths varying from $\sim$30 min. to 6 days, and applying specific methods to deal with detector artifacts. As an example, one of the latest searches, the Einstein@Home analysis of LIGO S6 data [21], has been able to exclude at a signal frequency of 500 Hz the presence of neutron stars with ellipticity larger than $5 \cdot 10^{-7}$ nearer than about 100 pc. A comparison of different all-sky methods has been done by using a large set of about 3000 simulated signals injected in LIGO S6 data [22].

3˙3. *Directed searches.* – In some cases the source rotational parameters are not well constrained. For instance, for CCOs (central compact objects), found in supernova remnants, the position is well known, while the spin frequency and spin-down are completely unknown because no pulsation is observed. In this case the search for CW is called *directed*. It is still feasible with coherent methods only if the range of frequency and spin-down to be searched is relatively small, otherwise a semi-coherent method can be used. Also searches targeted to specific small regions of the sky, like the Galactic center or globular clusters, are a kind of directed search. Photon astronomy can provide very helpful information, allowing to pin-down the range of possible values of the rotational parameters thus allowing to improve the search sensitivity (reducing the computational cost of the analysis at the same time).

A directed semi-coherent search for CW from nine young supernova remnants, done on LIGO S6 data, has been described in [6] and has been able to beat the indirect limit $h_{0,il}$ shown in sect. **2**. Recently, a coherent search, using about nine days of LIGO S6 data, has been done targeting the globular cluster NGC 6544, setting upper limits below the indirect limit for stars with spin-down age older than about 300 years [23].

3˙4. *Searches for neutron stars in binary systems.* – About 1300 pulsars, out of the 2500 observed so far in the electromagnetic band, are in a binary system. Moreover, a particularly interesting class of CW sources is represented by accreting neutron stars in low-mass x-ray binaries, like Scorpius X-1. For such kind of sources the gravitational wave signal is complicated by the intrinsic Doppler effect, which depends on the binary system Keplerian parameters, and possibly by irregularities in the rotation rate. This is a clear complication for the analysis, considering also that the keplerian parameters often have some non negligible uncertainty, especially in the case of accreting systems. Various pipelines have been developed to search for signals from neutron stars in binary systems, both tuned for specific systems, like Sco X-1 [24-26], or for all-sky searches [27, 28]. These pipelines have been compared in a mock data challenge [29]. Further methods, trying to improve search sensitivity or reduce the computational load of the analysis, are being developed [30-32].

4. – Conclusions

Continuous gravitational waves emitted by spinning neutron star are the subject of intense research by the LIGO and Virgo Collaborations. Several analysis pipelines have been developed to detect such kind of signals, emitted by both isolated stars and by stars in binary systems, and with different assumptions on the knowledge of the signal parameters. The analysis of LIGO and Virgo data did not result in any detection until now, but interesting upper limits have been placed, allowing to put non-trivial constraints on the characteristics and energy budgets of the sources. As the detectors' sensitivities increase, continuous gravitational waves could finally be detected, providing a wealth of information on neutron star structure and demography.

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