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The search for continuous gravitational waves with LIGO and Virgo detectors

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Continuous gravitational waves emitted by spinning neutron stars, isolated or in binary systems, are among the main targets of LIGO and Virgo interferometric detectors. No continuous wave has been detected so far, but significant upper limits, providing interesting constraints on the characteristics and demography of the potential sources, have been obtained. In this talk I will review the current status of continuous wave searches, highlight some recent results and discuss future prospects in this field.

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1. Introduction

Gravitational-wave astronomy was born in 2015 with the first direct detection of gravitational waves, produced by the coalescence of a binary black hole system [1]. Apart from coalescing binary systems, other sources of gravitational radiation can produce detectable signals. Among these there are spinning neutron stars, isolated or in a binary system. A neutron star, asymmetric with respect to its rotation axis, emits a continuous wave (CW) with frequency f_0 related to the rotation frequency f_{rot} and which depends on the mechanism producing the asymmetry.

CW signals are persistent and expected to be very weak. Their persistence allows to "integrate" the data over long periods, months or even years, in order to increase the signal-to-noise ratio. A huge number of CW sources potentially populates the Galaxy. In fact, a steadily increasing number of neutron stars are observed through their electromagnetic emission (currently over 2500, mostly pulsars), and of the order of at least 10^8 should exist in the Galaxy, a fraction of which is expected to emit CW signals in the sensitivity band of detectors, say between 20 Hz and 2kHz.

A recently proposed mechanism for the emission of CW involves black hole superradiance, triggered by light bosons, like QCD axions [2], [3]. The resulting signal, due to the “boson cloud” formed around a black hole, would be monochromatic, even though the several assumptions and simplifications of the model do not allow to exclude some randomness in the signal frequency.

There are also potential sources of "less-persistent" CW signals over which an increasing interest is building. For instance, young strongly magnetized neutron stars, called *magnetars*, or neutron stars which develop a dynamic instability, like *r-modes*, are expected to emit CW-like signals, with a frequency rapidly decreasing in time and lasting from hours to days in the sensitivity band of detectors. The development of suitable analysis methods for these kinds of signals is one of the focus of current research. See e.g. [4] for a recent review of possible sources of CW.

2. Continuous wave signals

In the theory of General Relativity, the signal emitted by a spinning neutron star is seen by the detector as 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 which steadily spins about one of its principal axes (as a consequence, e.g., of elastic stresses or a magnetic field not aligned to the rotation axis) the signal has a frequency $f_0 = 2f_{rot}$, and its amplitude is given by

$$h_0 = \frac{4\pi^2 G}{c^4}\frac{I_{zz}\varepsilon f_0^2}{d} \tag{2.1}$$

in which $\varepsilon = \frac{I_{xx}-I_{yy}}{I_{zz}}$ is the fiducial equatorial ellipticity, which depends on the star principal moments of inertia, and d is the star distance. In fact, neutron stars ellipticity is unknown, with thoretical maximum values in the range between $\sim 10^{-6}$ and $\sim 10^{-3}$, depending on the mechanism which produces the asymmetry and on the star equation of state, see e.g. [5], [6].

Because of the intrinsic star spin-down and the Doppler effect, caused by the detector motion (plus smaller relativistic modulations), the signal frequency at the detector is not constant. In the case of sources in a binary system, the frequency modulation is also due to the binary orbital motion. These effects cause the spread of the signal power across a range of frequencies, thereby reducing the signal detectability, if these effects are not properly taken into account.

3. The search for CW

Depending on the assumed degree of knowledge of the source parameters, different kinds of searches are done. When position and rotational parameters are known with high accuracy, coherent methods, based on matched filtering, can be used to gain signal-to-noise ratio (*targeted* search, see Sec. 3.1). This is, e.g., the case of pulsars for which these information come from the electro-magnetic observations. The other limiting case 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 is computationally bounded, see Sec. 3.2 for more details. Also several intermediate cases exist, like *narrow-band* and *directed* searches (Sec. 3.3), in which some of the parameters are assumed to be well or partially known. In the case of accreting neutron stars like Sco X-1, see Sec. 3.4, the signal frequency is expected to be randomly wandering. Similarly, in the case of "boson clouds" around black holes, while a monochromatic signal has been predicted, in practice the several unknowns call for robust search methods where the frequency could fluctuate with a given coherence time.

The quality of the data is critical for the search of CW. The presence of noise spectral lines, in particular, may have a significant impact on the search sensitivity. Identifying the source of disturbances, or at least developing veto procedures to deal with noise artefacts, is crucial to the analysis of detectors' data.

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. [8] for more details. While matched filtering maximises signal-to-noise ratio (under the assumption of Gaussian noise), its computational cost rapidly increases with the volume of the parameter space. For this reason it can be used only for targeted searches, or over a very small range of parameter values. The sensitivity of a targeted search is approximately given by (at 1% false alarm probability, 90% detection probability) $h_{0,min}(f) \approx 10 \cdot \sqrt{\frac{S_n(f)}{T_{obs}}}$, where $S_n(f)$ is the detector noise power spectral density at the frequency f, and T_{obs} is the observation time. The most recent targeted 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]. For 8 pulsars the upper limit on the signal strain amplitude is such to non trivially constrain the fraction of rotational energy lost to gravitational waves. The most stringent result has been set for the Crab pulsars, with a 95% confidence level upper limit $h_{ul} \simeq 5 \cdot 10^{-26}$, corresponding to a constraint of about one per thousand on the ratio $\dot{E}_{GW}/\dot{E}_{rot}$ among the GW and rotational luminosities for this pulsar.

On the Crab and Vela pulsars a more robust but less sensitive narrow-band search has been also done using Virgo VSR4 data, exploring a range of about 20 mHz around the central frequency

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[10], and has been repeated for more targets over LIGO O1 data, allowing to beat the spin-down limit for four pulsars (Crab, Vela, J1813-1749, J2229+6114) [11], [12].

3.2 All-sky searches

For all-sky searches fully coherent methods cannot be used because the number of templates that should be considered largely exceeds the available computing resources, see e.g. [13]. *Hierarchical* approaches have been developed, which allows to drastically reduce the computational load of the analysis at the cost of a sensitivity loss. In these methods the full data set is divided in several shorter segments which are properly processed and then incoherently combined (this is called a semi-coherent combination of the data). Candidates, that is potentially interesting points in the parameter space, are selected at this stage 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 is given, at 90% c.l. by $h_{0,min}(f) \approx \frac{\Lambda}{N^{1/4}}\sqrt{\frac{S_n(f)}{T_{FFT}}}$, where $\Lambda \in [15,\ 30]$, N is the number of segments in which the data have been divided, and T_{FFT} is the duration in seconds of each segment. The latest published results refer to the analysis of LIGO O1 data [14] which was done using different algorithms, with segment lengths varying from $\sim$30 min. to 6 days, and applying specific methods to deal with detector artefacts and to follow-up candidates. This search allowed to exclude the presence of neutron stars with ellipticity larger than about 10^{-5}, which is the maximum that a “standard” neutron star should be able to support, spinning at frequencies smaller than about 200 Hz and at a distance smaller than about 1 kpc.

3.3 Directed searches

In the case of some potentially interesting sources, like CCOs (central compact objects), found in supernova remnants, or the so-called "unidentified" Fermi-LAT sources (many of which are expected to be neutron stars), the position is well (or relatively well) known, while the spin frequency and spin-down are completely unknown because no pulsation is observed. In this case the search for CW (called *directed*) is still feasible with coherent methods only if the range of frequency and spin-down to be searched is relatively small, otherwise semi-coherent approaches, see previous section, 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. Observations in the electromagnetic band can provide very helpful information, allowing to restrict the range of possible values of the rotational parameters thus improving the search sensitivity (and reducing the computational cost of the analysis at the same time). See [7], [15] for recent directed semi-coherent searches for CW which provided interesting upper limits.

3.4 Searches for neutron stars in binary systems

Among the $\sim$2500 pulsars observed so far in the electromagnetic band, about 1300 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, see e.g. [16]. 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, which depends on the matter accretion rate. This is a clear complication for the analysis, considering also

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that the Keplerian parameters often have some non negligible uncertainty, especially in the case of accreting systems. Significant effort is being done in order to develop pipelines suitable for such kind of signals. The most sensitive searches up to date have been recently conducted on LIGO O1 data [17], [18].

4. Conclusions

The analysis of LIGO and Virgo data did not result in any detection of continuous gravitational wave signal 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 and more sensitive and robust data analysis pipelines are developed, continuous gravitational waves could finally be detected, providing a wealth of information on neutron star structure and demography. The persistent nature of CW will allow to make very accurate measures of the source parameters and to study tiny effects over long time scales. Finding signals from more exotic processes, like black hole superradiance, would permit to set a bridge between gravitation and other fields, like particle physics, opening new frontiers in the study of the Universe.

References

[1] Abbott B. P. et al., Phys. Rev. Lett. 116, 061102, 2016

[2] Arvanitaki A. et al., Phys. Rev. D 95, 043001, 2017

[3] Brito R. et al., arXiv:1706.06311

[4] Lasky D. P., PASA 32, e034, 2015

[5] Horowitz C J and Kadau K, Phys. Rev. Lett. 102, 191102, 2009

[6] Johnson-McDaniel N. K. and Owen B. J., Phys. Rev. D 88, 044004, 2013

[7] Aasi J. et al., The Astrophys. J. 813, 39, 2016

[8] Aasi J. et al., The Astrophys. J. 785, 119, 2014

[9] Abbott B. P. et al., The Astrophys. J. 839, 19, 2017

[10] Aasi J. et al., Phys. Rev. D 91, 022004, 2015

[11] Mastrogiovanni S. et al., Class. Q. Grav., 34, 135007, 2017

[12] Abbott B. P. et al, submitted to PRD

[13] Frasca S, Astone P and Palomba C., Class. Q. Grav. 22, S1013, 2005

[14] Abbott B.P. et al, Phys. Rev. D 96, 062002, 2017

[15] Abbott B. P. et al., Phys. Rev. D 95, 082005, 2017

[16] Papaloizou, J., and Pringle, J. E., MNRAS 184, 501, 1978

[17] Abbott B. P. et al., Phys. rev. D 95, 122003, 2017

[18] Abbott B. P. et al., The Astrophysical Journal 847, 47, 2017

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