Sifting the Gravitational-Wave Universe via Multimessenger Astronomy: Forthcoming Prospects for Continuous-Wave detection

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Summary. — The upgrade of worldwide gravitational-wave detector network has led to the first transient gravitational-wave detection, which has started to hone the comprehension we have about our Universe and some of its constituents. A broader picture would be however provided by the detection of continuous-wave signals, which could be more easily achieved by exploiting the synergy with multimessenger Astronomy. Thanks to electromagnetic observations we may indeed be able to know, with enough accuracy, the sky location, rotational and/or orbital parameters of a broad class of rapidly-rotating neutron stars. This would allow us to perform a multitude of targeted and directed continuous-wave searches, and would facilitate narrow-band searches for the same class of signals.
We will describe the prospects for detecting continuous gravitational waves, by especially employing novel strategies for neutron stars in binary systems directed to sources whose parameters have been electromagnetically estimated. Employing those methods to analyze data from the ever-more-sensitive advanced detectors will remarkably increase the chances of a continuous wave detection.

1. – Gravitational waves

Following a major upgrade, with consequent improvement in sensitivity [1], the two LIGO observatories resumed data taking in September 2015. On September 14, 2015, the advanced LIGO interferometers detected for the first time a coincident transient gravitational-wave signal produced by the coalescence of a pair of black holes [2], marking thus the official beginning of the gravitational-wave astronomy era. There are however other classes of gravitational-wave signals, which have still to be detected, such as long-lived continuous waves (CWs), which are expected to be emitted by rapidly rotating neutron stars (NSs) with nonaxisymmetric deformations [3]. We expect $\mathcal{O}(10^8)$ of these sources to exist in the Galaxy [4], but only $\sim 2\,500$ NSs (mostly pulsars) have been electromagnetically observed [5]. Roughly 1 300 of these observed radio pulsars are located

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in binary systems, and have rotation rates such to possibly emit CWs in the advanced LIGO-Virgo sensitivity band.

1˙1. *Detectors*. – The advanced kilometer-scale gravitational-wave LIGO and Virgo [6, 7, 8] network will be drastically enhanced in the upcoming years, thus increasing the chance of a continuous-wave detection. The Japanese KAGRA interferometer [9], and a third LIGO detector in India [10], should indeed join the global detector network after 2019 and 2022, respectively, providing improved source parameter estimation and sky localization [8].

Looking further ahead, we can envision more than a factor of 2 improvement over the Advanced LIGO design strain sensitivity by considering the cryogenic technologies foreseen for the so-called third generation interferometers such as Einstein Telescope [11], LIGO Voyager and LIGO Cosmic Explorer [12, 13], which are currently being designed, and are expected to become operational after 2020 and 2030, respectively.

1˙2. *Sources*. – Gravitational-wave sources can be loosely divided into four types [14]:

1. Coalescence of compact objects, such as NS-NS, NS-BH, BH-BH (where BH is Black Hole in short).

2. Burst sources generated in nearby supernova explosions, magnetar flares, and cosmic string cusps.

3. Stochastic background of gravitational waves, which consists of a random accumulation of signals from thousands or millions of individual sources, including compact binary systems, rotating NSs, and primordial perturbations during inflation.

4. CW sources emitted by rotating, non-axisymmetric, NSs.

The first two types of sources emit gravitational signals lasting for a very short amount of time, between a few milli-seconds and a few minutes, and fall into the category of transient signals. The last two items are classified as continuous signals and are typically very weak. CW signals are discussed in the next section.

2. – CW searches and Multi-messenger Astronomy

In the rest frame of the NS, CWs have a constant amplitude and are quasimonochromatic with a slowly decreasing intrinsic frequency. They are received at Earth-based detectors with a Doppler modulation due to the relative motion between the source and the detector. Consequently, the observed phase evolution depends on the intrinsic signal frequency, frequency time derivatives (also known as "spindown" terms), and source sky position. If the source is located in a binary system, there is a further frequency-modulation caused by the source orbital motion, which in general is described by five unknown Keplerian parameters [15, 16, 17].

In general, the strategy used to extract the faint CW signals from the interferometer noisy data is based on a coherent (i.e. the phase information is used) matched filtering analysis. The well-known technique of matched filtering consists of correlating the data against a template, which models the signal's amplitude and phase evolution over time. A template, or a filter, corresponds to a point in the parameter space we want to explore. Matched filtering maximizes the signal-to-noise ratio (SNR) over the amplitude parameters, but requires values to be chosen for the phase parameters. Hence, a search for CWs consists of performing matched filtering against a bank of templates, whose phase parameters are chosen to cover a certain parameter space of interest (see [16] and references therein).

The weakness of the expected signal requires long integration times, typically of the order of a few months or years, to accumulate sufficient SNR for detection as, for a coherent [incoherent([1])] search, the SNR scales as the square (fourth) root of the length of the observational time (i.e. the length of the data being analyzed) [18, 19].

Due to the demanding computational burden, all-sky, wide frequency searches over long observation times cannot be treated by using standard coherent methods, as is the case for targeted and narrow-band searches for known pulsars [20, 21]. All-sky searches are generally treated by employing hierarchical approaches [22, 23, 24, 25], which reduce the analysis computational time at the cost of a relatively small sensitivity loss. The additional source orbital parameters make the sieved parameter space to blow up, resulting in a prohibitive computational cost [16]. Hence, it becomes pressing to develop robust strategies to detect CWs emitted by NSs orbiting a companion object, and being able to reach a tradeoff between computational cost and sensitivity.

A particularly interesting type of potential CW sources are NSs in low-mass X-ray binaries, with Scorpius X-1 being the most prominent representative [26]. The uncertainty in the Scorpius X-1 binary parameters [27, 28] results, however, in a non negligible computational demand, which can be faced with the help of both multi-messenger astronomy and custom-tailored algorithms [29, 30, 17]. A painstaking effort to reduce the computational cost of a search for CWs from NSs in binary systems is described in [17], where an incoherent strategy is presented, including also the case of eccentric orbits. The method is based on selecting significant peaks from a short Fast-Fourier-Transform database, and exploiting the frequency modulation pattern produced by the source orbital motion to detect a potential CW signal. Based on simulation studies, sifting one month of single-detector data and 131 Hz-wide frequency range takes roughly 2.4 CPU hours, allowing us to detect signals with an amplitude of $\sim 7 \times 10^{-25}$ at a paltry computing cost.

The multi-messenger approach to gravitational-wave astronomy is very important as, thanks to electromagnetic observations we can know (with high accuracy) the source sky location, the rotational and orbital parameters of several NSs, being thus able to perform directed and targeted searches both for isolated stars and NSs in binary systems at an affordable computing cost. In particular, gravitational-wave searches in coincidence with neutrinos are useful to improve source sky localization [31].

Furthermore, the study of the weak interaction of Cosmic Neutrino Background can be useful to detect B-modes (one of the polarizations of the cosmic microwave background radiation) [32]. Since such signals come from the cosmic inflation, and are determined by the primordial gravitational-wave density, they can provide us with information about inflation and gravitational waves in the early universe.

3. – Concluding remarks

Gravitational-wave discovery provides not only a check on Einstein's theory, but can also help us to understand the dynamics of large-scale events in the Universe, like the death of massive stars, the birth and the collisions of black holes, the structure and properties of NSs. It can also allow us to perform very precise measurements of the

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([1]) In an incoherent method the phase information is lost.

Hubble constant (i.e. the expansion rate of our Universe), and even constraining the graviton Compton wavelength [33]. Furthermore, GWs from NSs, if detected, would provide us with relevant insights on the equation of state of matter at huge densities and on the NS degree of asymmetry. The detection of a stochastic background of gravitational waves from cosmological origin would allow us to have access to the very first instants of the Universe (roughly 13.8 billion years ago) and observe it differently than we have done so far.

Although CWs have not been detected so far by analysing data from LIGO and Virgo detectors, stringent upper limits have been set on the gravitational-wave signal strength for both isolated pulsars [25, 34, 35, 21, 36, 37] and pulsars in binary systems [29, 30]. We are confident that with the advent of ever-more-sensitive gravitational-wave detectors and the aid of more robust data analysis techniques we can really be able to detect CW signals.

Finally, gravitational-wave discovery is helping us to open a completely new window on the Universe, and we should not be surprised even to discover unexpected objects, as we are going to explore a parameter space that we have never had access to.

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