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GRAVITATIONAL WAVES FROM ROTATING NEUTRON STARS: CURRENT LIMITS AND PROSPECTS

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Rotating neutron stars that emit continuous gravitational waves are among promising targets of the LIGO and Virgo detectors: sufficiently large nonaxisymmetric deformation w.r.t. the axis of rotation of a star generates a time-varying mass-quadrupole moment and henceforth gravitational wave emission. The departure from an axisymmetric shape may be caused by the internal magnetic field and/or elastic stresses in the crust/core. If detected, it will provide novel insight into the presently obscured details of the interior neutron star structure. This talk presents basic types of searches for such signals: from *targeted* searches from known pulsars to *all-sky* wide parameter searches for unknown objects. Selected methods used in the data analysis and in calculating the upper limits on the gravitational waves in the initial phase of LIGO and Virgo projects are briefly described. Observational results of LIGO and Virgo collaborations include "beating" the spin-down limit for the Crab and Vela pulsars [7, 11], search for a coherent signal from the direction of the Cas A supernova remnant [5], as well as the Galactic center [1], SN1987A and the Sco-X1 binary with the cross-correlation method [6], and the all-sky searches for signals of unknown position and frequency [2, 4, 8].

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INTRODUCTION

Gravitational waves (GWs) predicted by A. Einstein [16] — variations of the curvature of space-time that propagate through space-time in a wave-like fashion — are a direct consequence of the general theory of relativity. Some properties of GWs are similar to those of electromagnetic waves: speed-of-light propagation and the presence of polarization (two distinct ones in general relativity). The *indirect* evidence for the existence of GWs comes from the observations of tight relativistic binary pulsar systems [18]. *Direct* detection

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of GWs will constitute a very precise test of the theory of relativity and open a new observational field: GW astronomy. The most promising GW detector concept is currently of the Michelson–Morley interferometer type. While a GW passes through such a detector, it changes the length of its arms and affects the interference pattern of the laser light circulating in the interferometer [24].

State-of-the-art interferometric GW detectors, LIGO * in the USA, and the European (Italian–French, with the contribution of Hungary, the Netherlands and Poland) Virgo ** have collected a large amount of data in the so-called Initial Era. Meanwhile, the advanced LIGO and Virgo detectors are under construction and they are forecasted to start collecting new, more sensitive data in 2015. It is expected that these advanced detectors will be sufficiently sensitive to directly record a GW. As the GW signals are extremely weak (the tidal deformations created by even the strongest anticipated sources are much smaller than 10^{-22}, typically 10^{-24}, which translates into distance differences that have to be measured much smaller than the size of an atomic nucleus), their detection constitutes a major challenge in engineering, data analysis and scientific computing. Several types of astrophysical GW sources are envisaged and investigated: coalescence of compact binaries containing neutron stars and black holes, supernova explosions, quantum effects in the early Universe as well as rotating, nonaxisymmetric neutron stars.

The departure from axisymmetry in the mass distribution of a rotating neutron star can be caused by strong magnetic fields and/or elastic stresses in its interior. Searching for such long-lived, periodic GW signals generated by the spinning star is a particularly computationally intensive task, because the GW signal is very weak, "buried" in the detector's noise. In order to recover satisfactory signal-to-noise ratio, long stretches of data must therefore be analyzed. The modulation of the signal due to the motion of the detector with respect to the solar system barycenter (especially the daily movement connected with the rotation of the Earth) has to be taken into account; the result depends on the location of the source and a modulation function of the intrinsic change of rotation frequency of the deformed neutron star. The most commonly used, and also the most simple model of the non-

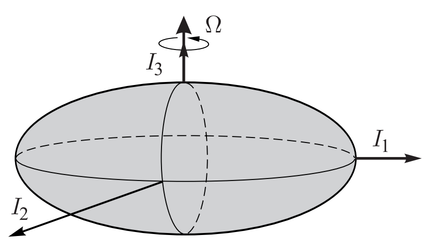

Fig. 1. Triaxial ellipsoid rotating along one of the main axes of the moment of inertia I as the simplest model of a deformed NS radiating purely quadrupolar GWs

*http://www.ligo.org
**https://wwwcascina.virgo.infn.it

axisymmetric rotating neutron star radiating purely quadrupolar waves involves a triaxial ellipsoid rotating about one of the principal directions of its moment of inertia tensor (see Fig. 1). Such a body radiates GWs at the frequency twice the rotational frequency of the star, $\Omega_{\rm GW} = 2\Omega$. Two GW degrees of freedom (wave polarizations) are the following functions,

$$h_+ = 2(\Omega^2/r)\Delta I_{21}(1 + \cos^2 \iota) \cos(2\Omega t + \Phi), \quad (1)$$

$$h_\times = 4(\Omega^2/r)\Delta I_{21} \cos \iota \sin(2\Omega t + \Phi), \quad (2)$$

of the remaining parameters: orientation of the spin axis w.r.t the observer, ι and ϕ, and the GW phase Φ. The $\Delta I_{21} = I_2 - I_1$ denotes the difference in moments of inertia. The amplitude of the wave, $h_0 \propto (\Omega^2/r)\Delta I_{21}$, spin frequency Ω, orientation angles ι and ϕ, and the GW phase Φ consist of 4 parameters of the problem.

The searches for continuous GWs may be divided into two classes: searches for GW from known pulsars, such as Crab or Vela, and searches from previously unknown sources (all-sky, blind surveys). In the latter case, one does not the intrinsic parameters of the source, and in addition, its location on the sky is unknown. Consequently, the parameter space grows and the problem becomes the computational challenge.

1. SELECTED METHODS AND ESTIMATES

The initial era of interferometric detectors (ended in 2011) did not bring the direct detection of the GWs. It allowed one, however, to put some interesting upper limits on the GW amplitude as a function of the GW frequency.

Using the quadrupole formula [17], the GW amplitude from a rotating triaxial neutron star described above may be estimated as follows:

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I \epsilon f^2}{d} = \\ = 4 \cdot 10^{-25} \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{I}{10^{45}\ \text{g} \cdot \text{cm}^2}\right) \left(\frac{f}{100\ \text{Hz}}\right)^2 \left(\frac{100\ \text{pc}}{d}\right), \quad (3)$$

where $I \equiv I_3$, $f = \Omega/2\pi$, $\epsilon = (I_1 - I_2)/I$ is the fiducial equatorial ellipticity of the star (a "deformation"), and d is the typical distance in the Galaxy. According to the recent theoretical studies of the dense matter equation of state, nucleonic matter may sustain deformations that provide ellipticities $\epsilon < 10^{-6}$–10^{-7}, whereas quark matter $\epsilon < 10^{-4}$–10^{-5} [20, 22, 25]. A useful quantity related to the amount of kinetic (rotational) energy of the star is the so-called spin-down limit. It is derived assuming that the GW emission is responsible for the change in the rotational energy, $\dot{E}_{\rm rot}$. For $E_{\rm rot} = 2\pi^2 I f^2$, $\dot{E}_{\rm rot} \propto I f \dot{f}$ is equated with the GW emission, $\dot{E}_{\rm GW} \propto \epsilon^2 I^2 f^6$ to obtain the spin-down limit amplitude

$$h_{\rm sd} = \frac{1}{d}\sqrt{\frac{5GI}{2c^3}\frac{|\dot{f}|}{f}} = \\ = 8 \cdot 10^{-24}\sqrt{\left(\frac{I}{10^{45}\ {\rm g \cdot cm^2}}\right)\left(\frac{|\dot{f}|}{10^{-10}\ {\rm Hz/s}}\right)\left(\frac{100\ {\rm Hz}}{f}\right)}\left(\frac{100\ {\rm pc}}{d}\right). \quad (4)$$

The comparison with Eq. (3) results in the limiting deformation $\epsilon_{\rm sd}$:

$$\epsilon_{\rm sd} = 2 \cdot 10^{-5}\sqrt{\left(\frac{10^{45}\ {\rm g \cdot cm^2}}{I}\right)\left(\frac{100\ {\rm Hz}}{f}\right)^5\left(\frac{|\dot{f}|}{10^{-10}\ {\rm Hz/s}}\right)}, \quad (5)$$

or

$$\epsilon_{\rm sd} = 0.2\left(\frac{h_{\rm sd}}{10^{-24}}\right) f^{-2} I_{45}^{-1} d_{kpc}.$$

The LIGO–Virgo collaboration uses three semi-independent methods in the searches for known pulsars, such as the Crab and Vela pulsars [3]. Two methods work with the time domain data that have been pre-processed (heterodyned) to remove the phase evolution of the signal, and decimated. The result is a complex data stream in which any signal would only be modulated by the detector's beam pattern. The first method applies the Bayesian parameter estimates to the data stream [15]. The second method uses the frequentist approach: it computes the maximum likelihood $\mathcal{F}$-statistic, or, in case where ι and ϕ are well-constrained, the $\mathcal{G}$-statistic [19].

The third method uses Short Fourier Transform of the time series obtained from the detector [12]. Narrow frequency bands around signal's expected frequency are corrected for the Doppler effect, Einstein delay and spin-down in the time domain and the data are down-sampled with a resampling technique. Two matched filters (for two GW strain polarizations) on the signal Fourier components are computed at the five frequencies at which the signal power is spread due to the signal amplitude and phase modulation.

In case of all-sky searches, months-long stretches of data need to be analyzed taking into account all sky directions, frequencies and its derivatives. As a result, fully coherent, blind searches are computationally prohibitive. The LIGO–Virgo collaboration uses several independent pipelines, such as the volounter-driven `Einstein@Home`*, `PowerFlux`, and all-sky $\mathcal{F}$-statistic developed by the Polgraw–Virgo group. The first two are well-established projects used to put constraints

*http://www.einstein-online.info

on the continuous GW emission in the LIGO science runs (most recent limits in [2,8]). The implementation of the $\mathcal{F}$-statistic performed by the Polgraw–Virgo group [13] (`polgraw-allsky`) was recently applied to the Virgo Science Run 1 (VSR1) data [4].

Performing a fully coherent search of the VSR1 data in real time over the whole sky, astrophysically interesting frequency f in the range from 100 to 1000 Hz, and $\dot{f}$ from $-1.6(f/100\text{ Hz})\cdot 10^{-9}$ Hz/s would require a 10^4 petaFLOP computer. The computational challenge is maintained by introducing a hierarchical scheme, in which short data segments are analyzed coherently first, and then results are combined incoherently. This leads to computationally manageable searches at the expense of the signal-to-ratio loss.

In case of the `polgraw-allsky` code, the coherent part involves time series of 2 sidereal days length, as compared to 1800 s used by `PowerFlux`, and 30 or 25 h in case of `Einstein@Home` [2, 9, 10]. The incoherent combination of candidates obtained from separate 2 day segments in the VSR1 data was performed by means of the *coincidence search*, similar to the first two `Einstein@Home` campaigns [9, 10]. VSR1 had in general a higher noise and a shorter duration than late LIGO runs, but due to a good efficiency of the `polgraw-allsky` code a much larger parameter space was analyzed. Figure 2 compares the parameter space searched over by the mentioned pipelines. The `polgraw-allsky` code is currently expanded in the direction of massive parallelization within the MPI framework [23], as well with the use of Graphical Processing Units (GPUs). These improvements will allow one to analyze future GW data on the petaFLOP-scale computers.

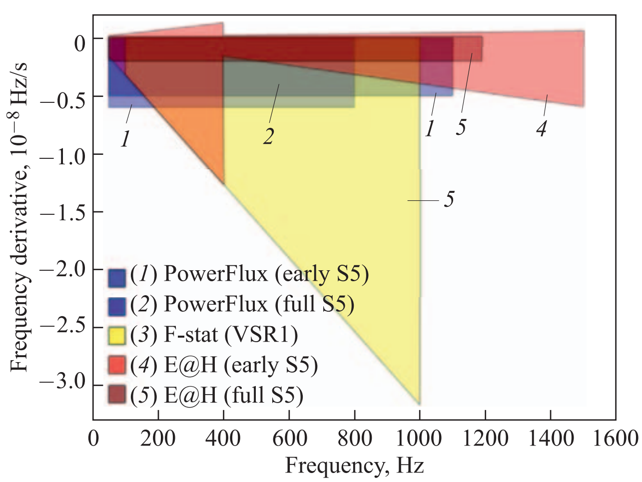

Fig. 2. Parameter space (frequency–frequency derivative, $f - \dot{f}$) searched by the all-sky pipelines using the data of LIGO and Virgo detectors in the Initial Era

2. CURRENT LIMITS AND OUTLOOK

The sensitivity of the `polgraw-allsky` VSR1 search was 50% to 2 times better, depending on the bandwidth, than that of the `Einstein@Home` [9], comparable to [10], and 2 to 5 times worse than the upper limits established in [2]. For the known-pulsar searches, the data registered for only two pulsars (Crab and Vela) were sensitive enough to put upper limits lower than the spin-down limit. The methods described in Sec. 1 gave consistent results: current limits for these objects constrain 1 and 10% of their respective spin-down power being emitted via gravitational waves [3], instead of 6 and 45% [7, 11]. Another 5 pulsars are within a factor of 4 of the spin-down limit (the main factors that contribute to the uncertainty are the poorly-known moment of inertia of the spinning object, and the distance). Figure 1 of [3] shows the upper limits' estimates on the number of pulsars considered in that search, plotted along the design sensitivity curve for joint analysis of Advanced LIGO and Virgo.

Other highlights from the Initial Era include the searches for continuous waves and subsequent upper limits for GW emission from the Galactic Center [1], Sco-X1 binary [6] and the supernova remnants SN1987A and Cassiopeia A [5]. From the theoretical side, more elaborate models of GW emission were recently considered. Specifically, [14] studied the detectability of GWs in a general case of a neutron star with the superfluid core, rotating along an axis inclined w.r.t. the main axes of the moment of inertia [21].

The order-of-magnitude increase in sensitivity planned for the Advanced Detectors promises first direct detection of the GWs. Though most probably the first detections will be mergers of neutron stars or black holes, careful (and time-consuming) analysis of the new continuous waves' data will certainly improve our understanding of the structure of rotating neutron stars, and hopefully yield detections instead of upper limits.

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