Searches for gravitational wave signals from rotating neutron stars

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Abstract. We present status of the search of the LIGO and Virgo detectors data for continuous gravitational wave signals originating from rotating neutron stars. We first review the mechanisms of gravitational wave emission from such sources then we describe the data analysis methods and finally we present recent results of the searches.

1. Introduction
The LIGO Scientific Collaboration (LSC) and the Virgo Collaboration operate a network of interferometric gravitational wave (GW) detectors with the goal of detecting gravitational radiation from astrophysical sources. There are four types of sources: bursts (e.g. supernova explosions), chirps (e.g. inspiral of compact binaries), periodic (e.g. rotating neutron stars), and stochastic (e.g. cosmic strings). So far LIGO detectors have had 6 data runs and consequently collected 6 data sets denoted S1 to S6, whereas Virgo detector has collected 4 data sets called VSR1 to VSR4. In this paper we shall review recent efforts to detect periodic gravitational wave signals from rotating neutron stars. In Section 2 we shall present the basic mechanisms of gravitational radiation from such sources, in Section 3 we describe the basic data analysis methods, and in Section 4 we shall review the recent results of the searches of LIGO and VIRGO data.

2. Mechanisms of gravitational wave radiation from rotating neutron stars
Rotating neutron stars can emit long-lived, narrow band, quasi-sinusoidal gravitational wave signals that are often referred to as continuous or periodic sources. The basic gravitational-wave emission is expected to be due to non-axisymmetric distortions of the neutron star with the dimensionless amplitude $h_o$ of the signal observable at the Earth given by

$$h_o = 4 \times 10^{-25} \left( \frac{\epsilon}{10^{-6}} \right) \left( \frac{I}{10^{38} \text{ kg m}^2} \right) \left( \frac{100 \text{ pc}}{d} \right) \left( \frac{\nu}{100 \text{ Hz}} \right)^2,$$

where $\epsilon$ is a relative measure of non-axisymmetry of the star, $I$ is the moment of inertia with respect to the rotation axis, $d$ is the distance to the star, and $\nu$ is the spin frequency. The non-axisymmetry can arise due to deformations of the crust of the neutron star that could be acquired during birth in a supernova, strong magnetic fields present in neutron stars [2], or differential heating from accreted matter leading to differential density gradients [3]. These effects can
lead to periodic GW signals with once and/or twice the neutron star spin frequency. Another possible emission mechanism is instability of the r-modes of the star driven by gravitational radiation, which results in a signal with dominant frequency equal to $4/3$ of the spin frequency [4]. Another mechanism is free precession due to misaligned rotation and symmetry axes, which leads to a rich spectrum of GW signals. Study of mechanisms of gravitational wave radiation from rotating neutron stars is currently the subject of intensive research by astrophysicists; however, the estimates of the amplitude of the signal are still very uncertain. Consequently a question arises: what is the largest expected amplitude of the continuous signal from a non-axisymmetric neutron star? A recent careful study [1] has shown that, depending on ellipticity $\epsilon$, the maximum amplitude $h_{\text{max}}$ in the band of interferometric detectors varies from $2.7 \times 10^{-26}$ to $1.6 \times 10^{-24}$ (see Figure 5 and Table II of [1] for details). An interesting upper limit on gravitational wave amplitude can be obtained by assuming that all energy emitted by a rotating neutron star is radiated in gravitational waves. This can be estimated for known pulsars, where the first derivative $\dot{\nu}$ of the spin frequency is measured. The spin down limit amplitude $h_{\text{sd}}$ is then given by

$$h_{\text{sd}} = 8 \times 10^{-24} \sqrt{\left( \frac{I}{10^{38} \text{ kg m}^2} \right) \left( \frac{100 \text{ Hz}}{\nu} \right) \left( \frac{\dot{\nu}}{10^{-10} \text{ Hz/s}} \right) \left( \frac{100 \text{ pc}}{d} \right)},$$

(2)

Sometimes the spin frequency of the star is unknown, but its age $\tau$ can be estimated. Using the age estimate $\tau = \nu/(4|\dot{\nu}|)$, which also assumes that the star is losing all its energy through gravitational radiation, we have an indirect spin down limit amplitude $h_{\text{isd}}$:

$$h_{\text{isd}} = 2 \times 10^{-23} \sqrt{\left( \frac{I}{10^{38} \text{ kg m}^2} \right) \left( \frac{1000 \text{ yr}}{\tau} \right) \left( \frac{100 \text{ pc}}{d} \right)},$$

(3)

An interesting indirect upper limit on the amplitude of the GW signal that is independent of the details of the emission mechanism can be obtained using the observation that the frequencies in the low mass X-ray binary systems seem to cluster in a narrow range around 300 Hz which is lower than the theoretical maximum spin frequency of around 1400 Hz. Thus one may suppose that there is balance between the angular momentum gained by accretion with that lost through gravitational radiation. This gives an amplitude $h_{\text{isdX}}$

$$h_{\text{isdX}} = 5 \times 10^{-27} \sqrt{\left( \frac{300 \text{ Hz}}{\nu} \right) \left( \frac{F_X}{10^{-8} \text{ erg cm}^{-2} \text{s}^{-1}} \right)},$$

(4)

where $F_X$ is the observed X-ray energy flux on Earth. The limit is independent of the distance to the source.

3. Data analysis methods

The estimates of the previous section show that the gravitational wave signal from a rotating neutron star is expected to be very weak and therefore very long data stretches (of the order of months or even years) need to be analyzed. Consequently in the analysis we need to take into account both the change of the frequency of the signal and the motion of the detector with respect to the solar system barycenter (SSB). This complication however, has the advantage that by detecting a continuous gravitational wave signal, we not only determine its frequency but also its frequency evolution and the position of the source in the sky. As a result the response of the detector to a continuous GW is a complicated amplitude and phase modulated signal, depending on many parameters. The data analysis method that gives the highest detection probability is the coherent matched-filtering method. Using the maximum likelihood estimation one can reduce
the dimensionality of the parameter space of the coherent search by using the so called $F$-statistic [5]. Even using the $F$-statistic, the coherent method applied to wide parameter searches, where frequency and sky position of the signal are unknown, is computationally prohibitive for the required observation time of the order of months. Therefore less computationally demanding semi-coherent methods were developed. These are StackSlide, Hough, and PowerFlux methods (see [9] for a more detailed description). These methods aim to detect an excess of power in the frequency bins corresponding to the time frequency path of a signal’s instantaneous frequency $f_{int}(t) = d\phi(t)/dt$, where $\phi(t)$ is the phase of the signal.

Neither the matched-filtering nor the semi-coherent methods optimize the sensitivity of a wide-parameter search, given a finite computing power. The sensitivity can be improved by combining several stages of coherent and semi-coherent steps. Usually there is a first step where a coherent search is used with an observation time of the order of days followed by a second step of semi-coherent analysis for an observation time of the order of months. Optimization is the subject of intensive research (see e.g. [7]).

To search for GW signals from known pulsars, a very efficient method was developed using Bayesian methodology [8] where one obtains distributions of the unknown parameters conditional on the data by marginalizing over the unknown parameters like phase and polarization angles and variance of the noise using their reasonable \textit{a priori} distributions.

4. Recent results of searches in the LIGO and Virgo data

Searches for continuous GW signals can be divided into three classes: \textit{targeted searches} - searches for gravitational waves from known pulsars, where frequency, sky position and sometimes polarization are known, \textit{directed searches} - position in the sky is known, and \textit{wide-parameter searches} - unknown sky position, frequency, distance, and polarization. All these types of searches were performed in LIGO and Virgo data. Here we summarize some of the recent results.

(a) \textbf{Targeted searches}

- \textit{Targeted search of LIGO S5 data} [10]. The search involved 116 known millisecond and young pulsars. The search used Bayesian analysis [8]. The pulsars included the Crab pulsar for which the spin down limit (see eq. (2)) was beaten and the limit on the power radiated by gravitational waves was less than 2% of the available spin down power. Also the spin down limit was reached for the X-ray pulsar J0537-6910 under the assumption that any gravitational wave signal from it stayed phase locked to the X-ray pulses over timing glitches. The lowest upper limit on gravitational wave amplitude was $2.3 \times 10^{-26}$ for pulsar J1603-7202.

- \textit{Targeted search of VIRGO VSR2 data for Vela pulsar} [11]. The analysis involved three independent methods: the Bayesian method used in LIGO S5 search [8] and two matched-filtering methods. One method used the $F$ and $G$ statistics [6] and the other method involved matched filter on the signal Fourier components [12]. All three methods produced consistent results. The spin down limit was beaten, with the limit to the power radiated by gravitational waves of around 40% of the available spin down power. This was possible because of the good sensitivity of the Virgo detector at low frequencies. We expect to improve the upper limit on the amplitude of GW from the Vela pulsar using recently collected data from the Virgo VSR4 run by a factor of two.

(b) \textbf{Directed searches}. A search was performed for continuous gravitational radiation from the neutron star in the supernova remnant Cassiopeia A (Cas A) [13]. The Cas A remnant is the youngest known with a confirmed central compact object. The search coherently analyzed 12 hours of S5 data using the $F$-statistic. A band of frequencies from 100 to 300 Hz was searched and a wide range of first and second frequency derivatives appropriate for
the age of the remnant and for different spin-down mechanisms. Confidence limits (95%) of $0.7 - 1.2 \times 10^{-24}$ on amplitude $h_o$ were imposed (see Figure 3 of [13]). Also, limits were imposed on the amplitude of the r-modes of the neutron stars. The upper limits obtained are within the range of some theoretical predictions.

(c) Wide-parameter searches

- **Einstein@Home search.** Einstein@Home [14] is a volunteer distributed-computing project with around 100 thousand participants contributing a few hundred teraflops of computing power. The project carries out wide-parameter searches for periodic gravitational signals using the $F$-statistic to perform a coherent analysis of around a day of data followed by a post-processing procedure to find significant candidate signals. The most recently completed analysis [15] involved a search of 840 hours of data from 66 days of S5 LIGO run. The data were divided into 30 h long stretches that were analyzed coherently. All of the sky was searched with a bandwidth from 50Hz to 1500Hz and the frequency derivative $\dot{f}$ range was $-f/\tau < \dot{f} < 0.1f/\tau$, for a minimum spin-down age $\tau$ of 1000 years below 400Hz and 8000 years above 400 Hz. The post-processing procedure involved coincidences among candidates found in 28 segments analyzed. The search has not revealed statistically significant signals. The estimated sensitivity (Figure 4 of [15]) shows that in the 125 Hz to 225 Hz band, more than 90% of sources with dimensionless gravitational-wave strain tensor amplitude greater than $3 \times 10^{-24}$ would have been detected. The Einstein@Home search of the whole S5 data set using a hierarchical method with a $F$-statistic coherent step followed by a Hough search has been completed with paper under review and another search of S6 LIGO data using an optimized hierarchical method [7] is currently running.

- **Power Flux search.** A search of the whole S5 data using the PowerFlux method has recently been completed [16]. An all sky search was performed with this method in the frequency band from 50Hz to 800Hz and with the frequency time derivative in the range from $-6 \times 10^{-9} \text{Hz/s}$ to 0. The 95% confidence upper limits (see Figure 1 of [16]) on $h_o$ for the most favorable circular polarization ranged from $4 \times 10^{-25}$ to $2 \times 10^{-23}$.

The searches for periodic gravitational waves have not yet led to the detection of a signal, but the upper limits obtained begin to be astrophysically interesting by imposing non-trivial constraints on the structure and evolution of the neutron stars.

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