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Prospects of continuous gravitational waves from *Fermi* LAT sources

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Summary. — Non-axisymmetric spinning Neutron Stars are expected to be sources of continuous gravitational waves. Only a small fraction of the total number of neutron stars believed to exist in the Galaxy is observed through their electromagnetic emission. This number steadily increasing recently, thanks to the *Fermi* Large Area Telescope and to radio surveys. The *Fermi* Large Area Telescope catalogue contains several potentially interesting sources for gravitational-wave searches, such as supernova remnants and the "unassociated" sources. In order to look for continuous gravitational signals the knowledge of the NS parameters, *i.e.* rotational frequency and position, is needed. Depending on the degree of accuracy with which these parameters are known, several types of searches can be performed. In this paper I will discuss the perspectives and considerations of continuous gravitational-wave searches for *Fermi* LAT sources.

1. – Introduction

Gravitational waves (GW) are perturbations in the space-time metric generated by sources with an asymmetry in their mass-energy distribution. GWs have a very weak coupling mass-energy distribution that may be encountered during propagation, hence it is expected that the only detectable sources are very compact and fast-moving astrophysical objects such as black holes (BH) and neutron stars (NS).

Firstly predicted by Einstein in 1916 [1], the first GWs have been observed on September 14th 2015 [2], following the coalescence and merging of two intermediate-mass BHs ($\sim 30 M_{\odot}$) and later on December 26th 2015, due to a second BHs merger. The measure of these two GWs have a carried out plenty of information such as the BHs' masses and spins. Moreover from the so-called *ring-down phase* it was also possible to infer the remnants mass and spin.

Furthermore, the observed GWs have been used as s probe to test general relativity in strong field regime, obtaining very strong constraints on alternative theories of gravitation [3]. NSs are another class of GWs emitters that have not been observed so far.

NSs are the leftover of a dying massive star and their electromagnetic (EM) emission is observed at several wavelengths. In particular, many new NSs have been discovered in recent years thanks to their γ-ray emission. NS are expected to be emitters of continuous GW signals, namely continuous-waves signals (CW). In this paper I will present the modern state of the art for GW searches from γ-rays sources present in *Fermi* LAT catalogues.

The paper is organized as follow. In sect. **2** I will give some basics on which is the CW signal that we expect to find in the data remarking the possible type of searches that we can perform. In sect. **3** I will recap the interesting sources present in the last *Fermi* LAT catalogue showing the most recent result of their GW counterpart. Finally in sect. **4** I will summarise the paper and present the future perspectives.

2. – Continuous gravitational signal and searches

The CW signal emitted by an asymmetric spinning NS can be written, following [4], as

$$h(t) = h_0 h^+ F_+(t,\psi)\cos(2\pi i f_{gw}(t)t + i\phi_0) + h_0 h^\times F_\times(t,\psi)\sin(2\pi i f_{gw}(t)t + i\phi_0), \tag{1}$$

where ι is the angle between the line of sight to the source and the star rotation axis, and the polarization angle ψ is defined as the direction of the major axis with respect to the celestial parallel of the source and ϕ_0 the initial phase. The functions $F_+(t,\psi), F_\times(t,\psi)$ are the detector *sidereal responses* and encode the interferometer response to the GW polarisations([1]). Given a source with measured rotation frequency f, frequency derivative $\dot{f}$ and distance d, the GW signal amplitude can be constrained assuming that all the rotational energy is lost via gravitational radiation. This absolute upper limit, called *spin-down limit*, is given by

$$h_{sd} = 8.06 \cdot 10^{-19} I_{38} \left(\frac{1\,\mathrm{kpc}}{d}\right) \left(\frac{\dot{f}}{\mathrm{Hz/s}}\right)^{1/2} \left(\frac{\mathrm{Hz}}{f}\right)^{1/2} \tag{2}$$

being I_{38} the star moment of inertia in unit of 10^{38} kg m^2. The corresponding spin-down limit on the star equatorial ellipticity can be easily obtained as

$$\epsilon_{sd} = 0.237 \left(\frac{h_{sd}}{10^{-24}}\right) \left(\frac{\mathrm{Hz}}{f}\right)^2 I_{38}^{-1} \left(\frac{d}{1\,\mathrm{kpc}}\right) \tag{3}$$

Even in the absence of a detection, establishing an upper limit below the spin-down limit for a given source is an important milestone, as it allow us to put a non-trivial constraint on the fraction of rotational energy lost through GWs.

Despite eq. (1) the signal at the detector is not monochromatic. In fact it is modulated by some effects such as the *Romer Delay*, due to the detector motion, and the source

([1]) The complex polarisation amplitudes $h^+, h^\times$ are given by

$$h^+ = \frac{1+\cos^2\iota}{2}, \qquad h^\times = \cos\iota.$$

intrinsic spin-down, due to the energy loss from the source. All these effects must be properly taken into account in order to increase the signal-to-noise ratio in the analysis. Generally different types of searches can be performed according to the knowledge on the source, *i.e.* frequency, spin-down and position in the sky.

2·1. *Targeted searches.* – When all the main parameters of the source are accurately known, an analysis based on matched filtering can be used to maximize the signal-to-noise ratio. The 90% confidence level sensitivity of this type of search scales with the observation time T_{obs} and detector noise spectrum S_n as

$$h_{min} \approx 10\sqrt{\frac{S_n}{T_{obs}}}, \tag{4}$$

where the numeric coefficient correspond to a false alarm probability of 1%.

2·2. *Directed searches.* – This kind of search is performed when the position of the source is known, but its rotational parameters are uncertain or unknown. This happens for instance for signals from supernova remnants, for which the presence of a central compact object is deduced from the continuous electromagnetic emission, but no pulsed emission is observed. Depending on the volume to be explored in the frequency and spin-down space, coherent methods can be applied or not. For a fully coherent search the sensitivity is

$$h_{min} \approx 20\text{–}30\sqrt{\frac{S_n}{T_{obs}}}. \tag{5}$$

2·3. *All-sky searches.* – Let us not assume the knowledge of the signal parameters and explore a large portion of the source parameter space. All-sky searches are mainly based on hierarchical procedures in which the data are divided into short chunks and combined incoherently. The most significant candidates are selected and then subject to a follow-up procedure. This allows to strongly reduce the computational cost of the analysis at the price of a sensitivity loss with respect to coherent methods. The 90% confidence level sensitivity of this method scales as

$$h_{min} \approx \frac{\Lambda}{N^{1/4}}\sqrt{\frac{S_n}{T_{bands}}}, \tag{6}$$

being Λ a factor (of the order of ≈ 20 for $\mathcal{O}(10^9)$ selected candidates), N the number of chunks in which the data are divided and T_{bands} the duration of each chunk.

3. – *Fermi* LAT sources and searches

The Large Area Telescope (LAT) is an instrument on the *Fermi* satellite that can detect continuous γ-ray emission in the range from 20 MeV to 300 GeV, measuring the arrival times, energies and directions of photons. The *Fermi* LAT has produced 3 catalogs so far [5] [6] [7], the last one is the *Fermi 4-years catalogue 3FGL* (2).

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(2) The LAT team distinguish between *associated* sources and *identified* sources. The associated sources are those for which a space correlation with a known source it is observed. An identified source is based also on the the correlation with luminosity variability in other wavelengths.

These catalogues contain several sources which are possible CW emitters. It is important to clarify that many promising CW sources are also observed in other wavelengths, such as radio or X-ray, and for this reason the LIGO and Virgo Collaborations have performed in the past their analysis for these sources. But there are still many γ-ray sources exclusively present in LAT's catalogues that remain unexploited.

γ-ray Pulsars(143 identified, 24 associated). – Most of the pulsars are timed in radio observations. However there are also some radio faint pulsars strongly emitting in γ-rays, such as J1813-1246 firstly discovered using LAT's γ-ray observations [8]. The timing measures of the pulsars periodicity are often not enough accurate to perform fully coherent GW searches using parameters obtained from γ-ray observations alone. The most recent work of CW searches from known pulsars was recently published [9]. In this work CW were searched from about 200 known pulsars timed in the radio band. In particular for 11 pulsars it was possible to beat the spin-down limit obtaining a very stringet upper-limit on the GW amplitude. As an example the upper-limit for the Crab and Vela pulsars are, respectively, $h_{crab} \approx 6 \cdot 10^{-26}$ and $h_{vela} \approx 3 \cdot 10^{-25}$ which correspond to a 0.002% and 0.008% of their energy lost in GW. If fully coherent target searches are not possible due to some uncertanties on the pulsars parameters it is possible to apply a full coherent narrow-band search [10]. Currently a work based on narrow-band searches involving CW searches from pulsars observed in different wavelengths is in preparation.

Supernova remnants (12 identified, 11 associated). – According to the standard stellar evolution a central compact object (CCO) is expected to be present in the centre of the remnant, eventually a NS. For a fraction of known supernova remnant such as Cassiopea A it is possible to observe the presence of a CCO but it is not possible to infer its nature. Cassiopea A and other 8 supernova remnants observed in different wavelengths were inspected for GW emissions using LIGO Science Run 6 run in a very recent study [11]. The search ran on the Atlas computing cluster at the Max Planck Institute for Gravitational Physics. This type of analysis used around 140150 thousands of CPU hours over 3220 processors. No detection of GWs was claimed and the upper-limits was set every 5 Hz on a very wide frequency band for the 9 supernova remnants. However many of the supernovae remnants present in LAT's catalogue remain not analysed.

Pulsar wind nebula (9 identified, 2 associated). – This type of sources shows a Crab-like electromagnetic emission in their supernova remnant due to the presence of a possible NS. By the way in many cases the star remains non-localized and target/directed searches cannot be applied. No CW searches were performed for this type of sources by the LIGO and Virgo Collaborations.

Supernova remnants/pulsar wind nebule (49 associated). – This sources show the electromagnetic spectra of a supernova remnant or pulsar wind nebula but they show a high variability and the identification or association is not very trivial. Also in this case coherent CW searches are not possible. No GW searches were performed for this kind of sources.

Table I. – *Applicability of different developed algorithms for gravitational waves search from neutron stars (rows) to interesting astrophysical targets in Fermi LAT catalogue (columns).*

	Known pulsar	Supernova remnant/ Pulsar wind nebulae	Unassociated
Targeted searches	✓	✗	✗
Directed searches	✓	✓	✗
All-sky	✓	✓	✓

Unassociated (1010). – These sources are about the 33% of the catalog and the majority are also present in the previous catalogs (this means they are persistent sources). It can be predicted that 47% of those objects are neutron stars, 44% are supernova remnants and 9% are other γ-ray sources [7]. It is then very important to consider also this type of sources in GW searches. No particular searches method exist for this kind of sources in the literature.

The most recent CW searches, that roughly cover the possibility of CW from this type of sources, is an all-sky search using S6 data [12]. The search ran on *Einsten@home* covering the entire sky and exploring a 500 Hz band. No detection was claimed and the smallest upper-limit reached was $h_0 \sim 5.5 \cdot 10^{-25}$ in the most sensible band of the interferometer.

On the other hand another all-sky search using a different pipeline was used to analyze S6 covering the frequency band from 100 Hz to 1500 Hz but with reduced integration time [13]. No detection was claimed by this analysis and a mean upper-limit of the GW amplitude was set on the analysed frequency band. It is important to note that even if the all-sky search generally covers all the sources present in the catalogue, an application of a CW search projected for a particular type of LAT's source will improve the performance of our analysis. Most of the sources present in the *Fermi* LAT catalogue remain then not fully exploited under a GW point of view.

In table I have summarized the type of CW searches performed for the sources present in the last *Fermi* LAT catalogue.

4. – Future perspectives and conclusions

As we have seen in the previous sections, the *Fermi* LAT γ-ray catalogue offers plenty of interesting sources from the gravitational-wave point of view, such as pulsars and supernova remnants. No detection of continuous GW from these type of sources was claimed by the LIGO and Virgo Collaborations, but however upper-limits were put.

Another large class of interesting sources are the unassociated sources that are expected to be composed by a large population of unseen galactic neutron stars. A GW detection from such kind of astrophysical sources will confirm the presence of a compact object and will allow us to infer the properties of the emitting source.

The types of GW searches that we can perform are determined by our knowledge on the source parameters. In general the more are the uncertainties, the more will be the computational time of the analysis and the worse will be the sensitivity reached. For this reason most of the *Fermi* LAT sources were not analysed by the two Collaborations.

Then it is very important to develop data analysis methods able to extract and evaluate the GW signal from the interferometers data offering a good trade-off between the computational time and the sensitivity. Machine learning techniques, which are not under development for *compact binary coalescence* [14], offer a good solution to this problem. Even if the training of the pipeline can take a long time, their application to the real case will be very fast allowing the analysis of most of the *Fermi* LAT sources.

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