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Search of Gravitational Waves from GRBs Inner Engine with the AURIGA Detector

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Abstract. The origin of GRBs could be explained by identifying their inner engines with NS-BH coalescences, which form, at the end of their evolution, a matter torus surrounding a BH. Once the torus has been formed, a strong emission of gravitational waves, which lasts for several seconds, occurs. The predicted gw signal is a linear chirp with slowly varying frequency in the kHz range. We simulate both the noise of the gw detector AURIGA using its predicted sensitivity ($10^{-22} < S_h^{1/2} < 10^{-21} Hz^{-1/2}$) in the band $860 \div 950\ Hz$ and gw signals which fall under the form of linear chirps on the detector. The Wigner-Ville distribution has been devised for a sub-optimal analysis of the AURIGA output. The analysis can be improved by considering a cumulative search based on the supposed coincidences of gws and GRBs.

1. Introduction

The detection of gravitational radiation from astrophysical sources is still an outstanding open problem in experimental gravitation. For a long time the relevant astrophysical model of strong gws emitter has been the stellar core collapse during a SN event. While some models based on SN explosions are still discussed nowadays, it seems that more interesting models of gws sources are coalescences of compact rotating objects which should form an accretion disk around a BH. In particular, a coalescence of a NS into a BH has been recently proposed by M. van Putten (van Putten & Ostiker 2001; van Putten

2002; van Putten 2001) as a model for the inner engine of GRBs. The estimated luminosity both in gravitational waves and in electromagnetic emissions are of the same order. The key feature of the model is the emission of gravitational waves with a slowly varying frequency and an almost constant amplitude (linear chirp). The expected gw signal is no longer impulsive as predicted by other inner engine models (supernovae, collapsars and hypernovae explosions). On the contrary, once the coalescence phase of the NS-BH system terminates, we have, for a time of the order of $10 \div 80$ *sec*, a sinusoidal gravitational wave with a linear growing frequency in the kHz range.

In this paper we analyze the linear chirp templates in their possibility of being detected by the gw detector AURIGA. The new AURIGA design, with a predicted sensitivity of $2 \cdot 10^{-22} < S_h^{1/2} < 10^{-21} Hz^{-1/2}$ (J-P Zendri et al., 2002) in the frequency band $860 \div 950\ Hz$, allows the detection of a linear chirp with unitary Signal-to-Noise Ratio (SNR) at a distance of $30 Mpc$, still insufficient for a detection of a single cosmological source ($D \simeq 100 \div 1000 Mpc$). However, cumulative searches making use of the trigger information registered by GRBs satellites could, in principle, reach sensitivities below the nominal sensitivity of detectors: their typical gains is $N^{1/4}$ (Tricarico et al. 2001), where N is the number of cumulated GRBs (for instance, $N^{1/4} \simeq 4.5$ can be achieved in one year).

The plan of the paper is as follows. In section 2 we make a survey of the most promising models of the inner engine of GRBs which behave like emitters of gws. In section 3, in order to deal with these linear chirps we resort to the Wigner-Ville distribution which is a suitable tool for concentrating the major part of the chirp energy along a straight line in the time-frequency plane. In section 4 we discuss the possibility to perform a cumulative search of gws in coincidence with GRB triggers.

2. GW Signals from GRBs Inner Engine

It is well known that a massive rotating star can emit gws as a consequence of its collapse and that the released energy in the electromagnetic channel involves the ejecta of the star, while the gravitational signal depends on the dynamics of the collapsing core.

A model for the inner engine of GRBs, based on a possible connection between GRBs and supernovae, is the so called “cannonball model” (Dar & De Rujula, 2001). Accordingly, a SN explosion generates a compact object (BH or NS) surrounded by an accretion disk of about the same mass. Such a system should emit ultrarelativistic jets (known as “CannonBalls”, CBs) which cool down and remove part of the material constituting the disk. When the CBs pierce the SN shell, they heat and emit collimated photons; far away from the shell, the CBs are decelerated by the interstellar medium and originate the afterglows. The waveform of emitted gws has been evaluated (Segalis & Ori, 2001) as a short serie of bursts of the length of $\approx 10^{-2}$ *sec* and an energy of about 10^{52} *erg*.

Nowadays, more effective gw sources come out from the coalescences of compact objects forming accretion disks (for an overview of these models see Fryer, Woosley & Hartmann, 1999). The proposed progenitors for coalescing systems are i) the merger of double NS (Janka & Ruffert 2001; Ruffert & Janka, 1999; Rosswog et al., 2000), which can produce an accretion disk of $\sim 0.01 M_{\odot}$; ii) the tidally disruption of a NS around a BH (Kluzniak & Lee, 1999), which originates a disk of some tenth of a solar mass; iii) a white dwarf-BH merger (Fryer et al., 1999); or iv) the inspiralling of a compact object into its companion's helium core (helium-mergers), (Zhang & Fryer, 2001; Fryer & Woosley 1998). The powering of GRBs through an accretion disk can proceed also as a consequence of a "failed supernova" or collapsar model, (MacFadyen, Woosley & Heger, 2001). Collapsars form when the iron core of a rotating massive supernova collapses onto a BH: while the stellar mass accretes the BH, the collapse is slowed down along the equator forming the accretion disk. All these models are prototypes of GRBs inner engines, and the great amount of available energy can justify an emission in both electromagnetic and gravitational channels as strong as $10^{50 \div 53}$ erg.

Among the models based on the coalescence, a very attractive scenario has been proposed by van Putten (van Putten & Ostiker 2001; van Putten 2002; van Putten 2001). In this model the inspiralling of a BH and a NS results in the formation of a torus surrounding a Kerr BH. The condition of "suspended accretion" of the BH is reached when the balance of the torques on the torus prevents its collapse, i.e. $\tau_+ = \tau_- + \tau_{rad}$, where τ_-, τ_+ and τ_{rad} are the torques due to the magnetic winds on the external surface (dissipating the angular momentum), to the rotational energy of the BH (sustaining the torus) and to the emission of radiations (both gravitational and electromagnetic) respectively. The state of suspended accretion lasts from few seconds to several tens of seconds, ensuring a gravitational waves emission from the torus comparable to the electromagnetic one from the BH, which originate GRBs through the standard fireball model (Piran, 1999). For a BH of $\sim 7M_{\odot}$, the emitted energy is about 10^{53} erg and the phase grows continuously with the time.

Depending on the phase behaviour, gw signals from models of GRB engine can be divided into two classes: bursts and quasi-periodic (or periodic) signals. As far as the first class is concerned (for instance bursts occur in the "CB model"), the Wiener filter matched to a delta function can be used as it maximizes the SNR for almost all the bursts wave forms. On the contrary, the Wiener filter produces a serie of cumulative errors when applied to the second class of signals. For these sources we suggest an analysis based on the Wigner-Ville distribution: a mathematical tool particularly suitable to put in evidence quasi-periodical phenomena. For example, considering the coalescence of a torus surrounding a BH, in the first order approximation, the frequency is approximately the double Kepler frequency

$$\omega_0 = 2\omega_K = 2\sqrt{G\frac{M+m}{R^3}} \ , \tag{1}$$

i.e. $(1 \div 2)$ kHz when the mass M of the black hole is $7M_{\odot}$. After a period of the same order of a long GRB ($\sim 10 \div 80$ sec), the torus will collapse. The frequency $\omega(t)$ is varying linearly with time (see e.g. van Putten & Sarkar, 2000; van Putten & Levinson, 2001): $\omega(t) = \omega_0 + \beta(t - t_0)$ where β, the slope of the instantaneous frequency, is a parameter which depends on the dynamical quantities α, T and ω_0: $\beta \equiv 2\alpha\omega_0/T$. The value of α has been evaluated to be of the order of 0.1 (van Putten & Sarkar, 2000; van Putten & Levinson, 2001). The gw template we get reads:

$$f_{t_0,\beta}(t) = \cos[\varphi_0 + \omega_0(t-t_0) + \frac{\beta}{2}(t-t_0)^2] \quad (t_0 < t < t_0+T) \ , \qquad (2)$$

where ω_0, t_0 and φ_0 are the initial frequency, time and phase respectively.

3. Search Method

The Wiener optimal filtering of the modulated chirp signal embedded in additive white noise consists in cross correlating the noisy signal with the expected whitened template $L(\omega)F_\beta(\omega)e^{-i\omega t_0}$, where $F_\beta(\omega)$ is the Fourier Transform of $f_{0,\beta}(t)$ and $L(\omega)$ is the innovation filter so that $L(\omega)\cdot L^*(\omega) = S(\omega)$; to preserve high SNR we need an huge family of $10^4 \div 10^6$ templates of tenth second duration ($\sim 10^5$ samples for 5 kHz sampling rate) which cover our uncertainties on the β, ω_0 and T parameters. Expected computational costs scale accordingly. So, while Wiener filtering is the optimal solution for a well modeled signal, it leads to cumulative errors when applied to an inadequately modeled source and we have to filter continuously in time, as the arrival time of the chirp is unknown. For this reason, we abandon the Wiener filtering and search for another method to detect the signal. The optimal filter gain, which represent the reduction of the standard deviation of noise after the filtering, is about 50 for the noise curve predicted for the next run of the AURIGA detector. The gw linear chirp has, apart its amplitude that we want to estimate, 4 parameters: initial time and frequency, duration and frequency variation rate. The signal sensed by the AURIGA detector has only 2 free parameter: the arrival time and the slope of the instantaneous frequency β, as the AURIGA band limits fix final time and chirp frequencies. The Wigner-Ville distribution gives a joint time-frequency representation of the energy of the signal we want to analyze (Qian & Chen, 1996; Anderson & Balasubramanian, 1999). For a signal $h(t)$ its definition reads

$$WVD_h(\omega,t) = \int h(t+\frac{\tau}{2})h^*(t-\frac{\tau}{2})\exp(-i\omega\tau)d\tau \ . \qquad (3)$$

The Wigner-Ville distribution (WVD) concentrates the energy of a linear chirp on the line $\omega = \omega_0 + \beta(t-t_0)$ while scatters the noise over the whole time-frequency plane. In addition, the integration of the WVD over the same line gives an estimate of the energy associated with the linear chirp. In order to directly detect the signal embedded in additive gaussian noise from the Wigner-Ville diagram, we need a much larger SNR (> 50) than required by the optimal Wiener filtering. However, we can define different strips Δ in the (t,ω)-plane with different slopes delimited by the inequality: $|\omega - \omega_0 - \beta(t-t_0)| < \epsilon$, where ϵ is the strip width. The integration along different strips corresponds to different values of the frequency variation rate. Moreover, we can cover all the time-frequency plane by changing the value of the slope β and the thickness ϵ of the strip. Because AURIGA is a resonant detector, its transfer function is characterized by two poles. In order to have the maximum effectiveness of the

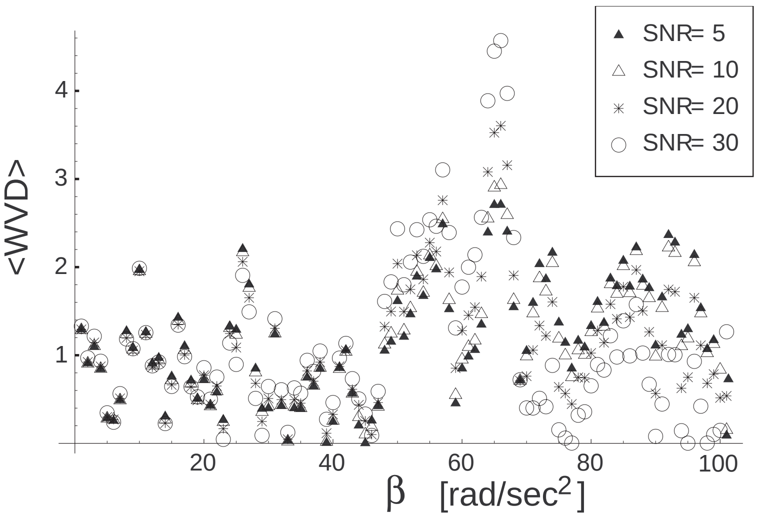

Figure 1. $< WVD >$ (in arbitrary units) vs the slope β of the integration strips over the (t, ω)-plane. Notice that, if the nominal SNR is > 20, we can identify the signal and estimate the β parameter with a sufficient accuracy.

chirp search, the resonant part of the detector dynamics must be removed by means of the whitening filter $1/L(\omega)$, which also ensures a complete decorrelation of noise. First we have calculated the Wigner-Ville distribution of the whitened output of the AURIGA detector (noise and signal) and then its averaged value over the strips Δ

$$< WVD >= \iint_{\Delta} WVD(t, \omega) dt\, d\omega \ . \tag{4}$$

We have reported in Figure 1 the scatter plot of $< WVD >$ as a function of the slope of the strip β; $< WVD >$ is calculated at different SNR=5,10,20 and 30 and a constant width $\epsilon = 5\ Hz$. Notice that the nominal SNR for a marginal detection with a single WV transform of a linear chirp is $SNR = 20$. However, cumulative analysis of all GRB triggers can be performed by means of the standard Student t-test or Mann-Whitney u-test (Tricarico et al., 2001) applied to the cumulated outcome of $< WVD >$. The mean value of nominal SNR for 1 year of GRBs can be reduced to $20/4.5 \sim 4.5$.

4. Conclusions

The almost daily detection of GRBs suggests that, after a year of cumulative search, we can gain a factor of ~ 4.5 in the survey distance of a gw detector. Optimal filtering would fully exploit the sensitivity of the detector but, unfortunely, it is very expensive in computational resources. The mean Wigner-Ville value, taken over chirp paths in the time-frequency plane, requires an high SNR (20 or higher for a single detection, 4.5 or higher cumulating the results of 1 year of GRBs triggers) to be statistically significant. Other sub-optimal methods (for instance wavelet decomposition analysis or the Steger's ridge detection algorithm described in Anderson & Balasubramanian, 1999) may be less demanding in SNR than the outlined method and will be investigated. The AURIGA detector turns out to be at the limit of a possible detection. However, a claim for a correlation of GRBs and linear chirp gw signals is of paramount importance for our understanding of GRB phenomena. The improvement of a factor 10 in the survey distance with respect to AURIGA, which should ensure a reasonable detection rate of 1 event per year, can be achieved by further technological progresses of both interferometers and bars gw detector. Presently, General Relativity is important to astrophysics as an interpreter (inner engine models) of GRBs observations. When GRBs will begin to be observed, general relativity will enter a new epoch as a provider of new observational data to astronomy.

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