Short Gamma Ray Bursts as possible electromagnetic counterpart of coalescing binary systems

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Abstract

Coalescing binary systems, consisting of two collapsed objects, are among the most promising sources of high frequency gravitational waves signals detectable, in principle, by ground-based interferometers. Binary systems of Neutron Star or Black Hole/Neutron Star mergers should also give rise to short Gamma Ray Bursts, a subclass of Gamma Ray Bursts. Short-hard-Gamma Ray Bursts might thus provide a powerful way to infer the merger rate of two-collapsed object binaries. Under the hypothesis that most short Gamma Ray Bursts originate from binaries of Neutron Star or Black Hole/Neutron Star mergers, we outline here the possibility to associate short Gamma Ray Bursts as electromagnetic counterpart of coalescing binary systems.

Key words. short Gamma Ray Burst - coalescing binary systems - gravitational waves - standard candles - cosmological distances.

1. Introduction

Coalescing binary systems containing two collapsed objects, i.e. a Neutron Star (NS), a stellar-mass Black Hole and a Neutron Star (BH-NS) or two stellar-mass Black Holes (BH-BH) or White Dwarf-White Dwarf (WD-WD), are supposed to emit a powerful rate of gravitational waves (GWs). They are considered among the most promising GWs sources for ground-based interferometers, of the current and future generation, such as LIGO (Laser Interferometer Gravitational-Wave Observatory) (Abramovici et al. 1992) and French/Italian VIRGO (Caron et al. 1997) and their advanced versions. BH-NS and, especially, BH-BH mergers emit more powerful GWs than NS mergers, for which the sensitivity of LIGO and VIRGO detectors is highest: therefore they can be detected up to larger distances. The horizon of first generation LIGO and VIRGO is 800 Mpc. BH-NS and BH-BH mergers is $\sim 20, 43$ and $100$ Mpc, respectively, while ADVANCED LIGO/VIRGO class interferometers should detect them up to distance of $\sim 300, 650$ and $1600$ Mpc. The rate estimated of detectable merging events has been based on the observed galactic population of NS binaries containing a radio pulsar (Phinney 1991; Burgay et al. 2003; Kalogera et al. 2004; Narayan et al. 1992). The best estimate of the NS merger rate in the Galaxy is presently $\sim 80^{+210}_{-20}$ Myr$^{-1}$, converting to $\sim 800^{+2000}_{-600}$ Gpc$^{-3}$ yr$^{-1}$ for a galaxy number density of $10^{-2}$ Mpc$^{-3}$ (Kalogera et al. 2004). The study of binary systems population gives results consistent with the above rate. The GWs signals from NS mergers are expected at a rate of one in $\sim 10^{+150}_{-10}$ years with VIRGO and LIGO and one every $1 \pm 15$ days with ADVANCED LIGO/VIRGO class interferometers. The BH-NS and BH-BH merger rates in the Galaxy are highly uncertain (Perna & Belczynski, 2002), they are estimated $\sim 1\%$ and $\sim 0.1\%$ of the NS merger rate, respectively, implying that BH-NS and BH-BH mergers contribute marginally to the GWs event rate, despite the larger distance up to which they can be detected. Recent observations support the hypothesis that a large fraction of short Gamma Ray Bursts (GRBs) are associated with the inspiral and merger of compact binaries. GRBs are powerful flashes of $\gamma$-rays which occur approximately once per day and are isotropically distributed over the sky (Meszaros 2006). The variability of the bursts on time scales as short as a millisecond indicates that the sources are very compact, while the identification of host galaxies and the measurement of redshifts for more than 100 bursts have shown that GRBs are of extra-galactic origin. GRBs are grouped into two broad classes by their characteristic duration and spectral hardness (Kouveliotou et al. 1993; Gehrels et al. 2006). The progenitors of most short GRBs (duration $\lesssim 2$ s, with hard spectra) are widely thought to be mergers of NS binaries or NS-BH binaries; see (Nakar et al. 2007) and references therein. A small fraction (up to $\sim 15\%$) of short-duration GRBs are also thought to be due to giant flares from a local distribution of soft-gamma repeaters (SGRs) (Duncan & Thompson 1992; Nakar et al. 2006; Chapman et al. 2008). Long GRBs (duration $\gtrsim 2$ s, with soft spectra), on the other hand, are associated with core-collapse Supernovae (Galama et al. 1998; Hjorth et al. 2003; Malesani et al. 2004; Campana et al. 2006), both the merger and Supernovae scenarios result in the formation of a stellar-mass Black Hole with accretion disk (Fryer et al. 1999; Cannizzo & Gehrels 2009), and the emission of gravitational radiation is expected in this process.

Since, as we said above, GWs measurements of well-localized inspiraling binaries can measure absolute source distances with high accuracy, simultaneous observation of GRBs (emitted by binary systems) and short GRBs would allow us to directly and independently determine both the luminosity distance and the redshift of the binary systems (Capozziello et al. 2010). It has long been argued that NS-NS and NS-BH mergers are likely to be accompanied by a Gamma Ray Burst (Eichler et al. 1989). Recent evidence supports the hypothesis that many short-hard GRBs are indeed associated with such mergers (Fox et al. 2005; Berger et al. 2007). This suggests the exciting possibility that it may be possible to simul-
taneously measure, for coalescing binary system, the GRBs and GWs. The combined electromagnetic and gravitational view of these objects is likely to teach us substantially more than what we learn from either data channel alone. In this paper, we discuss the possibility to search for GWs associated with 11 short GRBs that have been recently detected by the SWIFT satellite (see SWIFT website). In other words, we search for GWs from short-duration GRBs. Since the nature of the radiation depends on the somewhat-unknown progenitor model, and we analyze short GRBs, the search methods presented here require specific knowledge of the gravitational waveforms which is specifically targeting binary inspiral GW signals associated with short GRBs. We look for burst signals with duration \( \leq 2 \) s and frequencies in the LIGO/VIRGO band, approximately 100 \( \pm 1000 \) Hz. The paper is organized as follows. In Sec. 2 we discuss some GRB energy relations while, in Sec. 3 the energy loss by binary coalescing system is considered. In Sec. 4 the chirp mass is calculated by considering a sample of short GRBs in the SWIFT catalogue. Sect. 5 is devoted to discussion and conclusions.

2. Gamma Ray Bursts Energy Relations

GRBs are the most powerful explosions observed in the Universe (Meszaros 2006). They are believed to be detectable up to a very high redshift (GRB090423 has been detected at a redshift \( z \sim 8 \)).

One of characteristic parameters of GRBs is \( T_{90} \), which is the time interval within which 90\% of the flux is detected. GRBs can be roughly separated into two classes (Weekes 2003): long GRBs (with \( T_{90} > 2\) s), generally associated to Supernovae or Hypernovae and short GRBs (with \( T_{90} < 2\) s), generally associated to mergers of compact objects.

Another characteristic parameters is \( E_p \), which is the peak energy of the spectrum. Its measurement is available for only cutoff power law spectrum as the best fit value (Racusin et al., 2009). If we cannot measure \( E_p \), then we can use the relation between \( E_p \) and the power law spectral index \( \alpha_{PL} \) (Racusin et al., 2009):

\[
\log E_p = 2.76 - 3.61 \log(-\alpha_{PL}).
\]

Another interesting parameters is the collimation-corrected energy, \( E_y \), that is linked to peak energy, \( E_p \), by the so-called Ghirlanda relation (Ghirlanda et al. 2004):

\[
\log E_y = a + b \log \left( \frac{E_p}{300\text{keV}} \right)
\]

where \( a \) and \( b \) are calibration constants (Liang et al. 2008), shown in Table 1.

| Relation | \(a\) | \(b\) |
|----------|------|------|
| \(E_y - E_p\) | 52.26 \(\pm\) 0.09 | 1.69 \(\pm\) 0.11 |
| \(E_{iso} - E_p - t_0\) | 52.83 \(\pm\) 0.10 | 2.28 \(\pm\) 0.30 |
| \(-t_0\) | -1.07 \(\pm\) 0.21 |

Table 1. Parameter values obtained by Liang et al. 2008.

We want to investigate the link between short GRBs and coalescing binary systems, and we want show that, if the collimation-corrected energy is correlated to the energy of GWs (and if they are comparable), then the chirp masses associated to short GRBs are compatible with those associated to the coalescing binary systems.

3. Energy loss from binary coalescing system

The energy \( dE \) carried by a GW along its direction of propagation per area \( dA \) per time \( dt \) is given by:

\[
\frac{dE}{dAdt} = \frac{c^3}{16\pi G} \left( \frac{\partial h_+}{\partial t} \right)^2 + \left( \frac{\partial h_\times}{\partial t} \right)^2 .
\]

where \( h_+ \) and \( h_\times \) are the standard polarizations of GWs. The energy output \( dE/dt \) from a localized source in all directions is given by the integral (Maggiore 2007):

\[
\frac{dE}{dt} = \int F(\theta,\varphi)r^2 d\Omega.
\]

Replacing

\[
\left( \frac{\partial h_+}{\partial t} \right)^2 + \left( \frac{\partial h_\times}{\partial t} \right)^2 = 4\pi^2 f^2 h^2(\theta,\varphi)
\]

and introducing

\[
h^2 = \frac{1}{4\pi} \int h^2(\theta,\varphi) d\Omega,
\]

we write eq. (4) in the form

\[
\frac{dE}{dt} = \frac{c^3}{G}(\pi f)^2 h^2 r^2 .
\]

Specifically, for a binary system in a circular orbit, with the help of the eq. (7) and the definition of the characteristic amplitude of GW (Maggiore 2007), we have

\[
h = \left( \frac{32}{5} \right)^{1/2} \frac{G^{5/3}}{c^3} \frac{M_c^{3/2}}{r} (\pi f)^{2/3} .
\]

The energy loss of the system is then

\[
\frac{dE}{dt} = \left( \frac{32}{5} \right)^{1/2} \frac{G^{7/3}}{c^5} (M_c \pi f)^{10/3} ,
\]

where \( M_c \) is the chirp mass, \( r \) is the distance from the source and \( f \) is the frequency of the GW. Introducing the correction for the redshift, we can write eq. (8) as:

\[
\frac{dE}{dt} = \left( \frac{32}{5} \right)^{1/2} \frac{G^{7/3}}{c^5} (M_c \pi f)^{10/3} \left( \frac{1}{1+z} \right)^{20/3} .
\]

This expression is the same that one can obtain directly from the quadrupole formula (Scott & Hughes 2009). Since energy and angular momentum are continuously away by the gravitational radiation, the two masses in orbit spiral towards each other, thus increasing the orbital frequency \( \omega \). The GW frequency \( f = \omega/\pi \) and the GW amplitude \( h \) are also increasing functions of time. The rate of the frequency change is then

\[
\dot{f} = \left( \frac{96}{5} \right) \frac{G^{5/3}}{c^5} n^{8/3} M_c^{5/3} f^{11/3} .
\]

We have now all the ingredients to test our hypothesis.

Using a sample of short GRBs of the SWIFT Catalogue for which the redshift, the $T_{90}$ and the spectral index are measured (see SWIFT website), we have calculated the peak energy related to the rate loss energy, the frequency and the redshift of the binary system:

$$\mathcal{M}_c = \frac{32}{5} \left( \frac{1+z}{2} \right)^{3/2} \frac{T_{90}^{3/10}}{G^{7/10}} \left( \frac{dE}{dt} \right)^{3/10} \cdot$$ \hspace{1cm} (12)

Eq. (14) can be used to determine the chirp mass of the binary coalescing systems, using redshifts of short GRBs. We suppose the equivalence between $T_{90}$ and the coalescing time ($\tau$) for binary systems given by \cite[Buonanno A. 2007]{Buonanno2007}:

$$\tau \approx 130 \left[ \frac{1.21 M_\odot}{M} \right]^{4/3} \text{Hz}^4 \text{s}.$$ \hspace{1cm} (13)

The results are reported in the following Table 3. Then we suppose that the collimation-corrected energy is similar to GW’s energy and the frequency are tuned in the range $100 \div 1000$ Hz \cite[Capozziello et al. 2010]{Capozziello2010}, by eq. (13) we can write

$$\mathcal{M}_{c,\gamma} = \frac{32}{5} \left( \frac{1+z}{2} \right)^{3/20} \frac{T_{90}^{3/10}}{G^{7/10}} \left( \frac{dE}{dt} \right)^{3/10} \cdot$$ \hspace{1cm} (14)

The error on chirp mass is calculated by the error on the collimation-corrected energy with the standard error propagation. We suppose that the coalescence of binary systems is caused only by the emission of GWs (neglecting, for example, mass exchanges and neutrino emissions). Now, if we fix the cosmological model, we can calculate, in principle, the luminosity distance for each GRBs \cite[Izzo et al. 2009]{Izzo2009} by:

$$D_l(z) = \int_0^\infty \frac{d\xi}{H(\xi)}.$$ \hspace{1cm} (15)

Considering the $\Lambda$CDM model and fixing as priors $H_0 = 70.5 \pm 1.3 \text{km/s/Mpc}$ and $q_0 = -0.57 \pm 0.17$ \cite[Komatsu et al. 2009]{Komatsu2009} \cite[Virey et al. 2005]{Virey2005}, we can calculate the distances and then we can use them to estimate the GW amplitude by eq. (8). The error on the GW amplitudes can be assumed negligible. The results are reported in Table 2. In Fig. 1 the qualitative behavior of the chirp mass $\mathcal{M}_{c,\gamma}$ as a function of the frequency $f$ is reported for any GRB in the Table 2. The shift of the various curves is due to the ratio $E_{\gamma}/T_{90}$ and to the redshift $z$.

Table 2. Results obtained by coalescing binary systems and by the SWIFT Catalogue: in column 1, 2, 3 and 4, the GRB data, derived from the SWIFT Catalogue, are reported; in column 5, the chirp mass for each GRB in the range of frequency $100 \div 1000$ Hz (calculated by eq. (14)) is reported. In the last column we have the amplitude of the GWs calculated by eq. (8).

| GRB   | $z$  | $T_{90}$ (sec) | $E_{\gamma}$ (10^{52} erg) | $\mathcal{M}_c (M_\odot)$ | $h$ (10^{-22}) |
|-------|------|---------------|-----------------------------|---------------------------|----------------|
| 090426 | 2.61 | 0.33          | 1.53\pm0.15                | (54.6\pm1.6)+(5.4\pm0.2)  | 3.19\pm0.32   |
| 090205 | 4.7  | 1.54          | 1.88\pm0.19                | (91.2\pm2.7)+(9.1\pm0.3)  | 5.79\pm0.58   |
| 080913 | 6.44 | 1.08          | 7.48\pm1.05                | (261\pm11)+(261\pm1)      | 29.5\pm3.0    |
| 080516 | 3.2  | 1.38          | 2.68\pm0.27                | (57\pm2)+(5.6\pm0.2)      | 3.11\pm0.31   |
| 070724A | 0.46 | 0.27          | 0.46\pm0.05                | (6.6\pm0.2)+(0.66\pm0.02) | 0.266\pm0.027 |
| 070506 | 2.31 | 1.3           | 3.24\pm0.23                | (34\pm1)+(3.4\pm0.1)      | 1.57\pm0.16   |
| 070429B | 0.9  | 0.25          | 0.95\pm0.10                | (14.2\pm0.4)+(1.42\pm0.04) | 0.603\pm0.060 |
| 051221A | 0.55 | 0.9           | 2.04\pm0.19                | (8.1\pm0.2)+(0.81\pm0.02) | 0.328\pm0.033 |
| 050922C | 2.2  | 1.41          | 7.50\pm0.68                | (44\pm1)+(4.5\pm0.1)      | 2.48\pm2.5    |
| 050813 | 1.8  | 0.16          | 8.55\pm0.89                | (68\pm2)+(6.8\pm0.2)      | 5.56\pm0.56   |
| 050509B | 0.23 | 0.06          | 0.73\pm0.08                | (8.4\pm0.2)+(0.84\pm0.03) | 0.692\pm0.070 |

Table 3. The coalescing time for NS-NS, BH-BH, WD-WD systems, respectively.

*poses the collimation-corrected energy is similar to GW’s energy and the frequency are tuned in the range $100 \div 1000$ Hz \cite[Capozziello et al. 2010]{Capozziello2010}, by eq. (13) we can write

$$\mathcal{M}_{c,\gamma} = \frac{32}{5} \left( \frac{1+z}{2} \right)^{3/20} \frac{T_{90}^{3/10}}{G^{7/10}} \left( \frac{dE}{dt} \right)^{3/10} \cdot$$ \hspace{1cm} (14)

The error on chirp mass is calculated by the error on the collimation-corrected energy with the standard error propagation. We suppose that the coalescence of binary systems is caused only by the emission of GWs (neglecting, for example,

Figure 1. The chirp mass $\mathcal{M}_{c,\gamma}$ related to the various GRBs as function of the frequency $f$.
5. Conclusions

In this paper, we have derived chirp masses associated to a sample of short GRBs (under the hypothesis that they are emitted by binary systems whose redshifts can be estimated considering them comparable to the GRB redshift). In such a way, considering the coalescing time equal to the $T_{90}$ and the energy lost (during the final phase of the coalescing process) equal to the emission of short GRBs, we have found that the chirp masses, obtained by the simulation, are comparable to the theoretical chirp masses associated to the coalescing binary systems. In particular the range of the chirp masses is reliable for BH-BH coalescing systems, but for the GRB070724A, GRB070429B, GRB051221A, GRB050509B the chirp masses are also reliable for NS-NS and WD-WD coalescing systems. The masses of NSs are typically of order $1.4 M_\odot$, stellar-mass BHs, as observed in X-ray binaries, are in general more massive, typically with masses of order $10 M_\odot$, and therefore are expected to emit even more powerful GW signals during their inspiraling and coalescing phases (Bulik & Belczynski 2003). The standard models describing the GRB sources are, in general, gravitational collapse, or related to fast increases of the mass of one or more objects that involve an enormous release of neutrinos and antineutrinos (Meszaros 2008, Schönfelder & Volker 2007). As discussed, GRBs can be roughly separated into two classes (Weekes 2003), long GRBs (with $T_{90} \geq 2s$), associated to gravitational collapse of very massive stars, and short GRBs (with $T_{90} \leq 2s$), associated to mergers of compact objects. In particular we have discussed short GRBs, because a vast amount of energy that coalescing binary systems (NS-NS, BH-BH or WD-WD) are thought to release is comparable to the estimated energy release of GRBs ($\sim 10^{51}$ to $10^{52}$ erg) thereby suggesting that coalescing binary systems can be considered as possible source of observed GRBs (Narayan et al. 1992). A binary system composed by two objects is not stable because it loses energy by emitting GWs. Such a loss of energy causes a progressive approach of the two objects between them and so the coalescence of such objects. In several cases, an accretion disk is produced at the rate of $0.1 M_\odot s^{-1}$ with an energy release of $\sim 10^{53}$ erg (Eichler et al. 1989). On the other hand, the merging of such objects can release up to $10^{53}$ erg in 10ms (Eichler et al. 1989). A meaningful fraction is issued in the form of neutrinos $\sim 10^{53}$ erg (Eichler et al. 1989) and antineutrinos $\sim 10^{53}$ erg (Eichler et al. 1989) that annihilate by producing electrons and positrons. The final result of such a process is a sphere of energy that expands. Theoretical estimates yield merger rates that can easily accommodate the observed burst rate, with engine lifetimes and energy releases roughly consistent with burst properties of cosmological populations. The locations of short GRBs with respect to their host galaxies are compatible with the kicks delivered by NS-NS binary systems at their birth time. Short GRBs could be a primary source population for the Laser Interferometer Gravitational Wave Observatory and other ground-based GWs detectors. Next generation of interferometers (as LISA (see website) or Advanced-VIRGO and LIGO) could play a decisive role in order to detect GWs from these systems. At advanced level, one expects to detect at least tens NS-NS coalescing events per year, up to distances of order 2 Gpc, measuring the chirp mass with a precision better than 0.1%.

References

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