Gravitational wave bursts from long gamma-ray bursts

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ABSTRACT

One of the most luminous explosions detected, gamma-ray bursts, especially the so-called long-duration bursts, most probably consist of an intrinsic core-collapse to a black hole inside a super massive star. We point out that this collapse alone will give a generic gravitational wave burst. It has been shown that the strength of this burst depends on the dimensionless spin parameter of the collapsing object. Under descent assumptions the gamma-ray burst’s central engine powers the explosion electromagnetically due to the rotation of the newly formed black hole. We argue that the peak luminosity and the isotropic energy of the gamma-ray burst can be associated with the spin of the black hole, due to this mechanism. Since, both gravitational and electromagnetic emission depend on the spin, they can be correlated and thus give a straight estimate for the gravitational wave burst, when we have in hand a gamma-ray burst with known distance. We discuss detectability limits for present and future detectors.

Key words: gravitational waves; gamma-ray bursts;

1 INTRODUCTION

The recent detection of gravitational waves from binary black holes and binary neutron stars has signaled the beginning of the gravitational wave astronomy and the multi-messenger era. The capabilities of present and future interferometric detectors have to be compared and correlated with all possible sources of gravitational waves (GW). In this work we discuss a generic feature of the gravitational collapse to a black hole which is believed to play a fundamental role in the physical production of a long-duration gamma-ray bursts (hereafter GRBs).

Since their first discovery back in the 60s (Klebesadel et al. 1973) GRBs have been a great scientific challenge both observationally and, mostly, theoretically. These cosmological hyper-energetic explosions are likely also to release energy in the form of gravitational waves. The main mechanisms for producing them are compact stellar mergers, for short-duration GRBs and massive stellar collapses for long GRBs. The long and short characteristic was set up depending on the difference in their duration and through the years has led to these different mechanism characterization (Kouveliotou et al. 1993).

The connection between short GRBs and the coalescence of binary neutron stars was recently proven (LIGO Scientific Collaboration et al. 2017). The GW signal that will accompany such mergers, was the subject of extensive research both analytically and numerically (Baiootti 2016). On the other hand, for long GRBs there are studies discussing the GW production through different possible mechanisms, but the overall picture is subtle.

The death of massive stars of mass above $10M_\odot$ is widely accepted to originate a GRB. The main mechanism supposes that the inner core of the massive star directly collapses to a black hole. Other possibilities have been discussed such as the birth of a magnetar (Usov 1992). In this work we will stick with the previous assumption of a direct collapse to a black hole.

During the death of the massive star, its core will pass from a neutron star phase and then collapse to a black. The “collapsar” engine argues that hyper accretion from the stellar envelopes that have formed an accretion disk and/or energy extraction from the newly formed black hole will drive a relativistic jet, which will power the GRB (Paczynski 1998; MacFadyen & Woosley 1999; Lee et al. 2000).

In this context, there have been discussed some possible ways of GW production. When the black hole is formed, after the collapse of the inner core of a massive star, accretion of the remaining stellar shells will distort the black hole resulting in a well-studied "ring-down" (Berti 2014) dissipating all this accretion-induced excitation till the black hole settles down.

Another possibility discussed in the literature is that during the collapse of the inner core, instabilities will result to the development of fragmentation and the production of multiple compact components whose coalescence will be a powerful emitter of GW (Nakamura & Fuguita 1989; Bonnell & Pringle 1995; van Putten 2001).

The production of an accretion disk is also expected in the context of the core collapse of a massive star. If the mass of this disk is high enough for its self-gravity to be important, then gravitational instabilities could result in bar formation which would radiate GW (Fryer et al. 2002; van Putten 2002; Davies et al. 2002). Following

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the formation of a puffed up accretion disk, the possibility of electromagnetic interaction between the black hole and the torus could give rise to gravitational radiation (van Putten & Levinson 2003; van Putten et al. 2004).

In this work we will discuss and focus on the GW burst that will be certainly produced when the core of a super massive star collapses to a black hole. This is an intrinsic feature of the gravitational collapse to a black hole (Stark & Piran 1985). It is known that the energy emitted in GW through the collapse of a compact object to black hole depends strongly on the angular momentum of this object. Furthermore, the core collapse of a super massive star to a black hole is the leading candidate for the central engine of a long gamma-ray burst. Thus, every long GRB should be accompanied with such a gravitational wave burst. This new born black hole with act as the central engine and drive the GRB. The electromagnetic energy extraction from the rotating black hole sustained through accretion, is one of the main models (together with accretion onto the black hole) to deposit the energy needed to power the burst. This mechanism depends strongly on the magnetic field strength and topology but the amount of energy that can be extracted is purely a result of the angular momentum of the black hole.

Thus, we can tentatively consider that the GW burst and GRB energetics both follow the angular momentum of the collapsing object and the resulting black hole. If we that the mass distribution of the newborn black holes is narrow and mostly concentrated around \( \sim 3M_\odot \), then the above mentioned quantities are closely connected and correlated. Furthermore, associating the isotropic energy measured for a certain GRB, then \( E_{\text{iso}} \), depends on the available energy from the black hole which is a function of the dimensionless spin. In what follows we will try to put these ideas in a detailed context, describing the physical procedures and estimating detectability limits. Moreover, we will highlight the intrinsic properties of such bursts while pointing the assumptions that these ideas are based on.

## 2 Collapse to a Black Hole

In this Section we will review the possibilities of black hole formation, depending on the mass of the progenitor star and discuss the gravitational wave signal that this black hole formation will give. This will be separated in the gravitational wave burst produced at collapse and the quasi-normal modes that will accompany this burst till the black hole has settled down. The mass of the progenitor star plays a significant role on the outcome of the collapse. Depending on the mass of the progenitor Wolf-Rayet star (for details see Crowther (2007)) the procedure that the inner core will follow can have a slightly different physical path. For massive stars, whose mass exceeds \( 40M_\odot \), it is expected that the iron core will not produce an outgoing shock and it will directly collapse to a black hole. If the mass of the progenitor is in the range between \( 23M_\odot < M_{\text{prog}} < \sim 40M_\odot \), then the iron core will contract and produce a proto-neutron star together with an out-going shock. After some time, some of the outward moving stellar matter, which is gravitationally bound, will fallback and accrete to the neutron star triggering its collapse when it cannot support anymore its own mass.

Both scenarios for the death of massive stars have a common feature, the production of a stellar mass black hole and this process of gravitational collapse has been thoroughly studied and has an intrinsic gravitational imprint, a gravitational burst accompanied with quasi-normal modes of the newly born excited black hole till it settles down (Stark & Piran 1985; Baiotti et al. 2005; Baiotti & Rezzolla 2006; Baiotti et al. 2007; Duez et al. 2004). The first work on this subject in numerical relativity (in axisymmetry) was done by Stark & Piran (1985). They computed the first waveforms and estimated the GW energy from a rotating stellar collapse in axisymmetry. The overall results showed that the collapse depends on the dimensionless spin of the initial star. The waves are similar but with an increasing amplitude with increasing spin parameter. A systematic study in gravitational-wave emission from the collapse of neutron stars to rotating black holes in three dimensions was done by (Baiotti et al. 2007).

They made an analysis on the collapse of stars with different initial rotation rates and they confirmed that there exist a precise scaling in terms of the dimensionless spin parameter. In detail what they found is that the energy radiated in gravitational waves during and after the collapse scale as the dimensionless spin in the fourth power \( (\propto (J/M^2)^4) \). It was reported in (Baiotti et al. 2005) that the measured angular momentum of the newly formed black hole after the collapse is remarkably close to the initial one. Thus, knowing the spin parameter of the black hole formed will enable us to have an estimate on the energy release in gravitational radiation. This relation does not scale up to all spin parameters, as it was found that the GW emission from collapsing neutron stars has a maximum in the emitted GW energy. This maximum was found to be the result of a delayed collapse due to the angular momentum resisting the collapse and thereby causing a smaller perturbation in the metric fields during the collapse. This correlation of the emitted energy with the spin parameter will allow us in the upcoming section to estimate the energy of the gravitational wave burst through the observed isotropic luminosity of a long-GRB, as which we will discuss can be also related directly to the spin of the newly born black hole.

They further discuss and compute the overall efficiency of converting the binding energy in gravitational waves, which is \( \delta M/M \approx 10^{-7} - 10^{-6} \) and thus it seems not to be an efficient process. This efficiency is calculated by imposing to the initial models a pressure reduction to trigger the collapse. However, it is difficult to know exactly the physical conditions when the collapse is triggered and starts. The above mentioned efficiency can be viewed as a lower limit to the gravitational wave production. In the same study by (Baiotti et al. 2007) another series of collapses was performed not by reducing the pressure, but by adding an inward radial velocity \( 0.02 c \) to the interior matter. This may not be too far from reality, since velocity perturbations could happen in the interior shells of a massive star which is about to collapse. By imposing these velocity perturbations as an initial collapse trigger the efficiency goes up two orders of magnitude ( \( \delta M/M \approx 10^{-5} - 10^{-4} \)). The energy has the same scaling dependence on the dimensionless angular momentum to the fourth power, but it is interesting to notice that in this case where the collapse is triggered by velocity perturbations there is no maximum found, thus this energy scaling could go up to high spins. This means that, if we assume that the black hole, formed during a long GRB, is highly rotating, then the respective GW burst carries significant amount of energy.

To quantify the energy carried away in GW we use results from their models as they report them. The maximum energy emission comes from the most rapidly rotating star which gives \( E_{\text{GW}} \approx 1.4 \times 10^{-6} (M/M_\odot) M_\odot c^2 \) and under the assumption that this collapsed 10kpc away, they find an upper limit for the characteristic strain \( h_c \) of \( \approx 5.5 \times 10^{-22} (M/M_\odot) \) at a characteristic frequency \( f_c \), of \( \approx 500 \text{Hz} \). These limits where found for
be even close to maximal rotation (Woosley & Heger 2006). This means that moments before collapse the compact object has gained angular momentum higher than the breakup limit of a neutron star, and probably could support more mass than the usually estimated maximum mass (Baumgarte et al. 2000). If we assume that the relation of the GW energy radiated during collapse, which depends to the dimensionless angular momentum (to the fourth power), could scale up to higher spins, in the case of velocity perturbation trigger, then these events could be visible to advanced LIGO up to a limit of \( \sim 100\,\text{Mpc} \).

Since we are discussing about gravitational collapse to black hole we should also refer to quasi-normal-modes (QNM). The perturbed black hole horizon upon its formation will ring down till it settles down in axisymmetry. The QNM of a black hole depend on the mass of the black hole and its dimensionless angular momentum. There exist thorough studies on black hole QNM resulting in approximate formulas with high accuracy (\( \sim 5\% \)). The QNM are not expected to be detected, even in the collapse of a galactic neutron stars Ott (2009).

3 ELECTROMAGNETIC OUTPUT

Let us focus now on the expected electromagnetic radiation from the core-collapse of a massive star and the production of a long-GRB. We will not make any assumption on the production of high-energy gamma photons, we rather discuss about the reservoir of energy that will then give rise to the GRB. If the energy input for a long-GRB is given by the newborn black hole, then one of the main physical mechanisms is the electromagnetic extraction of energy from the spinning black hole (Blandford & Znajek 1977). This mechanism is widely discussed in GRB literature (Komissarov et al. 2009; Nagataki 2009). We will give a brief description of this mechanism here. Wolf-Rayet stars ending their life are thought to be the progenitors of long GRBs (Woosley & Bloom 2006). It is observed that Wolf-Rayet stars are magnetized (de la Chevrotière et al. 2014). During the collapse, advected matter will bring the preexisting magnetic flux at the vicinity of the black hole. This magnetic flux is trapped by the outer shells of the collapsing star, which will act as a massive disk to keep all these magnetic flux \( \Psi \) close to the horizon. This context is enough to give rise to a powerful Poynting dominated jet, which will be contaminated with baryons while drilling through the star. The rate that the black hole is losing energy is \( E \approx -\frac{1}{\pi c^2} \Psi^2 \Omega^2 \), where \( \Omega \) is the angular velocity of the black hole horizon, a function of the spin parameter. This is a widely studied and confirmed mechanism, both analytically and numerically (Komissarov 2001; McKinney 2006; Komissarov & McKinney 2007; Nathanael & Contopoulos 2014; Gralla et al. 2016). According to Christodoulou & Ruffini (1971) the available rotational energy for a black hole depends on its dimensionless spin parameter (\( a = J/M^2 \)) and reads as:

\[
E_{\text{rot}} = \left[ 1 - \frac{1}{2} \sqrt{(1 + \sqrt{1 - a^2})^2 + a^2} \right] \times M_{\text{BH}} c^2 \quad (3)
\]

To give an idea for the available energy for a black hole of \( \sim 3M_\odot \) we can give some values including two extreme values, for a spin parameter of \( a = 0.008 \), which we could say that is almost a non-rotating (Schwarzschild) black hole, nevertheless the available energy to extract is \( \sim 4 \times 10^{49} \text{ergs} \), whereas for a rotating black hole close to maximal rotation with spin \( a = 0.98 \), the available energy is \( \sim 1.25 \times 10^{54} \text{ergs} \). In order for these huge amounts of energy

\[ \text{Figure 1. The available energy from the black hole is plotted versus the energy in gravitational waves, both depend on the dimensionless spin parameter. The line where the shaded area starts indicates the model with spin parameter } a \approx 0.54, \text{ which could be detectable if it happens closer than } \sim 60\,\text{Mpc}. \]
to produce a GRB, a highly relativistic collimated plasma erupting at the outer shells of the star is needed.

This energy budget will be converted to radiation and will show up in the gamma-rays (details on the huge literature in Kumar & Zhang (2015)). From the observed high-energy radiation an estimate on the overall energetics can be made. If the distance to a GRB is known then the energy released can be estimated, thus for GRBs with known redshift the energy can be calculated assuming the burst is isotropic. For GRBs detected by Swift and GBM (onboard Fermi) the isotropic energy spans more than six orders of magnitude from $10^{48}\text{erg}$ till close to $10^{53}\text{erg}$ (Cenko et al. 2010; Fong et al. 2015). However, it is believed that these explosions are not isotropic and they are actually beamed resulting from a relativistic jet emerging in the vicinity of the black hole and drilling through the star (Zhang et al. 2004) to make itself visible when reaching a photosphere (Rees & Meszaros 2005). This energetic bursts give extreme luminosities, measured at the peak of the lightcurve, the isotropic luminosity in gamma-rays ranges between $\approx 10^{47}\text{ergs}^{-1}$ and $\approx 10^{52}\text{ergs}^{-1}$ (Kumar & Zhang 2015). This wide range in luminosities could be due to the difference in the magnetic field properties and strength close to the vicinity of the central engine, which is dictated by the above mentioned electromagnetic mechanism.

In order to relate the intrinsic energy that comes straight from the spin of the black hole to the observed energy, we should also take into account the beaming factor. To do that we should have an estimate on the opening angle of a GRB jet. By modeling the GRB afterglows in different energies and wavelengths (X-rays, radio) the jet break can be pinpointed. Opening angles have been observed to be in the tide range of $2 - 10$ degrees (Rhoads 1999; Sari et al. 1999). Assuming that the relativistic jet is conical would yield a solid angle of $\Omega_{\text{iso}} = 2\pi(1-\cos\theta)$. The isotropic energy calculated should be corrected as follows to give the true amount of energy released $E_{\text{iso}} = \Omega_{\text{iso}}/\Omega_c$, from this correction the true range of energies can be accounted. The small range for opening angles observed, allow us to take the same correcting factor for all cases. The isotropic energy should be corrected by a factor of $5 \times 10^{-3}$ (this is the exact case for an opening angle of 8 degrees, assuming a conical jet). As a result, the above mentioned observed and estimated isotropic energies give a range between $5 \times 10^{48}\text{erg}$ and $5 \times 10^{52}\text{erg}$. We have to state here that the discussion for the opening angle is limited to the brightest GRBs for which broadband observations exist. As pointed out by (Cenko et al. 2010) it would not be surprising if most Swift events have larger opening angles (or even isotropic), which would make jet-break estimates and measurements more difficult to account (Perna et al. 2003).

We will tentatively try to relate every burst that the observable isotropic energy can be estimated (e.g. with known redshift), to a certain spin parameter for its black hole powering the burst. Having discussed all the above, we decided to drop any assumption for the beamed luminosity coming towards us. This is because, assuming that for all bursts the correcting factor is lying inside a tide range, the distribution of the isotropic energy can be viewed as a distribution in spin parameters. The only difference would be an overall shift of two orders of magnitude, but the scaling will be the same.

In this respect we can invert equation (3)

$$a = 2 \times \sqrt{2 - c(-1 + c)} \sqrt{c}$$

where $c = f \times E_{\text{iso}}/M_{1500}c^2$ and $f$ is a factor correcting the isotropic energy in terms of beaming and also taking into account the efficiency of the radiation process. We can assume that $f$ is a universal constant, in other words for all GRBs it remains almost the same. Then we can view the distribution of GRB isotropic energy as an identical one of the distribution of spins of the black holes which act as the central engines of the bursts. We could tentatively have as a starting point the higher energetic ones, by limiting the higher possible spin from theory (Dessart et al. 2012).

We should also make a point here, that the spin of the black hole may slightly change during the course of the GRB. This can be accounted to the influence from the accretion disk that will form around it and also to episodic mass infall as big parts of the collapsing star enter the horizon, which could also give rise to energetic X-ray flaring activity (Nathanail et al. 2016). Of course, all this flaring activity and the structure of the X-ray afterglow is less energetic that the gamma-rays. The reason we can associate the isotropic energy to the original spin of the black hole is that the isotropic energy is governed by the prompt gamma-ray emission.

We have discussed so far how, from the isotropic energy of long-GRBs with known redshift, we can account for the spin parameter of newly born black holes after the core-collapse of super massive stars. The next step is to correlate the energy release after the formation of the black hole with the energy released in gravitational waves just before the GRB trigger, during the collapse to a black hole. As we discussed above, our knowledge from numerical studies of the gravitational collapse to a black hole is that the spin parameter of the resulting black hole is close to the spin (dimensionless angular momentum) of the initial compact star (or compact core) before collapse (Buonanno et al. 2007). Thus, having in hand the estimate for the spin, from the isotropic energy output, we can estimate the intensity of the gravitational wave burst produced during the collapse to a black hole. Of course, based on the current threshold limits of the interferometric detectors and the most optimistic expectations for the energy of such bursts, the closest would be $\approx 100\text{Mpc}$, if we expect a simultaneous detection from such an explosion. Nevertheless, we should state that the closest long-GRB detected is GRB980425 at a redshift of $z = 0.008$ (Finney et al. 1998; Soffitta et al. 1998) which is at $\approx 34\text{Mpc}$, which is closer than the estimated distance for a gravitational wave burst detection during the birth of a long-GRB.

The conclusion of all the above discussion, is that the energy released in GW during the collapse of the core of a massive star is related to the energy release in electromagnetic radiation, this is straightforward since both depend strongly on the spin parameter of the black hole. For the electromagnetic radiation this can be regarded as an assumption since other mechanisms have also been invoked to power the bursts. In Fig. 1 we show the relation between the available energy from the black hole and the corresponding energy that would be released during the gravitational collapse of the central compact core of a massive star to a black hole. The shaded area (colored magenta) is the region that could be possible detected by present interferometric detectors, the limit being the model discussed above with a spin parameter of $\alpha \approx 0.54$.

Some models in the shaded area could be detected as far as $\approx 100\text{Mpc}$. It is clear from eq. (1) that, for every order of magnitude increase in sensitivity, we gain an order of magnitude in distance further away. Some points that have to be made about this relation are in order here. The energy released in gravitational waves can be regarded as an upper limit since they were taken under the assumption that the collapse is triggered by velocity perturbations. For an isolated neutron star this is not expected to happen, but in the context of accreting matter onto a proto-neutron star in the core of a massive star this could be a possibility. A lower limit for the production of the GW burst could be given by the values given when the collapse is triggered by pressure reduction. This would...
scale down the relation in Fig. 1, 1 – 2 orders of magnitude, making them visible only as close as ~ 1 Mpc. Another comment has to be made about the existence of an intrinsic maximum on the gravitational energy release during the collapse. In the case of the pressure reduction trigger, its existence is clear. But in the case of velocity perturbation trigger, this hasn’t appeared in the range of spins used, with the higher spin being around $\alpha \simeq 0.6$ (Baiotti et al. 2007).

Furthermore, higher rotation for an initial neutron star would be close to the break up limit. However, in the context of a progenitor of long GRB it is expected that during the death of a massive star the inner regions of the star possess large amounts of angular momentum, maybe two orders of magnitude larger than the ones that give birth to ordinary neutron stars. Some of these would produce a black hole close to maximal spinning (Woosley & Heger 2006). On the other hand, other studies have shown that the condition of initial rapid rotation for the massive star could possibly not give birth to highly spinning black holes due to the production of a magnetorotational explosion that would prevent black hole formation. The spin parameter range they found for black holes formed after the death of fast rotating massive stars is bound $\alpha < 0.6$ (Dessart et al. 2012). If we translate this value in an upper bound for the available energy of the black hole, this is close to $10^{53}$ which is similar to the upper limit for the beaming-corrected energies from GRBs. Overall this is in favor of such a central engine.

Following the correlation discussed so far, we want to discuss how it would show up in both the distribution of the $E_{\text{iso}}$ and $E_{GW}$, once both have been observed. Since, for the time being no such gravitational wave burst detections exist, we use simulation data from core-collapse of massive stars. The evolution of rapidly rotating massive stars has been studied, in order to show the possibility of reaching the requirements needed for a GRB to be launched, when the black hole is formed. Results from these studies have estimated the value of the spin parameter. We use the results from tables 1 and 2 of Woosley & Heger (2006) and Table 1 of Dessart et al. (2012). Following the discussion in Dessart et al. (2012), we have left all models that produce a maximally rotating black hole out of this study. Using all the spin parameters for these models that produce a rotating black hole and could supposedly be progenitors of long-GRB, we apply eq. (2) to find the distribution of GW energy from such bursts. (right panel of Fig. 2). The inclusion of very small spin parameters make the distribution span almost 8 orders of magnitude and the mean value (yellow dashed) not aligned with the main peak. To produce the corresponding distribution of the isotropic energy of GRBs with known redshift we used the data from Table 2 and 3 of Atteia et al. (2017). These include 52 GRBs detected by Fermi/GBM and another 69 by Konus-Wind. Their distribution is shown in blue on the left panel of Fig. 2. To see how the gravitational wave energy trace this distribution, we overplot on the same panel the far right part of the distribution of the GW energy (energies between $10^{49.5}$ and $10^{52}$) shifted to the corresponding observed isotropic energies. As a first result these simulated data seem to trace well the observed distribution of $E_{\text{iso}}$. The cutoff after the peak in the gravitational waves energy comes from the fact that in Dessart et al. (2012) the spin of black holes formed is bound by $\alpha \sim 0.6$.

4 CONCLUSION
The gravitational collapse of the central compact core of a massive star to a black hole is thought to be the central engine of long GRBs. This gravitational collapse will give rise to a GW burst, which release energy proportional to its dimensionless angular momentum. The available rotational energy of a spinning black hole also depends of the dimensionless spin parameter. Thus, the GRB isotropic energy can give an estimate on the underlying spin of the
black hole. Then this can be used in order to estimate the energy released in GW.

A thorough automatic search could be established in the data of interferometric detectors after the electromagnetic detection of a GRB in order to find such GW bursts at the time just before this GRB was detected. In the future, if the sensitivity of the present detectors is enhanced by 1–2 orders of magnitude, then these bursts could be observed as far as 10Gpc.

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