Are Ultra Long Gamma Ray Bursts powered by a black hole spinning down?

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ABSTRACT

Gamma-ray bursts (GRBs) are violent explosions, coming from cosmological distances. They are detected in gamma-rays (also X-rays, UV, optical, radio) almost every day, and have typical durations of a few seconds to a few minutes. Some GRBs have been reported with extraordinary duration of $10^4$ sec. These are called Ultra Long GRBs. It has been debated whether these form a new distinct class of events or whether they are similar to long GRBs. According to Blandford & Znajek (1977), the spin energy of a rotating black hole can be extracted electromagnetically, should the hole be endowed with a magnetic field supported by electric currents in a surrounding disk. We argue that this can be the case for the central engines of GRBs and we show that the duration of the burst depends on the magnetic flux accumulated on the event horizon of the black hole. We thus estimate the surface magnetic field of a possible progenitor star, and we conclude that an Ultra Long GRB may originate from a progenitor star with a relatively low magnetic field.

Key words: gamma-ray bursts; ultra long GRBs; black holes; Blandford & Znajek;

INTRODUCTION

Gamma-ray bursts (GRBs), are flashes of gamma-rays from the cosmos, and consist some of the most energetic events ever detected, with luminosities exceeding $10^{50}$ erg/sec. Multi-wavelength observations of these enigmatic events allowed us to go deeper into the underlying physics (Gerhels & Ramirez-Ruiz 2009), but still a lot more work is needed to form a complete picture of them. Even more interesting are events that lasted a lot longer than the usual. Ultra Long GRBs have durations of $10^4$ sec, whereas the typical duration for long GRBs is a few seconds to a few minutes in the observer frame. Several Ultra Long Gamma-ray bursts have been reported (Levan et al. 2014, Evans et al. 2014, Gendre et al. 2013\textsuperscript{1}).

A great amount of theoretical work has been invested in order to understand what is the central engine and the emission mechanism of GRBs. In recent years the question of the central engine has been put aside, while research focuses on the emission region, the emission mechanisms and the effort to understand all the characteristics of the light curves and the spectra of the bursts (recent review Kumar & Zhang 2014). The idea of a black hole powering the burst is widely discussed for the so-called long-duration GRBs.

For the usual long GRBs, the progenitor of the burst is thought to be a Wolf-Rayet star. This is rather difficult to constrain because by the time we detect the burst the progenitor is not in its previous form. For Ultra Long GRBs, the idea of a blue supergiant (Gendre et al. 2013) is put into play so as to explain the long lived duration due to the accretion of a massive hydrogen envelope (Nakauchi et al. 2013). In both models though, the resulting collapse to a black hole is inevitable.

The extraction of rotational energy from a black hole through the Blandford & Znajek mechanism (1977) has been studied in great depth. The question is what is the timescale of this spinning down procedure. In the presence of strong magnetic fields this process will last for thousands of seconds, whereas for ultra strong magnetic field strengths it could last for only a fraction of a second (Lee et al. 2000, Contopoulos et al. 2014). This means that the black hole will spin down and loose its angular momentum, giving off electromagnetic (Poynting) energy that may be dissipated into high energy radiation. As we will now show, the duration of this process is inversely proportional to the square
of the magnetic flux accumulated on the black hole event horizon.

1 BLACK HOLE SPIN DOWN

Let us consider a supermassive progenitor star whose core collapses and forms a maximally rotating black hole. It is natural for the star to be magnetized. Highly conducting matter from the interior of the star will drive the advection of magnetic flux during the collapse. The material that is going to collapse into a black hole will be strongly magnetized, and therefore its core will pass through a spinning magnetized neutron star stage. A certain amount of magnetic flux \( \Psi_m \) is then going to cross the horizon. An equatorial thick disk (torus) will form around the black hole due to the rotational collapse. A black hole cannot hold its own magnetic field, but the material from the thick disk will act as a strong barrier that will hold the magnetic flux initially advected. As long as this is the case, the black hole will lose rotational/reducible energy at a rate

\[
\dot{E} \approx -\frac{1}{6\pi^2c}\Psi^2m\Omega^2, \tag{1}
\]

and will thus spin down very dramatically (Blandford & Znajek 1977 for low spin parameters; Tchekhovskoy et al. 2010, Contopoulos et al. 2013, Nathanail & Contopoulos 2014 for maximally rotating black holes).

The available rotational/reducible black hole energy is

\[
aG\dot{M}^2\Omega/c \equiv \dot{E}, \tag{2}
\]

where \( \Omega \) is the angular velocity of a rotating black hole. Equating (1) and (2) we attain the following analytic expression for the black hole spin down electromagnetic energy loss rate

\[
\dot{E} = \dot{E}_0 \frac{W(\frac{t}{t_BZ})}{1 + W(\frac{1}{2}e^{-\frac{1}{2}t/t_BZ})}, \tag{3}
\]

\( W(x) \) is the Lambert \( W \) function which solves the equation \( x = W(x)e^{W(x)} \). We can approximate eq. (3) with

\[
\dot{E} \approx \dot{E}_0 \frac{e^{-t/t_BZ}}{2 - e^{-t/t_BZ}} \approx \dot{E}_0 e^{-t/t_BZ}. \tag{4}
\]

where

\[
t_BZ \equiv \frac{24\nu^3}{g^2B^2c^4} = 2.6 \left( \frac{B}{5 \times 10^{15} \, G} \right)^{-2} \left( \frac{M}{10M_\odot} \right)^{-1} \, \text{sec} \tag{5}
\]

is a very important physical parameter. It gives the timescale of the spinning down procedure. In what follows, we will perform an analysis of two Ultra Long GRBs in order to extract this important parameter from their lightcurves.

We have shown here that rotating black holes, embedded in a strong fixed magnetic field, spin down almost exponentially (first derivation in Contopoulos et al. 2014). One can directly check that, for a magnetic field \( 10^{15} \, G \) the black hole spins down in a few hundred seconds. Such ultra-strong magnetic fields can be reached and survive during the core-collapse of a massive star, and are subsequently dispersed away from the black hole horizon. A massive disk/torus of material, that is held centrifugally around the black hole horizon, can support such ultra-strong magnetic fields (see e.g. Contopoulos & Papadopoulos 2012). Of course, many effects can modify the black hole electromagnetic spin down, making it difficult to discern its activation and evolution. GRB events may be ‘contaminated’ by extra events that possibly take place during the spin down. One such possibility is that large enough mass infalls may result in sudden black hole spin ups, with subsequent different electromagnetic spin downs. Such secondary events will begin from a different peak of the light curve, thus we cannot assume that they start from maximal rotation. Also, if the massive disk is dispersed faster than the duration of the spin down, the accumulated magnetic flux \( \Psi_m \) will not be conserved, and the spin down evolution will not be exponential. Notice that the electromagnetic interaction with the torus formed around the black hole may result in an extra spin down that may too be linked to GRBs (van Putten et al. 2009).

The aforementioned calculation describes how the system losess energy in the form of electromagnetic Poynting flux. It does not account for the exact emission mechanisms. We have proposed a model of how the central engine operates and the rate it is losing energy, but not how this energy becomes radiation. Let us here propose an idea for this process: In Nathanail & Contopoulos (2014) we performed a detailed study of the Blandford & Znajek (1977) mechanism and found that a generic feature of black hole magnetospheres is a poloidal electric current sheet that originates on the horizon at the equator. The structure of the magnetic field in the vicinity of the black hole studied in Nathanail & Contopoulos (2014) can be seen in figure 1. In the paraboloidal solution (assuming the torus is the bound-
The case of GRB 111209A: As BAT (the instrument of the Swift satellite that detects in the energy band 15 – 350keV and triggers for possible GRBs) was not looking at the part of the sky from which this GRB arrived, it was triggered after 150s of the actual time that this event was detectable (shown by the Konus-Wind instrument Hoversten et al. 2011). It is located at redshift of z=0.677 (Vreeswijk et al. 2011). This burst is reported as an Ultra Long GRB with $T_{90}$ around 800 sec. The total duration of the GRB activity is somewhat different from $T_{90}$, for this burst lasts for more than 20000 sec (Gendre et al. 2013). The Swift XRT light curves are taken from the Swift /XRT team website (Evans et al. 2009) at the UK Swift Science Data Centre (UKSSDC). We fit the light curve with our theoretical function for the description of black hole spin down, eq. (3). As data are sparse, we do not expect the theoretical curve to pass from all points but rather to show that they are following this prescription and that the system is loosing energy according to this loss rate. As we discussed before, we do not intend to fit all the flares (such as the one at around 400 sec and another around 2000 sec) of the lightcurve with a multi-segment power law, but rather to follow the decrease in the energy flux with one function which has a physical interpretation. In figures 3 & 4 we show the lightcurve of GRB 111209A (energy flux at 0.3 – 10 keV) together with the best fit of the theoretical curve (eq. 10). The plot in figure 4 is linear in time, and shows clearly that around 50000sec the energy flux stops decreasing and enters a plateau phase where the flux seems constant for the next 50000sec. It seems that the central engine of this event has changed its evolution at this point. There is a possibility that the black hole continues to spin down but other mechanisms cover its further evolution. We are actually entering an afterglow activity, possibly dominantly by external shocks.

The third candidate (namely GRB 121027A) of the new population of Ultra Long GRBs (Levan et al. 2014) has a more complicated structure. The signs of black hole spin down are still evident. The lightcurve, especially the big X-ray flare at $10^3$ sec, needs further analysis (Wu et al. 2013). That is why we decided not to include it here.

Our fit of the lightcurve allows us to estimate $t_{2\gamma}$, which is a really important physical parameter. Knowing $t_{2\gamma}$, and assuming that a stellar mass black hole ($10M_\odot$) formed after the core collapse of a massive star, we can estimate the strength of the magnetic field in the vicinity of the black hole. This can give us an estimate for the actual strength of the magnetic field at the surface of the star before the collapse and compare our findings with Wolf-Rayet polarization measurements and magnetic field estimations. By fitting eq. (3) to the lightcurve and correcting for cosmolog-

\textbf{2 ULTRA LONG GRBS}

According to the theoretical implications in the previous section, we searched the new population of Ultra Long GRBs (Levan et al. 2014) and looked for signs of black hole spin down. It is understood that a GRB environment can be really violent at the time of the burst, for this reason it is not straightforward to see a smooth central engine activity. Many effects can modify the black hole electromagnetic spin down, making it difficult to discern its activation and evolution. One such possibility is that large enough mass infalls may result in sudden black hole spin ups, with subsequent different electromagnetic spin downs. Furthermore, we want to follow the central engine evolution as it spins down and not fit all possible small flares in the lightcurve.

The case of GRB 101225A (the "Christmas-day burst"): It is located at redshift $z = 0.847$. Swift saw this source from the very beginning of its activity, after one Swift orbit (90 min) the source was still active suggesting a very long duration. This burst is reported as an Ultra Long GRB with $T_{90}$ more than 1377 sec (Campana et al. 2011, Thöne et al. 2011). The Swift XRT light curve are taken from the Swift /XRT team website (Evans et al. 2009) at the UK Swift Science Data Centre (UKSSDC). The fitting to the light curve with the theoretical function (eq. 3) for the description of black hole spin down is performed and yields the red curve in figure 3. This follows the energy flux evolution of the burst and shows qualitatively how the system looses energy.

Figure 3. Ultra Long GRB 101225A lightcurve. Log-Log plot, the red curve is the theoretical exponential black hole spin down. Energy flux at 0.3 – 10 keV.
The red curve is the theoretical exponential black hole spin down. The time that this exponential decay ends (when the flux becomes constant. We believe that we can follow till that time the spin down of the black hole formed after the core collapse. The red curve is the theoretical exponential black hole spin down. Energy flux at 0.3 – 10 keV.

\[ B_H \approx 10^{15} \text{ G.} \]

This magnetic field will drive the black hole spin down through a Poynting dominated outflow. The black hole event horizon for a maximally rotating black hole is \( r_H = GM/c^2 \), so in the case of \( 10M_\odot \) the event horizon has a radius of \( r_H \approx 10^6 \text{ cm} \). While collapsing, the conducting matter of the stellar interior brings this flux to the event horizon. Due to magnetic flux conservation we have

\[ B_H \pi r_H^2 = B_* \pi r_*^2. \]

Where \( B_* \) and \( r_* \) is the surface magnetic field and the radius of the star respectively. A typical radius for a Wolf-Rayet star is \( 10^{12} \text{ cm} \) (Crowther 2007). According to this value and the previous equation for the conservation of magnetic flux, we estimate the magnetic field on the surface of the star to be on the order of \( 10^3 \text{ G} \). Notice that this estimate does not take into account a possible magnetic field amplification due to differential rotation and convection under the cataclysmic conditions in the collapsing environment, which has been discussed in the literature (Obergaulinger et al. 2009). If we assume three orders of magnitude amplification our estimate of the surface magnetic field may be as low as 1 G. Putting everything together we have obtained an estimate of

\[ B_* \sim 1 \text{ to } 10^3 \text{ G} \]

According to a study of circular polarization and a search for magnetic fields in Wolf-Rayet stars, the most probable field strength in the observable part of its stellar wind is likely on the order of 10 to 100 G. Magnetic fields values of 22 – 128 G have been reported in the stellar winds of Wolf-Rayet stars (de la Chevrotiere et al. 2014). These magnetic field estimations are obtained from measurements of emission lines in the stellar winds and not on the stellar surface. At visible wavelengths, the stellar surface of Wolf-Rayet stars is hidden by a dense nebula. The corresponding surface value of the magnetic field must be much higher than the observed estimated values. In order to compare with observations we need to estimate the magnetic field in the stellar wind where the field is stretched into a monopole configuration and drops as \( 1/r^2 \) with distance. Under this assumption, the magnetic field in the stellar wind, ten stellar radii from the surface, would be on the order 0.01 to 10 G. This calculation leads us to believe that these bursts may very well be coming from a progenitor Wolf-Rayet star of a really low magnetic field strength and this may be the reason of its ultra long duration.

All these estimations are obtained with the physical image of a Wolf-Rayet star discussed extensively in the GRB literature (Woosley & Bloom 2006). Even if the idea of the progenitor star changes, our proposition that the duration of these bursts depends on the magnetic field will still hold. The idea that magnetic flux is the principal parameter that sets the luminosity of a GRB is discussed also in Teekhovskoy & Giannios (2015), although in their case the central engine turns-off when the steep decline stage starts.
3 CONCLUSION

Our results suggest that the duration of the central engine’s activity depends on the magnetic flux accumulated on the event horizon of the newly formed black hole after the core collapse of a supermassive star. This in turn depends on the surface magnetic field of the progenitor star. Based on these ideas we suggest that Ultra Long GRBs lie in the same class together with the usual long GRBs, and their extraordinary duration is due to the low surface magnetic field of the progenitor star.

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Ultra Long GRBs

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APPENDIX

A black hole embedded in a magnetic field supported by electric currents in a surrounding disk will lose rotational/reducible energy at a rate

\[
\dot{E} \approx -\frac{1}{6\pi^2c} \Psi_m^4 \Omega^2,
\]

and will thus spin down very dramatically (Blandford & Znajek 1977 for low spin parameters; Tchekhovskoy, Narayan & McKinney 2010; Contopoulos, Kazanas & Papadopoulos 2013, Nathanail & Contopoulos 2014 for maximally rotating black holes).

The available rotational/reducible black hole energy is \(aGM^2\Omega/c\) where \(a \equiv J/M\) is the black hole spin parameter (Christodoulou & Ruffini 1971), and \(G\) is the gravitational constant. The black hole will therefore spin down as

\[
\dot{\Omega} = \Omega - \frac{a/M}{1 + \sqrt{1 - (a/M)^2}},
\]

and

\[
\Omega_o \equiv \frac{c^3}{2GM} = 10^5 \left(\frac{M}{M_\odot}\right)^{-1} \text{rad/sec}
\]

is the angular velocity of a maximally rotating black hole. Eq. (10) yields \(a\) as a function of \(\Omega/\Omega_o\), which allows us to rewrite the equation for the black hole spin down with only unknown \(\Omega\) as

\[
\tau \frac{d}{dt} \left(\frac{\Omega/\Omega_o}{1 + (\Omega/\Omega_o)^2}\right) = -\left(\frac{\Omega}{\Omega_o}\right)^2,
\]

where

\[
\tau \equiv \frac{24c^5}{G^2B^2M} = 2.6 \left(\frac{B}{5 \times 10^{16} G}\right)^{-2} \left(\frac{M}{10M_\odot}\right)^{-1} \text{sec}
\]

is a very important physical parameter. It gives the timescale of the spinning down procedure. We have defined here a typical value for the initial black hole magnetic field

\[
B = \frac{\Psi_m}{\pi r_o^2} = \frac{\Psi_m c_7}{\pi G^2 M^2},
\]

where \(r_o = GM/c^2\) is the initial radius of the black hole horizon. Assuming that when the black hole forms it is rotating maximally, we can integrate eq. (12)

\[
\frac{1}{1 + (\Omega/\Omega_o)^2} + \ln \left(\frac{2(\Omega/\Omega_o)^2}{1 + (\Omega/\Omega_o)^2}\right) = \frac{1}{2} - \frac{1}{\tau},
\]

and solve numerically to obtain \(\Omega = \Omega(t)\). This results in the analytic expression eq. (3) for the black hole spin down electromagnetic energy loss rate (approximated in eq.(4)).

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