Two-Three-Peak GRBs and Their Implications for Central Engines

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ABSTRACT

In this letter we unify into a single model the millisecond (ms) protomagnetar central-engine and the collapsar central-engine models. We suggest that such a scenario could produce GRBs with three peaks. One for the ms-protomagnetar stage, a second one for the BH-formation event and a third one for the collapsar phase. We find in the literature that GRB 110709B presents such light curve morphology. We show that not only the light curve, but also the photon index evolution and the delay between the prompt emission and the afterglow of the second central-engine activity phase point towards a model like the one proposed here.

Key words: black hole physics — accretion — gravitation — gamma rays: theory

1 INTRODUCTION

The Collapsar model for long gamma-ray bursts (GRBs; Woosley & MacFadyen & Woosley, 1999, requires the collapse of a stellar core (up to the carbon layer) with a specific angular momentum \( a = J/M \), where \( J \) is the angular momentum of the collapsed core, and \( M \) is its mass) of \( a \geq 10^{6.5} \) cm s\(^{-1}\) (i.e., larger than the \( a \) of the last stable circular orbit; see van den Heuvel & Yoon, 2007; Woosley & Heger, 2012; Moreno Méndez, 2014). Under these conditions the stellar core collapses to a black hole (BH), surrounded by an accretion disk. This implies pre-collapse spin periods of \( P_{\text{spin}} \lesssim 0.5 \) day. This severely restricts the stellar evolution prior to collapse.

One of the most likely avenues to produce a massive stellar core with such a large amount of angular momentum is by utilizing the angular momentum stored in the orbital period of a binary (Paczynski, 1998; Brown et al., 2000; Lee et al., 2002; Tutukov & Cherepashchuk, 2003; Izzard et al., 2004; Podsiadlowski et al., 2004; Bogomazov et al., 2007). Making use of binary evolution with Case C mass transfer followed by a common envelope phase (as done in Lee et al., 2002; Brown et al., 2007, 2008; Moreno Méndez et al., 2011) binaries with a massive He star and an \( a \sim 1 M_\odot \) companion may evolve into an orbital period of less than a day. This allows to spin up the He star through tidal interaction and provides the required \( a \geq 10^{6.5} \) cm s\(^{-1}\) to its C core. This evolutionary method correctly predicted the spins of 4 BHs in binaries (see Moreno Méndez, 2014 and refs. therein). It also underpredicts the spins of BHs in high-mass X-ray binaries (HMXBs); however those may be explained through hypercritically accreting material (e.g., coming from a wind Roche lobe overflow) after the formation of the BH (see Moreno Méndez et al., 2008; Moreno Méndez, 2011 and Moreno Méndez & Cantiello, submitted).

Alternatively, Duncan & Thompson (1992) and later works (e.g., Metzger et al., 2011) have proposed utilizing the spin down of ms protomagnetars as the central engines for long GRBs. These engines have much less immediately available rotational and binding energy when compared to collapsars \( \sim 10^{54} \) erg vs \( \sim 10^{52} \) erg) as the mass and spin of the compact object are both smaller. Hence, it is already possible that they may trigger potentially less energetic GRBs/HNe (hypernovae). On the other hand, they may be much more common as the progenitor stars could be considerably less massive and, hence, much more abundant. It is likely that, for these engines to work, they must be much more efficient in their energy conversion. Nonetheless, it is still necessary for the progenitor of ms magnetars to rotate extremely rapidly prior to the collapse, both, to explain its ms rotation and, perhaps even, to amplify the magnetic field to magnetar range.

Most commonly, GRBs have a single episode in the prompt phase with some (s to ms) structure, nonetheless, several GRBs show quiescent times (e.g., Ramirez-Ruiz & Merloni, 2001). Some of these may show a two-peak structure. Many scenarios in terms of GRB jet composition and emission processes have been widely discussed to explain the structure of lightcurves with two salient peaks. Among them there are GRB 980923, GRB 990123, GRB 030329 (González et al., 2012; Fraija et al., 2011, 2012; GRB 990123, 041219A and 980923 have been described as to have early emission produced by the forward shock at its early stage when it propagates into the pre-accelerated and pair-loaded environment (Fraija et al., 2012 and refs. therein).

In this letter we study the possibility, previously suggested in Zhang et al. (2012), that GRB 110709B was the result of combination of factors that allowed both mechanisms, ms magnetar and collapsar, to play a part in this transient event. It is beyond the scope of this letter, however, to attempt any numerical simulations.
of central engines and/or core-collapse SNe; we refer the reader to recent literature on simulations of collapsars using Blandford-Znajek (Barkov & Komissarov 2008; Komissarov & Barkov 2009; Barkov & Komissarov 2010) or not (Dessart et al. 2008), as well as those using ms magnetars. In section 2 we briefly describe the ms-protoprotomagnetar/Collapsar scenario and suggest a list of observables which are two different events. Thus, hereafter we will refer to these as episodes 1, 2 and 3.

To explain the three episodes of GRB 110709B as the collapse of a single star (although, in a binary) we require a model that can differentiate these episodes and explain their time separation (of ~10 and 1 minutes, respectively). Thus, we propose a star which develops a centrifugally supported, massive, ~3.5M⊙ core which collapses in two stages. The first stage (1.5 to 2.5 M⊙) falls in a dynamical timescale and produces a ms magnetar which provides the central engine for the first episode of the GRB. The remaining 1 to 2M⊙ have too much angular momentum and fall in through an accretion disk in a viscous timescale. This results in a quiescent period, once the magnetar slows down (after ~100 seconds), through which the magnetar accretes another 1 to 2M⊙ from the remaining core. The second burst stage involves the collapse of the compact star into a Kerr BH releasing in a few seconds the binding energy which produces a second event. Lastly, the BH switches on as a BZ central engine and produces the third episode. We now proceed to detail these events.

2.1 Act I: Magnetar stage

Since we expect to rapidly (τ ≲ 10 minutes) form a Kerr BH, we consider a collapsing 3.5M⊙ core (RFe ≈ 10⁶ cm). The free-fall timescale of such an object is of the order of

\[ \tau_{ff} = \frac{\pi^{\frac{3}{2}} R_{Fe}^{\frac{1}{2}}}{GM_{Fe}} \approx \frac{3\pi}{4} \left( \frac{R}{10^6 \text{cm}} \right)^{\frac{3}{2}} \left( \frac{M}{3.5M_{\odot}} \right)^{-\frac{1}{2}} \text{s.} \]  

(1)

Instead, if the material is centrifugally supported and falls through an accretion disk, with viscosity \( \alpha \sim 0.01 \) (Lee et al. 2005) and thickness \( r/h \sim 1 \) (since it is still forming from a collapsing stellar hot core we expect it to be quite thick), the viscous timescale, \( \tau_v \), is

\[ \tau_v = \frac{3}{16} \left( \frac{4\pi f_{ff}}{\alpha} \right) \approx 900\text{s}, \]

(2)

which is comparable to the delay of the second episode in GRB 110709B.

The (Newtonian rotational kinetic energy of a protoneutron star (PNS); or a neutron star, NS) is then of the order of

\[ E_k = \frac{1}{2} I \omega^2 = \left( \frac{1}{2} \right) \left( \frac{2}{5} \right) \frac{GM_{Fe}^2}{R} \approx 133 \left( \frac{k}{2/5} \right) \left( \frac{M}{M_{Fe}} \right)^2 \left( \frac{10^6 \text{cm}}{R} \right) B, \]

(3)

where, a Bethe, 1 B = 10^{15} erg. Thus the slowdown of the compact object could power a GRB. Choosing a 2M⊙ protomagnetar of \( R_{ms} \sim 50 \) km (and spinning at break-up speed) will have 42.5 B of available energy; if one waits some tens of seconds for the neutrinos to cool down the PNS, the radius of the NS will be \( R_{ms} \sim 10 \) km, thus part of the binding energy would go into spinning up the NS and the available (rotational kinetic) energy will be ~ 213 B instead.

The rotational energy of the (proto)magnetar can be tapped through a torque exerted by the magnetic dipole of the magnetic field (B; Usov 1992). The power, or luminosity, for this process can be estimated from

\[ E_k \approx \frac{2 B^2 R^2 \Omega^2 c^3}{3 c^3} \approx 2.2 \left( \frac{B}{3 \times 10^{14} \text{G}} \right)^2 \left( \frac{\Omega}{10^{5} \text{s}^{-1}} \right)^4 \text{B s}^{-1}, \]

(4)

where \( R \) is the radius of the magnetic dipole and \( \Omega \) is the angular velocity.

After a few tens of seconds, the ms-magnetar engine slows down and the jets are shut down. At this point, matter accumulated in the accretion disk, and likely held there by propeller effect, will start streaming down onto the magnetar, increasing its mass and burying its magnetic field.

It is important that the supernova (SN) shock does not succeed at dismantling the core of the star, or else, there will be no sequel GRB. At most, the shock (and its reenergizing by the ms magnetar) could succeed at bouncing out the core to a few 10⁸ cm to 10⁹ cm. Then, the material would fall back and form a new accretion disk. This would provide the ingredients for the secondary central engine a few minutes later.

During this new accretion stage, the material forming the magnetar may be highly magnetized in the interior, but its exterior field may be low as the field may remain buried for an Ohmic timescale (which is much longer than the dynamical timescale). As the material from the accretion disk piles up on the surface of the magnetar it transfers angular momentum back onto its surface (and inwards, as the Alfvén timescale is extremely short). Even if the bulk of the magnetic field of the magnetar is buried by this new material, magneto-rotational instabilities (MRI) and dynamos may rebuild a substantial magnetic field in the accretion disk. The high temperature, high internal magnetic field and high rotation ration rate of the magnetar may keep it for a few tens of seconds from collapsing, however its high mass, well above the typical threshold for a NS, will eventually overcome the strong pressure and a Kerr BH will be formed.

2.2 Act II: BH formation

If we assume the binding energy released during the conversion from NS to BH is around 1 to 10% of the total mass, (we have assumed that even for a stiff equation of state, a large magnetic field, and almost Keplerian rotation this should occur below \( M_{NS} \sim 3.5M_{\odot} \)) then the total energy released in this event should be of the
order of
\[ E_T = kM_{NS}c^2 = 630 \left( \frac{k}{0.1} \right) \left( \frac{M_{NS}}{3.5M_\odot} \right) B, \]  

where \( k \) is the fraction of mass converted to energy. Under normal SN conditions, over 99% of the energy released leaves the star as neutrinos, without further interaction. For SN 1987A (Fraija et al. 2014), the kinetic energy was around \( E_{kin} \sim 1 \) B and the total energy released (in neutrinos) was \( E_T \sim 300 \) B. Assuming somewhat larger efficiency (larger density and temperature, thus, larger neutrino cross section), and considering we have more mass in the compact object we estimate the kinetic energy to be a few times larger than in SN 1987A, i.e., \( E_{kin} \sim 5 \) B, which coincides with the observations for GRB 110709B.

The first GRB episode drilled holes through the star. However, maybe due to a large azimuthal density gradient, the cocoons did not disrupt it. Still, some fallback or low-specific-angular-momentum material will likely start accumulating along these paths. We expect the SN shockwave to be directed up these partially clogged nozzles as the resistance is much lower in these directions. Given the nature of this collapse, where nuclear matter collapses into a BH (similar to the case of a short GRB, where a NS-NS or a BH-NS system merges) it is likely that this event will produce a substantial flux of neutrinos (and gravitational waves), hence, sparing the rest of the star from a dangerously energetic shockwave which could rapidly dismantle it. Otherwise, the central engine will not be in place to produce the third episode of GRB 110709B, which lasts in excess of 250 seconds.

Given the channeling of all the kinetic energy and the fact that the material that forms the collapsing magnetar is denser than that in the accretion disk, a quasi-thermalized, sharp, hard-X-ray signal would be expected. Thus, we do not expect this explosion to be SN-like, but instead more like a harder-GRB signal. Furthermore, the channeled shockwave and its echoes may further develop into a train of shockwaves (much like in a GRB) that will, likely, interact between themselves far away from the star. Similar to the scenario described by Ramirez-Ruiz & Merloni (2001) and Ramirez-Ruiz et al. (2001).

### 2.3 Act III: BZ engine

The second episode may again push the accretion disk outwards, allowing it to fall back in a timescale of a few tens of seconds. As further material and angular momentum are accreted into the BH, and as the magnetic field intensifies, a BZ central engine will replace the ms-magnetar engine. It is likely that the neutrino annihilation may also play a role in powering this third episode of GRB 110709B as well as in keeping a steep azimuthal density profile during the prolonged quiescent phase. In principle, this last event is (almost) unimpeded, thus, all the energy usually required to drill through the star may simply go into the jet. Hence, this new GRB will be observable for as long as the central engine remains in place. Something, likely, not seen in any previous GRB.

Following the analysis performed by Lee et al. (2000) we estimate the relevant quantities for a BZ central engine. First, we obtain the available energy to the BZ process:
\[ E_{BZ} = 1,800 \epsilon_{\alpha} f(\alpha_*) \frac{M}{M_\odot} B, \]  

where \( \alpha_* = Jc/(GM^2) = a/M, \)
\[ f(\alpha_*) = 1 - \sqrt{\frac{1}{2} \left( 1 + \sqrt{1 - \alpha_*^2} \right)}, \]  

and \( \epsilon_{\alpha} = 0.5 \), the maximum efficiency for energy extraction. Next, we calculate the power or luminosity of the BZ central engine (in Bethes per second) which depends not only on the spin of the BH (\( \alpha_* \)) but also on the magnetic field permeating the region (see appendix D in Lee et al. (2000)):
\[ P_{BZ} \approx 0.17 \alpha_*^2 \left( \frac{B}{10^{11} G} \right)^2 \left( \frac{M}{M_\odot} \right)^2 B \text{ s}^{-1}. \]  

Early during the BZ-engine regime, the mass of the BH should be above \( 3.5M_\odot \) (which it had when it was formed). This is also necessary as the magnetar switched off because of its low spin. Thus, the accreted material must resupply the central compact object with angular momentum. Similarly, the magnetic field will likely be regenerated during this accretion phase (the energetic cost is extremely low; see, e.g., Moreno Méndez (2014)). With these considerations in mind, we estimate then \( M_{BH} \sim 4M_\odot, \alpha_* \sim 0.7 \) and \( B \sim 10^{13} G \). Utilizing these numbers then the total energy available to the central engine is \( E_{BZ} \sim 260 \) B. The luminosity is then \( P_{BZ} \sim 1.3 \) B s\(^{-1}\). Hence, \( T_{BZ} \sim E_{BZ}/P_{BZ} \sim 200 \) s. These numbers reflect fairly well those observed for GRB 110709B, especially if we consider that part of the energy may be lost to neutrinos and GWs.

### 2.4 Regarding Afterglows

The fireball model (see Mészáros 2006; Zhang & Mészáros 2004 for recent reviews) satisfactorily explains GRBs and their afterglows (AGs). This model predicts an expanding ultrarelativistic fireball that moves into the external surrounding medium. As this fireball sweeps and accumulates circumstellar material on its head, it slows down and the relativistic beaming stops. For instance, the deceleration radius and timescale can be written as
\[ R_d = \left( \frac{3}{4\pi m_p} \right)^{1/3} \Gamma^{-2/3} \eta^{-1/3} E^{1/3}, \]  

and
\[ t_d = \left( \frac{3}{32\pi m_p} \right)^{1/3} (1+z) \Gamma^{-8/3} \eta^{-1/3} E^{1/3}, \]  

respectively, where \( E \) is the energy, \( \Gamma \) is the bulk Lorentz factor, \( \eta \) is the interstellar medium (ISM) density and \( m_p \) is the proton mass.

If the three episodes observed in GRB 110709B have a common progenitor, it would be expected that the AG produced by the last episode takes longer to occur than the previous ones. This is a consequence of material being swept out of its path onto larger radii by previous episodes. Furthermore, if the later episodes possess AGs, it is necessary that the earlier ones also had them.

According to the standard relativistic fireball model, the forward shock accelerates electrons up to relativistic energies. This generates magnetic fields through the first-order Fermi mechanism or through electric fields associated with the Weibel instability. The afterglow emission is more likely to be synchrotron, thus the spectrum has a break in the fast-cooling regime resulting in a spectral index of \( \alpha = 1.5 \) (Sari et al. 1998; Giblin et al. 1999).
s from first BAT trigger) and third (610 to 750 s from first BAT trigger) episodes are $9.54^{+0.11}_{-0.16} \times 10^{-6}$ erg cm$^{-2}$, $2.31^{+0.08}_{-0.05} \times 10^{-6}$ erg cm$^{-2}$ and $8.81^{+0.09}_{-0.12} \times 10^{-6}$ erg cm$^{-2}$, respectively.

We also analyze the spectrum between 835 s and 865 s corresponding to the last peak observed in the BAT light curve (see Zhang et al. 2012), tenths of seconds after the end of episode 3. We interpret this peak as the AG of episode 3 (see sec. 4). We find that the BAT spectrum (see Fig. 2) is well modeled with a PL with photon index $\alpha_1 = 1.59^{+0.14}_{-0.13}$ (where the subindex denotes that this belongs to the AG of episode 3).

4 DISCUSSION

The model described in sec. 3 predicts the existence of a second peak in the light curve. This second peak can easily be observed in most energy bands shown by Zhang et al. 2012. Nonetheless, as mentioned in sec. 3 their analysis assumes that episodes 2 and 3 are a single one, similar to other GRBs. For GRB 110709B, a more detailed analysis of the spectrum allows to differentiate three different episodes. Furthermore, our model predicts episode 2 to be harder in spectra than episodes 1 and 3. Unfortunately, data from higher energy band detectors does not seem to be available (Golenetskii & et al. 2011), but the data does suggest this may be possible.

Our model is also consistent with the, apparently controversial, observation that episode 2 cannot be explained with a thermal component in addition to the PL. In principle episode 2 could be expected to be more SN-like, given that it is, after all, the collapse of the PNS into a BH. However, a SN event would disrupt the star an no third episode would be, hence, expected. Instead, the shock produced by the collapse has to be channeled through the jet-drilled nozzles and, thus, could become a more hard GRB-like signal.

If all episodes of a multi-peak GRB are coming from the same object it should also be expected that the AG of episode 1 should appear earlier after its prompt-emission phase when compared to the AGs of the following episodes. By considering the values of the first episode: energy $E = 20$ B, redshift $z = 0.75$ ($\sim 3.1$ Gpc; Penacchioni et al. 2013), ISM density $\eta = 3$ cm$^{-3}$ and Lorentz factors $\Gamma = 160$ and $\Gamma = 50$, we obtain deceleration radii of $R_d = 3.5 \times 10^{16}$ cm and $R_d = 7.5 \times 10^{16}$ cm which correspond to deceleration times of $t_d = 40$ s and $t_d = 870$ s, respectively.

Now, taking into account the values for episode 3, energy $E = 18.5$ B, a clean ISM density $\eta = 10^{-3}$ cm$^{-3}$ and a bulk Lorentz factor of $\Gamma = 225$, we obtain a value of deceleration time $t_d = 225$ s which is in agreement with the observations.

The first jet propagates out of the star and into the ISM clearing a path, thus lowering $\eta$ from 3 cm$^{-3}$ to $10^{-3}$ cm$^{-3}$. Hence, the jet for the next episodes will not considerably slow down until it reaches the head of the first shell, at which point it will slow down and produce its AG. This is consistent with the observations. Zhang et al. 2012 report a component modeled with a power law of spectral index $\alpha_1 = 1.55 \pm 0.05$ at the very end of the prompt emission, between $\sim 36$ and $\sim 45$ s which strongly suggests an early AG for the first episode. Furthermore, D’Elia et al. 2011 confirm this AG with observations from XRT starting at $\sim 70$ s after the first BAT trigger. Instead, the AG of episode 3 may be related to the peak observed at $\sim 850$ s in the BAT and XRT lightcurves (see Zhang et al. 2012), i.e., some $\sim 225$ s after the end of the quienscent period separating episode 1 from episode 3. This is supported by our estimated spectral index of $\alpha_3 = 1.59^{+0.14}_{-0.13}$ (see sec. 3). These os, along with the PL shape and the fact they are observed with BAT (XRT and/or KW) imply synchrotron radiation from AGs.

3 OBSERVATIONS AND DATA ANALYSIS

GRB 110709B triggered the Burst Alert Telescope (BAT, Barthelmy & et al. 2005) onboard the Swift satellite at 21:32:39 UT on 2011 July 9 (Cummings 2011). This episode extended up to 55 s after the trigger (Zhang et al. 2012). Interestingly, there was a second BAT trigger at 21:43:25 UT on 2011 July 9, $\sim 11$ minutes after the first trigger time. The emission period extended up to 865 s after the first trigger (Cummings 2011): this period shows a first bump (episode 2), beginning at $\sim 550$ s after the first trigger and lasting about 60 s (ending at 610 s), followed by a second multi-peaked bump (episode 3, from 610 s to 750 s; see Fig. 1) of longer duration.

Zhang et al. (2012) performed a time-resolved spectral analysis of this second emission (episodes 2 and 3), dividing its time period in time slices of 50 s or more; they show that the spectra can be fitted with cutoff power laws and that there is a strong hard-to-soft spectral evolution. However, their choice of the time intervals is not suitable to look at the evolution of the spectral parameters during episode 2, as the corresponding time slice covers its whole duration. Therefore, we performed a more detailed analysis of the spectra of episodes 2 and 3, by considering sub-intervals of 10 s each. We processed the Swift/BAT data using the standard FTOOLS package (Heasoft, version 6.15). We analysed the spectra using two different spectral models: BB+PL and PL. We found that all the spectra are well modeled with PL, while the BB+PL can be discarded, as it is not well constrained. The lower panel in Fig. 1 shows the time evolution of the photon index of the PL model: it can be seen that a discontinuity in the hard-to-soft evolution comes out at the beginning of episode 3. This could suggest a different emission mechanism for episodes 2 and 3.

We obtain that the BAT band (15-150) keV fluences of the first (from $\sim$28 to 55 s from first BAT trigger), second (550 to 610 s from first BAT trigger) and third (610 to 750 s from first BAT trigger) episodes are $9.54^{+0.11}_{-0.16} \times 10^{-6}$ erg cm$^{-2}$, $2.31^{+0.08}_{-0.05} \times 10^{-6}$ erg cm$^{-2}$ and $8.81^{+0.09}_{-0.12} \times 10^{-6}$ erg cm$^{-2}$, respectively.

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5 CONCLUSIONS

Although our results do not show conclusive evidence for the presence of both, the ms magnetar and Collapsar engines working one after the other in the same progenitor, they do strongly suggest that the model where both contribute to GRB 110907B is consistent and favored. If this paradigm is confirmed in further GRBs it would reveal important information regarding the central engines.

GRB 110709B in its first episode has an estimated fluence of $F^{(1)} = 9.54^{+0.12}_{-0.10} \times 10^{-6}$ erg cm$^{-2}$. In the second episode $F^{(2)} = 2.31^{+0.66}_{-0.25} \times 10^{-6}$ erg cm$^{-2}$. And finally, in the third episode $F^{(3)} = 8.81^{+0.09}_{-0.12} \times 10^{-6}$ erg cm$^{-2}$. This translates ($z = 0.75$) into an isotropic energy of $E^{iso}_1 \approx 20.0$ B for the first episode. $E^{iso}_2 \approx 4.85$ B for the second one and $E^{iso}_3 \approx 18.5$ B for the third one. Note that, if not well focused (probably to cover less than 4$\pi$/100), either episode 1 or 2 would rapidly dismantle the star, thus preventing the second and/or third episodes from ever occurring. This is interesting as the first episode of GRB 110709B is not a low luminosity event. In ultra-long GRBs (ulGRBs) it is clear that the star must survive the SN dismantling by the cocoon, otherwise the central engine would be starved and the GRB would shut down at much earlier times. However, in ulGRBs, the engines have, usually, low power as can be seen by the low luminosity of such events. This result implies that a jet from a ms magnetar engine, where the SN shockwave fails, may be well collimated. It must also drill through the star rapidly enough such that the cocoon is starved and thus it does no blow away the star in a SN. This is not completely unheard of, as e.g. shown in the list of long GRBs by Hjorth & Bloom [2011], where a SN lightcurve seems to be nonexistent or, at best, really underluminous.

The delay of the second AG with respect to the first one, as well as with respect to the one observed in other double-peaked GRBs is interesting. It may indicate that those other GRBs may have had a previous ms-magnetar stage which failed to produce a GRB but which opened up a channel in the structure of the progenitor star through which the BH-forming shockwave could exit and later a collapsar engine would turn on and produce a GRB. This would produce the distinctive double-peaked lightcurve.

GRBs such as GRB 110709B, with two clear central-engine stages are capable of providing rare insights into, both, the ratio of energy that may be contained in the jet to that in the cocoon, as well as to the collapse of an overweight NS into a BH. It is of great importance to obtain data in a wider range of energy from these transients, as this should allow to distinguish between a stage such as episode 2 in our model, where a NS turns into a BH, from activity from a Collapsar central engine, i.e., episode 3.

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