Gamma-ray bursts and magnetars: observational signatures and predictions

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Abstract

Newly-born millisecond magnetars are competing with black holes as source of the gamma-ray burst (GRB) power, mainly with their rotational energy reservoir. They may be formed both in the core-collapse of massive stars, and in the merger of neutron star or white dwarf binaries, or in the accretion-induced collapse of a white dwarf, being thus a plausible progenitor for long and short GRBs, respectively. In ten years of activity, *Swift* has provided compelling observational evidences supporting the magnetar central engine, as the presence of a plateau phase in the X-ray light curve, the extended emission in SGRBs and the precursor and flaring activity. We review the major observational evidences for the possible presence of a newly-born magnetar as the central engine for both long and short GRBs. We then discuss about the possibility that all GRBs are powered by magnetars, and we propose a unification scheme that accommodates both magnetars and black holes, connected to the different properties and energetics of GRBs. Since the central engine remains hidden from direct electromagnetic observations, we review the predictions for the GW emission from magnetars hosted from GRBs, and the observational perspectives with advanced interferometers.

Keywords: Gamma-ray bursts: general, Magnetars

1. Introduction

Gamma-ray bursts (GRBs) display a bimodal duration distribution with a separation between the long GRBs (LGRBs) and the short GRBs (SGRBs) at about 2 s (Kouveliotou et al., 1993). Observations of the galaxies hosting LGRBs and the unambiguous association with bright type Ic supernovae (SNe; Hjorth and Bloom 2012) demonstrated that they have to do with the core-collapse of a sub-class of massive stars (20-40 $M_\odot$). Most LGRBs must therefore be a consequence of neutron star (NS) or black hole (BH) birth. On the other hand, SGRB environments, the mix of host-galaxy types and an absence of associated SNe (Berger, 2014) prompted the merger of compact object binaries (binary NS or NS-BH, Eichler et al. 1989; Narayan et al. 1992) as the most popular progenitor model. In the binary NS case, the expected remnant is a BH surrounded by a hyper-accreting disc of debris and the resulting accretion powers the SGRB and its afterglow, whereas a NS-BH merger can lead to the same configuration if the NS is tidally disrupted. It is possible that some mergers may lead instead to a transitory or stable NS (Metzger et al., 2008), as supported by the recent discovery of NSs with masses of about 2 $M_\odot$ (Demorest et al., 2010; Antoniadis et al., 2013).

Magnetars are a subset of NSs with extremely high magnetic fields that can exceed 10^{15} G at birth (Duncan and Thompson, 1992). A magnetar born with a rotation rate of $\sim$ 1 ms contains a large amount of energy, $\dot{E} = 0.5I\Omega^2 \sim 3 \times 10^{52}$ erg for a moment of inertia $I = 80$ km^2 $M_\odot$ (Lattimer and Prakash, 2007). This rotational energy reservoir is sufficient to power a GRB (Usov, 1992), and in the case of LGRBs it can contribute to energise the accompanying SN (Mazzali et al., 2014). Recent models of newly-born millisecond magnetars show that they are also capable of producing relativistic outflows (Komissarov and Barkov, 2007; Bucciantini et al., 2008). These arguments led to the conclusion that the birth of a magnetar is competing with BH as being source of the GRB power (the so-called "central engine").

The existence of magnetars **in our Galaxy** is demonstrated by direct observations of **anomalous X-ray pulsars (AXP) and** soft gamma-ray repeaters (SGR; **see Mereghetti 2008 for a review**). **The relative hardness, luminosities and flaring events from these sources suggest** that they are NSs with dipole fields $\sim 10^{15}$ G (Thompson and Duncan, 1995, 1996). A number of **magnetar-like flares** events have been studied, and the central engines confirmed to be magnetars with strong ($\sim 10^{14} - 10^{15}$ G) dipole magnetic fields, despite these are millions of years old (e.g. Kouveliotou et al., 1998; Mereghetti, 2008; Rea and Esposito, 2011).

The improvement of the observational technologies in the last ten years thanks to the advent of the *Swift* mission (Gehrels et al., 2004) revealed many unexpected features, posing severe questions to the most popular theoretical GRB models and to the BH central engine scenario. The discovery by the *Swift*/X-Ray Telescope (XRT, Burrows et al. 2005a) of a complex behaviour of the afterglow emission that largely deviates from the simple power-law decay predicted by the standard afterglow model (Meszaros and Rees, 1993), with the observation of a flattening in the X-ray light curve (X-ray plateau, Nousek et al. 2006), and of flares superimposed to the afterglow emission in the X-rays (Chincarini et al., 2010), strengthened the idea that the GRB source of energy should be active on a much longer timescale than the prompt emission itself ($\sim 10-100$ s).

The magnetar central engine has the merit of providing a straightforward interpretation for the X-ray plateau during the GRB afterglow, since the newly-born magnetar is expected to lose its rotational energy by emitting a relativistic wind at timescales comparable to those observed ($\sim$ hours; Dai and Lu 1998; Zhang and Mészáros 2001; Corsi and Mészáros 2009; Metzger et al. 2011). Direct comparison with observations (Dall'Osso et al., 2011; Bernardini et al., 2012, 2013; Lyons et al., 2010; Rowlinson et al., 2013) showed that this proposal is the most credible interpretation so far, and indicated that the plateau emission can be considered as compelling evidence supporting magnetars.

A magnetar central engine has also been advocated in SGRBs with an extended emission (EE) after the initial spike in the prompt phase (Norris and Bonnell, 2006). Several attempts to provide a theoretical explanation for the EE are related either to the magnetar spin-down power (Metzger et al., 2008), or to fall-back material accelerated to super-Keplerian velocities and ejected from the magnetar by the centrifugal forces exerted by its magnetosphere (Gompertz et al., 2014).

Another feature that is challenging for the standard scenario of accretion onto a BH is the presence of precursor activity in both LGRBs (Koshut et al., 1995; Lazzati, 2005; Burlon et al., 2008, 2009) and SGRBs (Troja et al., 2010). Together with X-ray flares, precursors imply that the intermittent mechanism powering the prompt emission may be suspended over timescales comparable to the prompt emission itself. Recently, we proposed a new scenario in the context of the magnetar central engine for which precursors are explained by assuming that the GRB prompt emission is powered by

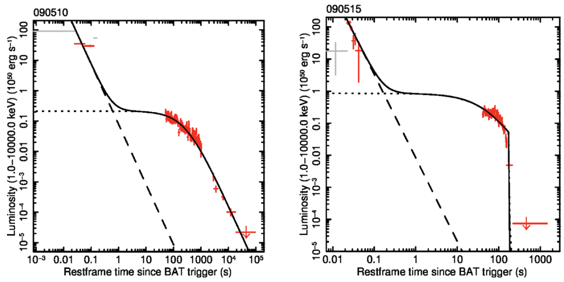

Figure 1: Examples of external (left panel) and internal (right panel) plateaus in short GRBs (from Rowlinson et al. 2013). Both panels show *Swift*/BAT and XRT rest-frame light curves fitted with the magnetar model. The light grey data points have been excluded from the fit. The dashed line shows the power-law component (steep decay) and the dotted line shows the magnetar component. The X-ray light curve in the left panel shows the so-called "canonical" behaviour, characterised by a steep-shallow-normal decays.

the accretion of matter onto the surface of the magnetar (Bernardini et al., 2013). The accretion process can be halted by the centrifugal drag exerted by the rotating magnetosphere onto the in-falling matter, allowing for multiple emission episodes and very long quiescent times. The same mechanism can be extended to late times, providing also an interpretation for flaring activity.

Here we review the major observational evidences for the possible presence of a newly-born magnetar as the central engine for both LGRBs and SGRBs, as the presence of a plateau phase in the X-ray light curve (Section 2), the extended emission in SGRBs (Section 3) and the precursor and flaring activity (Section 4). We then discuss about the possibility that all GRBs are powered by magnetars, and we propose a unification scheme that accommodates both magnetars and BHs, connected to the different properties and energetics of GRBs (Section 5). Since the central engine remains hidden from direct electromagnetic (EM) observations, and will remain so until gravitational wave (GW) signatures are detected, we review the predictions for the GW emission from magnetars in the context of LGRBs and SGRBs, and the observational perspectives with advanced interferometers (Section 6).

2. The X-ray plateau

One of the major outcome of the *Swift* mission is the discovery that the X-ray light curve of GRBs is more complex than what previously though (Tagliaferri et al., 2005; Nousek et al., 2006). About 40% of the well monitored[1] LGRB light curves show in their X-ray emission the so-called "canonical" behaviour (see e.g. fig. 1 and Nousek et al. 2006), characterised by a steep-shallow-normal decay. Up to $\sim$ 80% of the LGRB X-ray emission deviates from a single power-law decay, exhibiting a shallow decay phase (Evans et al., 2009; Margutti et al., 2013; Melandri et al., 2014). The presence of a plateau phase is a common feature also to $\sim$ 50% of SGRBs (Rowlinson et al., 2013; D'Avanzo et al., 2014).

Several empirical correlations have been found involving properties of this shallow decay X-ray phase ("plateau") and of the prompt emission (Dainotti et al., 2011; Bernardini et al., 2012). Among these, the most interesting one is the anti-correlation between the end time of the plateau phase t_p and the X-ray luminosity at the same time $L_p = L(t_p)$: $L_p \propto t_p^{-\alpha}$ (Dainotti et al., 2008, 2010, 2013). A $L_p - t_p$ anti-correlation is also followed by SGRBs, though with a different normalisation with respect to LGRBs (Rowlinson et al., 2014).

The presence of a plateau phase has been initially attributed to an injection of energy into the forward shock (see e.g. Zhang et al., 2006, and references therein), since the absence of significant spectral evolution during this stage agrees with the expectations from forward shock emission (Bernardini et al., 2012). However, there are several cases in both LGRBs and SGRBs where the shallow decay is followed by a sudden drop in the X-ray emission, that is not consistent with the forward shock model (see fig. 1).

A natural source for this energy injection[2] is the power emitted by a spinning-down newly-born magnetar (Dai and Lu, 1998; Zhang and Mészáros, 2001; Corsi and Mészáros, 2009; Metzger et al., 2011). A newly formed magnetar is expected to loose its rotational energy at a very high rate for the first few hours through magnetic-dipole spin down, something that provides a long-lived central engine in a very natural way. Assuming that the spin down is mainly due to EM dipolar radiation and to GW radiation, when the EM dipolar emission dominates (the GW emission is discussed in Section 6), the initial rotational energy loss depends on the dipolar magnetic field strength B and on its rotational period P as: $\dot{E}_{\rm sd} \propto B^2 P^{-4} \sim 10^{49} (B/10^{15}{\rm G})^2\, (P/{\rm ms})^{-4}$ erg s^{-1}, and is expected to be fairly constant over a timescale shorter than the spin-down timescale $t_{\rm sd} \propto P^2 B^{-2}$, and then it decays as $\dot{E}_{\rm sd} \propto t^{-2}$ (Dai and Lu, 1998; Zhang and Mészáros, 2001).

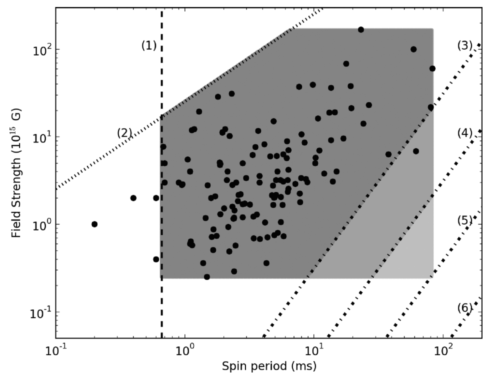

Figure 2: Physical range for the values of magnetic field strengths and spin periods (from Rowlinson et al. 2014). The upper and lower limits on the magnetic field strength and the upper limit on the spin period are determined using the sample of GRBs fitted with the magnetar model (overplotted as black circles; Lyons et al. 2010; Dall'Osso et al. 2011; Bernardini et al. 2012, 2013; Rowlinson et al. 2013; Gompertz et al. 2013; de Ugarte Postigo et al. 2014; Lü and Zhang 2014; Yi et al. 2014). The dashed black vertical line (1) at 0.66 ms represents the minimum spin period allowed before breakup of a 2.1 $M_{\odot}$ NS. The dotted black line (2) represents a limit on spin periods and magnetic field strengths imposed by the fastest slew time of the *Swift*/XRT in the rest frame of the highest redshift GRB in the sample, as plateaus with durations shorter than the slew time are unobservable. The black dash-dotted lines (3-6) represent the observational cut-offs for the faintest plateau observable assuming the lowest redshift in the GRB sample. These cut-offs change depends on the beaming and efficiency of the magnetar emission.

If the spin-down power is injected into the forward shock, then we expect an "external" plateau. Dall'Osso et al. (2011) proposed an analytic treatment to account for the contribution to the forward shock emission of the spin-down luminosity, that is successful to describe the X-ray emission of the canonical LGRBs (Dall'Osso et al., 2011; Bernardini et al., 2012, 2013) as well as of light curves with a shallow decay phase (Bernardini et al., 2012). On the other hand, if the magnetar spin-down power dissipates internally before hitting the forward shock, it generates an "internal" plateau, whose X-

[1] i.e. fast repointed by the *Swift*/XRT and for which observations were not limited by any observing constraint.

[2] Alternative explanations for the presence of a plateau phase have been proposed, as a late time accretion (Kumar et al., 2008) in the context of the collapsar scenario, or as a reverse shock powered by energy injection from an arbitrary central engine (Leventis et al., 2014; van Eerten, 2014). **A top heavy jet produced by a collapsar would reproduce the steep decay and the plateau phase phenomenology in both the X-ray and the optical energy bands (Duffell and MacFadyen, 2014).**

ray luminosity tracks the spin-down luminosity (Lyons et al., 2010). In this second case, if the magnetar is sufficiently massive that differential rotation is not able to support it, it collapses to a BH producing a sharp drop at the end of the plateau (see fig. 1 and Lyons et al., 2010; Rowlinson et al., 2013). Broadband modelling of the spin-down luminosity has been presented by Gompertz et al. (2015). The magnetic field strength and rotational period required to reproduce the observed plateaus in both LGRBs and SGRBs are of the order of $B \sim 10^{15}$ G and $P \sim 1$ ms (see fig. 2), comparable to the expectations for a newly-born millisecond magnetar (Duncan and Thompson, 1992).

The major advantage of this scenario for the plateau phase is that all the plateau properties are directly related to the central engine (specifically on B and P) and, consequently, to the prompt emission, giving a straightforward interpretation for the empirical correlations found in Dainotti et al. (2011) and Bernardini et al. (2012). In particular, the anti-correlation between the plateau luminosity and timescale is naturally accounted for analytically when one associates the initial spin-down luminosity with the plateau luminosity, and the spin-down timescale with the plateau duration: $L_p \sim \dot{E}_{\rm sd} \sim B^2 P^{-4} \sim P^{-2} t_{\rm sd}^{-1} \sim P^{-2} t_p^{-1}$ (see fig. 3). In this scenario the scatter of the anti-correlation is directly related to the distribution of the spin period (Bernardini et al., 2012; Rowlinson et al., 2014). Rowlinson et al. (2014) showed that the observed scatter implies a spin period range $\sim 0.66 - 35$ ms, that is consistent with the distributions of the spin period from the direct analysis of the X-ray plateaus (see fig. 2). The observed normalisation depends also upon the radiative efficiency and the beaming angle of the outflow. Rowlinson et al. (2014) used the observed data to place constraints on the likely beaming angles and efficiencies of the magnetar emission, concluding that for LGRBs it is most likely to be narrowly beamed ($< 20°$) with $\sim 20\%$ efficiency of conversion of rotational energy to observed X-ray emission. The apparent different normalisation for SGRBs may be associated with different redshift distributions or different beaming/efficiencies (Rowlinson et al., 2014).

3. The extended emission in SGRBs

A subclass of SGRBs ($\sim 15\%$, Berger 2014) shows a rebrightening in the prompt emission after the initial spike, firstly discovered in the BATSE sample (Lazzati et al., 2001; Norris and Bonnell, 2006) and then confirmed with *Swift* (e.g., Barthelmy et al., 2005b). This extended emission (EE) is long-lasting, up to ~ 100 s, its onset is usually delayed from the initial spike and it is characterised by a softer spectrum compared with the initial spike and LGRBs of similar duration. Its peak flux is usually lower, but it comprises a larger fluence than the initial spike (for further details see the comprehensive review on SGRBs by D'Avanzo, this volume).

In the case of SGRBs, the merger of two compact objects as a NS binary or a NS-white dwarf (WD) binary (Paczynski, 1986; Fryer et al., 1999; Rosswog and Ramirez-Ruiz, 2003; Belczynski et al., 2006; Giacomazzo and Perna, 2013), or the accretion-induced collapse of a WD (Metzger et al., 2008) may lead to the formation of a magnetar. In this context, the initial spike is powered by accretion onto the magnetar from a disc formed during the merging or the collapse, while the EE by a relativistic wind that extracts the rotational energy of the magnetar at later times, after the disc is disrupted (Metzger et al., 2008; Bucciantini et al., 2012). The different origin explains qualitatively the spectral and temporal differences between the initial spike and the EE. A different possibility is that also the EE is powered by late-time accretion from an accretion disc produced by a WD binary merger prior to collapse, powering an outflow similar to that produced during the prompt accretion episode (Metzger et al., 2008). A possible discrimination between these two scenarios is that EE powered by accretion should not be visible off-axis, since jets from the prompt and delayed accretion episodes are similarly collimated, while if the EE is powered by the spin down and, thus, is symmetric in the azimuth, then at least as many off-axis X-ray flashes are expected as standard SGRBs (Metzger et al., 2008). At the end of the prompt emission (initial spike and EE) the rotational energy reservoir is sufficient to power the late-time X-ray emission, producing the plateau phase (see Section 2 and Metzger et al. 2008, 2011; Gompertz et al. 2013).

Gompertz et al. (2014) proposed an alternative scenario in the context of magnetar central engine for EE, where it is powered by a magnetic "propeller". In this scenario, the material from the accretion disc surrounding the newly-formed magnetar is accelerated to super-Keplerian velocities and ejected from the system by the centrifugal forces exerted by the magnetosphere. After this phase, the late X-ray emission can still be powered by the magnetar spin down, as usual. This propeller emission can reproduce a variety of SGRB light curves (Gompertz et al., 2014), and it has the merit of associating the three different features (initial spike, EE and plateau phase) of SGRBs to different energy suppliers (accretion and propeller, spin down).

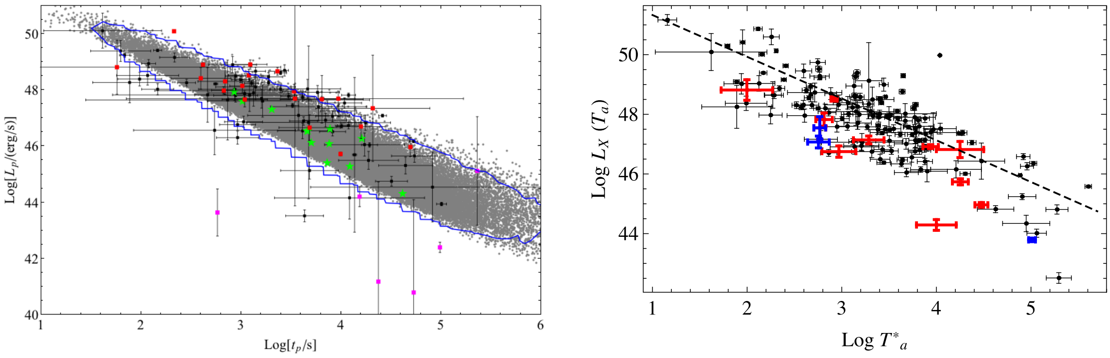

Figure 3: Plateau luminosity and timescale. Left panel (from Bernardini et al. 2012): the black squares are the sample analysed by Dainotti et al. (2010) and the colored symbols are the sample analysed in Bernardini et al. (2012). The grey dots are 100000 simulations of the luminosity at the spin-down time and the spin-down time assuming that the magnetic field and the NS period are normally distributed around the mean values found in Dainotti et al. (2010). The blue line marks the region that includes 99% of the simulations. Right panel (from Rowlinson et al. 2014): sample analysed in Rowlinson et al. (2014) (black = LGRBs, Blue = EE SGRBs and Red = SGRBs). The dashed black line is the observed plateau luminosity and timescale correlation for the full sample.

4. Switching on and off a GRB

One of the most challenging features of GRBs is the sporadic emission prior to the main prompt event observed in at least $\sim 15\%$ of LGRBs (Koshut et al., 1995; Lazzati, 2005; Burlon et al., 2008, 2009). These *precursors* have spectral and temporal properties similar to the main prompt emission, and smaller, but comparable, energetics (Burlon et al., 2008, 2009; Bernardini et al., 2013). They are separated from the main event by a quiescent time that may be extremely long (up to $\sim$ 100 s, rest frame), especially if measured in terms of the typical variability timescale of the prompt emission ($\sim$ 1 ms). In some cases, more than one precursor has been observed in the same burst, separated by several tens of seconds. Precursors have been observed also in $\sim 8\% - 10\%$ of SGRBs, with at least one case showing two distinct precursors (Troja et al., 2010). As for LGRBs, no substantial differences have been found between precursor and main event emission in SGRBs (Bernardini et al., 2013; Troja et al., 2010). Different models have been proposed to account for precursor emission, without reproducing all the observed features.

Another intriguing and unexpected feature of GRBs revealed by the *Swift*/XRT are flares superimposed on the X-ray light curves of LGRBs (Burrows et al., 2005b; Falcone et al., 2006; Chincarini et al., 2010). The vast majority of flares occurs before 1000 s (Chincarini et al., 2010), but some of them can be found up to 10^6 s after the main event (Bernardini et al., 2011). Recent analyses of the flare temporal and spectral properties (Chincarini et al., 2010) of a large sample of *early* time (i.e. with peak time $t_{pk} \lesssim 1000$ s) flares revealed close similarities between them and the prompt emission pulses, pointing to an internal origin of their emission. Therefore, the central engine itself should remain active and variable for long time. SGRBs show flaring activity with similar properties than for LGRBs when the different energetics and timescales of the two classes are taken into account, suggesting that: (i) flares and prompt pulses in SGRBs likely have a common origin; (ii) similar dissipation and/or emission mechanisms are responsible for the prompt and flare emission in LGRBs and SGRBs (Margutti et al., 2011).

Among X-ray flares, there are particularly bright events that show a dramatic flux increase (a factor 100 compared to the underlying X-ray emission) and comprise a substantial amount of energy compared to the main prompt event (see e.g. Margutti et al. 2010). As for the prompt emission, the energy density spectrum of these events can be fitted by a Band function (Band et al., 1993), though it peaks at lower energies ($E_{pk} \sim 5$ keV, Margutti et al. 2010). These *giant flares* can be regarded as *post-cursors*, namely emission episodes that follow the main prompt emission and share with it the same temporal and spectral properties.

Metzger et al. (2011) proposed a self-consistent model that directly connects the properties of the newly-born magnetar to the observed prompt emission, that is powered by a wind heated by neutrinos driven from the proto-magnetar. They assume two different possibilities to dissipate this power: magnetic dissipation and shocks. Magnetic reconnection may occur near the photosphere if the outflow develops an alternating field structure due to e.g. magnetic instabilities or a misalignment between the magnetic and rotation axes. Shocks may occur at larger radii because the Lorentz factor of the wind increases with time, such that the faster jet at late times collides with slower material released earlier, as in the standard internal shock model (Rees and Meszaros, 1994). While this model is successful to give an overall interpretation of the central engine activity and its influence to shape different GRB features, it still predicts a continuous outflow, though with erratic dissipation mechanism.

4.1. Pre- and post-cursors in GRBs: the accreting magnetar model

In Bernardini et al. (2013) we proposed a scenario for precursors assuming that the central GRB engine is a newly born magnetar. In this model the precursor and the prompt emission arise from the accretion of matter onto the surface of the magnetar. The main assumption is that the GRB prompt emission originates from a newly-born magnetar accreting material from an accretion disc, and the observed power is proportional to the mass accretion rate. Close to the surface of the magnetar, the behavior of the in–falling material is dominated by the large magnetic field of the neutron star, so that matter is channelled along the field lines onto the magnetic polar caps. The magnetic field begins to dominate the motion of matter at the magnetospheric radius r_m, defined by the pressure balance between the magnetic dipole of the magnetar and the in-falling material. The in-falling stellar envelope act to collimate the outflow into a jet (Uzdensky and MacFadyen, 2007). Accretion onto the surface of the magnetar proceeds as long as the material in the disc rotates faster than the magnetosphere. In the opposite case, accretion can be substantially reduced due to centrifugal forces exerted by the super-Keplerian magnetosphere: the source is said to enter the "propeller" phase (Illarionov and Sunyaev, 1975; Campana et al., 1998), accretion is inhibited and the GRB becomes quiescent. During this phase, matter continues to pile-up at r_m (at a few neutron star radii) until its pressure is high enough to overcome the centrifugal barrier again. Accretion onto the surface of the neutron star then restarts, giving rise to another high energy event. All the emission episodes are produced by the same mechanism and, thus, have the same observational properties. Figure 4 sketches the different phases of the magnetar (accretion and propeller) and how they reveal themselves in the GRB prompt emission light curves as observed by the *Swift*/Burst Alert Telescope (BAT, Barthelmy et al. 2005a).

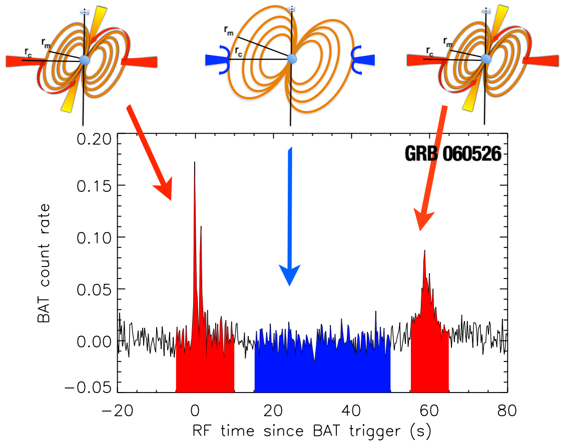

Figure 4: *Swift*/BAT count rate light curve of GRB 060526, with the main event and the post-cursor (red areas), and the quiescent time (blue areas). Right and left upper panels: accretion onto the surface of the magnetar. The magnetospheric radius r_m is smaller than the co-rotation radius r_c, where the magnetosphere centrifugal drag balances gravity: in-falling matter from the accretion disc rotates faster than the magnetosphere and accretion onto the magnetar surface takes place. This phase accounts for the precursor(s), the post-cursor(s) and the main event emission. Central upper panel: propeller phase. The magnetospheric radius r_m is larger than the co-rotation radius r_c: centrifugal forces on the in-falling matter at r_m are too large to allow for co-rotation, the net radial force is outward and the in-fall velocity drops to zero as well as the accretion power. This phase corresponds to the quiescent times. Since $r_m \propto \dot{M}^{-2/7}$, when enough matter is accumulated to fulfill the condition $r_m < r_c$ the propeller phase ends and accretion restarts, corresponding to a new emission episode.

Every emission episode (precursor, main emission or post-cursor) should lie above the characteristic luminosity corresponding to the onset of the propeller phase L_{min}, providing a strong observational test for the consistency of this model (see fig. 5 where GRB 061121 is portrayed as an example, and Bernardini et al. 2013). It is possible to have multiple precursors, if the centrifugal barrier is penetrated more than once. Similarly, late-time accretion of the outer layers of the accretion disc may be responsible for the giant flares, that for consistency have to be brighter than L_{min} (Bernardini et al., 2013). During the propeller phase the luminosity does not drop to zero. A smaller luminosity $L(r_m)$ is expected resulting from the gravitational energy release of the in-falling matter up to r_m, escaping through the pre-excavated funnel. This provides an upper limit to the observed quiescent time luminosity since only a fraction of it may leak out from the jet base.

The accretion process ends when the mass inflow rate decreases enough for the magnetospheric radius to reach the light cylinder (i.e. the radius at which the field lines co-rotate with the neutron star at the speed of light). Beyond this radius the field becomes radiative and expels much of the in-falling matter. After the end of the prompt emission, the GRB afterglow may be still influenced by the magnetar spin-down power, re-energising the afterglow and producing the X-ray plateau. The analysis of the plateau in the X-ray emission of the GRBs with precursors and/or post-cursors (see fig. 5 where GRB 060526 is portrayed as an example) allows us to have a direct estimate of the magnetic field and spin period of the magnetar (Dall'Osso et al., 2011) and to calculate the characteristic luminosities of the propeller phase for different GRBs, as reported in fig. 5. This provides an independent confirmation of the accreting magnetar scenario (Bernardini et al., 2013). The propeller mechanism as an explanation for the quiescent time can also be extended to short GRB precursors.

5. Are all GRBs powered by magnetars?

From a phenomenological point of view, we showed that a large fraction of both LGRBs and SGRBs can be powered by a magnetar, being either gravitational and/or rotational energy. But can all GRBs be powered by a magnetar? In Bernardini et al. (2013) we showed that the rate of magnetars related to SNe Ibc are consistent with the total number of observed LGRBs, accounting for both low-luminosity and normal LGRBs. Indeed, the collapse of a massive star accommodates both the direct collapse to a BH and the formation of a proto-magnetar in those cases where fast-rotating cores produce a magneto-rotational explosion. Despite the uncertainties, recent simulations seem to indicate that proto-magnetars are more easily produced than BHs by current stellar-evolutionary models (Dessart et al., 2012). Mazzali et al. (2014) showed that the kinetic energy of SNe spectroscopically associated to LGRBs is consistent with the maximum rotational energy of a magnetar ($\sim$ few $\times 10^{52}$ erg, Ott et al. 2006) and is significantly larger than the energy of the accompanying LGRBs. They thus proposed that all GRBs associated with luminous SNe are produced by magnetars.

Though in principle it is possible that all GRBs are produced by magnetars, there are direct evidences that several high-energetic LGRBs exceed the overall rotational energy budget of a magnetar. This limit may be overcome if the prompt emission is powered by accretion, thus adding the gravitational energy to the overall energy budget of the system. In this case, depending on the amount of accreted mass, the magnetar may survive the prompt emission and continue to influence the X-ray emission with its spin-down power (see e.g. the application of this scenario to GRB 130427A in Bernardini et al. 2014), or collapse to a BH. A BH may directly form from the collapse of the progenitor star, as in the standard collapsar scenario (Woosley, 1993). In this case, we do not expect any contribution to the afterglow emission from the central engine, namely the X-ray emission should follow a single power-law decay as, e.g., in GRB 061007 (Bernardini et al., 2013). A LGRB with energetics largely exceeding 10^{52} ergs and with a plateau phase would be a challenge for any magnetar model. A third possibility is that the proto-magnetar rotates fast enough that accretion never sets in, thus the resulting GRB will be powered by the rotational energy only. This may be the case of low-luminosity LGRBs or X-ray flashes as GRB 060218, as envisaged by Soderberg et al. (2006).

Concerning SGRBs, Giacomazzo and Perna (2013) showed that a stable magnetar may be produced in the NS binary merging. An alternative channel of isolated magnetar birth may be the accretion-induced collapse of a WD, or the merger and collapse of a WD binary. The rate of these events is difficult to constrain directly because the Ni mass synthesized is too low to produce a bright optical transient (Metzger et al., 2008). The lower energetics of SGRBs (typically, a factor 100 compared to LGRBs) do not exceed rotational energy reservoir limit of magnetars.

6. Gravitational wave emission from magnetars powering GRBs

Magnetars may be source of GWs if they spin fast enough to excite dynamical bar- mode or secular instabilities (see Corsi and Mészáros, 2009, and references therein). Dynamical bar-mode instabilities are excited when the magnetar rotational parameter β, i.e. the ratio of the rotational kinetic energy to the gravitational binding energy, is larger than $\beta = 0.27$ and grows on a dynamical timescale, which is about one rotational period, and may last for 10-100 rotations. At lower rotation rates ($\beta > 0.14$) secular instabilities are excited. Corsi and Mészáros (2009) analysed the standard scenario where the magnetar contributes to the LGRB emission with its spin-down power only, and showed that it would produce a GW signal emitted over relatively long timescales of minutes to about an hour, detectable for advanced interferometers up to $\sim$ 100 Mpc.

Accretion after the initial stage of formation of the magnetar will produce the spin-up of the star, making

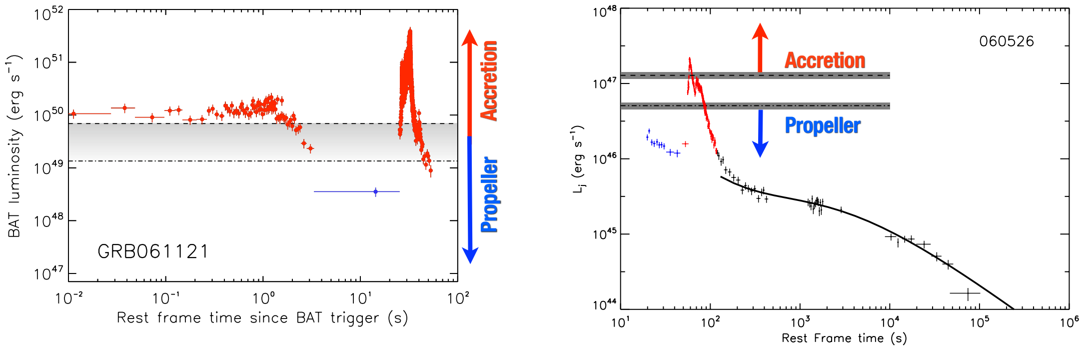

Figure 5: Left panel: 15 – 150 keV luminosity of GRB 061121 binned with signal-to-noise $S/N = 5$. The minimum luminosity before the onset of the propeller phase $L_{\rm min}$ (dashed line) and the maximum quiescent time luminosity $L(r_{\rm m})$ (dash-dotted line) are compared with the precursor (red dots), quiescence (blue dots) and main event (red dots) emission. Characteristic luminosities have been derived independently from the fitting of the late-time X-ray emission with the spin-down power of the magnetar. Right panel: 0.3 – 30 keV luminosity of GRB 060526. Luminosity lines are compared with the post-cursor in the X-ray band: the post-cursor emission (red points) is consistent with accretion onto the magnetar surface, while the quiescent time emission (blue points) is below the estimate for $L(r_{\rm m})$. The late time X-ray afterglow emission (black points) has been fitted assuming that the spin-down power emitted by the magnetar is the source of energy injected in the forward shock (black solid line), giving a direct estimate of the magnetar magnetic field and spin period: $B = 6.28 \times 10^{15}$ G, $P = 5.68$ ms.

the onset of the instabilities more likely and long lasting. Piro and Ott (2011) studied the effects of accretion on a newly-born magnetar in the context of propeller-powered SN explosion, and found that, depending on the magnetic field and the spin period, indeed accretion causes the magnetar to spin sufficiently rapidly to deform triaxially producing GWs. However, given the current LGRBs redshift distribution (Hjorth et al., 2012; Salvaterra et al., 2012), the detection of GW signals from LGRBs within the expected sensitivity volume (∼ 200 Mpc) of the forthcoming advanced LIGO and VIRGO detectors is challenging. More opportunities come from the LGRBs seen off-axis, that outnumber the ones that are pointing towards us a factor $\sim 2/\theta_{jet}^2 \sim 200$ for a beaming angle θ_{jet} a few degrees.

SGRBs are a more promising source for the detection of GWs. In particular, if their progenitor is a binary NS merger, depending on the total initial mass of the system and the NS equation of state, the post-merger phase can be characterised by a prompt collapse to a BH or by the formation of a supramassive NS, or even a stable NS. There are predicted GW signals detectable with advanced interferometers for all of the stages a NS binary can go through: inspiral, magnetar spin-down and eventual collapse to BH. In particular, distinctive signals from a magnetar are expected depending on the slightly larger compactness of the magnetar compared to the BH (Giacomazzo and Perna, 2013), and on the NS equation of state (Dall'Osso et al., 2015). A typical GW emission is also expected if the supramassive magnetar collapses to a BH due to accretion (Giacomazzo and Perna, 2012). Thus, measurement of GW signals would provide constraints on the nature of the binary progenitors giving rise to SGRBs. If SGRBs are indeed produced by accretion-induced collapse of a WD or WD mergers, they should not produce strong GW emission (Metzger et al., 2008).

7. Conclusions

Newly-born millisecond magnetars are competing with BHs as source of the GRB power (Usov, 1992). Their rotational energy reservoir is sufficient to power a large fraction of GRBs (Ott et al., 2006), and in the case of LGRBs it can contribute to energise the accompanying SN (Mazzali et al., 2014). They may be formed both in the core-collapse of massive stars (Dessart et al., 2012), and in the merger of NS or WD binaries, or in the accretion-induced collapse of a WD (Metzger et al., 2008), being thus a plausible progenitor for LGRBs and SGRBs, respectively. The existence of such extreme magnetic fields is demonstrated by direct observations of SGRs (Kouveliotou et al., 1998; Mereghetti, 2008; Rea and Esposito, 2011).

In ten years of activity, *Swift* has provided compelling observational evidences supporting the magnetar central engine:

- up to ∼ 80% of the LGRB and ∼ 50% of SGRB

X-ray emission exhibits a shallow decay phase (X-ray plateau, Evans et al. 2009; Margutti et al. 2013; Rowlinson et al. 2013; D'Avanzo et al. 2014; Melandri et al. 2014). A natural interpretation for this component is the spin-down power emitted by a magnetar (Dai and Lu, 1998; Zhang and Mészáros, 2001; Corsi and Mészáros, 2009; Metzger et al., 2011), whose luminosity is $\dot{E}_{\rm sd} \sim 10^{49}$ erg s^{-1}. Depending on the dissipation site of this power, there are external (i.e. the spin-down power is injected into the forward shock) or internal (the spin-down power dissipates internally before hitting the forward shock) plateaus. In this second case, the sharp drop in the X-ray emission, inconsistent with the forward shock model observed in some cases, is produced by the magnetar collapsing to a BH. This interpretation has been proved to be successful in describing LGRB (Lyons et al., 2010; Dall'Osso et al., 2011; Bernardini et al., 2012, 2013) and SGRB (Rowlinson et al., 2013; Gompertz et al., 2013) plateaus. One major advantage of this interpretation for the plateau phase is that the anti-correlation between the plateau luminosity and timescale (Dainotti et al., 2008, 2010, 2013) is naturally accounted for analytically when one associates the initial spin-down luminosity with the plateau luminosity, and the spin-down timescale with the plateau duration (Bernardini et al., 2012; Rowlinson et al., 2014);

- $\sim$ 15% of SGRBs shows an extended emission in the prompt emission after the initial spike (Norris and Bonnell, 2006), long-lasting ($\sim$ 100 s), with a softer spectrum, and comprising a larger fluence than the initial spike. Theoretical explanations for the EE are related to the magnetar central engine, either to its spin-down power (Metzger et al., 2008), or to fall-back material accelerated to super-Keplerian velocities and ejected from the system by the centrifugal forces exerted by its magnetosphere (Gompertz et al., 2014);
- a feature that is challenging for the standard scenario of accretion onto a BH is the presence of precursor activity in $\sim$ 15% of LGRBs (Koshut et al., 1995; Lazzati, 2005; Burlon et al., 2008, 2009) and $\sim$ 10% of SGRBs (Troja et al., 2010). Precursors imply that the intermittent mechanism powering the prompt emission may be suspended over timescales comparable to the prompt emission itself. In the context of the magnetar central engine precursors can be explained by assuming that the GRB prompt emission is powered by the accretion of matter onto the surface of the magnetar (Bernardini et al., 2013). The accretion process can be halted by the centrifugal drag exerted by the rotating magnetosphere onto the in-falling matter, allowing for multiple emission episodes and very long quiescent times. The same mechanism can be extended to late times, providing also an interpretation for giant flares, that are particularly bright events comprising a substantial amount of energy compared to the main prompt event (Margutti et al., 2010). These giant flares can be regarded as post-cursors, namely emission episodes that follow the main prompt emission and share with it the same temporal and spectral properties.

Though in principle it is possible that all GRBs are produced by magnetars, there are direct evidences that several high-energetic LGRBs exceed the overall rotational energy budget of a magnetar ($\sim$ few $\times 10^{52}$ erg, Ott et al. 2006). This limit may be overcome if the prompt emission is powered by accretion, thus adding the gravitational energy to the overall energy budget of the system. In this case, depending on the amount of accreted mass, the magnetar may survive the prompt emission and continue to influence the X-ray emission with its spin-down power, or collapse to a BH. A BH may directly form from the collapse of the progenitor star, as in the standard collapsar scenario (Woosley, 1993).

GW may be the ultimate probe into the central engine. Given the current LGRBs redshift distribution (Hjorth et al., 2012; Salvaterra et al., 2012), the detection of GW signals from LGRBs within the expected sensitivity volume ($\sim$ 200 Mpc) of the forthcoming advanced LIGO and VIRGO detectors is challenging for events observed on-axis. SGRBs are a more promising source for the detection of GWs, with predicted GW signals detectable with advanced interferometers for all of the stages a NS binary can go through (e.g. Giacomazzo and Perna, 2012, 2013; Dall'Osso et al., 2015). Measurement of GW signals would provide constraints on the nature of the binary progenitors giving rise to SGRBs.

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