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Review

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.

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 an 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 ~ 1 ms contains a large amount of energy, $\dot{E} = 0.5 I\Omega^2 \sim 3 \times 10^{52}$ 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 flare events have been studied, and the central engines confirmed to be magnetars with strong ($\sim 10^{14}$–10^{15} G) dipole magnetic fields, despite that these are millions of years old (e.g. Kouveliotou et al., 1998; Mereghetti, 2008; Rea and Esposito, 2011).

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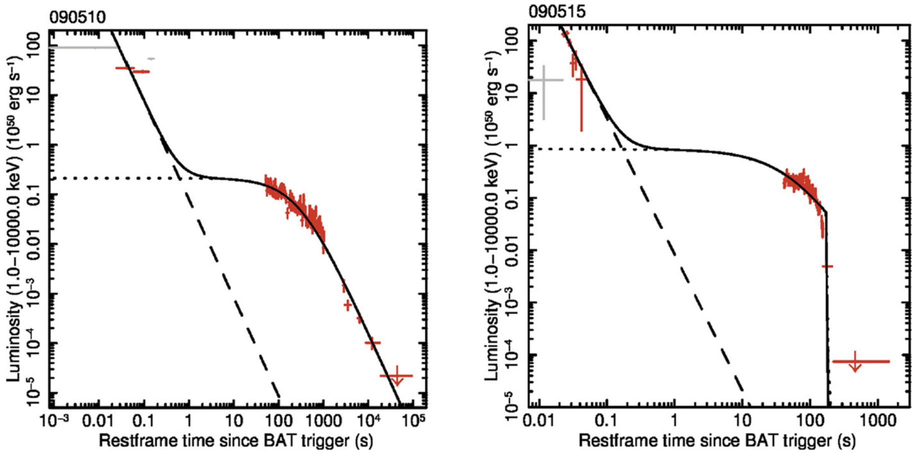

Fig. 1. Examples of external (left panel) and internal (right panel) plateaus in short GRBs (from Rowlinson et al., 2013). Both panels show *Swift*/BAT and XRT rest-frame light curves fitted with the magnetar model. The light grey data points have been excluded from the fit. The dashed line shows the 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 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 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). An L_p–t_p anti-correlation is also followed by SGRBs, though with a different normalisation with respect to LGRBs (Rowlinson et al., 2014).

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