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Giant flares in soft γ-ray repeaters and short GRBs

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Soft gamma-ray repeaters (SGRs) are a peculiar family of bursting neutron stars that, occasionally, have been observed to emit extremely energetic giant flares (GFs), with energy release up to approximately 10^{47} erg s^{-1}. These are exceptional and rare events. It has been recently proposed that GFs, if emitted by extragalactic SGRs, may appear at Earth as short gamma-ray bursts. Here, I will discuss the properties of the GFs observed in SGRs, with particular emphasis on the spectacular event registered from SGR 1806-20 in December 2004. I will review the current scenario for the production of the flare, within the magnetar model, and the observational implications.

Keywords: soft gamma-ray repeaters; short gamma-ray bursts; stars: neutron

1. Introduction

Soft gamma-ray repeaters (SGRs) are a small group (four known sources and one candidate) of neutron stars (NSs) discovered as bursting gamma-ray sources. During the quiescent state (i.e. outside bursts events), these sources are detected as persistent emitters in the soft X-ray range (less than 10 keV), with a luminosity of approximately 10^{35} erg s^{-1} and with a typical blackbody plus power law spectrum. Their NS nature is probed by the detection of periodic X-ray pulsations at a few seconds in three cases. Very recently, a hard and pulsed emission (20–100 keV) has been discovered in two sources (Mereghetti *et al.* 2005*a*), while an infrared counterpart has been reported in one case (Israel *et al.* 2005*a*).

SGRs undergo sporadic periods of activity and have been observed to emit three kinds of bursts. The most common are ‘short’ (less than 1 s, $L \sim 10^{40}$–10^{41} erg s^{-1}) and ‘intermediate’ (approx. 1–40 s, $L \sim 10^{41}$–10^{43} erg s^{-1}) super-Eddington bursts of hard X-rays/soft gamma-rays, which repetition time can vary between seconds to years. Occasionally, SGRs have been observed to emit much more energetic ‘giant flares’ (approx. 10^{44}–10^{47} erg s^{-1}). These are exceptional and rare events, observed only three times from the whole sample of SGRs (from SGR 0526-66 on 1979, Mazets *et al.* 1979; from SGR 1900+14 on 1998, Hurley *et al.* 1999; and from SGR 1806-20 on 2004, e.g. Hurley *et al.* 2005; Palmer *et al.* 2005). All three events started with an initial spike of 0.1–0.2 s duration, followed by a long pulsating tail (lasting approx. few hundreds of seconds) modulated at the NS spin period.

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One contribution of 35 to a Discussion Meeting Issue ‘Gamma-ray bursts’.

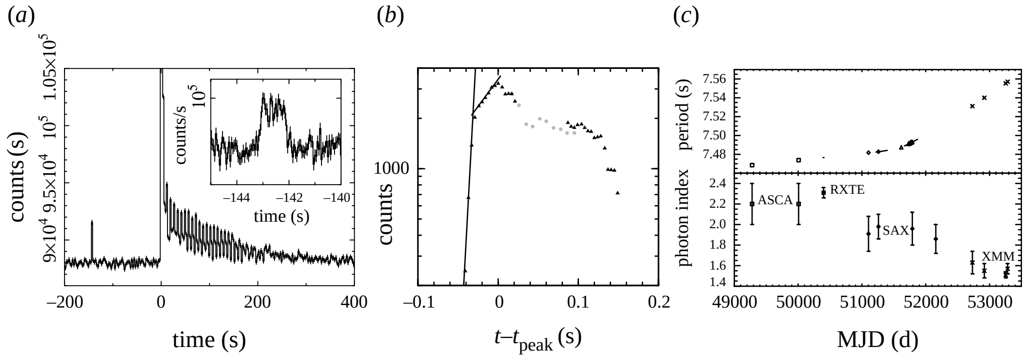

Figure 1. The giant flare from SGR 1806-20. (*a*) ACS lightcurve of the GF, binned at 2.5 s. The peak of the flare is not shown. The insert shows the lightcurve of the precursor at full resolution (50 ms), from Mereghetti *et al.* (2005*b*). (*b*) Lightcurve of the peak of the GF as detected by Cluster and Double Star. Note that the rise of the emission slow down during the final rise to the peak, from Schwartz *et al.* (2005). (*c*) A correlation between spectral hardening and spin-down rate during the pre-GF epoch, from Mereghetti *et al.* (2005*c*). All figures are reproduced by permission of the AAS.

Several characteristics of SGRs, including their bursting activity, are often explained in the context of the 'magnetar' model (Duncan & Thompson 1992; Thompson & Duncan 1995). Magnetars are ultra-magnetized NSs with a magnetic field $B\sim10^{14}$–10^{15} G, which is up to two order of magnitude larger than the average of the radiopulsars population and exceeds the threshold at which QED effects become important. This idea has been proposed to explain the very extreme properties of the SGRs bursts and flares: the frequent short bursts would then be associated with small cracks in the NS crust, driven by magnetic diffusion, or, alternatively, with the sudden loss of magnetic equilibrium through the development of a tearing instability, while the giant flares would be linked to global rearrangements of the magnetic field in the star magnetosphere and interior. Further support to the 'magnetar' model arises from the timing properties and energetic of SGRs. SGRs are characterized by a large spin-down rate ($\dot{P}\sim10^{-11}$ s s^{-1}, see Kouveliotou *et al.* 1998, 1999), consistent with magnetodipolar losses in a magnetar-like field. Furthermore, they lack a companion and their X-ray luminosity is approximately 100 times larger than their rotational energy reservoir, therefore they cannot be accretion or rotationally powered (as other isolated pulsars). A further source of energy is needed, likely the decay of the ultra-strong magnetic field.

2. December 2004: a spectacular giant flare from SGR 1806-20

(*a*) *The giant flare*

On 27 December 2004, all existing X-ray and gamma-ray observatories were saturated by the brightest extra-solar event ever recorded, i.e. a bright giant flare emitted by SGR 1806-20 (e.g. Hurley *et al.* 2005; Mereghetti *et al.* 2005*b*; Palmer *et al.* 2005; and references therein). The flare was preceded by a precursor (approx. 140 s before the event, figure 1), then the emission raised very quickly on a time-scale less than 1 ms. The main narrow peak lasted approximately 0.2 s, and was followed by a long (approx. 400 s) pulsating tail. Although gamma-ray and X-ray detectors were saturated, the spike energy has been measured via particle detectors on board RHESSI, Wind, GEOTAIL and with the SOPA and ESP instruments on board geosynchronous satellites (Hurley *et al.* 2005; Palmer *et al.* 2005; Terasawa *et al.* 2005). The isotropic energy release was $(1.6-5)\times 10^{46} d_{15}^2$ erg and $(5-10)\times 10^{44} d_{15}^2$ erg in the spike and pulsating tail, respectively (d_{15} is the distance in unit of 10^{15} pc). The time history and tail emission were very similar to those of the two previous GFs, but the narrow spike was two orders of magnitude more intense.[1] RHESSI and Wind emerged from saturation approximately 200 ms after the spike and detected the spectrum. The emission was thermal, and roughly modelled by a blackbody at $kT\sim 200$ keV. Furthermore, by using data from Cluster and Double Star-2, we have been able to resolve the details of the lightcurve of the narrow spike (see figure 1; Schwartz *et al.* 2005), finding evidence for three separate time-scales within the first 100 ms, all explained within the magnetar model. In addition to the initial, short (less than 0.25 ms) time-scale associated to the steep X-ray onset and to the longer one (approx. 100 ms) related to the overall duration of the peak, that can be related to the Alfvèn time in the external magnetosphere and in the star interior, respectively, we found evidence for an intermediate (approx. 5 ms) time-scale related to the final rise to the peak. This is naturally explained if the final rising time is limited by the propagation of a triggering fracture of approximately 5 km size, given the theoretical expectation $\ell \approx 4\ \mathrm{km}\ t_{\mathrm{rise}}/4\ \mathrm{ms}$ (Thompson & Duncan 2001).

The GF can therefore be caused by sudden reconfigurations of the star's magnetic field which, in turn, propagate outward through Alfvèn waves and produce large fractures in the crust. This scenario is strengthened by the detection of tens of Hz quasi-periodic oscillations (QPOs) in the tail of the event (Israel *et al.* 2005*b*), which have been associated to global seismic oscillations. After this discovery, it was realized that QPOs may be a common feature of all the three GFs; they appear in the data of the GF emitted from SGR 1900+14 (Strohmayer & Wattes 2005) and a marginal detection has been reported in the case March 1979 event (Barat *et al.* 1983).

Following the event, a transient radio source was observed with the VLA (Cameron *et al.* 2005; Gaensler *et al.* 2005*a*,*b*) leading to a precise localization. In turn, this allowed the discovery of a variable near IR counterpart ($K_{\mathrm{s}}=19.3$–20), the first one for an SGR (Israel *et al.* 2005*a*).

(*b*) *The pre- and post-giant flare evolution*

Since SGR 1806-20 is target of an ongoing campaign of observations, several details of the long-term variation of its emission before and following the GF are known. In particular, before the flare an increase in the level of activity of the SGR was observed (Hurley *et al.* 2003; Mereghetti *et al.* 2004).

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[1] A caveat is that the distance of SGR 1806-20 is debated. A firm lower limit of 6 kpc is inferred from the HI absorption spectrum. A likely association with a massive molecular cloud and with a cluster of massive stars indicate $d\sim 15$ kpc (see Cameron *et al.* 2005; McClure-Griffiths & Gaensler 2005).

Four XMM-Newton observations were obtained from April 2003 to October 2004, before the giant flare (Mereghetti *et al.* 2005*c*), and two during the aftermath (March 2005, Tiengo *et al.* 2005; October 2005, Rea *et al.* 2005). These data showed a doubling of the flux in September–October 2004, followed by a gradual recovery to the 'historical' level during the observations performed after the giant flare (see also Woods *et al.* 2004). The flux variation was accompanied by significant changes in spectral shape. A comparison of the four pre-flare observations with past ASCA and Sax data revealed that a gradual spectral hardening occurred between September 2001 and April 2003, correlated with a gradual increase in spin-down rate (figure 1), while the spectrum was definitely softer and the spin-down rate decreased in the post-flare data.

(*c*) *Onset of a twist in the external magnetosphere?*

Quite interestingly, the peculiar long-term variations of SGR 1806-20 observed before and after the GF (i.e. the correlation between spectral hardening, flux, spin-down rate and bursting activity increase) can be explained if the event is dictated by the onset of a twist in the external magnetosphere. Thompson *et al.* (2002) proposed that SGRs and AXPs may differ from standard radio pulsar since their magnetic field is globally twisted inside the star, up to a strength approximately 10 times the external dipole, and, at intervals, can twist up the external field. When this occurs, a number of observational consequences follow.

The twisted, force-free magnetosphere supports large currents, in excess of the Goldreich–Julian density. The presence of e^- flowing in the magnetosphere causes two main effects: (i) an extra heating of the star surface, by returning currents, which translates into an extra X-ray luminosity and (ii) a significant optical depth to resonant cyclotron scattering. Since the charge distribution is spatially extended, repeated scatterings then lead to the formation of a high-energy tail, which importance increases with the twist angle. Moreover, in a twisted configuration, the open field flux can be larger than in a dipole, leading to an increase in the spin-down torque. At the same time, the stresses building up in the NS crust and the magnetic footprints movements are responsible for an increase in the bursting activity. The growth of the twist can ultimately culminate in the release of a GF following either a crustal fracture or a global rearrangement of the field lines (or, more likely, a combination of the two). These events induce a forced opening of the field outwards and the launch of a hot fireball. The flare can be then followed by a simplification in the field structure and by a partial magnetospheric untwisting, which can be observed as a rapid drop in the flux, a spectral softening and a period derivative decrease.

3. A (dis-)connection between extragalactic SGRs and short GRBs?

The detection of the ultra-energetic GF from SGR 1806-20 reignited interest in the idea that GFs emitted by extragalactic SGRs can be seen at Earth as short GRBs (Hurley *et al.* 2005; Palmer *et al.* 2005). Around 10% of NSs can be born as magnetars, and the rate of GFs per source has been estimated to be 1/25, 1/50 per year. SGRs should be very young (the typical age of an active magnetar is approximately 10^4 yr), and there is evidence that magnetars may be created during the explosion of massive progenitors ($M \sim 25$–$60 M_{\mathrm{sun}}$, see, e.g. Eikenberry *et al.* 2004; Klose *et al.* 2004; Figer *et al.* 2005; Gaensler *et al.* 2005*c*). They should then trace regions of high star formation. The main causes of uncertainty are in maximum energy released in the flare, because the distance of SGR 1806-20 is not certain, and in the spectral properties of the narrow peak. By varying the assumptions about the peak spectral shape, Popov & Stern (2006) computed the possibility of detection by BATSE of GFs with an energy of 10^{44} or 10^{46} erg, as a function of the distance. They found that the first kind of event can be seen up to a few Mpc (therefore in M82, M83, NGC253 and NGC4945), while events similar to the SGR 1806-20 'hyperflare' (HF) can in principle be visible up to the Virgo cluster.

However, a series of recent works demonstrated that this prediction may be too optimistic. For instance we just report a few works.

- As pointed out by Palmer *et al.* 2005, the distribution of BATSE short GRBs is isotropic and does not show an excess from the Virgo cluster direction. This implies that the number of HFs in a galaxy like our own must be less than approximately 3×10^{-3} per year, or that some of them are even much more energetic than the December 2004 event and can be observed at larger distances.
- Popov & Stern (2006) have found no overlap between the BATSE short GRBs and M82, M83, NGC253 and NGC4945 nor, again, with the Virgo Cluster, concluding that the rate of galactic GFs with a release of approximately 10^{43}–10^{44} erg in the initial spike must be less than $1/30\ \mathrm{yr}^{-1}$ and the rate of HFs with a release of approximately 10^{46} erg in the initial spike is less than $1/1000\ \mathrm{yr}^{-1}$.
- A similar conclusion has been reached by Lazzati *et al.* (2005). These authors searched for BATSE GRBs with $T_{90} < 2$ s and a blackbody spectrum. They found three candidates but, in all the cases, the lightcurve was multi-peaked and no galaxy was found in the error box at the predicted distance. Based on that, they derived an upper limit on the rate of HFs of $1/130\ \mathrm{yr}^{-1}$.
- Similarly, negative results have been recently reported by Tanvir *et al.* (2005). This group has studied the correlation between 400 short BATSE GRBs with good localization and a sample of 1070 PSCz galaxies with heliocentric recession less than $2000\ \mathrm{km\ s}^{-1}$. This encompasses most galaxies within 25 Mpc, including the Virgo, Fornax and Ursa Major clusters. They found a correlation with the short GRBs sample, but it was stronger when the sample of galaxies was restricted to early morphological types. Whether or not this is indicative of a fraction of short GRBs related to GFs from SGRs or events as NS/NS mergers is still unclear.

Overall, these studies suggest that no more than a few percentage of the short GRBs seen by BATSE could be GFs from extragalactic SGRs. As emphasized by Hurley *et al.* (2005), Swift is providing an excellent opportunity to detect GFs from extragalactic SGRs. Its rapid response and large field of view allow a precise localization, and particularly interesting will be events detected from regions with extreme star formation.

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