

Magnetars' Giant Flares: the Case of SGR 1806–20

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Abstract We report on the properties of the SGR 1806–20’s Giant Flare occurred on 2004 December 27th, with particular interest on the pre and post flare intensity/hardness correlated variability. We show that these findings are consistent with the picture of a twisted internal magnetic field which stresses the star solid crust, until the latter is not able anymore to bear the imparted stresses, and finally cracks causing the giant flare (and the observed torsional oscillations). This crustal fracturing is accompanied by a simplification of the external magnetic field with a (partial) untwisting of the magnetosphere.

Key words: stars: pulsars: individual (SGR 1806–20) — stars: magnetic fields — gamma rays: X-rays: bursts — gamma rays: X-rays: stars

1 INTRODUCTION

Soft γ -ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) are two peculiar groups of neutron stars (NSs) which stand apart from other known classes of X-ray sources. They are all radio-quiet, exhibit X-ray pulsations with spin periods in the ~ 5 –12 s range, a large spin-down rate ($\dot{P} \approx 10^{-10}$ – 10^{-13} s s⁻¹) and a rather high X-ray luminosity ($L_X \approx 10^{34}$ – 10^{36} erg s⁻¹; for a recent review see Woods & Thompson 2004). The nature of the X-ray emission from these sources has been intriguing all along. In fact, for both AXPs and SGRs, the X-ray luminosity is too high to be produced by rotational energy losses alone, as for more common isolated radio pulsars.

The magnetic fields of SGRs and AXPs, as estimated from the classical dipole braking formula $B \sim 3.2 \times 10^{19} \sqrt{P\dot{P}}$ G, are all above the critical magnetic field, $B_{\text{QED}} \sim 4.4 \times 10^{13}$ G. At the same time, the lack of observational signatures of a companion strongly argues against an accretion-powered binary system, favoring instead scenarios involving isolated NSs. These findings led to the idea that the two classes of sources are linked together, and their X-ray emission related to their very high magnetic field. At present, the model which is most successful in explaining the peculiar observational properties of SGRs and AXPs is the “magnetar” model. In this scenario SGRs and AXPs are thought to be isolated NSs endowed with ultra-high magnetic fields ($B \sim 10^{14}$ – 10^{15} G) and their steady X-ray emission powered by magnetic field decay (Duncan & Thompson 1992).

The unpredictable flaring activity of magnetar candidates make them different from all other known classes of neutron stars. From the phenomenological point of view, the bursting/flaring events can be roughly divided in three types.

i) X/ γ -ray short bursts. These are the most common and less energetic SGR flaring events. They have short duration (~ 0.1 – 0.2 s), thermal spectra, and peak luminosity of $\sim 10^{40}$ – 10^{41} erg s⁻¹, well above the

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Eddington luminosity limit for a standard neutron star. They are irregular in time and can occur as single events or in a bunch. AXPs short bursts are slightly different, less energetic and with longer durations (Kaspi et al. 2003; Woods et al. 2005)

ii) Intermediate flares. The name comes from the fact that they are intermediate both in duration and luminosity between short bursts (i) and Giant Flares (ii). They have durations in the range $\sim 1\text{--}60$ s and luminosity of $\sim 10^{41}\text{--}10^{43}$ erg s $^{-1}$. Sometimes intermediate flares last longer than the pulsars' spin periods, and show clear modulation at the star spin period. These events have been observed in SGRs, but they were never revealed up to now from an AXP.

iii) Giant flares. These are by far the most energetic ($\sim 10^{44}\text{--}10^{47}$ erg s $^{-1}$) Galactic events currently known, second only to Supernova explosions. Only three of these events have been recorded in decades of monitoring of the high energy sky and all from SGRs: SGR 0526–66 on 1979 March 5 (Mazets et al. 1979), SGR 1900+14 on 1998 August 27 (Hurley et al. 1999) and the last and more energetic one on 2004 December 27 from SGR 1806–20. All of them are characterized by a very luminous hard peak lasting a bit less than a second, which decays rapidly into a soft pulsating (at the NS spin period) tail lasting hundreds of second.

2 SGR 1806–20 BEFORE THE GIANT FLARE

SGR 1806–20 is at the moment the most prolific SGR. It showed several periods of bursting activity since the time of its discovery in 1979 (Laros et al. 1986). RXTE observations led to the discovery of pulsations (period $P = 7.47$ s and period derivative $\dot{P} = 8 \times 10^{-11}$ s s $^{-1}$; Kouveliotou et al. 1998) and were subsequently used to monitor the timing properties of the source, such as the long term \dot{P} variations and the evolution of the pulse profile (Woods et al. 2002). The first high resolution X-ray spectra of this source, reported to date, were obtained by BeppoSAX in October 1998 and March 1999 (Mereghetti et al. 2000). These showed a spectrum equally well described in the 2–10 keV range by a power law with photon index $\Gamma = 1.95$ or by a thermal bremsstrahlung with temperature $kT_{\text{bb}} = 11$ keV. Similar flux values were measured at that time during all the observations, making believe SGR 1806–20 a fairly stable X-ray emitter, with luminosity of $\sim 3 \times 10^{35}$ (d/15 kpc) 2 erg s $^{-1}$ (2–10 keV) in the period 1993–2001.

Thanks to the INTEGRAL hard X-ray imaging capabilities, persistent emission from SGR 1806–20 was detected up to the γ -rays, showed a power law spectrum with photon index $\Gamma \sim 1.5\text{--}1.9$ extending up to 150 keV (Mereghetti et al. 2005a; Molkov et al. 2005).

Although a radio counterpart were never revealed in this source, ten years ago, VLA observations with an arcminute spatial resolution revealed a weak evidence for a variable jet-like structure, still under debate (Vashist, Frail & Kulkarni 1995; Frail, Vashist & Kulkarni 1997).

Recently, optical and IR studies of the environment of SGR 1806–20 found the source part of a cluster of massive stars of 3.0–4.5 Myr. Assuming coevality, this age suggests that the progenitor of SGR 1806–20 had an initial mass greater than $\sim 50 M_{\odot}$. This is consistent with the suggestion that SGRs are the end states of massive progenitors and may suggest that only very massive stars evolve into magnetars (Figer et al. 2005; Eikenberry et al. 2004; Fuchs et al. 1999).

During the last two years SGR 1806–20 displayed a gradual increase in the level of activity, as testified by the rate at which bursts were emitted and by an increase of the soft and hard X-ray luminosity (Woods et al. 2004), which culminated in 2004 December 27 with the emission of the Giant Flare. This gradual brightening was detected by XMM-Newton, through a series of observations, obtained from April 2003 to October 2004: while in 2003 the 2–10 keV emission was similar to that seen in previous measurements with other satellites, the source flux doubled in the following year (Mereghetti et al. 2005c).

3 THE SGR 1806–20 DECEMBER 27TH GIANT FLARE

On 2004 December 27th, SGR 1806–20 emitted an exceptionally powerful giant flare, with an initial hard spike lasting ~ 0.2 s followed by a ~ 600 s long pulsating tail showing about 50 cycles of high-amplitude pulsations at the known rotation period (Hurley et al. 2005; Palmer et al. 2005). The prompt emission saturated almost all γ -ray detectors, then an exact estimate of the peak fluence was difficult to infer. The GEOTAIL (Terasawa et al. 2005) and the SOPA (Palmer et al. 2005) geo-satellites were the only instruments not to saturate during the peak, revealing an isotropic peak luminosity of $\sim 2 \times 10^{46}$ d $_{15}^2$ erg s $^{-1}$ (d $_{15}^2$ is the source distance in units of 15 kpc), a hundred time higher than that of the two giant flares previously

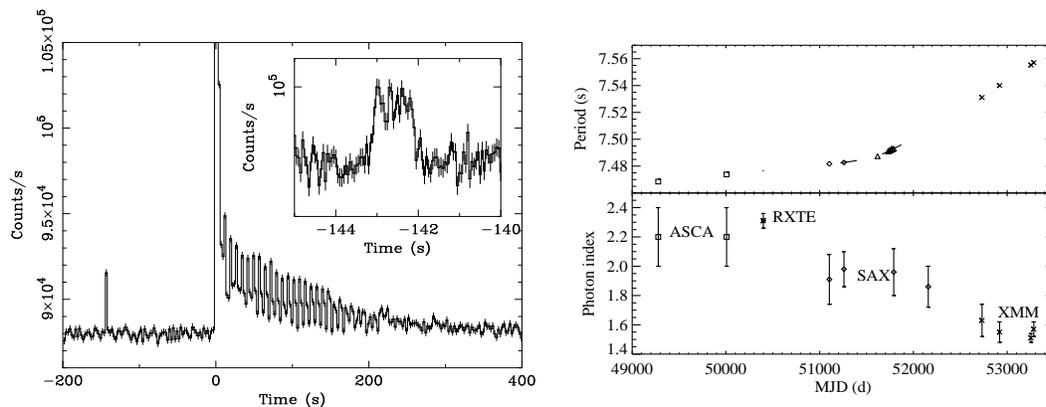


Fig. 1 *Left panel:* INTEGRAL light-curve of the SGR 1806–20 Giant Flare (from Mereghetti et al. 2005b); *Right panel:* Long term pre flare evolution of the pulse period and power law photon index of SGR 1806–20 (from Mereghetti et al. 2005c).

observed from other SGRs. The tail energetic was instead measured by several instruments, agreeing in a release of $\sim 5 \times 10^{43} \text{ d}_{15}^2 \text{ erg s}^{-1}$, comparable with the other giant flares' tails.

A radio afterglow was detected (Cameron et al. 2005), with a luminosity higher by a factor of 500 with respect to the previous giant flare of SGR 1900+14, suggesting a very large difference in the prompt burst energy. On the other hand, the consistency of the tail energy among the three giant flares can be attributable to the storage magnetic energy, then depending only on the source magnetic fields, which is believed to be quite similar among the whole class of the “magnetars”. Interestingly, this radio afterglow emission has been first observed as a resolved extended structure (Cameron et al. 2005, Gaensler et al. 2005). Later on a moving structure, variable in polarisation, was detected, which resumed the idea of a possible jet emission from this source (Taylor et al. 2005; Fender et al. 2005).

Very surprisingly torsional oscillations were detected during this Giant Flare, for the first time in an isolated NS. The higher frequency quasi periodic oscillations (QPOs) at ~ 92.5 Hz were detected between 170 and 220 s after the onset of the giant flare, in association with an emission bump that occurred in the DC component (and a reduction of the amplitude of the 7.56 s pulsations). These QPOs were detected only in the spin phase intervals away from the main peak and reached maximum amplitude corresponding to the DC component phase intervals. Evidence for ~ 18 and ~ 30 Hz QPOs was found between 200 and 300 s from the onset of the giant flare, and not obviously related to any specific interval of pulse phases (Israel et al. 2005; see also Israel et al. in this proceedings).

4 SGR 1806–20 AFTER THE GIANT FLARE

After the Giant Flare event, we continued to monitor the X-ray emission of SGR 1806–20, this time thanks to a prompt Chandra Target of Opportunity on this source (Rea et al. 2005a). The Chandra data clearly indicate that the spectrum softened significantly: we obtained a power law with $\Gamma \sim 1.8$. This has to be compared with the pre-flare values $\Gamma \sim 1.2$ (with the inclusion of the blackbody) or $\Gamma \sim 1.5$ – 1.6 (in the single power law model). The flux is $\sim 20\%$ lower than the pre-flare value, but still significantly higher than the historical flux level of $\sim 1.3 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$. Another difference with respect to the pre-flare properties is the smaller pulsed fraction (which changed from about 10% to 3%) and the pulse profile is now double peaked.

The post-flare evolution of SGR 1806–20 shows both similarities and differences when compared to that of SGR 1900+14, the only other case in which good spectral X-ray data have been collected after a giant flare. Even though the SGR 1806–20 giant flare was two orders of magnitude more energetic than that of SGR 1900+14 (and of SGR 0526–66 as well), it was followed by a very rapid decay of the X-ray luminosity. We find that the source flux has dropped below the pre-flare level after about one month, much faster than what observed after SGR 1900+14 giant flare. However in both cases this flux decrease was accompanied by a spectral softening (Woods et al. 1999; Rea et al. 2005a). This suggests that the post-flare

softening, a feature common to both sources, might be unrelated to the flare energetics and the decay rate of the X-ray flux after the flare.

5 DISCUSSION

In the recently proposed “twisted magnetosphere” model (Thompson, Lyutikov & Kulkarni 2002), it has been suggested that the internal magnetic field of a magnetar has a strong toroidal component, which can be comparable to the poloidal one. The presence of an internal twist exerts a Lorentz force on the highly conducting crust material. The net effect is to induce a rotation on the polar regions of the crust which is contrasted by the crustal rigidity. Although the crust may adjust quasi-plastically to the imparted stresses, from time to time it cracks and these multiple, small-scale fractures give rise to the shaking of the external field lines and the onset of short bursts while bigger cracks can produce giant flares. The progressive displacement of part of the crust produces a global twist of the external field and currents start to flow in the magnetosphere. Charged particles develop a large optical depth to resonant cyclotron scattering and returning currents hit the star surface heating it up. Both the emitted luminosity and the depth increase with the twist angle. Thermal photons emitted by the surface undergo resonant scattering in the magnetosphere and, since the spectral hardness increase with depth, the steady X-ray flux is expected to correlate with the power-law index. This implies that following such an episode, a decrease of the flux and a softening of the spectrum is expected.

The main observational consequences of a magnetospheric untwisting, namely a decrease in the X-ray flux, a softening of the spectrum and a decrease of the pulsed fraction appear to be present in the X-ray post-flare observations.

Since this work was presented we continued to monitor the decay of the persistent X-ray emission of SGR 1806–20 with XMM-Newton (Tiengo et al. 2005; Rea et al. 2005b). Consistently with the twisted magnetosphere scenario, the source is still decreasing in flux and correlatedly softening.

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