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Letter to the Editor

The calm after the storm: *XMM-Newton* observation of SGR 1806–20 two months after the Giant Flare of 2004 December 27⋆

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Abstract. *XMM-Newton* observed the soft gamma repeater SGR 1806–20 about two months after its 2004 December 27 giant flare. A comparison with the previous observations taken with the same instrument in 2003–2004 shows that the pulsed fraction and the spin-down rate have significantly decreased and that the spectrum slightly softened. These changes may indicate a global reconfiguration of the neutron star magnetosphere. The spectral analysis confirms that the presence of a blackbody component in addition to the power-law is required. Since this additional component is consistent with being constant with respect to the earlier observations, we explore the possibility of describing the long-term spectral evolution as only due to the power-law variations. In this case, the slope of the power-law does not significantly change and the spectral softening following the giant flare is caused by the increase of the relative contribution of the blackbody over the power-law component.

Key words. stars: individual: SGR 1806–20 – X-rays: stars

1. Introduction

On 2004 December 27 most of the X-ray and γ–ray satellite instruments were saturated by the brightest extra-solar event ever recorded (Borkowski et al. 2004; Hurley et al. 2005; Palmer et al. 2005a; Terasawa et al. 2005). Its initial ~0.2 s long spike was bright enough to cause significant perturbation in the Earth's ionosphere (Campbell et al. 2005) and to be detected also through its reflection on the Moon's surface (Mazets et al. 2005; Mereghetti et al. 2005a). The presence of a pulsating tail modulated at the spin period of the Soft Gamma Repeater (SGR) SGR 1806–20 allowed it to be identified as a giant flare from this source, in analogy to similar (but less energetic) events registered from SGR 0526–66 and SGR 1900+14 on 1979 March 5 (Mazets et al. 1979) and 1998 August 27 (Hurley et al. 1999), respectively. Giant flares are the most spectacular manifestations of a small class of young neutron stars which are thought to be magnetars. A magnetar is a neutron star with a very strong magnetic field ($B \sim 10^{14}$–10^{15} G), whose decay powers its high energy emission (Duncan & Thompson 1992; Paczynski 1992; Thompson & Duncan 1995). Apart from the very rare giant flares, SGRs frequently emit short (~0.1 s) bursts of soft γ-rays and are persistent sources of X-rays. This emission is pulsed, and the periods (in the ~5–10 s range) steadily increase at a rate of $\sim 10^{-10}$–10^{-11} s s^{-1}. These properties are shared with the Anomalous X-ray Pulsars (AXPs), which are also thought to be magnetars (Thompson & Duncan 1996, see Woods & Thompson 2004 for a recent review).

Here we present the results of an *XMM-Newton* target of opportunity observation of SGR 1806–20, the first one performed with this satellite after the giant flare.

2. Observation and data analysis

Due to visibility constraints, *XMM-Newton* could not observe SGR 1806–20 before March 2005. The observation was performed on 2005 March 7 and had a duration of 25 ks. An instrumental configuration similar to the previous observations of this source (Mereghetti et al. 2005b) was kept: the EPIC PN (Strüder et al. 2001) was operated in Small Window mode (time resolution 6 ms) while the EPIC MOS (Turner et al. 2001) had the MOS1 unit in Timing mode (time resolution 1.5 ms) and

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the MOS2 in Full Frame mode (time resolution 2.6 s). Both the PN and MOS mounted the medium thickness filter.

The data were processed using Version 6.1.0 of the *XMM-Newton Science Analysis System* (SAS) and the most recent calibration files (last update on 2005 May 14).

The MOS2 data allowed us to search for extended emission over the whole field of view (15′ radius), but apart from a bright point source at the position of SGR 1806–20 and a couple of weaker point sources, no other X-ray emitting structures were detected through a visual check of images in different energy bands. Given the huge flux of X-ray photons emitted during the giant flare and the large amount of dust very likely present along the line of sight, a dust scattering echo might be expected in X-ray observations following the giant flare (see e.g. Vaughan et al. 2004). However, at these late times, independent on the dust spatial distribution and composition, the scattering angle would be >20′ if single scattering occurs, and the efficiency for X-ray scattering at these large angles is very small (Draine 2003). The probability of multiple scattering at smaller angles is also rather small and therefore no information can be obtained from the lack of an X–ray dust echo of the SGR 1806–20 giant flare.

In the following we report the results of the timing and spectral analysis of the PN data. A similar analysis was performed also on MOS data giving consistent results.

The time of arrival of the detected events were corrected to the Solar System barycenter and the source and background photons (events with pattern 0–4) were extracted from circular regions of 40″ radius. The careful analysis of the source and background lightcurve led to the discovery of two weak bursts (∼10 counts each) of the duration of ∼0.1 s.

From folding and phase fitting analysis of the source lightcurve, a spin period of 7.5604 ± 0.0008 s was measured. The background subtracted pulse profile in the 2–10 keV energy band is shown in Fig. 1 together with those of the previous *XMM-Newton* observations (Mereghetti et al. 2005b). Being extracted from the same instrument and regions, these profiles can be directly compared: the average count rate is lower than in 2004 but still higher than in 2003. A sinusoidal fit to the profile gives a pulsed fraction of (3.8 ± 1.1)%, significantly smaller than the ∼10% value previously observed.

The source spectrum was extracted from a circle of 25″ radius and the background spectrum from composite regions located on the same chip as the source. We selected events with patterns 0–4 and excluded time intervals with high particle background, obtaining a net exposure time of 14.7 ks. The spectrum was rebinned to have at least 30 counts in each energy bin and not to oversample the instrumental energy resolution. The fits were performed in the energy range 1.5–12.0 keV, since the source is heavily absorbed and only few counts are detected at lower energies.

A fit with an absorbed power-law gives an unacceptable χ^2 value, while a good fit can be obtained by adding a blackbody component (see Table 1). In order to study the spectral evolution of SGR 1806–20 after the giant flare, we have reprocessed also the data of the previous *XMM-Newton* observations using the most recent calibration files and extracted the PN spectra similarly to what reported in Mereghetti et al. (2005b). Then we fitted simultaneously the five spectra with the power-law plus blackbody model keeping most of the parameters linked to common values. A very good fit was obtained allowing only the power-law photon index and normalization to vary independently (see Table 1). The long term evolution of the power-law parameters derived from this simultaneous fit is shown in Fig. 2, while the very small contribution of the fixed blackbody to the observed flux of SGR 1806–20 is indicated in Fig. 1.

3. Discussion

The new data obtained after the giant flare of 2004 December 27 show significant differences with respect to the previous *XMM-Newton* observations. During the four observations performed from April 2003 to October 2004, SGR 1806–20 had an almost constant pulsed fraction of ∼10% (Mereghetti et al. 2005b), while 70 days after the giant flare it had decreased to ∼4%. This was already noted in the *Chandra* observation of 2005 February 8 (Rea et al. 2005), and is now confirmed with higher confidence and by the direct comparison of pulsed profiles obtained from the same instrument (see Fig. 1). The lower value of the pulsed fraction appears therefore to be a long lasting consequence of the giant flare and must be taken into account when comparing the pulsed fluxes seen by *Rossi*XTE (Woods et al. 2005) with the total fluxes measured by imaging satellites.

Also the spin-down trend of SGR 1806–20 appears to have changed after the flare: the four spin periods measured by *XMM-Newton* in 2003–2004 could be linearly fit with $\dot{P} \simeq 5.5 \times 10^{-10}$ s s^{-1}, but the period found in this last observation is smaller than the extrapolation of this trend. It is instead consistent with the slower spin-down rate $\dot{P} \simeq 1.8 \times 10^{-10}$ s s^{-1}, measured during the first *Rossi*XTE observations performed after the giant flare (Woods et al. 2005). Together with the change in pulsed fraction, this result suggests that a substantial reconfiguration of the magnetosphere has occurred, very likely related to the large amount of energy released on 2004 December 27. In the model of magnetar's twisted magnetosphere (Thompson et al. 2002) such a large scale modification is foreseen after a giant flare, since the magnetosphere should relax into a less twisted configuration. As a consequence, the bursting activity should decrease and the spectrum should become softer. Only two bursts are detected by the PN in the ∼25 ks observation done after the flare, while in 2004 almost 70 bursts were detected in ∼70 ks, with the PN in the same configuration. Therefore, the burst activity had indeed dropped, as already reported in Rea et al. (2005), but not completely stopped (see also, e.g., Palmer el al. 2005b; Golenetskii et al. 2005). Also, the spectral softening is confirmed by the power-law fit of the PN spectrum. However, the high quality PN data allow us to establish that the SGR 1806–20 spectrum is not compatible with a simple power-law model. As already found in pre-flare data (Mereghetti et al. 2005b), the addition of a blackbody component gives a better fit. Since the present data do not show any significant time variability of the blackbody parameters, we have decided to study the spectral variability of SGR 1806–20 assuming that the blackbody does not vary with time. The results of this analysis are shown in Fig. 2: the flux of the power-law component increased steadily in the pre-flare

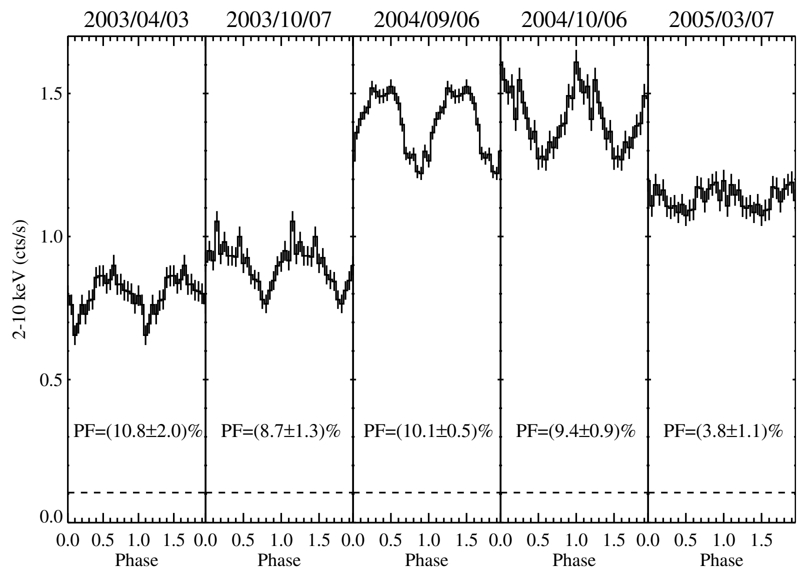

Fig. 1. Background subtracted pulse profiles in the 2–10 keV energy range of SGR 1806–20 as seen by the PN camera during the five *XMM-Newton* observations (the dates of the observations are reported at the top of each panel). The dashed line shows the blackbody contribution to the phase averaged count rate when the source spectrum is fitted using an absorbed power-law plus blackbody, with the absorption and blackbody parameters linked to the same value during the five observations (last line in Table 1). The pulsed fractions (PF) computed from a sinusoidal fit of the profiles are also indicated.

Table 1. Results of spectral analysis. Errors are at the 90% c.l. for a single interesting parameter.

N_H (10^{22} cm^{-2})	Γ	kT_{BB} (keV)	R_{BB} (km)$^{(a)}$	2–10 keV flux (erg cm^{-2} s^{-1})	χ^2_{red} (d.o.f.)
$6.8^{+0.4}_{-0.1}$	$1.68^{+0.10}_{-0.04}$	—	—	1.91×10^{-11}	1.49 (72)
6.0 ± 0.2	$0.8^{+0.2}_{-0.3}$	$0.91^{+0.14}_{-0.05}$	$1.9^{+0.2}_{-0.3}$	1.92×10^{-11}	1.02 (70)
$6.6 \pm 0.2^{(b)}$	$1.42^{+0.08(b)}_{-0.07}$	$0.69^{+0.06(b)}_{-0.07}$	$2.1^{+0.5(b)}_{-0.9}$	$1.93 \times 10^{-11(b)}$	$0.96\ (358)^{(b)}$

[a] Radius at infinity assuming a distance of 15 kpc.
[b] Simultaneous fit to the five *XMM-Newton* observations with only the power-law photon index and normalization free to vary independently.

observations, when the spin-down rate was very fast and the bursting activity became higher and higher, but after the giant flare it dropped down to a level intermediate between those observed in September–October 2004 and in 2003. In contrast, the power-law photon index showed only a mild evolution with time that does not appear to be directly related to source activity. Therefore, if a constant blackbody component is introduced in the spectral model, the overall softening visible by the comparison of single power-law fits of the spectra before and after the flare appears to be caused by the power-law intensity and not by a variation of the photon index. This result does not fit well in the scenario of the twisted magnetosphere relaxing after the giant flare, since the reduction of the twist angle should cause a decrease of the scattering depth and consequently increase the power-law slope, if the primary radiation does not vary.

An alternative interpretation of the observed spectra can be given without the working hypothesis that the blackbody has not varied with time. Comparing the parameters of the best fit to the post-flare spectrum alone with those of the previous *XMM-Newton* observations (Mereghetti et al. 2005b), an increase in the blackbody temperature and a decrease of the photon index emerge. This might mean that 70 days after the giant flare, the magnetar surface (or part of it) is hotter, as shown by the higher blackbody temperature, but also by the harder power-law, which might be produced by the scattering of harder seed photons[1] Also in this case, the overall spectral softening would be caused by the larger relative contribution of the blackbody component to the X-ray spectrum, both due to the increased blackbody temperature (and almost constant emitting area) and the lower power-law flux.

The only other SGR that has been studied in detail after a giant flare is SGR 1900+14 (Kouveliotou et al. 1999; Woods et al. 2001). *Rossi*XTE was able to observe it rather frequently in the weeks following the August 1998 giant flare, while the only observations performed with imaging satellites in that period were done by *Beppo*SAX and *ASCA* ~20 days after the giant flare. In these observations, SGR 1900+14 was brighter and had a softer spectrum than during the last

[1] In this case, the hardening of the primary spectrum should dominate over the steepening caused by the reduced scattering probability, possibly induced by the untwisting of the magnetosphere.

Letter to the Editor

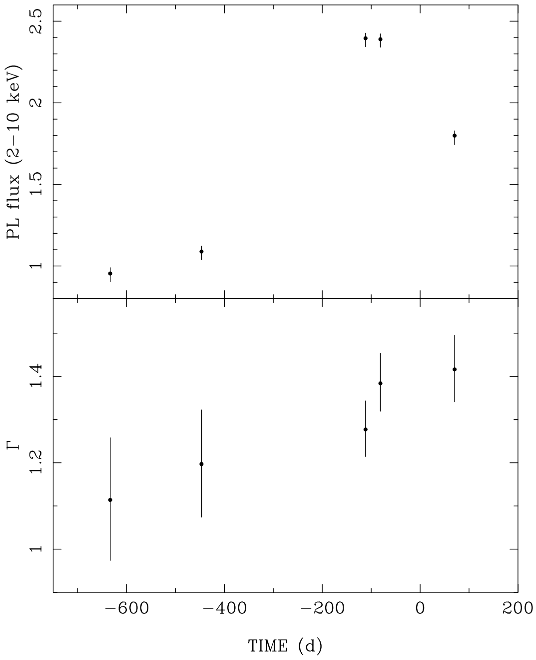

Fig. 2. Flux of the power-law component (in units of 10^{-11} erg cm^{-2} s^{-1}) and power-law photon index during the five *XMM-Newton* observations. The source spectra are fit simultaneously using an absorbed power-law plus blackbody with only the power-law parameters free to vary independently during the five observations. The origin of the time axis corresponds to the giant flare of 2004 December 27.

observations before the giant flare (Woods et al. 1999; Murakami et al. 1999). In the *Beppo*SAX spectrum, a blackbody with parameters consistent with pre-flare values was also detected (Woods et al. 1999). A hotter but rapidly cooling blackbody was instead observed immediately after a less intense flare of SGR 1900+14 in April 2001 (Lenters et al. 2003) and during a period of bursting activity of the AXP 1E 2259+586 (Woods et al. 2004); in the latter case, the blackbody had already returned to its quiescent temperature one day after the event, but for the much more energetic giant flares, longer cooling times might be expected if they caused crustal heating (Lyubarsky et al. 2002). Although the blackbody temperatures measured by *Beppo*SAX 20 days after the giant flare of SGR 1900+14 and by *XMM-Newton* 70 days after the much brighter flare of SGR 1806–20 are compatible with the quiescent values, they have rather large errors and in both cases their best-fit values are slightly higher than in the quiescent observations.

As already mentioned, *Chandra* observed SGR 1806–20 43 days after the flare and measured a total flux[2] ~15% higher than in the later *XMM-Newton* observation, which might mean that a decaying afterglow is still contributing to the SGR 1806–20 persistent flux at least one month after the huge event of 2004 December 27. However these data are too sparse to establish whether this variability is caused by a decaying afterglow or is related to its normal activity. As a comparison, the pulsed flux of SGR 1900+14 measured by *Rossi*XTE stayed at a level higher than usual for more than one year after the flare of 1998 August 27, but also in that case, the simultaneous presence of moderate bursting activity made the interpretation of this enhanced flux uncertain (Woods et al. 2001). Therefore, the possibility that part of the energy released in a giant flare can be stored for a long time in the magnetar crust and then gradually emitted as thermal radiation cannot be discarded by the present data; only high quality spectra taken a few days after a giant flare can settle this issue.

[2] Note that no blackbody component was detected in the *Chandra* spectrum. However, the data are consistent with the presence of a blackbody with the same parameters as in the *XMM-Newton* spectra (Rea et al. 2005), which have better statistical quality.

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