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Hard X-ray emission from magnetars

A case study for Simbol-X

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Abstract. The magnetar model involves an isolated neutron star with a very high magnetic field ($B \sim 10^{14-15}$ G), and is invoked to explain the emission processes of two classes of sources, the Anomalous X-ray Pulsars (AXPs) and the Soft Gamma-Ray Repeaters (SGRs). Five of them have been recently identified to be persistent sources in the hard X-ray band (20–200 keV). AXPs, in particular, present the hardest known persistent spectra in the hard X/soft γ-ray energy range. The broad band modeling of their spectra still suffers from the non-simultaneity of the observations and from a lack of sensitivity above 20 keV. We present the Simbol X simulated observations of these objects and show that that this mission could surely help to disentangle the contribution of the different spectral components, and to understand how they contribute to the secular flux variations observed in these sources.

Key words. Stars: neutron – Stars: X-rays – gamma rays: observations

1. Introduction

Most of the known neutron stars (NSs) are either isolated rotation powered pulsars, or accretion powered neutron stars hosted in binary systems. A dozen (plus a few candidates) of sources, dubbed magnetars, do not fit in either of these categories, since their dominant source of energy is believed to be the magnetic one. In fact, in the magnetar model (Duncan & Thompson 1992) it is the decay of the huge magnetic field ($B \sim 10^{14-15}$ G) of isolated neutron stars that powers their electromagnetic emission.

Magnetars are historically divided in two categories, due to the fact that they were discovered in different ways. We will briefly summarize their properties here. For a complete review of this kind of objects see Woods & Thompson (2006).

1.1. Soft Gamma-Ray Repeaters

SGRs were originally identified in the late '70s a subclass of Gamma Ray Bursts, due to the fact that these bursts had softer spectra and originated repeatingly from fixed positions across the sky. Four confirmed SGRs are known to date, three of them (1806–20, 1900+14, and 1627–41) are located in our Galaxy at several kpc, while one, 0525–66, is located in the Large Magellanic Cloud. They sporadically emit short ($\sim$0.1 s) and bright (L$\sim 10^{39}$-10^{42} ergs s^{-1}) bursts of soft gamma-ray radiation during active periods, alternat-

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ing with quiescent periods that can last several years. In rare occasions they emit so-called *giant flares*, which are characterized by very brights spikes (L~ 10^{44}-10^{46} ergs) lasting a fraction of a second, followed by a pulsating tail lasting a few hundred seconds. Up to know three out of four SGRs have emitted a giant flare, and the pulsations found in their tails pushed forward the idea that these objects were associated with neutron stars, with an extremely high magnetic field. In fact, the energy required to confine a fireball for the duration of the giant flare pulsating tail strongly points towards a magnetic field of the order of 10^{15} G.

Three of the confirmed SGRs have quiescent pulsating X-ray counterparts for which the period and its derivative could be measured. Assuming that this radiation is due to magnetic braking in a dipolar surface magnetic field, these values confirm the high magnetic field, and the absence of Doppler modulations in the observed light curves exclude the presence of companion stars.

1.2. Anomalous X-ray Pulsars

AXPs have been originally identified as a class due to their common X-ray and timing properties (Mereghetti & Stella 1995). Their rotational periods cluster in the 5-12 s range, their period derivatives in the 0.05-4×10^{-11} s s^{-1}. Their X-ray luminosity is $L_X \sim 10^{34-36}$ erg s^{-1} . From their timing porterties one can derive the dipole magnetic field at the surface of the NS as follows,

$$B = \left(\frac{3Ic^3 P\dot{P}}{2\pi^2 R^6}\right) \simeq 3.2 \times 10^{19} (P\dot{P})^{1/2} \text{ G}, \qquad (1)$$

where I ($\simeq 10^{45}$g cm^2) is the NS moment of inertia, and R ($\simeq 10^6$ cm) is the NS radius. The derived field values for AXPs exceed the quantum critical value of $B_Q \equiv m_e^2 c^3/(e\hbar) = 4.4 \times 10^{13}$ G. This fact together with the lack of an observable companion star and with the fact that L_X largely exceeds the rotational energy loss ($I\omega\dot{\omega}$), points towards the inclusion of the AXPs in the magnetar class. In addition the detection of Soft Gamma-Ray Repeater-like bursts from five AXPs (e.g. Gavriil et al. 2002) has strengthened the association between these objects and the SGRs.

2. INTEGRAL Results

The soft X-ray spectra of AXPs and SGRs are generally well described by a two component model, made of a black body with $kT \sim$ 0.4–0.5 keV, and a steep power law, with photon index $2 \leq \Gamma \leq 4$. Being their spectra below ~10 keV rather soft, the first detections above 20 keV of very hard high-energy tails associated with these objects came as a surprise (Kuiper et al. 2006; den Hartog et al. 2006; Revnivtsev et al. 2004; Mereghetti et al. 2005a; Molkov et al. 2005; Götz et al. 2006). These discoveries were possible thanks to unprecedented sensitivity of the IBIS/ISGRI imager (Ubertini et al. 2003; Lebrun et al. 2003) on board the *INTEGRAL* satellite (Winkler et al. 2003). It results that AXP spectra flatten ($\Gamma \sim 1$) above 20 keV (and the pulsed fraction of some of them reaches up to 100% (Kuiper et al. 2006)), while SGR spectra steepen at hard X-rays, as is illustrated in Fig. 1.

The discovery of these hard tails provides new constraints on the emission models for these objects since their luminosities might well be dominated by hard, rather than soft, X-rays. In fact, quite recently, Thompson & Belobodorov (2005) discussed how soft gamma-rays may be produced in a twisted magnetosphere, proposing two different scenarios: either thermal bremsstrahlung emission from the surface region heated by returning currents, or synchrotron emission from pairs created higher up (~ 100 km) in the magnetosphere. While both scenarios predict a power-law-like spectral distribution for the 20-100 keV photons, the cut-offs of the high energy emission are markedly different in the two cases, 100 keV vs. 1 MeV. A third scenario involving resonant magnetic Compton up-scattering of soft X-ray photons by a non-thermal population of highly relativistic electrons has been proposed by Baring & Harding (2007).

While at soft X-rays AXPs and SGRs have shown to be variable objects, as far as timing

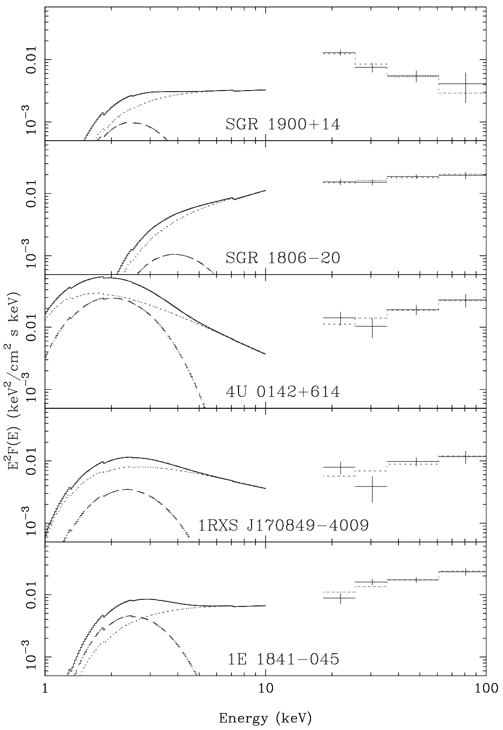

Fig. 1. Broad band X–ray spectra of the five magnetars detected by *INTEGRAL* . The data points above 18 keV are the *INTEGRAL* spectra with their best fit power-law models (dotted lines). The solid lines below 10 keV represent the absorbed power-law (dotted lines) plus blackbody (dashed lines) models taken from the literature. See Götz et al. (2006) and references therein for details.

and spectral properties are concerned, at hard X-rays the study of these characteristics is limited by the long integration times required in order to detect them with the current instrumentation. Nevertheless, some degree of variability in the hard X-ray emission of SGRs has been reported recently by different authors. Mereghetti et al. (2005a) report, besides clear flux variations, a possible spectral hardening of SGR 1806–20 as a function of its bursting activity (see Fig. 2). Similar results have been obtained by Esposito et al. (2006), who compared the broad band persistent spectrum of SGR 1900+14 measured with *Beppo*SAX in 1997 during a period of intense bursting activity with the one taken with IBIS/ISGRI six years later, during a phase of quiescence (see Fig. 3). The latter represents for the time being the most convincing evidence of spectral variability in an SGR hard tail.

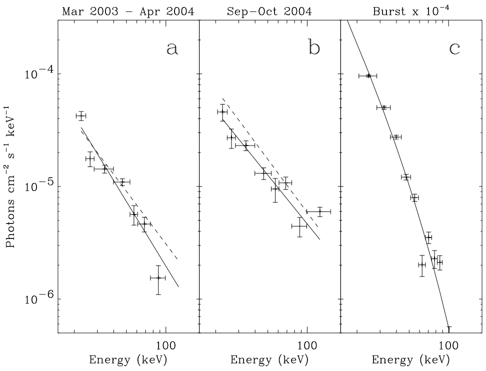

Fig. 2. IBIS/ISGRI spectra of SGR 1806–20. a) persistent emission March 2003-April 2004, b) persistent emission September-October 2004, c) one burst (scaled down by a factor 10^4). The solid lines are the best fits (power laws in a) and b), thermal bremsstrahlung in c)). The dashed lines indicate the extrapolation of power-law spectra measured in the 1–10 keV band with *XMM-Newton* Mereghetti et al. (2005b). From Mereghetti et al. (2005a).

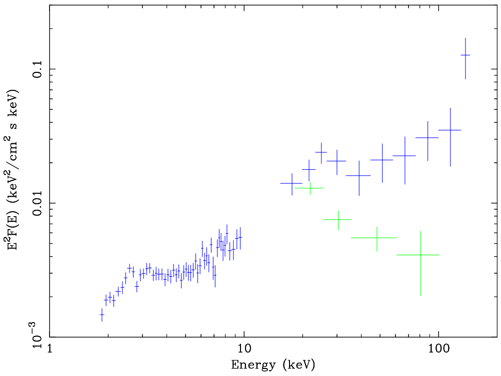

Fig. 3. Blue points: broad band spectrum of SGR 1900+14 taken on 1997 May 12 (observation A) with *BeppoSAX* (both MECS and PDS data). Green points: *INTEGRAL* data from March 2003 to June 2004. From Esposito et al. (2006)

3. Simbol-X Simulations

As mentioned above, the limited sensitivity of the current instrumentation does not allow us to study simultaneously the broad band spectra of magnetars. In fact, while at soft X-rays a 50 ks observation using focusing telescopes like *XMM* and *Chandra* are sufficient to derive precise spectral and timing characteristics, above 20 keV IBIS/ISGRI, the most sensitive instrument in this energy range nowadays, requires at least 500 ks to derive a useful spectrum, often still with large uncertainties. In addition due to the mission constraints the observation has to be split over several months. In these conditions it is clear that it is difficult to speak of *simultaneous* broad band spectra. This is a severe limitation to any sensible spectral modeling: for instance the three components identified in the AXPs spectra, the black body, the low-energy power law and the high energy one seem for the time being completely independent spectral components. In particular very little known concerning the transition region between 10 and 20 keV where no data is actually available. This gap, together with the unavoidable uncertainties in the inter-calibration of the different instruments increases our difficulties in deriving a physical model of the source that accounts simultaneously for the three components, and explains what is the physical driver of the measured spectral and flux variations.

Stimulated by these issues I tried to figure out if Simbol-X (Ferrando et al. 2007) could contribute to disentangle some of these aspects. This was done through some simulated observations performed with the *xspec* package, and following the recipes provided for this workshop by Jean Luc Sauvageot. The simulations included the low energy layer MPD (Marco Pixel Detector) and the high energy CZT, in a 20 m focal length configuration and 12 arcmin field of view with a 18 arcsec point spread function at 30 keV. For the background estimation the contributions of the diffuse X-ray background, the local bubble, and the cosmic rays interactions (the detectors are actively and passively shielded) have been taken into account.

3.1. 1RXS J170849.0–400910

1RXS J170849.0–400910 is one of the persistent AXPs that shows the largest degree of variability in its spectral parameters (see e.g Campana et al. 2007). I wanted to estimate the observation time needed in order to carefully characterize the spectral components of this AXP with Simbol-X. In order to do this I simulated a spectrum made of the sum of an absorbed black body and a broken power-law changing its slope from 2.8 to 1.5 at 15 keV. Such a sharp break may not be physical but is consistent with the available spectral data. From Fig. 4 one can see that in just 10 ks of observation time one can get a fairly good spectrum. In the figure I show the fit using an absorbed black body and a single power law. The fit is unacceptable ($\chi^2_r \sim 2$), and the break is clearly detected in the residuals at 15 keV.

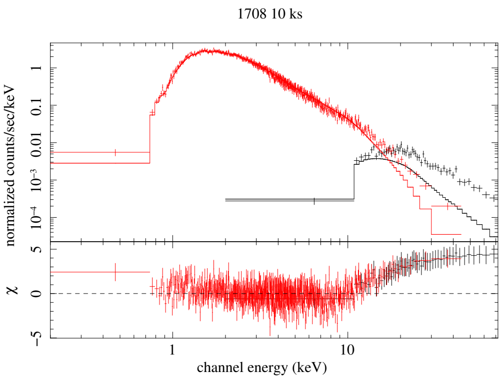

Fig. 4. 10 ks simulated Simbol X observation of 1RXS J170849.0–400910. The upper panel shows the model and the data while the lower panel shows the residuals with respect to the model. The data have been fitted with the model derived from soft X-ray data only.

This shows that even with a relatively short observation we can derive a good broad band spectrum with Simbol-X, and that we will be able to monitor the spectral changes of these sources on a time scale that is not accessible with the current instrumentation.

3.2. SGR 1806–20

For SGRs, and for SGR 1806–20 in particular, the presence of a spectral break around 15 keV is not settled yet. The available data suffer from non-simultaneity and inter-calibration uncertainties. As a working hypothesis I assumed a spectrum made again of an absorbed black body plus a broken power law, but this time the black body component is much fainter, as observed in this source by *XMM* (Mereghetti et al. 2005b), and the slope changes from 1.2 to 1.8 at 15 keV.

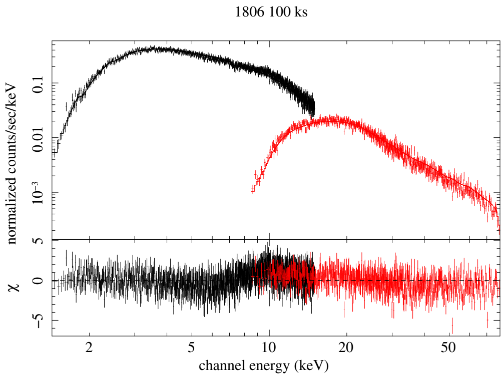

Fig. 5. 100 ks simulated Simbol X observation of SGR 1806–20. The upper panel shows the model and the data while the lower panel shows the residuals with respect to the model. The data have been fitted with a single power-law.

As can be seen from Fig. 5, where a fit using a single absorbed power law is shown, 100 ks at least are necessary to detect the spectral break (the χ^2_r increases from 1.21 to 1.03 if a break is included). The black body component, on the other hand, is not statistically needed. This is not surprising since the first detection of this component has been obtained with a 50 ks long *XMM*/pn exposure, and the latter is still 4-5 times more sensitive than Simbol-X at 2 keV, where the black body component is most prominent.

Increasing the exposure time to 1 Ms, see Fig. 6, both the spectral break and the black body component are evident if one looks at the residuals of the fit with a single absorbed power law. In fact the single power law fit is statistically not acceptable, yielding a χ^2_r of 3.3, which than decreases to 1.6 including a break and finally to 1.02 if one includes the black body.

This shows us that with reasonable exposure times Simbol-X will provide us for the first time with a good quality spectrum for the SGRs as well as for AXPs.

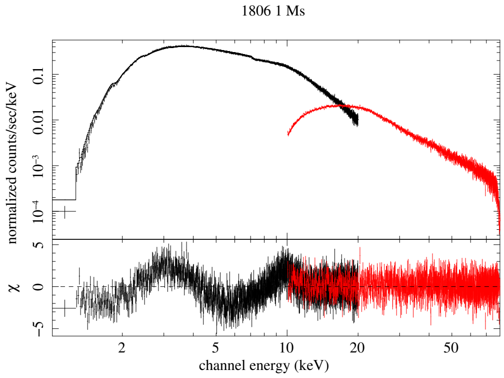

Fig. 6. 1Ms simulated Simbol X observation of SGR 1806–20. The upper panel shows the model and the data while the lower panel shows the residuals with respect to the model. The data have been fitted with a single power law.

4. Conclusions

One of the major issues today in the magnetar's field is that no clear physical model has been developed yet, in order to explain the broad band spectrum of AXPs and SGRs. An important reason for this is that with the current instrumentation it is not possible to obtain good quality broad band (0.1–200 keV) spectra. For every astrophysical object the broad band coverage is nowadays an important issue, but the unexpected discovery of very hard tails in AXPs is a unique feature, and deserves particular attention in this sense.

We have shown that with Simbol-X we will be able to monitor for the first time all the spectral components of these variable objects at once. In particular we will be able to pinpoint the differences between AXPs and SGRs, that before the IBIS/ISGRI hard X-ray observations looked very similar for what concerns their persistent emission. We will also be able to understand what is the driver of spectral changes in magnetars, i.e. if the changes below 10 keV are in reality caused by the variation of an underlying high-energy component.

Concerning the timing, pulsations in the hard X-ray band have been detected for a few AXPs and possibly for SGR 1806–20 (Götz et al., 2007, in preparation). Their detection needs long integration times, and the combination of different instruments on different satellites, which introduces unavoidable uncertainties in the estimation of the pulsed fraction. Simbol -X, being a focusing telescope with low background at hard X-rays, will surely reduce by an order of magnitude our uncertainties and the exposure times required. In addition it will allow us to do broad band phase resolved spectroscopy.

The detection of resonant cyclotron absorption lines would be the direct confirmation of the presence of a huge magnetic field in magnetars. Up to now, despite the deep searches below 10 keV, no firm detection of these features has been reported. One interesting feature around 6–15 keV has been reported by Iwasawa et al. (1992) using *Ginga* data, during the outburst of the AXP 1E 2259+586. Being this feature close to the upper energy boundary of the instrument, its detection is questionable. Simbol-X could clearly settle an issue like that.

A few of the AXPs are transients: this is a new subclass of magnetars that undergo large outbursts lasting years where their flux changes by more than 3 orders of magnitude (e.g. Israel et al. 2007). The mechanisms of these long outbursts is not known, and in addition due to several constraints, these sources could not be observed efficiently during their outbursts with hard X-ray telescopes. Such an outburst (but also the quiescent phase) observed at hard X-rays with Simbol-X could surely help to shed some light of the mechanisms that drive these long lived outbursts.

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References

Baring, M.,G., & Harding, A.K. 2007, Ap&SS, 308, 109
Campana, S., Rea, N., Israel, G.L., et al. 2007, A&A, 463, 1047
Duncan, R., & Thompson, C. 1992, ApJ, 392, L9
Esposito, P., Mereghetti, S., Tiengo, A., et al. 2006, Proceedings of the 363. WE-Heraeus Seminar on: Neutron Stars and Pulsars, astro-ph/0612787
Ferrando, P., et al. 2007, these proceedings
Gavriil, F.P., Kaspi, V.M., & Woods, P.M. 2002, Nature, 419, 142
Götz, D., Mereghetti, S., Tiengo, A., et al. 2006 A&A, 449, L31
den Hartog, P. R., Hermsen, W., Kuiper, L., et al., 2006, A&A, 451, 587
Kuiper, L., Hermsen, W., den Hartog, P. R. et al. 2006, ApJ, 645, 556
Israel G.L., Campana, S., Dall'Osso, S., et al. 2007, ApJ, 664, 448
Iwasawa, K., et al. 1992, PASJ, 44, 9
Lebrun, F., Leray, J.P., Lavocat, P., et al. 2003, A&A, 411, L141
Mereghetti, S., Stella, L. 1995, ApJ, 442, L17
Mereghetti, S. , Götz, D., Mirabel, I.F., et al. 2005a, A&A, 433, L9
Mereghetti, S., Tiengo, A., Esposito, P., et al. 2005b, ApJ, 628, 938
Molkov, S., Hurley, K., Sunyaev, R., et al., 2005, A&A, 433, L13
Revnivtsev, M. G., Sunyaev, R. A., Varshalovich, D. A., et al., 2004 Astronomy Letters, 30, 382
Thompson, C., & Beloborodov, A. M., 2005, ApJ 634, 565
Ubertini, P., Lebrun, F., Di Cocco, G., et al. 2003, A&A 411, L131
Winkler, C., Courvoisier, T.J.-L., Di Cocco G., et al. 2003 A&A, 411, L1
Woods, P. M. & Thompson, C. 2006, in "Compact Stellar X-ray Sources", eds. W.H.G. Lewin and M. van der Klis, Cambridge University Press, 547