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Unveiling Soft Gamma-Ray Repeaters with INTEGRAL

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Abstract Thanks to INTEGRAL's long exposures of the Galactic Plane, the two brightest Soft Gamma-Ray Repeaters, SGR 1806-20 and SGR 1900+14, have been monitored and studied in detail for the first time at hard-X/soft gamma rays.

This has produced a wealth of new scientific results, which we will review here. Since SGR 1806-20 was particularly active during the last two years, more than 300 short bursts have been observed with INTEGRAL and their characteristics have been studied with unprecedented sensitivity in the 15-200 keV range. A hardness-intensity anticorrelation within the bursts has been discovered and the overall Number-Intensity distribution of the bursts has been determined. In addition, a particularly active state, during which 100 bursts were emitted in 10 minutes, has been observed on October 5 2004, indicating that the source activity was rapidly increasing. This eventually led to the Giant Flare of December 27th 2004, for which a possible soft gamma-ray (>80 keV) early afterglow has been detected.

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The deep observations allowed us to discover the persistent emission in hard X-rays (20-150 keV) from 1806-20 and 1900+14, the latter being in a quiescent state, and to directly compare the spectral characteristics of all Magnetars (two SGRs and three Anomalous X-ray Pulsars) detected with INTEGRAL.

Keywords gamma-rays: observations · pulsars: individual SGR 1806-20, SGR 1900+14 · pulsars: general

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1 Introduction

Soft gamma-ray repeaters (SGRs, for a recent review see Woods & Thompson (2003)) are a small group (4–7) of peculiar high-energy sources generally interpreted as “magnetars”, i.e. strongly magnetised ($B \sim 10^{15}$ G), slowly rotating ($P \sim 5-8$ s) neutron stars powered by the decay of the magnetic field energy, rather than by rotation (Duncan & Thompson 1992; Paczynski 1992; Thompson & Duncan 1995). They were discovered through the detection of recurrent short (~ 0.1 s) bursts of high-energy radiation in the tens to \sim hundred keV energy range, with peak luminosity up to $10^{39}-10^{42}$ erg s $^{-1}$, above the Eddington limit for neutron stars. The rate of burst emission in SGRs is highly variable. Bursts are generally emitted during sporadic periods of activity, lasting days to months, followed by long “quiescent” time intervals (up to years or decades) during which no bursts are emitted. Occasionally SGRs emit “giant flares”, that last up to a few hundred seconds and have peak luminosity up to $10^{46}-10^{47}$ erg s $^{-1}$. Only three giant flares have been observed to date, each one from a different source (see, e.g., Mazets et al. (1979a) for 0526-66, Hurley et al. (1999) for 1900+14, Palmer et al. (2005); Mereghetti et al. (2005a); Hurley et al. (2005) for 1806-20).

Persistent (i.e. non-bursting) emission is also observed from SGRs in the soft X-ray range (<10 keV), with a typical luminosity of $\sim 10^{35}$ erg s $^{-1}$, and, in three cases, periodic pulsations with periods of 5 – 8 seconds have

been detected. Such pulsations proved the neutron star nature of SGRs and allowed the derivation of spin-down at rates of $\sim 10^{-10} \text{ s s}^{-1}$, consistent with dipole radiation losses for magnetic fields of the order of $B \sim 10^{14}\text{-}10^{15} \text{ G}$. The X-ray spectra are generally described with absorbed power laws, but in some cases strong evidence has been found for the presence of an additional blackbody-like component with a typical temperature of $\sim 0.5 \text{ keV}$ (Mereghetti et al. 2005b).

Over the last few years the INTEGRAL satellite (Winkler et al. 2003), launched in 2002 and operating in the 15 keV-10 MeV energy range, has provided a wealth of new results concerning the two brightest SGRs, 1806-20 and 1900+14. Most aspects concerning the SGRs, short bursts, giant flares, and persistent emission, have been investigated, and new results have been found for each of them. We will review them here.

2 SGR 1806-20

SGR 1806-20 was discovered by the Interplanetary Network (IPN) in 1979 (Laros et al. 1986). It lies in a crowded region close to the galactic centre. Kouveliotou et al. (1998) discovered a quiescent X-ray pulsating ($P=7.48 \text{ s}$) counterpart, which was spinning down rapidly ($\dot{P}=2.8 \times 10^{-11} \text{ s s}^{-1}$). If this spindown is interpreted as braking by a magnetic dipole field, its strength is $B \sim 10^{15} \text{ G}$. The source activity is variable, alternating between quiet periods and very active ones.

After a period of quiescence, SGR 1806-20 became active in the Summer of 2003 (Hurley et al. 2003). Its activity then increased in 2004 (see e.g. Mereghetti et al. (2004); Golenetskii et al. (2004)). A strong outburst during which about one hundred short bursts were emitted in a few minutes occurred on October 5 2004 (Götz et al. 2006a). Finally a giant flare, whose energy (a few 10^{46} erg) was two orders of magnitude larger than those of the previously recorded flares from SGR 0526-66 and SGR 1900+14, was emitted on December 27th 2004 (see e.g. Palmer et al. (2005); Mereghetti et al. (2005a); Hurley et al. (2005)).

2.1 Short Bursts

The results presented in this Section are based on observations obtained with the IBIS coded mask telescope (Ubertini et al. 2003), and in particular with its low-energy (15 keV-1 MeV) detector ISGRI (Lebrun et al. 2003). More than 400 short bursts have been detected with IBIS/ISGRI. They have been identified either using the triggers provided by the INTEGRAL Burst Alert System (IBAS, Mereghetti et al. (2003)), or by computing light curves with 10 ms time resolution and looking for significant excesses corresponding to the direction of SGR 1806-20.

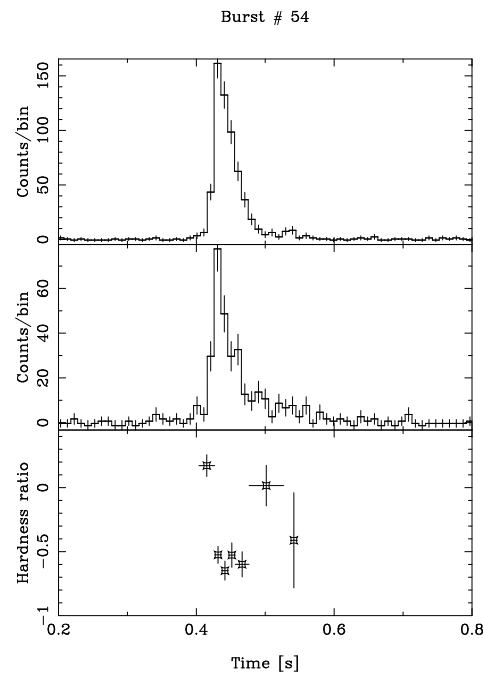


Fig. 1 IBIS/ISGRI light curves in the soft (20-40 keV, upper panel) and hard (40-100 keV, middle panel) energy range and hardness ratio (lower panel) for a short burst from SGR 1806-20.

Spectral Evolution All the bursts detected by IBIS are typical in terms of duration and spectra. The new result provided by the analysis of the INTEGRAL sample is the spectral evolution within the bursts. By computing time resolved hardness ratios, Götz et al. (2004, 2006a) showed that some bursts evolve significantly with time, especially the ones with a Fast Rise Exponential Decay (FRED) profile. The hardness ratios have been computed using the background subtracted light curves in two energy bands (20-40 (S) and 40-100 (H) keV) and were defined as $HR=(H-S)/(H+S)$. It turns out that the bursts' peaks tend to be spectrally softer than the bursts' tails. This behaviour had been reported earlier only for two peculiar bursts originating from SGR 1900+14. These two bursts were quite different from usual bursts, lasting about 1 s and having a very hard spectrum ($kT \sim 100 \text{ keV}$, Woods et al. (1999)). One example of this kind of evolution detected in regular bursts for SGR 1806-20 is shown in Fig. 1.

The spectral behaviour described above gives rise to a global hardness-intensity anti-correlation. In fact, by considering all the individual time bins of all the bursts this anti-correlation within the bursts has been discovered (see Fig. 2). To investigate the statistical robustness of the correlation found, the Spearman rank-order correlation coefficient of the 217 data points, R_s , has been computed, which is -0.49 . This corresponds to a chance probability of 4×10^{-15} (7.4σ) that the distribution is due to uncorrelated data. According to an F-test the data are significantly (8σ) better described by a linear

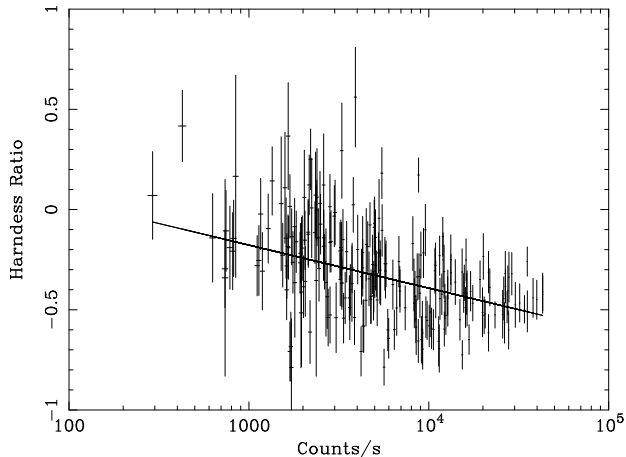


Fig. 2 Hardness ratio $((H-S)/(H+S))$ versus total count rate (20-100 keV, corrected for vignetting). The points are derived from the time resolved hardness ratios of the bursts with the best statistics. The line indicates the best fit with a linear function given in the text. From Götz et al. (2006a).

fit ($HR = 0.47 - 0.22 \times \log I$) than by a constant. This correlation still lacks of a solid theoretical interpretation since the current Magnetar scenario does not provide a clear prediction of the burst spectral evolution with time.

Number-Intensity Distribution We derived the fluences of 224 bursts using the vignetting and dead-time corrected light curves. We applied a conversion factor between counts and physical units derived by the spectral analysis of the brightest bursts and assuming that the averaged burst spectra do not change much between bright and faint bursts; for details see Götz et al. (2006a). These fluences have been used to compute the number-intensity distribution (Log N-Log S) of the bursts. The experimental distribution deviates significantly from a single power-law (Fig. 3). This is first of all due to the fact that the source has been observed at different off-axis angles. The faintest bursts are missed when the source is observed at large off-axis angles. In order to correct for this effect we have computed the effective exposure of the source, taking into account the variation of sensitivity at various off-axis angles. This yields the exposure-corrected cumulative distribution shown by the dashed line in Fig. 3.

Since the numbers at each flux level are not statistically independent, one cannot use a simple χ^2 minimisation approach to fit the cumulative number-intensity distribution. So we have used the unbinned detections and applied the Maximum Likelihood method (Crawford et al. 1970), assuming a single power-law distribution for the number-flux relation ($N(> S) \propto S^{-\alpha}$). We have used only the part of the distribution where completeness was achieved (i.e. $S \geq 3 \times 10^{-8}$ erg cm $^{-2}$). In this case the expression to be maximised is

$$\mathcal{L} = T \ln \alpha - \alpha \sum_i \ln S_i - T \ln(1 - b^{-\alpha}) \quad (1)$$

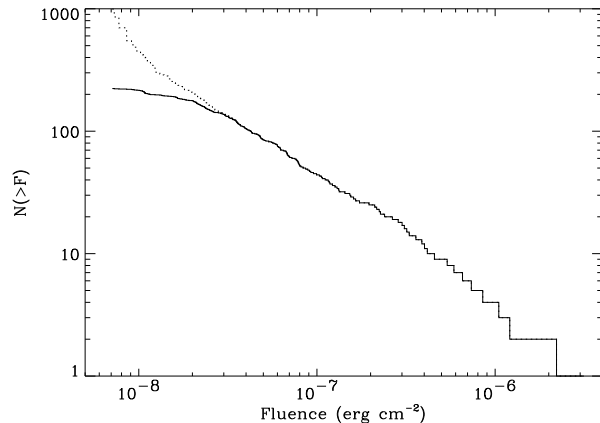


Fig. 3 Number-intensity distribution of all the bursts detected by INTEGRAL in 2003 and 2004. The continuous line represents the experimental data, while the dashed line represents the data corrected for the exposure. From Götz et al. (2006a).

where S_i are the unbinned fluxes, b is the ratio between the maximum and minimum values of the fluxes, and T is the total number of bursts. This method yields $\alpha = 0.91 \pm 0.09$. If a single power-law model is an adequate representation of data, the distribution of the quantities

$$y_i = \frac{1 - S_i^{-\alpha}}{1 - b^{-\alpha}} \quad (2)$$

should be uniform over the range (0,1). In our case, a Kolmogorov-Smirnov (K-S) test shows that a power law is an appropriate model, yielding a probability of 98.8% that the data are well described by our model.

We then divided the bursts into two samples comprising 51 and 173 bursts respectively. The division is based on the periods of different activity of the source: the 51 bursts were detected in 1 year and the 173 in 2.5 months. The two slopes derived with the Maximum Likelihood method are $\alpha = 0.9 \pm 0.2$ for the low level activity period and $\alpha = 0.88 \pm 0.11$ for the high level one. The two slopes are statistically consistent with each other and a K-S test shows that the probability that the two distributions are drawn from the same parent distribution is 93%. Thus we conclude that the relative fraction of bright and faint bursts is not influenced by the level of activity of the source.

The Large Outburst of October 5 2004 On October 5 2004 IBAS triggered at 13:56:49 UT on a series of bursts originating from SGR 1806–20. Detailed analysis of this event showed the presence of more than 100 bursts; the activity ended at 14:08:03 UT. Some bursts were so bright that they saturated the available telemetry share for IBIS, generating some data gaps lasting up to 10-20 s. The initial part of the outburst is shown in Fig. 4

The fluence of the entire outburst as measured by ISGRI is 1.5×10^{-5} erg cm $^{-2}$, with a spectrum which is

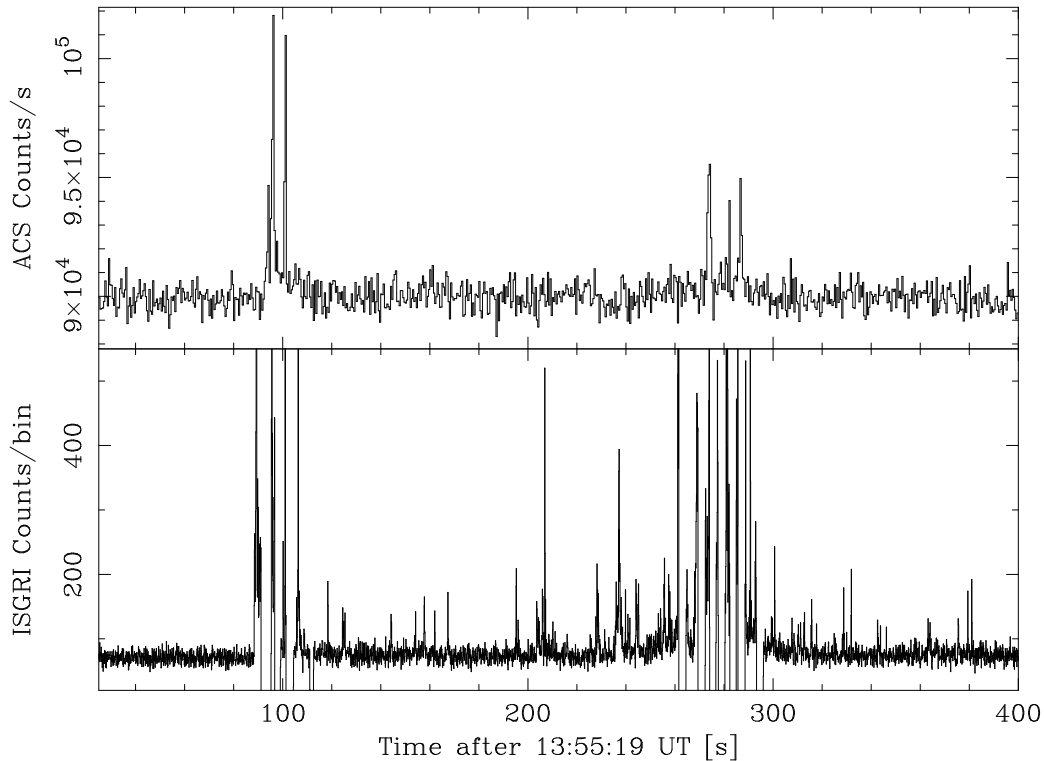


Fig. 4 Light curves of the initial part of the October 5, 2004 outburst of SGR 1806-20. Upper panel: light curve at energy greater than ~ 80 keV obtained with the SPI Anti-Coincidence System in bins of 0.5 s. Bottom panel: light curve in the 15-200 keV energy range obtained with the IBIS/ISGRI instrument (bin size 0.1 s). The gaps in the IBIS/ISGRI light curve are due to saturation of the satellite telemetry. From Götz et al. (2006a).

considerably harder than that of the usual short bursts: $kT=58\pm 2$ keV, using a thermal bremsstrahlung model. This fluence value is however heavily affected by the saturation of the brightest bursts and represents only a lower limit to the real fluence. In order to recover the complete fluence of the event we used the data from the Anticoincidence Shield (ACS) of the INTEGRAL spectrometer SPI (Vedrenne et al. 2003). As can be seen in Fig. 4 (upper panel), only the brightest bursts are visible in these data and hence they represent complementary information to the ISGRI data.

We used the Monte Carlo package MGGPOD (Weidenspointner et al. 2005) and a detailed mass modelling of SPI and the whole satellite (see Weidenspointner et al. (2003) and references therein) to derive the effective area of the ACS for the direction of SGR 1806-20. We computed the ACS light curve with a binsize of 0.5 s and estimated the background by fitting a constant value to all the data of the same pointing excluding the bursts. We used the background subtracted light curve to compute the fluence of each burst cluster in counts. The ACS data do not provide any spectral information, so we computed the conversion factor to physical units based on the spectral shapes derived from ISGRI data and on the effective area computed through our simulations. The resulting fluences above 80 keV are 1.2×10^{-5} and 9.4×10^{-6}

erg cm^{-2} for the first and second clusters respectively. Converting these fluences to the 15-100 keV band one obtains 7.4×10^{-5} and 3.2×10^{-5} erg cm^{-2} respectively. By adding these results to the ones obtained for the ISGRI total spectrum, one can derive the total energy output during the whole event, which is 1.2×10^{-4} erg cm^{-2} . This corresponds to 3.25×10^{42} erg for an assumed distance of 15 kpc (McClure-Griffiths & Gaensler 2005).

These results can be explained in the framework of a recent evolution of the magnetar model, where Lyutikov (2003) explains SGR bursts as generated by loss of magnetic equilibrium in the magnetosphere, in close analogy to solar flares: new current-carrying magnetic flux tubes rise continuously into the magnetosphere, driven by the deformations of the neutron star crust. This in turn generates an increasingly complicated magnetic field structure, which at some point becomes unstable to resistive reconnection. During these reconnection events, some of the magnetic energy carried by the currents associated with the magnetic flux tubes is dissipated. The large event described here can be explained by the simultaneous presence of different active regions (where the flux emergence is especially active) in the magnetosphere of the neutron star. In fact, a long outburst with multiple components is explained as the result of numerous avalanche-type reconnection events, as reconnection at

one point may trigger reconnection at other points. This explains the fact that the outburst seems to be composed by the sum of several short bursts. This kind of event may be correlated with a particularly complicated magnetic field structure. A large part of the energy stored in the magnetosphere has then been released during the giant flare on December 27, when a global restructuring may have taken place. This mode also suggests that short events are due to reconnection, while longer events have in addition a large contribution from the surface, heated by the precipitating particles, and are harder. This may explain the generally harder spectra observed. However more “classical” scenarios involving only crust fracturing with a large-scale shear deformation of the crust involving the collective motion of many small units, without an internal contribution, cannot be ruled out, see e.g. Thompson & Duncan (2001).

The October 5th event fits the trend of increasing source bursting activity shown by SGR 1806–20 in 2003 and 2004. In the same time span also the luminosity and spectral hardness of the persistent emission at high (20–150 keV, see below) and low (2–10 keV, Mereghetti et al. (2005b)) energies increased. On the other hand, this peculiar event did not mark a peak or a turnover in the SGR activity. In fact the two XMM observations of SGR 1806–20 performed just before (September 6 2004) and the day after this large outburst (as a ToO in response to it) yielded similar spectral parameters, fluxes and pulse profiles, and bursts were seen in both observations (Mereghetti et al. 2005b).

Thus events like these release a small (compared to giant flares) fraction of the energy stored in the twisted magnetic field of the neutron star, not allowing the magnetic field to decay significantly. They are rather related to phases of high activity due to large crustal deformations (indicating that a large quantity of energy is still stored in magnetic form) and can be looked at as precursors of a major reconfiguration of the magnetic field.

2.2 The Giant Flare of December 27 2004

A giant flare from SGR 1806–20 was discovered with the INTEGRAL gamma-ray observatory on 2004 December 27 (Borkowski et al. 2004), and detected with many other satellites (e.g. Palmer et al. (2005); Hurley et al. (2005)). The analysis of the SPI-ACS data (>80 keV) of the flare, presented in Mereghetti et al. (2005a), show that the giant flare is composed by an initial spike lasting 0.2 s followed by a ~ 400 s long pulsating tail, modulated at the neutron star period of 7.56 s. The initial spike was so bright that it saturated the ACS, so we could derive only a lower limit on its fluence, which turned out to be two orders of magnitude brighter (10^{46} ergs, see e.g. Terasawa et al. (2005)) than the previously observed giant flares from SGR 1900+14 (Hurley et al. 1999), and SGR 0526–66 (Mazets et al. 1979a). The energy contained in the tail (1.6×10^{44} ergs), on the other

hand, was of the same order as the one in the pulsating tails of the previously observed giant flares.

A ~ 0.2 s long small burst was detected in the ACS data 2.8 s after the initial spike. It is superposed on the pulsating tail and has no clear association with the pulse phase. This burst has been interpreted by Mereghetti et al. (2005a) as the reflection by the Moon of the initial spike of the giant flare. In fact this delay corresponds to the light travel time between INTEGRAL, the Moon, and back. A similar detection was reported with the Helicon-Coronas-F satellite (Mazets et al. 2005).

The most striking feature provided by the INTEGRAL data is the detection of a possible early high-energy afterglow emission associated with the giant flare. At the end of the pulsating tail the count rate increased again, forming a long bump which peaked around $t \sim 700$ s and returned to the pre-flare background level at $t \sim 3000$ – 4000 . This component decays as $\sim t^{-0.85}$, and is shown in blue in Fig. 5, while the overall long term background trend is shown in yellow, and the giant flare itself in red. The association of this emission with SGR 1806–20 is discussed in Mereghetti et al. (2005a). The fluence contained in the 400–4000 s time interval is approximately the same as that in the pulsating tail. With simple gamma-ray burst afterglow models based on synchrotron emission one can derive the bulk Lorentz factor Γ from the time t_0 of the afterglow onset: $\Gamma \sim 15(E/5 \times 10^{43} \text{ ergs})^{1/8}(n/0.1 \text{ cm}^{-3})^{-1/8}(t_0/100)^{-3/8}$, where n is the ambient density. This is consistent with the mildly relativistic outflow inferred from the radio data (Granot et al. 2006).

2.3 Discovery of the persistent emission

In 2005 two groups reported independently the discovery of persistent hard X-ray emission originating from SGR 1806–20 (Mereghetti et al. 2005c; Molkov et al. 2005). Up to then, spectral information on the persistent emission of SGRs was known only below 10 keV. The low energy spectrum is usually well described by the sum of a power law component and a black body.

The spectrum above 20 keV is rather hard with a photon index between 1.5 and 2.0 and extends up to 150 keV without an apparent cutoff. It connects rather well with the low energy (< 10 keV) spectrum (Mereghetti et al. 2005b), and the intensity and spectral hardness are correlated with the degree of bursting activity of the source (Mereghetti et al. 2005c; Götz et al. 2006a) and with the IR flux (Israel et al. 2005). Our group is continuously monitoring the hard X-ray flux of SGR 1806–20, and the long term light curve of the source is shown in Fig. 6. As can be seen, the persistent flux increased in 2003 and 2004 up to the giant flare (which is marked with a vertical line in the plot), and then decreased in 2005.

This behaviour can be interpreted as an increase of the twist angle in the magnetar magnetic field, which

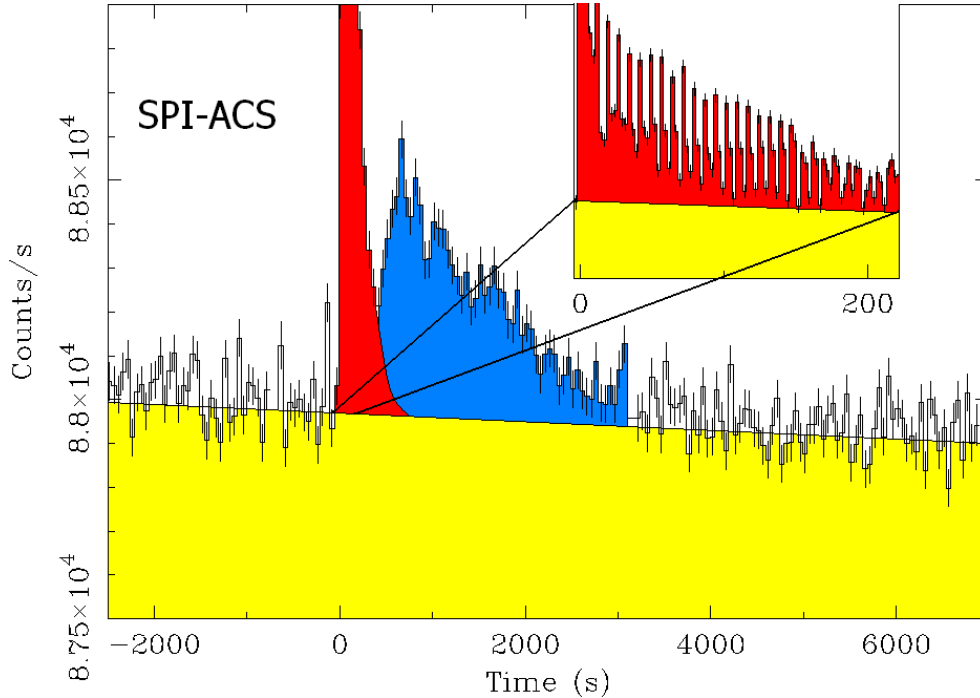


Fig. 5 Light curve of the Giant Flare of December 27 2004 as measured with SPI-ACS above 80 keV. The light curve is binned at 50 s, and hence the pulsating tail is not visible (it is visible in the inset where the light curve is binned at 2.5 s). (yellow: instrumental background, red: Flare tail, blue: high-energy afterglow, see text)

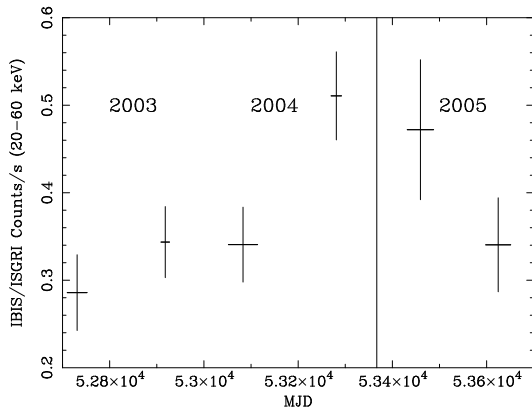


Fig. 6 Long term light curve of SGR 1806–20, as measured with IBIS. The vertical line represents the time of the giant flare of December 27 2004.

in turn increases the burst emission rate, and produces harder spectra, as predicted by Thompson et al. (2002).

3 SGR 1900+14

SGR 1900+14 was discovered in 1979 by Mazets et al. (1979b) when it emitted 3 bursts in 2 days. Since then short bursts were observed from this source with BATSE, RXTE and Interplanetary Network satellites in the years 1979-2002. SGR 1900+14 emitted a giant flare on August 27 1998 (e.g. Hurley et al. (1999)), followed by less

intense “intermediate” flares on August 29 1998 (Ibrahim et al. 2001) and in April 2001 (Lenters et al. 2003). The last bursts reported from SGR 1900+14 were observed with the Third Interplanetary Network (IPN) in November 2002 (Hurley et al. 2002). No bursts from this source were revealed in all the INTEGRAL observations from 2003 to 2005, but Swift has detected renewed activity in 2006 (Palmer et al. 2006a).

3.1 Discovery of the persistent emission

Using 2.5 Ms of INTEGRAL data, Götz et al. (2006b) reported the discovery of persistent hard X-ray emission, this time from a quiescent SGR, 1900+14. This emission extended up to ~ 100 keV, but with a softer spectrum compared to SGR 1806–20, having a photon index of 3.1 ± 0.5 . Also the luminosity is dimmer in this case, being $\sim 4 \times 10^{35}$ erg s $^{-1}$, a factor of three lower than SGR 1806–20. The INTEGRAL observations spanned March 2003 to June 2004, and did not include the recent reactivation of the source in March 2006 (Palmer et al. 2006a), when the source emitted a few tens of regular bursts plus an intense burst series, lasting ~ 30 s (Palmer et al. 2006b), reminiscent of the October 5 2004 event from SGR 1806–20. We recently analysed the INTEGRAL data spanning from August 2004 to March 2006, and found that the hard X-ray flux of the source flux did not increase up to a few weeks before its reactivation. This indicates that the reactivation was not triggered by a flux increase, at

least on the time scale of a few months sampled by INTEGRAL.

The soft and constant spectrum of SGR 1900+14 is possibly related to the fact that this source is still in a rather quiescent state.

4 Comparison with the Anomalous X-ray Pulsars

Hard X-ray persistent emission (>20 keV) has recently been detected from another group of sources, the Anomalous X-ray Pulsars (AXPs, Mereghetti & Stella (1995)), which share several characteristics with the SGRs and are also believed to be magnetars (see Woods & Thompson (2003)). Hard X-ray emission has been detected from three AXPs with INTEGRAL: 1E 1841–045 (Molkov et al. 2004), 4U 0142+61 (den Hartog et al. 2006) and 1RXS J170849–400910 (Revnivtsev et al. 2004). The presence of pulsations seen with RXTE up to ~ 200 keV in 1E 1841–045 (Kuiper et al. 2006) proves that the hard X-ray emission originates from the AXP and not from the associated supernova remnant Kes 73. The discovery of (pulsed) persistent hard X-ray tails in these three sources was quite unexpected, since below 10 keV the AXP have soft spectra, consisting of a blackbody-like component ($kT \sim 0.5$ keV) and a steep power law (photon index $\sim 3-4$).

In order to coherently compare the broad band spectral properties of all the SGRs and AXPs detected at high energy, we analysed all the public INTEGRAL data using the same procedures. Our results are shown in Fig. 7, where the INTEGRAL spectra are plotted together with the results of observations at lower energy taken from the literature (see figure caption for details).

As can be seen, AXPs generally present harder spectra than SGRs in hard X-rays. In particular, for the three AXPs, a spectral break is expected to occur between 10 and 20 keV in order to reconcile the soft and the hard parts of the spectrum. On the other hand SGRs, present a softer spectrum at higher energies also implying a break around 15 keV (especially for SGR 1900+14) but in the opposite sense with respect to the AXPs. The fact that the spectral break is more evident in SGR 1900+14 could be due to the fact that its level of activity was much lower during our observations, compared to SGR 1806–20. All three AXPs, on the other hand, can be considered to have been in a quiescent state since no bursts were reported from them during the INTEGRAL observation.

The magnetar model, in its different flavours, explains this hard X-ray emission as powered by bremsstrahlung photons produced either close to the neutron star surface, or at a high altitude (~ 100 km) in the magnetosphere (Thompson et al. 2002; Thompson & Beloborodov 2005). The two models can be distinguished by the presence of a cutoff at ~ 100 keV or ~ 1 MeV. Unfortunately current experiments like INTEGRAL are not sensitive

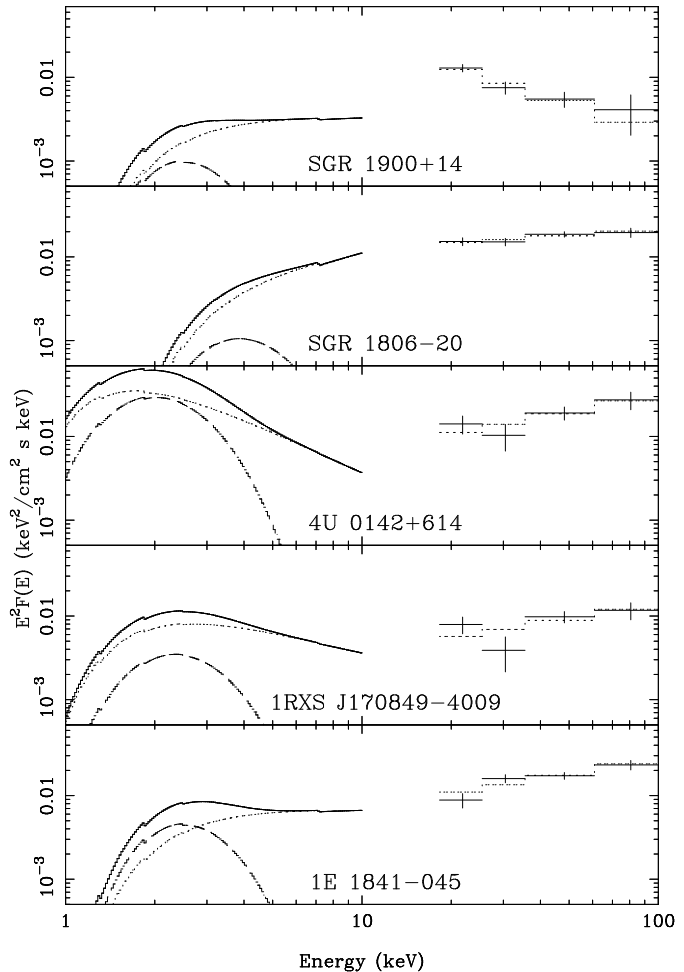


Fig. 7 Broad band X-ray spectra of the five magnetars detected by INTEGRAL. The data points above 18 keV are the INTEGRAL spectra with their best fit power-law models (dotted lines). The solid lines below 10 keV represent the absorbed power-law (dotted lines) plus blackbody (dashed lines) models taken from Woods et al. (2001) (SGR 1900+14, during a quiescent state in spring 2000), Mereghetti et al. (2005b) (SGR 1806–20, observation B, when the bursting activity was low), Göhler et al. (2005) (4U 0142+614), Rea et al. (2005) (1RXS J170849–4009), and Morii et al. (2003) (1E 1841–045). From Götz et al. (2006b).

enough to firmly assess the presence of the cutoffs and hence to distinguish between the two models.

5 Conclusions

Thanks to INTEGRAL, and in particular to its imager IBIS, we have been able to study most of the magnetars' phenomenology with unprecedented sensitivity at high energies. One of the most striking results is the discovery, which was particularly unexpected for AXPs, of the persistent hard X-ray emission. This discovery, which can be considered one of the most important INTEGRAL results at all, represents a new important input for theo-

reticians who started to include it in the magnetar model (see e.g. Belobodorov (2006)).

Also, the fact that short bursts evolve with time is a new feature that has to be considered with care within the magnetar model: up to now no clear explanation has been provided for this.

The large number of detected short bursts from SGR 1806–20 allowed us a good determination of the shape and slope of their Number-Intensity distribution, showing that a single power law holds over 2.5 orders of magnitude.

In addition, the fact that SGR 1806–20 has been particularly active in these last years, also emitting a once-in-a-lifetime event such as the giant flare (and its possible high energy afterglow), has allowed observations of relatively rapid changes of the bursting and persistent emission of a Magnetar and to interpret then with the evolution of a very strong and complicated magnetic field, confirming the magnetic field as the dominant source of energy in Soft Gamma-Ray Repeaters and Anomalous X-ray Pulsars.

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Unveiling Soft Gamma-Ray Repeaters with INTEGRAL

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Abstract Thanks to INTEGRAL long exposures of the Galactic Plane, the two brightest Soft Gamma-Ray Repeaters, SGR 1806-20 and SGR 1900+14, have been monitored and studied in detail for the first time at hard-X/soft-gamma rays.

This has produced a wealth of new scientific results, which we will review here. Since SGR 1806-20 was particularly active during the last two years, more than 300 short bursts have been observed with INTEGRAL and their characteristics have been studied with unprecedented sensitivity in the 15-200 keV range. A hardness-intensity anticorrelation within the bursts has been discovered and the overall Number-Intensity distribution of the bursts has been determined. In addition, a particularly active state, during which 100 bursts were emitted in 10 minutes, has been observed on October 5 2004, indicating that the source activity was rapidly increasing. This eventually led to the Giant Flare of December 27th 2004, discovered by INTEGRAL, for which a possible soft gamma-ray (>80 keV) early afterglow has been detected.

The deep observations allowed us to discover the persistent emission in hard X-rays (20-150 keV) from 1806-20 and 1900+14, the latter being in quiescent state, and to directly compare the spectral characteristics of all Magnetars (two SGRs and three Anomalous X-ray Pulsars) detected with INTEGRAL.

Keywords gamma-rays: observations · pulsars: individual SGR 1806-20, SGR 1900+14 · pulsars: general

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1 Introduction

Soft gamma-ray repeaters (SGRs, for a recent review see [55]) are a small group (4–7) of peculiar high-energy sources generally interpreted as “magnetars”, i.e. strongly magnetised ($B \sim 10^{15}$ G), slowly rotating ($P \sim 5$ -8 s) neutron stars powered by the decay of the magnetic field energy, rather than by rotation [4, 37, 44]. They were discovered through the detection of recurrent short (~ 0.1 s) bursts of high-energy radiation in the tens to hundreds of keV energy range, with peak luminosity up to 10^{39} - 10^{42} erg s $^{-1}$, above the Eddington limit for neutron stars. The rate of burst emission in SGRs is highly variable. Bursts are generally emitted during sporadic periods of activity, lasting days to months, followed by long “quiescent” time intervals (up to years or decades) during which no bursts are emitted. Occasionally SGRs emit also “giant flares”, that last up to a few hundred seconds and have peak luminosity up to 10^{46} - 10^{47} erg s $^{-1}$. Only three giant flares have been observed to date, each one from a different source (see, e.g., [25] for 0526-66, [12] for 1900+14, [38, 30, 15] for 1806-20).

Persistent (i.e. non-bursting) emission is also observed from SGRs in the soft X-ray range (<10 keV), with typical luminosity of $\sim 10^{35}$ erg s $^{-1}$, and, in three cases, periodic pulsations at a few seconds have been detected. Such pulsations proved the neutron star nature of SGRs and allowed to infer spin-down at rates of $\sim 10^{-10}$ s s $^{-1}$, consistent with dipole radiation losses for magnetic fields of the order of $B \sim 10^{14}$ - 10^{15} G. The X-ray spectra are generally described with absorbed power laws, but in some cases strong evidence has been found for the presence of an additional blackbody-like component with typical temperature of ~ 0.5 keV [32].

In the last years the *INTEGRAL* satellite [52], launched in 2002 and operating in the 15 keV-10 MeV energy range, has provided a wealth of new results concerning

the two brightest SGRs 1806–20 and 1900+14. Most aspects concerning the SGRs, short bursts, giant flares, persistent emission, have been investigated, and new results have been found for each of them. We will review them here.

2 SGR 1806–20

SGR 1806–20 was discovered by the Interplanetary Network (IPN) in 1979 [20]. It lies in a crowded region close to the galactic centre. [18] discovered a quiescent X-ray pulsating ($P=7.48$) counterpart, which was spinning down rapidly ($\dot{P}=2.8\times 10^{-11}$ s s $^{-1}$). If this spindown is interpreted as braking by a magnetic dipole field, its strength is $B\sim 10^{15}$ G. The source activity is variable alternating quiet periods to very active ones.

After a period of quiescence, SGR 1806–20 became active in the summer of 2003 [14]. Its activity then increased in 2004 (see e.g. [29, 6]). A strong outburst during which about one hundred short bursts were emitted in a few minutes occurred on October 5 2004 [8]. Finally a giant flare, whose energy ($\sim 10^{46}$ erg) was two orders of magnitude larger than those of the previously recorded flares from SGR 0526-66 and SGR 1900+14, was emitted on December 27th 2004 (see e.g. [38, 30, 15]).

2.1 Short Bursts

The results presented in this Section are based on observations obtained with the IBIS coded mask telescope [48], and in particular with its low-energy (15 keV–1 MeV) detector ISGRI [21]. More than 400 short bursts have been detected with IBIS/ISGRI. They have been identified either using the triggers provided by the INTEGRAL Burst Alert System (IBAS) [28], or by computing light curves with 10 ms time resolution and looking for significant excesses corresponding to the direction of SGR 1806–20.

Spectral Evolution All the bursts detected by IBIS are typical in terms of duration and spectra. The new result provided by the analysis of the *INTEGRAL* sample is the spectral evolution within the bursts. In fact, by computing time resolved hardness ratios ($HR=(H-S)/(H+S)$) using the background subtracted light curves in two energy bands (20–40 (S) and 40–100 (H) keV), [7, 8] showed that some bursts evolve significantly with time, especially the ones with a Fast Rise Exponential Decay (FRED) profile; in these cases the bursts' peaks tend to be spectrally softer than the bursts' tails. This behaviour had been reported earlier only for two peculiar bursts originating from SGR 1900+14. These two bursts were quite different from usual bursts, lasting about 1 s and having a very hard spectrum ($kT\sim 100$ keV) [53].

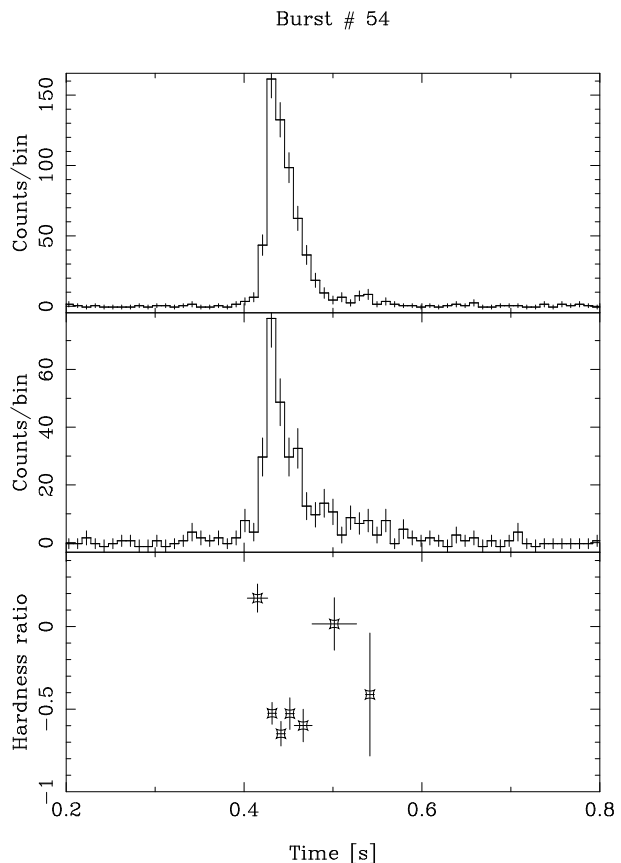


Fig. 1 IBIS/ISGRI light curves in the soft (20–40 keV, upper panel) and hard (40–100 keV, middle panel) energy range and hardness ratio (lower panel) for a short burst from SGR 1806–20.

One example of this kind of evolution detected in common SGR 1806–20 bursts is shown in Fig. 1.

The spectral behaviour described above gives rise to a global hardness-intensity anti-correlation. In fact, by considering all the individual time bins of all the bursts this anti-correlation within the bursts has been discovered, see Fig. 2. To investigate the statistical robustness of the correlation found, the Spearman rank-order correlation coefficient of the 217 data points, R_s , has been computed, which is -0.49 . This corresponds to a chance probability of 4×10^{-15} (7.4σ) that the distribution is due to uncorrelated data. According to an F-test the data are significantly (8σ) better described by a linear fit ($HR = 0.47 - 0.22 \times \log(I)$) than by a constant. This correlation still lacks of a solid theoretical interpretation since the current Magnetar scenario does not provide a clear prediction on the burst spectral evolution with time.

Number-Intensity Distribution We derived the fluences of 224 common bursts using the vignetting and dead-time corrected light curves. We applied a conversion factor between counts and physical units derived by the spectral analysis of the brightest bursts and assuming

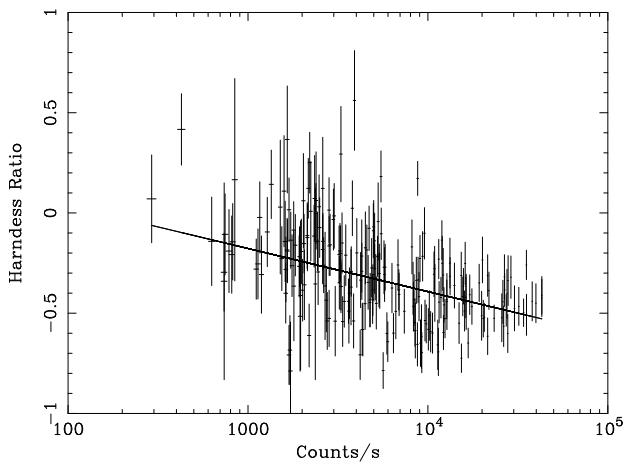


Fig. 2 Hardness ratio $((H-S)/(H+S))$ versus total count rate (20-100 keV, corrected for vignetting). The points are derived from the time resolved hardness ratios of the bursts with the best statistics. The line indicates the best fit with a linear function given in the text. From [8].

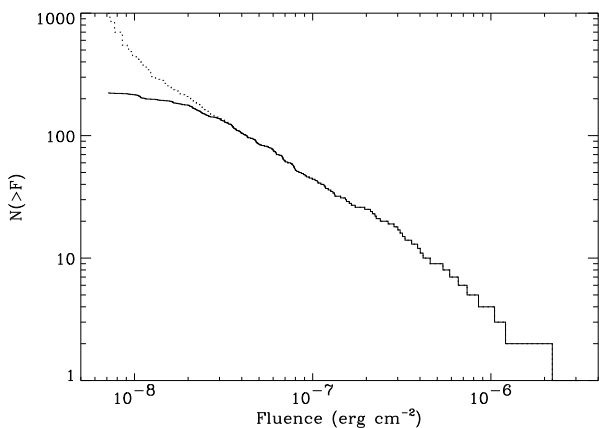


Fig. 3 Number-intensity distribution of all the bursts detected by *INTEGRAL* in 2003 and 2004. The continuous line represents the experimental data, while the dashed line represents the data corrected for the exposure. From [8].

that the averaged bursts spectra do not change much between bright and faint bursts; for details see [8]. These fluences have been used to compute the number-intensity distribution (Log N-Log S) of the bursts. The experimental distribution deviates significantly from a single power-law (Fig. 3). This is first of all due to the fact that the source has been observed at different off-axis angles. The faintest bursts are missed when the source is observed at large off-axis angles. In order to correct for this effect we have computed the effective exposure of the source, taking into account the variation of sensitivity at various off-axis angles. This yields the exposure-corrected cumulative distribution shown by the dashed line in Fig. 3.

Since the numbers at each flux level are not statistically independent, one cannot use a simple χ^2 minimisa-

tion approach to fit the cumulative number-intensity distribution. So we have used the unbinned detections and applied the Maximum Likelihood method [3], assuming a single power-law distribution for the number-flux relation ($N(> S) \propto S^{-\alpha}$). We have used only the part of the distribution where completeness was achieved (i.e. $S \geq 3 \times 10^{-8}$ erg cm $^{-2}$). In this case the expression to be maximised is

$$\mathcal{L} = T \ln \alpha - \alpha \sum_i \ln S_i - T \ln(1 - b^{-\alpha}) \quad (1)$$

where S_i are the unbinned fluxes, b is the ratio between the maximum and minimum values of the fluxes, and T is the total number of bursts. This method yields $\alpha = 0.91 \pm 0.09$. If a single power-law model is an adequate representation of data, the distribution of the quantities

$$y_i = \frac{1 - S_i^{-\alpha}}{1 - b^{-\alpha}} \quad (2)$$

should be uniform over the range (0,1). In our case, a Kolmogorov-Smirnov (K-S) test shows that a power law is an appropriate model, yielding a probability of 98.8% that the data are well described by our model.

We then divided the bursts in two samples comprising 51 and 173 bursts respectively. The division is based on the periods of different activity of the source. The two slopes derived with the Maximum Likelihood method are $\alpha = 0.9 \pm 0.2$ for the low level activity period and $\alpha = 0.88 \pm 0.11$ for the high level one. The two slopes are statistically consistent with each other and a K-S test shows that the probability that the two distributions are drawn from the same parent distribution is 93%. Thus we conclude that the relative fraction of bright and faint bursts is not influenced by the level of activity of the source.

The Large Outburst of October 5 2004 On October 5 2004 IBAS triggered at 13:56:49 UT on a series of bursts originating from SGR 1806–20. Detailed analysis of this event showed the presence of more than 100 bursts; the activity ended at 14:08:03 UT. Some bursts were so bright that they saturated the available telemetry share for IBIS, generating some data gaps lasting up to 10-20 s. The initial part of the outburst is shown in Fig. 4

The fluence of the entire outburst as measured by ISGRI is 1.5×10^{-5} erg cm $^{-2}$, with a spectrum which is quite harder than the one of usual short bursts: $kT = 58 \pm 2$ keV, using a thermal bremsstrahlung model. This fluence values is however heavily affected by the saturation of the brightest bursts and represents only a lower limit to the real fluence. In order to recover the complete fluence of the event we used the data from the Anticoincidence Shield (ACS) of the *INTEGRAL* spectrometer SPI [49]. As can be seen in Fig. 4 (upper panel), only the brightest bursts are visible in these data and hence they represent complementary information to the ISGRI data.

We used the Monte Carlo package MGGPOD [51] and a detailed mass modelling of SPI and the whole

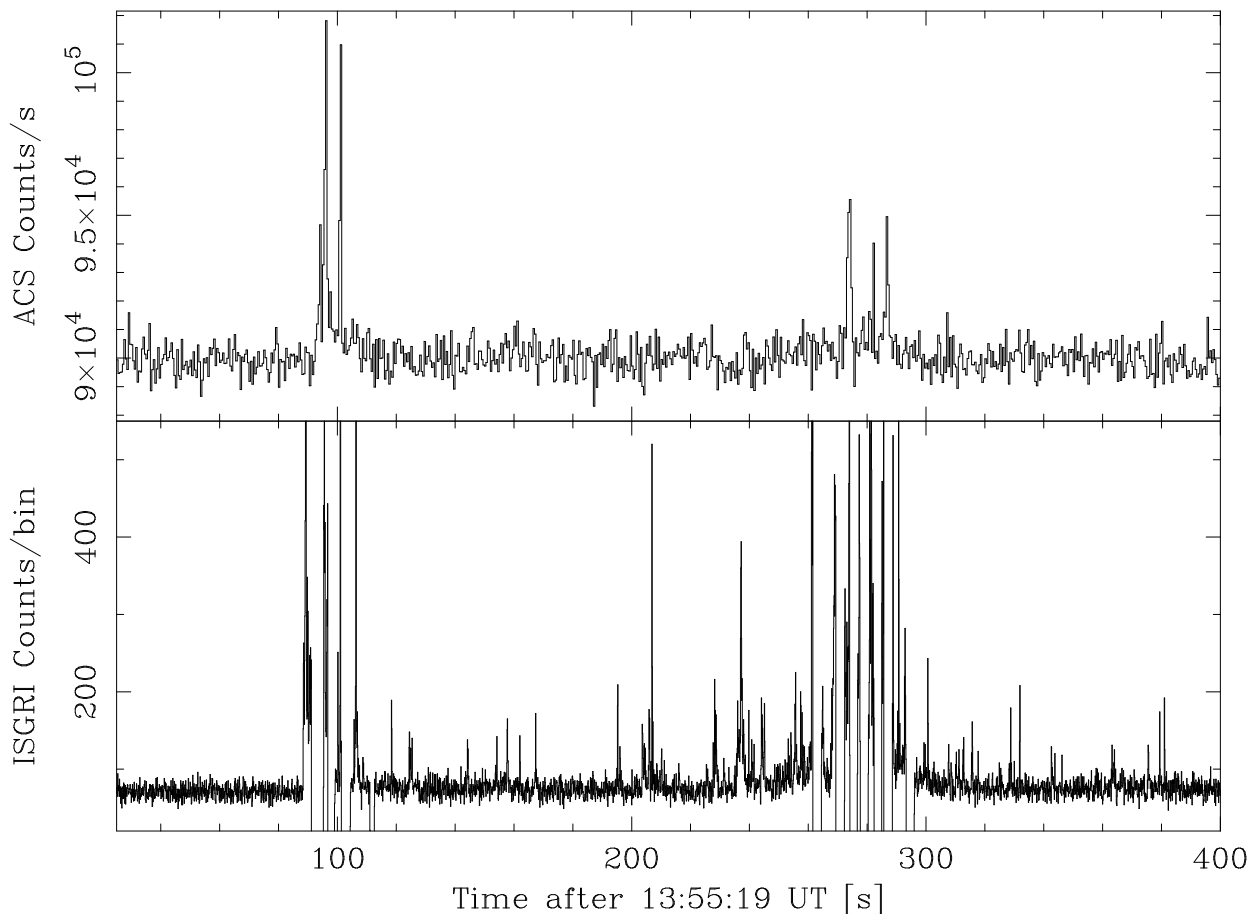


Fig. 4 Light curves of the initial part of the October 5, 2004 outburst of SGR 1806-20. Upper panel: light curve at energy greater than ~ 80 keV obtained with the SPI Anti-Coincidence System in bins of 0.5 s. Bottom panel: light curve in the 15-200 keV energy range obtained with the IBIS/ISGRI instrument (bin size 0.1 s). The gaps in the IBIS/ISGRI light curve are due to saturation of the satellite telemetry. From [8].

satellite (see [50] and references therein) to derive the effective area of the ACS for the direction of SGR 1806–20. We computed the ACS light curve with a binsize of 0.5 s and estimated the background by fitting a constant value to all the data of the same pointing excluding the bursts. We used the background subtracted light curve to compute the fluence of each burst cluster in counts. The ACS data do not provide any spectral information, so we computed the conversion factor to physical units based on the spectral shapes derived from ISGRI data and on the effective area computed through our simulations. The resulting fluences above 80 keV are 1.2×10^{-5} and 9.4×10^{-6} erg cm $^{-2}$ for the first and second clusters respectively. Converting these fluences to the 15-100 keV band one obtains 7.4×10^{-5} and 3.2×10^{-5} erg cm $^{-2}$ respectively. By adding these results to the ones obtained for the ISGRI total spectrum, one can derive the total energy output during the whole event, which is 1.2×10^{-4} erg cm $^{-2}$. This corresponds to 3.25×10^{42} erg for an assumed distance of 15 kpc [34].

These results can be explained in the framework of a recent evolution of the magnetar model, where [23] explains SGR bursts as generated by loss of magnetic equilibrium in the magnetosphere, in close analogy to solar flares: new current-carrying magnetic flux tubes rise continuously into the magnetosphere, driven by the deformations of the neutron star crust. This in turn generates an increasingly complicated magnetic field structure, which at some point becomes unstable to resistive reconnection. During these reconnection events, some of the magnetic energy carried by the currents associated with the magnetic flux tubes is dissipated. The large event described here can be explained by the simultaneous presence of different active regions (where the flux emergence is especially active) in the magnetosphere of the neutron star. In fact, a long outburst with multiple components is explained as the result of numerous avalanche-type reconnection events, as reconnection at one point may trigger reconnection at other points. This explains the fact that the outburst seems to be composed by the sum of several short bursts. This kind of event

might indicate a particularly complicated phase of the magnetic field structure which eventually led to a global restructuring of the whole magnetosphere with the emission of the giant flare on December 27. This mode also suggests that short events are due to reconnection, while longer events have in addition a large contribution from the surface, heated by the precipitating particles, and are harder. This may explain the generally harder spectra observed. However more “classical” scenarios involving only crust fracturing with a large-scale shear deformation of the crust involving the collective motion of many small units, without an internal contribution, cannot be fully ruled out, see e.g. [45].

The October 5th event fits in the trend of increasing source activity shown by SGR 1806–20 in the last two years and also manifested in the rise in luminosity and spectral hardness of the persistent emission at high (20–150 keV, see below) and low (2–10 keV, [32]) energies. On the other hand, this peculiar event did not mark a peak or a turnover in the SGR activity. In fact the two *XMM* observations of SGR 1806–20 performed just before (September 6 2004) and the day after this large outburst (as a ToO in response to it) yielded similar spectral parameters, fluxes and pulse profiles, and bursts were seen in both observations ([32]).

Thus events like these release a small (compared to giant flares) fraction of the energy stored in the twisted magnetic field of the neutron star, not allowing the magnetic field to decay significantly. They are rather related to phases of high activity due to large crustal deformations (indicating that a large quantity of energy is still stored in magnetic form) and can be looked at as precursors of a major reconfiguration of the magnetic field.

2.2 The Giant Flare of December 27 2004

A giant flare from SGR 1806–20 has been discovered with the INTEGRAL gamma-ray observatory on 2004 December 27 [1]. The analysis of the SPI-ACS data (>80 keV) of the flare, presented in [30], show that the giant flare is composed by an initial spike lasting 0.2 s followed by a ~ 400 s long pulsating tail. The tail decays exponentially as $\sim t^{-0.85}$ and is modulated at the neutron star period of 7.56 s. The initial spike was so bright that it saturated the ACS, so we could derive only a lower limit on its fluence, which turned out to be two order of magnitudes brighter (10^{46} ergs, see e.g. [43]) than the previously observed giant flares from SGR 1900+14 [12], and SGR 0525–66 [25]. The energy contained in the tail (1.6×10^{44} ergs), on the other hand, was of the same order as the one in the pulsating tails of the previously observed giant flares.

A ~ 0.2 s long small burst, was detected in the ACS data 2.8 s after the initial spike. It is superposed on the pulsating tail and with no clear association with the pulse phase. This burst has been interpreted by [30] as

the reflection by the Moon of the initial spike of the giant flare. In fact this delay corresponds to the light travel time between *INTEGRAL*, the Moon, and back. A similar detection was reported with the *Helicon-Coronas-F* satellite [26].

The most striking feature provided by the *INTEGRAL* data is the detection of a possible early high-energy afterglow emission associated to the giant flare. At the end of the pulsating tail the count rate increased again, forming a long bump which peaked around $t \sim 700$ s and returned to the pre-flare background level at $t \sim 3000$ – 4000 . This component is shown in blue in Fig. 5, while the overall long term background trend is shown in yellow, and the giant flare itself in red. The association of this emission with SGR 1806–20 is discussed in [30]. The fluence contained in the 400–4000 s time interval is approximately the same as in the pulsating tail. With simple gamma-ray bursts afterglow models derived on synchrotron emission one can derive the bulk Lorentz factor Γ from the time t_0 of the afterglow onset: $\Gamma \sim 15(E/5 \times 10^{43} \text{ ergs})^{1/8}(n/0.1 \text{ cm}^{-3})^{-1/8}(t_0/100)^{-3/8}$, where n is the ambient density. This is consistent with the mildly relativistic outflow inferred from the radio data [10].

2.3 Discovery of the persistent emission

In 2004 two groups reported independently the discovery of persistent hard X-ray emission originating from SGR 1806–20 [31,36]. Up to then, spectral information on the persistent emission of SGRs was known only below 10 keV. The low energy spectrum is usually well described by the sum of a power law component and a black body (see e.g. [32]).

The spectrum above 20 keV is rather hard with a photon index between 1.5 and 2.0 and extends up to 150 keV without an apparent cutoff. It connects rather well with the low energy (< 10 keV) spectrum [32], and the intensity and spectral hardness are correlated with the degree of bursting activity of the source [31,8] and with the flux of the recently discovered IR counterpart of the source [17]. Our group is continuously monitoring the hard X-ray flux of SGR 1806–20, and the long term light curve of the source is shown in Fig. 6. As can be seen, the persistent flux increased in 2003 and 2004 up to the giant flare (which is marked with a vertical line in the plot), and then decreased in 2005.

This behaviour can be interpreted, as an increase of the twist angle in the magnetar magnetic field, which in turn increases the burst emission rate and the multiple resonant cyclotron scattering, which produces harder spectra, as predicted by [46].

3 SGR 1900+14

SGR 1900+14 was discovered by [24] as it emitted 3 bursts in 2 days. Since then short bursts were observed

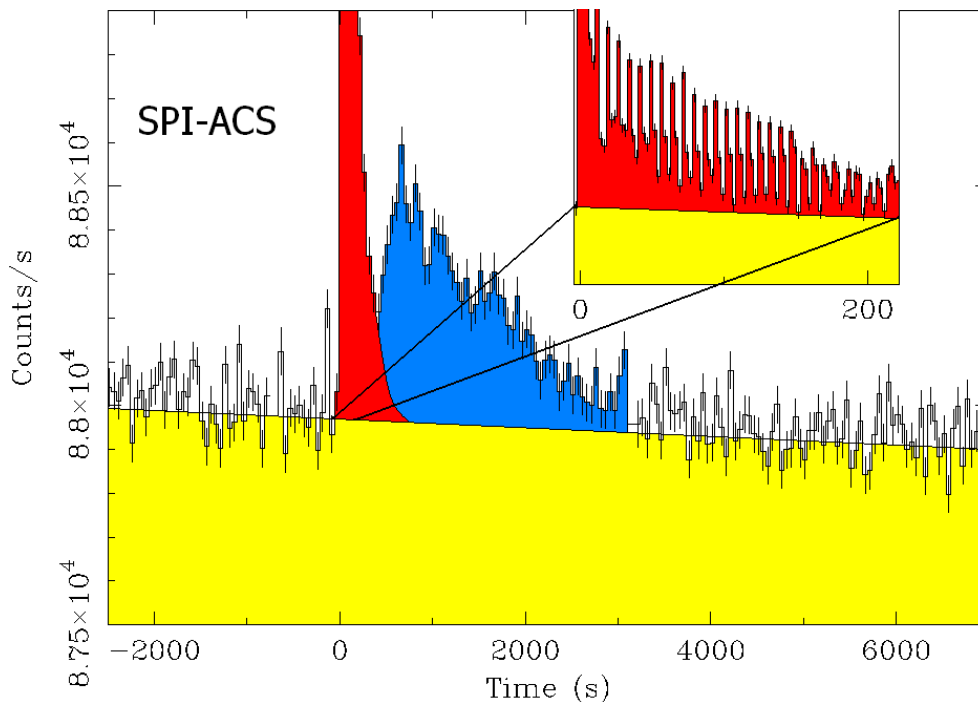


Fig. 5 Light curve of the Giant Flare of December 27 2004 as measured with SPI-ACS above 80 keV. The light curve is binned at 50 s, and hence the pulsating tail is not visible (it is visible in the inset where the light curve is binned at 2.5 s). (yellow: instrumental background, red: Flare tail, blue: high-energy afterglow, see text)

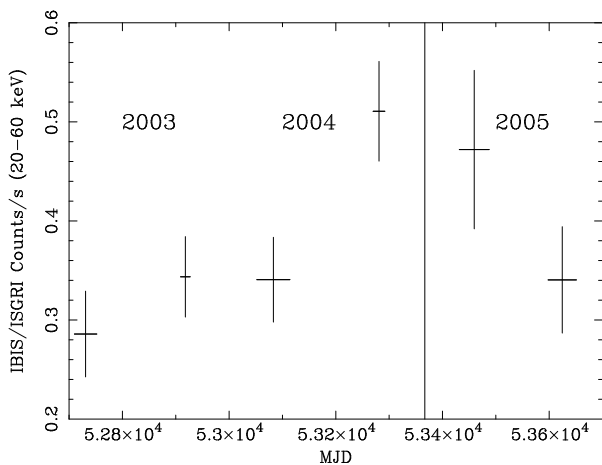


Fig. 6 Long term light curve of SGR 1806-20, as measured with IBIS. The vertical line represents the time of the giant flare of December 27 2004.

from this source with BATSE, *RXTE* and other satellites in the years 1979-2002. SGR 1900+14 emitted a giant flare on August 27 1998 (e.g. [12]), followed by less intense “intermediate” flares on August 29 1998 [16] and in April 2001 [22]. The last bursts reported from SGR 1900+14 were observed with the Third Interplanetary Network (IPN) in November 2002 [13]. No bursts from this source were revealed in all the *INTEGRAL* observations from 2003 to 2005.

3.1 Discovery of the persistent emission

Using 2.5 Ms of *INTEGRAL* data, [9] reported the discovery of persistent hard X-ray emission, this time from a quiescent SGR, as 1900+14. This emission extended up to ~ 100 keV, but with a softer spectrum compared to SGR 1806-20, having a photon index of 3.1 ± 0.5 . Also the luminosity is dimmer in this case, being $\sim 4 \times 10^{35}$ erg s^{-1} , a factor of three lower than SGR 1806-20. The *INTEGRAL* observation spanned from March 2003 to June 2004, and it did not include the recent reactivation of the source in March 2006 [39], when the source emitted a few tens of regular bursts plus an intense burst series, lasting ~ 30 s [40], reminiscent of the October 5 2004 event from SGR 1806-20 that preceded the giant flare of December 27. However, we recently analysed the *INTEGRAL* data spanning from August 2004 to March 2006, and the source flux has not increased up to a few weeks before its reactivation indicating still a weak activity of the source.

The soft and constant spectrum of SGR 1900+14 is possibly related to the fact that this source is still currently in a rather quiescent state.

4 Comparison with the Anomalous X-ray Pulsars

Hard X-ray persistent emission (>20 keV) has recently been detected from another group of sources, the Anomalous X-ray Pulsars (AXPs, [27]), which share several characteristics with the SGRs and are also believed to be magnetars (see [55]). Hard X-ray emission has been detected from three AXPs with *INTEGRAL*: 1E 1841–045 [35], 4U 0142+61 [11] and 1RXS J170849–400910 [42]. The presence of pulsations seen with RXTE up to ~ 200 keV in 1E 1841–045 ([19]) proves that the hard X-ray emission originates from the AXP and not from the associated supernova remnant Kes 73. The discovery of (pulsed) persistent hard X-ray tails in these three sources was quite unexpected, since below 10 keV the AXP have soft spectra, consisting of a blackbody-like component ($kT \sim 0.5$ keV) and a steep power law (photon index $\sim 3-4$).

In order to coherently compare the broad band spectral properties of all the SGRs and AXPs detected at high energy, we analysed all the public *INTEGRAL* data using the same procedures. Our results are shown in Fig. 7, where the *INTEGRAL* spectra are plotted together with the results of observations at lower energy taken from the literature (see figure caption for details).

As can be seen, AXPs generally present harder spectra than SGRs at hard X-rays. In particular, for the three AXPs, a spectral break is expected to occur between 10 and 20 keV in order to reconcile the soft and the hard parts of the spectrum. On the other hand SGRs, present a softer spectrum at higher energies also implying a break around 15 keV (especially for SGR 1900+14) but in the opposite sense with respect to the AXPs. The fact that the spectral break is more evident in SGR 1900+14 could be due to the fact that its level of activity was much lower during our observations, compared to SGR 1806–20. All three AXPs, on the other hand, can be considered in a quiescent state since no burst has been reported from them during the *INTEGRAL* observation.

The magnetar model, in its different flavours, explains this hard X-ray emission as powered by bremsstrahlung photons produced either close to the neutron star surface or at high altitude (~ 100 km) in the magnetosphere [46, 47]. The two models can be distinguished by the presence of a cutoff at ~ 100 keV or ~ 1 MeV. Unfortunately current experiments like *INTEGRAL* do not have the are not sensitive enough to firmly assess the presence of the cutoffs and hence to distinguish between the two models.

5 Conclusions

Thanks to *INTEGRAL*, and in particular to its imager IBIS, we have been able to study most of the magnetars' phenomenology with unprecedented sensitivity at high

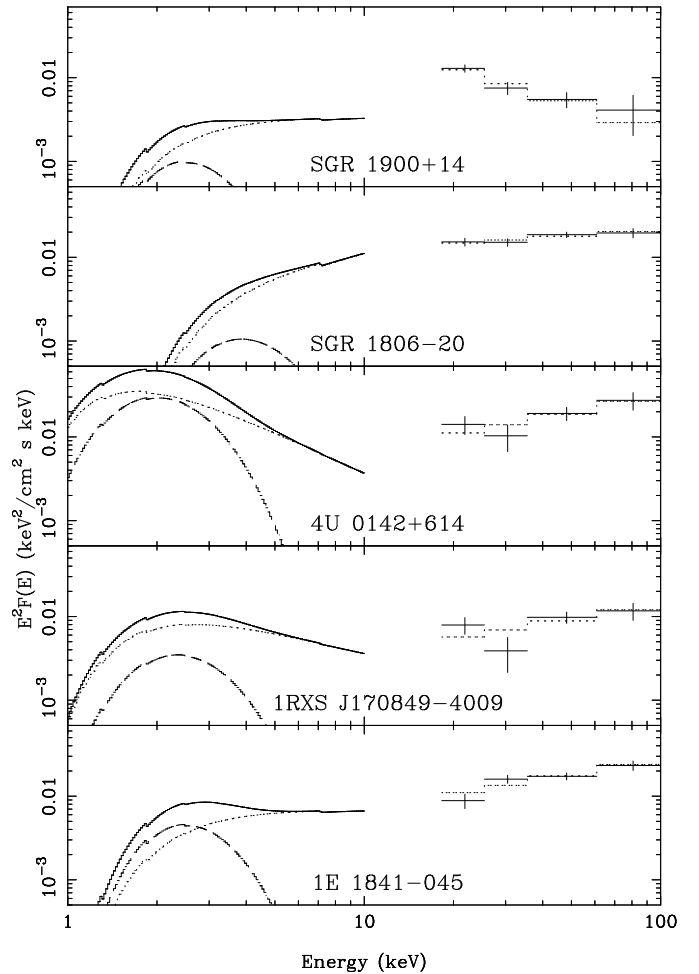


Fig. 7 Broad band X-ray spectra of the five magnetars detected by *INTEGRAL*. The data points above 18 keV are the *INTEGRAL* spectra with their best fit power-law models (dotted lines). The solid lines below 10 keV represent the absorbed power-law (dotted lines) plus blackbody (dashed lines) models taken from [54] (SGR 1900+14, during a quiescent state in spring 2000), [32] (SGR 1806–20, observation B, when the bursting activity was low), [5] (4U 0142+614), [41] (1RXS J170849–4009), and [33] (1E 1841–045). From [9].

energies. One of the most striking results is the discovery, which was particularly unexpected for AXPs, of the persistent hard X-ray emission. This result, which can be considered one of the most important *INTEGRAL* results at all, represents a new important input for theoreticians who started to include it in the magnetar model (see e.g. [2]).

Also, the fact that short bursts evolve with time is a new feature that has to be considered with care within the magnetar model: up to now no clear explanation has been provided for this.

The large number of detected short bursts from SGR 1806–20 allowed to well determine the shape and slope of the Number-Intensity distribution of the burst, showing that a single power law holds over 2.5 orders of magnitude.

In addition, the fact that SGR 1806–20 has been particularly active in these last years, including a once-in-a-lifetime event such as the giant flare (and its possible high energy afterglow), has allowed us to witness real-time rapid changes of the bursting and persistent emission of a Magnetar and to explain them with the evolution of a very strong and complicated magnetic field, confirming the magnetic field as the dominant source of energy in Soft Gamma-Ray Repeaters and Anomalous X-ray Pulsars.

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