In the last few years it has been recognized that two apparently distinct classes of peculiar high-energy sources are actually related and can be explained as young neutron stars with magnetic fields as high as $10^{14}$–$10^{15}$ Gauss. One of these "magnetars", SGR 1806–20, has recently emitted the most powerful giant flare ever recorded. The high-energy observations of SGR 1806–20 carried out with XMM-Newton and INTEGRAL in the past two years showed a long term trend of increasing activity preceding the 2004 December 27 event. INTEGRAL data of this giant flare provided unique evidence for hard X-ray emission lasting about one hour after the burst onset, possibly due to the interaction of mildly relativistic ejecta with the circumstellar medium.

1 Introduction

Observations carried out in the last decade have provided increasing evidence for the existence of neutron stars with magnetic fields as high as $10^{14}$–$10^{15}$ G, or magnetars. These objects, about a dozen of which are currently known, are powered by magnetic energy, contrary to the nearly 2000 neutron stars which are observed either as rotation-powered pulsars or X-ray sources powered by accretion in binary systems.

Two different classes of objects are thought to be magnetars: the Soft Gamma-ray Repeaters, discovered as sources of short bursts of hard X-rays (>30 keV) with super-Eddington luminosity, and the Anomalous X-ray Pulsars, discovered as persistent, soft (<10 keV) X-ray sources with pulsations of several seconds and spinning-down on time scales of $\sim 10^4$–$10^5$ years. An increasing number of common properties, pointing to a close relationship of these two apparently different classes of objects and leading to their interpretation as magnetars, has been found. Several good reviews are available on these sources. Here I will focus on some recent results on SGR 1806–20 obtained with XMM-Newton and INTEGRAL, the two major satellites for high-energy astrophysics of the European Space Agency.
Figure 1: Long term evolution of the pulse period and energy spectrum of SGR 1806–20. The power law photon index decreased from 2.2 to 1.5, indicating a spectral hardening, while the average spin-down rate changed from \( \approx 8.5 \times 10^{-11} \) s s\(^{-1}\) to \( 5.5 \times 10^{-10} \) s s\(^{-1}\).

2 The persistent emission from SGR 1806–20

Four observations of SGR 1806–20 carried out with XMM-Newton in 2003-2004 have provided the best spectroscopic results ever obtained in the 1-10 keV range for this source and allowed us to study its long term evolution with a homogeneous set of data from the same instrument. The source luminosity in Fall 2004 was \( \approx 10^{36} \) erg s\(^{-1}\), a factor two higher than that measured in all the previous observations. The spectrum on 2004 September 6 required the presence of a blackbody of temperature \( kT_{BB} \approx 0.8 \) keV, in addition to the power law that was found adequate to fit all the spectra obtained earlier (which had a lower statistics). In fact, although not formally required in the fits, a blackbody component with constant temperature and luminosity is compatible with all the XMM-Newton observations and the variations in luminosity and spectral shape can be explained only by changes in the power law component.

Comparison of the XMM-Newton results with earlier measurements indicates a long term hardening of the spectrum, correlated with an increase in the source average spin-down rate (see Fig. 1). Such a correlation, previously noticed by comparing different SGRs and Anomalous X-ray Pulsars, is observed here for the first time within the same source.

At higher energies, observations with INTEGRAL showed, for the first time in a SGR, the presence of persistent emission (i.e. not due to bursts) extending up to 150 keV. This result was possible thanks to the good sensitivity of the IBIS instrument coupled to its excellent imaging capabilities, which are essential to disentangle the hard X-ray emission from sources in crowded Galactic regions. The spectra reported in Fig. 2 show that the emission in the 20-150 keV range increased and hardened in Fall 2004, when also a higher rate of emitted bursts was observed. The spectrum of the persistent emission is harder than that of the bursts (one example is given in Fig.2(c)). This supports the interpretation of the persistent hard X-ray
Figure 2: IBIS/ISGRI spectra of SGR 1806–20: (a) persistent emission March 2003-April 2004, (b) persistent emission Sept.-Oct. 2004, (c) one burst (scaled down by a factor $10^4$). The solid lines in (a) and (b) are the best fits power law spectra with photon index $\Gamma = 1.9 \pm 0.2$ and $\Gamma = 1.5 \pm 0.3$, respectively. The dashed lines indicate the extrapolation of power-law spectra measured in the 1-10 keV range. The solid line in (c) is the best fit thermal bremsstrahlung spectrum with $kT=35$ keV.

emission as a truly different physical component\textsuperscript{12}, not due to the integrated flux of numerous weak bursts too dim to be seen individually.

Both the XMM-Newton and INTEGRAL results indicate a long-term growth in the level of non-thermal magneto-spherical activity that fits reasonably well in the scenario of a magnetar with a twisted-dipole magnetosphere configuration\textsuperscript{12}. In this model currents flowing in the magnetosphere are expected to lead to the formation of a high-energy tail through repeated resonant scattering of the thermal photons emitted at the star surface. A gradually increasing twist results in a larger optical depth and this causes a hardening of the X-ray spectrum. At the same time, the spin-down rate increases because, for a fixed dipole field, the fraction of field lines that open out across the speed of light cylinder grows. The stresses building up in the neutron star crust and the magnetic footprints movements can lead to crustal fractures which can be energetic enough to explain the observed increase in the bursting activity.

3 Properties of SGR 1806–20 bursts

Being at only 10° from the Galactic Center direction, SGR 1806–20 is located in one of the sky regions extensively observed by INTEGRAL. Thus more than 200 bursts have been detected to date, including the faintest ones ever observed from SGR 1806–20 in the 20-100 keV energy range. This will allow us\textsuperscript{13} to extend the burst LogN-LogS down to a fluence $S \sim 6 \times 10^{-9}$ erg cm$^{-2}$.

Time resolved spectroscopy of the bursts with higher fluence indicates that some of them display significant spectral variations as a function of time, generally with the softest emission at the peak\textsuperscript{14}. Analysis of the IBIS data indicates that the average spectral shape of the bursts is
### Table 1: Comparison of the three giant flares from SGRs

| Giant Flare Source | March 5, 1979 SGR 0526–66 | August 27, 1998 SGR 1900+14 | December 27, 2004 SGR 1806–20 |
|------------------|--------------------------|-----------------------------|-------------------------------|
| Assumed distance | 55 kpc                   | 10 kpc                      | 15 kpc                        |

#### Initial Spike

|                     | Duration (s) | Peak luminosity (erg s\(^{-1}\)) | Fluence (erg cm\(^{-2}\)) | Isotropic Energy (erg) |
|---------------------|--------------|-----------------------------------|---------------------------|------------------------|
| March 5, 1979       | ∼0.25        | 3.6 \(10^{44}\)                   | 4.5 \(10^{-4}\)           | 1.6 \(10^{44}\)        |
| August 27, 1998     | ∼0.35        | >3.7 \(10^{44}\)                  | >5.5 \(10^{-3}\)         | >6.8 \(10^{43}\)       |
| December 27, 2004   | ∼0.5         | \((2\div5)\) \(10^{47}\)         | 0.6\(\div2\)             | \((1.6\div5)\) \(10^{46}\) |

#### Pulsating tail

|                     | Duration (s) | Fluence (erg cm\(^{-2}\)) | Isotropic Energy (erg) | Spectrum | Pulse Period (s) |
|---------------------|--------------|---------------------------|------------------------|----------|-----------------|
| March 5, 1979       | ∼200         | 1 \(10^{-3}\)             | 3.6 \(10^{44}\)        | kT~30 keV| 8.1             |
| August 27, 1998     | ∼400         | 4.2 \(10^{-3}\)           | 5.2 \(10^{43}\)        | kT~20 keV| 5.15            |
| December 27, 2004   | ∼380         | 5 \(10^{-3}\)             | 1.3 \(10^{44}\)        | kT~15–30 keV| 7.56         |

#### References

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A thermal bremsstrahlung with temperature of the order kT~40 keV (see Fig. 2(c)), consistent with previous measurements of SGRs bursts in the hard (\(>20\) keV) X–ray range. However, such a spectral shape does not fit well the data below 10 keV, which show a decrement not compatible with a bremsstrahlung model. This had already been noticed in bursts from SGR 1900+14 observed with BeppoSAX and HETE-2. Similarly, the cumulative spectrum (1-10 keV) of the bursts seen in the 2004 XMM-Newton observations of SGR 1806–20 are better fitted by a blackbody with temperature ∼2 keV.

### 4 The giant flare of 2004 December 27

The bursting activity of SGR 1806–20 culminated on 2004 December 27, when the first giant flare from this source was discovered with INTEGRAL and detected by more than twenty-one satellites. This flare produced the strongest flash of gamma-rays at the Earth ever observed, causing saturation of most in-flight detectors, significant ionization of the upper atmosphere, and a detectable flux of radiation backscattered from the Moon.

Two similar, but less intense, giant flares had been seen in the past from two other SGRs. All events had a similar structure, consisting of a short initial spike with a harder spectrum, followed by a softer decaying tail lasting several minutes, modulated at the neutron star rotational period. The energetics involved in these three giant flares are compared in Table 1. Note that, especially for what concerns the initial spike, the measurements are subject to uncertainties due to instrumental effects induced by the extremely high photon rate, which often led to instrument saturation. The range of values shown in the table for SGR 1806–20 reflects different reports in the literature. Despite these uncertainties, some interesting considerations can be done.

For instance it is clear that the energy in the tails of the three events was roughly of the same order, while the initial spike of SGR 1806–20 was much more energetic than those of the previous flares from the other SGRs. The fact that the energy in the tail is similar in the three giant flares,
Figure 3: Light curve of the 27 December 2004 giant flare at energy $>80$ keV. The original data from the SPI-ACS (time resolution of 50 ms) have been rebinned at 50 s to better show the emission lasting until one hour after the start of the outburst (due to this rebinning the pulsations at 7.56 s in the time interval 0-400 s cannot be seen in this plot). Note that the peak of the flare reaching an observed count rate $>2 \times 10^6$ counts s$^{-1}$ is out of the vertical scale.

despite the much higher total energy release of SGR 1806–20 is consistent with a magnetic field of the same order in the three sources. In fact the pulsating tail emission originates from the small fraction of the energy released during the initial hard pulse that is trapped by closed field lines in the neutron star magnetosphere forming an optically thick photon-pair plasma\footnote{2}. The amount of energy that can be confined in this way is determined by the magnetic field strength, which is thus inferred to be of the same order in these three magnetars.

At the time of the flare, INTEGRAL was pointed $106^\circ$ away from the direction of SGR 1806–20 that therefore was outside the field of view of its imaging instruments. However, useful data could be obtained with the Anti-Coincidence Shield (ACS) of the INTEGRAL SPI instrument. In fact the ACS, with a total mass of 512 kg of bismuth germanate scintillators, besides serving as a veto for the SPI germanium spectrometer, works as a sensitive omnidirectional detector for gamma-ray bursts\footnote{27}. It provides light curves for photons of energy above $\sim 80$ keV in time bins of 50 ms. The initial spike of the giant flare from SGR 1806–20 was so bright to saturate the detector for about 0.6 s and to cause a reflection from the Moon strong enough to be detected\footnote{22} by the ACS after a light travel time delay of 2.8 s.

Contrary to the detectors on other satellites, which could observe the giant flare emission only for a few minutes before it faded below their sensitivity thresholds, the INTEGRAL ACS detected an additional component lasting about one hour\footnote{22}. As shown in Fig. 3, this emission is clearly distinct from the pulsating tail seen in the first $\sim 400$ s after the flare start. It peaked at $t \sim 650$ s and then decayed with time approximately as a power law $\sim t^{-0.85}$. Its fluence above 80 keV was of the order of $3 \times 10^{-4}$ erg cm$^{-2}$, which extrapolating to lower energies and assuming isotropic emission implies an emitted energy ($>3$ keV) of $\sim 1 - 2 \times 10^{44}$ ergs. This long lasting emission can be explained as a hard X–ray afterglow produced by the matter ejected relativistically during the initial spike. In this case the bulk Lorentz factor $\Gamma$ can be estimated from the time of the afterglow onset, as in simple gamma-ray burst afterglow models based on
synchrotron emission\cite{28}.

\[ \Gamma \sim 15 \left( \frac{E}{5 \times 10^{43} \text{ erg}} \right)^{1/8} \left( \frac{n}{0.1 \text{ cm}^{-3}} \right)^{-1/8} \left( \frac{t_0}{100 \text{ s}} \right)^{-3/8} \]

where \( n \) is the ambient density. The inferred value of \( \Gamma \) is smaller than the typical values of gamma-ray bursts, but consistent, considering the large involved uncertainties, with the mildly relativistic outflow derived from the modelling of the radio data obtained after the SGR 1806–20 flare.\cite{29}\cite{30}

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