Observation of Soft Gamma Repeaters with BeppoSAX

MARCO FEROCI

1 Istituto di Astrofisica Spaziale e Fisica Cosmica, Consiglio Nazionale delle Ricerche, Rome, Italy

ABSTRACT. In this paper I will briefly review what, in my view, are the main contributions of BeppoSAX to the understanding of the class of sources known as Soft Gamma Repeaters. These enigmatic sources were firmly identified as steady pulsars just during the operating lifetime of BeppoSAX. All the instruments onboard BeppoSAX have at some level contributed to this field with specific observations, always allowing high quality - sometimes unprecedented - studies of the quiescent counterparts or the bursting behavior of these sources. I will try to stress the results that were uniquely achieved by BeppoSAX and identify their impact on the knowledge of the physics at work in these sources.

1. Introduction

The field of Soft Gamma Repeaters (SGRs) underwent a golden age during the operating life of BeppoSAX. This was likely due to a rare combination of events: availability of suited instrumentation, effectiveness and ability of the investigators, and a significant co-operation by the sources. Periodicities were discovered in the X-ray quiescent counterparts of two SGRs, providing support to the interpretation of these sources as magnetars, the celestial objects hosting the highest known magnetic fields. In addition, one source - SGR 1900+14 - emitted two large flares, one of which similar to the famous 1979 March 5th event. Finally, one new source - SGR 1627-41 - was discovered by the BATSE experiment (not to mention the 0.5±0.5 new SGR that might have emitted just two short bursts and nothing more).

2. BeppoSAX Statistics

The BeppoSAX Narrow Field Instruments (NFI) have observed the three SGR sources that happened to be active during its operational life time (SGR 1900+14, SGR 1806-20 and SGR 1627-41) both during active and quiescent periods. In Table 1 we provide the complete and definitive journal of NFI observations of SGRs, providing information about the type of observation (Standard or Target of Opportunity) that also provide a hint on whether the specific source was active (ToO) or not (Standard) at the time of the observation. We caution the reader that this works effectively for the ToO observations, whereas for the standard ones it may well have happened that the source was, by chance, active at the time of a well-ahead planned Standard observation.

The total NFI time spent on the SGRs is approximately 735 ks. For comparison, in Table 2 we list the amount of time spent by the BeppoSAX NFI on several classes of targets. As can be seen, the SGRs used only 1.2% of the total BeppoSAX observing time, and 1% of the spacecraft pointings. But in contrast to the small fraction of observing time spent on these sources, the science return, also when measured through the number of papers published on refereed journals making a significant use of the BeppoSAX data, is pretty large leading so far to an average of ~0.6 papers per observation, and 0.02 papers per MECS ks.
The SGR sources were also serendipitously observed by the wide field BeppoSAX instruments, the Wide Field Cameras (WFC) and the Gamma Ray Burst Monitor (GRBM). The systematic and complete analysis of the serendipitous SGR observations with the WFC is still in progress. For the specific source SGR 1900+14, such an analysis brought (Jean in ‘t Zand, private communication) to a total exposure of 2.3 Msec, accumulated over the 6-year BeppoSAX lifetime: only 9 short bursts were observed, 3 of which were the precursors of the 18 April 2001 flare (see below). In addition to that,
the WFC detected the early phase of the 18 April 2001 flare (see below). For the other sources, especially SGR 1806-20 and SGR 1627-41, similar total exposures are expected after a complete scan of the full WFC data archive, whereas for SGR 0526-66 a smaller exposure time may be expected being off the Galactic plane.

On the GRBM side, the effective area of the instrument, peaked around 200 keV, and the onboard trigger parameters (optimized to events longer than 1 s) were not optimal for the detection of the soft short recurrent bursts from the SGR sources. It detected approximately 20 short events and the two large flares (27 August 1998 and 18 April 2001) from SGR 1900+14 (see below, and Figure 3).

3. Main BeppoSAX Results on SGRs: a biased view

In this section I will outline those that I consider the major results obtained through BeppoSAX in the field of SGRs. I will go through the results following their chronology, either in their appearance in the sky or in the literature, without any attempt to make neither the list or the report on each result exhaustive. For this reason, we refer the reader to the original papers for the individual observations.

3.1. GRBM Detection of the Giant Flare of 27 August 1998 from SGR 1900+14

After few years of burst-quiescence, on May 1998 the source SGR 1900+14 resumed to burst activity with the emission of a few short bursts. An ASCA observation of the quiescent source carried out, by chance, few days prior to the reactivation revealed a 5.16 s periodicity in the steady X-ray emission (Hurley et al. 1999).

On 27 August 1998 the source confirmed its new period of activity with the emission of the second giant flare in the history of the SGRs (the first one being the 1979 March 5th event from SGR 0526-66). Despite an intrinsic smaller luminosity with respect to the March 5th event, that of August 27 was the brightest signal so far received at Earth by a cosmic source outside our Solar System, reaching a peak flux in excess of $3 \times 10^{-2}$ ergs cm$^{-2}$ s$^{-1}$ above 15 keV (Mazets et al. 1999). The other exceptional property of this flare was in its soft gamma-ray light curve: the 5-minutes long exponential-like decay of the flux was indeed modulated with the same 5.16-s period of the quiescent pulsar (Figure 1, far top panel). In addition, the data of the BeppoSAX Gamma Ray Burst Monitor (40-700 keV) first revealed a very complex (a four-peaked repetitive pattern) structure of the pulse gradually setting in after $\sim$40 s (Figure 1, top panel) (Feroci et al. 1999).

A study of this event, carried out using the data from the BeppoSAX/GRBM and from Ulysses gamma ray burst monitor (25-150 keV) brought to the interpretation and fitting of the decay curve with the trapped fireball model (Feroci et al. 2001a, Thompson & Duncan 2001). The latter is a somewhat natural consequence of the interpretation of the giant flares in the context of the magnetar model (e.g., Thompson & Duncan 1995). In short, this model interprets the giant flare as due to a magnetically driven instability, involving a large propagating fracture in the crust of a neutron star hosting a magnetic field as large as $\sim 10^{14-15}$ G (Thompson & Duncan 2001). Half or more of the burst energy is suddenly released in the form of a relativistic outflow of electron-positron pairs and hard gamma-rays (the initial hard spike). Part of the fireball is instead trapped in the magnetic field and evaporates in a finite time (the evaporation time in the trapped fireball function), by emitting thermal radiation. A fraction of this thermal radiation (of the order of 20% in energy) is indeed Compton-reprocessed to a non-thermal tail by an extended pairs corona, living around the trapped fireball for the first $\sim$40 s after the initial spike (as indicated by the excess emission with respect to a pure trapped fireball light curve, Thompson & Duncan 2001, Feroci et al. 2001a). As can be seen from the bottom panel of Figure 1, the trapped fireball model nicely fits the decaying flux data, especially at the later stages where it drops much sharper than an exponential (that
Fig. 1. Top: The giant flare of 27 August 1998 as detected by the BeppoSAX GRBM, together with a 2-channel spectral evolution expressed in terms of a temperature evolution (from Feroci et al. 1999). Bottom: the light curve of the same event - here in the 25-150 keV energy range, binned at 5-s to average over the spin modulation - as described in terms of the evolution of a trapped fireball with different model parameters (see text and Feroci et al. 2001a for details).
actually significantly overestimates the source counts at the end of the decay curve), at the characteristics evaporation time of the fireball. The fit is very satisfactory in all the three energy ranges under study, 25-150 keV, 40-100 keV and 100-700 keV. Interestingly, the same model describes in a similarly excellent way the light curve of the March 5th event (Feroci et al. 2001a).

3.2. NFI Discovery of a blackbody component in the X-ray spectrum of the quiescent SGR 1900+14

Among the properties that the SGRs share with the Anomalous X-ray Pulsars (e.g., Mereghetti et al. 2002) is the shape of their energy spectrum. The link has become tighter after the discovery of a thermal component in the X-ray energy spectrum of SGR 1900+14, obtained by Woods et al. (1999a) using the BeppoSAX/NFI to observe the source in quiescence. This was the first detection of a blackbody component ($kT \sim 0.5$ keV) in the energy spectrum of an SGR. Later observations of the same source (e.g., Feroci et al. 2003, Mereghetti et al., in preparation) show that a spectral model including a blackbody plus a power law, with interstellar absorption, is indeed well appropriate to describe the energy spectrum when the source is in quiescence, whereas the active source state (that is, during an afterglow - see below) the blackbody is not requested, meaning that is absent or, more likely, overwhelmed by the non-thermal spectral component.

Chandra observations of the quiescent counterpart to SGR 0526-66 (Kulkarni et al. 2003) provided indications about the possible presence of a $\sim 0.5$ keV blackbody in the energy spectrum also of this source, thus confirming and extending the link even further. The definite proof about the link between SGRs and AXPs, however, was provided by the recent detection of SGR-like flares by AXP sources (Gavriil et al. 2002).

3.3. NFI Discovery and Localization of the X-ray counterpart to SGR 1627-41

Among the BeppoSAX "scores" in the field of SGRs, the remarkable discovery of the X-ray counterpart to the last confirmed SGR, 1627-41, has certainly a primary importance. In fact, after the first detection of a burst switch-on of this source on June 1998, its $\sim$ few arcminutes localization was obtained using the All Sky Monitor onboard RossiXTE, combined with the annulus provided by the InterPlanetary Network. Starting from these coordinates, Woods et al. (1999b) used the BeppoSAX/NFI to search for the quiescent counterpart and found the new source SAX J1635.8-4736, at a location superposed to the supernova remnant (SNR) G337.0-0.1. If the SGR and the SNR can be considered physically associated, then the distance of the SGR would be about 11 kpc, and the intrinsic source luminosity during the discovery observation was about $10^{35}$ erg s$^{-1}$, generally coherent with the quiescent luminosity of the other sources from this class.

The location of the new source just on top of the SNR radio profile (although offset by the radio core) corroborated the already claimed association between SGRs and SNRs. However, the latter association has been more recently argued against, not only for this source but for the whole class (Gaensler et al. 2001).

3.4. The Large Flare of 18 April 2001 from SGR 1900+14

This section is entirely dedicated to the large flare of 18 April 2001 from SGR 1900+14. For this event BeppoSAX played a major role, obtaining a series of unprecedented observations. Each of them is briefly reported in the following sections. For a more detailed discussion, we refer the reader to the referenced papers.
Fig. 2. The 18 April 2001 flare from SGR 1900+14 as detected by the BeppoSAX GRBM (top panel, Guidorzi et al. 2003) and its relative timing with the pulsations of the persistent 2-10 keV emission measured with the RossiXTE PCA few days after the flare (bottom panel, Woods et al. 2003).

3.4.1. GRBM Detection of the Prompt Event

At the time when the large flare went off, 18 April 2001 - 07:55 UT, the Sun was flooding the interplanetary space with a large and variable flux of protons. For this reason, the two other GRB detectors that could have provided high quality data of the event, Ulysses and Konus-Wind, were basically blinded from the solar particle flux. Therefore, the only instrument that provided high time resolution data of the event was the Gamma ray Burst Monitor onboard BeppoSAX (Guidorzi et al., 2001). The top panel of Figure 2 shows the count rate in the 40-700 keV energy range, with a time resolution of 7.8 ms.

As it appears also from the light curve, this event was extraordinary under many respects. Similarly to the two giant flares (5 March 1979 from SGR 0526-66 and 27 August 1998 from SGR 1900+14), the count rate is modulated at the same period as the quiescent pulsar. In this respect it is worth looking at the relative timing between the burst light curve and the pulsar, as derived by observations carried out with the Proportional Counter Array (PCA) onboard RossiXTE (Woods et al. 2003). This is shown in the bottom panel of Figure 2 that shows how the first 7 pulses of the burst are consistent with being in phase with the pulsar phase, whereas the last peak is the
only one off-set and seems almost unrelated with the main event. The timing history of the pulsar across the April 18 flare is reported in Woods et al. (2003). It shows that, contrary to what happened for the August 27 giant flare (Woods et al. 2001, Palmer 2002), no detectable glitch and pulse profile change was induced by this event.

Still on the light curve, two other features are worth to be noticed. First, the duration of the event. In this case it is approximately 40 s, whereas in the two giant flare was >3 minutes and ~5 minutes. This event, therefore, appears to be intermediate in duration, breaking the bi-modality that held until its detection between the short bursts (usually shorter than 1 s, and never above 4-5 s) and the giant flares (minutes), suggesting a possible continuous spectrum of durations. Also the energetics of the April 18 event was intermediate between the short bursts and the giant flares: the 40-700 keV peak luminosity was $\sim 1.3 \times 10^{41}$ erg s$^{-1}$ and the total emitted energy about $2 \times 10^{42}$ erg (assuming a distance of 10 kpc).

The other major difference in the light curve with respect to the giant flares, is the absence of the short, very hard peak at the beginning of the event. In the case of the August 27 event, based on the radio (Frail et al. 1999) and gamma-ray (Feroci et al. 2001a, Thompson & Duncan 2001) data, this peak was interpreted as a signature of the ejection of relativistic particles. If that interpretation was correct, then the absence of that peak in the April 18 implies that such a mini-fireball emission did not occurred, or was directed away from the observer.

Although different under many respect, the light curve of this event shares another property with the two giant flares: the envelope of the decay can be well described with the same trapped fireball model that describes exquisitely the light curves of the two giant flares! In this case the fireball parameters were $t_{\text{evap}} \sim 37$ s and fireball index $\sim 0.4$.

### 3.4.2. WFC Detection of the Prompt Event

The time of occurrence of the April 18 burst was in a sense very timely for BeppoSAX. In fact, it occurred at a time when BeppoSAX was manoeuvring to reach the planned pointing direction for the NFL. During some manoeuvres, the satellite needed to step through temporary attitudes. At the time of the burst the temporary attitude position was such that SGR 1900+14 was in the field of view of the WFC! Therefore, this lucky event brought to the first ever detection of a large SGR flare at soft X-rays. Unfortunately, the event was so bright that after only 3 s it triggered the self-protective instrument switch-off, preventing us to collect X-ray data for the rest of this exceptional event. On the other hand, the imaging capabilities of the BeppoSAX WFC allowed immediately to uniquely identify SGR 1900+14 as the emitting source. The first few seconds of data show an X-ray light curve significantly different from the simultaneous gamma-ray light curve, implying a large X-to-gamma spectral evolution (Figure 3). Instead, using only X-ray data we do not find significant spectral evolution, nor evident spectral features.

### 3.4.3. WFC Discovery of X-ray Precursors

At the time of the April 18 flare, the source SGR 1900+14 had been burst-quiet for about two years. Contrary to what happened with the August 27 giant flare, when the source went out of the burst-quiescence few months before the flare emitting several short bursts, in this case no "standard" short bursts were detected before the emission of the large flare. Instead, an inspection of the available pre-burst WFC data revealed 3 short (100, 125 and 55 ms in duration) and weak bursts, occurred between 2500 and 400 seconds before the main flare (Feroci et al. 2001b). None of these events was detected by the BeppoSAX/GRBM, or Ulysses or Konus-Wind, and the search for other pre-flare bursting activity failed to find any other precursor event in the gamma-ray data.
Fig. 3. The 18 April 2001 flare from SGR 1900+14 as detected by the BeppoSAX GRBM (40-700 keV, top panel) and by the BeppoSAX/WFC (2-10 keV, bottom panel), before the WFC instrument was switched off by the self-protective automatic procedure.

from these experiments. The three events thus represent the wake up of the source to a burst-active phase, that later continued with the April 18 flare and with several short bursts in the following months.

3.4.4. NFI Discovery of an X-ray Afterglow

Last but not least, BeppoSAX pointed its sensitive narrow field X-ray telescopes to the source less than 8 hours after the April 18 flare. The pointing lasted for about one day, and was repeated for the same exposure approximately a week later. The source was initially detected in 2-10 keV at a flux level ~5 times larger than the usual quiescent value. As it appears from the BeppoSAX data points (full triangles in Figure 4, top panel), the 2-10 keV flux decayed by a factor of 5 between the beginning of the first BeppoSAX observation and the second pointing, indicating a return to quiescence. Also the bursting activity accompanied the return to quiescence: several short bursts were detected during the first observation, whereas a single burst showed up in in the data of the second pointing. The data presented here were obtained removing the bursts from the flux history.

The BeppoSAX observation was also coordinated with a series of observations with RossiXTE/PCA (squares in the top panel of Figure 4) and Chandra/ACIS-S (circles). The overall set of data were fit with an analytic law including a constant component - accounting for an underlying persistent emission - plus a power law describing the excess (afterglow) emission. As can be seen from the dashed line in the top panel of Figure 4, an index of 0.89±0.06 provides a reasonably good description of the decay trend.

However, on top of the general decay trend, the BeppoSAX light curve shows a feature at times around \( t \sim 10^5 \) s after the burst. A bump stands out of the power law decay.
Any attempts to attribute this feature to an instrumental effect or to the Sun activity (that was pretty high during that period) failed, leading to the conclusion that it was related to the source itself. In the attempt to characterize the bump, we have carried out a time-resolved spectral and timing analysis of the BeppoSAX MECS data, bringing to the results shown in the middle and bottom panels of Figure 4 in terms of hardness ratio and pulsed fraction, respectively.

The spectral analysis reveals a general softening trend of the 2-10 keV radiation. In fact, from the spectral analysis of the two BeppoSAX individual observations a clear difference is found (Feroci et al. 2003). The spectrum of the first observation can be well fit with a simple power law (photon index \(\sim 2.6\)), with interstellar absorption. Instead, the spectrum of the second observation requires an additional spectral component, a blackbody with temperature \(\sim 0.6\) keV, with the power law becoming harder (photon index \(\sim 1.5\)). Therefore, the softening observed in the hardness ratio shows the gradual emergence of the blackbody component with respect to the power law when the source is returning to its quiescent status, confirming what already reported in Sect. 3.2. However, no special spectral signature seems associated with the bump.

The timing analysis shows that the pulsed fraction is generally decreasing, especially from the first to the second observation (see Woods et al. 2003 for a detailed discussion), and the bump seems indeed tracked also in the evolution of the pulsed fraction, although the statistical accuracy does not allow any clear statement about variability.
4. Conclusion

Despite the relative small amount of time spent by BeppoSAX on the class of Soft Gamma Repeaters sources, a number of unique results were obtained in this field through its data. These were largely due to the flexibility of this satellite, both in terms of instrumentation and managing of the observation program. On one hand, the large field of view covered with moderate sensitivity by the WFC and the GRBM allowed to detect unpredictable transient events, and collect high quality data for them. On the other hand, the good sensitivity of the imaging narrow field instruments, combined with their flexible scheduling, allowed to study the peculiar behavior of these stars soon after their outbursts and to discover a new counterpart.

I would like to close this review with the content of the last command uplinked to the satellite on 2002 April 30 at 13:24:52 UT, after the definitive switch off: Bravo BeppoSAX!

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