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Quiet but still bright: *XMM–Newton* observations of the soft gamma-ray repeater SGR 0526–66⋆

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ABSTRACT

SGR 0526–66 was the first soft gamma-ray repeater from which a giant flare was detected in 1979 March, suggesting the existence of magnetars, i.e. neutron stars powered by the decay of their extremely strong magnetic field. Since then, very little information has been obtained on this object, mainly because it has been burst inactive since 1983 and the study of its persistent X-ray emission has been hampered by its large distance and its location in a X-ray bright supernova remnant in the Large Magellanic Cloud. Here, we report on a comprehensive analysis of all the available *XMM–Newton* observations of SGR 0526–66. In particular, thanks to a deep observation taken in 2007, we measured its pulsation period ($P = 8.0544 \pm 0.0002$ s) 6 years after its latest detection by *Chandra*. This allowed us to detect for the first time a significant reduction of its spin-down rate. From a comparison with two shorter *XMM–Newton* observations performed in 2000 and 2001, we found no significant changes in the spectrum, which is well modelled by an absorbed power law with $N_{\rm H} = 4.6^{+0.7}_{-0.5} \times 10^{21}$ cm^{-2} and $\Gamma = 3.27^{+0.07}_{-0.04}$. The high luminosity ($\sim 4 \times 10^{35}$ erg s^{-1}, in the 1–10 keV energy band) still observed ∼25 years after the latest detection of bursting activity places SGR 0526–66 in the group of bright and persistent magnetar candidates.

Key words: stars: neutron – ISM: individual: N49 – supernova remnants – X-rays: individual: SGR 0526–66 – X-rays: stars.

1 INTRODUCTION

On 1979 March 5, an extremely bright gamma-ray burst (GRB), followed by a >60 s long tail pulsating at a period of 8.1 ± 0.1 s, was detected by many spacecrafts (Mazets et al. 1979). The event was localized within the young (∼5000–10 000 years old) supernova remnant (SNR) LHA 120–N49 (N49) in the Large Magellanic Cloud (LMC; Cline et al. 1982). These properties indicated that the burst was emitted by a young neutron star, leading Duncan & Thompson (1992) and Paczynski (1992) to propose the existence of neutron stars with magnetic fields of $\sim 10^{15}$ G that were called *magnetars*. The detection of many weaker bursts from the same direction in the following 4 years indicated that the March 5 event was not a typical GRB, but an exceptional outburst from a small class of sources which had been just discovered and called soft gamma-ray repeaters (SGRs). Indeed the 1979 March 5 event from SGR 0526–66 was the first 'giant flare' observed from an SGR. Only two other such events have been observed in the following years, each one from a different SGR (Hurley et al. 1999, 2005).

Up to now, only six SGRs have been discovered (plus a few candidates). They are characterized by the emission of short bursts of gamma-rays during sporadic periods of activity. In addition, they are also observed as pulsating X-ray sources with periods in the 2–9 s range and persistent luminosities up to $\sim 10^{36}$ erg s^{-1}. The magnetar model was developed to explain both their bursting and persistent emission (Thompson & Duncan 1995) and later extended

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Table 1. Log of the *XMM–Newton* observations of SGR 0526–66.

Observation	Date	Instrument	Mode[a]	Filter	Net exposure (ks)
A[b]	2000-07-08	PN	FF	Medium	4.3
		MOS1	FF	Medium	8.4
		MOS2	FF	Medium	8.5
B	2001-04-08	PN	FF	Medium	6.7
		MOS1	FF	Thick	4.6
		MOS2	FF	Medium	12.6
		PN	SW	Medium	5.8
		MOS1	FF	Medium	12.1
C	2007-11-10	PN	LW	Thick	60.3
		MOS1	SW	Thick	69.7
		MOS2	SW	Thick	69.7

[a]The time resolution of the operating modes is as follows: PN full frame (FF): 73 ms; PN large window (LW): 48 ms; PN small window (SW): 6 ms; MOS full frame (FF): 2.6 s and MOS small window (SW): 0.3 s.
[b]6 arcmin off-axis.

(Thompson & Duncan 1996) to the interpretation of the anomalous X-ray pulsars (AXPs). These are a group of nine X-ray sources (plus some candidates) with similar properties to those of the SGRs (see Mereghetti 2008 for a review).

The persistent X-ray emission from SGR 0526–66 was first detected with *ROSAT* (Rothschild, Kulkarni & Lingenfelter 1994) and then observed by *Chandra* in 2000 and 2001 (Kulkarni et al. 2003; Park et al. 2003), with a constant X-ray luminosity of $\sim 10^{36}$ erg s^{-1} (unabsorbed, in the 0.5–10 keV energy range). Being SGR 0526–66 a rather faint X-ray source, the pulsation of its persistent emission was detected only in the two *Chandra* observations carried out in 2000 and 2001 (Kulkarni et al. 2003). The periods measured with *Chandra* are compatible with the 8 s period detected in the pulsating tail of the 1979 giant flare and give a spin-down rate of $\dot{P} = (6.5 \pm 0.5) \times 10^{-11}$ s s^{-1}, a value in the same range as that of the other magnetar candidates.

In order to measure again the pulsation period and search for long-term flux and spectral changes, we obtained an ∼70 ks long observation of SGR 0526–66 with *XMM–Newton*, 6 years after the latest X-ray observation. In the following, we report on the results of this recent observation, together with the analysis of two short archival *XMM–Newton* observations performed in 2000 and 2001.

2 OBSERVATIONS AND DATA ANALYSIS

SGR 0526–66 was observed by *XMM–Newton* on 2007 November 10 for about 70 ks. The field containing SGR 0526–66 had already been observed by *XMM–Newton*, with shorter exposure times, on 2000 July 8 and 2001 April 8. In the 2000 observation, SGR 0526–66 was ∼6 arcmin off-axis, while in the other observations it was on-axis. We concentrate here on the analysis of the data collected with the EPIC (European Photon Imaging Camera) instrument, which is composed by a PN (Strüder et al. 2001) and two MOS X-ray cameras (Turner et al. 2001), sensitive in the 0.2–15 keV energy range. Details on the instrument settings (optical blocking filter and operating mode) for each observation are listed in Table 1. For the longest observation, we also used the data collected by the Reflection Grating Spectrometer (RGS; den Herder et al. 2001), which worked in parallel to the EPIC instrument and had a net exposure time of 71 ks for each of its two units (RGS1 and RGS2). This high-resolution spectrometer is sensitive in the 0.35–2.5 keV energy range.

All the data were processed using the *XMM–Newton* Science Analysis Software (SAS version 8.0.0) and the calibration files released in 2007 August. The standard pattern selection criteria for the EPIC X-ray events (patterns 0–4 for PN and 0–12 for MOS) were adopted. The RGS analysis followed the standard selection criteria as well.[1] Response matrices and ancillary files for each spectrum were produced using the SAS software package, and the spectra were fitted using XSPEC version 11.3.1. All errors reported in the following analysis are at 1σ.

2.1 Spectral analysis

The spectral analysis of SGR 0526–66 with *XMM–Newton* is complicated by the location of this source within the bright SNR N49, whose spatial extent (∼40 arcsec radius) is only slightly larger than the instrumental point spread function (the 90 per cent encircled energy fraction for a point source is ∼40 arcsec).

Rather than attempting to subtract the SNR contribution as a background component, we included it in the fits with a free normalization and a fixed spectral shape determined as explained below. To reduce the contamination from the soft X-ray emission of N49, we extracted the SGR EPIC spectrum in the 1–10 keV energy range from a circle of 10 arcsec radius (this includes 60 per cent of the point source counts at 5 keV). The background spectrum was extracted from a region outside the SNR, but in the same CCD as the SGR (see Fig. 1).

To model the soft and line-rich spectrum of the SNR, we took advantage of the high-resolution spectra collected by the RGS instrument during the longest observation. We extracted the first-order spectra from the standard region normally used for point sources, setting the centre of the SNR as source position (such a selection includes most of the photons detected from the SNR, thanks to its relatively small extension). The RGS spectral analysis was restricted to the 1–2 keV energy range. To model the SNR above 2 keV, we extracted a 1–10 keV PN spectrum from a 40 arcsec circle centred in the middle of the SNR and fitted it together with the spectra of the two RGS units. Based on the results of previous X-ray observations

[1] See http://xmm.esac.esa.int/external/xmm_user_support/documentation/sas_usg/USG/.

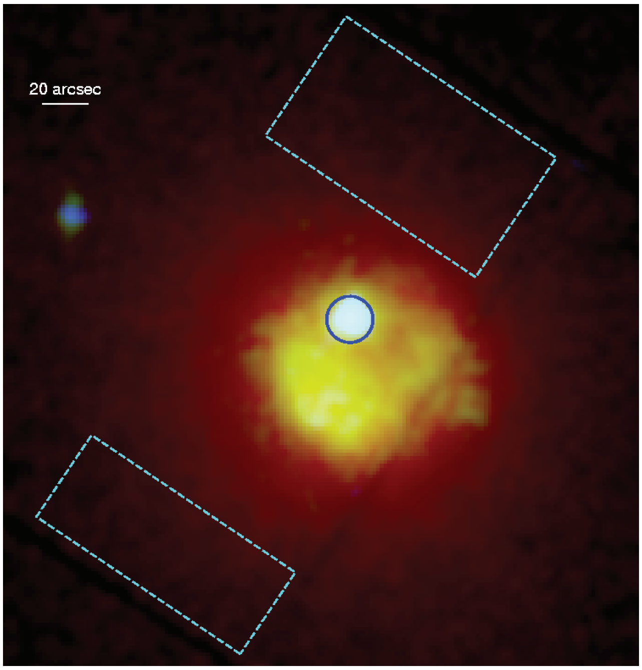

Figure 1. EPIC PN image of the field of SGR 0526–66 during the 2007 observation. Photon energy is colour-coded: red corresponds to 0.5–2 keV, green to 2–4 keV and blue to 4–10 keV. The source and background regions considered for the analysis are overplotted.

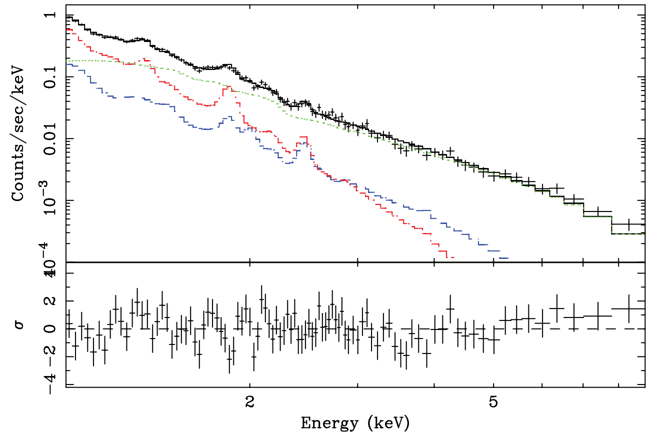

Figure 2. EPIC PN spectrum of SGR 0526–66 collected during the longest *XMM–Newton* observation in 2007. The model, obtained by a simultaneous fit of the PN and MOS spectra (see the corresponding parameters in Table 2), is an absorbed power law (green) and the sum of two plane-parallel shock components (in blue the warmer and in red the cooler one) to model the contamination from the SNR.

of N49 (Park et al. 2003; Bilikova et al. 2007), we used a model consisting of the sum of two plane-parallel shock components at different temperatures (VPSHOCK in XSPEC) both corrected for photoelectric absorption (PHABS in XSPEC). To this we added an absorbed power law to account for the emission from SGR 0526–66 . Its parameters were fixed at the best-fitting values found with *Chandra*: $N_{\rm H} = 5.6 \times 10^{21}$ cm^{-2}, $\Gamma = 3.06$, norm $= 1.18 \times 10^{-3}$ s^{-1} cm^{-2} keV^{-1} at 1 keV (Kulkarni et al. 2003). An overall normalization factor for each spectrum was also included to account for the cross-calibration uncertainties between the two RGS and the EPIC PN. A satisfactory fit [$\chi^2 = 2170/935$ degrees of freedom (d.o.f.)][2] was obtained with the following parameters: $N_{\rm H} = (1.3 \pm 0.3) \times 10^{21}$ cm^{-2}, $kT_1 = 0.577^{+0.002}_{-0.005}$ keV, $\tau_1 = 5.4^{+1.1}_{-0.8} \times 10^{12}$ s cm^{-3}, $kT_2 = 1.10 \pm 0.01$ keV, $\tau_2 > 3 \times 10^{13}$ s cm^{-3}, Ne/Ne$_\odot = 0.66 \pm 0.02$, Mg/Mg$_\odot = 0.59 \pm 0.01$, Si/Si$_\odot = 0.79 \pm 0.01$, S/S$_\odot = 1.00 \pm 0.04$, Ca/Ca$_\odot = 0.6 \pm 0.4$, Fe/Fe$_\odot = 0.45 \pm 0.02$. The abundances of the other elements are fixed to the solar values (Anders & Grevesse 1989). These parameters are in good agreement with previous studies of this SNR (Park et al. 2003; Bilikova et al. 2007). The unabsorbed flux in the 1–10 keV energy range is 7.1×10^{-12} erg cm^{-2} s^{-1} for the SNR and 1.6×10^{-12} erg cm^{-2} s^{-1} for the SGR.

We then fitted the EPIC spectra extracted from the small region around SGR 0526–66 with an absorbed power law[3] plus the model of the SNR described above. All the SNR model parameters were fixed at their best-fitting values, except for the normalization, in order to properly account for the unknown intensity of the SNR emission in the source extraction region.[4] A good fit ($\chi^2 = 274.1/233$ d.o.f.; see Fig. 2) is obtained with a hydrogen column density $N_{\rm H} = (4.6^{+0.7}_{-0.5}) \times 10^{21}$ cm^{-2} and a photon index $\Gamma = 3.27^{+0.07}_{-0.04}$. The lack of systematic residuals in correspondence with the SNR brightest spectral lines (see Fig. 2) indicates that the SNR contamination is sufficiently well modelled. The 1–10 keV (unabsorbed) flux of the power-law component is $(1.25^{+0.05}_{-0.02}) \times 10^{-12}$ erg cm^{-2} s^{-1}. This corresponds to a luminosity of 4.3×10^{35} erg s^{-1} for a distance of 55 kpc.

Since no time variability is expected in the SNR contribution, we can fit the SGR spectra of the older EPIC observations with the model described above, keeping the SNR model normalization fixed at the value obtained in the longest observation. The best-fitting parameters for an absorbed power-law model are reported in Table 2.

No spectral variability is detected and significant ($>3\sigma$) flux variations larger than $\sim$50 per cent among the different *XMM–Newton* observations can be excluded.

2.2 Timing analysis

For the timing analysis, the photon arrival times were converted to the Solar system barycentre with the BARYCEN SAS task. We used the same extraction region adopted for the spectra, but we performed the analysis in the 0.65–12 keV energy band to optimize the signal-to-noise ratio. The pulse periods measured with *Chandra* using the Z_2^2 test were 8.0436(2) s on 2000 January 4 and 8.0470(2) s on 2001 August 31 (Kulkarni et al. 2003). We searched for pulsations in the period range 8.0464–8.2423 s, selected by considering the 3σ lower limit on the most recent spin period value reported by Kulkarni et al. (2003) and extrapolating to the epoch of the *XMM–Newton* observation under the assumption of a (conservative) period derivative of $0 \le \dot{P} \le 10^{-9}$ s s^{-1}. In Fig. 3, we show the Z_2^2 periodogram obtained by using the combined events from the PN and MOS cameras.

[2] Although this fit is not statistically acceptable, a detailed modelling of the SNR emission is beyond the scope of this Letter and so we did not adopt more complex spectral models.

[3] More complex spectral models, which are usually used to fit magnetar spectra, were not adopted in this case due to the uncertainty of the background subtraction.

[4] We also applied a second normalization factor to both the SNR and the SGR models to account for the cross-calibration uncertainties between the EPIC cameras; the maximum flux discrepancy we find between the EPIC cameras is lower than 15 per cent.

Table 2. Best-fitting spectral parameters for the three EPIC observations (see Table 1) of SGR 0526–66 in the 1–10 keV energy range. The spectral model consists of a fixed component modelling the SNR contamination (see the text for details) and an absorbed power-law model for the SGR emission.

Observation	SNR norm.[a]	N_H (10^{21} cm^{-2})	Γ	Flux[b] (10^{-12} erg cm^{-2} s^{-1})	χ_r^2 (d.o.f.)
A	0.117 (fixed)	$3.8^{+0.2}_{-1.6}$	$3.1^{+0.4}_{-0.1}$	$1.3^{+0.2}_{-0.1}$	1.04 (65)
B	0.117 (fixed)	$5.3^{+0.6}_{-1.1}$	$3.3^{+0.1}_{-0.2}$	1.3±0.1	0.88 (166)
C	$0.117^{+0.002}_{-0.005}$	$4.6^{+0.7}_{-0.5}$	$3.27^{+0.07}_{-0.04}$	$1.25^{+0.05}_{-0.02}$	1.18 (233)

[a]Normalization factor applied to the best-fitting model of the RGS and PN spectrum of the whole SNR.
[b]Unabsorbed flux in the 1–10 keV range.

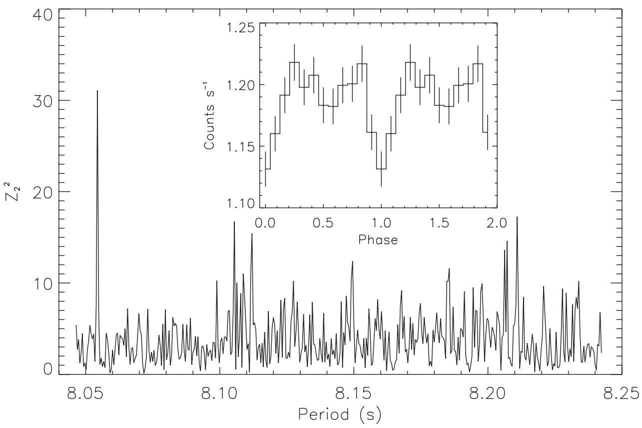

Figure 3. Z_2^2 diagram of the long *XMM–Newton* observation (PN and MOS data in the 0.65–12 keV energy range) of SGR 0526–66 in the range used for the period search (see Section 2.2). The peak at 8.0544 s is significant at 3.2σ. Inset: the corresponding EPIC pulse profile (0.65–12 keV, not background-subtracted).

Taking into account the number of searched periods (419), the peak value of 31.08 (chance probability of $\sim 3 \times 10^{-6}$) at ∼8.0544 s corresponds to a significance of ∼99.88 per cent (that is a 3.2σ detection).

To better estimate the period, we used an epoch folding technique and fitted the peak in the χ^2 versus trial period distribution as described in Leahy (1987). This led to $P = 8.0544 \pm 0.0002$ s. The resulting EPIC folded light curve is shown in Fig. 3. The pulsed fraction, defined as $(C_{max} - C_{min})/(C_{max} + C_{min})$, where C_{max} and C_{min} are the background-subtracted count rates at the peak and at the minimum, is (13.6 ± 0.9) per cent in the 0.65–12 keV energy range.[5] We repeated a similar analysis on the data sets from the two short *XMM–Newton* observations carried out in 2000 and 2001 (see Table 1), but, due to the paucity of photons, we did not detect any significant periodicity. Considering also the two periods measured by *Chandra* (Kulkarni et al. 2003), a linear fit to the period evolution of SGR 0526–66 is unacceptable (χ_r^2 of 15.6 for 1 d.o.f.). On the other hand, the period derivative inferred from our period measurement and the most recent *Chandra* detection is $(3.8 \pm 0.1) \times 10^{-11}$ s s^{-1}. Comparison with the value derived from the two *Chandra* measurements [$\dot{P} = (6.5 \pm 0.5) \times 10^{-11}$ s s^{-1}] indicates a significant decrease of the spin-down rate.

[5] The SNR contamination, evaluated from the model described in Section 2.1, is also included in the background. The error in the pulsed fraction does not include the systematic uncertainty due to the SNR contamination.

3 DISCUSSION AND CONCLUSIONS

Due to its location in the LMC, SGR 0526–66 is one of the magnetars less frequently observed. In addition to its larger distance with respect to Galactic magnetars, the analysis of its persistent X-ray emission is complicated by the bright soft X-ray emission of the N49 SNR. With a deep *XMM–Newton* observation performed in 2007, we could measure the pulsation period of SGR 0526–66 which was previously detected only in the pulsating tail following the 1979 March 5 giant flare (Mazets et al. 1979) and in two *Chandra* observations taken in 2000 and 2001 (Kulkarni et al. 2003). The pulsation profile (shown in Fig. 3) is double-peaked and the pulsed fraction is (13.6 ± 0.9) per cent. Although, to our knowledge, the pulse profile of SGR 0526–66 was never published before, these might be permanent properties of this source since a non-sinusoidal modulation and a pulsed fraction around 10 per cent were also reported for the *Chandra* data (Kulkarni et al. 2003).

Although the period measurements of SGR 0526–66 are very sparse, the value we derived shows, for the first time, a significant decrease in the spin-down rate of this source. In the magnetar model, a reduction of the spin-down rate can be interpreted as an indication of a more relaxed state of the twisted magnetosphere and should be associated with a low rate of bursting activity, a spectral softening and a decrease of the persistent X-ray luminosity (Thompson, Lyutikov & Kulkarni 2002). This behaviour is sometimes observed in magnetar candidates (see e.g. Mereghetti et al. 2005), but some exceptions have been found (see e.g. Gavriil & Kaspi 2004). In the case of SGR 0526–66, the bursting activity is indeed very low, since no bursts have been detected since 1983. However, we note that some bursts might have been missed due to its large distance and its location in a sky region not frequently monitored by γ-ray instruments.

The X-ray luminosity measured in 2007 is ∼30 per cent lower (and the spectrum slightly softer) than that reported from the analysis of *Chandra* data taken in 2000 and 2001 (Kulkarni et al. 2003). However, due to the different characteristics of the instruments and additional uncertainties due to the presence of contamination from the SNR diffuse emission, we consider these changes well within the systematic uncertainties. Using the two shorter *XMM–Newton* observations, taken almost simultaneously with the *Chandra* ones, we can instead extract the spectrum and model the SNR emission in the same way as we did for the 2007 observation. In this case, we are dominated by statistical errors and no significant changes in the spectral shape and source flux are detected.

The luminosity of SGR 0526–66, which can be well determined thanks to its accurately known distance, is higher than that of most magnetar candidates (see e.g. Durant & van Kerkwijk 2006). Since this high luminosity has not substantially varied for at least several years, it is probably a long-lasting property of this magnetar rather than a transient bright state related to its past bursting activity, culminating with the giant flare of 1979 March 5. This behaviour is radically different from the one displayed, as an example, by SGR 1627–41 that, after two distinct periods of bursting activity, rapidly decreased its persistent X-ray luminosity down to $\sim 10^{33}$ erg s^{-1} (Esposito et al. 2008). While it is unclear whether this behaviour is related to intrinsic differences between the sources (e.g. the magnetic field) or different evolutionary stages, this seems to support the emerging trend of separating the magnetars into transient and persistent objects, rather than in AXPs and SGRs. In this framework, SGR 0526–66 should therefore be considered a member of the persistent magnetars group.

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