On the cooling trend of SGR 0526–66

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Accepted 2012 April 25. Received 2012 March 27; in original form 2012 February 8

ABSTRACT
We present a systematic analysis of all archival Chandra observations of the soft gamma repeater SGR 0526–66. Our results show that the X-ray flux of SGR 0526–66 decayed by about 20 per cent between 2000 and 2009. We employ physically motivated X-ray spectral models and determine the effective temperature and the strength of the magnetic field at the surface as $kT = 0.354^{+0.031}_{-0.024}$ keV and $B = (3.73^{+0.16}_{-0.08}) \times 10^{14}$ G, respectively. We find that the effective temperature remains constant within the statistical uncertainties and attribute the decrease in the source flux to a decrease in the emitting radius. We also perform timing analysis to measure the evolution of the spin period and the period derivative over the 9-year interval. We find a period derivative of $\dot{P} = (4.0 \pm 0.5) \times 10^{-11}$ s s$^{-1}$, which allows us to infer the dipole magnetic field strength and compare it with the one determined spectroscopically. Finally, we compare the effective temperature of SGR 0526–66 with the expected cooling trends from magnetized neutron stars and suggest an initial magnetic field strength of $10^{15}–10^{16}$ G for the source.

Key words: stars: magnetars–X-rays: individual: SGR 0526-66.

1 INTRODUCTION

Soft gamma repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) are the prime representatives of magnetars – a class of neutron stars that are thought to be powered by the decay of their superstrong magnetic fields ($B \sim 10^{14–15}$ G; Duncan & Thompson 1992). Aside from emitting energetic bursts in hard X-rays and soft gamma-rays, magnetars are bright X-ray sources ($L_x \sim 10^{33}$ to $10^{36}$ erg s$^{-1}$), emitting pulsed X-rays either persistently or episodically (see Woods & Thompson 2006; Mereghetti 2008 for detailed reviews). X-ray observations of most of SGRs and AXPs over the last 30 years have shown that these sources are not steady emitters, exhibiting flux variability generally in conjunction with bursting activities (see e.g. Rea & Esposito 2011).

All known SGRs have been discovered when they went into a bursting phase, during which they emit repeated energetic bursts in soft gamma-rays. SGR 0526–66 was not an exception: it was discovered as the first SGR with an extremely bright gamma-ray burst on 1979 March 5 that was followed by a tail emission clearly pulsating at 8.1 s (Mazets et al. 1979). The burst location is within the supernova remnant (SNR), N49 in the Large Magellanic Cloud (Evans et al. 1980). The source exhibited 16 more bursts until 1983 April 5 with much lower intensity than that of the March 5 event (Aptekar et al. 2002). Since then, no bursts have been detected from SGR 0526–66.

Due to its large distance and the fact that the source is embedded in a SNR, spectral and timing studies of SGR 0526–66 have been limited. The persistent X-ray source was identified with ROSAT, yielding the earliest view of the source as it is in burst quiescence (Rothschild, Kulkarni & Lingenfelter 1994). SGR 0526–66 has been the target of two Chandra X-ray Observatory (CXO) observations in 2000 and 2001. Thanks to the superb angular resolution of CXO, X-ray spectroscopy and timing investigations of the persistent source became possible. Based on these observations, spin period of $\approx8.04$ s was measured and a tentative $P$ of $\approx6.5 \times 10^{-11}$ s$^{-1}$ was inferred (Kulkarni et al. 2003). X-ray spectrum of the SGR 0526–66 could be described well with the empirical model of an absorbed blackbody plus a power-law component. The resulting power-law index was much steeper than that of other SGRs, while it was similar to the power-law indices of AXPs, which led Kulkarni et al. (2003) to suggest that SGR 0526–66 is in a transition from the SGR-like phase to an AXP-like phase.

SGR 0526–66 and its associated SNR, N49, were recently observed with XMM–Newton. Tiengo et al. (2009) reported that the X-ray spectrum of the source does not show any significant changes compared to XMM–Newton observations performed in 2000 and 2001 and SGR 0526–66 is still a bright persistent source, emitting at an X-ray luminosity of $\approx4 \times 10^{35}$ erg s$^{-1}$. Very recently, Park et al. (2012) provided an in-depth analysis of the SNR using four Chandra observations that were obtained in 2009. They refined the
Table 1. Chandra observations of the SGR 0526−66.

| Date       | Observation ID | Exposure (ks) |
|------------|----------------|---------------|
| 2000-01-04 | 747            | 43.9          |
| 2001-08-31 | 1957           | 53.4          |
| 2009-07-18 | 10123          | 28.2          |
| 2009-07-31 | 10808          | 30.2          |
| 2009-09-16 | 10807          | 27.3          |
| 2009-09-19 | 10806          | 27.9          |

Sedov age of N49 as $r_{\text{Sed}} \approx 4800$ yr. Park et al. (2012) also analysed the X-ray spectra of SGR 0526−66 using phenomenological models, such as the sum of a blackbody and a power-law or two blackbody models. They found that the X-ray flux of SGR 0526−66 varied by about 15% between the observations performed in 2000/2001 and 2009. Further including archival ROSAT observations they detected a decay in X-ray flux by $\approx 30$% per cent for the last 17 years.

Here, we report on our systematic analysis of all archival Chandra observations of SGR 0526−66 to unveil the X-ray spectral characteristics of the source when it is in deep burst quiescence. We model the X-ray spectra with the Surface Thermal Emission and Magnetospheric Scattering (STEMS) model (Güver et al. 2007; Güver, Özel, Göğüş 2008; Özel et al. 2008; Güver et al. 2011) to determine the effective surface temperature, the surface magnetic field strength and the long-term X-ray flux of SGR 0526−66. We also perform timing analysis to construct the spin period evolution of the source and obtain the inferred dipole magnetic field strength. Finally, we compare our results with the expected cooling trends from magnetized neutron stars.

2 OBSERVATIONS AND DATA ANALYSIS

We list the observations used in our study in Table 1. Note that there are two more Chandra observations that contain SGR 0526−66 in the field of view. However, the source was observed off-axis by about 4 arcsec in one of the observations (ObsID 1041). The effects of vignetting do not allow a reliable source extraction without any contribution from the SNR. The other observation (ObsID 2515) has only 7 ks of effective exposure, which is too short to provide high enough signal-to-noise ratio X-ray spectrum. Therefore, we exclude these two pointings from our investigations.

We reprocessed all of the observations with the CIAO software suite, version 4.2, and CALDB 4.3.0 using the recently introduced chandra_repro tool. This tool automates the creation of new bad pixel file and level 2 event file. We applied barycentric correction to each event file using the axbary tool. To extract source spectra and light curves, we selected a circular region centring the neutron star with a radius of 2 arcsec, as shown in Fig. 1. For the background, we used an annular region that is centred on the coordinates of the neutron star and covers the range starting from 2.5 to 5 arcsec from the centre. Finally, we selected data from a larger annular region: centred on the neutron star and covering the range starting from 2.5 to 5 arcsec, to generate an X-ray spectrum of the SNR and obtain an independent measurement of the hydrogen column density, as detailed below. Source and SNR extraction regions are shown in Fig. 1. We extracted X-ray spectra using the specextract

\footnote{http://cxc.harvard.edu/ciao/ahelp/chandra_repro.html}

Figure 1. True colour image of the supernova remnant N49. Red, green and blue correspond to the 0.2–2.0, 2.0–4.0 and 4.0–10.0 keV ranges, respectively. Source (solid line) and SNR (dashed lines) extraction regions are also shown in cyan.

3 X-RAY SPECTRAL ANALYSIS

We fitted the data with XSPEC version 12.5.1n, using the STEMS, and assumed a reference gravitational redshift of 0.306 for the neutron star. We calculated the unabsorbed fluxes in the 0.5–6.5 keV energy range using the cflux model in XSPEC. The distance of the SGR is assumed to be 48.1 kpc (Macri et al. 2006). Uncertainties reported throughout the paper correspond to 68% confidence limits of parameters, unless indicated otherwise.

Uncertainties in the amount of interstellar absorption of X-ray photons often hamper efforts to precisely determine the intrinsic spectral shape of these sources. Furthermore, as a free parameter, hydrogen column density becomes strongly correlated with the determined temperature of the X-ray source essentially affecting the resulting best-fitting value (see e.g. Durant & van Kerkwijk 2006; Güver et al. 2012 for a detailed discussion). Therefore, an accurate estimation of the hydrogen column density is crucial to deduce the spectral characteristics of the source. The fact that SGR 0526−66 is embedded in the SNR N49 presents an advantage in this respect because it is possible to obtain an independent measurement of the hydrogen column density using the SNR. For that purpose, we extracted a SNR spectrum from the longest exposure and modelled it. Similar to the earlier studies of N49 (Park et al. 2003; Bilikova et al. 2007; Tiengo et al. 2009; Park et al. 2012), we fitted the remnant with a two-component model, consisting of two plane-parallel shocked plasma functions (Borkowski, Lyerly & Reynolds 2001; vphock in XSPEC) both absorbed by the interstellar medium, assuming a solar abundance as given by Anders & Grevesse (1989). We obtained an adequate fit with a $\chi^2$ = 1.44 for 99 degrees of freedom (d.o.f.). We note that the relatively high $\chi^2$ is mostly due to a small number of individual energy bins, which could be emission lines that cannot be resolved by the Advanced CCD
Imaging Spectrometer (ACIS-S) detector. Our best-fitting parameters are $N_{\text{H}} = (0.15 \pm 0.03) \times 10^{21} \text{cm}^{-2}$, $kT_{1} = 0.54 \pm 0.01 \text{keV}$, $\tau_{1} > 3.6 \times 10^{13} \text{cm}^{-3}$, $kT_{2} = 1.11 \pm 0.04 \text{keV}$, and $\tau_{2} = (1.21 \pm 1.1) \times 10^{10} \text{cm}^{-3}$, where $kT_{1}$, $kT_{2}$, $\tau_{1}$ and $\tau_{2}$ denote the temperature of the plasma and the upper limit on the ionization time-scale for each component. The elemental abundances we found are as follows: Ne/Ne⊙ = 0.90 ± 0.10, Mg/Mg⊙ = 0.64 ± 0.10, Si/Si⊙ = 0.66 ± 0.08, S/S⊙ = 1.01 ± 0.25 and Fe/Fe⊙ = 0.38 ± 0.04, all the other abundances were set to solar values. These results, especially the hydrogen column density, are in general good agreement with the results of Park et al. (2012). We use the hydrogen column density we inferred from this fit as a fixed parameter when analysing the spectra of SGR 0526–66 in the remainder of the paper.

We simultaneously fit all six spectra with the STEMS model. STEMS model assumes a fully ionized and strongly magnetized hydrogen atmosphere on the surface of the neutron star, which determines the general spectral characteristics of its X-ray emission (Özel 2001, 2003). In the magnetosphere, these surface photons are further scattered by mildly relativistic charges (Lyutikov & Gavriil 2006). The model has four parameters: the effective temperature, magnetic field strength at the surface, the resonant scattering optical depth and the velocity of charged particles in the neutron star magnetosphere (see e.g. Güver et al. 2007, 2008, 2011 for details). First, we allowed all STEMS parameters to vary in all observations. Such a fit resulted in a $\chi^{2}/\text{d.o.f.}$ of 1.074 for 515 d.o.f. Resulting effective surface temperature ($\sim 0.35 \text{keV}$), magnetic field strength ($\sim 3.61 \times 10^{14} \text{G}$), the magnetospheric scattering optical depth ($\sim 5.66$) and the average particle velocity ($\sim 0.55$) did not show statistically significant or systematic variations between different observations. However, due to rather low signal-to-noise ratio of individual X-ray spectra, the errors in individual model parameters were large. In order to obtain more constrained results on the effective temperature (therefore, the apparent emitting radius) and follow its time evolution, we linked the model parameters for magnetic field strength, magnetospheric scattering optical depth and the average particle velocity. This way, we obtained a $\chi^{2}/\text{d.o.f.}$ of 1.086/530. We note here that, despite adding more d.o.f. to the fit, the change in the fit statistics was negligible, further indicating that the other parameters do not show statistically significant variations. We obtained the following best-fitting parameter values when only the surface effective temperature and model normalization were allowed to vary between observations: the surface magnetic field strength $B = (3.74^{+1.11}_{-0.14}) \times 10^{14} \text{G}$, magnetospheric optical depth to resonant scattering $\tau = 5.37^{+0.51}_{-0.44}$ and the average velocity of particles $\beta = 0.52 \pm 0.03$. We then used the cflux model to calculate the unabsorbed X-ray flux in the 0.5–6.5 keV range for each observation. We present these flux measurements together with the effective surface temperature values for each observation in Table 2. We also show in Fig. 2 the 68 per cent confidence contours for the surface effective temperature and flux values. Both Fig. 2 and Table 2 show that although the X-ray flux of SGR 0526–66 decreases by a factor of 20 per cent over the last 9 years, the inferred temperature values are fairly constant during this period.

Given the fact that the surface temperature remains constant, we repeated our simultaneous fit by linking the surface effective temperature among all observations as well, in order to further constrain it, and allowed the normalization, hence the emitting area of the STEMS model, to vary between observations. This way, we obtained a $\chi^{2}/\text{d.o.f.}$ of 1.083/535. Fig. 3 shows the data together with the best-fitting model and fit residuals. As expected, the best-fitting values are very similar to what we found earlier: we obtain that the magnetic field strength at the surface is $B = (3.73^{+0.08}_{-0.10}) \times 10^{14} \text{G}$, the optical depth to resonant scattering at the neutron star

### Table 2. X-ray spectral fit results for SGR 0526–66.

| Date       | Unabsorbed flux $^a$ ($\times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2}$) | $kT_{\text{eff}}^a$ (keV) | Unabsorbed flux $^b$ ($\times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2}$) | Radius $^b$ (km) |
|------------|---------------------------------------------------------------|----------------|---------------------------------|----------------|
| 2000-01-04 | $1.33 \pm 0.02$                                              | $0.37^{+0.04}_{-0.04}$ | $1.31 \pm 0.02$                | $13.33 \pm 1.56$ |
| 2001-08-31 | $1.28 \pm 0.02$                                              | $0.36^{+0.04}_{-0.04}$ | $1.26 \pm 0.01$                | $13.09 \pm 1.54$ |
| 2009-07-18 | $1.06 \pm 0.02$                                              | $0.35^{+0.05}_{-0.04}$ | $1.04 \pm 0.02$                | $11.88 \pm 1.37$ |
| 2009-07-31 | $1.09 \pm 0.03$                                              | $0.35^{+0.05}_{-0.04}$ | $1.07 \pm 0.02$                | $12.05 \pm 1.39$ |
| 2009-09-16 | $1.04 \pm 0.02$                                              | $0.34^{+0.03}_{-0.04}$ | $1.00 \pm 0.02$                | $11.71 \pm 1.35$ |
| 2009-09-19 | $1.05 \pm 0.02$                                              | $0.34^{+0.03}_{-0.04}$ | $1.03 \pm 0.02$                | $11.85 \pm 1.37$ |

$^a$Calculated from each individual data set when all the model parameters were linked between the observations, except for the effective temperature and normalizations.

$^b$Calculated from each individual data set when all the model parameters were linked between the observations, except for normalizations.
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Figure 3. All six X-ray spectra of SGR 0526−66 obtained since 2000 (crosses), best-fitting model curves (solid lines) and the fit residuals (lower panel).

Figure 4. Variations of $\chi^2$/d.o.f. as a function of surface effective temperature (left-hand panel) and magnetic field strength (right-hand panel) as inferred from the X-ray spectral fit. Dashed and dash–dotted lines indicate the 68 and 90 per cent confidence levels for each parameter.

The magnetosphere is $\tau = 5.47^{+0.75}_{-0.49}$ and the average velocity of the magnetospheric particles is $\beta = 0.52 \pm 0.03$ and an effective temperature of $0.355^{+0.031}_{-0.024}$ keV. We note that the best-fitting value of the surface temperature does not significantly depend on the fixed hydrogen column density. Even when we allow the hydrogen column density to be a free parameter in the fit to the spectra of SGR 0526−66, we obtain a value of $N_H = (0.144 \pm 0.012) \times 10^{22}$ cm$^{-2}$, which is consistent with the value we obtained from analysing the spectrum of the surrounding SNR. The unabsorbed flux and the emitting radius values obtained from this fit are given in Table 2. In Fig. 4, we present $\chi^2$/d.o.f. contours over the surface effective temperature and magnetic field strength.
4 TIMING ANALYSIS

We performed timing analysis using all available CXO observations to determine the spin period evolution of SGR 0526−66 and to uncover variations in the pulsed fraction (PF). The time resolution of CXO observations in various subarray modes is approximately 0.4 or 0.8 s, which is not ideal but sufficient for timing purposes. Using the same selection regions described in Section 3, we extracted source events for each observation and applied barycentric correction using the axbary tool.

We also included the deep XMM–Newton observation performed in 2007 (ObsID 0505310101) in our timing investigation. We calibrated the European Photon Imaging Camera (EPIC)-pn data using SAS v.10.0.0 and the calibration files as of 2010 October. We extracted source events from a circular region with 10 arcsec radius. Note that the point spread function of XMM–Newton is not accurate enough to completely resolve the pulsar from the SNR; therefore, some fraction of unpulsed emission is expected to originate from the remnant (see Tiengo et al. 2009 for the details of contribution from the SNR). We used the barycen tool of SAS to convert each event arrival times to that of the Solar system barycentre.

To search for the pulsed signal from SGR 0526−66, we employed a $Z^2\text{}_{66}$ technique (Buccheri et al. 1983) with the number of harmonics set to $m = 2$. We performed the search in a period range between 8.0 and 8.1 s. We detected the pulsed signal with high significance in the first three CXO data sets as well as in the XMM–Newton data, while the detections in the CXO data sets with observation IDs 10806, 10807 and 10808 were marginal. In Table 3, we present only the statistically significant measurements of the spin period of SGR 0526−66, together with the chance probability and the $Z^2\text{}_{66}$ power of each measurement. To determine the rate of change of the spin period, we fit the measured periods with a first-order polynomial. We obtain a good fit with a spin-down rate of $(4.019 \pm 0.494) \times 10^{-11}\text{ s}^{-1}$. We present the evolution of the spin period as well as the best-fitting spin-down rate of SGR 0526−66 in Fig. 5. Note that our result regarding the spin evolution is based on only four measurements obtained over 9 years. A more precise measurement of the spin-down rate requires more frequent deep observations.

Finally, we constructed the pulse profile and calculated the root mean square (rms) PF for each observation with significant spin period detection. The rms PF is calculated as

$$\text{PF} = \left\{ \frac{1}{N} \sum_{i=1}^{N} (R_i - R_{\text{ave}})^2 - \Delta R_i^2 \right\}^{1/2} / R_{\text{ave}},$$

where $N$ is the number of pulse phase bins ($N = 16$), $R_i$ is the source count rate in each phase bin, $\Delta R_i$ is the associated uncertainty in the count rate and $R_{\text{ave}}$ is the average count rate of the pulse profile.

We present the rms PF values in Table 3. We find that rms PF of SGR 0526−66 is very low and remains constant around 4 per cent among CXO observations, while PF obtained from XMM–Newton observation is significantly lower (~1.5 per cent). Note, however, the fact that the rms PF value is normalized by the average count rate of the pulse profile and any blended emission from the SNR would increase the average rate and reduce the PF. It is likely that the drop of rms PF only seen in XMM–Newton observation is not intrinsic to the source.

5 DISCUSSION AND CONCLUSIONS

We performed a systematic analysis of the archival Chandra observations of SGR 0526−66. Fitting the X-ray spectra with a strongly magnetized atmosphere model allowed us determine the strength of the surface magnetic field as $B = 3.73 \times 10^{14}\text{ G}$ and the effective temperature as $0.355\text{ keV}$. We also obtained the optical depth to resonant scattering in the magnetosphere, $\tau = 5.47$, and the average velocity of the magnetospheric particles, $0.52c$. All these parameters remain constant over the course of 9 years within uncertainties.

What has been observed to change over this interval is the source flux: it decreased by about 20 per cent from 2000 to 2009 (see also Park et al. 2012). Such a flux decay can result from a $\sim 5$−6 per cent decrease in the surface temperature. This variation is comparable to the uncertainties in individual temperature measurements at the 1σ level. Therefore, we cannot unambiguously rule out a variation in the temperature. Nevertheless, no systematic variation in the best-fitting values of the surface temperature has been observed over the 9 years. Therefore, it is likely that the surface temperature of SGR 0526−66 remained constant throughout this period.

The decline in the observed flux can also be achieved with a decrease in the radius of the emitting region by about 10 per cent. We obtained through our spectral fits that the radius was about...
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Figure 6. Surface temperature of SGR 0526–66 inferred using the STEMS model together with a plausible age range (red cross sign) overplotted to surface temperature at the pole as a function of spin-down age for magnetars with different initial magnetic field strengths as calculated by Aguilera et al. (2008a,b).

On either cooling track, SGR 0526–66 is expected to enter a phase of more rapid cooling in the near future, based on its age and its current temperature, which we reported here. If its temperature indeed begins to decay rapidly, observations of the source over the next decade with planned X-ray telescopes, such as Advanced Telescope for High Energy Astrophysics, may reveal a more significant drop in the spectral temperature, accompanied by a further flux decay, as long as the source remains in its deep quiescence.

ACKNOWLEDGMENTS

We thank Deborah Aguilera and Jose Pons for sharing their theoretical calculations on the cooling of magnetars. We thank the referee for insightful suggestions that improved the clarity of the manuscript. TG acknowledges support from the Scientific and Technological Research Council of Turkey (TÜBITAK BİDEB) through a fellowship programme.

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