Spin-down rate and inferred dipole magnetic field of the soft gamma-ray repeater SGR 1627–41

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ABSTRACT

Using *Chandra* data taken in 2008 June, we detected pulsations at 2.594 39(4) s in the soft gamma-ray repeater SGR 1627−41. This is the second measurement of the source spin period and allows us to derive for the first time a long-term spin-down rate of $(1.9 \pm 0.4) \times 10^{-11}$ s s^{-1}. From this value, we infer for SGR 1627−41 a characteristic age of ∼2.2 kyr, a spin-down luminosity of ∼4×10^{34} erg s^{-1} (one of the highest among sources of the same class), and a surface dipole magnetic field strength of ∼2×10^{14} G. These properties confirm the magnetar nature of SGR 1627−41; however, they should be considered with caution since they were derived on the basis of a period derivative measurement made using two epochs only, and magnetar spin-down rates are generally highly variable. The pulse profile, double-peaked and with a pulsed fraction of 13 ± 2 per cent in the 2–10 keV range, closely resembles that observed by *XMM–Newton* in 2008 September. Having for the first time a timing model for this soft gamma-ray repeater (SGR), we also searched for a pulsed signal in archival radio data collected with the Parkes radio telescope 9 months after the previous X-ray outburst. No evidence for radio pulsations was found, down to a luminosity level ∼10–20 times fainter (for a 10 per cent duty cycle and a distance of 11 kpc) than the peak luminosity shown by the known radio magnetars.

Key words: stars: neutron – pulsars: general – X-rays: individual: SGR 1627−41.

1 INTRODUCTION

Anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) are isolated neutron stars with periods of several seconds ($P \sim 2$–12 s), rapid spin down ($\dot{P} \sim 10^{-11}$ s s^{-1}), bright (∼10^{34}– 10^{35} erg s^{-1}) and highly variable X-ray emission.[1] AXPs and SGRs are commonly interpreted in terms of the *magnetar* model. Magnetars are ultramagnetized neutron stars with magnetic fields largely in excess of the quantum critical field $B_{\mathrm{QED}} = m_e^2 c^3/\hbar e \simeq 4.4 \times 10^{13}$ G (Paczynski 1992; Duncan & Thompson 1992; Thompson & Duncan 1995, 1996). Contrary to what happens in ordinary radio pulsars, the

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[1] Ten AXPs and six SGRs are confirmed, and there are a few candidates; see catalogue at http://www.physics.mcgill.ca/∼pulsar/magnetar/main.html.

X-ray luminosity is larger than their rotational energy loss. Since no stellar companions have been detected thus far, accretion is unlikely to be responsible for the emission of AXPs and SGRs. Their persistent X-ray luminosity, as well as the bursts and flares typical of these sources, is instead believed to be powered by the decay of their ultrastrong magnetic field (see Woods & Thompson 2006 and Mereghetti 2008 for recent reviews).

AXPs were first recognized as a class of persistent X-ray pulsars, with the peculiarity that the X-ray luminosity exceeds that available from spin-down (whence the name 'anomalous'; Mereghetti & Stella 1995). SGRs were first noted as hard X- and gamma-ray transients (Laros et al. 1987), characterized by recurrent, short (<1 s) and relatively soft (peak photon energy $\sim$25–30 keV) flashes with super-Eddington luminosity. Although SGRs and AXPs have been discovered through very different channels, observations performed over the last few years highlighted several similarities among these two classes of objects and pointed towards a common magnetar nature (see e.g. Rea et al. 2009). In particular, short and hard X-ray bursts, originally considered as the defining characteristic of SGRs, have now been observed in several AXPs (see e.g. Gavriil, Kaspi & Woods 2002; Mereghetti et al. 2009).

SGR 1627−41 was discovered in 1998, when about 100 bursts in 6 weeks were observed by *Compton Gamma Ray Observatory* (*CGRO*)/BATSE and other instruments (Woods et al. 1999). Its soft X-ray counterpart was identified with *BeppoSAX* in 1998 at a luminosity level of $\sim$$10^{35}$ erg s^{-1} (Woods et al. 1999).[2] Subsequent observations carried out with *BeppoSAX*, *ASCA*, *Chandra* and *XMM–Newton* showed a spectral softening and a monotonic decrease in the luminosity, down to a level of $\sim$$10^{33}$ erg s^{-1} (Kouveliotou et al. 2003; Mereghetti et al. 2006; Esposito et al. 2008).

After nearly 10 years of quiescence, SGR 1627−41 reactivated on 2008 May 14, when several bursts were detected by *Swift*/BAT and other hard X-ray instruments (Esposito et al. 2008). The burst reactivation was associated with a large enhancement of the soft X-ray flux and a marked spectral hardening.

Until very recently, SGR 1627−41 was the only magnetar candidate with no pulsation period known. In order to search in depth for pulsations taking advantage of the high flux state, we asked for a long *XMM–Newton* observation to be carried out during its outburst. The observation was performed on 2008 September 27–28, and we could detect a clear pulsation period of 2.594 578(6) s (Esposito et al. 2009). However, no meaningful constraints on the period derivative could be derived from that observation.

Here, we report on a new measurement of the period using data gathered shortly after the burst activation by the *Chandra X-ray Observatory*. This allows us to estimate for the first time the spin-down rate of SGR 1627−41 and to infer its magnetic field, characteristic age and spin-down luminosity. Taking advantage of the new pieces of information about the timing properties of SGR 1627−41, we also searched for a pulsed signal in archival radio data collected at the Parkes observatory.

2 THE *CHANDRA* OBSERVATION: DATA ANALYSIS AND RESULTS

The *Chandra X-ray Observatory* (Weisskopf et al. 2000) pointed its mirror towards SGR 1627−41 on 2008 June 3 (MJD 54620) and observed the source for about 40 ks (observation identifier: 9126). The observation was carried out with the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003) instrument operated in the Continuous Clocking (CC) mode, which provides a time resolution of 2.85 ms and imaging along a single direction. The event telemetry was in faint mode. The source was positioned in the back-illuminated ACIS-S3 chip, sensitive to photons in the 0.2–10 keV energy range.

The data were processed using the *Chandra* Interactive Analysis of Observation software (CIAO, version 4.1) and we employed the most updated calibration files available at the time the reduction was performed (CALDB 4.1). Standard screening criteria were applied in the extraction of scientific products.[3] No significant background flares affected the observation.

The source photons for the timing and spectral analyses were accumulated from a 5×5 pixels region centred on SGR 1627−41 (one ACIS-S pixel corresponds to 0.492 arcsec); the background events were extracted from source-free regions of the same chip as the source. A total of about 1120 ± 40 counts above the background were collected from SGR 1627−41 in the 2–10 keV energy range.

2.1 Spectroscopy

The ancillary response file and the redistribution matrix for the spectral fitting were generated with the CIAO tasks ASPHIST, MKARF and MKACISRMF, using the specific bad-pixel file of this observation. The data were grouped with a minimum of 20 counts per energy bin and the spectrum was analysed with the XSPEC version 12.4 analysis package (Arnaud 1996).

Given the paucity of counts, we fit a simple model to the data: a power law corrected for interstellar absorption. We obtained the following best-fitting parameters ($\chi_r^2 = 1.13$ for 51 dof): absorption $N_H = 10^{+1}_{-2} \times 10^{22}$ cm^{-2} and photon index $\Gamma = 1.0^{+0.3}_{-0.2}$ (here and in the following all errors are at 1σ confidence level). The absorbed 2–10 keV flux was $\sim$$1.3 \times 10^{-12}$ erg cm^{-2} s^{-1}, corresponding to a luminosity of $\sim$$3 \times 10^{34}$ erg s^{-1}. These results are consistent with those reported in Woods et al. (2008) and confirm the bright and hard state of the source following the 2008 May 28 burst activation (Esposito et al. 2008, 2009).

2.2 Timing

For the timing analysis, the photon arrival times were converted to the Solar system barycentre with the CIAO task AXBARY using the source coordinates reported in Wachter et al. (2004). We searched for the presence of a periodic signal using a Z_2^2 test (see Esposito et al. 2009) over the period range 2.584 71–2.594 60 s; this range was determined by extrapolating from the 3σ lower limit on the value reported in Esposito et al. (2009), conservatively assuming a period derivative of $0 \leq \dot{P} \leq 10^{-9}$ s s^{-1}. The period search step size was $\sim$$8 \times 10^{-6}$ s, which is equivalent to oversampling the Fourier period resolution ($\frac{1}{2}P^2/T_{obs}$) by a factor of 10.

A significant signal was found in the Z_2^2 periodogram at $\sim$2.594 39 s (see Fig. 1). The probability of this peak (with a Z_2^2 value of 39.66) to appear by chance in the search, taking into account the number of trials (1177), is 6×10^{-5}. This corresponds to a 4σ detection. To refine our period estimate, we used an epoch

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[2] Here and through the Letter, we assume a distance to the source of 11 kpc ($d = 11.0 \pm 0.3$ kpc; Corbel et al. 1999).

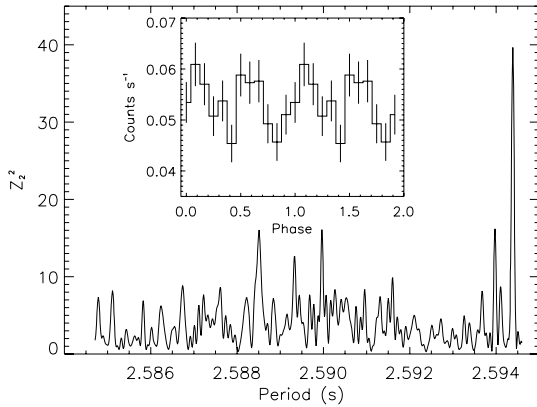[3] See the *Chandra* Science Threads at the *Chandra* X-ray Center web site, http://asc.harvard.edu/ciao/threads/index.html.

Figure 1. Z_2^2-periodogram of SGR 1627−41 in the 2–10 keV energy range. The peak at 2.594 39 s is significant at 4σ. The inset shows the corresponding pulse profile (2–10 keV, not background subtracted).

Figure 2. P–$\dot{P}$ diagram for the known magnetars; vertical bars indicate variability ranges. Lines of constant magnetic field strength (green) and characteristic age (red) are indicated. The 'transient' magnetars, the ones that show the largest variations of the persistent X-ray flux (up to two or three orders of magnitude), are plotted in blue. Data are from Mereghetti (2008) and our analyses.

folding technique and fitted the peak in the χ^2 versus trial period distribution as described in Leahy (1987). We obtained a best period of 2.594 39 ± 0.000 04 s. The corresponding folded light curve is shown in Fig. 1; the pulse profile is double-peaked and the rms pulsed fraction is (13 ± 2) per cent in the 2–10 keV energy range and after subtracting the background. The period derivative inferred from the *Chandra* and *XMM–Newton* measurements is (1.9 ± 0.4) × 10^{-11} s s^{-1}. Assuming that the spin-down rate has remained constant at this value, we repeated the search for pulsations in archival X-ray data described in Esposito et al. (2009). Again, we did not detect any significant signal.

To search for possible pulse shape variations as a function of time, we compared the *Chandra* light curve with that obtained in 2008 September with *XMM–Newton* by using a two-dimensional Kolmogorov–Smirnov test (Peacock 1983; Fasano & Franceschini 1987). Taking into account the unknown relative phase alignement,[4] the two profiles are compatibile. In fact, the probability that they come from the same underlying distribution is about 70 per cent.

3 SEARCH FOR RADIO PULSATIONS

The P–$\dot{P}$ diagram for magnetars (Fig. 2) shows that the timing properties of SGR 1627−41 are remarkably similar to those of the AXP 1E 1547.0−5408. The latter source, together with XTE J1810–197 (Camilo et al. 2006), is one of the two magnetars known to sporadically emit radio pulses (Camilo et al. 2007, 2008; Burgay et al. 2009). Although SGR 1627−41 was not detected as a radio pulsar immediately after the 2008 May activation (Camilo & Sarkissian 2008), we searched for radio emission in archival data taking advantage of the new pieces of information about its timing properties.

We analysed archival radio observations performed at 1.4 GHz with the Parkes radio telescope. The data were taken on 1999 March 22 with the central beam of the 20-cm multibeam receiver (Staveley-Smith et al. 1996) over a bandwidth of 288 MHz split in 96 3-MHz channels. The 2.3 h observation was 1-bit sampled every 1 ms.

We folded the data with 6250 values of the period spanning ±5 ms (corresponding to a ~4σ uncertainty on the value of P) around the
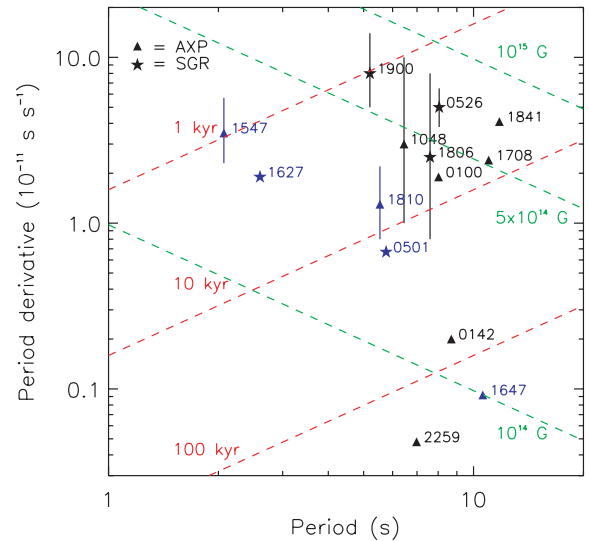
nominal value $P_{PKS} = 2.5889(12)$ s extrapolated from the current best X-ray ephemeris at MJD 51259, which corresponds to the epoch of the Parkes observation. Given the position in the sky of SGR 1627−41, assuming a distance of 11 kpc (Corbel et al. 1999) and a model for the distribution of free electrons in the interstellar medium (Cordes & Lazio 2002), the expected dispersion measure is DM ~1150 pc cm^{-3}. Given the uncertainties in the DM determination, we chose to dedisperse the signal with 390 DM values ranging from 0 to 2300 pc cm^{-3}. The expected broadening of the pulse due to interstellar scattering at the SGR 1627−41 position, according to the Cordes & Lazio model (Cordes & Lazio 2002), is ~50 ms at 1.4 GHz; the uncertainties of the interstellar medium model in this respect are, however, even larger than those related to the DM. The number of period and DM steps were hence chosen in such a way to produce a maximum total smearing in the folded profile of <10 ms, also compatible with the number of bins $n_{bin} = 256$ in which the folded profile was subdivided. No signal with signal-to-noise ratio greater than 6 was found in this search. Using the radiometer equation (e.g. Manchester et al. 2001), we find an upper limit for radio pulsed emission of 0.22 mJy for an approximately sinusoidal pulse profile, and of 0.08 mJy for a duty cycle of 10 per cent.

Since the two known radio-pulsating magnetars are sometimes visible through their individual pulses (Camilo et al. 2007), also a search for single dispersed pulses has been carried out, leading to the detection of a faint (signal-to-noise ratio: 6.2) candidate signal at DM ~ 93 pc cm^{-3}. The DM of the putative pulse (to be confirmed with further observations) is, however, likely too small to be associated with SGR 1627−41. A blind search for periodic signals at DM = 93 pc cm^{-3} resulted in no significant detection down to a flux density limit of ~0.01 mJy for a long period pulsar and ~0.2 mJy for a millisecond pulsar.

4 DISCUSSION AND CONCLUSIONS

With a rotation period of 2.59 s (Esposito et al. 2009), SGR 1627−41 is the second fastest spinning magnetar, after 1E 1547.0−5408

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[4] The accuracy of the timing solution does not allow us to phase-connect the *XMM–Newton* and *Chandra* data.

($P = 2.07$ s; Camilo et al. 2007). Using an archival *Chandra* observation, we have been able to obtain a second period measurement. The *Chandra* and *XMM–Newton* data sets, separated by about 114 d, imply a long-term average spin-down rate $\dot{P} = (1.9 \pm 0.4) \times 10^{-11}$ s s^{-1}. This value is compatible with the range 1.2×10^{-11} s s^{-1} $< \dot{P} < 6 \times 10^{-10}$ s s^{-1} derived from the long *XMM–Newton* observation.

Within the usual vacuum dipole framework (see e.g. Lorimer & Kramer 2004), the spin-down rate can be used to infer a surface magnetic field strength of $B \approx 3.2 \times 10^{19}(P\dot{P})^{1/2} \simeq 2 \times 10^{14}$ G, confirming the magnetar nature of SGR 1627−41. The characteristic age and the spin-down luminosity are $\tau_c = \frac{1}{2}P/\dot{P} \simeq 2.2$ kyr and $\dot{E} = 4\pi^2 I \dot{P} P^{-3} \simeq 4 \times 10^{34}$ erg s^{-1}, respectively, where $I \approx 10^{45}$ g cm^2 is the moment of inertia of the neutron star.

Our newly determined values of P and $\dot{P}$ for SGR 1627−41 are reported in Fig. 2 together with all the values available up to now for magnetar sources. As can be seen in Fig. 2, where the vertical bars indicate variability ranges, magnetar spin-down rates can be highly variable. For this reason, the magnetic fields, characteristic ages and spin-down luminosities inferred for magnetars should be taken with particular caution. In particular, this applies to SGR 1627−41, for which we have no information of possible variability of the period derivative. It is interesting to note that SGRs and AXPs do not populate different regions of the $P–\dot{P}$ plane, so that it would be difficult to discriminate between the two groups on the basis of their timing properties. This further supports the idea that SGRs and AXPs are actually members of the same class. What Fig. 2 suggests, instead, is that the *transient* and *persistent* sources might have different characteristics. The transient magnetars (in blue in Fig. 2), in fact, appear to have lower magnetic fields with respect to the persistent ones (irrespective of their classification, AXPs or SGRs). In this respect, the position of SGR 1627−41 in the $P–\dot{P}$ diagram is similar to that of other transient magnetar sources. The only exceptions are 4U 0142+614 and 1E 2259+586 which are not transient but have among the lowest derived values of B.

The neutron-star characteristic age is consistent with an association of SGR 1627−41 with the supernova remnant (SNR) G337.0−0.1 (see Esposito et al. 2009, and references therein). At a distance of 11 kpc (Corbel et al. 1999), the observed SNR angular diameter of ∼3 arcmin would correspond to a physical diameter of ∼9–10 pc. This is similar to the observed sizes for other young remnants (∼1–3 kyr, at the beginning of the Sedov phase) hosting a neutron star, like for example Kes 73 (Gotthelf & Vasisht 1997) and RCW 103 (Carter, Dickel & Bomans 1997).

The spin-down luminosity of SGR 1627−41 is one of the highest among magnetars and is roughly equal to the *Chandra* luminosity of 3×10^{34} erg s^{-1} (Section 2.1). In magnetars $\dot{E}$ ranges, in fact, from 6×10^{31} erg s^{-1} for 1E 2259+586 (Gavriil & Kaspi 2002) to 10^{35} erg s^{-1} for 1E 1547.0−5408 (Camilo et al. 2007). The observed correlation between the spin-down power and the non-thermal X-ray emission for ordinary pulsars by Possenti et al. (2002) predicts for SGR 1627−41 an X-ray luminosity of $\approx 10^{31}$ erg s^{-1} and a maximum value $L_{X,crit} = 10^{-18.5}(\dot{E}/\text{erg s}^{-1})^{1.48}$ erg s$^{-1} \simeq 5 \times 10^{32}$ erg s^{-1}. This makes it implausible that SGR 1627−41 is powered by star rotation unless the conversion efficiency is extremely high. Moreover, Camilo et al. (2007) noted in the case of 1E 1547.0−5408 that, despite the fact that the spin-down luminosity is comparable with the X-ray luminosity, it is unlikely that a significant fraction of the X-ray emission is powered by rotation, since the source displays the distinctive features of the pulsars powered by magnetic field decay. In fact, at variance with rotation-powered

pulsars[5] and cooling neutron stars, the source showed flux variations by orders of magnitude. Furthermore, the X-ray spectrum of 1E 1547.0−5408 includes a thermal component which is hotter ($kT \simeq 0.4$ keV) than that expected from a young, cooling neutron star (see e.g. Yakovlev et al. 2002). Such high temperatures are instead typical of magnetars, the surface of which can be substantially heated by energy deposition following burst-active periods and/or by dissipative currents in the crust. The considerations by Camilo et al. (2007) apply also to SGR 1627−41, with its X-ray luminosity variable by a factor of ∼100 (between the historical minimum and maximum, ∼ 2×10^{33} and ∼3×10^{35} erg s^{-1}; Esposito et al. 2008); also, the only high-statistics spectrum of SGR 1627−41, collected by *XMM–Newton* in 2008 September, when the luminosity was still high (∼10^{34} erg s^{-1}), suggests the presence of a thermal component, a blackbody with temperature $kT \simeq 0.5$ keV (Esposito et al. 2009). Finally, we also note that it is unlikely that the low luminosity observed in SGR 1627−41 while it was approaching its historical minimum during its decade-long quiescence arose mainly from rotational power. The X-ray emission was in fact very soft and possibly thermal (Kouveliotou et al. 2003; Mereghetti et al. 2006).

The mechanisms behind the pulsed radio emission of magnetars are poorly understood. It is not ruled out that their radio emission is related to the braking in a way similar to that of the ordinary radio pulsars, but the radio properties of the two magnetars detected so far in radio, XTE J1810−197 and 1E 1547.0−5408, are quite distinguishing: their flux is highly variable on daily time-scales, their spectrum is very flat, and their average pulse profile changes with time, from minutes to days (Camilo et al. 2006, 2007, 2008; Kramer et al. 2007). Remarkably, XTE J1810−197 and 1E 1547.0−5408 share small periods and high spin-down luminosities. Thus, in view of the similarities with the two radio-pulsating magnetars, SGR 1627−41 is a good candidate to be searched for pulses at radio frequencies.

Our analysis of archival Parkes data obtained at 1.4 GHz in 1999 March (about 9 months after the first detected X-ray outburst of SGR 1627−41) showed no pulsed signal in a $\pm 4\sigma$ interval bracketing the expected period, down to a flux density limit of $S \simeq 0.08$ mJy for a pulsar with a 10 per cent duty cycle [twice as good a limit as obtained by Camilo & Sarkissian (2008) with observations following the 2008 outburst]. For a distance of $d = 11$ kpc (Corbel et al. 1999), this limit translates into a pseudo-luminosity $L = Sd^2$ of approximately 10 mJy kpc^2, significantly smaller than the 1.4 GHz luminosity of the two known radio magnetars at their peak (∼100–200 mJy kpc^2), although still much larger than the smallest known luminosity of ordinary young (with spin-down age $\tau_c < 10^5$ yr) pulsars (∼1 mJy kpc^2). Given the remarkable and rapid variability of the pulsed flux shown by the two aforementioned known radio magnetars, the negative results of the two searches performed so far on SGR 1627−41 (Camilo & Sarkissian 2008 and this work) cannot anyway be conclusive and a longer term monitoring is necessary for satisfactorily assessing the radio properties of this source.

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[5] With the notable exception of the young pulsar PSR J1846−0258 at the centre of the SNR Kes 75, which showed large flux and spectral variations (Gavriil et al. 2008). This source, however, shares some (but not all) characteristics of magnetars, including a (relatively) high dipole magnetic field of 5×10^{13} G and the emission of SGR-like short bursts (Gavriil et al. 2008), and it is, therefore, unclear whether it is purely rotation powered.

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