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IS SGR 1900+14 A MAGNETAR?

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ABSTRACT

We present *Rossi X-Ray Timing Explorer* observations of the soft gamma-ray repeater SGR 1900+14 taken 1996 September 4–18, nearly 2 yr before the 1998 active period of the source. The pulsar period (P) of 5.1558199 ± 0.0000029 s and period derivative ($\dot{P}$) of $(6.0 \pm 1.0) \times 10^{-11}$ s s^{-1} measured during the 2 week observation are consistent with the mean $\dot{P}$ of $(6.126 \pm 0.006) \times 10^{-11}$ s s^{-1} over the time up to the commencement of the active period. This $\dot{P}$ is less than half that of $(12.77 \pm 0.01) \times 10^{-11}$ s s^{-1} observed during and after the active period. If magnetic dipole radiation were the primary cause of the pulsar spin-down, the implied neutron star magnetic field would exceed the critical field of $\approx 4.4 \times 10^{13}$ G by more than an order of magnitude, and such field estimates for this and other soft gamma repeaters (SGRs) have been offered as evidence that the SGRs are magnetars, in which the neutron star magnetic energy exceeds the rotational energy. The observed doubling of $\dot{P}$, however, would suggest that the pulsar magnetic field energy increased by more than 100% as the source entered an active phase, which seems very hard to reconcile with models in which the SGR bursts are powered by the release of magnetic energy. Because of this, we suggest that the spin-down of SGR 1900+14 is not driven by magnetic dipole radiation, but by some other process, most likely a relativistic wind. The $\dot{P}$, therefore, does not provide a measure of the pulsar magnetic field strength, nor evidence for a magnetar.

Subject headings: gamma rays: bursts — pulsars: individual (SGR 1900+14) — stars: neutron

1. INTRODUCTION

Soft gamma-ray repeaters (SGRs) are a class of astrophysical sources that emit bursts of high-energy X-ray and gamma-ray radiation which are among the most energetic events in the Galaxy. The apparent association of their positions with supernova remnants and the detection of pulse periods in their nonbursting emission strongly suggest that the SGRs are young neutron stars (e.g., Mazets et al. 1979 and the review by Rothschild 1995). The SGRs may also be related to the anomalous X-ray pulsars (Mereghetti, Stella, & Israel 1998), which have comparably long (>few second) periods. The observed SGR burst energies, assuming isotropic emission, range from typical values of $\sim 10^{41}$ ergs to as much as 10^{44} ergs in rare giant flares, such as that of 1979 March 5 from SGR 0529−66 in the Large Magellanic Cloud. Suggested energy sources for these bursts have included (1) the rotational energy of the neutron star, $\sim 10^{45}(P/3.1\ \mathrm{s})^{-2}$ ergs, where P is the spin period, which might be tapped by pulsar glitches (e.g., Baym & Pines 1971), (2) the magnetic field energy $\sim 10^{44}(B/B_q)^2$ ergs of *magnetars* with surface magnetic fields much greater than the quantum critical field $B_q = m_e^2 c^3/e\hbar \approx 4.4 \times 10^{13}$ G tapped by magnetic stress–driven crustal quakes and magnetic reconnection (Thompson & Duncan 1995), and (3) the gravitational binding energy of the neutron star, $\sim 10^{53}$ ergs, tapped by quakes (e.g., Ramaty et al. 1980) and driven by plate tectonics (Ruderman 1991).

Recent measurements of the rapid spin-down rates of the SGR pulsars have been taken (e.g., Kouveliotou et al. 1998, 1999) as evidence for the magnetar hypothesis, in which the magnetic energy of the neutron star exceeds the rotational energy. Pulsations have been observed from three of the SGRs: SGR 0526−66 (8 s; Mazets et al. 1979), SGR 1806−20 (7.47 s; Kouveliotou et al. 1998), and SGR 1900+14 (5.16 s; Hurley et al. 1999b). The period derivatives ($\dot{P}$) of these pulsars have been found by either direct measurement (SGR 1806−20 and SGR 1900+14) or by $\dot{P} = 0.5P/t_{\mathrm{snr}}$, where P is the pulse period and t_{snr} is the estimated age of the associated supernova remnant (SGR 0526−66). If the spin-down is driven by magnetic dipole radiation from an orthogonally rotating vacuum magnetic dipole, it can be shown (Pacini 1969) that the surface magnetic field is given by $B_0 \approx 3.2 \times 10^{19}(P\dot{P})^{1/2}$ G, which would yield surface magnetic fields of 6×10^{14}, 8×10^{14}, and 5×10^{14} G for SGR 0526−66 (Thompson & Duncan 1995), SGR 1806−20 (Kouveliotou et al. 1998), and SGR 1900+14 (Kouveliotou et al. 1999), respectively. Here we present *Rossi X-Ray Timing Explorer* (*RXTE*) observations, however, which suggest that the spin-down rate of SGR 1900+14 is due to torques other than those provided by the magnetic field and thus does not provide evidence of a supercritical surface dipole field.

2. OBSERVATIONS AND ANALYSIS

SGR 1900+14 was observed by the Proportional Counter Array (PCA) and High-Energy X-ray Timing Experiment (HEXTE) instruments on board the *RXTE* on a number of occasions during the period 1996 September 4–18. The total exposure time was ∼47 ks, with a temporal baseline of 15.4 days. For the first 22 ks, *RXTE* was pointed at a position R.A. (J2000) = 286°.82 and decl. (J2000) = 9°.32, which is ∼48″ from the precise VLA position of SGR 1900+14 (Frail, Kulkarni, & Bloom 1999), but well inside the 1° FWHM field of view of the *RXTE* pointed instruments. Midway through the observations, the pointing position was changed to exclude the bright 438 s binary X-ray pulsar 4U 1907+09 (in't Zand, Baykal, & Strohmayer 1998) from the field of view. The second half of the observation (25 ks) was then conducted at the pointing position R.A. = 286°.43 and decl. = 8°.98, which is ∼0°.35 from the position of the SGR. As luck would have it, this field also contained a relatively bright confusing source, the 89 s transient X-ray pulsar XTE J1906+09, which was discovered during the observation (Marsden et al. 1998). Finally, the Galactic ridge emission is also a significant contributor to the X-ray flux in the *RXTE* field of view (Valinia & Marshall 1998), due to the low Galactic latitude of SGR 1900+14 ($b \sim 0°.75$).

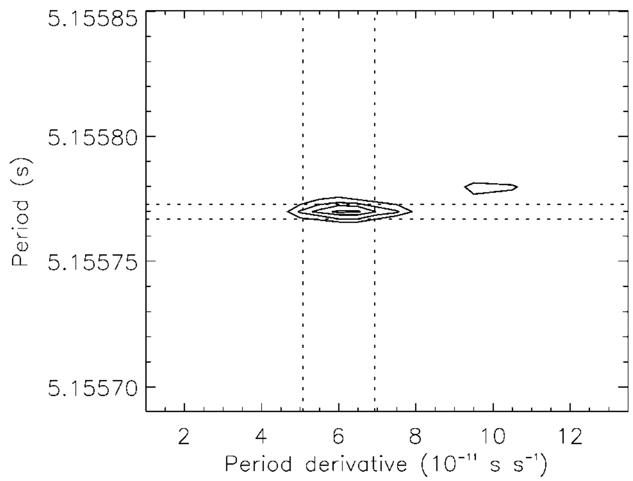

FIG. 1.—Determination of the SGR 1900+14 timing ephemeris. The grid of χ^2 values as a function of period and period derivative is shown for the 2–10 keV PCA data. Shown are four linearly spaced contours displaced from the peak by units of $\Delta\chi^2 = 20$. The dotted lines denote the 90% confidence regions of P and $\dot{P}$.

Because of these complications, we do not attempt to determine the X-ray spectrum of the SGR with the *RXTE* data and instead concentrate on the temporal analysis. For information on the X-ray spectrum of the source, the reader is referred to Hurley et al. (1999b), Kouveliotou et al. (1999), and Murakami et al. (1999).

The pointed X-ray instruments on board *RXTE* are HEXTE and the PCA. HEXTE consists of two clusters of collimated NaI/CsI phoswich detectors with a total net area of ∼1600 cm^2 and an effective energy range of ∼15–250 keV (Rothschild et al. 1998). The PCA instrument consists of five collimated xenon proportional counter detectors with a total net area of 7000 cm^2 and an effective energy range of 2–60 keV (Jahoda et al. 1996). The uncertainty in the timing of X-ray photons by the PCA and HEXTE is ≪1 ms (Rots et al. 1998) and is therefore negligible in the temporal analysis presented here.

The PCA and HEXTE photon times were corrected to the solar system barycenter using the JPL DE200 ephemeris and the SGR coordinates R.A. (J2000) = $19^h07^m14^s.33$ and decl. (J2000) = $+09°19'20''.1$ (Frail et al. 1999). The PCA data were searched for pulsations using the χ^2 folding method, which calculates the value of χ^2 for a pulsar light curve (versus a constant rate) folded on a range of trial pulsar periods. Here the pulse phase ϕ for a given photon time t is defined by the relation $\phi(t) = f(t - t_0) + 1/2\dot{f}(t - t_0)^2$, where the pulsar frequency f and frequency derivative $\dot{f}$ are related to the period P and period derivative $\dot{P}$ by the expressions $P = 1/f$ and $\dot{P} = -\dot{f}P^2$. A maximum value of χ^2 occurs when the data are folded on the true pulsar period and period derivative.

The PCA data were initially searched for pulsations using a range of ∼500 periods about 5.153642 s, the SGR 1900+14 period predicted from the timing ephemeris given in Kouveliotou et al. (1999). A significant χ^2 peak was seen, and a finer search was then conducted on a grid in P-$\dot{P}$ space around the peak, for a broad range of $\dot{P}$ including the value of $\dot{P} \sim 10^{-10}$ s s^{-1} found by Kouveliotou et al. (1999). The results of the grid search are shown in Figure 1. To estimate the confidence regions of P and $\dot{P}$ indicated by the peak in χ^2, we folded the 2–10 keV PCA data with P ($\dot{P}$) values slightly displaced from the peak value, while holding $\dot{P}$ (P) fixed at its peak value. The resultant light curves were then compared to a template light curve using the χ^2 test, and the 90% confidence contours were calculated using the χ^2 probability distribution. A folding time midway through the *RXTE* observation was used throughout the analysis to minimize correlations between P and $\dot{P}$.

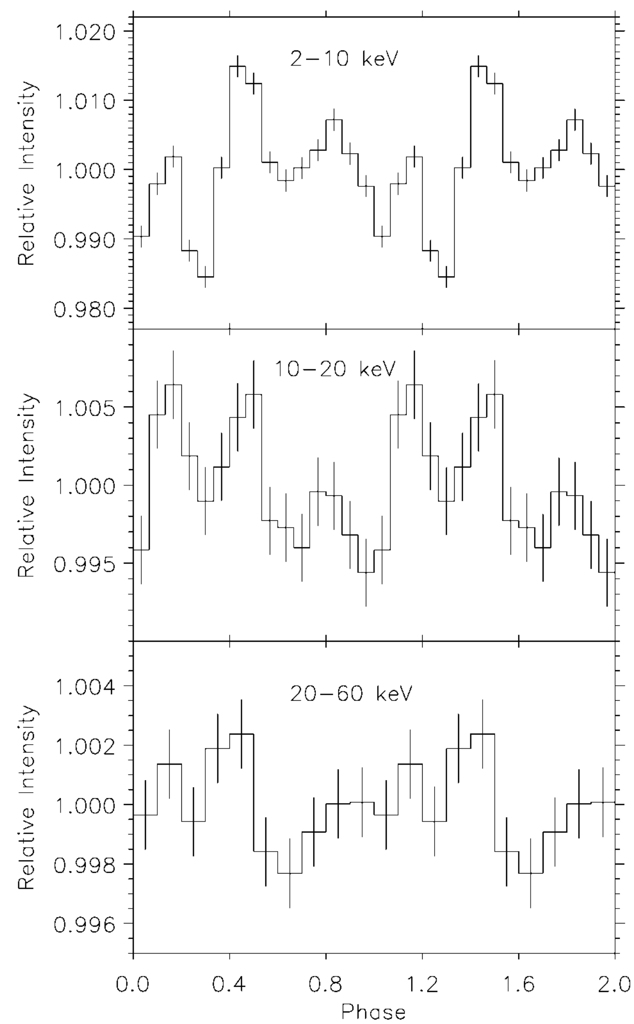

FIG. 2.—SGR 1900+14 folded light curve. The pulsar light curve is shown for three different PCA energy bands.

Using this analysis, we obtain a timing solution of $P = 5.1558199 \pm 0.0000029$ s and $\dot{P} = (6.0 \pm 1.0) \times 10^{-11}$ s s^{-1}, referenced to $t_0 = 50338.216$ (MJD). The errors are 90% confidence. A search of the 15–100 keV HEXTE data for the pulsar, using the PCA timing solution, failed to produce evidence of significant pulsations, which is not surprising given the faintness of the source and the presence of the bright confusing sources. The folded SGR 1900+14 pulsar light curve for three PCA energy ranges, using the above timing parameters, is shown in Figure 2. The pulsed fraction of the SGR 1900+14 is not constrained by these data, due to the uncertain X-ray flux from XTE J1906+09, 4U 1907+09, and the Galactic ridge in the *RXTE* bandpass.

3. DISCUSSION

The 2–10 keV SGR 1900+14 light curve obtained here is virtually identical to the light curves obtained just before (Hurley et al. 1999b) and just after (Kouveliotou et al. 1999) the commencement of the 1999 May active period of the source.

This indicates that the X-ray–emitting geometry is stable on timescales of years while the source is inactive. The light curve appears to have multiple components which vary differently with energy. There are three peaks in the 2–10 keV light curve, with a single relatively broad central peak surrounded by two narrower peaks. The narrow peaks have harder spectra than the broad peak, since the narrow peak emission dominates the emission from the broad peak above 10 keV. A simple explanation for the light-curve morphology is that the pulsed emission consists of different emission components arising from different regions of the stellar surface. The narrow components may be beamed emission from a collimated wind off of relatively small hot spots, while the broader component could be more isotropic emission from a larger and cooler area of the crust. The two narrow components are greatly reduced in the pulsar light curves obtained just after the giant flare of 1999 August 27 (Kouveliotou et al. 1999; Murakami et al. 1999), suggesting that the energy of the small hot spots may have been depleted during the active period.

The observed temporal history of the SGR 1900+14 pulsar is shown in Figure 3. The additional timing parameters of the present observations are important because they constrain the pulsar parameters long before the source went into outburst. Although the temporal coverage is incomplete, the *secular* spin-down rate seems to change abruptly sometime close to the initiation of bursting, at which point the spin-down continues steadily at an increased rate. These two different spin-down rates are denoted by the dotted lines in Figure 3, which are linear fits to the data before the outburst (up to and including the first observation of Kouveliotou et al. 1999) and the data during and after the outburst (beginning with the first observation of Kouveliotou et al. 1999 and ending with the Shitov 1999 observation). The third data point in Figure 3, from Kouveliotou et al. (1999), appears to be near the change point in the spin-down behavior because the period is consistent with the extrapolation of the pre-outburst timing solution, yet the $\dot{P}$ value measured during this observation is consistent with the outburst values. The fit to the data taken during and after the outburst period yields a value of $\dot{P} = (12.77 \pm 0.01) \times 10^{-11}$ s s^{-1} for the mean spin-down rate, and the corresponding pre-outburst value is $\dot{P} = (6.126 \pm 0.006) \times 10^{-11}$ s s^{-1}. Using these mean $\dot{P}$ values, the mean inferred dipole field strengths before and after the initiation of bursting would be 5.7×10^{14} and 8.2×10^{14} G, respectively, if the spin-down were driven by dipole radiation losses. These two values, which differ to a high degree of significance, would imply an abrupt increase in the SGR 1900+14 magnetic field energy of more than 100% around the time the source started bursting, which is contrary to the predictions of models in which the bursting is dissipating magnetic field energy.

This discrepancy clearly suggests that the SGR 1900+14 spin-down is not dominated by magnetic dipole radiation and that the observed value of $P\dot{P}$ provides no direct measurement of B and no direct evidence for a magnetar. Instead, the measured values of P and $\dot{P}$ suggest that the SGR spin-down may be due to *winds*, if we take the pulsar age to be that of the associated (Hurley et al. 1999a) supernova remnant G42.8+0.6. Assuming that the initial period of the pulsar was much smaller than it is now and that the braking index is constant in time, the pulsar age $t_{\rm age} = P/[(n-1)\dot{P}]$, where the braking index n is 3 for pure dipole radiation but much less ($n \sim 1$) for spin-down due to wind torques. Taking the estimated age of G42.8+0.6 to be $\sim 10^4$ yr (Vasisht et al. 1994; Hurley et al. 1996), we find that the braking index for SGR 1900+14 must be ~ 1, i.e., $n = 1 + 0.16/(t_{\rm age}/10^4$ yr), which indicates that the

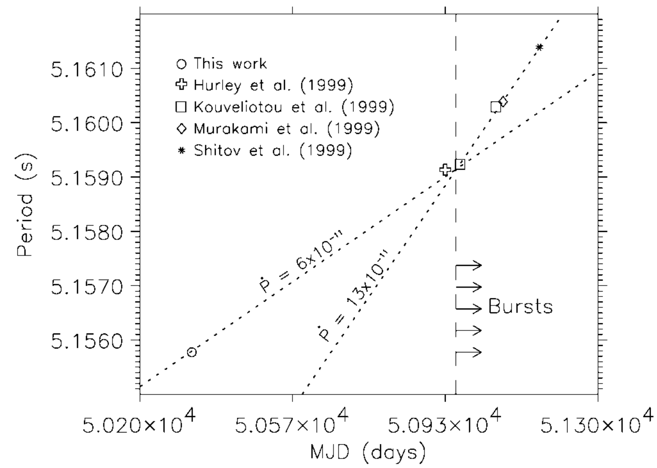

FIG. 3.—Timing history of SGR 1900+14. The vertical dashed line indicates the approximate time at which the source entered a bursting phase, and the dotted lines indicate linear fits to the data up to the onset of bursting and to the data after the onset.

pulsar spin-down is dominated by winds. The remnant age would have to be an order of magnitude smaller in order for the braking index to be consistent with that of dipole radiation, and in addition such an age would require an unreasonably large pulsar velocity of $\sim 2.5 \times 10^4$ km s^{-1} for it to have traversed from the center of the remnant to its present position, assuming a distance of 5 kpc (Vasisht et al. 1994; Hurley et al. 1996). Thus, the observations provide strong evidence that torques due to wind emission, and not magnetic dipole torques, dominate the spin-down dynamics of SGR 1900+14.

The spin-down behavior of SGR 1900+14 can be explained simply if we assume that the spin-down is caused almost entirely by wind emission, as was also considered by Kouveliotou et al. (1999). Possible mechanisms for the generation of this wind include thermal radiation from hot spots and Alfvén wave emission (Thompson & Blaes 1998). In this interpretation, the SGR emits a robust wind of particles and fields, both during bursting and quiescent intervals, which carries away angular momentum from the star. The emission of a relativistic wind produces an exponential spin-down of the pulsar $\Omega(t) = \Omega_0 \exp(-kt)$, where k is a constant parameterizing the rotational energy-loss rate due to the wind (Thompson & Blaes 1998). Using this relation and the values of P and $\dot{P}$ from our observations, we obtain $k = \dot{P}/P \sim 2700^{-1}$ yr^{-1}. Given an age of (1–2) $\times 10^4$ yr for G42.8+0.6, we obtain an initial pulsar spin period of $P_0 \sim 3$–120 ms for SGR 1900+14, which is similar to the spin periods of young isolated pulsars such as the Crab. This P_0 is most likely an upper limit, given the likelihood of active periods (with higher spin-down rates) in the past.

As mentioned above, one scenario is that the spin-down of SGR 1900+14 is due to Alfvén wave emission, in which a stream of particles and fields escape the star along magnetic field lines forced open by the wind pressure (Thompson & Blaes 1998). A supercritical magnetic field is not required for this mechanism to explain the SGR 1900+14 spin-down. From Thompson & Blaes (1998), the spin-down constant is given by

$$k = 1.5 \times 10^{-11} \left(\frac{B_*}{3 \times 10^{12}\ \rm G}\right)^2 \left(\frac{\delta B_*/B_*}{0.01}\right)^{4/3}\ \rm Hz, \qquad (1)$$

where B_* is the dipole field strength, δB_* is the wave amplitude, and we have assumed a neutron star moment of inertia and radius of 1.1×10^{45} g cm^2 and 10 km, respectively. This value of k is comparable to the measured value $k = \dot{P}/P \sim 10^{-11}$ Hz for SGR 1900+14, indicating that this mechanism can explain the spin-down of the SGR with conventional ($\sim 10^{12}$ G) field strengths, assuming that there is a mechanism to continuously generate Alfvén waves.

Even though a supercritical magnetic field on a global scale cannot account for the SGR pulsar spin-down, such fields on much smaller localized scales may nevertheless play an important role in the bursting process. Since the wind torques initially operate to spin down the neutron star crust, one might expect that if the core is not rigidly coupled to the crust, then the core could be spinning slightly faster and the resulting differential rotation could wind up any magnetic field threading between the core and crust, building up large internal magnetic field pressures. By analogy to the Sun, we might expect that the growing pressure of the internal field is episodically released by the surface break out of intense magnetic fields in localized regions, similar to the appearance of sunspots, which have local fields of 10^2–10^3 times the average global surface field of the Sun. Such spots of emerging magnetic flux on a neutron star may thus contain supercritical, or larger, localized fields, B_s within radii r_s, with total magnetic energies greater than $3 \times 10^{41}(B_s/B_q)^2(r_s/1\ \mathrm{km})^3$ ergs, and they may be accompanied by comparable tectonic stresses and heating from field diffusion in the crust. To contain the giant flare of 1999 August 27, for example, a local field with $B \sim B_q$ can contain the 3×10^{42} ergs of energy released (Frail et al. 1999) within a bubble of radius $r_s \sim 2$ km, which is a small fraction of the surface area of the star. The occurrence of such emerging magnetic flux spots could thus provide an episodic source of both magnetic and tectonic-gravitational energy release, both thermal and nonthermal, that power both the steady localized winds and the impulsive bursts of SGRs, much as the sunspot fields are dissipated in winds, flares, and diffusion on the Sun. The solar analogy was also discussed by Sturrock (1986) for Galactic gamma-ray bursts.

The SGR wind hypothesis can also explain other observed features of the burst and quiescent emission from SGRs. If both the quiescent X-ray emission and the spin-down torque of SGR 1900+14 are due to wind emission, the persistent X-ray flux and the spin-down luminosity should be correlated (this is not true of SGR 1806−20 because of the surrounding plerion—see below). Between the *ASCA* observations of Hurley et al. (1999b) and Murakami et al. (1999), the persistent X-ray flux of SGR 1900+14 increased by (140 ± 20)%. Using the appropriate mean $\dot{P}$ values from Figure 3, the spin-down luminosity increased by ∼120% over the same time interval, which is consistent with the steady X-ray flux and spin-down arising from the wind.

The radio signature of SGR winds have been observed from SGR 1900+14 (Frail et al. 1999) and SGR 1806−20 (Kulkarni et al. 1994). In the latter case, the SGR winds power a plerionic nebula with a total energy content ($\sim 10^{45}$ ergs) much greater than the energy given off in a typical burst interval ($\sim 10^{43}$ ergs; Kouveliotou et al. 1999), which explains the lack of variability seen from the SGR 1806−20 X-ray and radio counterparts (Sonobe et al. 1994; Vasisht, Frail, & Kulkarni 1995). In the case of SGR 1900+14, a *transient* wind nebula from relativistic particles injected during the giant flare of 1999 August 27 (Hurley et al. 1999c) was observed by the VLA (Frail et al. 1999). The different radio properties of the SGR 1806−20 and SGR 1900+14 counterparts are probably due to the different external pressures for the two sources, since SGR 1806−20 is still inside its high-pressure supernova remnant, while SGR 1900+14 is outside its associated supernova remnant, where the confining pressure is relatively low. The weak confining pressure of SGR 1900+14 inhibits the formation of a bright plerion (Frail et al. 1999). The observed nonthermal (photon index ∼2.2: Sonobe et al. 1994; Hurley et al. 1999b) quiescent X-ray spectra of the active SGR sources is characteristic of emission from a magnetized wind (Tavani 1994). Finally, the burst spectra of SGRs can be explained by the Compton upscattering of soft photons in a mildly relativistic wind, without involving a supercritical stellar field (Fatuzzo & Melia 1996).

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ERRATUM

In the Letter "Is SGR 1900+14 a Magnetar?" by D. Marsden, R. E. Rothschild, and R. E. Lingenfelter (ApJ, 520, L107 [1999]), there is a typographical error in Figure 1 that does not affect any of the scientific results of the Letter. The tick marks on the *y*-axis in this figure are mislabeled, indicating a wrong period for the peak in the χ^2 distribution. The values of the period and period derivative quoted throughout the text are the correct values and are unaffected by the typographical error. The corrected figure appears below.