Is SGR 1900+14 a Magnetar?

D. Marsden, R. E. Rothschild, and R. E. Lingenfelter

Center for Astrophysics and Space Sciences, University of California at San Diego

La Jolla, CA 92093

Received __________________; accepted __________________

Revised version submitted to the ApJ Letters 20 Apr 1999
We present RXTE observations of the soft gamma–ray repeater SGR 1900+14 taken September 4-18, 1996, nearly 2 years before the 1998 active period of the source. The pulsar period (P) of $5.1558199 \pm 0.0000029$ 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 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 spindown 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: pulsar: individual: SGR 1900+14 – stars: neutron – gamma-rays: bursts
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 review by Rothschild 1995). The SGRs may also be related to the anomalous X–ray pulsars (AXPs: Mereghetti, Stella, & Israel 1998), which have comparable 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 5 March 1979 from the SGR 0529–66 in the Large Magellanic Cloud. Suggested energy sources for these bursts have included, i) the rotational energy of the neutron star, $\sim 10^{45}(P/3.1\text{s})^{-2}$ ergs, where $P$ is the spin period, which might be tapped by pulsar glitches (e.g. Baym & Pines 1971), ii) the magnetic field energy $\sim 10^{14}(B/B_q)^2$ ergs of magnetars with surface magnetic fields much greater than the quantum critical field $B_q = m_e^2 c^3/eh \approx 4.4 \times 10^{13}$ G tapped by magnetic-stress driven crustal quakes and magnetic reconnection (Thompson & Duncan 1995), and iii) 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 spindown 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 (SGRs 1806–20 and 1900+14) or by $\dot{P} = 0.5P/t_{\text{snr}}$, where $P$ is the pulse
period and $t_{\text{snr}}$ is the estimated age of the associated supernova remnant (SGR 0526–66). If the spindown is driven by magnetic dipole radiation from an orthogonally rotating vacuum magnetic dipole, it can be shown (Pacini 1968) that the surface magnetic field is given by $B_0 \approx 3.2 \times 10^{19} \sqrt{P \dot{P}}$ G, which would yield surface magnetic fields of $6 \times 10^{14}$, $8 \times 10^{14}$, and $5 \times 10^{14}$ G for SGRs 0526–66 (Thompson & Duncan 1995), 1806–20 (Kouveliotou et al. 1998), and 1900+14 (Kouveliotou et al. 1999), respectively. Here we present RXTE observations, however, which suggest that the spindown 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 & Analysis

SGR 1900+14 was observed by the Proportional Counter Array (PCA) and High Energy X–ray Timing Experiment (HEXTE) instruments aboard the Rossi X–ray Timing Explorer on a number of occasions during the period September 4-18, 1996. The total exposure time was $\sim 47$ ks, with a temporal baseline of 15.4 days. For the first 22 ks, RXTE was pointed at a position RA (J2000)= 286$^\circ$.82 and Dec (J2000)= 9$^\circ$.32, which is $\sim 48''$ from the precise VLA position of SGR 1900+14 (Frail, Kulkarni, & Bloom 1999), but well inside the 1$^\circ$ 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 RA= 286$^\circ$.43 and Dec= 8$^\circ$.98, which is $\sim 0^\circ$.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 ∼ 0.75). 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 aboard RXTE are the High Energy X–ray Timing Experiment (HEXTE) and the Proportional Counter Array (PCA). HEXTE consists of two clusters of collimated NaI/CsI phoswich detectors with a total net area of ∼ 1600 cm² and and 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 cm² 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 RA(J2000) = 19h07m14.33 and Dec(J2000) = +09°19′20″.1 (Frail, Kulkarni, & Bloom 1999). The PCA data were searched for pulsations using the chi-squared folding method, which calculates the value of chi-squared for a pulsar lightcurve (versus a constant rate) folded on a range of trial pulsar periods. Here the pulse phase $\phi$ for a given photon time $t$ is defined by the relation $\phi(t) = f(t - t_0) + \frac{1}{2} \dot{f}(t - t_0)^2$, 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 $\dot{P} = -f P^2$. A maximum value of chi-squared 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 chi-squared 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 chi-squared, 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 lightcurves were then compared to a template lightcurve using the chi-squared test, and the 90% confidence contours were calculated using the chi-squared probability distribution. A folding time midway through the RXTE observation was used throughout the analysis to minimize correlations between $P$ and $\dot{P}$.

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 lightcurve 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 lightcurve obtained here is virtually identical to the lightcurves obtained just before (Hurley et al. 1999b) and just after (Kouveliotou et al. 1999) the commencement of the May 1999 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 lightcurve appears to have multiple components which vary differently with energy. There are three peaks in the 2 – 10 keV lightcurve, with a single relatively broad central peak surrounded by two narrower peaks. The narrow peaks have harder spectra than the broad peak, as the narrow peak emission dominates the emission from the broad peak above 10 keV. A simple explanation for the lightcurve 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 hotspots, 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 lightcurves obtained just after the giant flare of August 27, 1999 (Kouveliotou et al. 1999; Murakami et al. 1999), suggesting that the energy of the small hotspots 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 spindown rate seems to change abruptly sometime close to the initiation of bursting, at which point the spindown continues steadily at an increased rate. These two different spindown 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 spindown 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
\[ \dot{P} = (12.77 \pm 0.01) \times 10^{-11} \text{ s s}^{-1} \] for the mean spindown rate, and the corresponding pre-outburst value is \( \dot{P} = (6.126 \pm 0.006) \times 10^{-11} \text{ s s}^{-1} \). Using these mean \( \dot{P} \) values, the mean inferred dipole field strengths before and after the initiation of bursting would be \( 5.7 \times 10^{14} \text{ G} \) and \( 8.2 \times 10^{14} \text{ G} \), respectively, if the spindown 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 spindown 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 spindown may be due to \textit{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 \( t_{\text{age}} = P/[(n - 1) \dot{P}] \), where the braking index \( n \) is 3 for pure dipole radiation but much less (\( n \approx 1 \)) for spindown due to wind torques.

Taking the estimated age of G42.8+0.6 to be \( \sim 10^4 \text{ yr} \) (Vasisht, Frail, Kulkarni, & Greiner, 1994, Hurley et al. 1996), we find that the braking index for SGR 1900+14 must be \( \sim 1 \), i.e. \( n = 1 + 0.16/(t_{\text{age}}/10^4 \text{ yr}) \), which indicates that the pulsar spindown 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 \( \sim 2.5 \times 10^4 \text{ km s}^{-1} \) for it to have traversed from the center of the remnant to its present position, assuming a distance of 5 kpc (Vasisht, Frail, Kulkarni, & Greiner, 1994, Hurley et al. 1996). Thus the observations provide strong evidence that torques due to wind emission, and not magnetic dipole torques, dominate the spindown dynamics of SGR 1900+14.
The spindown behavior of SGR 1900+14 can be explained simply if we assume that the spindown is due almost entirely to wind emission, as was also considered by Kouveliotou et al. (1999). Possible mechanisms for the generation of this wind include thermal radiation from hotspots 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 spindown 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 \( k = \dot{P}/P \sim 2700^{-1} \text{ yr}^{-1} \). Given an age of \((1 - 2) \times 10^4 \text{ yr} \) for G42.8+0.6, we obtain an initial pulsar spin period of \( P_0 \sim 3 - 120 \text{ ms} \) 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 spindown rates) in the past.

As mentioned above, one scenario is that the spindown 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 spindown. From Thompson & Blaes (1998), the spindown constant is given by

\[
k = 1.5 \times 10^{-11} \left( \frac{B_*}{3 \times 10^{12} \text{ G}} \right)^2 \left( \frac{\delta B_*}{B_*} \right)^{4/3} \text{ Hz},
\]

where \( B_* \) is the dipole field strength, \( \delta B_* \) is the wave amplitude, and we have assumed a neutron star moment of inertia and radius of \( 1.1 \times 10^{45} \text{ g cm}^2 \) and \( 10 \text{ km} \), respectively. This value of \( k \) is comparable to the measured value \( k = \dot{P}/P \sim 10^{-11} \text{ Hz} \) for SGR 1900+14, indicating that this mechanism can explain the spindown of the SGR with conventional \((\sim 10^{12} \text{ G})\) field strengths, assuming that there is a mechanism to continuously generate Alfvén waves.
Even though a supercritical magnetic field on a global scale can not account for the SGR pulsar spindown, 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 $10^2$ to $10^3$ times the average global surface field of the Sun. Such spots of emerging magnetic flux (EMF) on a neutron star may thus contain supercritical, or larger, localized fields, $B_s$ within radii $r_s$, with total magnetic energies $> 3 \times 10^{41}(B_s/B_q)^2(r_s/1\ \text{km})^3$ erg, and they may be accompanied by comparable tectonic stresses and heating from field diffusion in the crust. To contain the giant flare of August 27, 1999, for example, a local field with $B \sim B_q$ can contain the $3 \times 10^{42}$ ergs of energy released (Frail, Kulkarni, & Bloom 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 EMF-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 spindown torque of SGR 1900+14 are due to wind emission, the persistent x-ray flux and the spindown 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)%%20%. Using the appropriate mean $\dot{P}$ values from Figure 3, the spindown luminosity increased by $\sim 120\%$ over the same time interval, which is consistent with the steady x–ray flux and spindown arising from the wind.

The radio signature of SGR winds have been observed from SGRs 1900+14 (Frail, Kulkarni, & Bloom 1999) and 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), explaining 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 August 27, 1999 (Hurley et al. 1999c) was observed by the VLA (Frail, Kulkarni, & Bloom 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 SNR 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, Kulkarni, & Bloom 1999). The observed nonthermal (photon index $\sim 2.2$; 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).

We thank Duane Gruber for suggesting improvements in the timing analysis. This work was funded by NASA grant NAS5-30720.
REFERENCES

Baym, G., & Pines, D. 1971, Ann. Phys., 66, 816

Fatuzzo, M. & Melia, F. 1996, ApJ, 464, 316

Frail, D. A., Kulkarni, S. R., & Bloom, J. S. 1999, Nature, in press

Hurley, K. et al. 1996, ApJ, 463, L13

Hurley, K. et al. 1999a, ApJ, 510, L107

Hurley, K. et al. 1999b, ApJ, 510, L111

Hurley, K. et al. 1999c, Nature, 397, 41

in’t Zand, J. J. M., Baykal, A., & Strohmayer, T. E. 1998, ApJ, 496, 386

Jahoda, K. et al. 1996, EUV, X–ray, and Gamma–Ray Instrumentation for Astronomy VII, SPIE Proc. 2808, eds. O. H. V. Sigmund & M. Gumm (Bellingham: SPIE), 59

Kouveliotou et al. 1998, Nature, 393, 235

Kouveliotou, C. et al. 1999, ApJ, 510, L115

Kulkarni, S. R. et al. 1994, Nature, 368, 129

Marsden, D. et al. 1998, ApJ, 502, L129

Mazets, E. P. et al. 1979, Nature, 282, 587

Mereghetti, S., Stella, L., & Israel, G. L. 1998, in The Active X–ray Sky: Results from BeppoSAX and Rossi-XTE, Nuclear Physics B Proceeding Supplements, eds. L. Scarsi, H. Bradt, P. Giommi, & F. Fiore, (Elsevier Science: New York), 253

Murakami, T. et al. 1999, ApJ, 510, L119
Pacini, F. 1968, Nature, 221,

Ramaty, R. et al. 1980, Nature, 287, 122

Rothschild, R. E. 1995 in High Velocity Neutron Stars and Gamma–Ray Bursts, AIP Conference Proceedings 384, eds R. E. Rothschild & R. E. Lingenfelter (AIP Press: New York), 51

Rothschild, R. E. et al. 1998, ApJ, 496, 538

Rots, A. H. et al. 1998, ApJ, 501, 749

Ruderman, M. 1991, ApJ, 382, 587

Shitov, Yu. P. 1999, IAUC 7001

Sonobe, T., et al. 1994, ApJ, 436, L23

Sturrock, P. A. 1986, Nature, 321, 47

Tavani, M. 1994, ApJ, 431, L83

Thompson, C. & Duncan, R. C. 1995, MNRAS, 275, 255

Thompson, C., & Blaes, O. 1998, Phys. Rev. D, 57, 3219

Valinia, A. & Marshall, F. E. 1998, ApJ, 505, 134

Vasisht, G., Frail, D. A., Kulkarni, S. R. & Greiner, J. 1994, ApJ, 431, L35

Vasisht, G., Frail, D. A., & Kulkarni, S. R. 1995, ApJ, 440, L65

This manuscript was prepared with the AAS LaTeX macros v4.0.
Fig. 1.— Determination of the SGR 1900+14 timing ephemeris. The grid of chi-squared 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 $\dot{P}$.

Fig. 2.— The SGR 1900+14 folded lightcurve. The pulsar lightcurve is shown for three different PCA energy bands.

Fig. 3.— The 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.
