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VARIABLE SPIN-DOWN IN THE SOFT GAMMA REPEATER SGR 1900+14 AND CORRELATIONS WITH BURST ACTIVITY

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ABSTRACT

We have analyzed *Rossi X-ray Timing Explorer* Proportional Counter Array observations of the pulsed emission from SGR 1900+14 during 1996 September, 1998 June–October, and early 1999. Using these measurements and results reported elsewhere, we construct a period history of this source for 2.5 yr. We find significant deviations from a steady spin-down trend during quiescence and the burst active interval. Burst and Transient Source Experiment observations of the burst emission are presented and correlations between the burst activity and spin-down rate of SGR 1900+14 are discussed. We find an 80 day interval during the summer of 1998 when the average spin-down rate is larger than the rate elsewhere by a factor ∼2.3. This enhanced spin-down may be the result of a discontinuous spin-down event or "braking glitch" at the time of the giant flare on 1998 August 27. Furthermore, we find a large discrepancy between the pulsar period and average spin-down rate in X-rays as compared to radio observations for 1998 December and 1999 January.

Subject headings: pulsars: general — stars: individual (SGR 1900+14) — X-rays: bursts

1. INTRODUCTION

Soft gamma repeaters (SGRs) form a rare class of persistent X-ray sources that are associated with young ($\sim 10^4$ yr) supernova remnants (see Kouveliotou 1999 for a review). Three of the four SGRs have stellar spin periods within a narrow range of 5–8 s (Mazets et al. 1979; Kouveliotou et al. 1998; Hurley et al. 1999a); one (SGR 1627−41) may rotate at 6.4 s (Woods et al. 1999a), but the detection of this period is marginal and was not confirmed in a recent *ASCA* observation (Hurley et al. 1999b). SGR 1806−20 and SGR 1900+14 were recently found to spin down on long timescales at a rate $\sim 10^{-11}$ to 10^{-10} s s^{-1} (Kouveliotou et al. 1998, 1999). This spin-down has been interpreted as evidence that they are neutron stars with very intense magnetic fields in the 10^{14}–10^{15} G range, i.e., magnetars (Duncan & Thompson 1992). Magnetars are defined as a star whose magnetic field energy dominates all other sources of energy, including rotation (Thompson & Duncan 1995, 1996). Except for their emitting brief (∼0.1 s), intense ($\sim 10^{39}$–10^{42} ergs s^{-1}) bursts of low-energy γ-rays (Kouveliotou 1995) and having harder persistent emission spectra, the characteristics of SGRs are similar to those of the anomalous X-ray pulsars (AXPs; Mereghetti & Stella 1995; van Paradijs, Taam, & van den Heuvel 1995).

The spin-down histories of at least some SGRs and AXPs have both a steady spin-down component and a variable perturbing component. Two AXPs with well-sampled period histories, 1E 1048.1−5937 and 1E 2259+586, have shown evidence for such perturbations (Mereghetti 1995; Iwasawa, Koyama, & Halpern 1992; Heyl & Hernquist 1998, and references therein). SGR 1806−20 has a long-term average spin-down rate of $8.3(3) \times 10^{-11}$ s s^{-1}, although the local period derivative in 1996 November was $2.8(14) \times 10^{-11}$ s s^{-1} (Kouveliotou et al. 1998), suggesting a nonconstant spin-down.

Recently, deviations from a constant spin-down rate have been found for SGR 1900+14 (Kouveliotou et al. 1998; Woods et al. 1999b). SGR 1900+14 was observed on 1998 April 30 with the *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*) when the source was not burst active, i.e., in quiescence. Timing analysis of its persistent X-ray flux revealed coherent pulsations with a period of 5.16 s (Hurley et al. 1999a). On 1998 May 26 the source became extremely active (Hurley et al. 1999c), and it has since remained in an active state, during which numerous bursts have been recorded with the Burst and Transient Source Experiment (BATSE) aboard the *Compton Gamma-Ray Observatory* (*CGRO*). Due to Earth occultation of the source for BATSE, the most notable event from this source, emitted on 1998 August 27, went undetected. This exceptional flare (Hurley et al. 1999d) was much more energetic (factor of ∼500) than the brightest burst emissions detected from this SGR before or since and rivals in intensity the brightest SGR outburst ever recorded, the famous 1979 March 5 event from SGR 0526−66 (Mazets et al. 1979).

We observed SGR 1900+14 with the *Rossi X-ray Timing Explorer* (*RXTE*) Proportional Counter Array (PCA) at the beginning of its active period during 1998 late May and early June as well as directly following the 1998 August 27 flare. We confirmed the pulsar period (Kouveliotou et al. 1999) and derived a source spin-down rate, $\sim 1 \times 10^{-10}$ s s^{-1}, hence establishing SGR 1900+14 as a magnetar with $B_{\rm dipole} = (2–8) \times 10^{14}$ G. Comparing our data with the *ASCA* data, we noted that the spin-down of this magnetar was not constant from April through August, varying from 5×10^{-11} to 14×10^{-11} s s^{-1} (Kouveliotou et al. 1999). Shitov (1999) reported the detection of radio pulsations at 5.16 s from SGR 1900+14 during 1998 December and 1999 January (see Table 1).

BeppoSAX Narrow Field Instrument observations of SGR

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TABLE 1

Period and Period Derivative Measurements for SGR 1900+14

Time of Observation	Exposure (ks)	Epoch (MJD TDB)	Period (s)	Period Derivative (10^{-11} s s^{-1})	Instrument	Reference
1996 Sep 4–19	100.9	50,337.0	5.15581568(19)	8.27(14)	*RXTE*	This work
1997 May 12–13	45.7	50,580.5	5.157190(7)	…	*BeppoSAX*	Woods et al. 1999b
1998 Apr 30–May 2	84.6	50,935.0	5.1589715(8)	…	*ASCA*	Hurley et al. 1999a
1998 May 31–Jun 9	43.5	50,970.0	5.15917011(55)	8.2(6)	*RXTE*	This work
1999 Aug 28–Oct 8	146.9	51,070.0	5.16026572(12)	5.93(3)	*RXTE*	This work
1998 Sep 15–16	33.2	51,071.5	5.160262(11)	…	*BeppoSAX*	Woods et al. 1999b
1998 Sep 16–17	39.0	51,073.3	5.160295(3)	…	*ASCA*	Murakami et al. 1999
1998 Dec 12–1999 Feb 4	…	51,159.5	5.16129785(8)	12.3228(34)	BSA[a]	Shitov 1999
1999 Jan 3–4	31.9	51,181.5	5.160934(56)	…	*RXTE*	This work
1999 Mar 21	9.1	51,259.0	5.16145(18)	…	*RXTE*	This work
1999 Mar 30	8.4	51,268.0	5.16156(11)	…	*RXTE*	This work

[a] BSA is the Pushchino Bol'shaya Steerable Array.

1900+14 were performed on 1997 May 12 and 1998 September 15. The 1997 May 12 observation provided a broad baseline for the spin-down during quiescence. The average spin-down rate between the *BeppoSAX* period measurement of 1997 May and the *ASCA* measurement of 1998 April was 5.82(2) × 10^{-11} s s^{-1} (Woods et al. 1999b). This rate differs significantly from the values measured during the burst active period, confirming that long-term variations in the spin-down rate—possibly related to burst activity—occur. An archival *RXTE* observation from 1996 September extended the baseline of the quiescent spin-down and agrees to first order with the slower spin-down observed during quiescence (Marsden, Rothschild, & Lingenfelter 1999).

To further investigate the period history during the burst active period, we have observed SGR 1900+14 with the *RXTE* PCA periodically between 1999 January 3 and 1999 July 27. We combine a subset of these data with previously reported results, in addition to a separate analysis of all *RXTE* observations from 1996 September through 1998 October, and construct a period history for SGR 1900+14 over 2.5 yr. We also report on the burst rate history of SGR 1900+14 as seen with BATSE and discuss possible correlations between the burst activity and the changes observed in the spin-down.

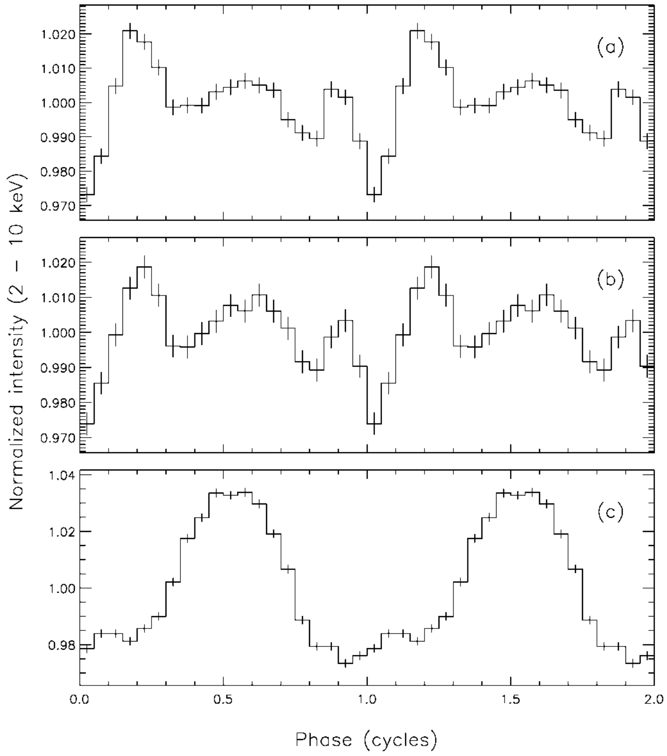

Fig. 1.—Phase-folded profiles of SGR 1900+14 as seen with the *RXTE* PCA (2–10 keV) for (*a*) 1996 September, (*b*) 1998 May–June, and (*c*) 1998 August–October.

2. *RXTE* PCA OBSERVATIONS OF PULSED EMISSION

SGR 1900+14 was observed with the *RXTE* PCA in 1996 September for 100 ks over 16 days. An analysis of a subset of these data provided a period and period derivative of 5.1558199(29) s and 6.0(10) × 10^{-11} s s^{-1}, respectively, at the chosen epoch 50,338.216 MJD (Marsden et al. 1999). In order to compile a uniform database, we have reanalyzed these data using a phase-folding technique. Using event mode data, we energy-selected all observations for 2–10 keV photons, binned the data at 0.125 s time resolution, and barycenter-corrected the bin times. Adopting a constant period phase model we derived from an epoch-fold search, we calculated the phase at multiple points during the observation. These phases could not be well fit with a linear phase model, so we included a second-order term (i.e., frequency derivative). This fit yielded a good reduced χ^2_ν of 0.6 for 15 degrees of freedom (dof) (see Table 1). The phase-folded profile (2–10 keV) for this ephemeris is given in Figure 1*a*. The period and period derivative derived from this fit (see Table 1) are similar to but not within the errors reported by Marsden et al. (1999). We estimate the average spin-down rate between 1996 September and 1998 April (quiescence) by performing a least-squares fit to all period measurements during this time interval and find a value 6.13(2) × 10^{-11} s s^{-1}. The statistical error here has been inflated by the square root of the reduced χ^2_ν (168) of the linear fit. The period derivative measurement for 1996 September has been extrapolated for 250 days in Figure 2 (dotted lines represent $\pm 1\ \sigma$) to clearly indicate the discrepancy between the local slope and the long-term trend. The improved precision of the period derivative measurement within this observation and the inclusion of the *BeppoSAX* period measured from 1997 May allows us to conclude that there are significant deviations from a constant spin-down rate during quiescence.

We have also reanalyzed *RXTE* PCA observations of SGR 1900+14 during 1998 May–June and 1998 August–October. For the first sequence of observations from 1998 May 31 through June 9, we processed the data as before and find a second-order phase model represents the data well with a reduced χ^2_ν of 1.3 for 13 dof (see Table 1). The phase-folded

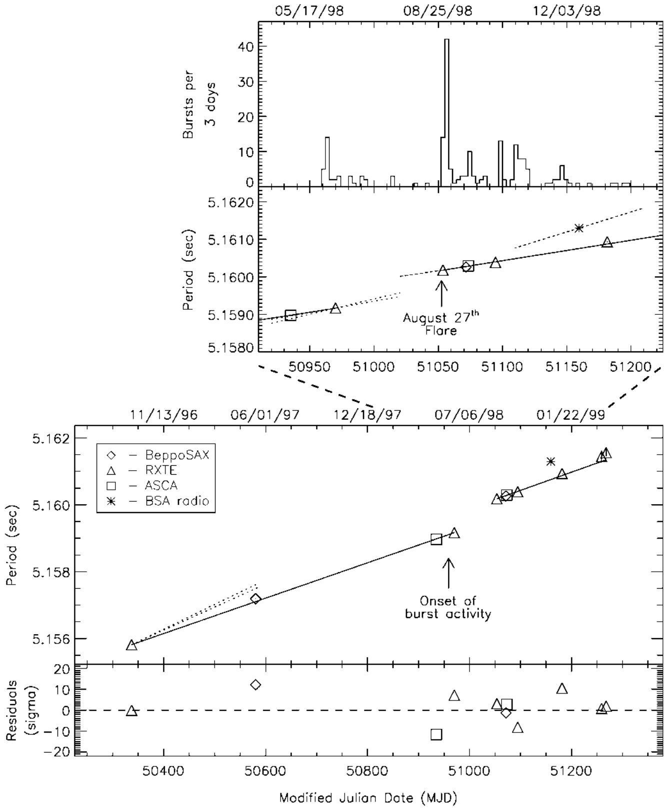

FIG. 2.—*Bottom:* Period history of SGR 1900+14 from 1996 September through 1999 March. The lower axis label is the modified Julian date, and the upper axis is mm/dd/yy. The solid lines indicate least-square fits to the period measurements found in two separate intervals (1996 September–1998 June and 1998 August–1999 March). Due to the long series of observations with *RXTE* from 1998 August 28 to October 8, two period measurements from the beginning and end are shown. Residuals of fit are shown in lower panel. Dotted lines represent extrapolation of local period derivative measurement ($\pm 2\ \sigma$; see Table 1) found in 1996 September *RXTE* observation. *Upper right:* Inset of lower figure showing burst rate history (*upper panel*) and period history (*lower panel*) of SGR 1900+14 from 1998 April 7 through 1999 February 16. Dotted lines represent extrapolation of local period derivative measurement ($\pm 2\ \sigma$).

profile (Fig. 1*b*) is consistent with the light curve found in 1996 September, which shows the profile did not change over a long time period (1.7 yr), as well as after significant burst activity. We have extended the baseline of the second sequence of observations from 6 days (Kouveliotou et al. 1999) to 42 days. Due to the large number of bursts detected during these observations (more than 1000), we have binned the data with finer time resolution (0.05 s) to better filter out these bursts. Over this much longer baseline, a simple second-order phase model fits the data reasonably well, but not completely (χ^2_ν = 2.4 for 25 dof). The phase-folded profile (Fig. 1*c*) is significantly different during these observations as pointed out by Kouveliotou et al. (1999) and shows that the pulse shape changes observed during the tail of the August 27 flare (Mazets et al. 1999) persist for months. Combination of these observations with a more recent *RXTE* observation campaign will allow us to better investigate these low phase amplitude deviations.

A new series of *RXTE* PCA observations of SGR 1900+14 began on 1999 January 3 and has recently finished on 1999 July 27. We have selected a subset of three observations sufficiently long to obtain an accurate measurement of the pulsar period. For each of these observations, we have used standard 1 data (2–60 keV) binned at 0.125 s time resolution with barycenter-corrected time bins. Using a phase-folding technique, we have calculated the period for each observation. The results of these measurements are summarized in Table 1. Although summed over a different energy range, the phase-folded profile is the same as that found during the fall of 1998. The X-ray periods measured during 1999 lie slightly above the extrapolation of the period derivative found during the fall of 1998. We find that a linear least-squares fit to the period measurements after 1998 August 27 yields an average period derivative 6.07(15) × 10^{-11} s s^{-1}; again, the statistical error is inflated by the square root of the reduced χ^2_ν (56). We note that the reported radio period measurement during 1998 December and 1999 January is highly discrepant (the reported period is more than 5000 σ away from the linear fit, and the period derivative is double what is found in X-rays over the same time interval; see Fig. 2).

3. BATSE OBSERVATIONS OF BURST EMISSION

Between 1998 May and 1999 January, BATSE triggered on 63 bursts from SGR 1900+14. The on-board BATSE trigger criteria were set at low-energy trigger (channels 1 + 2; 25–100 keV), nominal trigger (channels 2 + 3; 50–300 keV), and high-energy trigger (channels 3 + 4; 100–2000 keV), each for significant time intervals during the burst active period. Due to the relatively soft nature of the typical burst emission from SGRs, BATSE's sensitivity to SGR events changed according to which trigger criterion was in use. Other factors, such as inability to read out on-board memory before the next event, resulted in untriggered events as well. In order to obtain a more complete database, we performed an off-line search for untriggered events from SGR 1900+14.

BATSE consists of eight NaI detectors which form a regular octahedron and are sensitive to photons with energies 25 keV–2 MeV (Fishman et al. 1989). Using *CGRO* spacecraft pointing information, we calculated the zenith angles for each detector and determined the two detectors with the lowest zenith angles for each spacecraft orientation. For all days during each orientation, we searched the DISCLA data (1.024 s time resolution) for simultaneous fluctuations in these detectors for energy channel 1 (25–50 keV). The background was estimated by fitting a first-order polynomial to 10 s of data before and after each bin with a 3 s gap between the background interval and the bin searched. An off-line trigger was defined as a fluctuation greater than 4.5 σ and 3.0 σ in the two brightest detectors, respectively, an excess of counts below 50 keV relative to the counts between 50 and 300 keV for the brightest detector, and a duration less than 7 s. Each trigger was visually inspected and coarsely located based upon the relative rates in the BATSE modules. Between 1998 May 24 and 1999 February 3, we detected most of the SGR 1900+14 events which triggered BATSE in addition to 137 untriggered events. Some triggered events were not detected off-line because the DISCLA data has coarser time resolution than the timescale on which most SGR events trigger (64 ms) or the trigger occurred during a telemetry data gap. The large number of untriggered events relative to triggered bursts is due to extended periods (more than 4 months) when the BATSE trigger was in "high-energy mode." Based upon our experience with classifying BATSE triggers, we expect the number of false triggers within our sample to be less than 5%. Figure 2 displays the burst rate (per 3 day interval) over the time period searched. No emission from SGR 1900+14 triggered the BATSE instrument between 1992 August (Kouveliotou et al. 1993) and 1998 May 25. We note that the most recent trigger from this SGR was recorded on 1999 April 29, so it appears the burst activity has ceased for the time being.

4. DISCUSSION

We have shown that during quiescence, the spin-down rate of SGR 1900+14 is not constant. The deviations observed may be caused by processes such as orbital Doppler shifts, persistent but variable emission of Alfvén waves and/or particles from magnetars (Thompson & Blaes 1998), radiative precession in such an object (Melatos 1999), or discontinuous spin-up events (glitches) as seen in radio pulsars (Thompson & Duncan 1996; Heyl & Hernquist 1998). Due to the sparsely sampled data for this source, we cannot exclude any of these models currently, although periodic modulations must be longer than 16 days or less than ∼2 days with a small phase amplitude. More frequent measurements are required before anything definitive can be said about modeling these deviations.

The period history of SGR 1900+14 appears to be divided into two sections during which the spin-down rate is nearly, but not exactly, constant. The pulse period and period derivative reported by Shitov (1999) for a radio pulsar connected with SGR 1900+14 appears incompatible with the X-ray spin history presented here. Before 1998 June 9 and after 1998 August 27, the average rate is 6.1×10^{-11} s s^{-1}. These two sections are separated by 80 days during which the period increased by 1 ms, which implies an average rate of 14.0×10^{-11} s s^{-1}. It appears that the period history during this interval allows for two obvious descriptions: (1) a gradual increase of the nominal spin-down rate and (2) a discontinuous spin-down event associated with the 1998 August 27 flare.

According to the first picture, following the initial flurry of burst activity in late 1998 May, the spin-down rate increased by a factor ∼2.3. This rate persisted for ∼80 days, then decreased to near its original value after 1998 August 27. If this were the correct description, then we cannot attribute the enhanced spin-down directly to the magnitude of the burst activity. The number of bursts recorded with BATSE between the onset of activity in 1998 May and August 26 was 40 (the extraordinary, multiepisodic burst of 1998 May 30 [Hurley et al. 1999c] is counted here as a single event). Following the 1998 August 27 flare, 123 bursts were recorded up to 1999 February 3, including a multiepisodic event on 1998 September 1 similar to (although less intense than) the 1998 May 30 event. The total burst energy recorded in the events following the August 27 flare is more than double the energy released through burst emission prior to the flare. If one assumes that the burst rate or the burst energy released is correlated with the increase in spin-down, then one would expect to see an even steeper spin-down rate between 1998 August 28 and 1999 January 3, which is not the case. The increased breaking torque on the star must then be attributed to something other than the burst activity as measured by the burst rate or the burst energy of the smaller, more common bursts.

An alternative scenario to account for the rapid spin-down during the period 1998 June–September is that the star underwent a more or less steady spin-down at a long-term average rate of $\sim 6 \times 10^{-11}$ s s^{-1} from June through most of August. The star then suffered a discontinuous upward jump in period or a "braking glitch," which is attractive to link with the occurrence of the very energetic flare of 1998 August 27. Extrapolating the long-term trends found before and after August 27, we find that this braking glitch would have a magnitude $\Delta P = 5.72(14) \times 10^{-4}$ s. This corresponds to a rotational energy loss for the star $\Delta E_{\mathrm{rot}} \approx 2 \times 10^{41} (M_*/1.4\ M_\odot)(R_*/10\ \mathrm{km})^2$ ergs if the whole star participates, or 0.5% of the energy released in high-energy photons during the August 27 flare. Physical mechanisms causing such a glitch are discussed in a companion paper (Thompson et al. 1999).

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