THE ASTROPHYSICAL JOURNAL, 609:L000–L000, 2004 July 1

MS# 17879 APJL 75(1), pt. 2 Copyeditor: pfr
Thursday May 20 2004 04:56 PM

DISCOVERY OF A TRANSIENT MAGNETAR: XTE J1810−197

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Received 2003 October 23; accepted 2004 May 19; published 2004 May XX

ABSTRACT

We report the discovery of a new X-ray pulsar, XTE J1810−197, that was serendipitously discovered on 2003 July 15 by the *Rossi X-Ray Timing Explorer* (*RXTE*) while observing the soft gamma repeater SGR 1806−20. The pulsar has a 5.54 s spin period; a soft X-ray spectrum (with a photon index of ≈4), and is detectable in earlier *RXTE* observations back to 2003 January but not before. These show that a transient outburst began between 2002 November 17 and 2003 January 23 and that the source's persistent X-ray flux has been declining since then. The pulsar exhibits a high spin-down rate $\dot{P} \approx 10^{-11}$ s s^{-1} with no evidence of Doppler shifts due to a binary companion. The rapid spin-down rate and slow spin period imply a supercritical characteristic magnetic field $B \simeq 3 \times 10^{14}$ G and a young age $\tau \leq 7600$ yr. Follow-up *Chandra* observations provided an accurate position of the source. Within its error radius, the 1.5 m Russian-Turkish Optical Telescope found a limiting magnitude $R_C = 21.5$. All such properties are strikingly similar to those of anomalous X-ray pulsars and soft gamma repeaters, providing strong evidence that the source is a new magnetar. However, archival *ASCA* and *ROSAT* observations found the source nearly 2 orders of magnitude fainter. This transient behavior and the observed long-term flux variability of the source in absence of an observed SGR-like burst activity make it the first confirmed *transient magnetar* and suggest that other neutron stars that share the properties of XTE J1810−197 during its inactive phase may be unidentified transient magnetars awaiting detection via a similar activity. This implies a larger population of magnetars than previously surmised and a possible evolutionary connection between
q1 magnetars and other neutron star families.

Subject headings: pulsars: general — pulsars: individual (XTE J1810−197) — stars: magnetic fields — stars: neutron — X-rays: stars

1. INTRODUCTION

Soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are a remarkably distinct class among the growing population of isolated neutron stars. They rotate relatively slowly with spin periods in the narrow range $P \sim 5$–12 s and spin-down rather rapidly at $\dot{P} \sim 10^{-11}$ s s^{-1}. Both are radio-quiet, persistent X-ray sources ($L \sim 10^{34}$–10^{36} ergs s^{-1}) with the unique property of sporadic emission of short (<0.1 s), superbright ($L_{\rm peak} > L_{\rm Edd}$) bursts of X-rays and soft γ−rays. No evidence has been found of a binary companion or a remnant accretion disk to power their emission, although it is more than an order of magnitude higher than can be provided by their rotational energy. Nine sources are currently firmly identified, including four SGRs and five AXPs (see Hurley 2000 and Mereghetti et al. 2002). Four more candidates need confirmation.

The magnetar model provides a coherent picture in which SGR and AXP radiation is powered by a decaying supercritical magnetic field, in excess of the quantum critical field $B_c = 4.4 \times 10^{13}$ G (Duncan & Thompson 1992; Thompson & Duncan 1995). Evidence of magnetars has come from the energetic burst emission (Paczyński 1992; Hurley et al. 1999; Ibrahim et al 2001), the long spin period and high spin-down rate (Kouveliotou et al. 1998; Vasisht & Gotthelf 1997), and the lack of binary companion or accretion disks (Kaplan et al. 2001). Further evidence has recently come from spectral line features that are consistent with proton-cyclotron resonance in the $B \simeq 10^{15}$ G field (Ibrahim et al. 2002, 2003b) and from the burst activity of two AXPs, as predicted by the magnetar model (Gavriil et al. 2002; Kaspi et al. 2003).

SGRs and AXPs generally have little flux variability during their nonbursting states. Here we present the discovery of the first X-ray pulsar that has the properties of quiescent AXPs and SGRs but is a transient. We discuss the implications for the characteristics and populations of magnetars.

2. A NEW X-RAY PULSAR NEAR SGR 1806–20

Following the Interplanetary Network (IPN) report of renewed burst activity from SGR 1806−20 on 2003 July 14 (Hurley et al. 2003), we observed the source on July 15 with the Proportional Counter Array (PCA) on board the *Rossi X-Ray Timing Explorer* (*RXTE*). PCA data in the event-mode configuration E_125US_64M_0_1S were collected from all layers of the operating Propotional Counter Units (PCUs; 0, 2, and 3) in the 2–8 keV band, corrected to the solar system

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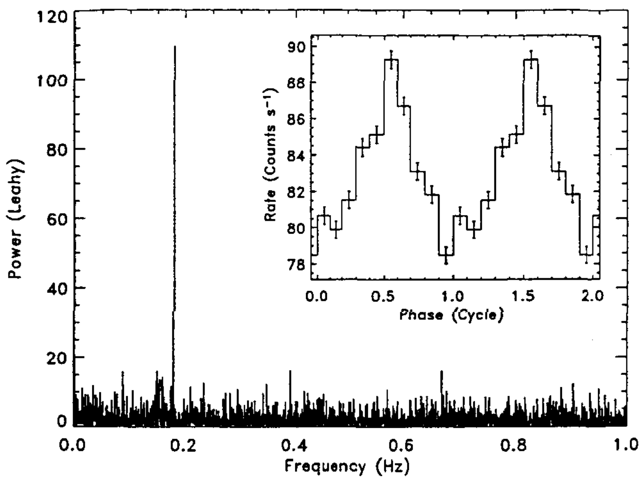

FIG. 1.—Fast Fourier transform power spectrum of the *RXTE* PCA July 15 observation of the FOV of SGR 1806−20 showing a highly significant periodic signal at 0.18052(6) Hz. The inset shows the epoch-folded pulse profile in 10 phase bins. Errors in the frequency and period correspond to the 3 σ confidence level. Note that the ≈0.13 Hz signal due to SGR 1806−20 is not detected here, indicating a low pulsed flux. Subsequent observations confirmed this.

barycenter, and binned in 0.125 s intervals. A strong periodic signal with a barycentric period of 5.540(2) s at a chance probability of 2.5×10^{-12} was clearly identified in the first observation that lasted for only 2.6 ks (Ibrahim et al. 2003a; see Fig. 1). The large discrepancy between this pulse period and the expected 7.5 s of SGR 1806−20 implied the presence of a new X-ray pulsar in the PCA 1°2 field of view (FOV).

A PCA scanning observation was performed on July 18, following a path that covered a region surrounding SGR 1806−20. During scans, the count rates due to individual sources are modulated by the response of the PCA collimator. The resulting light curves are corrected for internal background (using the "CM" L7 background model) and are fitted to a model of known and unknown sources, convolved with the collimator response. For unknown sources, a trial position is assumed and adjusted until the best fit is achieved. The sources included in this fit were the new source, SGR 1806−20, the galactic ridge, and an overall diffuse level. The uncertain spatial distribution of the galactic ridge emission in the FOV was modeled as an unresolved ridge at 0° latitude. The best-fit position and 3 σ contour obtained for the position of the new source, designated XTE J1810−197, are shown in Figure 2 (Markwardt et al. 2003b).

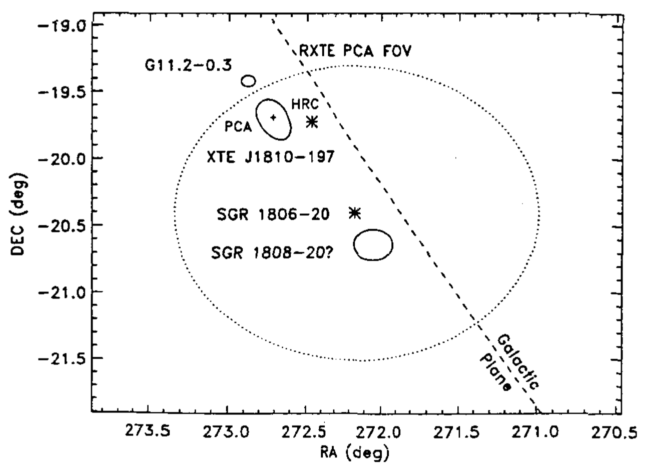

FIG. 2.—PCA FOV during the SGR 1806−20 pointed observation, showing the neighborhood of SGR 1806−20, including XTE J1810−197, the supernova remnant G11.2−0.3 that contains the 65 ms pulsar PSR J1811−1925, and the potential SGR 1808−20 (Lamb et al. 2003). The positions of XTE J1810−197 from the PCA scan and HRC observations are indicated. Also shown is the 3 σ PCA error contour, with semimajor axes of 5.5′ and 10′.

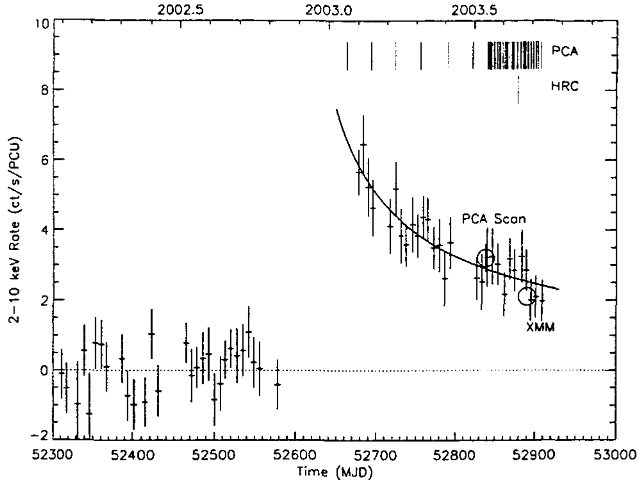

FIG. 3.—Monitoring light curve of XTE J1810−197, showing the transient outburst beginning in 2003 (1 mcrab = 2.27 counts^{-1} s^{-1} PCU^{-1} = 2.4×10^{-11} ergs cm^{-2} s^{-1}; 2–10 keV). We have subtracted from the rate an offset of 0.68 counts s^{-1} PCU^{-1}, which we ascribe to diffuse and unresolved emission in the region and not accounted for by our model. Epochs of PCA dedicated pointed observations with the source in the FOV are indicated in the top row of vertical bars. The epoch of the first HRC pointing is shown separately. The flux from the *XMM-Newton* spectrum (§ 2.4), converted to an approximate PCA flux using the PIMMS simulator, is shown as the lower circle. The upper circle is the flux derived from the dedicated PCA scan.

Two follow-up *Chandra* observations with the High Resolution Camera (HRC) on August 27 and November 1 localized the source precisely to $\alpha = 18^{h}09^{m}51^{s}.08$, $\delta = -19°43'51''.74$ (J2000) (Gotthelf et al. 2003, 2004; Israel et al. 2004). Pulsations in the HRC data definitively identified the source. The HRC position is 14′ from the best-fit PCA position. Typically, accuracies of 1′–2′ have been obtained in past scans for bright sources. The presence of the diffuse galactic ridge and other, unmodeled, faint sources in the FOV—in particular, the supernova remnant G11.2−0.3—resulted in large systematic errors, for which a priori estimates were difficult.

We observed the first *Chandra* HRC error box with the 1.5 m Russian−Turkish Telescope (Antalya, Turkey) on 2003 September 3 and 6. Optical Cousins *R* filter images of the field around the source were obtained using the Andor CCD (2048 × 2048 pixels, 0″24 pixel scale, and 8′ × 8′ FOV) with 15 minute exposure times (three frames). Seeing was about 2″. We did not detect a counterpart to a limiting magnitude of 21.5 (2 σ level) in the R_C band, comparable to the limits in V (22.5), I (21.3), J (18.9), and K (17.5) obtained by Gotthelf et al. (2004). Recently, Israel et al. (2004) reported a likely IR counterpart with $K_s = 20.8$ and $F_X/F_{IR} > 10^3$.

3. LONG-TERM LIGHT CURVE: A TRANSIENT SOURCE

XTE J1810−197 appeared consistent with a previously unidentified source that had been present since 2003 February at the edge of a galactic bulge region regularly scanned with the PCA (Swank & Markwardt 2001). These observations include brief dwells of about 150 s, in which the 5.54 s pulsations could be seen, confirming identification of the source.

Figure 3 shows the 2002–2003 light curve of XTE

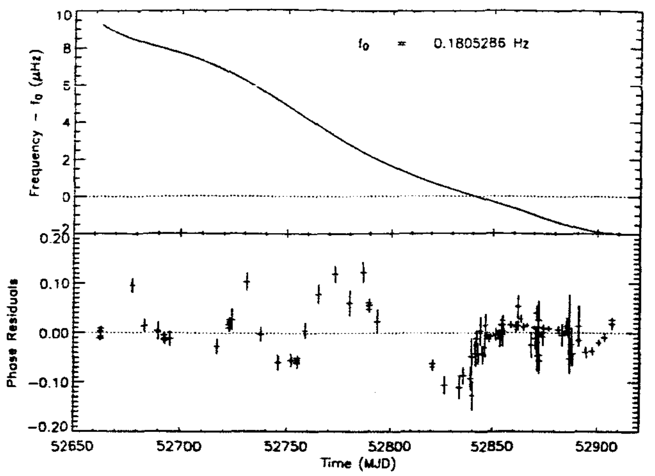

FIG. 4.—Frequency evolution (*top*) and phase residuals (*bottom*) for the PCA timing solution of XTE J1810−197.

J1810−197 from the bulge scan measurements, when fixed at the *Chandra* position. The scans are the only set of PCA observations that can consistently resolve the contributions of the source and diffuse background. Clearly XTE J1810−197 became active sometime between 2002 November and 2003 February. The distribution of 1999–2002 pre-outburst fluxes allows us to place a 3 σ upper limit on previous outbursts of less than 2 counts s^{-1} PCU^{-1} or 1 mcrab (2–10 keV) from the baseline level, as long as the outburst did not fall in an observing gap (the maximum gap was 3 months).

The flux decay can be fitted to power-law or exponential models. For the exponential model, the *e*-folding time is 269 ± 25 days. The power-law model has the potential of retrieving the epoch at which the outburst began. Assuming the flux is proportional to $[(T - T_0)/(52{,}700 - T_0)]^{-\beta}$, at time T and with outburst time T_0 in MJD, $\beta = 0.45$–0.73 were acceptable (1 σ), with $52{,}580 \leq T_0 \leq 52{,}640$, that is, 2002 November 2 to 2003 January 1. Additional information came from observations of the nearby pulsar PSR J1811−1925 that had XTE J1810−197 in the FOV (observation IDs [ObsIDs 70091-01 and 80091-01). Its pulsations were detected on 2003 January 23 (MJD 52,662) but not on 2002 November 17 (MJD 52,595).

4. SPECTRUM

A PCA spectrum was estimated by reanalyzing the July 18 light curves in each spectral band, this time using the *Chandra* position and allowing a contribution from G11.2−0.3 (Markwardt et al. 2003a). The resulting spectrum of XTE J1810−197
q3 was clearly soft, despite large uncertainty in the column densities of any of the models. For the column fixed at 1 × 10^{22} cm^{-2} (typical for sources in the region and subsequently measured to be the case by *XMM-Newton*), a power-law fit has a photon index $\Gamma = 4.7 \pm 0.6$, with a 2–10 keV absorbed flux of 5.5 × 10^{-11} ergs cm^2 s^{-1}. Additional PCA data that address the spectral evolution during the outburst are presented in Roberts et al. (2004).

The source was observed with *XMM-Newton* on 2003 September 8. Our results with EPIC PN *and* MOS1 together confirm those reported by Tiengo & Mereghetti (2003) and by Gotthelf et al. (2004) with EPIC PN. A two-component power-law plus blackbody model gave a good fit, with well-constrained 3 σ parameters of $\Gamma = 3.75(3.5$–$4.1)$, $kT = 0.668(0.657$–$0.678)$ keV, $n_H = 1.05(1.0$–$1.13) \times 10^{22}$ cm^{-2},

TABLE 1

POLYNOMIAL SPIN PARAMETERS

Parameter	Jan 23–Sep 25	Jul 13–Sep 25
MJD range	52,662.9–52,907.3	52,833.4–52,907.3
Epoch (MJD)	52,788.0	52,788.0
χ^2/dof [a]	1258/100	193/62
ν (Hz)	0.180530831(4)	0.180530266(1)
$\dot{\nu}$ (10^{-13} Hz s^{-1})[b]	−6.72(2)	−3.765(2)

[a] The errors were determined with the χ^2 normalized to degrees of freedom (dof).

[b] The next higher orders are $9.0(2) \times 10^{-20}$, $9.9(4) \times 10^{-27}$, $-1.65(6) \times 10^{-32}$, $-2.9(8) \times 10^{-40}$, and $2.5(1) \times 10^{-45}$ in cgs units.

and $\chi^2_\nu = 1.04$ ($\nu = 896$). The total unabsorbed flux in 0.5–8.0 keV is 1.35 × 10^{-10} ergs cm^{-2} s^{-1}, which gives a source luminosity of $1.6 \times 10^{36} d_{10}^2$ ergs s^{-1} (d_{10} is the source's distance in units of 10 kpc).

The HRC position is consistent with a point source seen in archival *ROSAT* and *ASCA* observations during 1993–1999 (Bamba et al. 2003). The source was in a faint state with a much softer spectrum ($kT \approx 0.15$ keV) and an unabsorbed luminosity of $5.9 \times 10^{34} d_{10}^2$ ergs s^{-1} (see also Gotthelf et al. 2004).

5. TIMING: FREQUENCY HISTORY AND SPIN-DOWN RATE

Our timing analysis used a variety of PCA observations, including pointed observations dedicated to XTE J1810−197 (ObsID 80150-06), G11.2−0.3 (ObsID 80149-02), SGR 1806–20 (ObsID 80150-01), plus the bulge scans (ObsIDs 80106 and 70138). The total exposure time was about 216 ks between 2003 January 23 and September 25. Folded light curves were extracted (2–7 keV; top PCU layers) based on a trial folding period. A sinusoidal profile fitted well and was used to estimate the pulse times of arrival and uncertainties. By using a combination of all data sets, we were able to extend a phase-connected solution through the complete time span. While we attempted several models, a polynomial is commonly used.

Figure 4 shows the frequency evolution and phase residuals for the polynomial fit with frequency and six derivatives (see Table 1 for parameters). While the choice of polynomial order is somewhat arbitrary, a lower order produces significantly worse residuals. The weighted rms residuals are 165 ms. Reminiscent of the behavior of 1E 2259+586 after a bursting episode (Kaspi et al. 2003), the spin-down is initially steeper but evolves to a quieter and slower rate. The weighted rms deviation since July is only 94 ms for a steady spin-down (i.e., second-order polynomial; Table 1). The mean pulse period derivative is 1.8 × 10^{-11} s s^{-1} over the full time span of the data and is 1.15 × 10^{-11} s s^{-1} for the July–September time span.

With 245 days of data, it is possible to rule out a long-period orbit (≳100 days) as being entirely responsible for the frequency slowdown (Markwardt et al. 2003a). While a phase-connected solution is possible for an orbit *plus* a spin-down, such models are dominated by the spin-down component (best fit $\dot{\nu} = -5.4 \times 10^{-13}$ Hz s^{-1} for a mildly eccentric orbit with a period of 232 days; compare to Table 1).

To look for short-period orbits, we made Lomb-Scargle periodograms of the phase residuals obtained from subtracting the polynomial model. They show no significant peaks at the 95% confidence level. For orbital periods down to 20 minutes, the peak periodogram power was 21, for a maximum orbital amplitude, $a_x \sin i$, of 70 lt-ms. Such a limit is independently inferred from the high stability of the spin-down rate during the past 80 days. This would imply a mass function of 4 × 10^{-7} $M_\odot/P_d^2$, with P_d being the binary period in days. Thus, except for orbits improbably close to face-on, a companion mass would be restricted to being planetary in size.

6. DISCUSSION

The nature of a neutron star is principally determined by the energy mechanism that powers its emission. XTE J1810−197's rotational energy loss ($\dot{E} \approx 4 \times 10^{33}$ ergs s^{-1}) is at least 50 times
q4 lower than its implied luminosity [$L_X = (2–16) \times 10^{35}$ ergs s^{-1}, assuming $d_{10} = 0.3–1$; see § 2.4]. The source's distance is almost certainly in that range (from inferred n_H) and most likely ~5 kpc (Gotthelf et al. 2004). L_X is notably in the range of AXP and SGR luminosities. A binary system is unlikely since a Doppler shift cannot explain the observed frequency trend and becasue there are strong limits on the mass of any companion in a short-period orbit (§ 2.5). The spectrum of the source is significantly softer than the typically hard spectra of high-mass X-ray binaries. The optical and infrared magnitudes (§ 2.2) are sufficient to rule out interpreting the transient X-ray source as a distant Be star binary, while they are consistent with those of AXPs and SGRs.

The neutron star's own magnetic field is then a candidate to power the source's emission and dominate its spin-down. For a dipole field, the spin period and spin-down rate imply a characteristic magnetic field $B = 3.2 \times 10^{19}\sqrt{P\dot{P}} = 2.6 \times 10^{14}$ G and age $\tau = P/2\dot{P} \leq 7600$ yr. Such a supercritical field strength and relatively young pulsar age are typical of magnetars, which together with the aforementioned properties establish XTE J1810−197 as a new member of the class.

The transient behavior and long-term flux variability exhibited by the source are unusual for SGRs and AXPs. Only following a burst episode does the persistent flux show a comparable trend.[11] The power-law index of the flux decay (§ 2.3) falls within the range of those of SGRs (0.47–0.9); however, no SGR-like bursts were detected from the source. With the IPN, five bursts were recorded on 2002 December 5–6 (Hurley et al. 2002). One was localized to SGR 1806−20 by *Ulysses* and KONUS-*Wind*, but the others remain unlocalized.

Alternatively, a flux enhancement without SGR-like bursts is viable in the magnetar model. Given that the magnetic field has to be greater than $B_0 \sim 2 \times 10^{14}(\theta_{max}/10^{-3})^{1/2}$ G to fracture the crust and induce burst activity (Thompson & Duncan 1995; θ_{max} is the crust yield strain), the energy associated with disturbances in $B < B_0$ may excite magnetospheric currents or dissipate in the crust, causing a sudden increase in the persistent flux followed by a long-lasting cooling phase.

The behavior of XTE J1810−197 bears important implications for magnetars and other classes of isolated neutron stars. It argues for the possibility of transient AXPs and SGRs, and thus strengthens the AXP identification of the candidate AX J1845.0−0288[12] that was questioned because of the large flux variability it showed (Vasisht et al. 2000; Mereghetti et al. 2002). The existence of transient magnetars suggests the presence of faint quiescent ones that have not yet been recognized as such. This indicates that magnetars are more common than estimated (Kouveliotou et al. 1994; Heyl & Kulkarni 1998) and may extend to encompass members of other peculiar classes of neutron stars. Candidates sources are some compact central objects (Pavlov 2004) and dim isolated neutron stars (Haberl 2004). XTE J1810−197 is the first example of a neutron star to evolve from such a dormant state to that of a magnetar.

We thank the anonymous referee for important comments; C. Thompson, R. Duncan, and G. Pavlov for useful discussions; and S. Snowden and M. Still for help with *XMM* data. A. I. I. is supported by NASA grants NAG5-13186 and NAG5-13740; S. R., M. R., and V. K. by NSERC Discovery and Steacie grants, Canada Research Chairs, NATEQ, CIAR, and NASA; S. S.-H. by NSERC UFA and Discovery grants and NASA LTSA NCG5-356; P. M. W. by NASA grant NAG5-11608; and K. H. by a *Ulysses* grant under JPL contract 958056.

[11] See, e.g., SGR 1900+14 (Woods et al. 2001; Ibrahim et al. 2001; Feroci et al. 2003), 1E 2259+586 (Kaspi et al. 2003; Woods et al. 2003), and SGR 1627−41 (Kouveliotou et al. 2003).

[12] No $\dot{P}$ has been measured for this source.

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