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The Discovery of a *Transient* Magnetar

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Abstract. The newly discovered X-ray transient XTE J1810–197 exhibits almost all characteristics of magnetars. It possesses a relatively long spin period of 5.54 s and a rapid spin down rate of $\approx 10^{-11}$ s s^{-1}, while showing no evidence for Doppler shifts due to a binary companion. This yields a magnetar-strength dipole field $B = 3 \times 10^{14}$ G and a young characteristic age $\tau \leq 7600$ yr. The spectrum of the source is notably soft (photon index ≈ 4) and optical observations with the 1.5 m *Russian-Turkish* Optical Telescope *RTT150* revealed a limiting magnitude of $R_c = 21.5$, both consistent with those of Soft gamma repeaters and anomalous X-ray pulsars. However, the source shows a significant flux decline for over nine months and is present in archival *ASCA* and *ROSAT* observations at nearly two orders of magnitude fainter luminosity. Putting all evidence together shows that we have found the first confirmed *transient* magnetar. This suggests the presence of other unidentified transient magnetars in a state similar to XTE J1810-197 in its inactive phase. The detection of such sources is one of the important areas in which future X-ray timing missions can make a significant impact.

INTRODUCTION

Soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are a distinct class of X-ray pulsars. Both are radio-quiet, persistent X-ray emission sources ($L \sim 10^{34} - 10^{36}$ erg s^{-1}) and are distinguished with intermittent activity of short (< 0.1 s), bright ($L_{peak} > L_{EDD}$) bursts of X-rays and soft $\gamma-$rays. 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}. There is no evidence 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. To date, nine sources are firmly identified, including four SGRs and and five AXPs. Four more candidates need confirmation.

Mounting observational evidence have indicated that SGRs and AXPs are powered by super-critical magnetic fields ($B \sim 10^{15}$ G), as predicted by the magnetar model (Duncan & Thompson 1992; Thompson & Duncan 1995). These include the energetic burst emission (Paczynski 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), the lack of binary companion or accretion disks (Kaplan et al. 2001), and the detection of spectral line features consistent with proton cyclotron resonance in a magnetar-strength field (Ibrahim et al. 2002; Ibrahim, Swank & Parke 2003). Until recently only SGRs were observed to burst. The recent bursting activity from two AXPs unified the two families of objects in the magnetar framework (Gavriil, Kaspi & Woods 2002; Kaspi et al. 2003).

Here we outline the discovery of the new transient magnetar XTE J1810-197 (Ibrahim et al. 2004) and discuss the implications of this finding to our understanding of the magnetar population.

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OBSERVATIONS AND RESULTS

A New X-ray Pulsar near SGR 1806–20

On 2003 July 14, SGR 1806–20 entered a mild burst-active phase that was detected by the *Interplanetary Network (IPN*; Hurley et al. 2003). We observed the source as a target of opportunity on July 15 with the Proportional Counter Array (PCA) onboard the *Rossi X-ray Timing Explorer (RXTE)*. In the first observation that lasted for only 2.5 ks, a strong periodic signal with a barycentric period of 5.540(2) s was clearly identified at a chance probability of 2.5×10^{-12} (Ibrahim et al. 2003; see Fig. 1). The large discrepancy between this pulse period and the expected 7.5 s pulse period of SGR 1806–20 implied the presence of a new X-ray pulsar in the PCA $1^\circ.2$ field of view.

A PCA scan was performed on July 18, following a path that covered a region surrounding SGR 1806–20 (see Ibrahim et al. 2004 for the scan details). The resulting best fit position of the new source, designated XTE J1810–197, is $\alpha = 18^{\rm h}10.9^{\rm m}$ and $\delta = -19^{\rm o}42'$ (J2000) with a 3σ error contour with semi-major axes of $5.5'$ and $10'$ (Markwardt, Ibrahim & Swank 2003).

Two follow-up *Chandra* observations with the High Resolution Camera (HRC) on August 27 and November 1 localized the source precisely to $\alpha = 18^{\rm h}09^{\rm m}51^{\rm s}.08$ and $\delta = -19^{\rm o}43'51''.74$ (J2000), with an error circle radius of $0.8''$ (Gotthelf et al. 2003a, 2003b; Israel et al. 2003). 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 field of view — in particular the SNR G11.2–0.3 — resulted in large systematic errors, for which a priori estimates were difficult.

Long Term Light Curve

The source appeared consistent with a previously unidentified source that had been present in the PCA monitoring program of the galactic bulge region since 2003 February. XTE J1810–197 is covered in part of the scans where it is near the center of the PCA field of view for ≈ 150 seconds. Re-examining the data during these brief points revealed the pulsations, which confirmed the identification of the source.

Fig. 3 shows the 2002–2003 light curve, when fixed at the *Chandra* position. Clearly XTE J1810–197 became active sometime between 2002 November and 2003 February. The distribution of 1999–2002 pre-outburst fluxes allow us to place a 3σ upper limit on previous

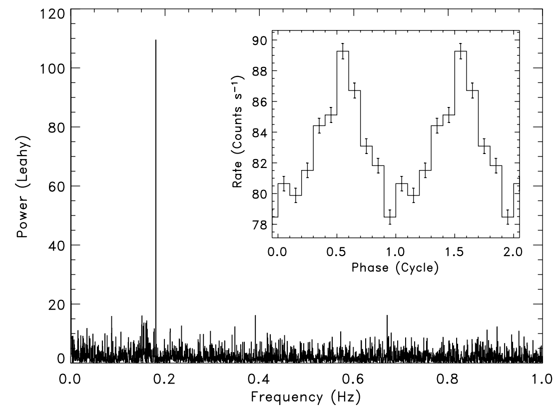

FIGURE 1. Fast Fourier Transform power spectrum of the RXTE PCA July 15 observation of the field of view of SGR 1806–20 showing a highly significant periodic signal at 0.18052(6) Hz. The inset shows the epoch folded pulse profile in 10 phase bins. Errors in the frequency and period correspond to the 3σ confidence level. The event-mode data were collected from all layers of the operating PCUs (0, 2 & 3) in the 2–8 keV energy range, binned in 0.125 s intervals and corrected for the solar system barycenter. Note that the ≈ 0.13 Hz signal due to SGR 1806–20 is not detected here, indicating a low pulsed flux.

outbursts of < 2 ct/s/PCU 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 $((T - T_0)/(52700 - T_0))^{-\beta}$ or exponential (with e-folding time is 269 ± 25 days) models. The power-law model has the potential of retrieving the epoch T_0 at which the outburst occurred. For acceptable solutions with $\beta = 0.45 - 0.73$ (1σ), $52580 \leq T_0 \leq 52640$, that is, 2002 November 2 to 2003 January 1. Additional information came from observations of the nearby PSR J1811–1925 that had XTE J1810–197 in the field of view. An observation on 2002 November 17 (MJD 52595) showed that the pulsations were not detected, while they were by 2003 January 23 (MJD 52662).

Spectrum and Optical Counterpart

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, Ibrahim & Swank 2003). The resulting spectrum of XTE J1810–197 was clearly soft, despite large uncertainty in the column densities for any model. 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 was

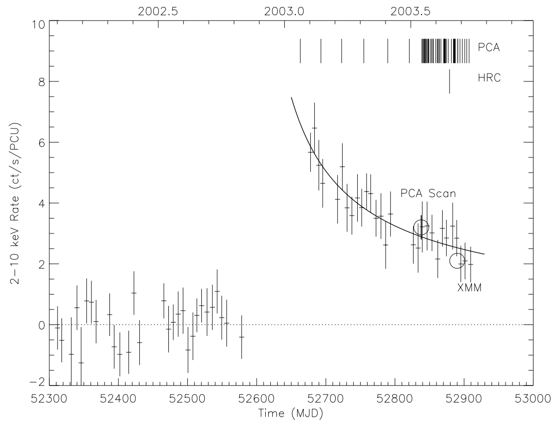

FIGURE 2. Monitoring light curve of XTE J1810–197, showing the transient outburst beginning in 2003 (1 mCrab = 2.27 ct/s/PCU = 2.4×10^{-11} erg cm^{-2} s^{-1}, 2–10 keV). Epochs of PCA dedicated pointed observations with the source in the field of view are indicated in the top row of vertical bars. The epoch of the first HRC and XMM observations are shown separately.

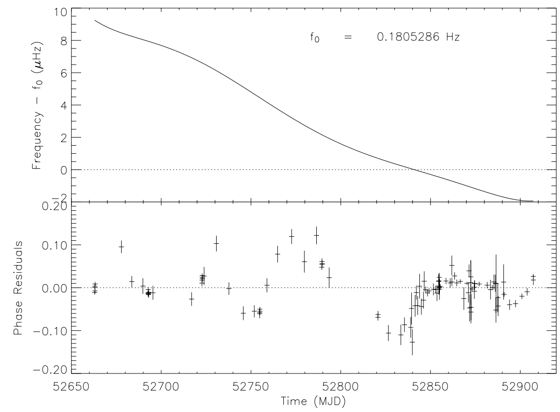

FIGURE 3. (top) Frequency evolution and (bottom) phase residuals for PCA timing solution of XTE J1810–197. Folded light curves were extracted (2–7 keV; top PCU layers) based on a trial folding period. A sinusoidal profile fit well, and was used to estimate the pulse times of arrival (TOAs) and uncertainties.

5.5×10^{-11} ergs cm^2 s^{-1}.

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. (2003b) with EPIC PN. A two-component power-law plus blackbody model gave a good fit, with well constrained 3σ 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}, and $\chi^2_\nu = 1.04$ (ν=896). The total unabsorbed flux in 0.5–8.0 keV is 1.35×10^{-10} erg cm^{-2} s^{-1} for a source luminosity of $1.6 \times 10^{36} d_{10}^2$ erg s^{-1}, with d_{10} the 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. The source was in a faint state with a much softer spectrum ($kT \approx 0.15$ keV) and unabsorbed luminosity of $5.9 \times 10^{34} d_{10}^2$ erg s^{-1} (see also Gotthelf et al. 2003b).

We observed the first *Chandra* HRC error box with the 1.5 m $Russian-Turkish$ Telescope, $RTT150$ (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 $8' \times 8'$ Field of View) with 15 min exposure times (3 frames). Seeing was about $2''$. No counterpart is detected to a limiting magnitude of 21.5 (2σ 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. (2003b). Recently, Israel et al. (2003) reported a likely IR counterpart with $K_s = 20.8$ and $F_X/F_{IR} > 10^3$.

Frequency History and Spin-down Rate

The timing analysis used a variety of PCA observations, including pointed observations dedicated to XTE J1810–197 observations of G11.2-0.3/PSR J1811–1925, SGR 1806–20 that have the source in the field of view, plus the bulge scans. The total exposure time was about 216 ks between 2003 January 23 and September 25. While we attempted several models, a polynomial is commonly used.

Fig 4. shows the frequency evolution and phase residuals for the polynomial fit with frequency and 6 derivatives (see Ibrahim et al. 2004 for parameters). 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 mean pulse period derivative is 1.8×10^{-11} s s^{-1} over the full time span of the data, and 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 ($\geq$ 100 days) as entirely responsible for the frequency slow down (Markwardt et al. 2003). While a phase-connected solution is possible for an orbit *plus* a spin-down, such models are dominated by the spin-down component.

To look for short period orbits we made Lomb-Scargle periodograms. No significant peaks are detected 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 $4 \times 10^{-7} M_\odot / P_d^2$, P_d being the binary period in days. Thus, except for orbits improbably close to face-on, a companion mass would be restricted to be planetary in size.

DISCUSSION

The nature of a neutron star source is principally determined by the energy mechanism that powers its emission. The rotational energy loss due to the pulsar spin-down $\dot{E} \approx 4 \times 10^{33}$ erg s^{-1} is at least 50 times lower than the implied *XMM* unabsorbed luminosity. $L_X = (2-16) \times 10^{35}$ ergs s^{-1}, assuming $d_{10} = 0.3-1$. The distance to XTE J1810–197 is almost certainly in that range, and most likely ~ 5 kpc (Gotthelf et al. 2003b). A binary system is unlikely since a Doppler shift can not explain the observed frequency trend and there are strong limits on the mass of any companion in a short period orbit. The spectrum of the source is significantly softer than typically hard spectra of high mass X-ray binaries. Besides, the optical and infrared magnitudes are sufficient to rule out interpreting the transient X-ray source as a distant Be–star binary, while consistent with those of AXPs and SGRs.

The neutron star's own magnetic field is then a candidate to power its emission and dominate its spin-down. For a dipole magnetic 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 super-critical 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 uncommonly observed from magnetars. Only following a burst episode did the persistent flux show a comparable trend. The power-law index of the flux decay of the source falls within the range of those of SGRs (0.47-0.9; Woods et al. 2001, 2003; Ibrahim et al. 2001; Kouveliotou et al. 2003). However, no SGR-like bursts were detected from the region by the PCA on 2002 November 17 or 2003 January 23. No observations are available in between. With IPN, five bursts were recorded on 2002 December 5 and 6 (Hurley et al. 2002). One was localized to SGR 1806–20 by *Ulysses* and Konus-*Wind* but the others remain unlocalized. Due to the lack of PCA monitoring, a firm conclusion on a burst episode from the source during the intervening interval is difficult to reach since soft SGR-like bursts can escape detection in $\gamma-$ray burst monitors.

Alternatively, a quiescent outburst like that seen from the source 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 detection of a transient magnetar bears important consequences to magnetars and other classes of neutron stars. It suggests a larger population of magnetars than previously thought. A portion should be present in a faint state similar to that of XTE J1810–197 prior to its RXTE detection. Candidates sources are isolated radio-quiet neutron stars. With their higher sensitivity, future X-ray timing missions can observe such transient magnetar candidates and possibly identify them as such while in the quiescent state via measurement of their spin-periods and spin-down rates.

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