THE SPIN-DOWN OF SWIFT J1822.3−1606: A NEW GALACTIC MAGNETAR

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ABSTRACT
On 2011 July 14, a new magnetar candidate, Swift J1822.3−1606, was identified via a rate trigger on the Swift/Burst Alert Telescope. Here we present an initial analysis of the X-ray properties of the source, using data from the Rossi X-ray Timing Explorer, Swift, and the Chandra X-ray Observatory, spanning 2011 July 16–October 8. We measure a precise spin period of $P = 8.43771968(6)$ s and a spin-down rate of $\dot{P} = 2.54(22) \times 10^{-13}$ s$^{-1}$, at MJD 55761.0, corresponding to an inferred surface dipole magnetic field of $B = 4.7(2) \times 10^{13}$ G, the second lowest thus far measured for a magnetar, though similar to those of 1E 2259+586 and several high-magnetic field radio pulsars. We show that the flux decay in the 1–10 keV band is best fit by a double exponential with timescales of 9 ± 1 and 55 ± 9 days. The pulsed count rate decay in the 2–10 keV band, by contrast, is better fit by a single exponential decay with timescale 15.9 ± 0.2 days. After increasing from ~35% for ~20 days after the onset of the outburst, the pulsed fraction in the 2–10 keV band remained constant at ~45%. We argue that these properties confirm this source to be a new member of the class of objects known as magnetars. We consider the distribution of magnetar periods and inferred dipole magnetic field strengths, showing that the former appears flat in the 2–12 s range, while the latter appears peaked in the $10^{14}$–$10^{15}$ G range.

Key words: pulsars: individual (Swift J1822.3-1606) – stars: magnetars – stars: neutron – X-rays: bursts

Online-only material: color figures

1. INTRODUCTION

On 2011 July 14, the Swift/Burst Alert Telescope (BAT) triggered on several bursts of hard X-ray emission from the direction of a previously unknown source, subsequently named Swift J1822.3−1606 (Cummings et al. 2011). The spin period of the new source was soon identified to be $P = 8.4377$ s (Göğüş et al. 2011). The simplest interpretation of these initial observations is that Swift J1822.3−1606 is a previously unknown Galactic magnetar.

However, because of suggested similarities between Swift J1822.3−1606 and the unusual Be X-ray binary J1626−5156, it was suggested that perhaps Swift J1822.3−1606 is a Be X-ray binary (Göğüş et al. 2011; Bandyopadhyay et al. 2011). This hypothesis was challenged by Halpern (2011), who, due to the lack of an optical counterpart (de Ugarte Postigo & Munoz-Darias 2011), argued that the properties of Swift J1822.3−1606 are in line with those of other magnetars, in particular, the transient magnetar XTE J1810−197. Here we report on timing and flux properties of Swift J1822.3−1606 that agree strongly with the magnetar identification.

Magnetars are neutron stars powered by the decay of extreme magnetic fields (Thompson & Duncan 1995, 1996; Thompson et al. 2002). Soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are thought to be observational manifestations of magnetars, and we refer to them as such here. Magnetars exhibit X-ray bursts, spin periods in the relatively narrow range of $P = 2$–12 s, and are observed to spin-down with time. As inferred from $P$ and spin-down rate $\dot{P}$ via the conventional vacuum dipole model which implies an inferred dipole magnetic field strength of $B = 3.2 \times 10^{19}(P \dot{P})^{1/2}$ G, their inferred $B$-fields tend to be significantly larger than for classical pulsars, typically $B > 10^{14}$ G. Magnetars are also observed to display variability in nearly all of their observed properties: flux and pulsed flux, spectrum, pulse profile, timing noise, and glitches (see Mereghetti 2008; Rea & Esposito 2011 for reviews).

The true underlying distribution of magnetar $B$ strengths is an open question. The recent discovery of a magnetar with a very low inferred magnetic field of $B < 7.5 \times 10^{12}$ G (Rea et al. 2010) has raised the question of how low the dipolar field can be for magnetar-like activity to be observed. Moreover, the discovery of a magnetar-like outburst from the high-B rotation-powered pulsar (RPP) PSR J1846–0258 (Gavriil et al. 2008; Kumar & Safi-Harb 2008) highlights the question of whether RPPs and magnetars represent two distinct classes of objects, or if magnetars represent the high-B tail of a single population.

In this Letter, we present analyses of Rossi X-ray Timing Explorer (RXTE), Swift, and Chandra X-ray Observatory (Chandra) data. We perform a phase-coherent timing analysis and show that the spin evolution is consistent with a constant spin-down rate. We present an analysis of the decay of the source’s intensity after the outburst, and show that the pulsed fraction is steady after increasing for ~20 days after the outburst. We argue that these properties confirm that Swift J1822.3−1606 is a new Galactic magnetar.

2. OBSERVATIONS

2.1. Swift Observations

On 2011 July 14 the Swift/BAT triggered on a rate increase from the previously unknown source, Swift J1822.3−1606 (Cummings et al. 2011). A total of 27 observations were subsequently taken with the X-Ray Telescope (XRT; target IDs 32033 and 32051). The observations span 85 days: 2011 July 15–October 8 (MJD 55757 – 55842). Typical observations were 2 ks long and amount to a total exposure of 55 ks.

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*a* See the Magnetar Catalog: http://www.physics.mcgill.ca/~pulsar/magnetar/main.html
Cleared Swift data in both windowed-timing (WT) mode with 1.8 ms time resolution and photon-counting (PC) mode with 2.5 s time resolution were downloaded from the Swift quick-look data archive. For the lone PC mode observation, an anular source region with an outer radius of 20 pixels and an inner radius of 5 pixels was extracted. The inner radius was excluded because of pile-up. For the WT mode observations, a 16 pixel strip centered on the source was used. Events in the 2–10 keV energy range were extracted from the WT mode data for the timing analysis. The PC mode data have insufficient time resolution to be useful for the PC mode.

### 2.2. RXTE Observations

Swift J1822.3−1606 data were obtained with the Proportional Counter Array (PCA; Jahoda et al. 2006) on board RXTE. The PCA consists of five proportional counter units (PCUs) sensitive to 2–60 keV photons. We downloaded 27 public observations from the HEASARC archive (observing program P96048). Data were collected in GoodXenon mode, which records the arrival time of each event with 1 μs resolution. The observations span 84 days: 2011 July 16–October 8 (MJD 55758 – 55842). Typical observations were 6 ks long, amounting to a total exposure of 144 ks.

For our timing analysis, we extracted 2–10 keV photons from the top detection layer of each PCU to reduce contamination from the particle background. Data from individual PCUs were then merged. When more than one observation occurred in a 24 hr period, we combined the data.

### 2.3. Chandra Observations

Chandra ACIS-S observations were made on 2011 July 27 (MJD 55769.2, ObsID 12612), August 4 (MJD 55777.1, ObsID 12613), and September 18 (MJD 55822.7, ObsID 12614) with net exposures of 15.0 ks, 13.7 ks, and 10.0 ks, respectively. Observations were obtained in continuous clocking mode, with 2.85 ms time resolution. We carried out the data reduction using CIAO 4.3 with CALDB 4.4.3. We reprocessed the data to retain events on the chip node boundary, then extracted the source counts from a 6′ width aperture and the 0.3−8 keV energy range for our timing analysis, and 2–8 keV for the pulsed fraction analysis.

### 3. ANALYSIS AND RESULTS

#### 3.1. Phase-coherent Timing Analysis

Our timing analysis of Swift J1822.3−1606 follows the phase-coherent approach, in which we account for each rotation of the pulsar and utilized a combination of data from RXTE, Swift, and Chandra. Events were reduced to barycentric dynamical time (TDB) at the solar system barycenter using the XRT position of R.A. = 18°22′20″, decl. = −6°04′50″ (J2000; Pagani et al. 2011) and the JPL DE200 solar system ephemeris. Events were then binned into time series with 31.25 ms time resolution.

Each RXTE (2−10 keV), Swift (2−10 keV), and Chandra (0.3−8 keV) time series was folded with 64 phase bins using a spin-period determined from a periodogram analysis. We found an initial timing solution and used this to re-fold each profile to produce higher quality pulse times of arrival (TOAs). For RXTE data, using 128 phase bins created good pulse profiles with optimal TOA uncertainties. For Swift and Chandra data, 64 bin profiles resulted in higher significance pulse profiles and TOA uncertainties. Template profiles with 128 and 64 bins were created by aligning and summing all RXTE profiles.

### 3.2. Source Intensity Evolution

To measure the source intensity and decay after the outburst, we first checked for the presence of dust scattering rings, to produce higher quality pulse times of arrival (TOAs). For RXTE data, using 128 phase bins created good pulse profiles with optimal TOA uncertainties. For Swift and Chandra data, 64 bin profiles resulted in higher significance pulse profiles and TOA uncertainties. Template profiles with 128 and 64 bins were created by aligning and summing all RXTE profiles.

### Derived Parameters

| Parameter                  | Value                |
|----------------------------|----------------------|
| Date                       | MJD 55761.0          |
| Epoch                      | MJD 55758 – 55842    |
| Number of TOAs—RXTE        | 25                   |
| Number of TOAs—Swift       | 26                   |
| Number of TOAs—Chandra     | 3                    |
| P (s)                      | 8.4377(1969)(6)      |
| 1/m (ms)                   | 2.55(22) × 10⁻¹³     |
| rms residuals (ms)         | 25.1                 |
| rms residuals (periods)    | 0.0029               |

Note. Uncertainties are formal 1σ TEMPO errors.
such as those observed around 1E 1547−5408 (Tiengo et al. 2010), because these can bias the inferred source count rate. We checked for deviations from the point-spread functions in the first Swift PC mode and Chandra observations following the outburst, and we found no evidence for dust scattering.

To measure the evolution of the total flux, we measured a flux for each Swift WT mode observation using XSPEC, by assuming several different models. We found that the flux is relatively model independent, varying by <10% between models. A detailed spectral analysis will follow in a subsequent paper.

To measure the 2–10 keV pulsed count rate for each Swift and Chandra observation, barycentered time series were folded with the ephemeris (Table 1), with 16 phase bins. For the RXTE data, barycentered photons were selected only from PCU2, to minimize instrumental effects. Events were then folded as above. The pulsed count rate for each folded profile was then determined using a rms method as described in Dib et al. (2008), using five Fourier harmonics of the pulse profile. The pulsed fraction was determined by dividing the pulsed count rate by the total source count rate. Because the PCA is not a focusing instrument, the pulsed fraction could not be accurately determined from these data.

Figure 2 shows the evolution of the source intensity (top panel, as measured with Swift), the pulsed source intensity (middle panel, as measured with Swift and RXTE), and the pulsed fraction (bottom panel, as measured with Swift and Chandra). To describe the total flux decay quantitatively, we fit the 2–10 keV pulsed count rate evolution with the same models as above, also including data from RXTE. Pulsed count rates from a given source for RXTE and Swift will differ owing to instrumental effects (e.g., effective area), but should be offset by a constant, with the same trends between instruments, as observed here. Thus, RXTE PCA pulsed count rates were scaled to the Swift XRT pulsed count rates, such that the scaling factor minimized the residuals of the fit. With a $\chi^2_\nu$ of 3.25 for 49 degrees of freedom, the best-fit decay timescale is 15.9 ± 0.2 days. A power-law model provided a much worse fit with a $\chi^2_\nu$ of 84 for 50 degrees of freedom. The fit to a double exponential model did not provide a significant improvement over the fit to the single exponential. If we constrain the decay timescales to be the same as for the total flux (see above), we find that the $\chi^2_\nu$ is 6.95 for 50 degrees of freedom.

The bottom panel of Figure 2 shows the 2–10 keV pulsed fraction of Swift J1822.3−1606 with Swift and Chandra data. The pulsed fraction increases from ~35% to 45% during the first 20 days after outburst, after which it is statistically consistent with being constant ($\chi^2_\nu$ of 1.8/27).

4. DISCUSSION

The regular spin-down we report for Swift J1822.3−1606, together with flux and pulsed flux decays similar to those seen in other magnetar outbursts, demonstrates that this source indeed shares critical properties with other known magnetars; we hence classify it as such. The inferred surface dipole $B$ for Swift J1822.3−1606 of $4.7 \times 10^{13}$ G is smaller than those of all but one confirmed magnetar, SGR 0418+5729 (Rea et al. 2010), though it is close to that of AXP 1E 2259+586 ($B = 5.9 \times 10^{13}$ G; Gavriil & Kaspi 2002). Further, Swift J1822.3−1606’s $B$ is similar to that measured for several RPPs, including the lone RPP observed to display magnetar-like outbursts, PSR J1846−0258, which has $B = 4.9 \times 10^{13}$ G (Gotthelf et al. 2000).

If Swift J1822.3−1606 suffered a large glitch with recovery at the outburst, as seen in some other magnetars (e.g., Kaspi et al. 2003), the following exponential decay in $P$ could contaminate our measurement of $P$ and thus $B$. Then, the true value of $B$ would be smaller than the one reported here. However, the exponential recovery timescale for such a glitch in Swift J1822.3−1606 would have to be significantly longer than those observed in other magnetar glitches (e.g., 17 days for 1E 2259+586), since there is no evidence of a recovery in the 84 day timing solution reported here. Thus, any contamination of $B$ owing to glitch recovery is likely to be small.

The post-outburst flux evolution of Swift J1822.3−1606 is best characterized by a double exponential decay with timescales of $9 \pm 1$ and $55 \pm 9$ days. This is reminiscent of the flux decay observed after the outburst from the transient AXP XTE J1810−197, which was fit with a two exponential decay model, albeit with longer decay timescales of 250 and 370 days (Bernardini et al. 2009).

Exponential flux decays as observed here are similar to what has been observed after several other magnetar outbursts (e.g., Rea et al. 2009; Gavriil et al. 2008), though power-law decays are also common (e.g., Woods et al. 2001; Kouveliotou et al. 2003). Lyubarsky et al. (2002) predicted power-law decays in magnetar outbursts assuming crustal cooling following an impulsive heat injection. Beloborodov & Thompson (2007), by contrast, considered magnetar outbursts as a result of sudden twisting of magnetic field lines in the magnetosphere, with the...
relaxation a result of their untwisting. In this model, the relaxation is predicted to be approximately linear, a functional form observed in one outburst of 1E 1048.1−5937 (Dib et al. 2009). Beloborodov (2009) showed that other functional forms for the decay, including exponential, are possible, as the untwisting is predicted to be strongly non-uniform, being erased by a propagating “front” whose speed depends on the initial twist configuration. The diversity in functional forms for the flux decays of magnetars hence favors the model put forth by Beloborodov (2009).

Although the flux (both pulsed and total) of Swift J1822.3−1606 clearly shows exponential decay, no comparable decay in P is seen, arguing for decoupling between the two evolutions. Indeed no such correlated evolution has been seen in other magnetar outbursts, and large glitches with recovery have been observed in magnetars showing no radiative changes (e.g., Dall’Osso et al. 2003; Dib et al. 2008). Hence, the flux decay provides no evidence for possible contamination of P by glitch recovery and the value we measure is likely to be due to dipolar spin alone.

Interestingly, the most recently discovered magnetars (including SGR 0418+5729 and Swift J1822.3−1606, but also SGRs 0501+4516, 1833−0832, and Swift J1834.9−0846; Göğüș et al. 2010a, 2010b; Rea et al. 2010; Kuiper & Hermsen 2011) all have B \( \lesssim 1 \times 10^{14} \) G, effectively lowering the “average” inferred B-field for magnetars. This raises the question of what is the true distribution of magnetar field strengths. In Figure 3, we plot the distributions of the periods and inferred magnetic fields of all confirmed magnetars, as well as of all known B > 10^{12} G radio pulsars.

The P distribution of magnetars remains narrow, spanning less than an order of magnitude, in great contrast to those of radio pulsars. We note that the period distribution for magnetars within the observed range appears consistent with being flat; a fit to the histogram mean yields a \( \chi^2 \) of 0.63. If borne out by future discoveries, this will need to be addressed in any population studies. The B distribution for observed magnetars, by contrast, appears peaked in the 10^{14}−10^{15} G range, even with the relatively low B we have measured for Swift J1822.3−1606, albeit with the possible low tail represented by SGR 0418+5729. This is apparent as a “gap” between the peak of the magnetar distribution and the tail of the radio pulsar distribution. If magnetars represent the high-B tail of the birth B distribution of neutron stars, then their peaked B distribution may indicate that burst rates of magnetars fall rapidly with decreasing B, since the majority of magnetars have been discovered via bursting behavior. This would be broadly consistent with the theoretical findings of Perna & Pons (2011), who calculate expected burst rates in neutron stars and show that all neutron stars can exhibit magnetar-like bursts, though the burst rate drops with decreasing B and increasing age. That the number of radio pulsars plummets rapidly above B \( \sim 10^{13} \) G could genuinely be due to falloff in the intrinsic distribution, or to smaller radio beams for these preferentially longer-period pulsars, but may also indicate that radio emission is harder to produce at higher B (e.g., Baring & Harding 2001). Although radio emission has
The characteristic age ($\tau_c = \frac{P}{2\dot{P}}$) for Swift J1822.3−1606 is 525 kyr, comparable to that of AXP 1E 2259+586 but larger than for all other magnetars, except for SGR 0418+5729 (>24 Myr). 1E 2259+586 is firmly associated with the supernova remnant CTB 109 which is thought to be ~9 kyr old (Sasaki et al. 2004), much smaller than the AXP’s characteristic age of 250 kyr. This demonstrates that $\tau_c$ can be an unreliable indicator of the true age, which can perhaps be ascribed to epochs of greater spin-down torque earlier in the star’s history, when the dipolar field was larger. This hypothesis can explain the large $\tau_c$ of SGR 0418+5729, although the latter’s greater distance from the Galactic Plane suggests it may indeed be the oldest known magnetar (but see Alpar et al. 2011 for an alternative discussion). Turolla et al. (2011) suggest that the observed properties of SGR 0418+5729 are consistent with it being an aged magnetar in which the external $B$ has decayed significantly. Further evidence for SGR 0418+5729 being older than other magnetars includes lower energy bursts and a very low quiescent luminosity. Whether Swift J1822.3−1606 more closely resembles SGR 0418+5729 or 1E 2259+586 remains to be seen. The measurement of its flux in quiescence and the discovery of an associated supernova remnant would help resolve this issue.

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