Changes in the X-ray Emission from the Magnetar Candidate 1E 2259+586 during its 2002 Outburst

P.M. Woods[*], V.M. Kaspi[†], C. Thompson[**], F.P. Gavriil[†], H.L. Marshall[‡], D. Chakrabarty[‡], K. Flanagan[‡], J. Heyl[§] and L. Hernquist[§]

[*]*Universities Space Research Association at the National Space Science and Technology Center*
[†]*Department of Physics, McGill University*
[**]*Canadian Institute for Theoretical Astrophysics*
[‡]*Center for Space Research, Massachusetts Institute of Technology*
[§]*Harvard-Smithsonian Center for Astrophysics*

Abstract.
An outburst of several tens of SGR-like bursts was detected from the Anomalous X-ray Pulsar (AXP) 1E 2259+586 in 2002 June. Coincident with this burst activity were gross changes in the pulsed flux, persistent flux, energy spectrum, pulse profile and spin down of the underlying X-ray source. We present RXTE and XMM-Newton observations of 1E 2259+586 that show the evolution of the aforementioned source parameters during and following this episode and identify recovery time scales for each. Specifically, we observe an X-ray flux increase (pulsed and phase-averaged) by more than an order of magnitude having two distinct components. The first component is linked to the burst activity and decays within $\sim$2 days during which the energy spectrum hardens considerably relative to the quiescent state of the source. The second component decays over the year following the glitch/outburst according to a power law in time with an exponent -0.22. The pulsed fraction decreased initially to $\sim$15% RMS, but recovered rapidly to the pre-outburst level of $\sim$23% within the first three days. The pulse profile changed significantly during the outburst, and recovered almost fully within two months of the outburst. A glitch of size $\Delta\nu_{\rm max}/\nu = (4.24 \pm 0.11) \times 10^{-6}$ was observed in 1E 2259+586 that preceded the onset of the observed burst activity. The glitch could not be well fit with a simple partial exponential recovery. An additional exponential rise in frequency with a time scale of 15 days resulted in a significantly better fit to the data, however, a systematic drift in the phase of the pulse profile cannot be excluded as the cause for the apparent slow rise in frequency. The changes in the source properties of 1E 2259+586 during its 2002 outburst are shown to be qualitatively similar to changes seen during/following burst activity in two Soft Gamma Repeaters (SGRs), thus further solidifying the common nature of SGRs and AXPs as magnetars. Finally, the changes in persistent emission properties coincident with burst activity in 1E 2259+586 enabled us to infer previous burst active episodes from this and other AXPs. The non-detection of these outbursts by all-sky gamma-ray instruments suggests that the number of active magnetar candidates in our Galaxy is larger than previously thought.

INTRODUCTION

Anomalous X-ray Pulsars (AXPs) and Soft Gamma Repeaters (SGRs) are two intriguing classes of isolated neutron stars. Each member of these groups is a persistent X-ray source, most are X-ray pulsars spinning down rapidly, and some have entered episodes where they emit high luminosity (up to $10^7\ L_{\rm Edd}$ in some cases) bursts of hard X-rays and soft gamma-rays. Both AXPs and SGRs are very likely magnetars [1, 2], or neutron stars with very strong magnetic fields ($B_{\rm dip} = 10^{14} - 10^{15}$ G), whose bright X-ray emission is powered by the decay of these strong fields. The global properties of AXPs and SGRs are reviewed elsewhere in this volume ([3] and [4], respectively).

The characteristics of the persistent X-ray emission from magnetar candidates (i.e. AXPs and SGRs) as a class are correlated with their propensity to burst. For example, the most active burst sources show the most rapid spin-down (e.g. [5]), the strongest timing noise [6, 7], and the hardest X-ray spectra [8]. Moreover, nearly all spectral and temporal properties of the persistent X-ray emission from individual magnetar candidates show changes during burst active episodes or outbursts (e.g. [9]). Until recently, correlated source variability during outbursts has only been seen in the SGRs. On 2002 June 18, an outburst of more than 80 individual bursts was recorded from the AXP 1E 2259+586 [10] using the *Rossi X-ray Timing Explorer (RXTE)* Proportional Counter Array (PCA). Coincident with this outburst were changes in the spectrum and timing properties of the persistent X-ray emission. Below, we summarize the observed changes in the source and compare those changes to the effects seen in SGRs during burst active episodes.

For a more complete description of this work, please see [11]. Several aspects of the outburst from 1E 2259+586 are also covered in [3] and a complete analysis of the bursts is presented in [12].

OBSERVATIONS AND ANALYSIS

The AXP 1E 2259+586 has been monitored with the *Rossi X-ray Timing Explorer (RXTE)* Proportional Counter Array (PCA) since 1997 (e.g. [7]). Following the burst discovery, several Target-of-Opportunity (ToO) *RXTE* observations were performed during the next several weeks before routine monitoring observations resumed. Here, we report on all *RXTE* observations between 2000 March and 2003 June.

1E 2259+586 was also observed by the *X-ray Multi-Mirror Mission (XMM-Newton)* fortuitously one week before the outburst. We combine this with a ToO observation 3 days following the outburst and three other *XMM-Newton* observations of the surrounding supernova remnant (CTB 109) that bracket the 1E 2259+586 outburst. Details of all observations and the analysis techniques used can be found in [11].

TABLE 1. Spin Parameters for 1E 2259+586 from 3.2 years of phase-coherent timing using *RXTE* PCA data.

Frequency[a] , ν (Hz)	0.14328703257(21)
Frequency Derivative, $\dot{\nu}$ (Hz s^{-1})	$-9.920(6)\times10^{-15}$
Epoch (MJD TDB)	52400.0000
$\Delta\nu$ (Hz)	$5.25(12)\times10^{-7}$
$\Delta\nu_g^b$ (Hz)	$>8.7\times10^{-7}$
τ_g (days)	14.1(7)
$\Delta\nu_d$ (Hz)	$\Delta\nu_g+\sim5\times10^{-9}$
τ_d (days)	15.9(6)
$\Delta\dot{\nu}$ (Hz s^{-1})	$+2.18(25)\times10^{-16}$
t_g (MJD TDB)	52443.13(9)
RMS Timing Residual (ms)	44.9
Start Observing Epoch (MJD)	51613
End Observing Epoch (MJD)	52900

[a] Numbers in parentheses represent 1σ uncertainties in the least significant digits quoted.
[b] Lower limit given at 90% confidence.

PULSE TIMING

Within two days of the outburst, it was clear from the PCA data that a glitch had occurred in 1E 2259+586 [10]. As more post-glitch data were collected, it was realized that the timing properties of this glitch were very unusual as compared to glitches in other neutron stars [11]. In particular, we found that a simple exponential relaxation model could not fit the post-glitch frequency evolution. The model that best fit the frequency evolution of 1E 2259+586 across the glitch is given by

$$\nu = \nu_0(t) + \Delta\nu + \Delta\nu_g\,(1-e^{-(t-t_g)/\tau_g}) - \Delta\nu_d\,(1-e^{-(t-t_g)/\tau_d}) + \Delta\dot{\nu}\,t,$$

where $\nu_0(t)$ is the frequency evolution pre-glitch, $\Delta\nu$ is an instantaneous frequency jump, $\Delta\nu_g$ is the resolved frequency jump that grows exponentially on a time scale τ_g, $\Delta\nu_d$ is the post-glitch frequency drop that decays exponentially on a time scale τ_d, t_g is the glitch epoch, and $\Delta\dot{\nu}$ is the post-glitch change in the long-term frequency derivative. The best fit parameters are given in Table 1.

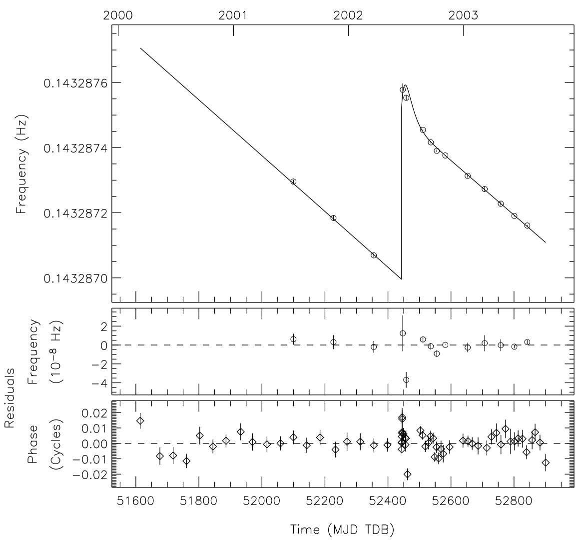

FIGURE 1. *Top Panel* – Frequency evolution of 1E 2259+586 around the time of the outburst for a model including an exponential rise and fall in frequency post-glitch. The solid line represents the best-fit model. The circles denote frequency measurements for independent subsets of data. The effect of the glitch is obvious, as is the partial recovery. *Middle Panel* – The frequency residuals of the independent frequency points minus the model. *Bottom Panel* – Phase residuals with respect to the best-fit model. Closer inspection of the residual cluster just following the outburst epoch reveals that there is a low amplitude systematic trend. This is discussed further in the text.

The frequency evolution of 1E 2259+586 just before and following the outburst as determined by our fit is shown in Figure 1. The glitch epoch (t_g) precedes the PCA observation containing the burst activity by 12.5 ± 2.1 hours. The exponential growth term clearly improves the fit to the full data set ($\Delta\chi^2 = 316$ for 2 dof when compared to the simple exponential recovery model), and the two time scales (two weeks) are very similar to one another. Finally, the long-term post-glitch spin-down rate *decreases* significantly (8σ) in magnitude.

There is a systematic trend in the phase residual cluster just post-glitch which may be due to significant pulse shape changes observed in 1E 2259+586 or an inadequacy in our model. We should note that the pulse profile evolution occurred during the interval where resolved spin up is inferred, thereby making phase coherent timing less reliable. Still, it is very unlikely that the deviation we observe from a pure exponential decay is due entirely to pulse profile evolution as this would require a very large ($\sim$0.35 cycle) systematic drift of the pulse profile during the two weeks following the outburst.

X-RAY FLUX AND SPECTRUM

Using the PCA folded pulse profiles, we constructed a pulsed flux history (2−10 keV) of 1E 2259+586 from 2000 March through 2003 June. At the time of the outburst, there is a sudden increase in the pulsed flux by a factor $\sim$18. Most of this enhancement decays away rapidly within a day, however, the pulsed flux does not fully recover to the pre-outburst level even after one year.

From the *XMM-Newton* observations and a subset of the *RXTE* observations, we calculated the pulsed fraction of 1E 2259+586 over this same time interval which allowed us to convert our pulsed flux measurements to unabsorbed phase-averaged fluxes [11]. The converted pulsed fluxes as well as independent flux measurements from *XMM-Newton* following the glitch are shown in Figure 2. All fluxes are plotted in log space relative to the glitch epoch (Table 1).

Clearly, the flux decay is not well described by a single component model (e.g. exponential or power law). The temporal decay of the flux during the PCA observations containing the burst activity ($<$1 day) is much more rapid than the decay during the year following the burst activity. We split the data into two segments ($<$1 day and $>$1 day after the glitch), and fit each independently to a power-law model ($F \propto t^{\alpha}$). The measured temporal decay indices for the two segments are -4.8 ± 0.5 and -0.22 ± 0.01, respectively. Note that the slope of the initial, rapid flux decay is highly dependent upon the chosen epoch. If the true fiducial point for this decay component followed the glitch, the slope of this decay component would be much flatter [11].

During the burst activity 2002 June 18 and immediately following the glitch, the spectrum of 1E 2259+586 became significantly harder. The thermal component became much hotter reaching 1.7 keV at its maximum and the photon index flattened to $\sim$2.5 [10]. Using the combined *XMM-Newton* and *RXTE* data sets, we traced the evolution of the X-ray spectrum of 1E 2259+586 following the outburst (Figure 3). The flux evolution is discussed earlier. All other spectral parameters (i.e. kT, Γ, etc.) recover to within 25% of their pre-outburst values within the first 1−3 days of the outburst.

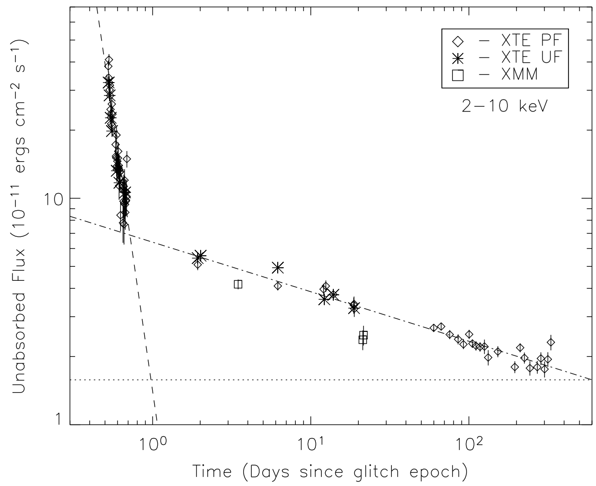

FIGURE 2. The time evolution of the unabsorbed flux from 1E 2259+586 following the 2002 June outburst. The glitch epoch (Table 1) is used as the reference time for this plot. Diamonds denote inferred unabsorbed flux values calculated from *RXTE* PCA pulsed flux measurements. Asterisks and squares mark independent phase-averaged unabsorbed flux values from *RXTE* and *XMM-Newton*, respectively. The dotted line denotes the flux level measured using *XMM-Newton* 1 week prior to the glitch. The dashed line is a power-law fit to the PCA flux measurements during the observations containing the burst activity ($<$1 day). The dot-dash line marks the power-law fit to all data $>$1 day following the glitch.

DISCUSSION

Virtually all measurable X-ray properties of 1E 2259+586 changed suddenly and dramatically during the 2002 June outburst. Continued observations with *RXTE* and *XMM-Newton* have allowed us to track the recovery of several source parameters shown to change during this outburst. Many of the observed variations resemble phenomena seen during SGR burst active episodes. Specifically, the harder X-ray spectrum, the flux enhancement, power-law flux decay, and pulse profile change. This work shows that not only are the bursts from 1E 2259+586 similar to SGR bursts [12], but the effects of these bursts on the persistent X-ray emission are also similar to what is seen in SGRs. This establishes yet another bond between SGRs and AXPs, confirming their common nature.

The cumulative properties of the outburst in 1E 2259+586 lead us to conclude that the star suf-

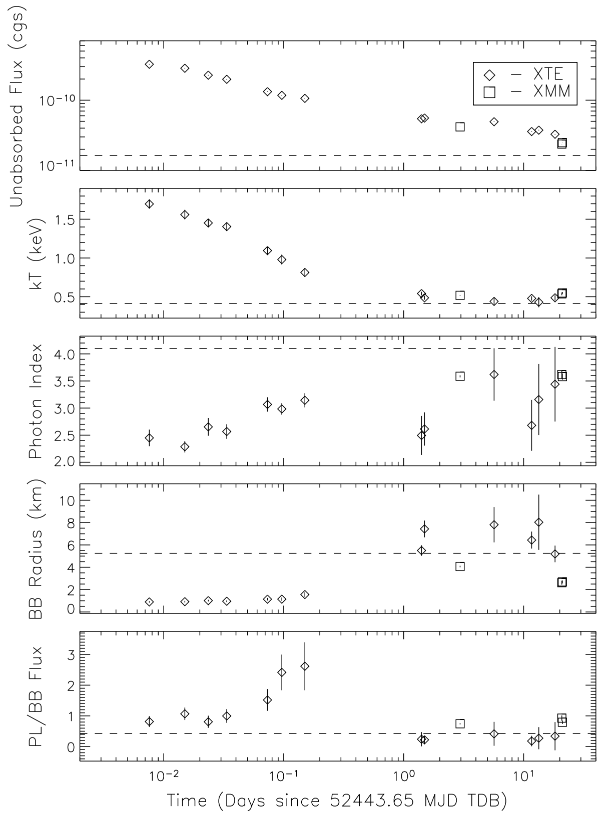

FIGURE 3. The spectral evolution of 1E 2259+586 through and following the outburst of 2002. From the top panel down: the unabsorbed flux (2−10 keV), the blackbody temperature (kT), the photon index, the blackbody radius, and the ratio of power-law (2−10 keV) to bolometric blackbody flux. A distance of 3 kpc was assumed [13] to compute the blackbody radius. Horizontal dashed lines denote the values of each parameter during the *XMM-Newton* observation one week prior to the outburst.

fered some major event that was extended in time and had two components, one tightly localized on the surface of the star (i.e. a fracture or a series of fractures) and the second more broadly distributed (possibly involving a smoother plastic change). This event affected both the superfluid interior and the magnetosphere. The glitch points toward a disturbance within the superfluid interior while the extended flux enhancement and pulse profile change suggests an excitation of magnetospheric currents and crustal heating. This physical interpretation is discussed in greater detail elsewhere [11].

Previous reports of flux variability [14, 15], pulse profile changes [14], and glitch activity [16] in 1E 2259+586 likely indicate previous episodes of burst activity in this source. What is most intruiging about this outburst and others inferred from past behavior is that not a single burst has been detected with large FOV gamma-ray detectors (e.g. BATSE, Konus, Ulysses, etc.) that traditionally detect burst active episodes in SGRs. This shows that we are missing low intensity SGR-like outbursts from magnetar candidates in our Galaxy (i.e. the SGRs are a sensitivity limited sample), therefore, there may be a larger population of active magnetar candidates in our Galaxy than previously thought.

ACKNOWLEDGMENTS

We thank P. Plucinsky (PI of the CTB 109 observations) for providing *XMM-Newton* data on 1E 2259+586. PMW acknowledges financial support through NASA (NAG 5-11608). VMK and FG received funding from NSERC via a Discovery Grant and a Steacie Fellowship Supplement, as well as from NATEQ, CIAR and NASA.

REFERENCES

1. Thompson, C., and Duncan, R., *MNRAS*, **275**, 255 (1995).
2. Thompson, C., and Duncan, R., *ApJ*, **473**, 322 (1996).
3. Kaspi, V., *these proceedings* (2004).
4. Kouveliotou, C., *these proceedings* (2004).
5. Woods, P., et al., *ApJ*, **576**, 381 (2002).
6. Woods, P., et al., *ApJ*, **535**, L55 (2000).
7. Gavriil, F., and Kaspi, V., *ApJ*, **567**, 1067 (2002).
8. Marsden, D., and White, N., *ApJ*, **551**, L155 (2001).
9. Woods, P., et al., *ApJ*, **552**, 748 (2001).
10. Kaspi, V., et al., *ApJ*, **588**, L93 (2003).
11. Woods, P., et al., *ApJ in press* (2004).
12. Gavriil, F., Kaspi, V., and Woods, P., *ApJ in press* (2004).
13. Kothes, R., Uyaniker, B., and Aylin, Y., *ApJ*, **576**, 169 (2002).
14. Iwasawa, K., Koyama, K., and Halpern, J., *PASJ*, **44**, 9 (1992).
15. Baykal, A., and Swank, J., *ApJ*, **460**, 470 (1996).
16. Heyl, J., and Hernquist, L., *MNRAS*, **304**, L37 (1999).