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The Long-term Radiative Evolution of Anomalous X-ray Pulsar 1E 2259+586 after its 2002 Outburst

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Abstract. We present an analysis of five X-ray Multi-Mirror Mission (XMM) observations of the Anomalous X-ray Pulsar (AXP) 1E 2259+586 taken in 2004 and 2005 during its relaxation following its 2002 outburst. We compare these data with those of five previous XMM observations taken in 2002 and 2003, and find that the observed flux decay is well described by a power-law of index $-0.69 \pm 0.03$. As of mid-2005, the source may still have been brighter than pre-outburst, and was certainly hotter. We find a strong correlation between hardness and flux, as seen in other AXP outbursts. We discuss the implications of these results for the magnetar model.

Keywords: anomalous X-ray pulsar, magnetar, neutron star
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INTRODUCTION

It is now commonly believed that Soft Gamma-ray Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) are neutron stars with ultra-strong magnetic fields, i.e. magnetars. SGRs exhibit various kinds of activity including bursts and outbursts. Their outbursts last hundreds of days and decay following a power-law of index $-0.5$ to $-0.9$ [1, 2, 3]. Similar albeit less energetic bursts and outbursts have also been observed from AXPs. AXP 1E 1048.1–5937 was observed to emit SGR-like bursts in 2001 [4]. AXP 1E 2259+586 was seen to undergo a major SGR-like outburst in 2002 [5, 6]. AXP XTE J1810–197, CXOU J164710.2–455216 and candidate AXP 1E 1845–0258 have also exhibited transient behavior that could be explained by SGR-like outbursts [7, 8, 9, 10].

During 1E 2259+586’s 2002 outburst, the pulsed and persistent fluxes rose suddenly by a factor of $\geq 20$ and decayed on a time scale of months. Coincident with the X-ray brightening, the pulsar suffered a large glitch of fractional frequency change $4 \times 10^{-6}$ [5, 6]. In the first few hours of the outburst, the pulsar’s pulse profile changed significantly, its pulsed fraction decreased, and its spectrum hardened dramatically. Over 80 short SGR-like bursts from the pulsar were observed at the same time [11]. A near-infrared ($K_s$) enhancement was also observed during the epoch of the outburst [5] and was found to have decayed at the same rate as the X-ray flux [12].

In this paper, we present a spectral and pulsed fraction analysis of ten XMM observations of AXP 1E 2259+586 taken between 2002 and 2005, as the source relaxed back toward quiescence. We compare the X-ray flux and spectral evolution of 1E 2259+586 with those of other magnetars, and interpret these results in terms of the magnetar model.

RESULTS

We analyzed 10 XMM observations of 1E 2259+586 taken between 2002 and 2005, before and after its 2002 outburst. We used data from the XMM European Photon Imaging Camera (EPIC) pn camera to extract spectra and pulse profiles, fit the spectra with a photoelectrically absorbed blackbody plus power-law model and calculated the pulsed fraction of the pulse profiles. The best-fit spectral parameters, fluxes and pulse fractions are plotted against observation date in Figure 1. We also plotted the X-ray flux and spectral evolution of 1E 2259+586 from RXTE monitoring observations during the same epochs in Figure 1a.

We fit 1E 2259+586’s 2–10 keV unabsorbed fluxes after the 2002 outburst with a power-law decay model (defined as $F(t) = F_0(t - t_g)^{\alpha} + F_q$, where $F(t)$ is the unabsorbed flux, $F_q$ is the quiescent flux, $\alpha$ is the power-law index and $t_g$ is the glitch epoch MJD 52443.13),
and found a good fit with $\chi^2_2(\nu)$ of 0.66(5). The best-fit power-law index is $-0.69 \pm 0.03$. The best-fit power-law model is shown in Figure 2 as a solid line. We also fit the same data with an exponential decay model, as Gotthelf and Halpern [14] did, and got $\chi^2_2(\nu) = 1.08(5)$ and a decay time scale of 13.3 ± 0.7 days.

In order to look for correlations between spectral hardness and flux as observed in other AXPs [11, 15, 16, 17], we have looked for a correlation between hardness ratio and observed flux. We define hardness ratio to be the ratio of 2 – 10 keV to 0.1 – 2 keV absorbed flux. We find the hardness ratio to be strongly correlated with the 2 – 10 keV absorbed flux (as shown in Fig. 3) in our observations.

We folded the light curve of each epoch’s data at the pulsar’s period to obtain average profiles, and calculated the RMS pulsed fraction, $PF$, of these pulse profiles (see details in Zhu et al. [18]). Although the pulse profile changed temporarily after the outburst (from a simple double peaked profile to triple peaked [5, 6]), the RMS pulsed fraction, measured from our ten XMM observations taken before and after the outburst, is consistent with being constant (as shown in Fig. 1).

**DISCUSSION**

In 2004 and 2005, the source’s temperature and unabsorbed fluxes were still higher than the pre-burst value (Fig. 1). This suggests that the source was not fully back to the pre-outburst flux level. Our power-law fit to the flux decay shows that the after-outburst quiescent flux level is $(1.75 \pm 0.02) \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$, which is
significantly higher than the pre-outburst value \((1.59 \pm 0.01 \times 10^{-11} \text{ergs}^{-1} \text{cm}^{-2})\). Either the 2005 flux had still not returned to its quiescent level, or perhaps the pulsar somehow anticipated the upcoming outburst, as indicated by a dip in flux prior to the outburst. Also possible is that this (and maybe other) AXPs do not have a well defined constant quiescent flux, but have long-term flux variations. Indeed there is possible evidence for X-ray variations. Indeed there is possible evidence for X-ray variations.

SGR 1900+14’s flux was found to follow a power-law of index \(-0.713 \pm 0.025\) after its 1998 August 27 flare [1]. This has been interpreted as the cooling of the magnetar outer crust following a sudden release of magnetic energy [20]. A power-law decay of index \(~ -2/3\) is predicted by this model. This model could also explain the X-ray flux decay of SGR 1627–41, though with some fine tuning [3]. We fit the \(\text{XMM}/2-10 \text{keV}\) unabsorbed fluxes of IE 2259+586 with a power-law plus constant model, and found the best-fit power-law index to be \(-0.69 \pm 0.03\), close to that of SGR 1900+14, and that predicted by the model. This suggests that the IE 2259+586 outburst afterglow may also be explained by the diffusion of heat in the outer crust.

The near-infrared flux decay of IE 2259+586 after its 2002 outburst was also found to follow a power-law of index \(-0.75_{-0.22}^{+0.33}\) [12]. The decay index we found for the X-ray afterglow is close to that of the near-infrared decay. This confirms the conclusion that the IR decay and X-ray decay are correlated.

A hardness-intensity correlation was observed in data from RXS J170849.0–400910 [16], and IE 1048.1–5937 [17]. We also found such a correlation in our IE 2259+586 XMM observations. As shown in Figure 3, the spectrum clearly becomes softer as the flux decreases. This correlation is expected in the twisted magnetosphere model [21], but may also arise in models involving a fixed magnetosphere and purely thermal activity [22].

A clear anti-correlation between IE 1048.1–5937’s pulsed fraction and unabsorbed flux has been observed [23, 24, 17]. No such correlation was found in our observations of IE 2259+586. Its pulsed fractions observed during and following the outburst are consistent with being constant. Gotthelf and Halpern [14] found that XTE J1810–197’s pulsed fraction measured between 2003 and 2006 after its outburst decreased with the decay of its flux, i.e. XTE J1810–197’s pulsed fraction is directly correlated with flux. Thus the striking anti-correlation between pulsed fraction and flux observed from IE 1048.1–5937 is clearly not universal.

The fact that the RMS pulsed fraction remained constant while the blackbody radius (in the blackbody plus power-law model) changed by a factor of \(\sim 2\) (Fig. 1) is worth considering, if the empirical blackbody plus power-law spectrum model somehow resembles the real radiation mechanism. Pulsed fraction should generally decrease when the thermally radiating region on the star grows, provided that this region is not very small compared to the entire surface. Any realistic spectral model which takes radiative transfer in the atmosphere and scattering through the magnetosphere into account should be able to reproduce the observation in this regard as well.

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\footnote{Later the afterglow of SGR 1900+14 August 27 flare was fitted with a power-law plus constant model instead of the single power-law model used by Woods et al. [1], and a decay index of \(\sim 0.9\) was found [2].}