The Variable X-ray and Near-IR Behavior of the Particularly Anomalous X-ray Pulsar 1E 1048.1−5937

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Abstract. We present the results of X-ray and near-IR observations of the anomalous X-ray pulsar 1E 1048.1−5937, believed to be a magnetar. This AXP underwent a period of extreme variability during 2001-2004, but subsequently entered an extended and unexpected quiescence in 2004-2006, during which we monitored it with RXTE, CXO, and HST. Its timing properties were stable for >3 years throughout the quiescent period. 1E 1048.1−5937 again went into outburst in March 2007, which saw a factor of >7 total X-ray flux increase which was anti-correlated with a pulsed fraction decrease, and correlated with spectral hardening, among other effects. The near-IR counterpart also brightened following the 2007 event. We discuss our findings in the context of the magnetar and other models.

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

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INTRODUCTION

Anomalous X-ray pulsars (AXPs) are a class of pulsars with observed X-ray luminosities in excess of what can be provided by rotational spin-down. Observationally, they possess extremely large inferred surface magnetic fields (∼10^{14} G), exhibit a variety of variable behaviour such as X-ray bursts, timing glitches and changes to their flux and spectrum, and are now known to be emitters of optical and infrared (IR), and in some cases even radio radiation. It is believed that they, like the soft gamma repeaters (SGRs), are magnetars: isolated neutron stars powered by the decay of enormous magnetic fields [1, 2]. The resulting effects of the magnetic field on the crust and magnetosphere produce the observational signatures found in AXPs and SGRs.

Monitoring of AXP timing properties with the Rossi X-ray Timing Explorer has been ongoing for >10 years. The 6.45-s pulsar 1E 1048.1−5937 is an AXP with a particularly unique history. Prior to 2004, this pulsar was highly rotationally unstable, so that phase coherence could only been maintained for months at a time [3]. During 2001-2002, 1E 1048.1−5937 underwent two prolonged flux “flares” (not to be confused with SGR giant flares) that were unlike behaviour seen previously in any other magnetar. The time-resolved flux increases took place over ∼weeks, and the gradual decay of the larger flare lasted years [3, 4, 5]. At the same time, erratic torque variability, X-ray spectral variability [6], SGR-like bursts, and a near-IR flux enhancement [7, 8] occurred. Thus, we proposed for simultaneous monitoring observations with the Chandra X-ray Observatory and the Hubble Space Telescope in 2006.

PRE-2007 “QUIESCENCE”

Between 2004-2006, 1E 1048.1−5937 appeared to be in a state of relative quiescence. Our RXTE observations showed that the pulsed flux was at the same level as during its pre-2001 quiescence, and a phase coherent timing solution was maintained for >3 years, longer than ever before maintained; see Figure 1a. CXO observations in 2006 revealed that the X-ray spectrum, when fit to an absorbed blackbody plus power-law model, had varied slightly, but intruigingly, did not return to quiescent levels like the pulsed and total flux did; see Figure 2. In February 2006, 1E 1048.1−5937 was detected using the HST filter F160W (similar to H-band) at a lower flux level than all previous detections (mF_{160} = 22.70 ± 0.14 mag); in subsequent observations, it had dropped below detectability (see Fig. 4b). We also analysed archival Very Large Telescope observations, and detected the counterpart once faintly at K_S = 21.0 ± 0.3 mag in 2005 (Fig. 4c). These results are presented in more detail in Tam et al. [9].
FIGURE 1. The evolution of 1E 1048.1−5937’s rotational and pulsed properties; figure from Tam et al. [9]. Fluxes and pulsed fraction are given for 2–10 keV. (a) Spin frequency as measured with RXTE monitoring. (b) Frequency derivative; see also Gavriil and Kaspi [3]. (c) RXTE-derived pulsed flux. (d) Simulated total unabsorbed flux, described in the text. (e) Pulsed fraction.

THE MARCH 2007 EVENT

In late March 2007, the quiescent phase unexpectedly ended with the sudden reactivation of 1E 1048.1−5937 in a new flare, discovered through our RXTE monitoring (Dib et al. ATel #1041). The details of our analysis were originally published in Tam et al. [9].

X-ray results. Simultaneous with a large glitch, RXTE saw a factor of ∼3 increase in the pulsed flux (2–10 keV), with a rise time of <1 week (Fig. 1); details of the RXTE results will be presented by Dib et al. (in preparation). Follow-up observations with CXO (Gavriil et al. ATel #1076), Swift (Campana et al. ATel #1043, Israel et al. ATel #1077), and XMM-Newton (Rea et al. ATel #1121) revealed that the total flux initially increased by a factor of >7 (2–10 keV) relative to the quiescent flux, while the pulsed fraction decreased from ∼75% to ∼20%. We also observed a spectral hardening (Fig. 2) correlated with the flux increase, and a change in the pulse profile from nearly sinusoidal to having multiple peaks after the flare [9].

We confirmed the anti-correlation between total X-ray flux and pulsed fraction (Figs. 2 and 3) noted previously by Tiengo et al. [6] and Gavriil et al. [5]. The clear dependence, shown in Figure 3, is well described by a power law [9]. Given this relationship, and the definition of pulsed fraction as pulsed flux divided by total flux, we can simulate a well sampled data set, demonstrating how we expect the total flux behaved in the past. This is shown in Figure 1d.
AXP emission models. The source of the anti-correlation between pulsed fraction and total flux is not obvious. In principle, it could be the result of a growing hot spot on the magnetar surface, produced by either changing internal processes, or changes in returning magnetospheric currents. This is complicated by such complex effects as surface thermal emission \[10\], light bending and radiative beaming, and magnetospheric scattering \[11, 12\]. The observed hardness-intensity correlation is predicted by the twisted magnetic field model \[11\], and can also possibly be explained by surface thermal emission \[10\].

An alternative model for AXP emission is accretion from a fallback debris disk around an ordinary pulsar \[13\], in which both the pulsar’s spin-down rate (Fig. 1b) and X-ray luminosity (Fig. 1d) are heavily dependent on the mass accretion rate. Gavriil and Kaspi \[3\] showed that for a pulsar undergoing spin down, we would expect \( L_X \propto |\dot{\nu}|^{7/3} \). However, we find that the factor of \( > 10 \) variability in \( \dot{\nu} \) between 2002-2004 was not reflected in a factor of \( > 200 \) change in X-ray luminosity as expected; in fact, the unabsorbed flux changed by merely \( \sim 6 \times \), and asynchronously with \( \dot{\nu} \).

Near-IR results. Following the March 2007 event, optical/IR observations were obtained with the Magellan Telescope (Wang et al. ATel #1044) and the VLT (Wang et al. ATel #1071, Israel et al. ATel #1077); see Figure 4. A detailed analysis will be forthcoming (Wang et al. in preparation). These new observations showed that the optical/IR flux may in fact be correlated with X-ray flux, contrary to what was previously suggested \[14\]. Near-IR variability is seen as correlated with X-rays in another AXP \[15\], but appears uncorrelated in two other cases \[16, 17\]. Such inconsistent behaviour is puzzling for the accretion disk model, since near-IR radiation is thought to be closely tied to X-ray emission via reprocessing of the X-rays in the disk. Optical/IR emission from magnetars has been attributed to high-energy processes (such as curvature or ion cyclotron emission) occurring in the magnetosphere \[18\]. Regardless, more frequent monitoring of AXP variability will be required in order to set constraints on optical/IR models.

CONCLUSIONS

From \( \sim 10 \) yrs of multiwavelenth observations, it is apparent that all spin and radiative activity from 1E 1048.1–5937 prior to 2004 can be linked to the large flares of 2001-2002, and that this AXP was in a relative quiescence between 2004-2006, which ended in March 2007 with another flaring event. We speculate that the observed behaviour, such as the varying X-ray flux anti-correlated with pulsed fraction and correlated with hardness, may be consistent with current magnetar scenarios.

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