X-RAY AND NEAR-IR VARIABILITY OF THE ANOMALOUS X-RAY PULSAR 1E 1048.1–5937: FROM QUIESCENCE BACK TO ACTIVITY

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Received 2007 July 13; accepted 2007 December 2

ABSTRACT

We report on new and archival X-ray and near-IR observations of the anomalous X-ray pulsar 1E 1048.1–5937 performed between 2001 and 2007 with the Rossi X-Ray Telescope Explorer (RXTE), the Chandra X-Ray Observatory, the Swift Gamma-Ray Burst Explorer, the Hubble Space Telescope (HST), and the Very Large Telescope. Monitoring with RXTE revealed that following its ~2001–2004 active period, 1E 1048.1–5937 entered a phase of timing stability; at the same time, simultaneous observations with Chandra and HST in 2006 showed that its X-ray and near-IR radiative properties, all variable prior to 2005, stabilized. Specifically, the 2006 X-ray spectrum is consistent with a two-component blackbody plus power law, with an average $kT = 0.52$ keV and $\Gamma = 2.8$, at a mean flux level of $\sim 6.5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (2–10 keV). The near-IR counterpart in 2005–2006 was detected at $H \sim 22.7$ mag and $K_s \sim 21.0$ mag, considerably fainter than previously measured. In 2007 March, this newfound quiescence was interrupted by sudden X-ray flux, spectral, and pulse morphology changes, simultaneous with a large glitch and near-IR enhancement. Our RXTE observations revealed a factor of ~3 increase in pulsed flux (2–10 keV), while observations with Chandra and Swift saw the total X-ray flux increase much more than the pulsed flux, reaching a peak value of $>7$ times the quiescent value (2–10 keV). We find a strong anticorrelation between X-ray flux and pulsed fraction, and a correlation between X-ray spectral hardness and flux. Simultaneously with the radiative and timing changes, we observed the X-ray pulse profile change significantly from nearly sinusoidal to having multiple peaks. We compare these remarkable events with other magnetor outbursts and discuss implications in the context of AXP emission models.

Subject headings: pulsars: general — pulsars: individual (1E 1048.1–5937) — stars: neutron

1. INTRODUCTION

The small handful of unusual objects known as anomalous X-ray pulsars (AXPs) are characterized by their slow spin periods (5–12 s), large inferred magnetic fields ($\sim 10^{14}$ G), and persistent X-ray luminosities in great excess of available spin-down power. These young, isolated pulsars have properties common to another class of objects, the soft gamma repeaters (SGRs). For recent reviews, see Woods & Thompson (2006) and Kaspi (2008). Potentially the most intriguing and most revealing property shared by AXPs and SGRs is their highly volatile nature: both are known to exhibit occasional and sudden dramatic flux and spin variability in the form of X-ray bursts, flares, and glitches. The magnetar model (Duncan & Thompson 1992; Thompson & Duncan 1995, 1996) was instrumental in explaining both the “anomalous” X-ray emission and the episodes of burst activity. It identified the sources as highly magnetized isolated neutron stars, with field strengths on the order of $10^{14}$ to $10^{15}$ G. The magnetar model uniquely, and correctly, predicted that SGR-like bursts would be observed from AXPs. A major proposed effect of this enormous magnetization is the “twisting” of the magnetosphere, with associated magnetospheric currents and heating of the crust at the twisted field-line footpoints (Thompson et al. 2002). This gives rise to the unusual X-ray spectrum, which has generally been empirically well characterized by a two-component model consisting of a power law plus blackbody. Bursts of high-energy emission occur, presumably when the crust succumbs to magnetic stresses and deforms, leading to a rapid rearrangement of the external magnetic field. Recently, Beloborodov & Thompson (2007) proposed the existence of a plasma corona contained within the closed magnetosphere to explain the broadband spectrum of magnetars that extends from the infrared (IR) to hard X-rays beyond 100 keV (Kuiper et al. 2006).

1E 1048.1–5937 has had an unusual history, even by AXP standards.7 Prior to 2002, monitoring of the pulsed flux with the Rossi X-Ray Timing Explorer (RXTE) showed that its spin-down was so unstable that phase coherence could be maintained for periods of only months at a time (Kaspi et al. 2001), behavior which echoed earlier reports of $\dot{P}$, flux, and spectral variability (Oosterbroek et al. 1998). Two small bursts, the first ever found in an AXP, were discovered in 2001 from 1E 1048.1–5937 (Gavriil et al. 2002), clinching the suspected association between AXPs and SGRs. Since 2002, tri-weekly RXTE observations of 1E 1048.1–5937 allowed the changing pulsed flux and spin-down rate to be monitored on relatively short timescales. Gavriil & Kaspi (2004, hereafter GK04) reported order-of-magnitude torque variability on timescales of weeks to months that only marginally correlated with large luminosity variations. The unusually slow and long-lived pulsed flux “flares” (not to be confused with the SGR giant flares; see Woods & Thompson 2006) that began in late 2001 and lasted into 2004 are in some ways unlike activity seen in any other AXP or SGR thus far. The ~2–10 keV spectrum and pulsed fraction are also variable on long timescales, the latter being anti-correlated with luminosity (Mereghetti et al. 2004; Tiengo et al. 2005). At near-IR wavelengths, the flux varied dramatically during 2002–2003 (Wang & Chakrabarty 2002; Israel et al. 2002);
unfortunately, the sparsity of near-IR observations prohibits measurements of the variability timescale, although a near-IR/X-ray anticorrelation has been suggested (Dunant & van Kerkwijk 2005). Further activity in the form of another burst and a small pulsed-flux increase was seen in 2004 (Gavriil et al. 2006).

Here we report on a series of simultaneous Chandra X-Ray Observatory and Hubble Space Telescope (HST) observations obtained during the course of 2006, as well as on archival Chandra, XMM, and Very Large Telescope (VLT) observations, in § 2. We also present RXTE timing results from the past 3 yr. In 2007 March, 1E 1048.1—5937 unexpectedly entered yet another new phase of activity, and we report on Target-of-Opportunity (ToO) observations with Chandra and Swift taken after the 2007 March event. In § 3.1 we discuss the 2004–2006 period of radiative and spin quiescence in the context of both magnetar and accretion models, and in § 3.2 we describe and interpret the events following the 2007 March flare.

2. OBSERVATIONS, ANALYSIS, AND RESULTS
As part of a long-term project, we regularly monitor AXPs using RXTE. 1E 1048.1—5937 is by far the most frequently observed AXP due to its relatively poor rotational stability. The RXTE observations (see § 2.1) are crucial in measuring the spin evolution of the source and its pulsed flux. However, the high background and large unimaged field of view of RXTE make spectral measurements of 1E 1048.1—5937 difficult and total flux (and consequently pulsed fraction) measurements impossible. To make these measurements, we obtained five Chandra observations (see § 2.2) approximately equispaced throughout 2006. In order to probe the origin of the near-IR emission of this source, we observed with the HST (see § 2.3) simultaneously with Chandra. The motivation for simultaneous Chandra and HST observations was to search for correlated variability in the different bands, as that provides insight into the physical mechanisms generating the radiation. We also examined archival K_s-band observations with the VLT (see § 2.4), which contribute to our monitoring of its near-IR brightness. Following the 2007 March glitch detected in our RXTE monitoring observations of 1E 1048.1—5937 (Dib et al. 2007), we initiated three Chandra and two Swift Gamma-Ray Burst Explorer (see § 2.2) ToO observations to follow the X-ray flux and spectrum of the source. In order to characterize the long-term evolution of 1E 1048.1—5937 we also incorporate and re-analyze archival XMM-Newton and Chandra observations (see Gavriil et al. [2006] for details on how these data were processed). Separate postburst optical and near-IR observations of 1E 1048.1—5937 are reported in detail elsewhere (Wang et al. 2007).

2.1. RXTE

We have observed 1E 1048.1—5937 regularly since 1997 with RXTE (Kaspi et al. 2001; GK04). Our data were obtained using the Proportional Counter Array (PCA) on board RXTE, which consists of five identical and independent xenon/methane Proportional Counter Units (PCUs). We use our RXTE observations of 1E 1048.1—5937 to look for the presence of bursts (see Gavriil et al. 2004 for details), to look for pulse profile changes, to monitor its pulsed flux, and to monitor its frequency evolution using phase-coherent timing when possible.

For the timing analysis, we created barycentered light curves in the 2–5.5 keV band with 31.25 ms time resolution. As past monitoring has shown that it can be difficult to maintain pulse phase coherence over timescales longer than a few weeks, observations of 1E 1048.1—5937 since 2002 are done three times per week, with the three observations carefully spaced so as to allow a phase-coherent analysis and a precise frequency measurement. Thus, for each observation we fold at the pulse period determined via periodogram, cross-correlate the folded profiles with a high signal-to-noise ratio template, and fit the resulting phases with a linear function whose slope provides the average frequency. Frequencies determined in this way are shown in Figure 1. As can be seen in this figure, the 2004–2006 frequencies were actually much more stable than in the past; we therefore attempted a fully phase-coherent analysis as well. This will be described elsewhere (R. Dib et al., in preparation). Frequency derivatives, which are also displayed in Figure 1 and are from GK04 and R. Dib et al. (in preparation), are clearly much more stable in the 2004–2006 interval than previously.

This period of rotational stability was accompanied by X-ray pulsed flux stability and relative quiescence: the pulsed flux time series of 1E 1048.1—5937 in the 2–10 keV band is presented in Figure 1. The pulsed flux was calculated using a method similar to that described in Woods et al. (2004) and is based on the rms of the folded profile, but without variance subtraction.

The long period of rotational stability ended in 2007 March, when a large glitch was observed (Dib et al. 2007). The glitch also signaled the end of the period of pulsed flux quiescence. The pulsed flux suddenly increased by a factor of ∼3 in the energy range.
range 2–10 keV. The upper limit on the rise time of the pulsed flux for this event is approximately one week. The peak pulsed flux reached by the source was ~10% larger than the peak flux reached during the largest of the two previously observed flares, and the rise time was at least 4 times smaller. On 2007 May 17, the date of the last X-ray-imaging observation included in this paper, the pulsed flux had decreased by ~10%. It is as yet difficult to compare the decay timescale of the pulsed flux of this new event to that of the previous flares; however, it will be possible in the near future.

2.2. Chandra and Swift

X-ray-imaging observations were carried out with the Chandra and Swift satellites. The date, total exposure time, and resulting count rate for each region-filtered background-subtracted observation are listed in Table 1, and a detailed description of our spectral fitting is given in §2.2.1.

1E 1048.1–5937 was observed five times in 2006 with Chandra in quasi-equispaced intervals, and three times in 2007 April. The observations were made with the Advanced CCD Imaging Spectrometer (ACIS) camera using the S3 chip in continuous clocking (CC) mode. This mode generates a 1 × 1024 pixel image, which is read out every 2.8 ms; pile-up in this mode is not an issue. The subsequent analysis was based on the “Level 2” events files for which the event times are photon arrival times (as opposed to readout times for the “Level 1” events). Following the standard threads we then corrected the “Level 2” events for certain caveats related to ACIS CC-mode data. We extracted a rectangular region centered on the source with a width typically of ~30 pixels. We estimated the background using rectangular regions on either side of the source which extended from ~10 pixels beyond the edge of the source region to ~10 pixels from the edge of the image. Following the standard threads, the source and background spectra were then extracted using CIAO version 3.4. We grouped the source spectrum such that there were no fewer than 20 counts per bin after background subtraction. The response matrix function (rmf) and area response function (arf) for each observation were also generated using CIAO and CALDB. We used Timed Exposure (TE) mode response matrices because of the absence of available spectral calibration for CC mode.

1E 1048.1–5937 was observed three times in 2007 with Swift using the X-Ray Telescope (XRT). XRT has two observing

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**Table 1**

**Chandra, XMM, and Swift Observing Parameters and Results**

| Date          | MJD   | Obs. ID | Exposure (s) | Count Rate (counts s⁻¹) | $\Gamma^a$ | $kT^c$ (keV) | Unabs. Flux $^{a,b}$ (10⁻¹² erg cm⁻² s⁻¹) | $F_{PL}/F_{BB}^{a,c}$ | Pulsed Fraction $^d$ |
|---------------|-------|---------|--------------|--------------------------|-----------|-------------|------------------------------------------|---------------------|------------------------|
| **Archival XMM Observations**             |       |         |              |                          |           |             |                                          |                     |                        |
| 2000 Dec 28   | 51,906| 0112780401| 4447         | 1.46(18)                 | 3.31(22)  | 0.65(17)   | 4.8(4)                                   | 0.6(2)              | 0.76(2)                |
| 2003 Jun 16   | 52,806| 0147860101| 41145        | 3.429(9)                 | 2.93(4)   | 0.599(6)   | 11.5(1)                                  | 1.21(5)             | 0.44(4)                |
| 2004 Jul 9    | 53,195| 0164570301| 32679        | 0.985(6)                 | 2.75(5)   | 0.542(15)  | 9.6(1)                                   | 2.1(2)              | 0.56(1)                |
| **Chandra Observations**                  |       |         |              |                          |           |             |                                          |                     |                        |
| 2004 Jul 10   | 53,196| 4653    | 28860        | 1.36(7)                  | 2.87(7)   | 0.56(1)    | 9.3(1)                                   | 1.2(1)              | 0.56(1)                |
| 2004 Jul 15   | 53,201| 4654    | 28085        | 1.317(7)                 | 2.87(7)   | 0.55(1)    | 9.4(2)                                   | 1.2(1)              | 0.55(1)                |
| **Monitoring Chandra Observations**        |       |         |              |                          |           |             |                                          |                     |                        |
| 2006 Feb 26   | 53,792| 6733    | 22085        | 1.072(8)                 | 2.79(6)   | 0.51(1)    | 7.1(1)                                   | 2.0(2)              | 0.63(1)                |
| 2006 Apr 20   | 53,845| 6734    | 20553        | 1.157(9)                 | 2.75(5)   | 0.50(1)    | 7.1(2)                                   | 2.0(2)              | 0.61(1)                |
| 2006 Jun 14   | 53,900| 6735    | 22085        | 0.985(9)                 | 2.95(9)   | 0.55(1)    | 6.3(1)                                   | 1.4(2)              | 0.64(1)                |
| 2006 Jul 30   | 53,946| 7347    | 22176        | 0.821(8)                 | 2.72(6)   | 0.51(1)    | 6.8(2)                                   | 1.2(2)              | 0.70(1)                |
| 2006 Sep 23   | 54,001| 6736    | 22022        | 1.306(7)                 | 3.14(11)  | 0.56(1)    | 5.1(1)                                   | 1.0(2)              | 0.64(1)                |
| **ToO Chandra Observations**               |       |         |              |                          |           |             |                                          |                     |                        |
| 2007 Apr 6    | 54,196| 7647    | 20079        | 4.241(15)                | 2.30(4)   | 0.56(1)    | 36.9(5)                                  | 1.6(1)              | 0.29(5)                |
| 2007 Apr 16   | 54,206| 7648    | 18387        | 3.959(15)                | 2.27(4)   | 0.55(1)    | 36.0(5)                                  | 1.7(1)              | 0.28(6)                |
| 2007 Apr 28   | 54,218| 7649    | 19082        | 4.332(15)                | 2.12(4)   | 0.55(1)    | 36.0(5)                                  | 1.8(1)              | 0.28(5)                |
| **ToO Swift Observations**                 |       |         |              |                          |           |             |                                          |                     |                        |
| 2007 Apr 3    | 54,193| 30912001| 4905         | 0.58(1)                  | 2.7(2)    | 0.58(6)    | 35(2)                                    | 2.6(6)              | 0.22(3)                |
| 2007 Apr 13   | 54,203| 30912003| 4829         | 0.55(1)                  | 2.8(4)    | 0.62(4)    | 32(2)                                    | 0.7(3)              | 0.17(3)                |
| 2007 May 17   | 54,237| 30912009| 3626         | 0.51(1)                  | 2.3(4)    | 0.7(1)     | 35(3)                                    | 2(1)                | 0.22(3)                |

Notes.—All quoted errors represent 1 σ uncertainties. The archival XMM and Chandra observations have been previously reported by Mereghetti et al. (2004), Tiengo et al. (2005), and Gavriil et al. (2006).

- These results are from a simultaneous spectral fit to all the data using as a model a photoelectrically absorbed blackbody with temperature $kT$ and a power law with photon index $\Gamma$. In the simultaneous fit the column density, $N_H$, was constrained to be the same for all observations. The resulting $N_H$ from the global fit was $N_H = (0.97 \pm 0.01) \times 10^{22}$ cm⁻²; see the text for details.

- Total unabsorbed flux in the 2–10 keV band.

- Ratio of the 2–10 keV flux in the power-law component, $F_{PL}$, to the 2–10 keV flux in the blackbody component, $F_{BB}$.

- The 2–10 keV pulsed fraction, using the definition of pulsed fraction described in Woods et al. (2004).
modes: photon counting (PC) and windowed-timing (WT). PC mode provides a $\sim 600 \times 600 \text{ pixel}^2$ image with low ($\sim 2.5 \text{ s}$) time resolution, whereas WT mode provides a one-dimensional $\sim 200 \text{ pixel}$ wide image with high ($\sim 0.74 \text{ ms}$) time resolution. XRT automatically switches from WT to PC mode when the count rate exceeds $\sim 2 \text{ counts s}^{-1}$. In our analysis we ignored the WT mode data, as they were too short to be of use. We used the PC-mode event files from the standard pipeline; these were cleaned and barycentered. Using FTOOL xrtcentroid, we determined the centroid of the image, and input the cleaned, barycentered events into the command line interface xselect.\textsuperscript{12} We selected a circular source region with a 25 pixel radius centered on the centroid of the image. Since the source was slightly piled up, we excluded a 4 pixel radius circular region centered on the centroid of the image. We used 4 pixels because that is the recommended exclusion radius for a source with 1E 1048.1$-$5937’s spectrum (L. Angelini, private communication). For the background, we selected events from an annulus with an inner radius of 50 pixels and outer radius of 130 pixels. We further filtered our events by selecting only those that had grades 0$-$12. With xselect we then created source and background PHA files. The FTOOL xrtmkarf was used to create the arfs, and we input the source PHA file with the excluded center so that it would be corrected for pile-up. We used the file provided by CALDB appropriate for PC-mode data events of grades 0$-$12 to make the rmf.

2.2.1. Global Spectral Fit

We extracted spectra of 1E 1048.1$-$5937 from all archival, monitoring, and ToO observations collected from Chandra, XMM, and Swift. A description of the recent data analysis is in § 2.2, and the archival analysis was described in Gavriil et al. (2006). Using the fitting package XSPEC\textsuperscript{13} version 12.3.1, we modeled the X-ray spectra with a photoelectrically absorbed blackbody plus power law. We used the phabs photoelectric absorption XSPEC model, which assumes the solar abundance table of Anders & Grevesse (1989) and uses the bbodycomp photoelectric cross-section table from Balucinska-Church & McCammon (1992) with the new He cross section from Yan et al. (1998). We fit this model to all the observations simultaneously, allowing the column density $N_{H}$ to vary but with the sole constraint that it be the same for all observations. We restricted our fit to the $0.7$–$5 \text{ keV}$ band. The total global fit had $\chi^2 = 1.07$ for $\nu = 4200$ degrees of freedom (dof). Individually, the observations were equally well modeled (except for a relatively high $\chi^2$ value in one observation; see § 2.2.2). Our best-fit column density obtained from the global fit is $N_{H} = (0.97 \pm 0.01) \times 10^{22} \text{ cm}^{-2}$, in agreement with Durant & van Kerkwijk (2006b). The results of our spectral fitting are listed in Table 1 and plotted in Figure 2.

2.2.2. Possible Spectral Feature

All observations had spectra that were well modeled by a photoelectrically absorbed blackbody plus power law. However, the Chandra observation on 2007 April 6 (observation ID 7647), the first after the 2007 March event, had a relatively high $\chi^2 = 1.33$ ($\nu = 353$ dof). There is possible evidence for an absorption line at $\sim 2.7 \text{ keV}$ (see Fig. 3). Adding a Gaussian line improved the fit ($\chi^2 = 1.20$ for $\nu = 351$ dof) with $\Delta \chi^2 = 48.3$. With the line width fixed at 0.1 keV, we measure a line energy of $2.73 \pm 0.03 \text{ keV}$. Allowing the line width $\sigma$ to be a free parameter, we obtain $\sigma = 0.16 \pm 0.03 \text{ keV}$, a line energy of $2.74 \pm 0.03 \text{ keV}$, and $\chi^2 = 1.19$ for 351 dof. We find no evidence of a phase dependence for this possible line. A detailed phase-resolved spectroscopic analysis will be presented in a forthcoming paper.

To test the significance of adding such a line, we performed the following simulation. We generated 10,000 simulated spectra by adding Poisson noise to a blackbody plus power law model spectrum having the same parameters as our best-fit model. We then determined the maximum change in $\chi^2$ after adding a Gaussian line. To avoid local minima and ensure that we found the true minimum $\chi^2$ for each simulation iteration, instead of fitting for the peak energy, we stepped through different line energies between 0.6 and 7.0 keV with a step size of 0.025 keV. The width of each line was held fixed at 0.1 keV and its normalization was allowed to vary. In all the simulation iterations, none had a change in $\chi^2$ greater than 48.3. The probability that this feature is due to random chance is <0.13%, accounting for the number of trials.

We note, however, that with the addition of the line, the overall fit is still unacceptable; we speculate that other features may be present as well, although at marginal significance. For example, there is a small but intriguing feature at $\sim 1.3 \text{ keV}$, which is approximately half the energy of the line discussed above. The evidence for a line must be considered tentative because CC mode, which uses the TE mode response matrices, is not spectrally

\textsuperscript{12} See http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/xtools/xselect.html.

\textsuperscript{13} See http://xspect.gsfc.nasa.gov.
calibrated, and there exist calibration lines between 1.7 and 3 keV in the TE response. However, this is true for the other Chandra observations, including those in which we find no such features.

2.2.3. Pulse Morphology and Pulsed Fraction Study

Using our Chandra and Swift observations, we were also able to study the source’s pulse morphology, flux, and pulsed fraction. For the Chandra observations, we barycentered our corrected Level 2 event lists and then extracted background-subtracted light curves in the different bands using the same source and background regions as for the spectral analysis. We folded these light curves at the optimal frequency as determined by a periodogram.

The frequencies we obtained all agreed with the ephemerides determined with our contemporaneous RXTE data. Figure 4 (left) displays the Chandra pulse profiles in the 1–3 and 3–10 keV bands. Note that after the flare (last three panels in Fig. 4, left), the pulse profile changed from single to at least triple peaked. To study the pulse morphology evolution quantitatively we decomposed the pulse profiles into their Fourier components. In Figure 4 (right) we plot the Fourier components in terms of their ratio to the fundamental (the $n = 0$ and fundamental are excluded from the plot). Note that before the flare the profile consisted of only the fundamental and an $n = 2$ Fourier component. After the flare, the profile exhibited significant Fourier components of order $n = 2, 3, 5$. Interestingly, despite the drastic changes in the other Fourier components, the $n = 4$ component remains consistent with zero throughout the flare.

Similarly, for the Swift observations we used the barycentered, cleaned, and pointed PC-mode data events. The XRT WT data consisted of too few pulses to be useful. Swift PC-mode data have only 2.5 s resolution, providing fewer than three pulse phase bins for this 6.45 s pulsar. We attempted to improve on the coarse sampling by utilizing advanced “bin splitting” techniques (G. Israel, private communication); however, we find only marginal evidence for a pulse profile change from these data (but see Campana & Israel 2007).

Using our folded pulse profiles we measured rms pulsed fractions$^{14}$ using the method described in Woods et al. (2004). Our 2–10 keV rms pulsed fractions are listed in Table 1 and plotted in Figures 1 and 2. The XMM pulsed fractions, taken from Gavriil et al. (2006), were extracted in the same fashion. Because of the low time resolution of the Swift data, the rms pulsed fraction would be artificially reduced if the pulse contained as much harmonic content as the Chandra data during the flare. Thus, for each Swift observation we simulated, given its observed pulsed fraction and mean count rate, what its true pulsed fraction would be assuming a pulse profile with as much harmonic content as the nearest Chandra observation. On average we found a reduction of no more than ~73%. Note in Figure 2 the observed tight correlation between total flux and pulsed fraction (see also Tiengo et al. 2005), which we discuss in detail in § 3.2.2.

2.3. HST

We observed 1E 1048.1–5937 using HST simultaneously with Chandra on four occasions in 2006: February 26, April 20, July 30, and September 23 (Program ID 10761). Observations were made with the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) instrument, a 256 × 256 square pixel HgCdTe detector. Combined with camera 3, it provided a focus ratio of f/17, a field of view of 51′ × 51′, and a plate scale of 0.2″ pixel$^{-1}$. The detector was read out in MULTIACCUM mode, and a spiral dither pattern with 5″ spacings was applied. We observed using the filter F110W (similar to the ground-based J-band filter) on two occasions and F160W (similar to H band) on four occasions. The average FWHM of the point-spread function (PSF) was ~0.4″ for all NICMOS observations. Observing parameters are summarized in Table 2.

The data underwent “on-the-fly reprocessing” involving standard pipeline routines before being retrieved from the HST Archive. The calibration routine calnicb performed basic data reduction steps, and calnicb produced a single final image for each observation, combining the dithered mosaic input images. DAOPHOT (Stetson 1987) for IRAF version 2.12.2 was used to perform PSF photometry. Absolute calibration of our measurements was done using the NICMOS Photometric Keywords,$^{15}$ for which the uncertainties are believed to be less than 5%; we found the aperture correction to correspond with the calibration keywords by simulating PSFs with the Tiny Tim$^{16}$ software package.

In order to determine limiting instrumental magnitudes in each of the observations, we performed PSF photometry on a set of a hundred trial images to which a single artificial star was added. This artificial star was placed in a 0.3″ box in a blank region near the nominal position of the IR counterpart. By varying the brightness of the star, we define the 3$\sigma$ detection limit at the instrumental magnitude for which the PSF photometry recovers the artificial star with an uncertainty of 0.3 mag (see Hulleman et al. 2000).

$^{14}$ For a simple signal of the form $c(\phi) = A \sin(2\pi \phi) + B$, the rms pulsed fraction is given by $PF_{rms} = (1/\sqrt{2})(A/B)$, and the peak-to-peak pulsed fraction is given by $PF_{rm} = A/B$. We opted to use the rms with Fourier filtering (A. Archibald et al., in preparation) because it is a more robust estimator of the pulsed fraction than peak-to-peak.

$^{15}$ See http://www.stsci.edu/hst/nicmos/performance/photometry.

$^{16}$ See http://www.stsci.edu/software/tinytim/tinytim.html.
At the position of 1E 1048.1−5937, as measured by Wang & Chakrabarty (2002) in the Ks-band with the Magellan telescope, we find one point source in the F160W image from 2006 February 26 only. To confirm the positional coincidence of this source with the Magellan object, we astrometrically tied $N = 31$ nearby field stars in our HST image to those from the Magellan image. A $0.05"$ offset was found for the 1E 1048.1−5937 candidate. The Magellan source’s relative positional uncertainty, given its 0.4" FWHM radius, is roughly FWHM/$\sqrt{N} \sim 0.07\"$. Therefore, we consider this HST object the counterpart of 1E 1048.1−5937.

Thus, we measure our lone detection of 1E 1048.1−5937 to have $m_{F160W} = 22.70 \pm 0.14$ mag; uncertainties indicate the nominal errors determined by DAOPHOT and incorporate PSF fitting uncertainties. Limiting magnitudes for the three latter HST F160W observations in which no counterpart was seen are presented in Table 2. To deepen the sensitivity, geometric transforms were computed to register and combine the three nondetection data sets. In the combined data, we tentatively detect an extremely faint counterpart of brightness $m_{F160W} = 23.42 \pm 0.20$ mag, where the 3 $\sigma$ upper limit is $\geq 23.5$ mag. We find no F110W counterpart down to a 3 $\sigma$ upper limit of $m_{F110W} > 25.0$ and 24.8 mag on February 26 and April 20, respectively. Results are plotted in Figure 5.

To examine how this compares with past results, we also calibrated our measurements using the $H$ magnitudes from Durant & van Kerkwijk (2005). A relative offset is found between HST’s F160W filter and ground-based $H$ band, as a function of $J - H$ color. We know the color of 1E 1048.1−5937 only during a brightened state ($J - H \approx 0.9$ in 2002 April; Wang & Chakrabarty 2002), and suspect that it is not constant; therefore, this is not a perfect comparison, but provides a rough estimate. Based on the magnitudes of seven nearby field objects, we measure $H = 22.73$ mag on February 26, which is very near what we find for $m_{F160W}$.

2.4. VLT

We have analyzed archival observations of 1E 1048.1−5937 which were obtained with NAOS-CONICA (NACO), the near-IR adaptive optics (AO) instrument at the VLT of the European Southern Observatory. The source was observed for 900 s in the $K_s$-band using the S27 camera ($28" \times 28"$ field of view and 27 mas pixel$^{-1}$ pixel scale) on four occasions (April 11, April 29, May 27, and June 6) in 2005. Star A (Wang & Chakrabarty 2002), located 9.5" from the AXP, was used as the wave front-sensing (WFS) star. Due to the relative faintness of the WFS star ($v' = 16.5$ mag), the AO correction was only partial.

The observations, either dithered sets of five $2 \times 90$ s integrations (on the first night) or of $10 \times 90$ s integrations, were corrected for dark current, flat-fielded (using averages derived from the science frames), and corrected for variations in the sky (using median averages of the flat-fielded science frames). Finally, the reduced science images were aligned using integer pixel offsets.
We also show the corresponding magnitude on the right axis; however, the trans-

turation (Wang & Chakrabarty 2002; Israel et al. 2002; Durant & van Kerkwijk 2005).

Results from this work fall after 2004, while data prior to that are from previous liter-

Note that post-2007 event optical and near-IR observations of 1E 1048.1—5937 were obtained with VLT and Magellan (Wang et al. 2007; Israel et al. 2007). Preliminary results of the $K_s$-band observations are shown in Figure 5, and details on some of the observations can be found in Wang et al. (2007).

### 3. DISCUSSION

Explaining the origin of the different types of AXP viability across the electromagnetic spectrum is a major challenge for the magnetar model. Many fundamental questions remain open. In the case of 1E 1048.1—5937, how are timing instabilities related to radiative variability? AXP spin-up glitches sometimes are accompanied by major radiative events, as in the 2002 outburst of AXP 1E 2259+586 (Kaspi et al. 2003), and sometimes not, as in the large glitch of 1E 1841—045 (Dib et al. 2008). Moreover, are the gradual large-scale changes seen in the 2001–2002 flares of 1E 1048.1—5937 of a similar origin to AXP outbursts like that of 1E 2259+586 or XTE J1810+157 (Ibrahim et al. 2004), and how can they be accounted for by magnetar models? Also, what is the nature of the optical/IR emission observed in five out of eight confirmed AXPs? Suggested origins include coherent or curvature emission in the plasma magnetosphere (Eichler et al. 2002; Beloborodov & Thompson 2007), but so far this has not been confirmed. Are the low- and high-energy emission mechanisms intimately connected (Heyl & Hernquist 2005)? Correlated post-

burst flux decay in the X-ray and near-IR regimes has been seen in at least one other AXP (Tam et al. 2004).

![Figure 5](image-url)

**TABLE 2**

| Date       | MJD   | Exposure (s) | Filter* | Limiting Magnitude | Detection | $\nu F_\nu$ $^b$ (10$^{-15}$ ergs s$^{-1}$ cm$^{-2}$) |
|------------|-------|--------------|---------|-------------------|-----------|------------------------------------------|
| VLT Observations |
| 2006 Feb 26.............. | 53,792 | 2637 | F110W | $\geq$25.0 | ... | $<0.37$ |
| 2006 Feb 26.............. | 53,792 | 1196 | F160W | $\geq$23.7 | 22.7(14) | $<0.49; 1.3 \pm 0.2$ |
| 2006 Apr 20.............. | 53,845 | 2637 | F110W | $\geq$24.8 | ... | $<0.45$ |
| 2006 Apr 20.............. | 53,845 | 1196 | F160W | $\geq$23.1 | ... | $<0.49$ |
| 2006 Jul 30.............. | 53,946 | 1037 | F160W | $\geq$23.3 | ... | $<0.74$ |
| 2006 Sep 23.............. | 54,001 | 1037 | F160W | $\geq$22.9 | ... | $<1.0$ |
| HST Observations |
| 2005 Apr 11............... | 53,324 | 900  | $K_s$ | $\geq$20.3 | ... | $<7.0$ |
| 2005 Apr 29............... | 53,471 | 900  | $K_s$ | $\geq$20.6 | ... | $<3.1; 3.7 \pm 1.0$ |
| 2005 May 27.............. | 53,489 | 900  | $K_s$ | $\geq$21.2 | 21(0)3 | $<7.0$ |
| 2005 Jun 6.............. | 53,527 | 900  | $K_s$ | $\geq$21.4 | ... | $<2.6$ |

Notes.—Magnitude uncertainties reflect errors determined by DAOPHOT; upper limits are $3\sigma$ limits, as defined in the text. Measured quantities are “observed,” i.e., they have not been corrected for redening/extinction effects.

* Although the filter system of HST does not precisely match standard ground-based near-IR filters, note that F110W $\approx J$ band and F160W $\approx H$ band.

$^b$ To convert standard IR magnitudes to flux, we take as the $K_s$-band $0$ mag zero point $\nu F_\nu = 9.28 \times 10^{-7}$ ergs s$^{-1}$ cm$^{-2}$, derived from Cox (2000). HST fluxes are determined from NICMOS Photometric Keywords.

and median-combined to create an average image for each night.

Using DAOPHOT, we tried PSF photometry on each of the four averaged images, using different models for the PSF. Because the AO correction is only partial, we found that the PSF is reasonably well modeled by a Moffat function of exponent 2.5 in combination with a look-up table. The width of the PSF that was determined for each observation was 0.34 (April 11), 0.43 (April 29), 0.24 (May 27), and 0.20 (June 6). Only in the observation of May 27 did we detect the near-IR counterpart to 1E 1048.1—5937.

We calibrated the instrumental magnitudes and magnitude limits using stars X2–X8 and A and B against the calibrated $K_s$ magnitudes of Wang & Chakrabarty (2002). The rms uncertainty in the calibration is about 0.2 mag. The near-IR counterpart to 1E 1048.1—5937 was detected at $K_s = 21.0 \pm 0.3$ on 2005 May 27; the 3 $\sigma$ upper limits for April 11, April 29, May 27, and June 6 are $K_s > 20.3, K_s > 20.6, K_s > 21.2$, and $K_s > 21.4$, respectively. Limiting magnitudes were determined with the same method described in § 2.3. Results are shown in Figure 5.

Explaining the nature of the different types of AXP variability across the electromagnetic spectrum is a major challenge for the magnetar model. Many fundamental questions remain open in the case of 1E 1048.1—5937.
Given the many observational properties that have been characterized for 1E 1048.1–5937 in this work and for other AXPs in similar studies, which property will emerge as being the most constraining of physics is hard to know. The most promising behaviors are those which show clear correlations with others, or those that are common to many or all AXPs and SGRs. In this section we discuss the behavior of 1E 1048.1–5937, and focus on the phenomena that are potentially the most useful for testing the magnetar or other competing models. We first consider the quiescent phase we have observed in 2004–2006, and its implications for AXp models, then subsequently discuss the source’s return to activity in 2007 March.

3.1. The 2004–2006 Quiescent Phase

3.1.1. X-Ray Flux and Spectrum

The X-ray flaring observed pre-2004 contrasts strongly with the stable pulsed fluxes we observed in 2004–2006 (Fig. 1c). Clearly the source’s stable state is also its faintest. The X-ray spectrum during this quiescent phase is also fairly constant, with $kT$ evolving postflare, on the timescale of several years. Interestingly, $kT$ does not return to its preflare value as measured in 2000 December (see Fig. 2a). Similarly, the photon index (Fig. 2b) decreased in 2004–2006, away from its softer preflare value. Meanwhile the pulsed fraction (Figs. 1e and 2e) was slowly rising in 2004–2006, as the source grew fainter, as if, unlike $kT$ and $\Gamma$, it was slowly recovering to the preflare value. Thus, overall the quiescent period is characterized by slow evolution, on timescales of years, in which the source flux and pulsed fraction slowly relaxed back to their preflare values, while the source spectrum varied significantly (Fig. 2e) and did not relax back to its preflare state. This is suggestive of a fixed energy-loss rate in quiescence, although perhaps with a different magnetospheric current configuration, which impacts the surface emission via return currents (Thompson et al. 2002). We note, on the other hand, that the 2006 and pre-2001 pulse profiles were very similar if not identical (Kaspi et al. 2001), and that the Thompson et al. (2002) simple prediction for the decay time of the sort of magnetospheric twist required for 1E 1048.1–5937 is an order of magnitude too large for standard parameters. The evolution could also be purely due to the thermal component (Özel & Guver 2007).

3.1.2. Timing Stability

Simultaneous with the slow evolution of the X-ray flux, pulsed fraction, and spectrum, the pulsar’s rotational behavior clearly stabilized, with the source spinning down relatively smoothly at a value close to the long-term average in 2004–2006 (Fig. 1a). Whereas previously this AXP distinguished itself from others by defying attempts at phase-coherent timing and exhibiting large torque variations (Fig. 1b), in 2004–2006 1E 1048.1–5937 resembled, from a timing point of view, other AXPs which are relatively stable rotators, at least when not glitching (e.g., Kaspi et al. 1999; Dib et al. 2008). This behavior demonstrates a clear relationship between timing and radiative properties, and that the “noise” seen in the frequency derivative during 2001–2004 is likely physically different from the “timing noise” observed ubiquitously in radio pulsars and in otherwise radiatively stable AXPs.

In the context of the magnetar model, magnetospheric activity can account for both torque and X-ray flux variability, although the former is most sensitive to currents anchored closest to the magnetic poles, so that only a broad correlation between flux and torque is expected (Thompson et al. 2002) and indeed is seen when considering many AXPs and SGRs (Marsden & White 2001). That the torque and luminosity in 1E 1048.1–5937 do not vary simultaneously or in a clearly correlated way is thus not necessarily problematic if the magnetospheric current configuration is changing, although it does demonstrate that the magnetar model in this particular regard is not strongly predictive.

Although the magnetar model is favored, it has also been suggested that accretion from a fossil debris disk could explain AXP spin characteristics (Chatterjee et al. 2000; Alpar 2001) as well as all aspects of the broadband emission (Ertan & Câliskan 2006). While it is now evident that accretion alone cannot be responsible for all observed properties, most notably the energetic X-ray bursts, a “hybrid” model has been invoked that puts a thin debris disk around a highly magnetized pulsar (Eksi & Alpar 2003). In this hybrid case, both the persistent luminosity and pulsar spin-down are related to the mass transfer rate, $M$. According to GK04, who compare 1E 1048.1–5937’s torque changes with changes in $R_{\text{XE}}$ pulsed flux, the scale of their variability does not obey an expected relationship for an accreting pulsar undergoing spin-down, thus presenting a challenge to models of fossil disk accretion. It could be argued, however, that since the only pulsed flux $P_X$ was being monitored, the total X-ray luminosity $L_X$ is still an unknown quantity. We address this by using the quantitative correlation we establish between pulsed fraction $F_P$ and total unabsorbed flux $F_X$ (discussed in § 3.2.2 and shown in Fig. 6) to simulate a well-sampled set of phase-averaged flux data as a function of $R_{\text{XE}}$ pulsed flux $P_X$, given that $F_P$ is simply $P_X/F_X$. The resulting “new” total flux, $F_X$, is shown in Figure 1d, along with $\dot{\nu}$ in Figure 1b for comparison. At its most variable in 2002–2004, the absolute value of $\dot{\nu}$ changed by a factor of $>10$ in less than a year, while the maximal change in total unabsorbed flux is a factor of $\approx 6$ from peak to quiescence. Note that these variations are not simultaneous. For a pulsar experiencing a spin-down torque due to mass accretion while in a quasi-equilibrium “tracking” phase (i.e., the AXP phase), a strong correlation described by $L_X \propto |\dot{\nu}|^{3/2}$ can be derived from Chatterjee et al. (2000, eq. [3]) where the magnitudes of torque and $\dot{\nu}$ are proportional, the radius of the magnetosphere is defined by the Alfvén radius, which is also a function of $M$, and $L_X \propto M$. Thus, a factor of $>10$ change in $\dot{\nu}$ should be reflected by a factor of $>200$ simultaneous change in $L_X$, and $F_X$, if this model is correct. Clearly this is not observed, rendering this particular accretion scenario unlikely. This point is further emphasized by the significant time offset between the changes in torque and flux. Overall, the fact that 1E 1048.1–5937’s long history of highly irregular spin-down is mirrored by trends in its X-ray emission only in a broad, rather than strict, sense strongly suggests that active accretion is not happening in this case.

3.1.3. Near-IR Quiescence

Our original purpose for making simultaneous Chandra/HST observations was to compare low-level near-IR and X-ray flux and spectral changes, with each observed with the same instrument, in order to look for correlations. Given that the near-IR source had faded considerably in the HST observations, rendering it only marginally detected in 2006, this was not possible. Compared to the handful of near-IR detections made throughout 2002–2003 (see Fig. 5), it is clear that 2005–2006 marked a period of near-IR quiescence in 1E 1048.1–5937. At the time of the 2005 VLT observations in which the AXP was faintly seen in the $K_s$ band, its flux was consistent with the last detection in mid-2003. With HST in 2006 we find that its $H$ and $J$ magnitudes have dropped lower than ever before observed. There is marginal evidence for near-IR flux variability during quiescence on comparably short timescales to the variability in X-ray spectral parameters, although closely spaced near-IR monitoring observations are required to confirm this.
That the near-IR faded roughly in concert with the X-ray flux is notable, suggesting a correlation similar to that seen in AXP 1E 2259+586 (Tam et al. 2004). This is discussed further below. However, such a correlation can be argued to be expected in both the magnetar and disk models. In the magnetar model it would imply that the near-IR emission is magnetospheric and hence varies, as do the X-rays, when the magnetospheric configuration varies (Heyl & Hernquist 2005; Beloborodov & Thompson 2007). In the disk model, a correlation between near-IR emission and X-ray flux is naturally expected, since the putative disk is heated via X-ray illumination (Ertan et al. 2006; Wang et al. 2006); however, why the torque should have varied strongly and nonsimultaneously is a puzzle (see above).

In any case, the concurrence of the near-IR and X-ray quiescence and the timing stability is unlikely to be an accident. Similarly, the presence of the two flares and the subsequent strong torque changes are also not likely to be by chance.

3.2. The 2007 March Event and its Aftermath

1E 1048.1−5937 reactivated in 2007 March, when a sudden pulsed flux increase was observed (Fig. 1c), accompanied by a large spin-up glitch, the details of which will appear elsewhere (R. Dib et al., in preparation). Our follow-up X-ray observations with Chandra and Swift show that the spectral parameters, pulse shape, total flux, and pulsed fraction are drastically changed since this flare occurred (Figs. 2 and 4). In particular, the total X-ray flux was >7 times greater in the 2–10 keV band compared with quiescence, while the pulsed fraction decreased from ~75% to ~20%. Compared to the previous long-term flares from 1E 1048.1−5937, the onset of this event took place more quickly by a factor of >4, the peak pulsed flux is ~10% greater, and the “high” state appears to be lasting longer. Optical and near-IR follow-up with the Magellan Telescope and VLT (Wang et al. 2007; Israel et al. 2007) reveals an increase in both the \(I\) and \(K_s\) bands of ~1.3 mag. Very recently, Rea et al. (2007) reported on XMM ToO observations, and revealed that nearly 3 months after the flare onset the total X-ray flux has decreased slightly but is still ~5 times brighter than in quiescence.

3.2.1. Near-IR Enhancement

Previously, an anticorrelation between near-IR and X-ray flux in this AXP was suggested, based on the correspondence of the highest near-IR detection with a low point in X-ray pulsed flux\(^{17}\) (Durant & van Kerkwijk 2005). Given the new measurements from both before and after the recent event, such an anticorrelation is highly questionable. The significant rise in near-IR flux now appears correlated with the most recent X-ray flare. Interestingly, in 2002 a high near-IR detection was between the two X-ray flares; this suggests that the near-IR emission is not exactly correlated with the X-rays, but rather an enhancement that can precede, follow, or last longer than an X-ray enhancement. A near-IR brightening preceding an X-ray enhancement would rule out illuminated disk models for this source; frequent mid- or near-IR observations are required to check this. As discussed above, AXP 1E 2259+586 also demonstrated strongly correlated near-IR and X-ray flux decay following its large 2002 outburst (Tam et al. 2004), but in contrast, 4U 0142+61 was highly variable in the near-IR despite X-ray stability (Durant & van Kerkwijk 2005), and has shown no evidence of near-IR changes coinciding with X-ray bursts (Gonzalez et al. 2007). Note that the claim of correlated flux decay in the case of XTE J1810−197 (Rea et al. 2004) is under dispute (Camilo et al. 2007). Such inconsistent behavior is puzzling for both the magnetar and disk models.

3.2.2. Correlation between Pulsed Fraction and Total Flux

One conclusion to be drawn from Figures 1b and 1e is that 1E 1048.1−5937’s pulsed fraction \(P_F\) is strongly anticorrelated with the total X-ray flux \(F_X\), a trend already noticed by Tiengo et al. (2005) and Gavriil et al. (2006). Now, with our larger sample of

\(^{17}\) Note that an error in Fig. 4 of Durant & van Kerkwijk (2005) places the brightest \(K_s\) flux on the wrong date; we have corrected this in our Fig. 5c.
data covering a wider dynamic range, we can quantify this correlation: we find a power-law dependence of $\mathcal{P}_x \propto F_x^n$, where $n = -0.46 \pm 0.02$ (see Fig. 6), with $F_x$ in the $2 - 10$ keV range. In fitting, we set the index as a free parameter, i.e., not tied to any model; therefore, some scatter is expected, as is evident in the large $\chi^2 = 9.36$ produced by the fit ($\nu = 14$ dof). However, in finding the uncertainty on $n$, we have scaled the $\mathcal{P}_x$ data uncertainties to force $\chi^2 = 1$, effectively scaling up $\sigma_n$ as well. A similar correlation has been proposed in another AXP, 1RXS J170849.0-400910 (Dib et al. 2008), although in that case it is such that the pulsed flux remains nearly constant in the presence of $>50\%$ total flux changes (Campana et al. 2007).

How could an increase in phase-averaged flux be met with a simultaneous decrease in pulsed fraction? A growing hot spot on the neutron star surface—a result of either a changing magnitude, configuration of returning magnetospheric currents, or internal processes—could at least in principle produce such an effect, if the initial hot spot size were large enough that its size as viewed from a distant observer were a significant fraction of the stellar surface. We note that Özel & Guver (2007) suggest that magnetar afterglows may be dominated by surface thermal, rather than magnetospheric, changes; detailed simulations of AXP pulsations using gravitational light bending and appropriate radiation beaming functions (e.g., Dedeo et al. 2001) in addition to magnetospheric scattering (Thompson et al. 2002; Fernández & Thompson 2007) are needed to see if the observed correlation can be reproduced.

3.2.3. Correlation between Hardness and Total Flux

A prediction made by the twisted magnetosphere model of Thompson et al. (2002) is that enhanced emission should also be spectrally harder, since both are associated with larger magnetospheric twist angles. Indeed, we observed a correlation between the total X-ray flux and spectral hardness: see Figure 6. Similar behavior has also been reported in 1RXS J170849.0-400910 (Rea et al. 2005a; Campana et al. 2007). This can be interpreted as a confirmation of an important magnetar model prediction, namely, that both the spectral hardness and the total flux should increase for an increasing magnetospheric twist angle (Thompson et al. 2002). Hardening of the spectrum might also be an expected effect of increased luminosity if a large injection of thermal seed photons is repeatedly up-scattered due to resonant cyclotron scattering feedback processes in the magnetosphere, thereby shifting the photon energies higher. Recently, Özel & Guver (2007) have suggested that the hardness-intensity correlation in magnetars is a result of purely surface thermal changes, with no change in the magnetospheric configuration. It would be interesting to apply their model to the 1E 1048.1-5937 data, as they span a much greater dynamic range in flux than did the sources studied by Özel & Guver (2007). This is beyond the scope of our paper, however.

3.2.4. 2007 Pulse Profile Changes

As seen in the Chandra data obtained after 2007 March, the pulse profile of 1E 1048.1-5937 changed abruptly after the X-ray flux enhancement and glitch. Several new harmonics are clearly visible, and are present in a largely energy-independent way (Fig. 4). This extra power in the higher harmonics clearly signals a complication of the surface and/or magnetospheric configuration. This change contrasts with that seen after the 2002 outburst of 1E 2259+586, which involved mainly an exchange of powers between the fundamental and first harmonic, with higher harmonics remaining relatively unchanged (Woods et al. 2004). Also, the change contrasts with that seen during the 1998 SGR 1900+14 giant flare, in which the SGR pulse profile simplified greatly immediately postflare (Göğüş et al. 2002). However, the opposite occurred following the 2004 giant flare from SGR 1806-20 (Palmer et al. 2005), when a sinusoidal-to-complex evolution in pulse morphology took place, similar to that of 1E 1048.1-5937. This diversity of behaviors in magnetars postoutburst is problematic for understanding the underlying physics; indeed it indicates a wide variety of phenomenon phase space, which itself must be explained by models. The peculiar suppression of the fourth harmonic in the postglitch 1E 1048.1-5937 profile is particularly puzzling to us; perhaps it indicates an important and unchangeable symmetry in the combined emission and viewing geometries, or perhaps it is a chance occurrence and will not occur again in future events.

3.2.5. 2007 April Spectral Feature?

In the Chandra observation made on 2007 April 6, the one closest to and just after the 2007 March event, the X-ray spectrum of 1E 1048.1-5937 could not be well fit by a simple continuum model, in contrast with the other data sets. We identified a possible absorption line near 2.7 keV, although we note that the spectral model including this line is still not a good fit to the data. This suggests that other low-level features may be present as well, including a possible feature at roughly half the above line’s energy, ~1.3 keV. The putative 2.7 keV line joins the growing list of puzzling and sometimes statistically marginal AXP/SGR spectral features (Ibrahim et al. 2002, 2003; Rea et al. 2003, 2005a). Examples of some feature detections that are clearly statistically significant are, interestingly, repeatedly near ~13 keV, e.g., in 1E 1048.1-5937 (Gavriil et al. 2002, 2006), in XTE J1810-197 (Woods et al. 2005), and very recently AXP 4U 0142+61 (Gavriil et al. 2007; F. P. Gavriil et al., in preparation). The feature we see in the 2007 April data for 1E 1048.1-5937 is unlike any of these. It is perhaps more reminiscent of the absorption features seen in some “isolated neutron stars” (e.g., Bigmani et al. 2003; van Kerkwijk et al. 2004), and, if similarly interpreted as an electron cyclotron feature, implies a magnetic field of ~3 x 10^11 G, or ~6 x 10^14 G for a proton cyclotron line. The latter value is of course more line in the field expected near the surface of a magnetar. However, the feature could also be an atomic transition (e.g., Mori & Ho 2007); it is difficult to know given the present data. Regardless, the spectrum 10 days later, on 2007 April 16, showed no such feature, indicating that whatever its origin, it had subsided, and on a shorter timescale than that of any profile or flux relaxation.

3.2.6. Comparison of the 2007 1E 1048.1-5937 Event with Other Similar Events

The 2001–2002 flares observed in 1E 1048.1-5937 are unique in that they had very well resolved rise times of many weeks (GK04). The 2007 April event, by contrast, involved an X-ray pulsed flux enhancement that rose at least 4 times faster. In this sense it is perhaps more similar to the 2002 outburst of 1E 2259+586 (Kaspi et al. 2003), although in that case a brief rise could have been missed by the sparse monitoring. During that outburst, 1E 2259+586 exhibited an order-of-magnitude increase in pulsed and phase-averaged flux, as well as numerous other changes including (but not limited to) ~80 SGR-like bursts. Similarly to 1E 1048.1-5937, both the total and pulsed flux increased during the 1E 2259+586 outburst, and the pulsed fraction decreased, going from 23% in quiescence down to 15% (Woods et al. 2004). However, the pulsed fraction was not as tightly correlated to the pulsed flux: the pulsed fraction recovered within ~3 days (Zhu et al. 2007), whereas the flux took several months to return to its pre-outburst value (Woods et al. 2004). In terms of energetics, the total energy in 2–10 keV released in the 1E 2259+586 outburst was 3 x 10^39 and 2 x 10^41 erg during the rapid and gradual decay.
components, respectively (see Table 5 of Woods et al. 2004). For 1E 1048.1—5937, we estimate that up to 2007 April 28, the date of the last Chandra observation, the total energy emitted is comparable, roughly $7 \times 10^{39}$ erg ($2 - 10$ keV), based on the pulsed fraction—total flux correlation and assuming a distance of 2.7 kpc (Gaensler et al. 2005), or $8 \times 10^{38}$ erg assuming 9.0 kpc (Durant & van Kerkwijk 2006a). Near-IR flux variability, possibly (in the case of 1E 1048.1—5937) and likely (in 1E 2259+586) correlated to X-ray flux, was observed following both events. That the 2007 1E 1048.1—5937 event clearly involved a large rotational glitch, as did the 2002 1E 2259+586 event, is also a commonality, although glitches at the time of the 2001–2002 flares could easily have been missed because of the large amount of timing noise and our inability to phase connect the data at that time (R. Dib et al., in preparation). SGR-like bursts from 1E 1048.1—5937 have not been observed thus far in 2007, but that does not preclude their existence given that our observing duty cycle is so low. Similarly to 1E 1048.1—5937, 1E 2259+586 exhibited a pulse profile change, albeit one involving only the fundamental and first harmonic, in contrast to the appearance of higher harmonic structure in 1E 1048.1—5937. Finally, as in 1E 1048.1—5937, spectral hardening was observed during the 1E 2259+586 flare. Thus, overall the 2007 1E 1048.1—5937 event has practically all properties consistent with the 2002 1E 2259+586 event, but differs from its earlier flares primarily in rise time.

The transient AXP XTE J1810–197 presents another interesting example for comparison. This AXP, which “turned-on” in late 2002 or early 2003 (Ibrahim et al. 2004), has been steadily declining in X-ray flux since, reaching apparent quiescence in 2005–2006 (Gotthelf & Halpern 2007). Unfortunately, very little is known about the onset of enhanced emission, i.e., whether it was accompanied by a glitch/burst, or what the timescale of the rise was. While the exponential decay timescale of several years does resemble that of 1E 1048.1—5937’s 2001–2002 postflare behavior, how the most recent flare will fade is as yet undetermined. Furthermore, the peak and quiescent fluxes of XTE J1810-197 differed by a much greater amount, nearly 2 orders of magnitude (Gotthelf et al. 2004), while the recent total 2–10 keV flux increase in 1E 1048.1—5937 was by a factor of $\sim 7$. Spectrally, XTE J1810–197 was harder in outburst and softer in quiescence, similar to 1E 1048.1—5937, when modeled as a two-temperature blackbody (Gotthelf & Halpern 2007) or as a blackbody plus power law (W. Zhu, private communication). One major distinction, however, is the clear evidence for a positive correlation between pulsed fraction and total flux in XTE J1810–197 (Gotthelf & Halpern 2007). While it may be tempting to link the transience between pulsed fraction and total flux in XTE J1810–197 (Gotthelf et al. 2004), while the recent total 2–10 keV flux differences at the time of the 2001

We have considered $\sim 10$ yr of multiwavelength observations of 1E 1048.1—5937. The source, in 2004—2006, gradually relaxed apparently back to quiescence in most respects, only to “awaken” suddenly in the glitch/flare event of 2007 March. By observing 1E 1048.1—5937 while quiescent, it has become apparent that previous instabilities in timing and X-ray and near-IR flux were likely all linked to the major long-term flaring events of 2001–2002, whose nature is yet unknown but likely includes changes in the stellar magnetosphere’s current configuration. The asynchronous spin and X-ray flux variability we have observed are incompatible with expectations of the fossil disk accretion model. Following the most recent 2007 event, we observed total X-ray flux variability that is strongly correlated with X-ray pulsed fraction, X-ray spectral hardness, and changes in near-IR flux. These observations largely agree with expectations of the magnetar model. To date, the 1E 1048.1—5937 2007 event is ongoing, as is continued multiwavelength monitoring.

We thank Joe Hill and Lorella Angelini for their help with the Swift XRT data analysis, and Zhongxiang Wang for his help with the near-IR analysis. We thank the anonymous referee for many judicious comments that have improved the quality of the paper. F. P. G. is supported by the NASA Postdoctoral Program administered by Oak Ridge Associated Universities at NASA Goddard Space Flight Center. P. M. W gratefully acknowledges support for this work from NASA/SAO through grant GO7-8077A. This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center, and is based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with program 10761. This work has been supported by SAO grant GO7-8077Z, an NSERC Discovery Grant, the Canadian Institute for Advanced Research, and Le Fonds Québecois de la Recherche sur la Nature et les Technologies.

No. 1, 2008

VARIABILITY OF X-RAY PULSAR 1E 1048.1—5937

513
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