ANOMALOUS X-RAY PULSAR 1E 1048.1−5937: PULSED FLUX FLARES AND LARGE TORQUE VARIATIONS

FOTIS P. GAVRIIL1 AND VICTORIA M. KASPI1,2

Received 2004 April 5; accepted 2004 May 25; published 2004 June 4

ABSTRACT

We report on continued monitoring of the anomalous X-ray pulsar (AXP) 1E 1048.1−5937 using the Rossi X-Ray Timing Explorer. We confirm that this pulsar has exhibited significant pulsed flux variability. The principal features of this variability are two pulsed X-ray flares. Both flares lasted several months and had well-resolved few-week–long rises. The long rise times of the flares are a phenomenon not previously reported for this class of object. The epochs of the flare peaks were MJD 52,218.8 ± 4.5 and 52,444.4 ± 7.0. Both flares had shorter rise than fall times. The flares had peak fluxes of $2.21 \pm 0.16$ and $3.00 \pm 0.13$ times the quiescent value. We estimate a total 2–10 keV energy release of $\sim 2.7 \times 10^{40}$ and $\sim 2.8 \times 10^{41}$ ergs for the flares, assuming a distance of 5 kpc. We also report large (factor of $\sim 12$) changes to the pulsar’s spin-down rate on timescales of weeks to months, shorter than has been reported previously. We find marginal evidence for correlation between the flux and spin-down rate variability, with probability of nonrandom correlation 6%. We discuss the implications of our findings for AXP models.

1. INTRODUCTION

Anomalous X-ray pulsars (AXPs) are an exotic manifestation of young neutron stars. AXPs are known for their steady, soft X-ray pulsations in the period range of 6–12 s. The detection of X-ray bursts from two AXPs has confirmed the common nature of these objects with that of soft gamma repeaters (SGRs; Gavriil et al. 2002; Kaspi et al. 2003), another exotic type of young neutron star. Both classes of objects are believed to be magnetars, i.e., powered by the decay of an ultrahigh magnetic field that has a magnitude of $10^{14}–10^{15}$ G on the stellar surface. For recent AXP reviews, see Kaspi & Gavriil (2004) and Kaspi (2004).

One issue in AXP research has been flux stability. Historically, two AXPs have been reported to be highly flux variable. Oosterbroek et al. (1998) collected all published flux measurements for AXP 1E 1048.1−5937 and concluded that its total flux varies by as much as a factor of 10 between observations spaced by typically 1–2 yr over ~20 yr. Those data were from a diverse set of instruments, including imaging and nonimaging telescopes. Similarly, flux variability by a factor of greater than 4 was reported for AXP 1E 2259.1+586 by Baykal & Swank (1996), using data also from a variety of instruments.

However, long-term Rossi X-Ray Timing Explorer (RXTE) monitoring of the pulsed flux of 1E 1048.1−5937 by Kaspi et al. (2001) and of 1E 2259.1+586 by Gavriil & Kaspi (2002) using a single instrument and set of analysis software showed no evidence to support such large variability.1 Also, Tiengo et al. (2002), following a short XMM-Newton observation of 1E 1048.1−5937, compared the observed flux with those measured by two other imaging instruments, ASCA and BeppoSAX. They found that in the three observations, the total flux was steady to within ~30%–50%. They argued that the nonimaging detections included in the Oosterbroek et al. (1998) analysis may have been contaminated by other sources in the instrument’s fields of view; in particular, the bright and variable X-ray source η Carina lies only 38′ away.

A possible solution to this puzzle came with the discovery of a large (greater than 10 times) long-lived flux enhancement from 1E 2259.1+586 at the time of a major outburst in 2002 June 18. This event was accompanied by many other radiative changes as well as by a large rotational spin-up (Kaspi et al. 2003; Woods et al. 2004). This suggests that past flux variability reported in AXPs could be attributed to similar outbursts that went undetected.

We report here, using data from our continuing RXTE monitoring program, the discovery of significant pulsed flux variability in 1E 1048.1−5937. This variability is mainly characterized by two long-lived pulsed flux flares, having well-resolved rises a few weeks long. These are unlike any previously seen flux enhancements in AXPs and SGRs and thus likely represent a distinct physical phenomenon. We find no evidence for any major associated bursting behavior. We also report large variations in the spin-down torque on timescales of a few weeks/months. We find only a marginal correlation between the flux and torque variations. We argue that this poses another significant challenge to any disk-accretion model for AXPs but is not inconsistent with the magnetar model.

2. ANALYSIS AND RESULTS

All observations reported here were obtained with the Proportional Counter Array (PCA; Jahoda et al. 1996) on board RXTE. The timing observations described below are a continuation of those reported by Kaspi et al. (2001). We refer the reader to that paper for details of the analysis procedure. This RXTE monitoring program has shown that in general, AXPs have sufficient stability for phase-coherent timing (see Kaspi & Gavriil 2004 for a review). 1E 1048.1−5937 is an exception. For this pulsar, we have achieved phase-coherent timing only over relatively short data spans. In 2002 March, we adopted the strategy of observing this source every week with three short (~2 ks) observations. These closely spaced observations allow us to measure the spin frequency with high precision weekly without phase-connecting over long baselines. This therefore allows us to determine the spin-down rate with interesting precision on timescales of a few weeks. Figure 1a

---

1 Department of Physics, McGill University, Rutherford Physics Building, 3600 University Street, Montreal, QC H3A 2T8, Canada.
2 Department of Physics and Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139.
3 Total flux measurements with RXTE were difficult given the large field of view of the PCA and the low count rates for the AXPs relative to the background.
Figure 1.—Spin, flux, and spectral history of 1E 1048.1−5937. (a) Observed spin frequencies vs. time. The points represent individual frequency measurements. The solid lines represent the phase-connected intervals as reported by Kaspi et al. (2001). The dashed line is the long-term average spin-down. (b) Pulsed flux time series in the 2–10 keV band. Arrows indicate the times at which the bursts reported by Gavriil et al. (2002) occurred. (c) HR as a function of time. The HRs displayed were computed for the pulsed flux in the energy range (4–6 keV)/(2–4 keV).

shows the long-term spin history of 1E 1048.1−5937 as measured by RXTE.

Figure 2a shows the spin-down rate \( \dot{\nu} \) as a function of time over the interval for which we can make this measurement. Plotted values of \( \dot{\nu} \) were calculated by measuring the slopes of each 5 adjacent values of \( \nu \). Note how \( \dot{\nu} \) clearly varies greatly during our observations, on all timescales to which we are sensitive. From MJD 52,400 to MJD 52,620 \( \dot{\nu} \) had changed by a factor of \( \sim 12 \). During the \( \sim 120 \) day interval from MJD 52,620 through MJD 52,740, \( \dot{\nu} \) was a factor of \( \sim 4 \) larger than the long-term average spin-down (\( \dot{\nu}_{\text{avg}} \)). This was followed by an abrupt decrease in magnitude by a factor of \( \sim 2 \), which was not resolved, and by subsequent additional variations. At no time did we observe any episode of spin-up.

We also monitor the pulsed flux of this source. In this analysis, data from each observing epoch were also folded at the optimal pulse period. We calculated the rms pulsed flux using the method described by Woods et al. (2004). Given 1E 1048.1−5937’s highly sinusoidal pulse profile we used only the first two harmonics to calculate the pulsed flux. This method of measuring flux is different from the one used in Kaspi et al. (2001), which involved fitting a spectral model to extract a pulsed flux in cgs units. Given the short length of the observations, fitting a spectral model to the individual observations was not practical. The pointing for two observations was slightly off-source, so we had to correct for reduced collimator response. The pointing was on-source for all other observations. Figure 1b shows our pulsed flux time series in the 2–10 keV band. Pulsed flux time series in the 2–4 and 4–6 keV bands look similar.

The pulsed flux time series clearly has significant structure. The most obvious features are two long-lived flares. The first flare was smaller and shorter lived than the second. The latter clearly displayed significant structure in its decay. In estimating the following flare properties, we define the first flare as having occurred between MJDs 52,198 and 52,318 and the second having started on MJD 52,386, and we take its end to be our last observation on MJD 53,030, although it clearly has not yet ended (see Fig. 2). We estimate that the first flare had a peak flux of \( \sim 2.11 \pm 0.16 \) times the quiescent pulse flux, with the peak occurring at MJD 52,218.8 ± 4.5. Its rise time was \( 20.8 \pm 4.5 \) days and its fall time \( 98.9 \pm 4.5 \) days. The second flare peak was on MJD 52,444.4 ± 7.0 and had a peak value of \( 3.00 \pm 0.13 \) times the quiescent pulsed flux. Its rise time was \( 58.3 \pm 7.0 \) days, and its fall time is greater than 586 days. We estimate 2–10 keV fluences of \( (111 \pm 12) \times 10^{-6} \) counts PCU−1 and \( (1136 \pm 38) \times 10^{-6} \) counts PCU−1 for the first and second flare, respectively. Tiengo et al. (2002) measured a total flux in the 2–10 keV energy range of \( \sim 5 \times 10^{-12} \) ergs cm−2 s−1 and a pulsed fraction of \( \sim 94\% \) for energies >2 keV from XMM-Newton observations of 1E 1048.1−5937. This information, along with our measured quiescent pulsed flux, allows us to scale our fluences to estimate the total energy released in each flare. Assuming a distance of 5 kpc (see discussion in Özel et al. 2001), we find a total energy release of \( \sim 2.7 \times 10^{49} \) ergs for the first flare and \( \sim 2.8 \times 10^{41} \) ergs for the second flare, both in the 2–10 keV band.

Although we clearly detect both large flux variations and large changes in the spin-down rate, the correlation between the two is marginal. The Spearman rank order correlation coefficient \( r_s = 0.28 \), where 0 indicates no correlation and 1 indicates total correlation. The probability of obtaining this value

\[ r_s = 0.28, \quad \text{where} \quad 0 \leq r_s \leq 1, \quad \text{and} \quad P(r_s) = 0.12 \]
of $r_t$ or higher by random chance is 6%. Thus, there is marginal evidence of some correlation, equivalent to a $\approx 2\sigma$ result. From Figure 2, it is clear why any correlation is not strong: for example, $\dot{r}$ changes very little during the rise of the second flare, in the interval MJD 52,380–52,420. Also, there is no short-term flux change when $r_t$ suddenly reaches its maximum absolute value (near MJD 52,620), nor when it abruptly changes by a factor of $\sim 2$ around MJD 52,740.

Hardness ratios (HRs) were measured by comparing the pulsed flux, as measured by the method described above, in the 2–4 keV band to that in the 4–6 keV band. Figure 1c shows our HR measurements. The mean HR is 0.78. There is evidence for spectral variability. The reduced $\chi^2$ of the HR time series is 3.6 for 143 degrees of freedom. However, there is no evidence for any correlation of HR with pulsed flux or torque. Our uncertainties, however, are quite large; monitoring observations with an imaging instrument would improve this situation.

Intriguingly, the peak of the first flare was coincident with the epochs during which we observed two SGR-like X-ray bursts from the direction of this source in 2001 (Gavriil et al. 2002; indicated by arrows in Fig. 1). However, we found no other SGR-like bursts in any of the remaining data. For a detailed description of our burst-searching algorithm, see Gavriil et al. (2004). We also searched our folded time series for pulse morphology variations using the method detailed by Gavriil & Kaspi (2002). We find no evidence for significant pulse profile changes at any epoch in our data set.

3. DISCUSSION

The long-lived flux enhancements with well-resolved rises that we have observed in 1E 1048.1−5937 are very different from previously detected X-ray flux variations in AXPs and SGRs, which show very abrupt rises associated with major outbursts (e.g., Kaspi et al. 2003; Woods et al. 2004). The long-lived flux decay in those sources has been attributed to burst afterglow, which is a cooling of the crust following an impulsive heat injection from magnetospheric bursts (Lyubarsky et al. 2002). The much more gradual flux rises that we have observed in 1E 1048.1−5937 comprise a new phenomenon not yet observed in any other AXPs despite several years of careful and frequent RXTE monitoring. These flux variations may provide a new diagnostic of the physical origin of the persistent nonthermal emission in SGRs and AXPs, since they are not contaminated by burst afterglow. Also interesting are the large variations in spin-down rate or torque. Torque variations by nearly a factor of 5 were already reported from RXTE observations (Kaspi et al. 2001), on timescales of years. Here we have shown that the torque can change by at least a factor of $\sim 2$ more and on much shorter timescales, namely, a few weeks to months.

In considering the observed pulsed flux and torque variations, whether they are correlated is an important issue. Our weekly monitoring of the source unfortunately commenced only after most of the first flare decayed. Prior to that, the monthly observations, taken in the form of brief snapshots, did not allow anything about the rotational behavior of the source to be determined when phase-coherent timing was not possible. This was the case during the first flare. During the second flare, the spin frequency was, interestingly, most stable during the rise and peak of the flare. Furthermore, the stable spin-down rate was at a lower magnitude than the long-term average. Subsequently, $\sim 60$ days after the flux began to decay, the rate of spin-down began to increase. Given timing observations during only one flare, it is unclear whether these features are coincidences or not. However, there is no strong evidence to support otherwise; similar torque variations were seen in the past and were not accompanied by any flaring (see Fig. 1). Significant torque variations unaccompanied by severe flux variability have been noted for 1E 1048.1−5937 prior to our RXTE monitoring (e.g., Paul et al. 2000). Nevertheless, statistically, the probability that they are uncorrelated is only 4%; studying Figure 2 suggests that if anything, slope transitions are correlated, if not the slopes between transitions. Continued RXTE monitoring will help identify any true correlations, particularly if the source exhibits more variability.

Can the magnetar model explain such behavior? The persistent emission in magnetars has a spectrum that is well described by a two-component model, consisting of a blackbody plus a hard power-law tail. The thermal component is thought to arise from heat resulting from the active decay of a high internal magnetic field (Thompson & Duncan 1996); however, thermal X-ray flux changes are not expected on as short a timescale as we have measured in the absence of major bursts. Thompson et al. (2002) put forth a model in which the nonthermal component arises from resonant Compton scattering of thermal photons by currents in the magnetosphere. In magnetars, these currents are maintained by magnetic stresses acting deep inside its highly conducting interior, where it is assumed that the magnetic field lines are highly twisted. These magnetospheric currents in turn twist the external dipolar field in the lesser conducting magnetosphere. These magnetic stresses can lead to sudden outbursts or more gradual plastic deformations of the rigid crust, thereby twisting the footpoints of the external magnetic field and inducing X-ray luminosity changes. The persistent nonthermal emission of AXPs is explained in this model as being generated by these currents through magnetospheric Comptonization and surface backheating (Thompson & Duncan 1996; Thompson et al. 2002). Changes in X-ray luminosity, spectral hardness, and torque have a common physical origin in this model, and some correlations are expected. Larger twists correspond to harder persistent X-ray spectra, as is observed, at least when comparing the harder SGR spectra to those of the softer AXPs. As noted by Kaspi et al. (2001), 1E 1048.1−5937’s hard photon spectral index ($\Gamma = 2.9$) suggests that it is a transition object between the AXPs ($\Gamma = 3–4$) and the SGRs ($\Gamma = 2.2–2.4$). Hence, if during the flares 1E 1048.1−5937’s magnetosphere was twisted to the SGR regime, we expect spectral index variations of $\sim 0.5$. Spectral measurements of such precision are not feasible with our short RXTE monitoring observations.

Decoupling between the torque and the luminosity can be accounted for in the magnetar model. According to Thompson et al. (2002) the torque is most sensitive to the current flowing on a relatively narrow bundle of field lines that are anchored close to the magnetic pole, and so only a broad correlation in spin-down rate and X-ray luminosity is predicted and in fact is observed for the combined population of SGRs and AXPs (Marsden & White 2001; Thompson et al. 2002). However, for a single source, whether an X-ray luminosity change will be accompanied by a torque change depends on where in relation to the magnetic pole the source of the enhanced X-rays sits. Similarly, large torque variations, as we have observed, may occur in the absence of luminosity changes if the former are a result of changes in the currents flowing only in the small polar cap region.

Note that energetically, the total release in these flares is comparable to, although somewhat less than, that in the after-
glows seen in SGRs and in AXP 1E 2259.1+586 (see Woods et al. 2004 for a summary). It easily can be accounted for given the inferred magnetic energy of the star.

Although the magnetar model for AXPs has been spectacularly successful in explaining their most important phenomenology, the anomalous behavior noted for 1E 1048.1−5937 raises the possibility that perhaps it has a physical nature different from other AXPs. It has also been suggested that AXPs might be powered by accretion from fossil disks (Chatterjee et al. 2000; Alpar 2001). An increase in luminosity \( L_X \) can easily be explained in accretion models by an increase in the mass accretion rate \( \dot{M} \), given that \( L_X \propto \dot{M} \). Transient changes in \( \dot{M} \) are perhaps not unreasonable to expect in fossil disk models, given the huge variations seen in \( \dot{M} \) of conventional accreting sources. However, in an accretion scenario, we expect correlations between luminosity and torque. In conventional disk-fed accreting pulsars undergoing spin-up, one expects \( \dot{n} \propto \dot{L}_X^{3/7} \). Such a correlation is seen approximately in accreting pulsars, with discrepancies possibly attributable to changed beam- or improper measurement of bolometric luminosities, the former due to pulse profile changes and the latter due to finite bandpasses (Bildsten et al. 1997). As discussed by Kaspi et al. (2001), for a source undergoing regular spin-down as in 1E 1048.1−5937, the prediction is less clear; the form of the correlation depends on the unknown functional form of the torque. For the propeller torque prescription of Chatterjee et al. (2000), we find that \( L_X \propto \dot{n}^{0.7} \), a much stronger correlation than in the conventional spin-up sources. For a change in \( L_X \) by a factor of \( \sim 3 \) as we have seen in the rise of the second flare, we would expect a simultaneous change in \( \dot{n} \) by greater than 50%, clearly ruled out by our data. Conversely, for the abrupt change of \( \dot{n} \) by a factor of \( \sim 2 \) (near MJD 52,740), we expect a change in \( L_X \) by a factor of \( \sim 5 \), definitely not seen. This appears to pose a significant challenge to fossil disk accretion models for 1E 1048.1−5937.

Two infrared observations taken on MJD 52,324 (Israel et al. 2002) and MJD 52,372 (Wang & Chakrabarty 2002) have shown that the IR counterpart of this source is variable. However, the pulsed X-ray flux at both those epochs was consistent with the quiescent value. Furthermore, even though the X-ray flux has not yet returned to its quiescent value, recent observations show that the source’s proposed IR counterpart is consistent with the fainter of the two previous observations (Durant & van Kerkwijk 2004). This decoupling between the IR and the X-ray flux contrasts with what was observed in AXP 1E 2259.1+586, whose IR flux increased then decayed in concert with the X-ray flux at the time of its 2002 outburst (Kaspi et al. 2003; C. Tam et al. 2004, in preparation). This is puzzling and suggestive of more than one mechanism for producing IR emission in AXPs.

We thank M. Lyutikov, S. Ransom, M. Roberts, C. Thompson, and P. Woods for useful discussions. This work is supported by NSERC Discovery Grant 228738-03, NSERC Steacie Supplement 268264-03, a Canada Foundation for Innovation New Opportunities Grant, FQRNT Team and Centre Grants, and NASA Long-Term Space Astrophysics grant NAG5-8063. V. M. K. is a Canada Research Chair and Steacie Fellow. 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.

REFERENCES

Alpar, M. A. 2001, ApJ, 554, 1245
Baykal, A., & Swank, J. 1996, ApJ, 460, 470
Bildsten, L., et al. 1997, ApJS, 113, 367
Chatterjee, P., Hernquist, L., & Narayan, R. 2000, ApJ, 534, 373
Durant, M., van Kerkwijk, M. H., & Hulleman, F. 2004, in IAU Symp. 218, Young Neutron Stars and Their Environments, ed. F. Camilo & B. M. Gaensler (San Francisco: ASP), 251
Gavriil, F. P., & Kaspi, V. M. 2002, ApJ, 567, 1067
Gavriil, F. P., Kaspi, V. M., & Woods, P. M. 2002, Nature, 419, 142
———. 2004, ApJ, 607, 959
Israel, G. L., et al. 2002, ApJ, 580, L143
Jahoda, K., Swank, J., Stark, M., Strohmayer, T., Zhang, W., & Morgan, E. 1996, Proc. SPIE, 2808, 59
Kaspi, V. M. 2004, in IAU Symp. 218, Young Neutron Stars and Their Environments, ed. F. Camilo & B. M. Gaensler (San Francisco: ASP), 231
Kaspi, V. M., & Gavriil, F. P. 2004, in The Restless High-Energy Universe, ed. E. P. J. van den Heuvel, J. J. M. in ‘t Zand, & R. A. M. J. Wijers (Amsterdam: Elsevier), in press (astro-ph/0402176)