# Long-Term *RXTE* Monitoring of the Anomalous X-ray Pulsar 1E 1048.1–5937

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# ABSTRACT

We report on long-term monitoring of the anomalous X-ray pulsar (AXP) 1E 1048.1–5937 using the Rossi X-ray Timing Explorer. The timing behavior of this pulsar is different from that of other AXPs being monitored with RXTE. In particular, we show that the pulsar shows significant deviations from simple spin-down such that phase-coherent timing has not been possible over time spans longer than a few months. We find that the deviations from simple spin down are not consistent with single "glitch" type events, nor are they consistent with radiative precession. We show that in spite of the rotational irregularities, the pulsar exhibits neither pulse profile changes nor large pulsed flux variations. We discuss the implications of our results for AXP models. We suggest that 1E 1048.1–5937 may be a transition object between the soft gamma-ray repeater and AXP populations, and the AXP most likely to one day undergo an outburst.

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

### 1. Introduction

The nature of anomalous X-ray pulsars (AXPs) has been a mystery since the discovery of the first example some 20 years ago. Although it is clear that they are young neutron

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stars, it is not clear why they are observable: their X-ray emission defies conventional explanations that rely on either accretion or rotation power as the radiation energy source. Although only five AXPs are known, their origin is likely to be of great importance to our understanding of the fate of massive stars and the basic properties of the young neutron star population.

AXP observational properties can be summarized as follows (e.g. Mereghetti & Stella 1995): (i) they have spin periods in the narrow range  $\sim 6-12$  s; (ii) they exhibit regular spin-down on time scales of  $10^3-10^5$  yr; (iii) they show no evidence for Doppler shifts due to binary motion; (iv) they lie in the Galactic plane, implying youth; (v) two appear to be located at the geometric centers of supernova remnants (SNRs), also indicating youth; (vi) all have much softer X-ray spectra than accretion-powered pulsars; (vii) they have no known counterparts at any other energy range, including radio or optical (but see below); and (viii) their X-ray luminosities greatly exceed their inferred spin-down powers, hence rotation power is implausible. For an excellent recent review of these objects, see Mereghetti (1999).

Suggested models for AXPs fall into two broad categories. One model proposes that AXPs are young, isolated, highly magnetized neutron stars or "magnetars" (Duncan & Thompson 1992). In this case, AXP spin-down is due either to magnetic dipole radiation as in radio pulsars, which implies large surface magnetic fields,  $10^{14} - 10^{15}$  G, or it could be due to angular momentum loss from Alfvén wave emission following crust cracking due to stresses caused by an even larger magnetic field (Thompson & Blaes 1998, Thompson et al. 2000, Duncan 2000). Similar fields are inferred independently in the soft gamma repeaters (SGRs) which, aside from their soft gamma-ray outbursts, exhibit AXP-like X-ray pulsations in quiescence (Kulkarni & Frail 1993, Thompson & Duncan 1995, Kouveliotou et al. 1998). In this model, the AXP X-ray luminosities could come from the decay of the large magnetic field (Thompson & Duncan 1996) or from enhanced thermal emission from the young cooling neutron star (Heyl & Hernquist 1997). The magnetar model does not presently explain all AXP properties, however; for example it is unclear why all the observed rotation rates should fall in so narrow a range.

The second model of AXP emission is that they are powered by accretion. Conventionally, accreting material would come from a companion (Mereghetti & Stella 1995), however the absence of Doppler shifts allows only very low mass and compact companions unless all known systems are seen fortuitously face-on (Mereghetti, Israel, & Stella 1998, Wilson et al. 1999). The companion may have been disrupted leaving behind a fossil accretion disk (van Paradijs, Taam, & van den Heuvel 1995, Corbet et al. 1995), although neither scenario is consistent with the apparent youth of these objects. An alternative is that AXPs are neutron stars with accretion disks of material leftover from the supernova explosion (Chatterjee, Hernquist, & Narayan 2000, Alpar 1999, Marsden et al. 2001, Chatterjee & Hernquist 2000). However, very constraining optical observations of one AXP, 1E 2259+586, detect no evidence for any companion, nor evidence for an accretion disk (Hulleman et al. 2000). A recent detection of a possible very faint optical counterpart to the AXP 4U 0142+61 also renders the presence of an accretion disk problematic (Hulleman, van Kerkwijk, & Kulkarni 2000).

One way to distinguish between these classes of models may be through timing observations. In the magnetar model for AXPs, relatively smooth spin-down should be expected, punctuated by occasional abrupt spin-up or spin-down events or "glitches," as well as low-level, long-time-scale deviations from simple spin-down, or "timing noise." Both phenomena are well known among young radio pulsars (e.g. Lyne 1996), although their physical origins in magnetars may be considerably different given the much larger inferred magnetic field. Indeed large amounts of timing noise have been seen in SGRs (e.g. Woods et al. 2000). However no extended spin-up should be seen in the magnetar model. Further, Melatos (1999) suggested that deformation of the neutron star due to a large magnetic field would result in radiative precession, which would manifest itself observationally as a long-term periodicity in timing data.

On the other hand, accretion power is usually associated with much noisier timing behavior, which can be correlated with spectral, luminosity, and pulse morphology changes. In addition, some accreting binary systems undergo extended (~years) episodes of spin-up, although these generally seem to alternate with long intervals of spin-down as well (Bildsten et al. 1997).

Until recently, monitoring of AXPs produced only measured frequencies at individual epochs separated by many months or years. This method of timing is not sensitive to spin irregularities on a wide range of interesting time scales. Such "incoherent" timing can offer no insight into the spin behavior of the source between observations, nor to the abruptness of apparent changes in spin-down rate. For example, although 1E 2259+586 and 1E 1048.1–5937 have the longest recorded timing histories of all AXPs (e.g. Corbet & Mihara 1997, Baykal et al. 1998, Paul et al. 2000), the histories are poorly sampled and observed apparent deviations from simple spin-down have been given very different interpretations (e.g. Melatos 1999, Heyl & Hernquist 1999, Baykal et al. 2000).

Kaspi, Chakrabarty & Steinberger (1999) [hereafter KCS99], making use of the scheduling flexibility of the *Rossi X-ray Timing Explorer*, showed that "phase coherent timing," that is, long-term monitoring that permits absolute pulse numbering between observations (a technique that has been used for radio pulsars for many years), can

successfully be applied to at least two AXPs. This implies that AXPs can be extremely stable rotators: KCS99 showed that for AXPs 1E 2259+586 and RXS J170849.0-400910, deviations from a simple linear spin-down model described the rotational behavior to within a few percent of the pulse period over years. Such stability, together with phase-coherent timing, allowed Kaspi, Lackey, and Chakrabarty (2000) to detect a sudden spin-up event having all the hallmarks of a classical radio pulsar glitch in RXS J170849.0-400910.

Whether such glitches are ubiquitous in AXPs, and how their amplitude distributions and frequencies compare to those well studied in radio pulsars, are unknown. Similarly, whether great rotational stability during glitch-free intervals is common to all AXPs is also unknown, as is the origin of deviations from simple spin-down that have been seen in the long-term timing histories of 1E 2259+586 and 1E 1048.1–5937.

1E 1048.1-5937 is a 6.4 s X-ray pulsar discovered in *Einstein* observations of the Carina nebula (Seward, Charles, & Smale 1986). It has been shown to have a soft X-ray spectrum (e.g. Oosterbroek et al. 1998 and references therein), like other AXPs. It exhibits no evidence for any binary companion, as no Doppler shifts of the pulse period are seen (Mereghetti, Israel, & Stella 1998), and no optical counterpart to a limiting magnitude of  $m_V \sim 20$  has been detected (Mereghetti, Caraveo, & Bignami 1992). Occasional monitoring observations over more than 20 years show that the pulsar is spinning down, though significant deviations from a simple spin-down model have been noted (Mereghetti 1995, Corbet & Mihara 1997, Oosterbroek et al. 1998, Paul et al. 2000, Baykal et al. 2000). The paucity of data thus far has made it impossible to unambiguously identify the origin of the deviations.

Here we report on our monthly Rossi X-Ray Timing Explorer (RXTE) monitoring of 1E 1048.1-5937 in which we have attempted phase-coherent timing like that achieved for 1E 2259+586 and RXS J170849.0-400910. We show that the spin behavior of 1E 1048.1-5937 is qualitatively and quantitatively different from those of the other two AXPs. In particular, in our observations, 1E 1048.1-5937 has exhibited rotation that is much less stable than those of the other AXPs timed as part of our RXTE program. We also show that 1E 1048.1-5937 occasionally suffers rotational anomalies on short time scales that cannot be described by simple spin-down laws, classical glitches, or radiative precession. Further, we use the same RXTE observations to search for pulse profile changes and/or pulsed flux variations, and to check for correlations with timing behavior. We find no such correlations. In §2 we describe our observations, in §3 we describe our analysis procedures and results, and we discuss the implications of our results in §4.

### 2. Observations

The observations we report on were made with RXTE's Proportional Counter Array (PCA; Jahoda et al. 1996). The PCA consists of 5 collimated xenon/methane multianode proportional counter units (PCUs), each having a front propane anti-coincidence layer. The instrument is sensitive to photons in the energy range 2-60 keV from a  $\sim 1^{\circ}$  field of view (FWHM), with a total effective area of approximately  $6500 \text{ cm}^2$ . Observations of 3–6 ks in length of 1E 1048.1–5937 were made on a monthly basis during 1996 November 24–1997 December 13 and 1999 January 23–2000 August 11. In addition, we used a handful of archival observations from 1995 and 1996; these generally had longer integration times than the other data sets. We used the GoodXenonwithPropane data mode, which records the arrival time (1  $\mu$ s resolution) and energy (256 channel resolution) of all unrejected events. Due to the soft spectrum of the object, we only analyzed events from the top xenon layer of each PCU. In the timing analysis, we further restricted the data set by including only those events that fall within an energy range of 2-5.5 keV, as this maximizes the signal-to-noise ratio of the pulsar, given the spectral properties of the source and background. Photon arrival times at each epoch were adjusted to the solar system barycenter and binned at 62.5 ms intervals.

Our monitoring strategy for this source is identical to that for two other AXPs as described in KCS99. At first, each time series was epoch-folded using the best estimate frequency determined initially from either a periodogram or Fourier transform, though later folding was done using an approximate timing ephemeris. Resulting pulse profiles were cross-correlated in the Fourier domain with a high signal-to-noise template created by adding phase-aligned profiles from previous observations. We implemented a Fourier-domain filter by using only the first 6 harmonics in cross-correlation. The cross-correlation produces an average time-of-arrival (TOA) for each observation. The TOAs are then fit to a polynomial using the pulsar timing software package TEMP0.<sup>4</sup> Pulse phase  $\phi$  at any time t can be expressed as a Taylor expansion

$$\phi(t) = \phi(t_0) + \nu(t - t_0) + \frac{1}{2}\dot{\nu}(t - t_0)^2 + \frac{1}{6}\ddot{\nu}(t - t_0)^3 + \frac{1}{24}\ddot{\nu}(t - t_0)^4 + \dots,$$
(1)

where  $\nu \equiv 1/P$  is the pulse frequency, and  $t_0$  is a reference epoch. Unambiguous pulse numbering is made possible by obtaining monitoring observations spaced so that the best-fit model parameters have a small enough uncertainty to allow prediction of the phase of the next observation to within ~ 0.2. Typically this necessitates two closely spaced observations

<sup>&</sup>lt;sup>4</sup>http://pulsar.princeton.edu/tempo

(within a few hours of each other) followed by one spaced a few days later, and regular monthly monitoring thereafter, as long as phase coherence can be maintained.

To minimize use of telescope time, our monitoring data consisted of brief (usually 3 ks) snapshots of the pulsar. These snapshots suffice to measure TOAs to good precision. However, for any one epoch, the period, as determined by Fourier Transform or epoch-folding, had typical uncertainty of  $\sim 3$  ms, which is quite large by normal timing standards. Thus, our snapshot method of measuring TOAs can determine spin parameters with extremely high precision *only when phase coherence can be maintained*. However when this is not possible, little information is available about the timing behavior of the source.

### 3. Results and Analysis

### 3.1. Timing

We maintained unambiguous phase coherence for 1E 1048.1–5937 in our monthly observations from 1999 January 23 through 1999 November 15. We required a fourth-order polynomial to characterize the 17 arrival times. The best-fit  $\nu$ ,  $\dot{\nu}$ ,  $\ddot{\nu}$  and  $\ddot{\nu}$  are listed in Table 1; we call this fit "Coherent 1999." The residuals (the differences between the observed and model-predicted TOAs) are shown in Figure 1 for the case when only  $\nu$ ,  $\dot{\nu}$  and  $\ddot{\nu}$  are fitted; the clear quartic trend shows that the  $\ddot{\nu}$  term is very significant. Following removal of the fourth-order polynomial, the RMS residual is 49 ms, or 0.0075*P*, and the residuals are featureless. These results alone clearly imply that the rotational behavior of 1E 1048.1–5937 is quite different from that of 1E 2259+586 and RXS J170849.0–400910. Those pulsars exhibit much more stable rotation (apart from the one glitch in RXS J170849.0–400910) on comparable and even longer time scales, that is, terms of higher order than  $\dot{\nu}$  are very small or negligible for those pulsars on time scales of over a year. In fact, we show next that 1E 1048.1–5937's rotation during the Coherent 1999 interval was *more stable* than it was during other intervals spanned by our observations.

After the observation of 1E 1048.1–5937 on 1999 November 15, we were unable to maintain phase coherence. The next observation occured on 1999 December 12, 33 days later, and had phase residual 0.5 relative to our Coherent 1999 fit (Table 1). So large a residual makes absolute pulse numbering impossible. Ascribing the entire anomaly to a change in  $\nu$ , this implies a *minimum* change of  $|\Delta\nu/\nu| \simeq 1 \times 10^{-6}$ . This is a lower limit since additional full rotations could not have been detected. The subsequent three observations also could not be phase-connected so we initiated a series of three closely spaced observations in order to reachieve phase lock. These took place starting 2000 April 11. These unambiguously imply that the spin frequency, averaged over the interval 2000 April 11–16 was (0.15498892±0.00000013) Hz, epoch 51650.0. The 2000 April observations and those obtained until the last epoch about which we report (2000 August 11), have probably been properly phase connected; the best-fit spin parameters are given in Table 1. We call this fit "Coherent 2000." It includes only  $\nu$  and  $\dot{\nu}$ . For the 8 TOAs included in the fit, the RMS residual was 198 ms or 0.08*P*, and no significant higher-order derivatives were necessary. The high RMS in this interval suggests our phase-connection may not be correct; if it is incorrect, then these 8 observations in all probability cannot be connected at all, as the solution in Table 1 is by far the best pulse numbering scheme that we are able to find.

The frequency in the Coherent 2000 fit is *smaller* than that predicted by the Coherent 1999 fit extrapolated to the Coherent 2000 epoch, by  $\Delta\nu/\nu = (-1.25 \pm 0.08) \times 10^{-5}$  (assuming the frequency measured using the 2000 April data alone). This change is in the opposite direction to, and much larger than that expected in a classical glitch, like those observed in Vela-like radio pulsars as well as in RXS J170849.0-400910, although it is somewhat smaller than the possible "anti-glitch" observed in SGR 1900+14 (see §4). Furthermore, data from 1999 December through 2000 March (4 TOAs) do not fit with *either* the Coherent 1999 or Coherent 2000 ephemerides. Since those 4 TOAs are each separated by one month, we cannot characterize the pulsar's behavior in that interval. However it is clear that the timing anomaly was not a single classical glitch or even an "anti-glitch," as the data cannot be described by a single, sudden change in frequency. If one wished to characterize the pre-Coherent 2000 event as an anti-glitch, one requires another event of comparable magnitude to have occured just after the Coherent 1999 fit ended.

To investigate whether such behavior has occured in the past, we analyzed archival *RXTE* data obtained in 1995, 1996 and 1997. The spacing of the available observations was unfortunately non-optimal for a phase-coherent analysis. However one interval (1997 January 25 through 1997 May 18) had observation spacings that we believe yield a reliable, phase-coherent ephemeris in spite of potential phase counting errors. This is because, fortunately, *BeppoSax* observed the source on 1997 May 11, and we can use the observed frequency (Oosterbroek et al. 1998) to identify the correct ephemeris by demanding consistency, as only one of the possible solutions agrees. We refer to this fit as "Coherent 1997;" it is presented in Table 1.

Although archival RXTE observations at epochs within ~1 month of the start and end of the range spanned by Coherent 1997 exist, the fit does not predict them well. Thus it seems likely that, as in the behavior we have observed in 1999–2000, the pulsar suffered some sort of timing anomaly just prior to, and just after the Coherent 1997 span. The alternative is that Coherent 1997 suffers from phase counting errors and that the agreement with the *BeppoSax* data is fortuitous, although we think that this is unlikely.

The spacing of the archival *RXTE* data taken after the last epoch spanned by the Coherent 1997 fit again has non-optimal spacing for a phase-coherent analysis. Furthermore, there are no independent observations of 1E 1048.1–5937 during this time that can help discriminate among possible models. However, our attempts at phase-coherent timing show that only one model both characterizes the data well and has  $\dot{\nu} < 0$ . Although it is conceivable that during the short span from 1997 July 17–December 13 the pulsar exhibited  $\dot{\nu} > 0$ , we assume that this is unlikely, given the strong evidence against any spin-up in the 20 yr during which it has been observed. This is admittedly dangerous as one goal of our observations is to find epochs of spin-up; the assumption is therefore an important caveat. We refer to this fit as "Coherent 1997a." The spin parameters for this fit are given in Table 1.

We can compare our pulse ephemerides with measurements of pulse frequency made over the past 20 yr in order to look for long-term trends. Figure 2 shows the resulting spin history of 1E 1048.1–5937 with previously measured spin frequencies plotted as points with their corresponding 1 $\sigma$  error bars. Data were taken from the compilation of Oosterbroek et al. (1998), with added data from Paul et al. (2000) and Baykal et al. (2000). Our timing ephemerides are plotted as lines representing the four separate phase-connected segments (see Table 1). Fits Coherent 1997 and 1999 are shown in pink and are robust. Fit Coherent 1997a and 2000 are shown in blue because of the possibility that they may have pulse misnumberings (see above). In Figure 2, the dotted line represents an extrapolation of the  $\nu$  and  $\dot{\nu}$  from the Coherent 1999 fit. The lower plot shows the same data set with the linear term subtracted off. This magnifies deviations from the simple linear trend. The long-term timing history clearly indicates that determining a braking index will be difficult if not impossible as the long-term deviation from linear spin down is not dominated by a simple  $\ddot{\nu}$ term.

#### 3.2. Pulse Morphology

Many accretion-powered pulsars are known to exhibit significant changes in their average pulse profiles. Such changes can be correlated with the accretion state, and hence accretion torque and timing behavior (Bildsten et al. 1997). Furthermore, X-ray pulse profiles from the SGRs 1806–20 and 1900+14 have shown differences at different epochs depending on time since outburst (Kouveliotou et al. 1998, Kouveliotou et al. 1999). Such pulse profile changes, if they existed for 1E 1048.1–5937, would result in substantial timing anomalies, as our analysis assumes a fixed profile. To test this assumption, we have looked

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for evidence for pulse profile changes in our *RXTE* monitoring data.

Pulse profiles were first phase aligned using the same cross-correlation procedure used for timing. Each profile was scaled, a DC offset added, and the result subtracted from the average profile to yield "profile residuals" for each observation. To evaluate the significance of the difference between the observed and average profile, we calculated a  $\chi^2$  statistic. The resulting  $\chi^2$  values were then compared with their expected distribution given the number of degrees of freedom (N - 4 where N = 64 is the number of phase bins) using a Kolmogorov-Smirnov (KS) test. For 1E 1048.1–5937, the KS test showed that the distribution of  $\chi^2$  values is consistent with having been drawn from a  $\chi^2$  distribution having 60 degrees of freedom. Thus, 1E 1048.1–5937 does not exhibit any significant pulse profile variations, and our assumption of a fixed profile is justified.

# **3.3.** Spectroscopy and Flux

In accreting systems in which the neutron star is undergoing spin-up, changes in torque should be correlated with changes in X-ray flux, since  $\dot{\nu} \equiv N/2\pi I \propto \dot{M}\sqrt{r_m}$ , where N is the torque, I is the moment of inertia,  $\dot{M}$  is the mass accretion rate, and  $r_m$  is the magnetospheric radius. Accretion torque theory predicts that  $r_m \propto \dot{M}^{-2/7}$ , and since X-ray luminosity  $L_x = GM\dot{M}/R$ , where M and R are the neutron star mass and radius, respectively, one expects  $\dot{\nu} \propto \dot{M}^{6/7}$  or  $\dot{\nu} \propto L_x^{6/7}$  (Pringle & Rees 1972, Lamb, Pethick, & Pines 1973). Though this naive prediction does not hold precisely for accreting binaries, in general a strong correlation is seen (Bildsten et al. 1997). For AXPs, because they are spinning down, the above may not hold, however. Chatterjee et al. (2000) suggest that AXPs might be spinning down in the propeller regime due to accretion from a fall-back disk. In that case,  $L_x \propto \dot{M}$  is still likely to hold, along with  $\dot{\nu} \propto \dot{M}r_m^2$  (see, e.g., Menou et al. 1999). Thus, if we take  $r_m \propto \dot{M}^{-2/7}$  as above, then we expect  $L_x \propto \dot{\nu}^{7/3}$ , an even stronger correlation than in the simple spin-up case. Since for 1E 1048.1–5937 we find clear variations in  $\dot{\nu}$ , it is therefore interesting to ask whether there are correlated spectral and/or flux changes.

As pointed out by Baykal et al. (2000), given the large field-of-view of the PCA and that the bright nearby but unrelated source  $\eta$  Carinae exhibited large flux changes over the course of our observations, direct flux measurements of 1E 1048.1–5937 could not be made with our *RXTE* data. Instead, we have determined the pulsed component of the flux, by using off-pulse emission as a background estimator. This renders our analysis insensitive to changes in the fluxes of other sources in the field-of-view. Data from each observing epoch were folded at the expected pulse period as for the timing analysis, except for this portion of the analysis, we used only 8 phase bins. For each phase bin, we maintained resolution of 128 spectral bins over the PCA range. We used the off-pulse interval as our background measurement for this analysis; given the broad morphology of the average pulse profile, only one phase bin could be used. The background phase bin was determined by cross-correlating each (spectrally summed) profile with the average pulse profile. The pulse profiles were then phase aligned, so that the same off-pulse bin was used for background in every case. The remaining 7 phase bins were summed, and their spectral bins regrouped using the FTOOL grppha, such that no bin had fewer than 20 counts after background subtraction. Energies above 10 keV were ignored in our analysis. The regrouped, phase-summed data sets, along with the background measurement, were used as input to the X-ray spectral fitting software package XSPEC<sup>5</sup> (Arnaud 1996). Response matrices were created using the FTOOLs xtefilt and pcarsp.

For the spectral analysis, although Oosterbroek et al. (1998) have shown that the spectrum of 1E 1048.1–5937 demands a two-component model, our limited statistics and hence spectral resolution do not allow a meaningful two-component fit. Therefore we have fit our data with a simple power law. In all fits,  $N_H$  was held fixed at  $1.54 \times 10^{22}$  cm<sup>-2</sup>, the value found by Oosterbroek et al. when they used a simple power-law model. Thus, in our fits, the power-law index and normalization were free to vary. Our fits are largely insensitive to the choice of  $N_H$  since we detect photons with energies greater than 2 keV only.

In order to extract a pulsed flux at each observing epoch, still using XSPEC, we reanalyzed each spectrum, this time holding the photon index fixed at 3.9 (the mean photon index of all our observations – we detected no significant variation in photon index within our ~25% uncertainties in the parameter), as well as holding  $N_H$  fixed at the same value as before. This mean photon index in roughly consistent, within uncertainties, with that found by Oosterbroek et al. (1998) when they attempted a single-component model fit to their *BeppoSAX* data. At each epoch, only the normalization was fit, and the uncertainty determined using the XSPEC command error. Corresponding 2–10 keV pulsed fluxes are plotted in Figure 3. The color coding is identical to that given in Figure 2 and serves to indicate the epochs over which we have phase-coherent timing solutions, and, more importantly, where those epochs begin and end. In particular, black points could not be phase connected. It is clear that there are no significant changes in pulsed flux associated with the epochs beginning and ending periods over which we could phase connect.

In fact, we do not find evidence for any large variability in the pulsed flux. The mean

<sup>&</sup>lt;sup>5</sup>http://xspec.gsfc.nasa.gov

2–10 keV pulsed flux value is  $(6.73 \pm 0.24) \times 10^{-12}$  erg cm<sup>-2</sup> s<sup>-1</sup>, the RMS flux value is  $2.1 \times 10^{-12}$  erg cm<sup>-2</sup> s<sup>-1</sup> and the  $\chi^2$  value for deviations from the mean is 1.3 for 50 degrees of freedom. This  $\chi^2$  strictly speaking does suggest some low-level variability; longer individual observations are clearly necessary to verify this is the case. However, as we discuss below (§4.2.2), the pulsed flux is certainly much more stable than previous analyses have suggested (Oosterbroek et al. 1998).

Note that our method results in fluxes that cannot be directly compared with those made with instruments having higher spectral resolution, as we have assumed an incorrect spectral model. The same is implied by our use of one phase bin for background, since imaging instruments can use nearby blank fields for their background estimate, and it is possible that some pulsar emission contaminates the off-pulse bin. Though our results may be systematically different from those obtained with other instruments, the systematic shift should be constant for all our *RXTE* observations, implying that our pulsed flux time series can be safely used to monitor the source's pulsed flux variations.

Finally we note that the observed absence of spectral variations in  $1E \, 1048.1 - 5937$ is consistent with the observed absence of pulse morphology variations  $(\S3.2)$ , because the pulse profile shows no energy dependence. This was verified by creating separate time series in the energy ranges 2-5 and 5-8 keV, and folding each with the same ephemeris, using the full 64 phase bins. The resulting profiles were scaled and had their DC level adjusted for comparison. The result is shown in Figure 4, where it is clear that both profiles have the same morphology to within the uncertainties. This is in contrast to what has been suggested for other AXPs (Iwasawa, Koyama, & Halpern 1992, Corbet et al. 1995, White et al. 1996, Sugizaki et al. 1997), and to what we find from our RXTE observations of other AXPs (Gavriil & Kaspi in preparation). The absence of significant pulse profile changes with energy in 1E 1048.1-5937 (see Fig. 4), even between energy ranges in which thermal and non-thermal emission dominate, suggests that the two mechanisms are related, or that the decomposition into two distinct components is misleading. This latter point is in contrast to what is seen in rotation-powered pulsars, in which the thermal component arises from cooling and results in a broad sinusoidal pulse, while the non-thermal component is powered by the spin-down luminosity and typically has a narrow pulse (e.g. Strickman, Harding, & de Jager 1999).

#### 4. Discussion

# 4.1. Comparison of the Timing Properties of 1E 1048.1–5937 with Those of Other Sources

The timing behavior of 1E 1048.1–5937 is different from that observed in the two other AXPs for which phase-coherent timing results have been reported, namely 1E 2259+586 and RXS J170849.0–400910 (KCS99, Kaspi, Lackey, & Chakrabarty 2000). 1E 1048.1–5937 has exhibited far noisier behavior on time scales of weeks to months, to the point that phase-coherent timing using monthly monitoring observations is in general not practical. Denser sampling would certainly help.

Even at its most stable, 1E 1048.1-5937 is much less stable a rotator than other AXPs. One method that has been used to characterize timing noise in radio pulsars is the  $\Delta_8$  statistic (Arzoumanian et al. 1994), where  $\Delta_8 \equiv \log(|\ddot{\nu}|t^3/6\nu)$ , for  $t = 10^8$  s. Although not a perfect characterization of stability, since it only accounts for the phase deviation due to the second derivative as measured over a single, specified time interval, Arzoumanian et al. found that  $\Delta_8 = 6.6 + 0.6 \log \dot{P}$  provided a reasonable description of their radio pulsar sample, with scatter about the relation of approximately unity. In that study,  $t = 10^8$  s was chosen for consistency among sources, since  $\ddot{\nu}$  changes with time for random processes like the phase and/or frequency wanderings seen in radio pulsars. Measuring  $\ddot{\nu}$  for  $t < 10^8$  s should, if anything, underestimate the true value of  $\Delta_8$ .

For 1E 1048.1–5937, the longest phase-coherent stretch we have is that described by the "Coherent 1999" fit (see §3.1), which spans only ~300 days, much less than  $10^8$  s. Nevertheless, for this span  $\Delta_8 = 3.8$ , while the Arzoumanian et al. relation predicts 0.2. This clearly implies much larger timing noise in 1E 1048.1–5937 than is ever seen in the radio pulsar population. For comparison, the  $\Delta_8$  values for the AXPs 1E 2259+586 and RXS J170849.0–400910 are consistent with those of the radio pulsar population (KCS99), although the glitch in the latter must be accounted for.

As discussed in §3.1, single glitches in 1E 1048.1–5937 cannot explain our timing results because there exist data, for example, in the interval between the Coherent 1999 and 2000 spans that do not fit with either ephemeris. This requires that two substantial glitches have occured within three months. Although such frequent glitching has been seen in the radio pulsar population (e.g. in PSR B1737–30; Shemar & Lyne 1996), such closely spaced glitches always have very different amplitudes, with one typically an order of magnitude smaller than the other. This is presumably because it takes time to build up a sufficient angular velocity differential between crust and superfluid for there to be stresses on vortex lines that are large enough for a major glitch to occur. For 1E 1048.1–5937, both glitches would have had to have been large, and, as noted in §3.1, must have been "anti-glitches," ie sudden spin-down events.

Large deviations from simple spin down have been reported for SGRs 1806-20 and 1900+14. SGR 1806-20 was timed phase-coherently over a 178-day span, and showed considerable instability that was characterized by a  $\Delta_8$  value much greater than that of radio pulsars, and comparable though somewhat larger than that seen for 1E 1048.1–5937 (Woods et al. 2000). As for SGR 1900+14, it exhibited interesting timing behavior following a major outburst that occured on 1998 August 27 (Marsden, Rothschild, & Lingenfelter 1999, Woods et al. 2001). Because of sparse sampling after the burst, it was not possible to distinguish between two scenarios: (i) that the SGR suffered a major  $(\Delta \nu / \nu \simeq 10^{-4})$  anti-glitch near or after the outburst, or (ii) that following and not necessarily directly associated with the outburst, it underwent a prolongued period of enhanced spin-down, with spin-down rate a factor of  $\sim 2.3$  higher than the pre-burst rate. The timing behavior of 1E 1048.1-5937 is reminiscent of that of SGR 1900+14, as both sources have shown substantial changes in spin-down rate, though the more frequent monitoring of 1E 1048.1–5937 has allowed us to rule out a single large anti-glitch model. However, the pulsed flux time series (Fig. 3) of 1E 1048.1-5937 clearly shows that it exhibited no outbursts or even enhanced pulsed flux at any time that could be associated with its timing anomalies. (We note that the pulsed fraction of SGR 1900+14 did not change pre- and post- burst (Woods et al. 1999), therefore comparing its flux with the pulsed component for  $1 \ge 1048.1 - 5937$  is reasonable.) Furthermore, it has not shown any pulse profile variations over the course of our observations, while a substantial change in the X-ray light curve for SGR 1900+14 was observed at the time of the outburst (Kouveliotou et al. 1999, Woods et al. 2001).

### 4.2. The Magnetar Model

# 4.2.1. Timing

Mechanisms that have been invoked to explain the timing behavior of SGR 1900+14 under the magnetar hypothesis, if they are to explain 1E 1048.1-5937 as well, must account for the differences in the behavior of the two sources. A large "anti-glitch," a coupling between different components of the differentially rotating magnetar via vortex line unpinning, has been discussed to explain the event if it was sudden. However, the glitch trigger was most likely the large August 27 ouburst (Thompson et al. 2000). Therefore this mechanism cannot explain the behavior of 1E 1048.1-5937. Furthermore, as discussed above, no single glitch can describe the 1E 1048.1-5937 data, and no SGR has been seen to undergo two major outbursts in so short a time span. Another model for the timing anomaly seen in SGR 1900+14 is that braking over a prolongued interval was driven by particle outflow following a major, large-scale crust fracture (Thompson et al. 2000). However, this also demands a burst have occured, so does not appear applicable to 1E 1048.1–5937. Thompson & Blaes (1998) have shown that persistent seismic activity will accelerate the spin down of a neutron star that is rotating slowly and has a large magnetic field. Such seismic activity, which generates Alfvén waves in the magnetosphere, could be driven by small-scale crustal fractures, and variations in the rate of these fractures could explain variations in spin-down during outburst-free epochs (Thompson et al. 2000). It remains to be seen whether the variations in the spin-down rate of 1E 1048.1–5937, which are very likely *larger* than those seen in the SGR, can be explained in this model. Duncan (2000) has proposed that pure shear oscillations, which manifest themselves as toroidal modes, could cause angular momentum loss following crustal twisting fractures that need not produce observable X-ray bursts if the bulk of the released energy were in the deep crust. He argues that the deviations from simple spin-down seen in the long-term history of AXP 1E 2259+586 can be accounted for in this scenario. If so, then perhaps those of 1E 1048.1–5937, though larger, can be as well.

Radiative precession, previously suggested to be the cause of the long-term spin-down variations for 1E 1048.1–5937 (Melatos 1999), appears to be ruled out by the now obvious non-periodic nature of the frequency variations we have observed (Fig. 2). Indeed this model was already at odds with the timing data for AXP 1E 2259+586 (KCS99), and continued monitoring of the latter has only strengthened this conclusion (work in preparation). Radiative precession was predicted to occur for neutron stars with magnetar-like magnetic fields, in which rotation is like a rigid body. However, such precession is likely to be damped quickly because of the presence of superfluid and vortex pinning in the neutron star interior (see Kaspi, Lackey, & Chakrabarty 2000 and references therein). Thus, the absence of radiative precession is not inconsistent with the magnetar model.

# 4.2.2. Variability

Our data (§3.3, Fig. 3) provide evidence, for the first time using a single instrument and analysis procedure, that the pulsed flux of 1E 1048.1–5937 is relatively stable on time scales ranging from days to years, although we did find marginal evidence for low-level (< 25%) variability.

Previously, Oosterbroek et al. (1998) compiled flux data from a variety of different X-ray instruments that observed 1E 1048.1–5937. That compilation suggested that the pulsar shows variability by over a factor of  $\sim 5$  on time scales of a few years, although the exact factor is difficult to determine from their plot because of the absence of uncertainty

estimates. The reality of those flux changes is not supported by our results. Given that the various instruments have different spectral responses which could result in inconsistent flux measurements if an erroneous spectral model is used, it is perhaps not surprising that they find much greater scatter than our data suggest exist. One caveat is that we measure pulsed flux, while they report flux, so the results could be reconciled if the pulsed fraction is variable. However the pulsed fraction would have to be highly anti-correlated with the phase-averaged flux in order to exactly cancel out variations in the pulsed flux.

Baykal & Swank (1996) found evidence for flux variations by factor of up to  $\sim 5$  in 1E 2259+586 over the course of 20 years, albeit also using data from many different instruments, as in the Oosterbroek et al. compilation. Baykal et al. (2000) have also reported a complete absence of flux variations in this same source as measured with *RXTE* over  $\sim 800$  days. They note that the steady flux coincides with epochs over which the pulsar's timing has also been stable (KCS99) and suggest that this is not a coincidence. Our results for 1E 1048.1–5937 demonstrate that the pulsed flux can be stable even in the presence of significant torque variations, and also raise doubt about the reliability of comparing fluxes made with different instruments.

### 4.3. Accretion Models

Most of the known accreting pulsars are in high-mass X-ray binaries with massive companions. Given the absence of a luminous optical counterpart in the AXPs including 1E 1048.1–5937, comparison to the low-mass X-ray binary pulsars is more appropriate. There are only five known members of this class. One of them, the 7.7 s accreting pulsar 4U 1626–67, shares many properties with the AXPs: its pulse period falls in the same range, it shows no detectable Doppler shifts, it underwent steady spin-down for years, and its X-ray luminosity is steady for years at a time (Chakrabarty et al. 1997). However, 4U 1626–67 has a known optical/UV counterpart (a 42-min binary period has been inferred) and underwent an abrupt torque reversal accompanied by a substantial change in X-ray spectrum (Chakrabarty et al. 1997). Neither before nor after the torque reversal was the spectrum of 4U 1626–67 as soft as AXP spectra (Angelini et al. 1995).

Nevertheless, it is of interest to compare the timing noise properties of 1E 1048.1-5937 with those of 4U 1626-67. We computed a power spectrum of the detrended (i.e. with  $\nu, \dot{\nu}$ , and  $\ddot{\nu}$  removed) phase residuals from the Coherent 1999 data using a Lomb-Scargle periodogram (Press et al. 1992). We quote torque noise strength in terms of fluctuation power in pulse frequency derivative  $P_{\dot{\nu}}$  (see, e.g., Boynton 1980). Although our pulse phase measurements did not span a sufficient time baseline to obtain a reliable measure of the

frequency dependence of the underlying noise process, it was possible to constrain the noise strength over the observed time scales. At frequencies in the range  $4 \times 10^{-8} < f < 2 \times 10^{-7}$  Hz (i.e., time scales of 2–10 months), the power spectrum of fluctuations in pulse frequency derivative  $\dot{\nu}$  has a continuum strength in the range  $(4-20)\times10^{-22}$  Hz<sup>2</sup> s<sup>-2</sup> Hz<sup>-1</sup>. This is much weaker than the level observed in the persistent accreting pulsars (Bildsten et al. 1997) with the exception of 4U 1626–67, which has  $P_{\dot{\nu}} \simeq 4 \times 10^{-22}$  Hz<sup>2</sup> s<sup>-2</sup> Hz<sup>-1</sup> Chakrabarty et al. 1997). We note that recent work on the high-mass X-ray binary 4U 1907+09 shows that it too is a comparably stable rotator (Baykal et al. 2001). Given that in the Coherent 1999 interval 1E 1048.1–5937 was at its most stable, we conclude that the timing observations alone cannot rule out an accreting binary scenario for this AXP. Still, we regard the case for 1E 1048.1–5937 as an accreting binary, even with a very low-mass companion, as weak, given the other evidence against this hypothesis, namely, the very different spectrum, and the absence of pulsed flux or pulse morphology changes correlated with the timing behavior, and the steady spin-down over some 20 yr.

It is more difficult to dismiss the possibility that  $1E \ 1048.1-5937$  is accreting from a "fallback" disk comprising material left over from the supernova explosion, since there is not yet a consensus on the properties such a disk would have or on the expected timing and variability properties of the pulsar. However, one definite expectation is that such a disk would be a significant emitter in the optical and infrared, especially given the absence of a binary companion to cause tidal truncation of the disk's outer edge. The present limits on optical/IR emission from  $1E \ 1048.1-5937$  (Mereghetti, Caraveo, & Bignami 1992) already provide an interesting constraint. Future optical/IR observations following a more precise localization using the *Chandra X-ray Observatory* should conclusively test the fallback disk model.

# 4.4. 1E 1048.1–5937: An AXP – SGR transition object?

The timing behavior of 1E 1048.1–5937 appears to be different from that of other AXPs on a variety of time scales. While that of 1E 2259+586 also shows significant deviations from a simple spin-down model, this pulsar has also shown tremendous stability on time scales of several years, a characteristic which 1E 1048.1–5937 has shown no evidence of possessing.

Inspection of some of the overall properties of AXPs reveals that 1E 1048.1-5937 is unusual in other respects as well. Table 2 presents a compilation of spectral parameters and pulsed fractions for the known AXP population (a similar compilation was presented by Mereghetti 1999). From the Table it is clear that 1E 1048.1-5937 has the lowest photon index of any AXP (implying its non-thermal component is the hardest) and the highest effective temperature (implying its thermal component is the hottest). Further, it shows the highest ratio of blackbody to total flux (once energy band is accounted for), and the largest pulsed fraction.

As discussed above, the timing instabilities of 1E 1048.1–5937 are at least qualitatively reminiscent of those seen for SGRs (e.g. Marsden, Rothschild, & Lingenfelter 1999, Woods et al. 2000, Woods et al. 2001). We note that the harder spectrum of 1E 1048.1–5937 as characterized by its small photon index (Table 2) is in fact the closest of any AXP's to those measured in the X-ray band for SGRs 1806–20 and 1900+14. For those sources, measured photon indexes are 2.2 in quiescence for SGR 1806–20 (Sonobe et al. 1994) and 1.1 pre-burst and 1.8 post-burst for SGR 1900+14 (Woods et al. 2001), respectively. Further, the thermal component of 1E 1048.1–5937's spectrum has a high temperature (0.64 keV, Table 2) comparable to that seen for SGR 1900+14 post-burst, 0.62 keV (Woods et al. 2001). The pulsed fraction of SGR 1900+14, however, only ~11% (Woods et al. 1999), is considerably lower than for 1E 1048.1–5937.

These similarities suggest that 1E 1048.1-5937 may be a transition object between the AXP and SGR populations. We note that an AXP-like photon index recently measured for the quiescent counterpart to SGR 0525-66 is steeper than those of the other SGRs, and indeed is similar to those of the AXPs, providing independent evidence for overlap of the two populations (Kulkarni et al. 2000). Thus, we suggest that 1E 1048.1-5937 is the AXP that is the most likely to one day exhibit SGR-like outbursts. Continued *RXTE* monitoring of 1E 1048.1-5937 will easily detect such events; without such an obvious signature, however, only more closely spaced monitoring observations can determine the nature of the timing irregularities exhibited by this "anomalous" anomalous X-ray pulsar.

# 5. Conclusions

Long-term RXTE monitoring of the AXP 1E 1048.1–5937 has shown it to be a noisier rotator than the other AXPs monitored by RXTE (KCS99). Indeed, phase-coherent timing over spans longer than a few months has not been possible for 1E 1048.1–5937. Furthermore, we have observed deviations from simple spin-down that are inconsistent with a single glitch event, and inconsistent with being quasi-periodic as predicted for radiative precession. Only denser sampling will help determine the nature of the spin-down irregularities in this source. Our RXTE observations also show that the pulsar has exhibited no pulse profile variations nor large pulsed flux variations. The latter is inconsistent with the simplest predictions of accretion theory, although deep optical/IR upper limits are the best hope for conclusively ruling out an accretion origin of the X-ray emission. We note that the spin and spectral properties of 1E 1048.1–5937 are, among AXPs, the most reminiscent of the SGRs. We therefore suggest that this pulsar may be a transition object between the two populations, and the AXP most likely to one day undergo an outburst.

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Table 1. Spin Parameters for  $1E \ 1048.1 - 5937$ .

	Coherent 1997	Coherent 1997a	Coherent 1999	Coherent 2000
Dates First observing epoch (MJD) Last observing epoch (MJD)	$1997 \; \mathrm{Jan-May} \\ 50473 \\ 50586$	1997 Jul – Dec 50646 50795	1999 Jan – Nov 51201 51497	2000 Apr – Aug 51645 51767
Total number of observations	11	10	17	8
$\nu$ (Hz)	0.155033822(3)	0.155028540(3)	0.1550076627(13)	0.154988861(13)
$\dot{\nu}$ ( $10^{-13} \text{ Hz s}^{-1}$ )	-2.054(12)	-3.328(12)	-5.5404(18)	-9.15(3)
$\ddot{\nu}$ ( $10^{-21} \text{ Hz s}^{-2}$ )	-	-	-6.18(10)	-
$\ddot{\nu}$ ( $10^{-28}~{\rm Hz}~{\rm s}^{-3})$	-	-	-1.9(2)	-
Epoch of $\nu$ (MJD)	50515.0	50730.0	51299.4	51650.0
RMS residual (ms)	93	156	49	198

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Table 2. Properties of Known Anomalous X-ray Pulsars<sup>a</sup>

NAME	$kT \ (keV)^{b}$	$\Gamma^{c}$	$L_{BB}/L_{tot}^{\rm d}$	Pulsed Fraction <sup>e</sup>	Refs.
4U 0142+61 <b>1E 1048.1–5937</b> 1E 1841–045 RXS J170849.0–400910	0.34-0.44 $0.64 \pm 0.01$  $0.41 \pm 0.03$	$\begin{array}{c} 3.4 - 4.2 \\ 2.52 \pm 0.20 \\ 3.4 \pm 0.3 \\ 2.9 \pm 0.3 \end{array}$	0.2–0.38 (0.5–10 keV) 0.55 (2–10 keV)  0.17 (0.8–10 keV)	$\begin{array}{c} 13\% \ (410 \ \mathrm{keV}) \\ 70\% \ (0.510 \ \mathrm{keV}) \\ \sim 15\% \ (110 \ \mathrm{keV}) \\ \sim 50\% \ (410 \ \mathrm{keV}) \end{array}$	1, 2 $3$ $4, 5$ $6$

 $^{\rm a}{\rm The}$  AXP candidate AX J1845.0–0300 (Torii et al. 1998, Gotthelf & Vasisht 1998) is omitted pending confirmation.

<sup>b</sup>Equivalent black-body temperature.

<sup>c</sup>Power-law photon index.

<sup>d</sup>Fraction of total luminosity in the black-body component.

<sup>e</sup>The given pulsed fractions have been estimated using a consistent definition so may differ from the originally reported value – see Pivovaroff, Kaspi & Camilo (2000).

References. — (1) White et al. 1996; (2) Israel et al. 1999; (3) Oosterbroek et al. 1998; (4) Gotthelf & Vasisht 1997; (5) Vasisht & Gotthelf 1997; (6) Sugizaki et al. 1997; (7) Corbet et al. 1995; (8) Rho & Petre 1997; (9) Parmar et al. 1998

Note. — All spectral parameters quoted are from two-component fits as reported in the given references, unless only a single component fit was done. Uncertainties are as quoted in the references. Where different observations conflicted (e.g. for  $4U\ 0142+61$ ), a range is given.



Fig. 1.— Arrival time residuals for 1E 1048.1–5937 during 1999 with  $\nu$ ,  $\dot{\nu}$  and  $\ddot{\nu}$  removed. The remaining quartic trend is clear; once it is fitted out by incorporating  $\ddot{\nu}$ , the residuals are trendless and consistent with zero within the uncertainties.



Fig. 2.— Spin history for 1E 1048.1–5937. The points represent past measurements of the frequency of the pulsar (see Oosterbroek et al. 1998 and references therein, Paul et al. 2000 and Baykal et al. 2000). The solid lines represent the phase-connected intervals as reported in this paper (see Table 1). Panel A shows the observed frequencies over time. The dotted line is the extrapolation of the  $\nu$  and  $\dot{\nu}$  of the Coherent 1999 fit (Table 1). Panel B shows the difference between the ephemeris indicated by the dotted line and the data points. In both panels, the pink curves indicate the timing behavior during intervals for which we have reliable phase-coherent ephemerides, while the blue curve indicates a phase-coherent ephemeris that may have pulse misnumberings (see §3.1 and Table 1).



Fig. 3.— Pulsed flux time series in the 2–10 keV band for RXTE observations of 1E 1048.1–5937. The color coding is identical to that in Figure 2. See §3.3 for details of the analysis procedure.



Fig. 4.— Average pulse profiles of 1E 1048.1–5937 in two energy bands as observed by RXTE.