

Differences between the two anomalous X-ray pulsars: variations in the spin-down rate of 1E 1048.1–5937 and an extended interval of quiet spin-down in 1E 2259+586

Altan Baykal,^{1★} Tod Strohmayer,² Jean Swank,² M. Ali Alpar³ and Michael J. Stark⁴

¹Physics Department, Middle East Technical University, Ankara 06531, Turkey

²Laboratory for High Energy Astrophysics NASA/GSFC Greenbelt, MD 20771, USA

³Department of Physics, Sabanci University, Istanbul, Turkey

⁴Department of Physics and Astronomy, Denison University, Granville, OH 43023, USA

Accepted 2000 June 29. Received 2000 June 12; in original form 1999 June 16

ABSTRACT

We analysed the *Rossi X-ray Timing Explorer* (*RXTE*) archival data of 1E 1048.1–5937 covering a time-span of more than one year. The spin-down rate of this source decreases by ~ 30 per cent during the observation. We could not resolve the X-ray flux variations because of contamination by eta Carinae. We find that the level of pulse frequency fluctuations of 1E 1048.1–5937 is consistent with typical noise levels of accretion-powered pulsars. Recent *RXTE* observations of 1E 2259+586 have shown a constant spin-down with a very low upper limit on timing noise. We used the *RXTE* archival X-ray observations of 1E 2259+586 to show that the intrinsic X-ray luminosity times-series is also stable, with an rms fractional variation of less than 15 per cent. The source could have been in a quiet phase of accretion with a constant X-ray luminosity and spin-down rate.

Key words: accretion, accretion discs – binaries: general – stars: individual: 1E 1048.1–5937 – stars: individual: 1E 2259+586 – stars: low-mass, brown dwarfs.

1 INTRODUCTION

The two sources considered in this paper belong to a small group of X-ray pulsars which are called anomalous X-ray pulsars (hereafter AXPs), with periods in the ~ 5 –12 s range. This narrow pulse period distribution of the AXPs, is significantly different from that of high-mass X-ray binaries (HMXRBs) where the pulse periods span a range from 69 ms to 25 min. Their X-ray spectra have steep power-law indices ~ 3 –4 in addition to soft blackbody components with $kT \sim 0.5$ keV in some of the sources (Stella, Israel & Mereghetti 1998). They lack observed optical counterparts. Their X-ray luminosities are at the order of 10^{35} – 10^{36} erg s⁻¹ and spin-down rates are relatively constant.

The first proposed model for AXPs was accretion from low-mass X-ray companions at lower accretion rates ($L_x = GMM/R \sim 1 \times 10^{35}$ erg s⁻¹) with magnetic fields of $B \sim 10^{11}$ G (Mereghetti & Stella 1995). In this scenario, the observed pulse periods of AXPs can be explained as rotation periods of neutron stars close to the equilibrium periods for accretion from a disc. However, orbital signatures such as periodic delays in pulse arrival times or periodic flux changes have not been observed in the AXPs. This has led several researchers to alternative interpretations based on the single pulsar hypothesis. Corbet et al. (1995)

suggested the possibility of accretion from a molecular cloud. Alternatively, AXPs could be isolated stars that are accreting from a disc formed as remnants of the common envelope evolution of HMXRBs (van Paradijs, Taam & van den Heuvel 1995; Ghosh, Angelini & White 1997). On the other hand Thompson & Duncan (1993) proposed that these sources are highly magnetized ($\sim 10^{14}$ – 10^{15} G) isolated neutron stars (magnetars) which are slowing down owing to electromagnetic dipole radiation. According to the magnetar theory there should be several unseen very large glitches in pulse period histories of 1E 1048.1–5937 and 1E 2259+586 (Heyl & Hernquist 1999). These glitches should be at least a factor of hundred larger than the radio pulsar glitches in $\delta\nu/\nu$ (Thompson & Duncan 1996; Heyl & Hernquist 1999).

1E 1048.1–5937 was discovered by the *Einstein* satellite during the observations of the Carina nebula (Seward, Charles & Smale 1986). 1E 2259+586 is located at the centre of the radio/X-ray supernova remnant G109.1–1.0 (Fahlman & Gregory 1981). Both sources lack bright optical counterparts (Mereghetti, Caraveo & Bignami 1992; Coe & Jones 1992). If they are binary systems, their companion stars should be either white dwarfs or helium-burning stars with $M < 0.8 M_\odot$ (Mereghetti, Israel & Stella 1998; Baykal et al. 1998).

The torque changes of 1E 1048.1–5937 and 1E 2259+586 were studied by Mereghetti (1995), Corbet & Mihara (1997) and

★ E-mail: altan@astro.physics.metu.edu.tr

Baykal & Swank (1996). Both sources showed pulse frequency changes which can support the accretion hypothesis. In this work, we present two new pulse frequency measurements from long observations in the archival *RXTE* data base. In the ~ 400 d time-span of the observation, we found the spin-down rate of 1E 1048.1–5937 to change by 30 per cent. Recent pulse timing analysis of 1E 2259+586 (Kaspi, Chakrabarty & Steinberger 1999) has shown that the source had constant spin-down over a 2.6-yr time span, with very low timing noise. We extracted archival data of 1E 2259+586 and constructed a bolometric X-ray luminosity time-series. We found that the X-ray luminosity is almost constant while the spin-down rate is constant (Kaspi et al. 1999).

2 DATA ANALYSIS

The archival observations of 1E 1048.1–5937 and 1E 2259+586 are listed in Table 1. The results presented here are based on data collected with the Proportional Counter Array (PCA, Jahoda et al. 1996). The PCA instrument consists of an array of five proportional counters operating in the 2–60 keV energy range, with a total effective area of approximately 7000 cm² and a field of view of $\sim 1^\circ$ FWHM.

Background light curves and the pulse height amplitudes were generated using the background estimator models based on the

Table 1. *RXTE* observations of 1E 1048.1–5937 and 1E 2259+586.

Time of Observation mm/dd/yy	Exposure s
Source Name	1E 1048.1–5937
29/07/96–31/07/96	62 586
08/03/97	21 165
08/10/97–09/10/97	14 971
Source Name	1E 2259+586
29/09/96–01/10/96	74 758
25/12/96	928
25/01/97	1004
22/02/97	1076
25/02/97–26/03/97	100 237
18/04/97	727
10/05/97	988
18/06/97	922
17/07/97	847
12/08/97	729
19/09/97	1038
16/10/97	832
14/11/97	884
13/08/98–02/12/98	121 833

rate of very large events (VLE), spacecraft activation and cosmic X-ray emission with the standard PCA analysis tools (FTOOLS) and were subtracted from the source light curve obtained from the first ‘good xenon’ layer of event data. The background subtracted light curves were corrected with respect to the barycentre of the solar system. From the long archival data string, pulse periods for 1E 1048.1–5937 were found by folding the time-series on statistically independent trial periods (Leahy et al. 1983). Master pulses were constructed from these observations by folding the data on the period giving the maximum χ^2 . The master pulses were arranged in 55 phase bins and represented by their Fourier harmonics (Deeter & Boynton 1985) and cross-correlated with the harmonic representation of average pulse profiles from each observation. The pulse arrival times are obtained from the cross-correlation analysis. The linear trend of pulse arrival times is a direct measure of the pulse frequency during the observation,

$$\delta\phi = \phi_o + \delta\nu(t - t_o) \quad (1)$$

where $\delta\phi$ is the pulse phase offset deduced from the pulse timing analysis, t_o is the mid-time of the observation, ϕ_o is the phase offset at t_o , $\delta\nu$ is the deviation from the mean pulse frequency (or additive correction to the pulse frequency). The pulse period measurements of 1E 1048.1–5937 from archival *RXTE* observations are presented in Table 2.

During the *RXTE* observations the pulse frequency derivative of 1E 1048.1–5937 decreased approximately by 30 per cent (see Table 2). However these changes cannot be correlated with X-ray flux changes since eta Carinae lies 45 arcmin away from 1E 1048.1–5937. The strong flux changes of eta Carinae (Corcoran et al. 1997) contaminate the FOV of 1E 1048.1–5937 since the FWHM of *RXTE*/PCA $\sim 1^\circ$. It should also be pointed out that in the archival *RXTE* observations, there are found short, ~ 2000 s, observations separated by months; owing to the pulse frequency derivative changes we have not phase connected them in order to avoid any cycle count ambiguity. Similarly, two successive *Ginga* observations of 1E 1048.1–5937 which were separated by 10 d cannot be combined in phase because of the cycle count ambiguity (Corbet & Day 1990).

Einstein, *EXOSAT* and *Ginga* observations of 1E 1048.1–5937 provided five pulse frequency measurements over 10 yr, which were consistent with a constant spin-down rate of $\dot{\nu} \sim 3.8 \times 10^{-13}$ Hz s⁻¹ (Mereghetti 1995). This is ~ 38 times higher than that of 1E 2259+586 (Baykal et al. 1998). Observations with *ROSAT* in 1992–1993 indicated that the spin-down rate almost doubled from its value in 1988 (Mereghetti 1995). The mean flux decreased by a factor of 3 compared with the value measured with *EXOSAT* in approximately the middle of 1985 (Corbet & Mihara 1997). These variations are consistent with accretion-powered X-ray emission.

Table 2. *RXTE* Pulse Period Measurements of 1E 1048.1–5937.

Epoch(MJD)	Pulse Period (s)	
50294.67	6.449769 ± 0.000004	Mereghetti et al. (1998)
50515.69	6.450198 ± 0.000018	This work
50729.71	6.450486 ± 0.000018	This work
Time Span (MJD)	Derivative of Pulse Frequency Hz s ⁻¹	
50294.67–50729.71	$-(4.74 \pm 0.18) \times 10^{-13}$	
50294.67–50515.69	$-(5.40 \pm 0.38) \times 10^{-13}$	
50515.69–50729.71	$-(3.72 \pm 0.52) \times 10^{-13}$	

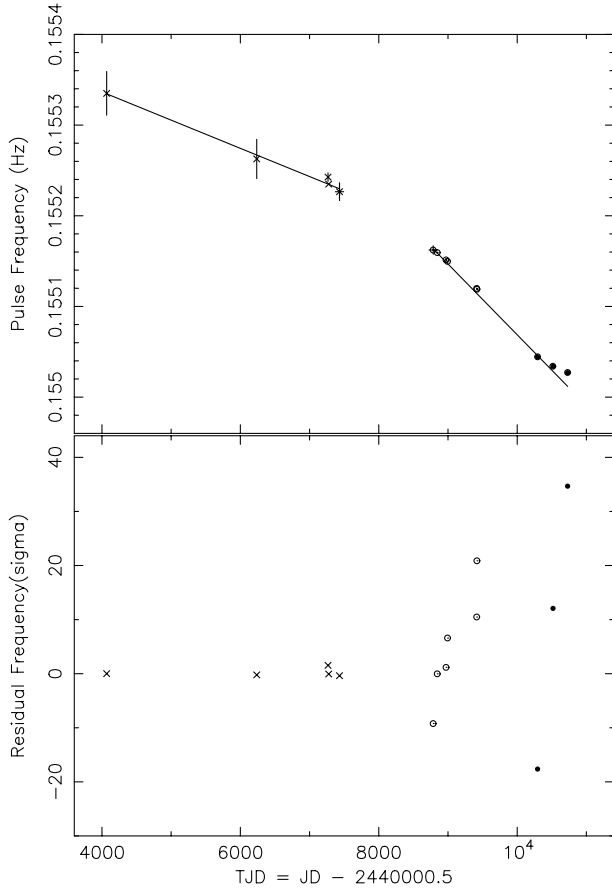


Figure 1. Pulse frequency time-series of 1E 1048.1–5937. The solid lines (upper panel) are fits to the measurements before and after 1988 September, respectively. Residuals from these linear trends are shown in terms of sigma values (lower panel). Measurements with *Einstein*, *EXOSAT* and *Ginga* (x) fit a trend well, while the later measurements with *ROSAT* and *ASCA* (open circles) and *RXTE* (filled circles) fit a trend of higher spin-down, but with well-measured deviations.

In order to deduce the pulse frequency changes of 1E 1048.1–5937, the residuals of pulse frequencies are extracted from their linear trends and the residuals are presented in terms of their sigma values. Fig. 1 (lower) clearly shows that the pulse frequency fluctuations are significant at the order of several σ levels. The residual pulse frequencies between $\sim 48600 - \text{MJD}$ $\sim 50800 - \text{MJD}$ yield a noise strength on the order of $S \approx (2\pi)^2 \langle \delta\nu^2 \rangle / T \approx (2\pi)^2 \langle \delta\phi^2 \rangle / T^3 \sim 10^{-17} \text{ rad}^2 \text{ s}^{-3}$, where $\langle \delta\nu^2 \rangle$ and $\langle \delta\phi^2 \rangle$ are the normalized variances of residual pulse frequencies and pulse arrival times and T is the total time-span (see Cordes 1980 for further definitions of noise strength). This value is comparable with typical accretion powered pulsar noise strength Baykal & Ögelman (1993).

Recent *RXTE* observations of 1E 2259+586 have shown a constant spin-down rate with a low upper limit on timing noise (Kaspi et al. 1999). The residuals of the pulse arrival times gives an upper limit to the noise strength at $T_{\text{observation}} \sim 2.6 \text{ yr}$, $S \approx (2\pi)^2 \langle \delta\phi^2 \rangle / T_{\text{observation}}^3 \sim 10^{-24} \text{ rad}^2 \text{ s}^{-3}$. This value is five decades lower than the value which is deduced from 15 yr of pulse period history of 1E 2259+586 (Baykal & Swank 1996; Baykal & Ögelman 1993) and two orders lower than that of the Crab pulsar (Boynnton et al. 1972) or that of the LMXRB pulsar 4U 1626–67 (Chakrabarty et al. 1997). This upper limit is indeed very low for an accretion-powered X-ray pulsar. If the pulse period changes are as a result of the variations in the accretion process, the X-ray luminosity would be a constant (Ghosh & Lamb 1979). In order to check the variations in its X-ray luminosity, we derived the X-ray luminosities for all observations from the X-ray spectra.

The X-ray background spectrum was calculated using the background estimator models based upon the rate of very large events (VLE), spacecraft activation and cosmic X-ray emission as used to calculate background light curves. The X-ray spectra are fitted with a power-law spectrum with a photon index 4.78 and column density $N_{\text{H}} = (2.2 \pm 0.8) \times 10^{22} \text{ cm}^{-2}$, parameters consistent with those obtained from *ASCA* and *SAX* measurements in the 2–10 keV range (Corbet et al. 1995; Parmar et al. 1998). The resultant background subtracted X-ray luminosity time-series in the energy range 2–10 keV is presented in Fig. 2. The variation in

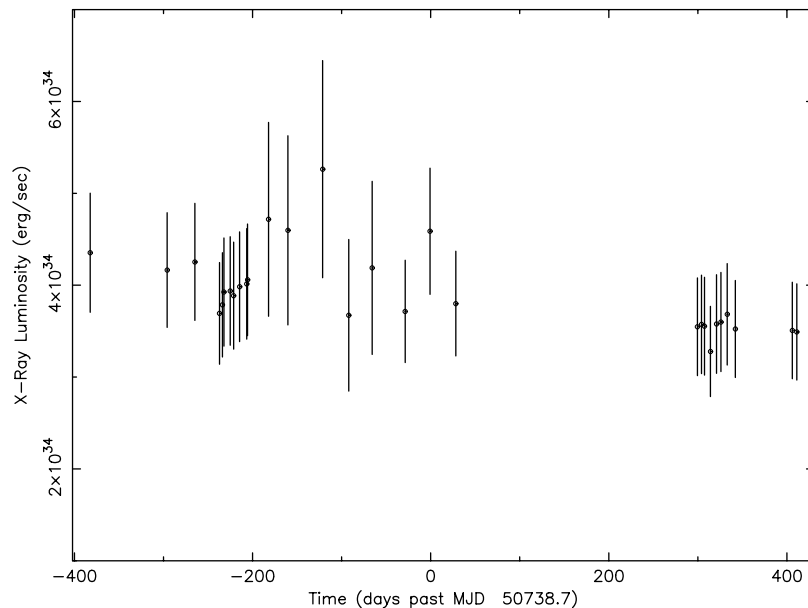


Figure 2. X-ray luminosity time-series of 1E 2259+586.

the bolometric X-ray luminosity is less than 15 per cent. This is consistent with low timing noise and secular spin-down according to accretion models.

In *Ginga* observations 1E 2259+586 had flux levels a factor of two higher than average (Iwasawa, Koyama & Halpern 1992). This implied that, if because of accretion, the rate on to the source was variable and fluctuations in the spin-down rate would be expected. Indeed for this era high noise levels $S \sim 10^{-19} \text{ rad}^2 \text{ s}^{-3}$ are found (Baykal & Swank 1996).

3 DISCUSSION

In the pulse timing analysis of 1E 1048.1–5937, we found pulse frequency changes on the time-scale of 400 d. The source spin-down rate has doubled since 1992 (Mereghetti 1995; Corbet & Mihara 1997). The pulse frequency measurements since 1992 show significant fluctuations from the average spin-down trend. The level of pulse frequency fluctuations of 1E 1048.1–5937 are found to be consistent with typical noise levels of accretion powered pulsars (Baykal & Ögelman 1993).

Two soft gamma-ray repeaters (SGR) SGR 1806–20, SGR 1900+14 were recently identified as magnetars (Kouveliotou et al. 1998, 1999). The similarity of SGR and AXP pulse periods and secular spin-down trends raised the question whether all AXPs are actually magnetars. According to the magnetar theory pulse frequency fluctuations may be caused by processes such as variable emission of Alfvén waves or particles from magnetars (Thompson & Blaes 1998), radiative precession of magnetars (Melatos 1999), or discontinuous spin-up events (glitches) like those seen in radio pulsars (Thompson & Duncan 1996, see also Kaspi, Lackey & Chakrabarty 2000). Heyl & Hernquist (1999) investigated the pulse frequency histories of 1E 1048.1–5937 and 1E 2259+586 and proposed that the irregularities of these sources are explained by several large glitches with sizes $\delta\nu \sim 2 \times 10^{-4} \text{ s}^{-1}$ and $\sim 5 \times 10^{-6} \text{ s}^{-1}$, respectively. While the values of $\delta\nu$ are only about 20 times those of the Vela and Crab pulsars, respectively, the values of $\delta\nu/\nu$ are several orders of magnitude larger than radio pulsar glitches and they occur much more frequently than scaling from the statistics of large radio pulsar glitches would lead us to expect (Alpar & Baykal 1994).

In summary, both sources have shown pulse frequency fluctuations on the order of a few decades (Mereghetti 1995; Baykal & Swank 1996). The level of torque changes of 1E 2259+586 over a time scale of 15 yr is consistent with accretion-powered X-ray binaries (Baykal & Swank 1996). The steady level of the bolometric X-ray luminosity during the quiet spin-down epoch (Kaspi et al. 1999) is consistent with accretion models. Alternatively it may turn out to be made out of discrete glitches over a background of relatively quiet spin-down, as in isolated pulsars and magnetars (Heyl & Hernquist 1999). Continued phase coherent X-ray timing of this source should prove extremely important in finally deciding its nature. The correlation of the spin-down rate of 1E 1048.1–5937 with the X-ray flux supports

the possibility that it is an accreting source (Mereghetti 1995; Corbet & Mihara 1997). Our work indicates that the source has high timing noise. To see the exact nature of correlations between X-ray flux and pulse frequency derivatives, an even more extensive broad band X-ray observation should be carried out.

ACKNOWLEDGMENT

We thank the referee for helpful comments.

REFERENCES

- Alpar M. A., Baykal A., 1994, MNRAS, 269, 849
 Baykal A., Ögelman H., 1993, A&A, 267, 119
 Baykal A., Swank J., 1996, ApJ, 460, 470
 Baykal A., Swank J. H., Strohmayer T., Stark M. J., 1998, 336, 173
 Bildsten L. et al., 1997, ApJS, 113, 367
 Boynton P. E. et al., 1972, ApJ, 175, 217
 Chakrabarty D. et al., 1997, ApJ, 474, 414
 Coe M. J., Jones L. R., 1992, MNRAS, 259, 191
 Corbet R. H. D., Mihara T., 1997, ApJ, 475, L127
 Corbet R. H. D., Day C. S. R., 1990, MNRAS, 259, 191
 Corbet R. H. D., Smale A. P., Ozaki M., Koyama K., Iwasawa K., 1995, ApJ, 443, 786
 Corcoran M. F. et al., 1997, Nat, 390, 587
 Cordes J. M., 1980, ApJ, 237, 216
 Deeter J. E., Boynton P. E., 1985, in Hayakawa S., Nagase F., eds, Proc. Inuyama Workshop on Timing Studies of X-Ray Sources. Univ. Nagoya, Nagoya, p. 29
 Fahlman G. G., Gregory P. C., 1981, Nat, 293, 202
 Ghosh P., Lamb F. K., 1979, ApJ, 232, 259
 Ghosh P., Angelini L., White N. E., 1997, ApJ, 478, 713
 Heyl S. H., Hernquist L., 1999, MNRAS, 304, L37
 Iwasawa K., Koyama K., Halpern J. P., 1992, PASJ, 44, 9
 Jahoda K., Swank J., Giles A. B., Stark M. J., Strohmayer T., Zhang W., 1996, Proc. SPIE, 2808, 59
 Kaspi V. M., Chakrabarty D., Steinberger J., 1999, ApJ, 525, L33
 Kaspi V. M., Lackey J. R., Chakrabarty D., 2000, ApJ, 537, L31
 Kouveliotou C. et al., 1998, Nat, 393, 325
 Kouveliotou C. et al., 1999, ApJ, 510, L115
 Leahy D. A., Darbro W., Elsner R. F., Weisskopf M., Itahn S., Sutherland P. G., Grindlay J. C., 1983, ApJ, 266, 160
 Melatos A., 1999, ApJ, 519, L77
 Mereghetti S., 1995, ApJ, 455, 598
 Mereghetti S., Stella L., 1995, ApJ, 442, L17
 Mereghetti S., Caraveo P., Bignami G. F., 1992, A&A, 263, 172
 Mereghetti S., Israel G. L., Stella L., 1998, MNRAS, 269, 689
 Parmar A. N., Oosterbroek T., Favata F., Pightling S., Coe M., Mereghetti S., Israel G. L., 1998, A&A, 330, 175
 Seward F., Charles P. A., Smale A. P., 1986, ApJ, 305, 814
 Stella L., Israel G. L., Mereghetti S., 1998, Adv. Space Res, 22, 7, 1025
 Thompson C., Blaes O., 1998, Phys. Rev. D, 57, 3219
 Thompson C., Duncan R. C., 1993, ApJ, 408, 194
 Thompson C., Duncan R. C., 1996, ApJ, 473, 322
 van Paradijs J., Taam R. E., van den Heuvel E. P. J., 1995, A&A, 299, L41

This paper has been typeset from a $\text{\TeX}/\text{\LaTeX}$ file prepared by the author.