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 Alpar [3], Michael J. Stark [4]

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

[2] Laboratory for High Energy Astrophysics NASA/GSFC Greenbelt, Maryland 20771 USA

[3] Department of Physics, Sabancı University, Istanbul, Turkey

[4] Department of Physics, Marietta College, Marietta, OH 45750, USA

Received ______________________; accepted ______________________

ABSTRACT

We analysed the 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% 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 (Baykal & Ögelman 1993, Bildsten et al., 1997). Recent RXTE observations of 1E 2259+586 have shown a constant spin down with a very low upper limit on timing noise (Kaspi et al., 1999). 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%. The source could have been in a quiet phase of accretion with a constant X-ray luminosity and spin down rate.

Subject headings: accretion, Low Mass X-Ray Binaries, magnetars, 1E 1048.1-5937, 1E 2259+586

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∼0.5 keV in some of the sources (Stella et al., 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 ($L_x = GM\dot{M}/R \sim 1 \times 10^{35}$erg s^{-1}) with magnetic fields of B∼ 10^{11} Gauss (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 disk. 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 which are accreting from a disk formed as remnants of the common envelope evolution of HMXRBs (van Paradijs et al. 1995, Ghosh et al. 1997). On the other hand Thompson & Duncan (1993) proposed that these sources are highly magnetized (∼10^{14}-10^{15} Gauss) isolated neutron stars (magnetars) which are slowing down due 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 center 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 $M<0.8M_o$ (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 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 day time span of the observation, we found the spin-down rate of 1E 1048.1–5937 to change by 30 %. Recent pulse timing analysis of 1E 2259+586 (Kaspi et al., 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 5 proportional counters operating in the 2-60 keV energy range, with a total effective area of approximately 7000 cm^2 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 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 barycenter 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,

$$\delta\phi = \phi_o + \delta\nu(t - t_o) \tag{1}$$

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 measurments 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 % (see Table 2). However these changes cannot be correlated with X-ray flux changes since Eta Carinae lies 45' a way 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, $\sim$ 2000 sec, observations separated by months; due 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 days 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 5 pulse frequency measurements over 10 years, which were consistent with a constant spin-down rate of $\dot{\nu} \sim 3.8\times10^{-13}$ Hz s^{-1} (Mereghetti 1995). This is $\sim$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 to the value measured with EXOSAT in mid of $\sim$ 1985 (Corbet & Mihara 1997). These variations are consistent with accretion-powered X-ray emission.

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 – MJD $\sim$ 50800 MJD yield a noise strength on the order of $S \approx (2\pi)^2 < \delta\nu^2 > /T \approx (2\pi)^2 < \delta\phi^2 > /T^3 \sim 10^{-17}$ rad^2 sec^{-3}, where $< \delta\nu^2 >$ and $< \delta\phi^2 >$ 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 $T_{observation} \sim 2.6$ years, S$\approx (2\pi)^2 < \delta\phi^2 > /T^3_{observation} \sim 10^{-24}$ rad^2 sec^{-3}. This value is 5 decades lower than the value which is deduced from 15 years of pulse period history of 1E 2259+586 (Baykal & Swank 1996, Baykal & Ögelman 1993) and 2 orders lower than that of the Crab pulsar (Boynton et al., 1972) or that of the LMXRB pulsar 4U 1626-67 (Chakrabarty 1997). This upper limit is indeed very low for an accretion-powered X-ray pulsar. If the pulse period changes are due to 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_H=(2.2$\pm$ 0.8)$\times$ 10^{22} 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 the bolometric X-ray luminosity is less than %15. 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 et al. 1992). This implied that, if due to accretion, the rate onto the source was variable and fluctuations in the spin down rate would be expected. Indeed for this era high noise levels $S \sim 10^{-19}\mathrm{rad}^2\mathrm{sec}^{-3}$ 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 days. 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 Alfven waves or particles from magnetars (Thompson & Blaes 1998), radiative precession of magnetars (Melatos 1999), or discontinous spin up events (glitches) like those seen in radio pulsars (Thompson & Duncan 1996, see also Kaspi et al., 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 $\delta\nu \sim 2 \times 10^{-4}$ s^{-1} and $\sim 5 \times 10^{-6}$ 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 years 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.

Acknowledgements :

We thank the referee for helpful comments.

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Figure Caption

Fig. 1 Pulse frequency time series of 1E 1048.1-5937. The solid lines (upper panel) are fits to the measurements before and after Sep 1988, 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.

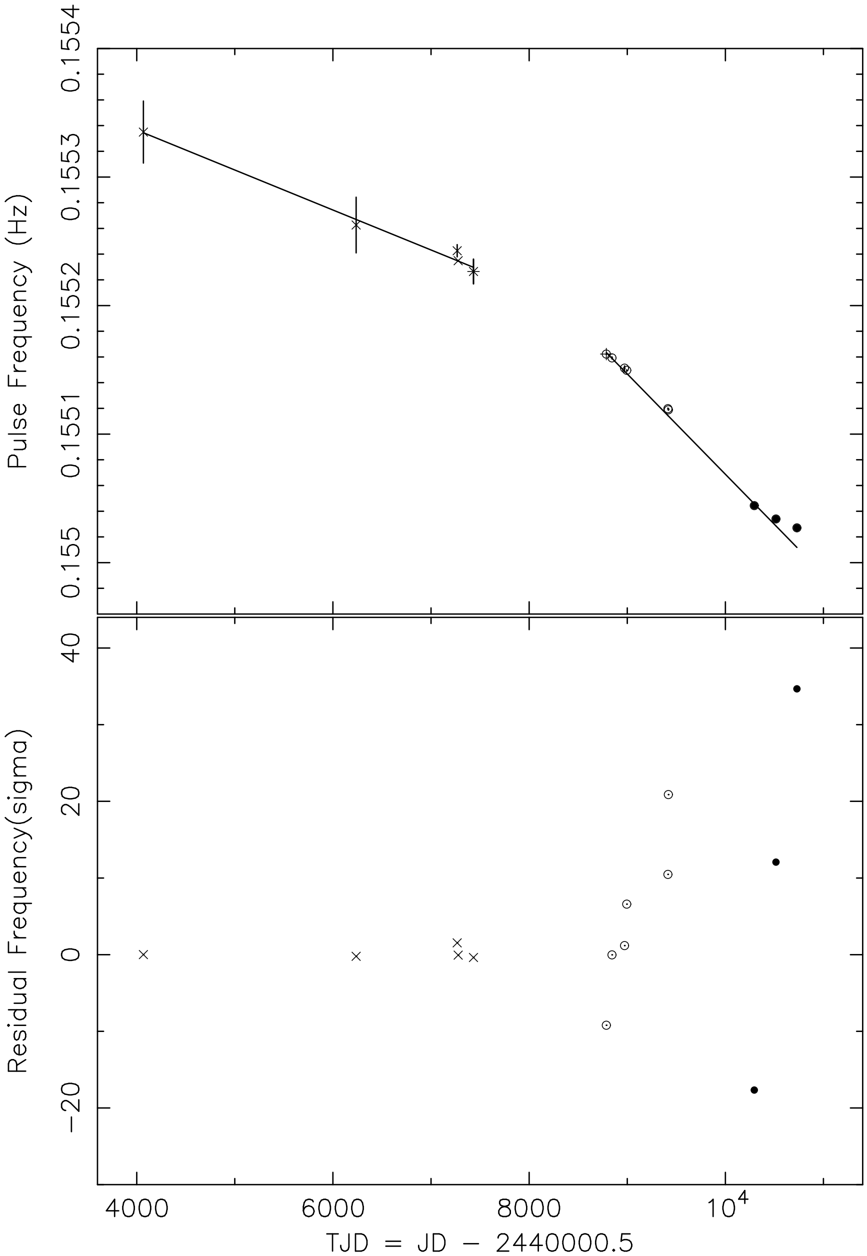
Fig. 2 X-ray luminosity time series of 1E 2259+586.

Table 1: RXTE observations of 1E 1048.1-5937 and 1E 2259+586

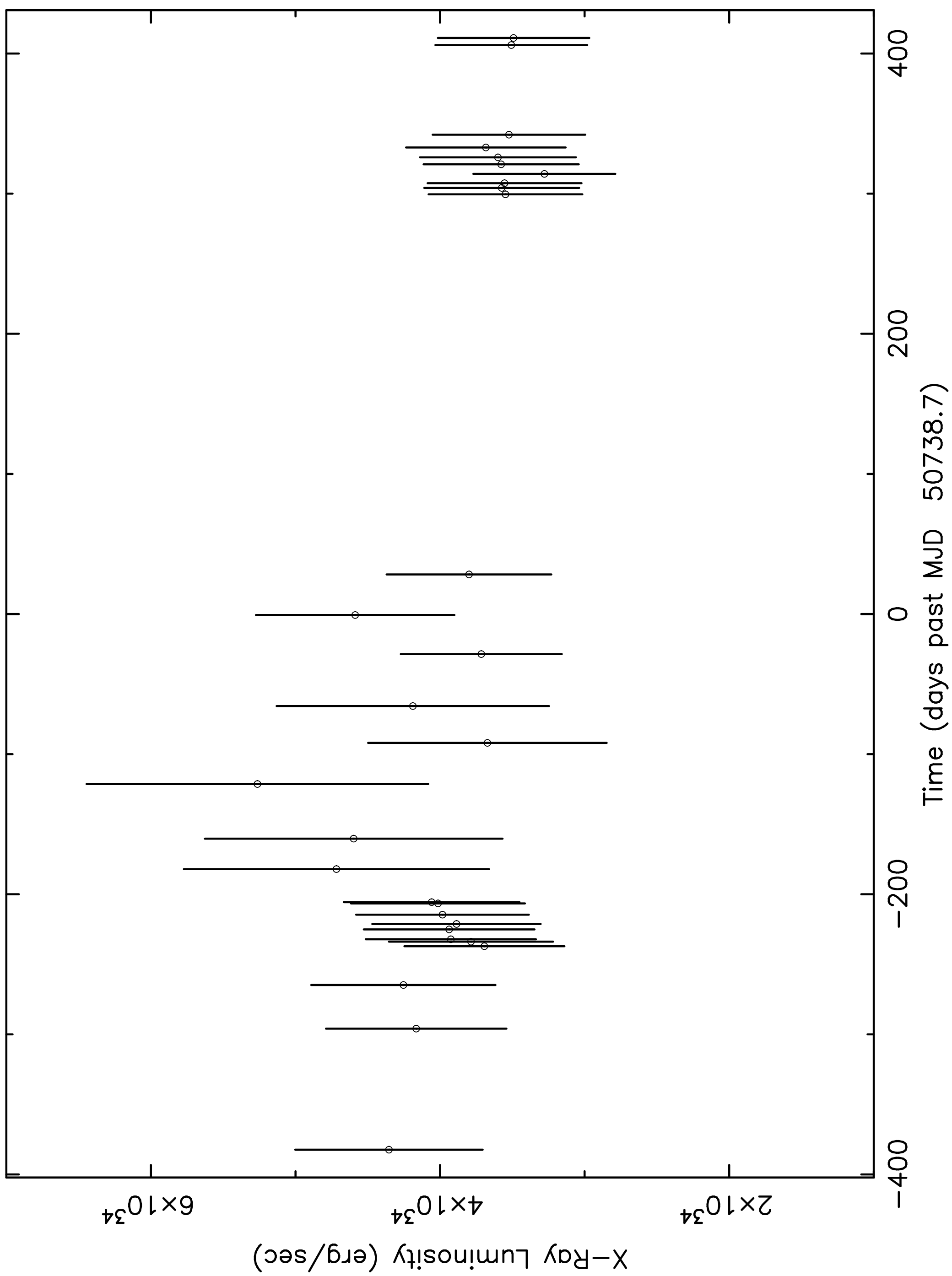
Time of Observation mm/dd/yy	Exposure sec
Source Name	1E 1048.1-5937
29/07/96-31/07/96	62586
08/03/97	21165
08/10/97-09/10/97	14971
Source Name	1E 2259+586
29/09/96-01/10/96	74758
25/12/96	928
25/01/97	1004
22/02/97	1076
25/02/97-26/03/97	100237
18/04/97	727
10/05/97	988
18/06/97	922
17/07/97	847
12/08/97	729
19/09/97	1038
16/10/97	832
14/11/97	884
13/08/98-02/12/98	121833

Table 2: RXTE Pulse Period Measurements of 1E 1048.1-5937

Epoch(MJD)	Pulse Period (sec)	
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 sec^{-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	$-(3.72 \pm 0.52) \times 10^{-13}$	


Pulse Frequency (Hz)
0.155
0.1551
0.1552
0.1553
0.1554
Residual Frequency(sigma)
−20
0
20
40
4000
6000
8000
10^4
TJD = JD − 2440000.5

1


Time (days past MJD 50738.7)
X−Ray Luminosity (erg/sec)
−400
−200
0
200
400
2×10^34
4×10^34
6×10^34