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Spin-down rate of 1E 2259+586 from RXTE observation

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Abstract. We present new X-ray observations of the X-ray pulsar 1E 2259+586, obtained during March 1997, with the Rossi X-Ray Timing Explorer (RXTE). We have measured the pulse frequency derivative $\dot{\nu} = (-1.08 \pm 0.04) \times 10^{-14}$ Hz s^{-1} from pulse arrival times obtained in a sequence of 5 observations spread over one month. This $\dot{\nu}$ is consistent with the long term spin-down trend. We also found that the observed X-ray luminosity is consistent with that measured at quiescent X-ray flux levels by previous missions. Our observations imply that 1E 2259+586 was spinning down steadily without exhibiting any stochastic torque noise fluctuations during the month covered by our observations.

Key words: accretion, X-ray binaries, 1E 2259+586

1. Introduction

The X-ray pulsar 1E 2259+586 is located at the geometric center of the semi-circular shell of diffuse X-ray emission of the supernova remnant G109−1.0 (Gregory & Fahlman 1980). Radio observations indicate that the age of G109−1.0 is about 10^4 yr and the distance to it is 3.6–4.7 kpc (Hughes et al. 1984). The pulse frequency of the pulsar is 0.1433 Hz (pulse period 6.8 sec) and the average spin down rate since its discovery is $\dot{\nu} = -1 \times 10^{-14}$ Hz s^{-1}. If 1E 2259+586 is an isolated, spinning-down pulsar, this rate yields a rotational energy loss of 10^{31} erg s^{-1} which is much less then the intrinsic X-ray luminosity of $\sim 10^{35}$ erg s^{-1} (Corbet 1995). Koyama et al., (1987, 1989) claimed that the spin-down rate and unabsorbed X-ray luminosity can be understood if 1E 2259+586 is in a binary system with a neutron star magnetic field of 5×10^{11} Gauss and spinning close to the equilibrium period (Ghosh & Lamb 1979). However, efforts to find orbitally induced Doppler shifts in the X-ray pulsations which would reveal the binary period have been unsuccessful. The upper limits of $a_x/c \sin i$ from previous missions such as Einstein, EXOSAT, Ginga and ROSAT have been very small. For example, recent RXTE observations (Mereghetti et al., 1998) have given the lowest upper limit $a_x/c \sin i < 30$ msec at the 99% confidence level. According to these new upper limits, if 1E 2259+586 is in a binary system, its companion star must be either a white dwarf, or a helium-burning star with $M < 0.8 M_{\circ}$ (Mereghetti et al. 1998). Alternatively, 1E 2259+586 could be an isolated star which is accreting from a disk and is formed by remnants of the common envelope evolution of a high-mass X-ray binary (van Paradijs et al. 1995, Ghosh et al. 1997).

Analyses of the ROSAT observations (Baykal & Swank 1996) have shown that the source is not steadily spinning-down. A spin-up episode which is superposed on a long term spin-down trend was found. The deviations from the secular spin-down trend are also consistent with other accretion powered X-ray pulsars (Baykal & Ögelman 1993), which are several orders of magnitude greater than those of radio pulsars. This result favors accretion onto a neutron star from a very low mass companion or from a residual disk. In this research note, we present the pulse timing results and X-ray spectrum of 1E 2259+586 from RXTE observations. The main goal of these new RXTE observations is to resolve the pulse frequency derivative ($\dot{\nu}$) during the observation time span and measure the source X-ray luminosity. These quantities enable us to further test the current accretion hypothesis for this source.

2. Observation and Data Analysis

1E 2259+586 was observed between 1997 February 25 and March 26 on 5 different days separated from each other by approximately one week. Each 25 ksec observation was taken in approximately one day. 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 effec-

Send offprint requests to: Altan Baykal tive area of approximately 7000 cm^2 and a field of view, $\sim 1^\circ$ FWHM.

2.1. Torque and X-ray Luminosity

Background light curves and the pulse height amplitudes are generated using background estimator models based upon the rate of very large events (VLE), spacecraft activation and cosmic X-ray emission with the standard PCA analysis tools and are subtracted from the source light curve obtained from the Good Xenon event data. After correcting the background subtracted light curves with respect to the barycenter of the solar system, data sets in each observation were folded on statistically independent trial periods (Leahy et al. 1983). A master pulse was constructed by folding the data on the period giving the maximum χ^2. The master pulse with 55 phase bins was represented by its Fourier harmonics (Deeter & Boynton 1985) and cross-correlated with the harmonic representation of average pulse profiles from each observation. The pulse arrival times so obtained are represented in Fig. 1. The quadratic trend of pulse arrival times is a direct measure of the change of the pulse frequency during the observation (or intrinsic pulse frequency derivative),

$$\delta\phi = \phi_o + \delta\nu(t - t_o) + \frac{1}{2}\dot{\nu}(t - t_o)^2 \quad (1)$$

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), and $\dot{\nu}$ is the pulse frequency derivative of the source. Table 1 presents the timing solution of 1E 2259+586 from our RXTE observations. The pulse frequency derivative obtained from the quadratic trend of the pulse timing analysis is $\dot{\nu}_{RXTE} = -(1.08 \pm 0.04) \times 10^{-14}$ Hz s^{-1} which is consistent with the average spin-down rate over a time span of 19 years, $< \dot{\nu} >= -(1.15\pm0.06)\times10^{-14}$ Hz s^{-1}. Fig. 2 presents the previous pulse frequency history of 1E 2259+586 together with the new RXTE observation.

Table 1. Timing Solution of 1E 2259+586 for RXTE Observations

Epoch(MJD)	50516.494628
Pulse Frequency (Hz)	0.1432886474 $\pm$ 1.8$\times10^{-9}$
Pulse Freq. Derivative (Hz s^{-1})	$-(1.08 \pm 0.04) \times 10^{-14}$

The background spectrum was calculated using the same 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

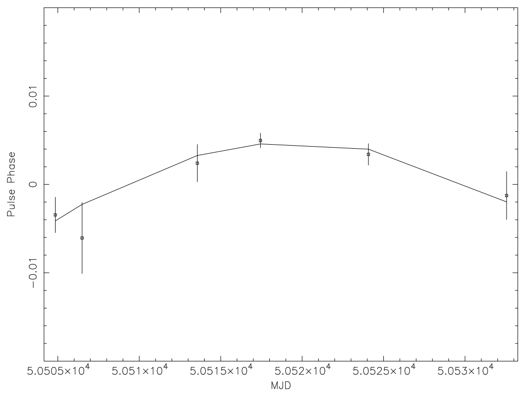

Fig. 1. Phase ofsets in pulse arrival times.

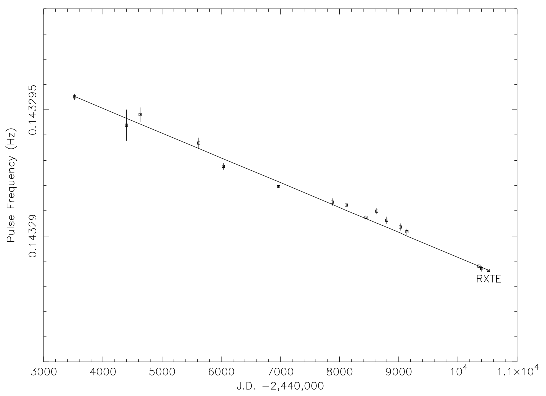

Fig. 2. Pulse frequency history of 1E2259+586, including the latest RXTE measurement.

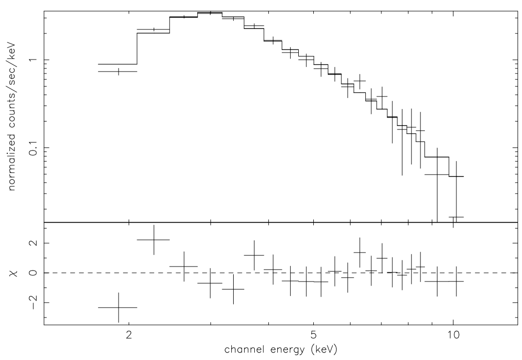

Fig. 3. (top) RXTE PCA X-ray spectrum of 1E2259+586 with the fit to the power law model. (bottom) The residuals to the fit. The reduced $\chi^2 = 1.1$.

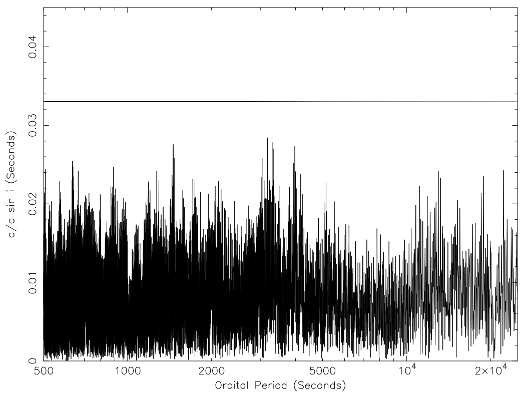

Fig. 4. Results of a search for orbital Doppler delays for 1E 2259+586. The horizontal line denotes the a_x/c sin i values corresponding to detection at the 99% confidence level.

curves. The resultant background subtracted spectrum in the energy range 2-10 keV yields X-ray luminosity $L_x = (0.38\pm0.06)\times10^{35}(\frac{d}{4\mathrm{kpc}})^2$ erg s^{-1} which is consistent with that obtained from ASCA and SAX measurements in 2-10 keV (Corbet et al., 1995, Parmar et al., 1997). The best fitting power law X-ray spectrum with column density N_H=(2.2± 0.8) × 10^{22} cm^{-2} and photon index 4.78 is presented in Fig. 3. The background contamination from the supernova remnant is only a few percent of the total source flux (Rho & Petre 1997). ASCA and Beppo SAX observations have found a soft black-body component with a temperature of 0.44 keV (Corbet et al. 1995, Parmar et al. 1997). Our fits to the X-ray spectra do not resolve the soft black-body component since the RXTE/PCA detectors are insensitive to energies less than about 2 keV. There is no evidence for any deviation from a power law that might be attributable to a cyclotron feature.

2.2. Search for Orbital Period

In searching for orbital Doppler modulation, orbital periods from $\sim$ 500 sec to $\sim 2.5 \times 10^4$ sec were considered by oversampling the independent Fourier periods (Leahy 1983) by a factor of 4. For each trial orbital period, 8 pulse profiles are obtained at the different intervals of the orbital phase by correcting the light curve for the secular spin-down rate and folding the light curve at the the pulse period. The resulting pulse profiles were cross-correlated with the master pulse, which was obtained from all observations. To search for any sinusoidal modulation in the 8 pulse arrival times, Fourier amplitudes of the arrival times were computed and are presented as a function of the trial orbital period in Fig. 4. In the absence of an orbital signal, the expected distribution of Fourier amplitudes is the χ^2 distribution with 2 degrees of freedom (van der Klis 1989). As seen in Fig. 4, no significant signal detection is found at the 99% confidence level. The upper limit for any undetected signal is estimated as $a_x \sin i < 0.028$ light-s, which is very close to the earlier upper limit given by Mereghetti et al. (1998). (We note that a slight improvement of the upper limit arises from the better statistics due to the longer RXTE observation with respect to previous observations) The above upper limits on Doppler shifts confirms that if the 1E 2259+586 is in a binary system, then the companion star must be either a white dwarf, or a helium-burning star (Mereghetti et al., 1998).

2.3. Torque and X-ray Luminosity Changes in Accretion Powered Disk Fed Binaries and 1E 2259+586

In disk-fed systems, the accretion onto the neutron star is believed to be from a Keplerian disk (Ghosh & Lamb 1979). The torque on the neutron star is given by

$$I\dot{\Omega} = n(w_s)\dot{M}\; l_K, \tag{2}$$

where $l_K = (GMr_o)^{1/2}$ is the specific angular momentum added by a Keplerian disk to the neutron star at the inner disk edge $r_o \approx 0.5r_A$, where $r_A = (2GM)^{-1/7}\mu^{4/7}\dot{M}^{-2/7}$ is the Alfven radius, μ is the neutron star magnetic moment, $n(w_s) \approx 1.4(1 - w_s/w_c)/(1 - w_s)$ is a dimensionless function that measures the variation of the accretion torque as estimated by the fastness parameter $w_s = \Omega/\Omega_K(r_o) = 2\pi P^{-1}G^{-1/2}M^{-5/7}\mu^{6/7}\dot{M}^{-3/7}$. Here w_c is the critical fastness parameter at which the accretion torque is expected to vanish ($w_c \sim 0.35 - 0.85$ depending on the electrodynamics of the disk, Lamb 1989). In this model, the torque will cause a spin-up if the neutron star is rotating slowly ($w_s < w_c$) in the same sense as the circulation in the disk, or spin-down, if it is rotating in the opposite sense (see Lamb 1991). Even if the neutron star is rotating in the same sense as the disk flow, the torque will spin-down the neutron star if it is rotating too rapidly ($w_s >> w_c$). In such a model one should see positive correlation between angular acceleration ($\dot{\Omega}$) and mass accretion rate ($\dot{M}$) if the disk is rotating in the same sense as the neutron star. If the flow is from Roche Lobe overflow then the accreting material carries positive specific angular momentum l, therefore it is hard to imagine accretion flow reversals and hence the spin-up/down torques should be correlated with mass accretion rate $\dot{M}$.

In Ginga observations the source had flux levels a factor of two higher than average (Iwasawa et al. 1992). This implied that the mass accretion rate on the source is indeed variable and fluctuations in the spin-down rate and possible spin-up trends should be expected (Baykal & Swank 1996). However, our RXTE observations found the source with an X-ray flux consistent with the secular spin-down. Therefore, it is quite natural to find the secular spin-down rate from pulse arrival times, although this observation gives the spin-down rate of the source over the shortest observing interval since the discovery of the source.

Recent observations of accreting neutron stars have shown stochastic spin-up/down trends on time scales from days to a few years (Bildsten et al. 1997). In intervals between stochastic changes disk-fed sources show secular spin-up or down trends with lower values of noise strength (Baykal 1997). Some of the sources switch from spin-up to spin-down states without showing great changes in their mass accretion rates (Bildsten et al. 1997). These unusual behaviors led Baykal (1997) and Nelson et al. (1997) to the possibility of retrograde circulation of accretion disks. GX 4+1 shows correlation between the X-ray flux and the spin-down rate (Chakrabarty et al. 1997) which may suggest a retrograde accretion disk. In the application of the above observational results and current accretion theory to 1E 2259+586, the spin-down rate should decrease or it should switch to spin-up at higher accretion rates (higher X-ray flux). On the other hand if the source has a very unusual counter-rotating accretion disk, in the high state the spin-down rate should increase with respect to the low state. Future X-ray observations at a high state could address this important question.

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