Pulse Frequency Changes of 1E 2259+586 and the Binary Interpretation

Altan Baykal

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

NAS/NRC Resident Research Associate Physics Department, Middle East Technical University, Ankara 06531, Turkey

and

Jean Swank

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

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ABSTRACT

Pulse frequencies from the archival *ROSAT* observations of 1E 2259+586 are presented. A short term spin-up episode superposed on the secular spin-down trend is observed. Combining the previously published pulse frequencies, we estimate the variance of the angular velocity over a 15 year span of observations. The level of fluctuations in angular velocity is similar to that of established accreting binary neutron stars. These results favor accretion by a neutron star from a very low mass companion as the source of the X-ray luminosity, although accretion by a solitary neutron star from a residual disk might be possible.

Subject headings: binaries:close — stars:individual (1E 2259+586) — stars:neutron — X-rays:stars

1. Introduction

There are 5 pulsars known, 4U 0142+61, 1E 1048.1-5937, 4U 1626-67, RXJ 1838.4-0301, and 1E 2259+586, which have pulse periods close to 7 s and several other similarities (Mereghetti & Stella 1995). Most notably, they are all faint optically and are pulsars which are not accreting from high mass companions. All but the most recently discovered, RXJ 1838.4-0301, are known to have had long episodes of spin down, rather than the usual spin-up that first identified Her X-1 and Cen X-3 as neutron stars rather than white dwarfs (Lamb, Pethick & Pines 1973). The coincidence of similarities has led Mereghetti & Stella (1995) to suggest they form a class of low mass X-ray binaries. On the other hand, van Paradijs, Taam, & van den Heuvel (1995) suggest that they are single neutron stars accreting from a disk, and are formed by recent remnants of the common envelope evolution of a high mass X-ray binary. The class of objects may include or be related to soft gamma-ray repeaters. The flux from SGR 0525-66 in N49 was pulsed with a period of about 8 s after the 1979 March 5 burst, as noted by (Corbet et al. 1995), and SGR 1806-20 data have suggested a pulse period of 2.8 s (Ulmer et al. 1993). Among all these sources only 4U 1626-67 has a secure optical identification and a binary period identified in the optical data. So far none of these pulsars has shown X-ray evidence of binary Doppler shifts. Evidence for binarity in any of the sources other than 4U 1626-67 is of interest to help identify their nature.

The source 1E 2259+586 has been observed by many X-ray missions. It is an X-ray source with a flux of about 1μJy and has a soft spectrum with moderate column density, so that the *ROSAT* PSPC and HRI saw about 1 and 0.5 counts s^{-1}, respectively. For 1E 2259+586 the upper limits on $a_x \sin i$ have been very small. We have examined whether the source is steadily spinning down or doing so in a "noisy" manner with fluctuations of the frequency. Both wind and disk accretion produce frequency fluctuations. Radio pulsars do as well, but the magnitudes are smaller. The fluctuation properties of the pulsar might identify it as akin to either binary or single pulsars.

The pulsar is located near the geometrical center of curvature of the semi-circular shell of diffuse X-ray emission of the supernova remnant G 109-1.0 (Gregory & Fahlman 1980, Fahlman & Gregory 1981). The remnant shows semicircular structure in both X-ray and radio band observations. Radio observations indicate that the age of G109-1.0 is about 10^4 yr and its distance 3.6–4.7 kpc (Gregory & Fahlman 1980, Hughes et al. 1981, Gregory et al. 1983, Hughes et al. 1984). Rho & Petre (1995) have carried out a detailed study of the diffuse low energy X-ray emission seen by *ROSAT* and Corbet et al. (1995) determined *ASCA* spectra of diffuse emission knots near the pulsar.

The pulsar's frequency is 0.1433 Hz (pulse period 6.98 s). All observations reported to date have traced a secular spin down (Corbet et al. 1995). The average slowing down of the source ($\dot{\nu} = -2.43 \times 10^{-11}$ Hz s^{-1}) yields a rotational energy loss of 10^{31} erg s^{-1} (assuming a neutron star), which is much less then the intrinsic X-ray luminosity of 2×10^{35} erg s^{-1}. Koyama et al. (1987, 1989) argued that the spin down rate and unabsorbed X-ray luminosity can be understood if the source is a neutron star with a magnetic field of 5×10^{11} G rotating close to the equilibrium period (Ghosh & Lamb 1979). The *Ginga* spectral data was at first interpreted as indicating a trough in the energy range 5-10 keV that could be confirming the strength of the magnetic field (Koyama et al. 1989), but the *ASCA* data suggest this is actually a cross over region in a two component spectrum (Corbet et al. 1995).

A candidate for an optical counterpart was suggested by Fahlman et al. (1982), on the basis of a report of infrared pulsations (Middleditch et al. 1983). However recent IR observations (Davies et al. 1989, Davies & Coe 1991) have not verified its existence. Coe & Jones (1992) found no counterpart brighter than V=23, which constrains a low mass binary companion at 4 kpc to be no brighter than a main sequence K star. An orbital period about 2300 s was suggested by Fahlman & Gregory (1983) based on the Einstein observations, but the more sensitive observations made by *Tenma* (Koyama et al. 1987) and *EXOSAT* (Hanson et al. 1988, Morini et al. 1988) did not confirm this period. In recent *Ginga* observations there was marginal evidence (≤ 4 sigma) of an orbital period at 2120 s (Koyama et al. 1989).

Because of the lack of significant detection of a binary period or of an optical counterpart, several alternative scenarios have been proposed to explain the pulse frequency changes without the need for accretion from an observable companion. Starquakes (or glitches) in a rapidly rotating magnetic white dwarf (Usov 1994) or in a neutron star with very high magnetic field ($\sim 0.7 \times 10^{14}$ G) (Thompson & Duncan 1993) have been proposed as possible underlying mechanisms for pulse frequency changes. Corbet et al. (1995) discussed accretion onto a non-binary neutron star from the molecular cloud on which the supernova remnant is impinging or from other circumstellar debris. The solitary neutron stars in these scenarios would in general have fluctuations in rotation frequency different from those of most radio pulsars, as well as different from neutron stars in binary sytems.

In this work we have obtained pulse frequencies using the four archival data sets of *ROSAT* observations which were each separated by $\sim$ 200 days. They yield the first observed indication of a spin-up episode of 1E 2259+586 since the initial observation. Considering the variations in the pulse frequencies, we compare the noise in angular velocity to that of other pulsars.

In §2, we document the archival *ROSAT* observations. In §3, we discuss the spectra; these provide the luminosity estimates needed in §6. In §4 we describe the determination of the pulse frequencies and limits on binary Doppler shifts. In §5 we present our analysis of the angular frequency noise. We discuss the results in §6. We compare the noise to that observed in other accreting and non-accreting pulsars and to that expected in accreting systems and we assess the evidence for correlation of frequency and luminosity fluctuations. Finally, in §7 we conclude that the neutron star is likely to be accreting from a disk, that no observations have yet contradicted the possibility that the source of the material is a binary companion, and that the source has strong variability that could be important to understanding it.

2. Observations

The pulsar 1E 2259+586 was observed four times by *ROSAT*, twice with the position sensitive proportional counter (PSPC) and twice with the high resolution imager (HRI). The PSPC is a gas filled proportional counter sensitive over the energy range 0.1-2.4 keV with an energy resolution $\Delta E/E \approx 0.43$ at 0.93 keV. The HRI has no intrinsic energy resolution, but has its highest sensitivity in the energy band 0.4-2.4 keV. Detailed descriptions of the satellite, mirrors, and the detectors can be found in Trümper (1983), Pfeffermann et al. (1986), Aschenbach (1988) and Zombeck et al. (1990). The observations reported here were extracted from the *ROSAT* archival data base. The reduction of the *ROSAT* archival data and correction of the photon arrival times to the solar system barycenter was performed using IRAF/PROS software. The observations reported in this work took place 1991 July 9–10 (PSPC), 1992 January 8–10 (HRI), 1992 June 25–27 (HRI) and 1993 February 7–8 (PSPC) with total effective exposure times of 34053 s, 22319 s, 27933 s and 8673 s respectively.

3. Spectra

The pulsar spectra were extracted from a 2 arcmin radius circle centered on the pulsar. Background was taken from a surrounding annulus out to a radius of 3.5 arcmin. The PSPC observations can be fit with either power-law or blackbody spectral models with acceptable χ^2. The results of the fits are listed in Table 1. The measured flux during the first PSPC observation was 1.7 10^{-11} erg cm^{-2} s^{-1} in the band 0.5–2.4 keV and $\sim$ 20% higher in the second PSPC observation. Corbet et al. (1995) found that at least two components were required to fit the *ASCA* spectral data. They found that a power-law and blackbody combination gave an adequate fit to both BBXRT and *ASCA* data and fit *Ginga* data better than did a single power-law, although the combination was not sufficient for a good fit above 10 keV. The two component model does not significantly improve fits to the *ROSAT* data alone (the energy range is too narrow), but the last *ROSAT* observation used the PSPC and has a similar flux in the region of overlap with the *ASCA* energy range (0.5-2.4 keV). Assuming that the spectral parameters were the same, we fit the PSPC and *ASCA* SIS data (averaged over pulse phase) together, allowing the models for the two data sets to differ only in a normalization factor. Results of this fit, for which the implied *ASCA* flux was 0.85($\pm$0.01) of the *ROSAT* flux, are also shown in Table 1. The combined data are consistent with the assumed model. Figure 1 shows the fit to both the data sets and the contributions of the components to the incident flux. Both components contribute in the *ROSAT* range. We compared power-law plus black body fits to the *EXOSAT* data (in the HEASARC data base), the *ASCA* data, and the 1989 and 1990 *Ginga* fits (Iwasawa et al 1992). The total (0.5-10 keV) intensities of the components in the fits vary by as much as a factor of 3, with no obvious correlation. It is not clear whether the spectral decomposition really reflects distinct physical emission sources or is an approximation to the true emission spectrum.

4. Pulse Frequencies

After correcting the photon arrival time with respect to the barycenter of the solar system, data sets in each observation were folded on statistically independent trial frequencies (Leahy et al. 1983). Master pulses were constructed for each observation by folding the data on the period giving maximum χ^2. The master pulses with 50 phase bins were represented by their harmonics (Boynton and Deeter 1985, Deeter and Boynton 1985) and cross correlated with harmonic representations of pulse profiles from segments of the data. The segments were typically 2000 s and 4000 s time spans for PSPC and HRI data sets respectively. In the arrival time analysis we did not see any significant Doppler delays and the pulse frequencies were determined from slopes of least squares straight line fits to each subset of residual phases. In order to check the compatibility of our results with the previously published pulse frequency in the *ASCA* data (Corbet et al. 1995) we pursued the same analysis with *ASCA* data and verified the published pulse frequency. Table 2 lists the pulse periods estimated in this work together with previously published results. Figure 2 shows the pulse frequency (P^{-1}) history of 1E 2259+586.

We searched the longest *ROSAT*/PSPC observation (34 k s exposure time within a span of 1 day) for Doppler delays of orbital periods shorter than 4500 s. For each trial orbit period between 1000 s and 4500 s (at 10 s intervals), we folded the data in each of eight orbital phase bins on the best-fit pulse period. We cross correlated each of the eight profiles with the master pulse. Then the arrival times were fit to a circular orbit with a projected semimajor axis $a_x \sin i$. At the 3σ level we did not see any significant Doppler shifts and obtained an upper limit of $a_x \sin i \sim 0.26$ s, which is a factor of three larger then that of the previous *Ginga* observation (Koyama et al. 1989).

The time series of the *ROSAT* and *ASCA* data showed no flares on time scales of 1000 s, as are seen from 4U1626-67 (Levine et al. 1988 and references therein). The power density spectra showed no quasiperiodic oscillations at $\sim$ 0.02-0.05 Hz as are seen for 4U1626-76 (Shinoda et al. 1990; Angelini et al. 1995).

5. Noise Strength

In order to study whether the source has been spinning down smoothly or noisely, we examined the pulse frequency residuals from a linear secular spin down. Lamb, Pines & Shaham (1978) discussed the different types of noise that can affect the arrival times of pulses. The root mean square technique used in this work for the estimation of noise strengths was discussed in detail by Cordes (1980), Deeter (1984) and Cordes & Downs (1985). The applications made by Baykal et al. (1993 a,b) are examples of its use in characterizing random walk processes.

In the present case we first removed a linear trend from the pulse frequency data by fitting a straight line to the entire span of data (Fig. 2). The fit had $\chi^2 = 50$ with 11 degrees of freedom. Then we divided the residuals into two subsets and fit the residuals in each subset with a straight line. With each fit is associated a mean squared residual. Other accretion powered X-ray binaries such as Her X-1, and Vela X-1 have pulse frequency histories consistent with random walk (Boynton 1981, Deeter 1981, Deeter et al. 1989, de Kool & Anzer 1993, Baykal & Ögelman 1993). Random walk in angular frequency can be characterized by a rate R of steps $\delta\Omega$. The mean square residuals are proportional to $R < \delta\Omega^2 >$, which is called the noise strength S. Mean square residuals for the case of random walk in frequency with strength S (Cordes 1980; Lamb, Pines & Shaham 1978), after removing a polynomial of degree m over an interval of length T, should scale with S and T:

$$< \sigma_R^2(m,T) >= ST < \sigma_R^2(m,1) >_u \tag{1}$$

where $< \sigma_R^2(m,1) >_u$ is a dimensionless normalization factor which depends on the degree m

of the polynomial removed prior to computing the mean square residual; this factor can be obtained by determining the expected mean square residual ($<\sigma_R^2(m,1)>$) with unit noise strength ($S=1$) over an interval of unit length ($T=1$). We computed the normalization for our specific case of nonuniformly sampled data through Monte-Carlo simulations, and found agreement within 15% with the theoretical evaluation for equispaced data sampling (Cordes 1980; Deeter 1984). (The mathematics of our mean square frequency residuals for a random walk in frequency is like that of mean square phase residuals for random walk in phase, for which results are given in Deeter's Table 2.). Following these authors, we estimated the noise strengths of the actual data for the total observation time scale (5616 days), $S=(1.5\pm0.4)\times10^{-19}$ rad^{2}s^{-3} and for its half value (2808 days), $S=(1.1\pm0.3)\times10^{-19}$ rad^{2}s^{-3}. These are consistent with each other, which implies that the assumed noise model (see Eq. 1) is consistent with our data at least over a factor of two in frequency. There are insufficient data to make significant estimates of the noise strengths at higher frequencies. The weighted mean of these measurements is $S=(1.3\pm0.2)\times10^{-19}$ rad^2 s^{-3}. This estimated mean noise strength assuming a first order red noise process is consistent with that found by Baykal & Ögelman (1993), $(0.2-1.9)\times10^{-19}$ rad^{2}s^{-3}, using the data given by Nagase (1989), that is, the *Einstein* Observatory through *Ginga* points given in Table 2. Although the data at hand are not sufficient to distinguish the type of noise process (i.e white or red noise) at all timescales, so far the fluctuations of 1E 2259+586 can be described in terms of random walk in pulse frequency.

The behavior of random walk in frequency is such that the fluctuations can dominate over secular changes on short enough time scales (as long as the time scales remain longer than the random walk steps). The general trend of the source can be expressed as a secular trend, $\dot{\Omega}_{secular}$, plus a fluctuating component Ω_f. A time T after starting, we would have

$$<(\Delta\Omega_f)_T^2>=ST \tag{2}$$

where the observed noise strength $S = R < \delta\Omega^2 >$ (note that in Eq. 2, we do not include a factor to correct for polynomial subraction on the right hand side as in Eq. 1). Defining the mean rate of divergence of Ω_f by $\dot{\Omega}_f = \Delta\Omega_f/T$, the mean square fluctuation of the white noise variable can be written as

$$< (\dot{\Omega}_f)^2_T >= \frac{S}{T}. \tag{3}$$

According to the above equation, the observed r.m.s. fluctuation in the time derivative of the angular frequency should have a magnitude of about $(\frac{S}{T})^{1/2}$. For 1E 2259+586, $\dot{\Omega} = -6. \pm 1.7 \times 10^{-14}$ rad s^{-2} for the entire observation span of T=5616 days, and the secular term dominates the r.m.s. noise term of $(\frac{S}{T})^{1/2} = 1.8 \times 10^{-14}$ rad s^{-2} on this time scale. As seen from Figure 2 and Table 2 there was a spin-up episode after J.D. 2,448,446 on the time scale of 183 days. For this interval the values of Ω at the end points give $\Delta\Omega/T \approx 10 \pm 8 \times 10^{-14}$ rad s^{-2} , while the r. m. s. noise term on this time scale is 9.8×10^{-14} rad s^{-2}. Thus it is as large as the secular trend. This indicates that the short term spin-up episode of 1E 2259 + 586 is consistent with having been an effect of the white torque noise.

6. Discussion

6.1. Comparison of noise properties of accreting pulsars and radio pulsars

Several estimates of noise strengths and power spectra for timing noise in radio pulsars have been made in the last decade (Cordes & Downs 1985, Boynton & Deeter 1985, see also Alpar et al. 1986). These estimates have yielded noise strengths in the range $10^{-26} - 10^{-21}$ rad^2 s^{-3} for pulse frequency fluctuations described as a random walk in ν. The same quantities have been estimated for 16 accretion powered X-ray binary pulsars, including 1E 2259+586 (Baykal & Ögelman 1993). In this analysis, noise strengths were found in the range $10^{-19} - 10^{-13}$ rad^2 s^{-3}, significantly larger than those of the radio pulsars. The rotational noise strengths approximately scaled with average X-ray luminosity L_x, as

$$S \sim 10^{-17}\ L_{37}\ \mathrm{rad}^2\mathrm{s}^{-3}, \tag{4}$$

where L_{37} is the X-ray luminosity in units of 10^{37} erg s^{-1}. For 1E 2259 + 586 the observed luminosity 2×10^{35} erg s^{-1} yields $S \sim 2 \times 10^{-19}$ rad^2 s^{-3} which is consistent with our current estimate of the noise strength. The above results shows that 1E 2259+586 is a factor 10^2–10^7 noisier then the radio pulsars and its noise strength is consistent with the empirical relation of the other accretion powered X-ray sources (not including the group of pulsars with pulse periods around 7 s under consideration here. In all of those for which we have measurements the accretion is from a binary companion. The causes of the fluctuations are not understood, but in a binary system, there are many possible effects that could prevent achievement of a steady state.

Several other scenarios that could give rise to accretion from a disk around a solitary neutron star have been discussed. Accretion from circumstellar debris around a neutron star formed in a supernova has been proposed to explain soft gamma-ray repeaters (Katz et al. 1994). In this model a supernova leaves planets orbiting around the neutron star. These planets then collide to produce debris, some fragments of which fall onto the neutron star to produce gamma-ray bursts. Such circumstellar debris can contribute angular momentum to the neutron star and also power steady X-ray emission (Corbet et al. 1995, van Paradijs et al. 1995), if the debris forms a disk which is gaseous in at least the inner regions. Alternatively, material from a supernova could fall back on the neutron star possibly forming a disk around it that would both accrete and spread outward. Planets could be formed in condensation of the outer regions (e.g. Podsiadloski 1993 for application to the formation of planets, and van Paradijs et al. 1995 for formation of disks that could lead to solitary accreting pulsars). Such disks might be visible in the light curves of supernovae like SN1987A (Meyer-Hofmeister 1992). The accretion would not necessarily be smooth. In soft gamma ray repeaters there are discrete, sporadic events, although the bursts are at least sometimes followed by continuous emission. If the accretion were taking place from a circumstellar debris disk that is irregular in distribution, there could be luminosity and torque fluctuations. Instabilities in disk accretion might also make the luminosity vary on a variety of timescales (Meyer-Hofmeister 1992; Mineshige et al. 1993).

6.2. Comparison of luminosity and torque fluctuations

Our pulse frequency measurements include a short term spin-up episode. While accretion together with spin down is possible because of torques on the neutron star arising in the magnetosphere-disk interaction (Ghosh & Lamb 1979), a spin-up episode is expected to be driven by an increased accretion rate.

In order to investigate the possible correlation between the pulse frequency changes and X-ray luminosity changes we constructed a time series of 1-2 keV X-ray flux. We use the flux in the narrow band, 1-2 keV, that is included in the range of most of the detectors which have observed 1E 2259+586. We have used HEASARC's software, PIMMS and XSPEC, to estimate the 1-2 keV flux values. Figure 3a shows the X-ray flux time series of these fluxes. There is some sensitivity to the spectral model, which is reflected in the error bars being larger than statistical. The flux values for collimated instruments (*HEAO 1*, *EXOSAT*, *Tenma*, and *Ginga*), are all higher than those from imaging experiments (*Einstein* Observatory, *ROSAT*, and *ASCA*). However, the contributions of the supernova remnant have been measured and are too soft to add significantly to the fluxes detected above 1 keV where these are included in the field of view (Koyama et al. 1989; Rho & Petre 1995), and the same luminosity trends seen in Figure 3a appear in estimates of the 2-10 keV fluxes. As seen from the figure, the *Ginga* flux at J.D. 2,448,113.0 was twice that of the previous observation by the same instrument.

We constructed the time series of average pulse frequency derivatives from the differences between consecutive measurements of the pulse frequency (Fig. 3b). As seen from Figure 3, there is no direct correlation between the X-ray flux and average pulse frequency changes. The short term spin-up followed the one large change in X-ray luminosity, but after a lag of 400 days. This is probably too long a time delay for the events to be truly correlated. The long gaps between the observations make it impossible to recover short term pulse frequency derivatives. If there have been correlated X-ray luminosity and pulse frequency changes, they occurred while the the source was not monitored.

Although a detailed correlation between torque and luminosity cannot be tested, we can still expect a statistical correlation of properties. If we assume the steps in angular frequency arise from accretion events which are of short time scale compared to the sampling intervals that have been made, we can relate these events to the noise strength.

If 1E 2259+586 is an equilibrium rotator (Koyama et al. 1987, 1989) with $r_c \sim r_A$, where r_c is the corotation radius and r_A is the Alfven radius, angular momentum added or subtracted from the neutron star at the Alfven radius can be written as,

$$I\delta\Omega = \delta M l + \dot{M}\delta t \delta l. \tag{5}$$

Here δM is the fluctuation in mass transferred during a time scale δt, $l = (GM_n r_A)^{1/2}$ is the specific angular momentum added to the neutron star at the Alfeven radius, and M_n is the mass of the neutron star. A change in the accretion rate $\delta\dot{M}$ may change the Alfven radius and hence the specific angular momentum as well. Then the strength of the random walk in Ω is given by

$$S = R\delta t^2 \frac{36}{49}(\frac{\delta\dot{M}}{\dot{M}})^2 \frac{\dot{M}^2 G M_n r_A}{I^2}, \tag{6}$$

where $r_A = 1 \times 10^9 \mu_{30}^{\frac{4}{7}} \dot{M}_{15}^{-\frac{2}{7}}$ cm (compare Lamb 1989). This implies

$$R\delta t^2 = 12(\frac{\delta L}{L})^{-2} I_{45}^2 \dot{M}_{15}^{-\frac{12}{7}} B_{12}^{-\frac{4}{7}} \tag{7}$$

We have used μ_{30} for the neutron star magnetic moment in 10^{30} G cm^3, I_{45} for its moment of inertia in 10^{45} gm cm^2, B_{12} for its surface magnetic field in 10^{12} G, and $\dot{M}_{15}$ for the accretion rate in 10^{15} gm s^{-1}. Between the data sets we see X-ray flux changes of $\sim 50\%$. With $\dot{M}_{15} \sim 1$ and $I_{45} \approx 1$, $R\delta t^2 \sim 50 B_{12}^{-\frac{4}{7}}$ days. Thus the noise strength and luminosity variations would be statistically consistent for event durations and separations both around $50 B_{12}^{-\frac{4}{7}}$ days. If B_{12} is only about 0.1, these time scales would be around 200 days. In any case, the events are probably shorter than the 400 day lag between the flare observed by *Ginga* and the spin-up between the *ROSAT* observations. A program of more closely sampled measurments will be required to resolve the luminosity and spin change events.

7. Conclusion

The pulse frequency history of 1E 2259+586 shows fluctuations (including a spin-up episode) that are consistent with those of accreting binary systems. X-ray luminosity variations have been observed which are of a magnitude and rate consistent with their being related to the frequency variations, if the accretion is through a disk. While more exotic explanations of the changes might be possible, these results affirm the possibility that the accretion is of a familiar nature. Mereghetti (1995) has made a similar argument for 1E 1048.1-5937, pointing out a change in the spin down rate.

Accreting pulsars for which frequency noise has been measured, are all in binary systems. One of these is 4U 1626-67, which is similar to 1E 2259+586 in not showing X-ray Doppler shifts and in having long periods of secular spin-down (Bildsten et al. 1993).

If 1E 2259+586 is in a binary, the *Ginga* observation upper limit of 0.08 lt-s for the projected semimajor axis for trial periods from 10^3–10^4 s gives an upper limit to the mass function of $f(M) < 1.0 \times 10^{-3}(P_{orb}/2000\ \mathrm{s})^{-2} M_{\odot}$. For a period near 2000 s, and $M_n = 1.4\ M_{\odot}$, this limit constrains the mass of the companion to $M_c < 0.13 M_{\odot}$ for an inclination angle $i = 90^o$.

The *Ginga* upper limit on the Doppler amplitude is not very constraining, since the expected amplitude is much smaller. Gravitational radiation is probably the dominant mechanism for angular momentum loss of such a short period binary (Faulkner 1971, Rappaport et al. 1982, Nelson et al. 1986). Using the $n = 3/2$ polytropic representation for the secondary and assuming the secondary fills its Roche lobe, Rappaport et al. (1987) showed that the mass transfer rate for a hydrogen-depleted, completely degenerate secondary would be

$$\dot{M} \sim 3 \times 10^{15} (\frac{M_n}{M_{\odot}})^{2/3} (\frac{P_{orb}}{2000s})^{-14/3}\ \ \mathrm{gm\ s^{-1}}. \tag{8}$$

where $P_{orb} \sim 46.14 (M_c/M_{\odot})^{-1}$ s is the orbital period. If $P_{orb} = 2120$ s, then $M_c \sim 0.02 M_{\odot}$, $\dot{M} \sim 2.9 \times 10^{15}$ gm s^{-1} and $L_x \sim\ 5 \times 10^{35}$ erg s^{-1}. This is within a factor of 2 of the average unabsorbed luminosity (assumed to be the intrinsic luminosity) and a slightly longer period would bring it into agreement. The projected semimajor axis should be at most ~ 0.02 lt-s.

Recent theoretical considerations have indicated that there could also be disks around solitary neutron stars that could be sources of accretion for longer than the age of the supernova remnant associated with 1E 2259+586. Fluctuations in frequency and X-ray luminosity such as those observed from 1E 2259+586 have not been ruled out for such objects. But there are no known examples and the predictions of their properties are not definite.

In many low mass X-ray binaries accreting through Roche Lobe overflow the disk is seen through reprocessing of X-rays from the central source (van Paradijs & McClintock 1994). Following Mereghetti & Stella (1995), we deduce that the optical counterpart for

1E 2259+586 would have $V \sim 20.8$ (including reddening of $A_v \sim 2.5$) (Coe & Jones 1992, Davies & Coe 1991), much brighter than the current limit $V \sim 23$. However, Davies & Coe point out that for low $\dot{M}$ and therefore low gas density in the accretion flow, disk material might be optically thin and not process the radiation effectively. The optical appearance is a possible difference between a disk around a solitary neutron star and one formed by mass flow in a low mass binary. An initial ring around a neutron star will have diffused outward as part of it accreted. Reprocessing of a given X-ray flux in a more extended disk, if it were optically thick, would probably lead to a brighter optical source. However, the properties of the disk, when X-ray illumination is taken into account, are not straightforward (Ko & Kallman 1991) and are beyond the scope of this paper.

There are many questions about both the evolution that would lead to the required binary and the evolution that could lead to accretion from a disk associated with a solitary neutron star, as well as about a possible relation to soft gamma-ray repeaters. Doppler shifts and optical identification would narrow the choices greatly. Meanwhile, the ensemble of observations show that the flux and the torques vary significantly in a way that so far is typical of an accreting binary. These variations are not resolved in the observations to date and would require sampling on time scales of several to a few hundred days to investigate correlations of the changing source parameters.

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Table 1: Spectral Fit Parameters[a] for PSPC observations

Obs.	model	norm.[b] (10^{-2})	α	norm.[c] (10^{-4})	kT(keV)	$N_H(10^{22}\mathrm{cm}^{-2})$	χ^2
1991	PL	6.71 ± 0.56	3.69 ± 0.13			1.07 ± 0.04	1.31
1993		4.56 ± 0.98	3.13 ± 0.34			0.85 ± 0.09	0.49
1991	BB			6.48 ± 0.29	0.32 ± 0.075	0.62 ± 0.02	1.53
1993				5.60 ± 0.52	0.35 ± 0.024	0.47 ± 0.06	0.51
1993	PL+BB[d]	0.996 ± 0.503	2.90 ± 0.29	4.80 ± 0.36	0.41 ± 0.044	0.61 ± 0.08	1.20

[a]Spectral fits were performed using the program XSPEC.

[b]Normalization for power-law model. Units are photons keV^{-1} cm^{-2} s^{-1} at 1 keV.

[c]Normalization for blackbody model. Norm = L_{39}/D_{10}^2, where L_{39} is the source luminosity in units of 10^{39} erg s^{-1} and D_{10} is the distance to the source in units of 10 kpc.

[d]Spectrum fitting *ROSAT* data, with *ASCA* data fit by 0.85 ± 0.01 of the same spectrum.

Table 2: The Measured Pulse Periods [a]

Epoch	J.D.-2,440,000	Period (s)	Satellite
1978	3522.5	6.978586 ± 0.000006	*HEAO-1*
1980	4398.5	6.97864 ± 0.000030	*Einstein*
1981	4629.0	6.97862 ± 0.000014	*Einstein*
1983	5620.0	6.978675 ± 0.000010	*Tenma*
1984	6036.0	6.978720 ± 0.000006	*EXOSAT*
1987	6968.9	6.978759 ± 0.000002	*Ginga*
1990	7876.0	6.978789 ± 0.000007	*Ginga*
1990	8113.0	6.978795 ± 0.000002	*Ginga*
1991	8446.0	6.978818 ± 0.000004	*ROSAT* PSPC
1992	8629.0	6.978806 ± 0.000006	*ROSAT* HRI
1992	8798.0	6.978824 ± 0.000007	*ROSAT* HRI
1993	9025.0	6.978837 ± 0.000006	*ROSAT* PSPC
1993	9138.0	6.9788465 ± 0.0000056	*ASCA*

[a] The pulse period measurements before those of *ROSAT* and *ASCA* are compiled from Iwasawa et al. (1992).

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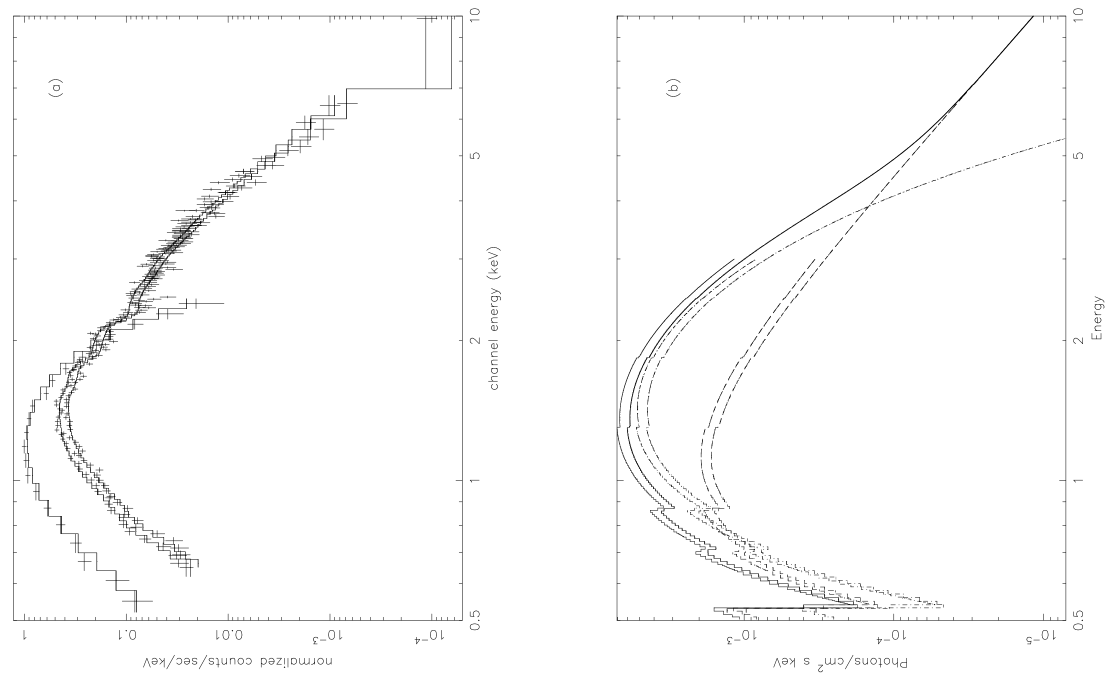
Fig. 1.— Average *ROSAT* and *ASCA* (1993) spectra of 1E 2259+586. (a) Observed and predicted counts s^{-1} keV^{-1} for the PSPC and the two SIS detectors for the same power-law plus blackbody model for both instruments, except for an overall normalization constant. (b) Model components (*dashed* power-law, *dot-dashed* blackbody) and resulting incident spectra (*solid line*) in photons cm^{-2} s^{-1} keV^{-1}, for both instruments.

Fig. 2.— Pulse frequency history of 1E 2259+586. Open symbols are from previously published data. Filled symbols are for the *ROSAT* observations reported here.

Fig. 3.— Flux (1-2 keV) and average angular acceleration history of 1E 2259+586. (a) Flux average for the 1-2 keV range for models fitting the data. (b) Average angular acceleration between frequency measurements.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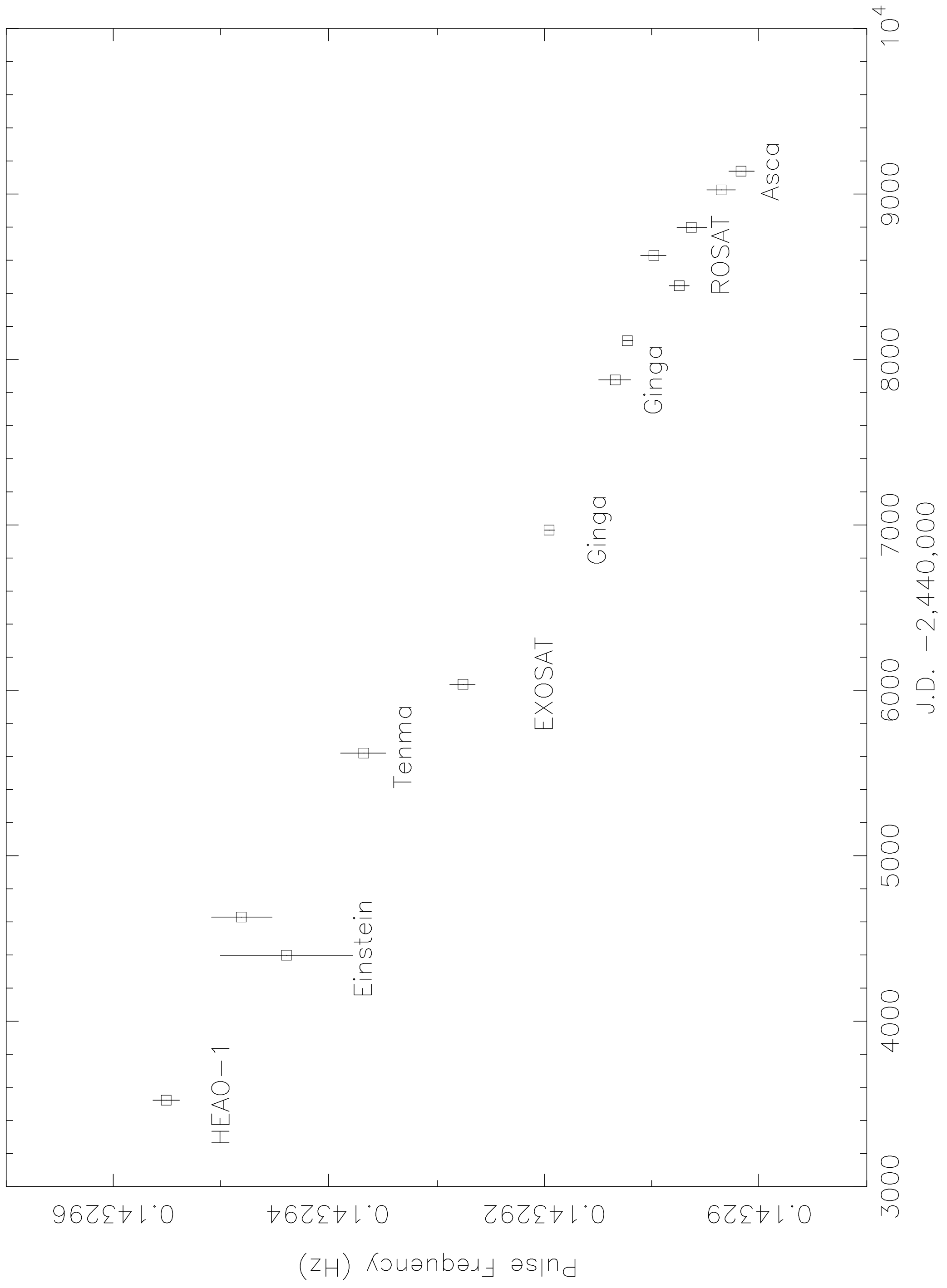
normalized counts/sec/keV
channel energy (keV)
(b)
Photons/cm² s keV
Energy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Einstein
Tenma
EXOSAT
Ginga
Ginga
ROSAT
Asca
Pulse Frequency (Hz)
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0.14329
J.D. −2,440,000
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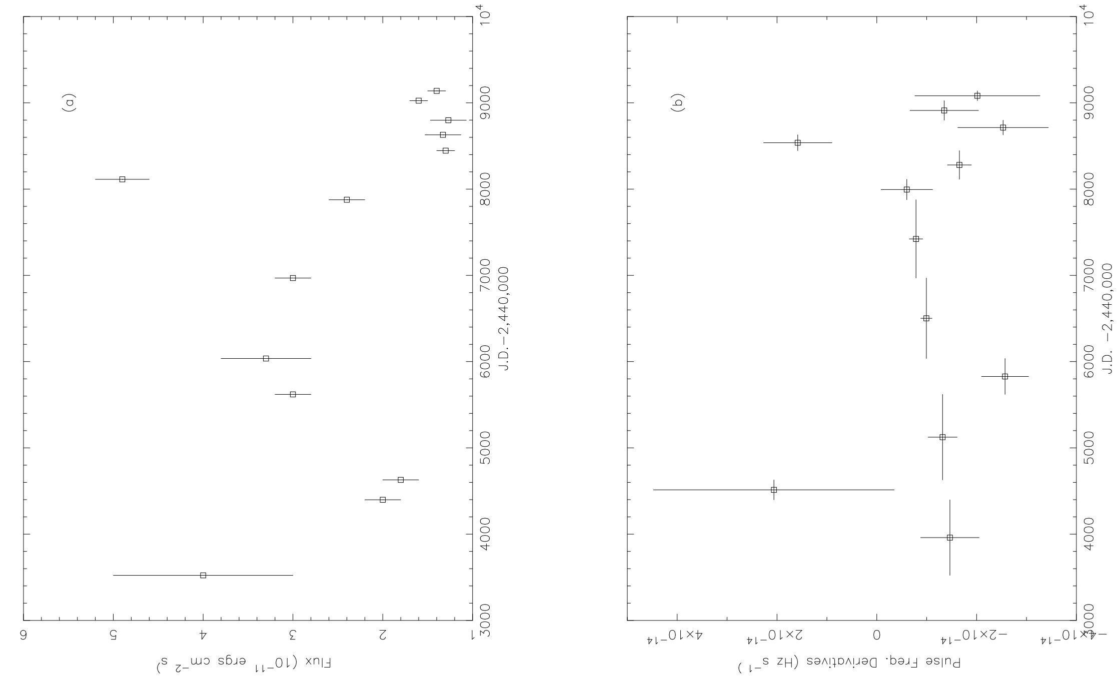
4000
5000
6000
7000
8000
9000
10^4


(a)
J.D. −2,440,000
Flux (10−11 ergs cm−2 s)
(b)
J.D. −2,440,000
Pulse Freq. Derivatives (Hz s−1)