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OBSERVATIONS OF ACCRETING PULSARS

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ABSTRACT

We discuss recent observations of accreting binary pulsars with the all-sky BATSE instrument on the *Compton Gamma Ray Observatory*. BATSE has detected and studied nearly half of the known accreting pulsar systems. Continuous timing studies over a two-year period have yielded accurate orbital parameters for 9 of these systems, as well as new insights into long-term accretion torque histories.

1. INTRODUCTION

There are over 30 known accreting pulsar systems. These contain a rotating high-magnetic-field ($B \geq 10^{11}$G) neutron star in orbit with a stellar companion which transfers mass to the neutron star via Roche-lobe overflow or a stellar wind. The gravitational energy released by mass accretion yields thermal and non-thermal radiation, most prominently at X-ray and gamma-ray energies. Neutron stars in accreting pulsar systems are often called "X-ray pulsars" or "accretion-powered" pulsars. An earlier comprehensive review of accreting pulsars is that of Nagase (1989).

In this paper, we discuss recent observational results on 14 of the accreting pulsar systems, using data from the Burst and Transient Source Experiment (BATSE) on the *Compton Gamma Ray Observatory* (*GRO*). We list these systems in Table 1, together with current information on position, pulse period (P_{spin}), orbital period (P_{orb}), and stellar type of the companion. Figure 1 indicates the location of the BATSE-studied pulsars and other pulsars in the ($P_{spin} - P_{orb}$) plane, commonly known as the "Corbet-diagram" (see Corbet 1986; Stella, White, and Rosner 1986; and Waters and van Kerkwijk 1989). The three types of high-mass (≥ 3 $M_{\odot}$) systems (wind-fed, disk-fed, and Be) populate relatively distinct regions of the diagram. The continuous BATSE spin-period measurements allow tests of models of the long-term spin evolution of pulsars in all three classes of systems.

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TABLE 1

ACCRETING PULSARS OBSERVED WITH BATSE AS OF 1993 DECEMBER

System	RA (2000)	Dec. (2000)	Period[a]		Companion (MK Type)
	[hh mm ss.s]	[° ′ ″]	Pulse [s]	Orbital [d]	
Low-mass systems					
Her X-1	16 57 49.7	+35 20 32	1.24	1.7	HZ Her (A9-B)
4U 1626-67	16 32 16.7	-67 27 42	7.66	0.02?	KZ TrA (low mass dwarf)
GX 1+4	17 32 02.1	-24 44 46	120	?	V2116 Oph?[b] (M6III)
High-mass supergiant systems					
Cen X-3	11 21 15.2	-60 37 24	4.8	2.09	V779 Cen (O6-8f)
OAO 1657-415	17 00 47.6	-41 39 14	37.7	10.4	? (B0-6Iab?)[c]
Vela X-1	09 02 06.8	-40 33 18	283	8.96	HD77581 (B0.5Ib)
4U 1538-52	15 42 23.3	-52 23 10	530	3.73	QV Nor (B0I)
GX 301-2	12 26 37.6	-62 46 13	681	41.5	Wray 977 (B1.5Ia)
Be-binary systems					
4U 0115+63	01 18 31.9	+63 44 24	3.6	24.31	V635 Cas (Be)
EXO 2030+375	20 32 15.3	+37 38 15	41.8	46.03	(Be)
A 0535+26	05 38 54.6	+26 18 57	105	110.58	HDE245770 (O9.7IIIe)
A 1118-616	11 20 57.2	-61 55 00	405	?	He 3-640 (O9.5III-Ve)
Systems with an undetermined companion					
GS 0834-430	08 35 55.1	-43 11 22	12.3	111.6	?
GRO J1008-57	10 09 46	-58 17 32	93.5	?	?

[a] For epoch TJD 8500.

[b] Suggested companion (Glass & Feast 1973; Davidsen et al. 1977; Chakrabarty et al. 1994)

[c] Companion not yet identified, but spectral type inferred from orbit and eclipse measurements (Chakrabarty et al. 1993).

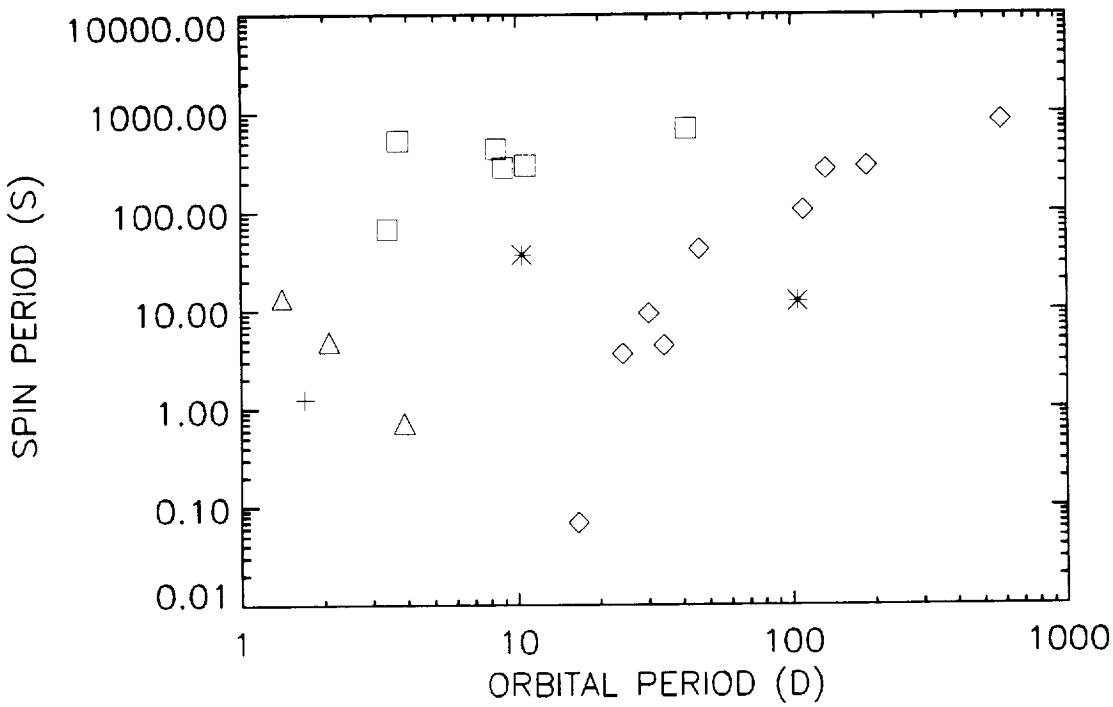

Figure 1. Corbet Diagram. Wind-fed systems are indicated by squares, high-mass disk-fed systems by triangles, Be-binaries by diamonds, low-mass systems by crosses, and systems with an unidentified stellar companion by asterisks

2. OBSERVATIONS

Observations of accreting binary pulsars have been carried out by BATSE since the launch of *GRO* in April 1991. The observations used the eight large area detectors (LADs) of the BATSE instrument, which have overlapping fields of view covering a total of 4π steradian. Each detector has an effective area of about 1500 cm^2 at 40 keV and an energy resolution of about 35% FWHM (Fishman *et al.* 1989). The LADs are sensitive from about 20 keV to 2 MeV and pulsar timing observations are primarily carried out from 20 keV to 60 keV. Several data types were used for pulsar analysis:

DISCLA data: Count rate samples of all 8 detectors at 1.024 s intervals in 4 energy channels.

CONT data: Count rate samples of all 8 detectors at 2.048 s intervals in 16 energy channels.

PSR data: Count rate samples folded into 64 phase bins with a programmable folding period and 16 energy channels (4 for periods shorter than about 20 ms).

DISCLA and CONT data have been used for timing and spectral studies of pulsars with pulse periods greater than about 2 s and 4 s respectively. PSR data have been used for study of fast accreting pulsars, in particular Her X-1. The DISCLA and CONT data provide continuous flux information on all pulsars not occulted by the earth, while the PSR data have typically been programmed to study specific pulsars with known pulse periods.

To detect a pulsar, the count rates from detectors with significant projected area towards the pulsar are weighted and summed. Systematic orbital background is subtracted either by filtering or by use of a background model. The power spectrum of the resulting residual counting rate is calculated and searched for significant peaks. Once a pulsar is detected, timing measurements are carried out in the usual fashion by constructing a pulse-phase or pulse-arrival time model which accounts for barycenter corrections, the orbit of the pulsar, and torque-induced spin-frequency changes. The best-fit model is used to determine the orbital parameters of the pulsar system.

The measured sensitivity of the BATSE detectors for pulsed flux detection is shown in Figure 2. Searches up to this time (Jan 1994) have used 1-4 day observation periods. The sensitivity is affected by earth-orbital noise for periods greater than about 200 s. The sensitivities for individual CONT energy channels are indicated in Figure 2, as well as sensitivities obtained by combining several energy channels. Typically, the lowest three CONT channels shown in Figure 2 are used for pulsar detection. Also shown for comparison is the approximate *pulsed* Crab flux; the total Crab flux is a factor of about 5-10 higher depending on energy.

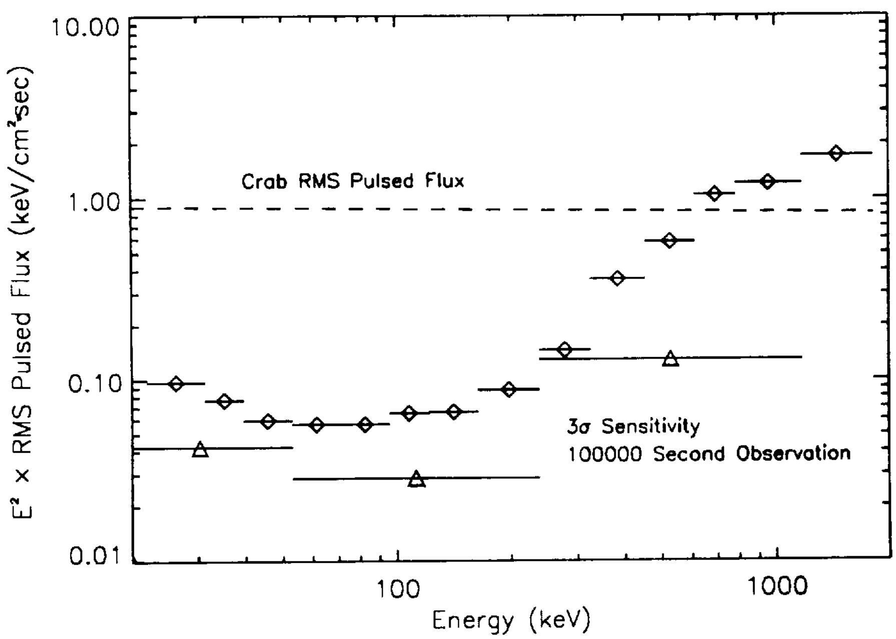

Figure 2. BATSE Pulsed-Flux Sensitivity.

3. RESULTS

Dynamical Studies

BATSE has determined the orbits of OAO 1657-415 and GS 0834-430 and has provided improved or additional orbital solutions for 7 other systems: 3 Be-binary systems (EXO 2030+375 A0535+26, and 4U 0115+63), 3 high-mass supergiant systems (Cen X-3, Vela X-1, and 4U 1538-52), and one low-mass system (Her X-1). In addition, one new accreting pulsar has been discovered, GRO J1008-57. Because many of these sources are transient in nature, the continuous monitoring capability of BATSE allowed timing measurements to be performed whenever the systems were active, thus providing the necessary coverage to determine or improve the orbital parameters.

Table 2 provides the current best-fit orbital parameters for 15 accreting pulsar systems. We have used BATSE data to derive orbital parameters for 9 of these systems. We discuss a few of these briefly below.

OAO 1657-415. This system was initially discovered as an X-ray source by the *Copernicus* satellite (Polidan *et al.* 1978). The source was observed by several other X-ray satellites and showed both spin-up and spin-down behavior but no definite indication of orbital modulation of the pulse period. Observations with BATSE (Chakrabarty *et al.* 1993) detected the 10.4 day orbital period of this system and determined that OAO 1657-415 was an eclipsing high-mass system. The optical companion has not yet been identified, but the spectral type is likely B0-6Iab, inferred from the orbit and eclipse measurements. Identification of the companion and measurement of its orbital Doppler curve would constrain the mass of the neutron star in this system.

GS 0834-430. This system was initially discovered in an outburst during February, 1990 by the WATCH detectors on the *Granat* spacecraft (Lapshov *et al.* 1992). Pulsations at 12.3 s were discovered by *Ginga* in November, 1990 and an accurate position determined (Aoki *et al.* 1992). A 114 day periodicity in the outbursts was later reported by *Granat*/WATCH, indicating a likely orbital period (Lapshov *et al.* 1992). BATSE observations were carried out using both occultation analysis for unpulsed flux, and standard timing analysis for the pulsed component and has been reported in Wilson *et al.* (1994a). BATSE has observed seven outbursts of GS 0834-430 since *GRO* began observations, allowing measurement of the orbital parameters of the system (see Table 2).

Accurate measurement of the orbital eccentricity is important, but is complicated by the uncertainty in the decoupling of the accretion and Doppler induced pulse-frequency changes. If the eccentricity is very close to zero, the companion is probably a 2-5 $M_\odot$ giant that has circularized the orbit due to dissipation in its envelope. On the other hand, if the eccentricity is small but finite (e.g. 0.1-0.2) the companion is almost certainly not a giant, but might possibly be a B or perhaps a Be star. An optical/IR companion has not yet been identified.

TABLE 2

ORBITAL PARAMETERS OF ACCRETING PULSAR SYSTEMS

		Orbital epoch (TJD)	P_{orb} (days)	$a_x \sin i$ (light seconds)	e	ω (degrees)	$f_x(M)$ (solar masses)	Refs.[a]
	Low-mass system							
•	Her X-1	8799.61235 ± 0.00001[c]	$1.700167412 \pm (4.0 \times 10^{-8})$[i]	13.1853 ± 0.0002	$< 1.3 \times 10^{-4}$[f]	...	0.8517 ± 0.0001	1,2
	High-mass supergiant systems							
	LMC X-4	7741.9904 ± 0.0002[d]	1.40839 ± 0.00001	26.31 ± 0.03	0.006 ± 0.002	...	9.86 ± 0.03	3
•	Cen X-3	$8561.656702 \pm (7.1 \times 10^{-5})$[c]	$2.08706533 \pm (4.9 \times 10^{-7})$	39.627 ± 0.018	$< 1.6 \times 10^{-3}$[g]	...	15.343 ± 0.021	4
•	4U 1538-52	5278.979 ± 0.020[c]	3.72840 ± 0.00003[j]	52.8 ± 1.8[h]	...	...	11.4 ± 1.2	5,6,7
	SMC X-1	7740.35906 ± 0.00003[c]	$3.89229118 \pm (4.8 \times 10^{-7})$[e]	53.4876 ± 0.0004	< 0.00004[g]	...	10.8481 ± 0.0002	8
	4U 1907+09	5575.465 ± 0.35[k]	8.3745 ± 0.0042	80.2 ± 7.2	$0.16^{+0.14}_{-0.11}$	330^{+18}_{56}	7.9 ± 2.1	9,10
•	Vela X-1	8563.5364 ± 0.0033[c]	8.964416 ± 0.000049[h]	113.61 ± 0.30	0.0883 ± 0.0023	153.2 ± 1.7	19.60 ± 0.16	11,12
•	OAO 1657-415[b]	8515.99 ± 0.05[c]	10.4436 ± 0.0038	106.0 ± 0.05	0.104 ± 0.005	93 ± 5	11.7 ± 0.2	13
	GX 301-2	3906.06 ± 0.16[d]	41.508 ± 0.007	371.2 ± 3.3	0.472 ± 0.011	309.9 ± 2.6	31.9 ± 0.8	14
	Be-binary systems							
•	4U 0115+63	8355.206 ± 0.004[d]	24.309 ± 0.010[h]	140.13 ± 0.08[h]	0.3402 ± 0.0002[h]	47.66 ± 0.03	5.00 ± 0.01	15,16
	2S 1553-54	2596.67 ± 0.03[c]	30.2 ± 0.1	162.7 ± 1.0	...	...	5.0 ± 0.1	17
	V 0332+53	5651.5 ± 1[d]	34.25 ± 0.10	48 ± 4	0.31 ± 0.03	313 ± 10	0.10 ± 0.02	18
•	EXO 2030+375	8798.2 ± 0.7[d]	46.03 ± 0.01	268 ± 25	0.33 ± 0.03	228.2 ± 5.7	9.8 ± 2.7	19
•	A 0535+26	9058.7 ± 0.6[d]	110.3 ± 0.3	267 ± 13	0.47 ± 0.02	130 ± 5	1.64 ± 0.23	20
	System with undetermined companion							
•	GS 0834-430	8591.70 ± 0.51[c]	111.64 ± 0.18	205.7 ± 5.0	0.128 ± 0.063	275 ± 30	0.75 ± 0.05	21

Orbital elements for sources marked with bullets (•) have been measured with *GRO*/BATSE.

[a] References: (1) Deeter et al. 1991; (2) Wilson et al. 1994b; (3) Levine et al. 1991; (4) Finger et al. 1993; (5) Makishima et al. 1987; (6) Corbet et al. 1993; (7) Rubin et al. 1994; (8) Levine et al. 1993; (9) Makishima et al. 1984; (10) Cook & Page 1987; (11) Deeter et al. 1987; (12) Finger 1993; (13) Chakrabarty et al. 1993; (14) Sato et al. 1986; (15) Rappaport et al. 1978; (16) Cominsky et al. 1994; (17) Kelley et al. 1983; (18) Stella et al. 1985; (19) Stollberg et al. 1994; (20) Finger et al. 1994b; (21) Wilson et al. 1994a.

[b] Companion not yet identified, but inferred to be a B-supergiant from orbit and eclipse measurements (Chakrabarty et al. 1993).

[c] $T_{\pi/2}$ = epoch of 90° mean orbital longitude.

[d] T_{peri} = epoch of periastron passage.

[e] Epoch TJD 2836.18277 ± 0.00020. $\dot{P}_{orb}/P_{orb} = (-3.36 \pm 0.02) \times 10^{-6}\ \mathrm{yr}^{-1}$.

[f] 2σ upper limit.

[g] 3σ upper limit.

[h] This element held fixed at this value in fitting other elements.

[i] Orbital period for specified orbital epoch, computed using P_{orb} and $\dot{P}_{orb}$ from Deeter et al. 1991. Held fixed in fitting other elements.

[j] Orbital period for specified orbital epoch, computed using P_{orb} and $\dot{P}_{orb}$ from Rubin et al. (1994).

[k] Orbital epoch for longitude $309° \pm 15°$. Held fixed in fitting other elements.

EXO 2030+375. This system was discovered by *EXOSAT* in May, 1985 (Parmar *et al.* 1989). The orbital period was determined to be $\sim$ 46 days, with some ambiguity in the orbital determination due to the finite extent of the *EXOSAT* observations. BATSE has observed EXO 2030+375 in a dozen consecutive orbits, allowing a very precise orbit to be determined, particularly for orbital phases near periastron (see Stollberg *et al.* 1994 and Table 2).

A 0535+26. Although this system has been observed in outburst many times and at many wavelengths (for a review, see Giovannelli and Graziati, 1992), the orbit of the system has never been accurately determined. Recent activity in 1993 of the A 0535+26 system has allowed observations over three consecutive orbits with BATSE leading to the first definitive published orbital parameters (see Finger *et al.* 1994b and Table 2).

GRO J1008-57. This 93.5 s pulsar was discovered by BATSE on 14 July 1993, reached maximum intensity approximately 10 days later, and remained active for a total of about one month (Wilson *et al.* 1994c). The pulsar showed significant frequency evolution with spin-down and spin-up behavior roughly correlated with the hard X-ray flux increase and decrease respectively, similar to the Doppler-induced behavior observed in outbursts of EXO 2030+375. The spin evolution of the system, its transient nature, the fact that the luminosity is a significant fraction of the Eddington luminosity for a fiducial distance of 5 kpc, and the low galactic latitude of 1° are all strongly suggestive of a Be-binary pulsar. From the Corbet-diagram (Figure 1) a 93.5 s Be-binary pulsar might be expected to have an orbital period of 100-200 d. However, no additional emission has been detected from this source through the end of 1993.

Her X-1. This system is perhaps the best studied of all accreting binary pulsars. New results from BATSE (Wilson *et al.* 1994b) show a correlation between the hard X-ray flux at the peak of the main-on portion of the 35d cycle and the spin-frequency derivative, i.e. spin-down is correlated with low-flux as predicted by models such as those of Ghosh and Lamb (1979). Also, BATSE observations of the turn-on times of the 35d cycle indicate a possible correlation of early turn-on with decreased mass-transfer.

4U 1538-52. Analysis of this system using BATSE data has only recently begun. Preliminary results given by Rubin *et al.* (1994) show a secular spin-up trend after almost 10 years of spin-down behavior. Further BATSE analysis will yield a significantly improved orbital solution for this system.

Torque Studies

Accreting pulsars provide a laboratory for the studies of the torque exhibited during magnetic accretion, allowing for a comparison to existing theory (see Ghosh & Lamb 1979). The continuous monitoring capability of BATSE has allowed long-term studies of accretion torques in several systems. These include Her X-1, Vela X-1, Cen X-3, GX 1+4, 4U 1626-67, and OAO 1657-415. The frequency histories for these sources for a period of over two years are shown in Figures 3a&b. Figure 3a shows spin-frequency histories for sources whose accretion is thought to be disk-fed. These are discussed in more detail below. For comparison, Figure 3b shows measurements of Vela X-1, which is a wind-fed accretor, and OAO 1657-415, which may be either disk-fed or wind-fed and sits in the Corbet diagram intermediate between the two types of systems.

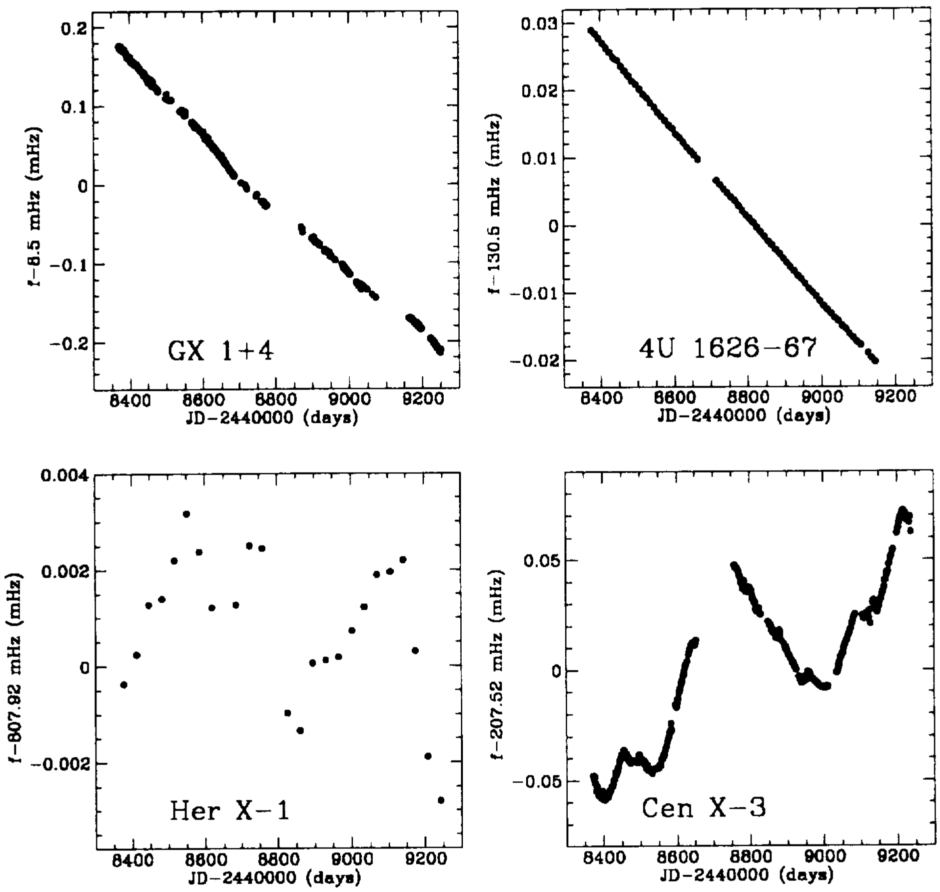

Figure 3a. Spin-frequency history for probable disk-fed systems.
(For Her X-1, mean frequencies for each main-on portion of the 35d cycle.)

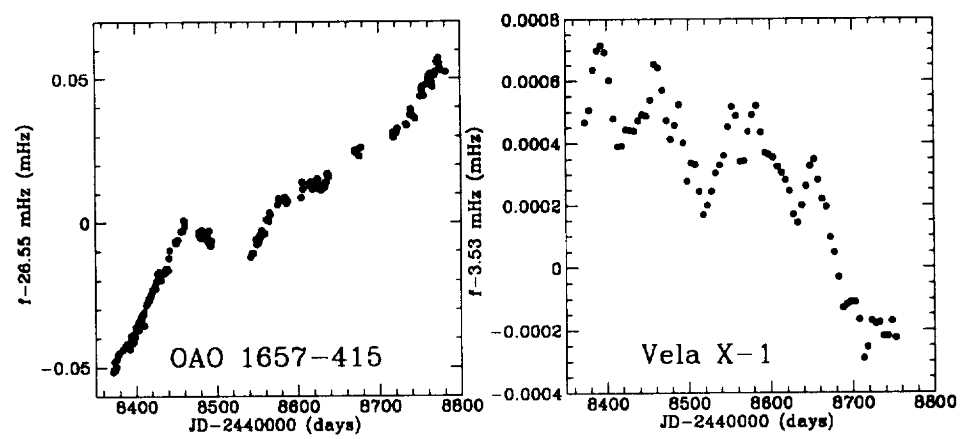

Figure 3b. Spin-frequency history for probable wind-fed systems.

The very different qualitative behavior of the various systems is immediately apparent from Figure 3. In particular, GX 1+4 and 4U 1626-67 both show a monotonic spin-down with nearly constant average rate while other disk-fed and wind-fed systems exhibit frequent changes in sign of the frequency derivative.

The torque however does switch sign on decade time scales in GX 1+4 and 4U 1626-67. From its discovery until the late 1980s, GX 1+4 was observed to be in a state of monotonic spin-up. Given its short spin-up time ($t_{su} \approx 40$ yr) compared to the system evolution time ($t_{evol} \gtrsim 10^6$yr), this was clearly not a permanent state, and *GINGA* and BATSE observations of a switch to spin-down in GX 1+4 (Makishima *et al.* 1988 Chakrabarty *et al.* 1994) showed that this was indeed the case. BATSE has found that 4U 1626-67 ($t_{su} \approx 4000$ yr) has also changed from spin-up to spin-down (Bildsten *et al.* 1994), and surprisingly, with the same average value of the torque but opposite sign. Since a disk reversal in this Roche-lobe overflow system is hard to imagine, we interpret the steady spin-down as a sign that the pulsar is spinning near its equilibrium period, where the magnetospheric radius equals the co-rotation radius (see Ghosh & Lamb 1979), requiring a magnetic field strength of order $\approx 3 \times 10^{12}$ G for 4U 1626-67 (and 10^{14} G for GX 1+4).

The simplest working hypotheses given the observations and the accretion torque theories of Ghosh and Lamb are then: (1) since $t_{su} \ll t_{evol}$, X-ray pulsars quickly reach the equilibrium period, as determined from the accretion rate and magnetic field strength, (2) once there, the X-ray pulsar oscillates about the equilibrium period by having counteracting periods of spin-up and spin-down. This hypothesis was checked with pre-BATSE data by comparing the observed long-term ($\gtrsim$ yrs) torque to the fiducial value, $N_f = \dot{M}(GMr_{co})^{1/2}$, where $\dot{M}$ is the maximum inferred mass accretion rate, M is the neutron star mass, and $r_{co} = (GM/\omega_s^2)^{1/3}$ is the co-rotation radius and ω_s is the angular spin frequency. For both GX 1+4 and 4U 1626-67 (and also SMC X-1 and 1E 2259+586) the observed long-term average torque, N_o, always satisfies $N_o \gtrsim 0.2N_f$, which, within the uncertainties, is consistent with accretion from matter near the co-rotation radius. These sources, which might be called "steady-staters", show monotonic spin-up or spin-down over a few year time scale.

As can be seen from Figure 3, other disk-fed sources such as Her X-1 and Cen X-3 show quite different behavior. The long-term ($\gtrsim$ yrs) torque, N_o, measured for these sources (as well as LMC X-4) was nearly a factor of 100 smaller than N_f, implying different torquing behavior than in the "steady-staters". These "wanderers" have frequency histories that are more consistent with a random-walk (Baykal & Ogelman 1993), which could arise if the torque had a value near N_f, but changed sign on a shorter timescale. The measured long term torque would thus be less than N_f. Recent short timescale ($\lesssim$10$-$20 d) torque measurements for Her X-1 and Cen X-3 by BATSE always find a torque larger than N_o, but never in excess of N_f (Wilson *et al.* 1994b, Finger *et al.* 1994a).

This classification scheme suggests that all disk-accreting pulsars show torques with magnitude $\lesssim N_f$ on the shortest timescales and differentiate themselves by the torque switching time. The wanderers switch within $\sim$ 60 days, whereas the steady-staters switch once in 10-20 years. The primary issue for these systems is identifying the physics that sets this timescale.

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