Recent Results from Observations of Accreting Pulsars

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Abstract. Since its launch in 1991, the Compton Gamma Ray Observatory (CGRO) has provided a wealth of new information on binary systems containing a magnetized neutron star accreting from a stellar companion. In particular, the all-sky monitoring capability of the BATSE instrument has allowed the first long-term continuous measurements of the flux and torque histories of the brighter accreting pulsar systems. These have given new insights into the processes by which mass and angular momentum are exchanged between the accretion disk and the neutron star, and the role of radiation and X-ray driven winds in these systems. Observations of transient pulsars with BATSE and OSSE have provided new quantitative tests of standard theories of disk-magnetosphere interactions. Although many new insight have been gained, some of the observations present new puzzles and challenge current models of accretion processes. We review these observations, as well as a sampling of other recent results from CGRO and the ROSSI X-ray Timing Explorer (RXTE).

INTRODUCTION

Spinning magnetized neutron stars with stellar companions provide unique sites for studying mass and angular momentum transfer in binaries, as well as the winds and mass loss from evolved stars. Measurement of the x-ray and hard x-ray flux yields a measure of the mass accretion rate ($\dot{M}_{\rm ns}$), while measurement of the time dependence of the spin frequency ($\nu_{\rm spin}$) can yield estimates of the torque on the neutron star (N), the mass of the companion ($M_{\rm c}$), the orbital period ($P_{\rm orb}$), and the eccentricity (e).

Since the first discovery of an accreting pulsar system, Cen X-3, over 25 years ago, observations have identified the basic classes of accreting pulsars, and have motivated simple "standard models" for the accretion torques and capture of material in these systems (see the reviews: [45,61,26,40,62]). Prior to the launch of CGRO, observations of accreting pulsars were carried out primarily with pointed X-ray telescopes. Since the launch of CGRO in 1991, the Large Area Detectors (LADs) of the Burst and Transient Source Experiment (BATSE) with their 4π steradian field of view have provided continuous monitoring of the brighter accreting pulsars, except for brief periods of earth-occultation. This has made it possible to establish the torque histories of these sources on time scales from days to years. Continuous monitoring has also allowed detailed study of the outburst characteristics of transient pulsars.

In the next section we present an overview of accreting pulsars and the CGRO observations of them. This is followed by a review of results on several selected topics of recent interest including, torque-flux measurements in transient systems, torque switching behavior in wind- and disk-fed systems, characteristics of transient outbursts, the population and orbits of transient systems, the recently detected very-high energy emission from Cen X-3, and some recent results from RXTE. Much of this review covers results obtained by BATSE since the launch of CGRO. We draw heavily from the extensive article by Bildsten et al. [5] (hereafter referred to as Paper I) which discusses the BATSE results in detail.

OVERVIEW

As of the time of this review, there are 44 known accreting pulsars, 26 of which are transients, with spin periods, $P_{\rm spin}$, ranging from 0.069 s through 1413 s (see Table 1). Half of these pulsars have been observed by CGRO, with many of these observations being quite extensive. These sources are thought to be rotating, highly magnetized neutron stars, which radiate X-rays and γ-rays due to accretion of matter. For many of these pulsars a binary companion, from which the accreting matter originates, has been identified. The strong magnetic field ($B \sim 10^{11-13}$ G) controls the accretion flow close to the neutron star forcing captured material to flow along magnetic field lines to the magnetic poles. Misalignment of the rotation axis with the dipole field and asymmetric emission from the accreting polar cap leads to pulsed emission at $\nu_{\rm spin}$ with a luminosity $L_{\rm acc} \sim GM_{\rm ns}\dot{M}_{\rm ns}/r_{\rm ns}$, where $M_{\rm ns}$ and $r_{\rm ns}$ are the mass and radius of the neutron star. The angular momentum of the accreting material and interactions between the accretion flow and the magnetic field produce torques on the neutron star, which can result in observable spin frequency changes over a few days.

Binary accreting pulsars can be classified according to the mass of the donor star as either *low-mass* ($M_{\rm c} \lesssim 2.5\, M_\odot$) or *high-mass* ($M_{\rm c} \gtrsim 6\, M_\odot$) systems. The high mass binaries may be divided into those with main-sequence Be star companions and those with evolved OB supergiant companions. The supergiant binaries may be further subdivided into those accreting via Roche-lobe overflow mediated by an accretion disk (disk accretors) and those accreting from the companion's stellar wind (wind accretors). As shown in Figure 1 these classes appear to occupy distinct regions in a $P_{\rm spin}$-$P_{\rm orb}$ diagram [11,60]. Su-

Table 1: Known Accretion-Powered Pulsars (as of Feb. 1997)

	System[a]	l_{II}	b_{II}	P_{spin} (s)	P_{orb} (d)	Companion (MK Type)
	Low-mass binaries					
BO	GRO J1744–28	0.0	+0.3	0.467	11.8	
BO	Her X-1	58.2	+37.5	1.24	1.70	HZ Her (A9-B)
B	4U 1626–67	321.8	-13.1	7.66	0.0289	KZ TrA (low-mass dwarf)
BO	4U 1728–247 (GX 1+4)	1.9	+4.8	120		V2116 Oph (M6III)
	High-mass supergiant and giant systems					
	SMC X-1	300.4	-43.6	0.717	3.89	Sk160 (B0 I)
BE	Cen X-3	292.1	+0.3	4.82	2.09	V779 Cen (O6–8f)
	RX J0648.1–4419	253.7	-19.1	13.2	1.54	HD 49798 (O6p)
	LMC X-4	276.3	-32.5	13.5	1.41	Sk-Ph (O7 III-V)
B	OAO 1657–415	344.4	+0.3	37.7	10.4	(B0–6Iab)
BO	Vela X-1	263.1	+3.9	283	8.96	HD77581 (B0.5Ib)
	1E 1145–614	295.5	-0.0	297	5.65	V830 Cen (B2Iae)
	4U 1907+09	43.7	+0.5	438	8.38	(B I)
B	4U 1538–52	327.4	+2.1	530	3.73	QV Nor (B0Iab)
B	GX 301–2	300.1	-0.0	681	41.5	Wray 977 (B1.5Ia)
	Transient Be-binary systems					
	A 0538–67	276.9	-32.2	0.069	16.7	(B2 III-IVe)
BO	4U 0115+63	125.9	+1.0	3.61	24.3	V635 Cas (Be)
	V 0332+53	146.1	-2.2	4.37	34.2	BQ Cam (Be)
BO	2S 1417–624	313.0	-1.6	17.6	42.1	(OBe)
BO	EXO 2030+375	77.2	-1.3	41.7	46.0	(Be)
BO	GRO J1008–57	283.0	-1.8	93.5	≈ 248	(Be)
BO	A 0535+26	181.4	-2.6	105	110	HDE245770 (O9.7IIe)
	GX 304–1	302.1	+1.2	272	133 (?)	V 850 Cen (B2Vne)
B	4U 1145–619	295.6	-0.2	292	187	Hen 715 (B1Vne)
B	A 1118–616	292.5	-0.9	405		He3-640 (O9.5 III-Ve)
O	4U 0352+309	163.1	-17.1	835		X Per (O9 III-Ve)
	RX J0146.9+6121	129.9	-0.5	1413		LSI +61° 235 (B5 IIIe)
	Persistent systems with an undetermined companion					
	RX J1838.4–0301	28.8	+1.5	5.45		
	1E 1048–593	288.2	-0.5	6.44		
	1E 2259+586	109.1	-1.0	6.98		
	RX J0720.4-3125	244.2	-8.2	8.38		
	4U 0142+614	129.4	-0.4	8.69		
	Transient systems with an undetermined companion					
B	RX J0059.2–7138[c]	302.1	-45.5	2.76		
	RX J0502.9–6626	277.0	-35.5	4.06		
B	GRO J1750–27	2.4	+0.5	4.45	29.8	
	2E 0050.1–7247	302.9	-44.6	8.9		
	2S 1553–54	327.9	-0.9	9.26	30.6	
B	GS 0834–430	262.0	-1.5	12.3	106	
B	GRO J1948+32	64.9	1.8	18.7		
B	GS 1843+00	33.1	+1.7	29.5		
	GS 2137+57 (Cep X-4?)	99.0	+3.3	66.2		
B	GS 1843–024	30.2	-0.0	94.8		
	Sct X-1	24.5	-0.2	111		
B	GRO J2058+42	83.6	-2.7	198	$\sim$110	
	GPS 1722–363	351.5	-0.6	414		

[a]Sources labeled by B,O, and E have been detected with BATSE, OSSE, or EGRET respectively.

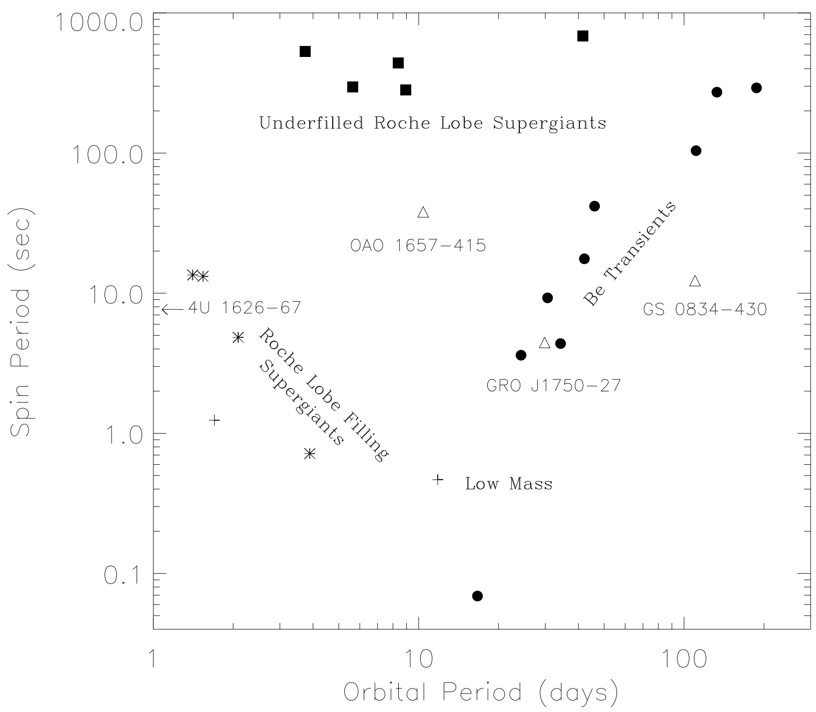

FIGURE 1. Spin period of accreting pulsars versus the binary period. Be transients are plotted as open circles, low-mass objects as plus signs, disk-fed OB supergiants with asterisks and wind-fed OB supergiants with squares. Triangles denote sources with unknown companions. For clarity the low mass system 4U 1626-67 has been left off the plot.

pergiant systems (asterisks) filling, or close to filling their Roche lobe have short spin ($P_{\rm spin} \lesssim 10$ s) and orbital periods ($P_{\rm orb} \lesssim 4$ d). They are persistent, quite luminous ($L \gtrsim 10^{37}\,{\rm erg\,s^{-1}}$), and tend to show long episodes ($\gtrsim P_{\rm orb}$) of relatively steady torques. Wind-fed supergiant binaries (squares) have longer orbital and spin periods. They are persistent, but less luminous ($L_{\rm x} \sim 10^{35}$–10^{37} erg s^{-1}), and display rapid fluctuations in accretion torque on timescales much shorter than their orbital period. The pulsars with Be star companions (circles) populate a third region of the diagram, displaying a correlation between their spin and orbital periods. These are are transients, with outbursts associated with periastron passage in their eccentric orbits. Low mass systems (pluses) vary widely in their properties. Three of these sources are persistent, while the newly discovered GRO J1744-28, which is covered in a separate review, is a transient.

An additional class, the so-called "6 second pulsars" has also been proposed [37]. These persistent sources with pulse periods near 6 s shown no evidence of binary companions. It has been suggested they are isolated pulsars which accrete from a circumstellar disk formed from the remnants of a previous evolutionary stage [54].

BATSE has continuously monitored the spin frequency and 20$\sim$70 keV pulsed flux of 8 persistent pulsars (see Table 1) on a daily basis, and monitored the spin frequency and pulsed flux during $\sim$60 outbursts from 13 transients. These observations have uncovered 5 new accreting pulsars, have allowed the first measurement of 6 orbits and the refinement of 7 others, and provide the first long-term (6 yr), continuous, spatially uniform survey of the activity of transient accreting pulsars. Extensive references are given in Paper I.

OSSE has observed 3 persistent accreting pulsars and 7 transients (see Table 1). Pulse profiles for GX 1+4 are given by Maisack et al. [34]. The OSSE observations of the Be/X-ray transient A0535+262 revealed a cyclotron line in the phase averaged flux spectrum at 110 keV, implying a magnetic field near 10^{13} G [23]. The phase resolved spectra have been analyzed by Maisack et al. [33,35]. Negueruela et al. [41] compare the OSSE observations of 4U 0115+63 with BATSE, optical, and IR observations. A summary of Be/pulsar binary results is given by Grove [24]. OSSE observations of the transient low-mass accretion pulsar GRO J1744-28 revealed pulse phase lags within its bursts [51].

A detection by EGRET of an outburst of $>$ 100 MeV photons from the persistent pulsar Cen X-3 has been reported by Vestrand et al. [56]. This discovery is discussed below.

RECENT RESULTS

Torques In Transient Pulsar Outbursts

Dramatic spin frequency increases are observed during the largest transient pulsar outbursts, implying the presence of accretion disks. Comparisons of the torques inferred from BATSE frequency observations during large transient outbursts with simultaneous flux and QPO measurements have provided new tests of accretion theory.

At the boundary between an accretion disk and a neutron star magnetosphere, the accretion flow changes from nearly Keplerian motion to an inflow constrained to move along the magnetic field lines, which rotate with the neutron star. This poorly understood boundary region is located at a radius [44,31]:

$$r_{\rm m} \;=\; K\mu^{4/7}(GM_{ns})^{-1/7}\dot{M}_{ns}^{-2/7} \qquad (1)$$

where K is a constant thought to be between 0.5 and 1 and μ the neutron star magnetic moment. Equation 1 with $K = 0.91$ gives the Alfvén radius for spherical accretion. Assuming the gas deposits its angular momentum at the magnetospheric boundary and that field lines transport all of this angular momentum to the star, the accreting pulsar will experience a spin-up torque

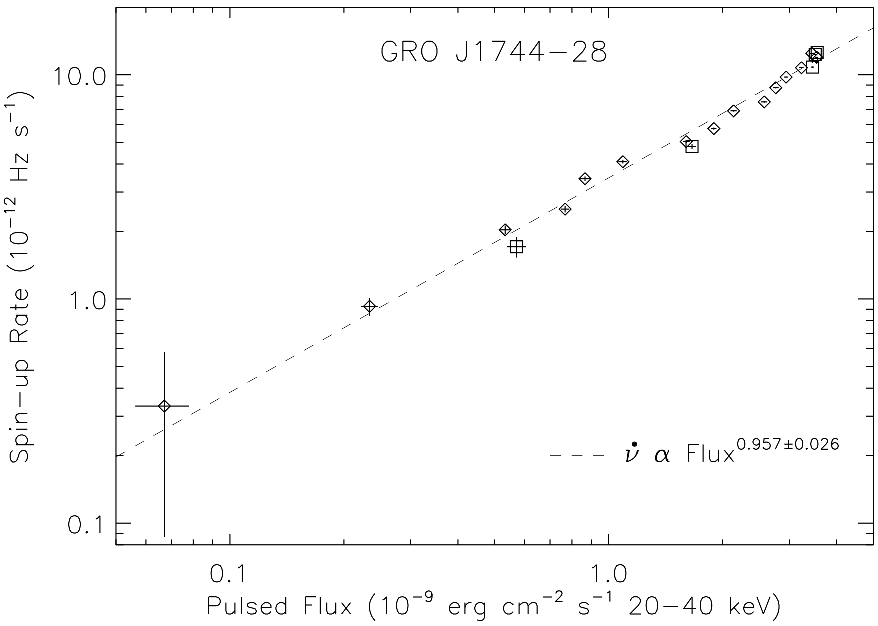

FIGURE 2. The spin-up rate versus flux relationship for GRO J1744-28 during the discovery outburst. The square symbols are on the rise of the outburst, the diamonds are on the decline. The line gives the best fit power-law, which has an index of 0.957 ± 0.026.

$$N \;=\; I2\pi\dot{\nu}_{\rm spin} \;\approx\; \dot{M}_{\rm ns}(GM_{\rm ns}r_{\rm m})^{1/2} \tag{2}$$

where I is the moment of inertia of the neutron star. $(GM_{\rm ns}r_{\rm m})^{1/2}$ is the specific angular momentum of matter in a Keplerian orbit at the inner disk radius $r_{\rm m}$.

At lower mass accretion rates torques caused by the interaction of the magnetic field with the accretion disk [22] must be considered. The torques are predicted to be negative and dominate the direct accretion of angular momentum (eq. 2), causing spin-down, when the magnetosphere approaches the corotation radius. At the corotation radius, $r_{\rm co} = (GM_{\rm ns})^{1/3}(2\pi\nu_{\rm spin})^{-2/3}$, the period of the Keplerian orbit is synchronous with the rotation of the neutron star. At yet lower mass accretion rates, the magnetospheric radius expands outside the corotation radius, and the accretion flow shuts-off by the centrifugal force acting on any material corotating with the magnetic field. This centrifugal inhibition of accretion is expected during the quiescent state of transient pulsars [50].

At high mass accretion rates the spin-up rate $\dot{\nu}_{\rm spin}$ is predicted to depend on the flux F as $\dot{\nu}_{\rm spin} \propto F^{\alpha}$ with $\alpha = 6/7$ (assuming that $F \propto \dot{M}_{\rm ns}$). The first observational test of this prediction was with the EXOSAT observation of EXO 2030+375, which found $\dot{\nu}_{\rm spin} \propto F^{\alpha}$ with $\alpha \sim 1.2$. The test was over a fairly small dynamic range in $\dot{\nu}_{\rm spin}$, because of the difficulty of simultaneously determining the spin-up rate and the pulsar's orbital parameters.

The observations with BATSE of the bursting pulsar GRO J1744-28 [19] provide a test of the predicted relation between spin-up and flux over a larger dynamic range. This is shown in Figure 2, which compares the observed spin-up range with the 20-40 keV pulsed flux. The power-law behavior is clear, with points from the rise and fall of the outbursts matching nicely. On the other hand, minor systematic variations from the best fit power-law are evident. The best fit power-law index of $\alpha = 0.954 \pm 0.026$ is near, but formally inconsistent with the expected 6/7. This could be due either to a deviation from the torque predicted by equation 2, or a non-linear relationship between the hard X-ray pulsed flux and mass accretion-rate.

In general, a non-linear dependence of the flux on mass accretion-rate is expected. Pulsar beaming patterns change with luminosity, changing the spectra, pulse profile and the overall degree of beaming. Changes in the pulse profile (and hence the pulse fraction) will particularly effect the pulsed flux used in Figure 2. Empirical determination of the dependence of the magnetospheric radius on mass accretion rate (eq. 1) by torque-flux comparisons may therefore not be feasible.

Observations in 1994 of Quasi-Periodic Oscillations (QPO) in A 0535+262 [18] provided an alternative probe of the dependence of the magnetospheric radius on mass accretion rate. The relationships between the QPO frequency, the spin-up rate, and the flux observed in this outburst are shown in Figures 3 and 4. Also shown are the predictions of the beat frequency model [1] and the Keplerian frequency model [53]. In the beat frequency model the QPO

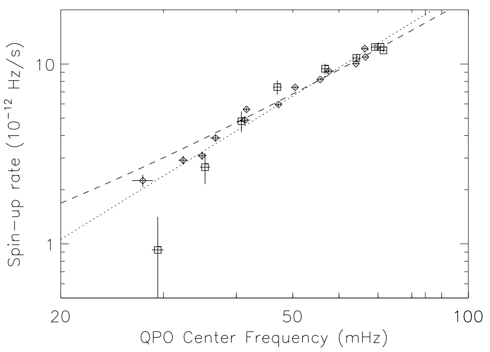

FIGURE 3. The spin-up rate versus the QPO frequency for A 0535+262. Squares are on outburst rise, diamonds on outburst decline. The lines give the predicted relationship for the beat frequency (dashed) and Keplerian frequency (dotted) models, with best fit normalizations.

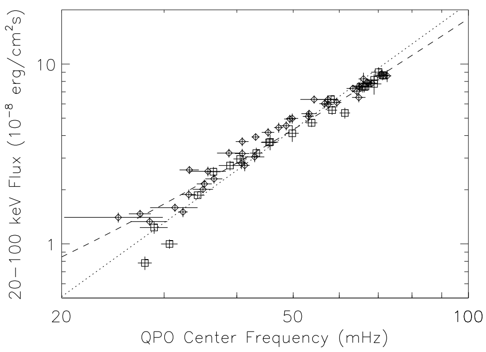

FIGURE 4. The flux versus the QPO frequency for A 0535+262 (Finger, Wilson & Harmon 1996). Squares are on outburst rise, diamonds on outburst decline. The lines give the predicted relationship for the beat frequency (dashed) and Keplerian frequency (dotted) models, with best fit normalizations.

frequency is given by

$$\nu_{\rm QPO} = \nu_{\rm k}(r_{\rm m}) - \nu_{\rm spin} = (GM)^{1/3} r_{\rm m}^{-2/3} - \nu_{\rm spin} \tag{3}$$

where $\nu_{\rm k}(r_{\rm m})$ is the Keplerian orbital frequency at the inner edge of the accretion disk and $\nu_{\rm spin} = 9.67$ mHz is A 0535+262's spin frequency. In the Keplerian frequency model, $\nu_{\rm QPO} = \nu_{\rm k}(r_{\rm m})$. In either model the QPO provides a measure of the location of the accretion disk-magnetosphere boundary. Comparisons of the flux or torque with the QPO frequency therefore test equation 1 fairly directly.

The data follow the expected trends of $\dot{\nu}_{\rm spin} \propto \nu_{\rm k}^2$ and $F \propto \nu_{\rm k}^{7/3}$, and the measured normalization constants in these relationships are consistent with reasonable neutron star parameters and the measured magnetic field of $B = 9.5 \times 10^{12}$ G (Grove et al. 1995) if we assume $K = 1$. The Ghosh & Lamb value $K = 0.5$ [22] is, however, ruled out. This suggests that the neutron star's magnetic field fully threads the disk [32].

Torque Reversals in Persistent Accreting Pulsars

Continuous monitoring by BATSE has revealed that torque switching between spin-up and spin-down is a common feature in the bright persistent pulsars, a result anticipated in earlier statistical analyses [6,14]. In the BATSE data the switching appears as abrupt transitions between torque states of comparable magnitude but opposite sign. Figure 5 shows the distinctive sawtooth quality of the spin-frequency histories of two pulsars, Cen X-3 and OAO 1657-415. In these systems, the torque reversals occur on timescales of weeks. In other systems such as GX 1+4 [8] and 4U 1626-67 [9] the reversals occur at intervals of years. Interestingly, in all four torque-reversal systems, the spin-up torque is somewhat larger in magnitude than the spin-down torque.

A further important clue is provided by the GX 1+4 system: during periods of prolonged spin-down, the magnitude of the spin-down torque is correlated with the observed 20-100 keV flux [8]. This is opposite in sign to the correlation expected in some models (see below).

Three classes of models have been suggested to explain the phenomenon of torque reversal:

Accretion from a prograde disk interacting with the pulsar magnetosphere. In this model, the pulsar accretes matter near equilibrium from a radius comparable to the corotation radius. In one variant [22] positive torques arise from the specific angular momentum of the material as well as by threading of the disk by the pulsar magnetic field inside r_{co}. Spin-down torques arise from fields which thread the disk outside r_{co} The sum of these torques can be positive or negative depending on the radius from which mass is accreted, which is governed by $\dot{M}_{\rm ns}$. Wang [58] has recently analyzed this type of model for the case of oblique rotators. In other variants of this class

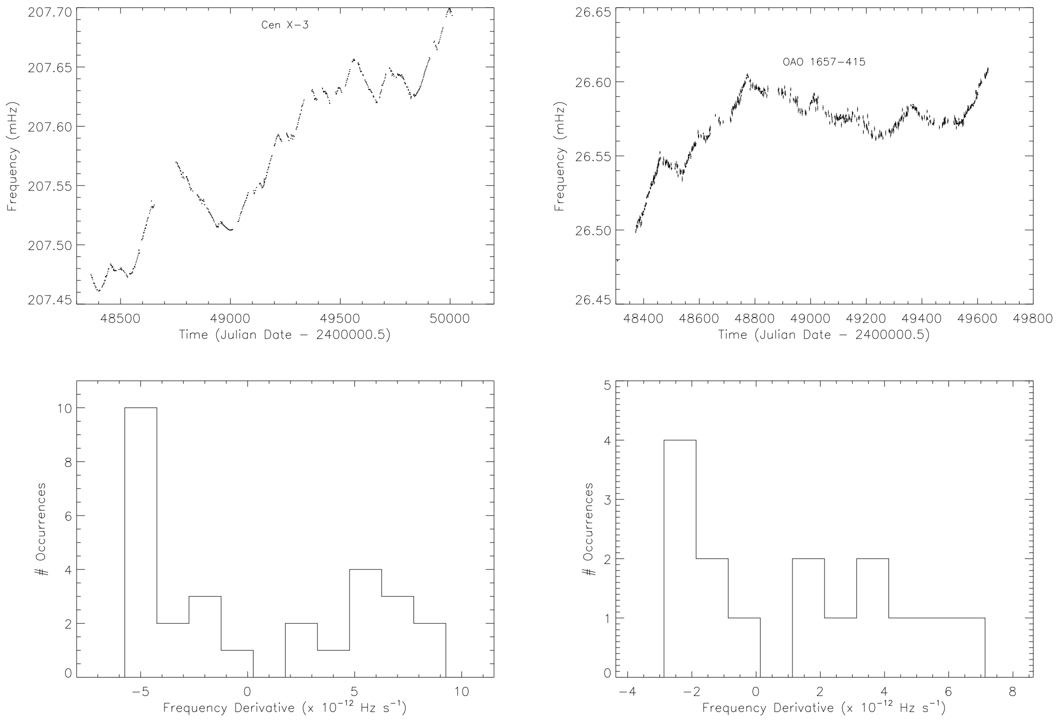

FIGURE 5. Torque histories and $\dot{\nu}_{\rm spin}$ distributions for Cen X-3 (left) and OAO 1657-415 (right). The frequency derivatives ($\dot{\nu}_{\rm spin}$) were obtained by performing a linear fit to the $\nu_{\rm spin}$ measurements in each spin-down or spin-up period (see Koh 1997).

of model [4,3] the spin-down torque is due to loss of angular momentum in a magnetohydrodynamic outflow. The sign of the torque is again determined by the radius from which matter is being accreted, which in turn depends on $\dot{M}_{\rm ns}$. To explain torque reversals, these models require abrupt changes in $\dot{M}_{\rm ns}$, between values that would produce spin-up and spin-down torques of approximately equal magnitude. These models do not naturally explain the correlation between enhanced flux and spin-down torque observed in GX 1+4.

Transition from Keplerian to advection-dominated sub-Keplerian flow. Recently, Yi et al. [64] have proposed that torque reversals are due to transitions from the familiar Keplerian flow to an advection-dominated flow. This happens at a critical mass accretion rate, $\dot{M}_{crit}$ below which the disk becomes optically thin and has very low density. The specific angular momentum of material at the disk inner edge is lower in the advection-dominated flow, resulting in a lower inflow of angular momentum. An attraction of this model is the prediction of an $\dot{M}_{crit}$ at which a sharp torque transition is expected, like those observed in the four systems mentioned above. It remains to be seen whether allowable values of $\dot{M}_{crit}$ span the range of observed values in the torque-reversal systems.

Disk reversal: prograde-retrograde. Nelson et al. [42] have recently discussed how torque reversals might be the result of disk reversals, similar to the suggestion of Makishima et al. [36] for the torque reversal seen in GX 1+4. If matter is accreted via Roche lobe overflow, disk reversals are not expected because of the high specific angular momentum of the matter flowing from the companion. However, simulations [20,46] have shown that retrograde disks are expected to form episodically in wind-fed systems.

Koh [30] discusses the likelihood that all four of the systems for which torque reversals are observed have disks that are fed by wind accretion. For Cen X-3, Day & Stevens [13] have argued that X-ray heating of the companion will suppress any radiative wind and give rise to a X-ray driven thermal wind. OAO 1657-415 lies in the Corbet diagram between the wind accretors and the disk accretors [7] and might thus be expected to show signs of both. Koh shows that the X-ray and normal radiative wind components of OAO 1657-415 may be comparable. Chakrabarty & Roche [10] suggest that V2116 Oph, the companion to GX 1+4, may be an FGB star with a slow dense stellar wind. The system 4U 1626-67 is less well characterized. The companion is expected to be very low-mass but has not yet been identified. Nelson et al. [42] estimate that an X-ray driven wind from the companion could account for the inferred mass accretion rate if there is efficient capture of the wind, a reasonable assumption given that the neutron star dominates the gravitational potential of the system. Thus the torque switching observed by BATSE could be due to the presence of a wind component, in some cases driven by X-ray heating. However, these models do not naturally explain why the observed spin-down torque is always slightly smaller in magnitude than the spin-up torque.

Further observations of the torque reversals with RXTE will be helpful in discriminating between the various models.

Outbursts of Be/X-ray Pulsar Systems

The majority of the known accreting pulsars are transients, normally detected only during outbursts which last from days to months. The identified optical counterparts of transient accreting pulsars which have been identified are spectral class Be (or Oe) stars. With the exception of the LMXB transient pulsar GRO J1744-28, the transient pulsars with no identified counterpart are also likely to have Be star companions. BATSE has observed more the 60 transient pulsar outbursts in six years of observations.

Be stars are main-sequence stars of spectral type B that show (or have shown) Balmer emission lines (see [48] for a review). This line emission is thought to be associated with circumstellar material shed by the rapidly rotating star into its equatorial plane, forming a dense stellar wind. In Be star / neutron star binaries, capture of material from this dense wind by the neutron star causes the outbursts. These outbursts are often associated with the

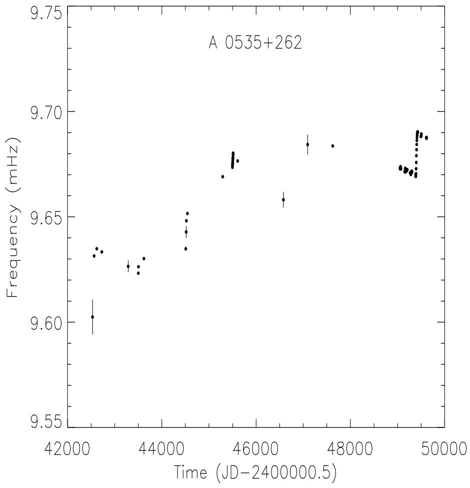

FIGURE 6. The long term history of A0535+262 frequency measurements (Bildsten et al. 1997).

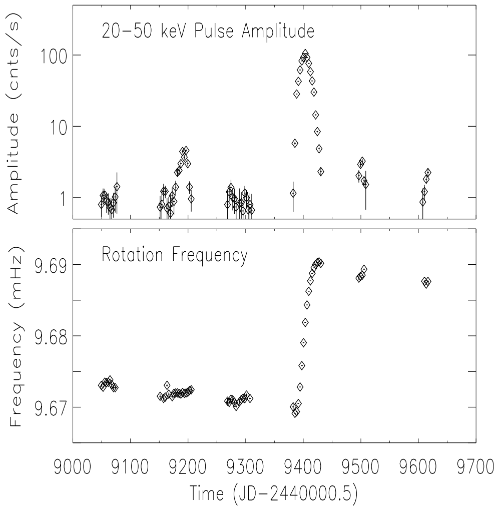

FIGURE 7. A0535+262 spin frequency and pulse amplitude measurements from BATSE observations (Finger, Wilson & Harmon 1996).

periastron passage of the pulsar's wide eccentric orbit. Direct wind accretion is often assumed to occur during the smaller outbursts, however it is now clear that an accretion disk is present in the largest outbursts. A review of these "Be/X-ray binary" systems is given by Apparao [2].

One of the best observed Be/X-ray pulsars is A0535+262 [21]. An orbital period of 111 days was inferred from the regular spacing of the x-ray outbursts [39] and confirmed by pulse timing measurements using BATSE [16]. The long-term history of frequency observations is shown in Figure 6. There is an overall trend of increasing spin frequency. Spin-up of the pulsar occurs almost entirely during the largest outbursts. Motch et al. [38] classify the outbursts as either "normal", with low flux and little or no spin-up, "giant", with high flux, rapid spin-up and a peak at a later orbital phase than normal outbursts, or "missing", with no outburst detected at an orbital phase where they might be expected. Prior to 1991 the most extensive observations were of the giant outbursts which were mainly observed by target-of-opportunity programs.

The BATSE observations are shown in Figure 7. These show a series of six outbursts, one per 111 day orbit, with the fourth (February-March 1994) a giant outburst, and the others normal outbursts. No outbursts were detected during the six orbits prior to or the eight orbits after those shown in Figure 7. Outside of the giant outburst the pulsar is spinning-down. The presence of series of normal outbursts, and the association of giant outbursts with them, is not evident in the pre-1991 data due to the selectivity of coverage.

Giant outbursts and series of normal outbursts are observed in many other sources. Both behaviors have been seen in V0332+53 [50]. The initial dis-

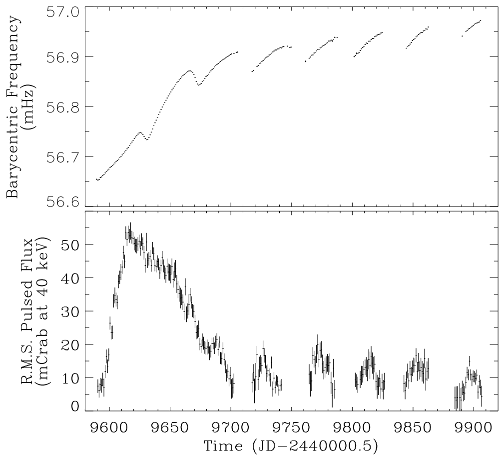

FIGURE 8. The barycentric pulse frequency (not orbitally corrected) and pulsed flux of 2S 1417-624 observed by BATSE (Finger, Wilson & Chakrabarty 1996).

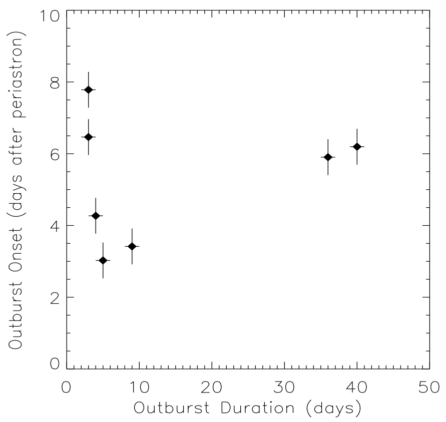

FIGURE 9. The time of 4U 0115+634 outburst onsets relative to periastron passage versus the outburst durations from BATSE observations. 4U 0115+634 has a 24.3 day orbit.

covery of EXO 2030+375 [43] was during a giant outburst, while BATSE observations show a series of 13 consecutive normal outbursts [52]. Figure 8 shows a series of outburst of 2S 1417-634 [17] which began with a giant outburst and ended with five normal outbursts. BATSE observations also show consecutive series of outbursts from GRO J1008-57, GRO J2058+42, 4U 0115+375, 4U 1145-619 and GS 0834-430 (Paper I). The persistent wind-fed source GX 301-2 also shows behavior that is similar in many aspects [29].

The peaks of the giant outbursts have been observed to be delayed in orbital phase from the peaks of the normal outbursts, with the delay correlated with the peak luminosity [63,38]. The BATSE observations suggest this effect is a result of the correlation of the peak luminosity and outburst duration. For a given source the outburst onsets observed by BATSE are found to be restricted in orbital phase, with these phases uncorrelated with peak flux or outburst duration. This is shown in Figure 9 for 4U 0115+634. This suggests that the giant outbursts begin in the same manner as normal outbursts. The standard explanation for the normal outbursts is direct wind accretion of the Be stellar disk material [59], while the giant outbursts are explained as an episode of enhanced outflow from the Be star. Based on the BATSE observations, it was proposed in Paper 1 that an accretion disk exists for extended periods, with tidal torques on the outside of the disk causing inflow near periastron that results in the normal outbursts. With a sufficient build-up of material in the outer disk, some of these normal outbursts trigger a thermal disk instability similar to that in dwarf nova [49] and soft x-ray transients [55,28], initiating a giant outburst.

The Population and Orbits of Accreting Be/Pulsar Systems

BATSE has detected 13 transient pulsars with high-mass companions, all known or suspected Be/X-ray pulsars (see Table 1). This constitutes a complete sample of 20-50 keV transient sources with pulsed flux in excess of $\sim 2 \times 10^{-10}$ erg cm^{-2} s^{-1}. Paper I and Koh [30] have used this sample to draw conclusions about the population of high-mass transient pulsars in the galaxy. The transients detected by BATSE are primarily Be/X-ray binaries.

The progenitor system of a Be/X-ray binary is likely a compact system of two B stars. The more massive star evolves more rapidly and transfers mass to the companion via Roche-lobe overflow, resulting in a helium star . The transfer of angular momentum to the companion is consistent with the observation that many Be stars exhibit very high rotational velocities. Next, the helium star undergoes a supernova explosion producing a neutron star in a wide eccentric orbit, if the system remains bound. Because the kick velocities are expected to be larger than typical orbital velocities of the pre-supernova system, most such systems are expected to be disrupted. In the limit of large kick velocities, Kalogera [27] has derived an expression for the distribution of eccentricities. Paper I compares the distribution of eccentricities for the BATSE sample of pulsars against this predicted distribution. The results are

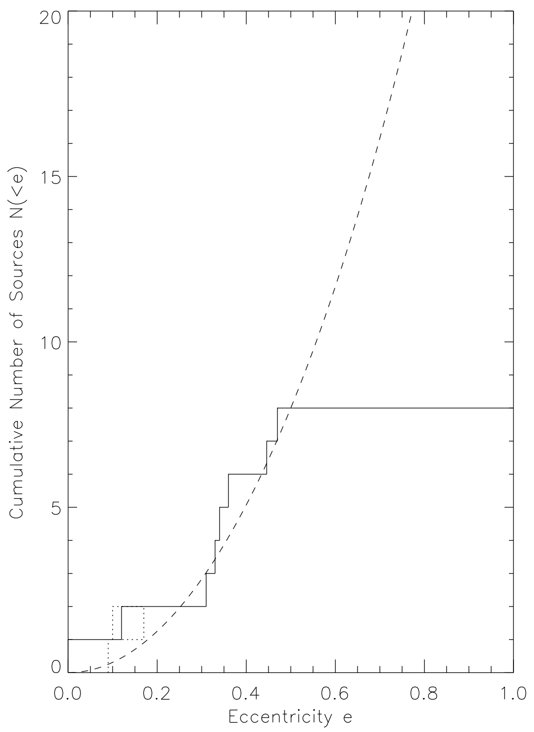

FIGURE 10. The cumulative distribution of Be/X-ray pulsar binary eccentricities. The predicted distribution (normalized to 8 sources with $e < 0.5$) is given by the dashed line. The dotted lines give the ranges of eccentricity for the cases of 2S 1553-54 and GS 0834-430 (see Paper I).

shown in Figure 10.

The predicted and observed distributions are consistent for $e < 0.5$, but diverge significantly above. Whereas approximately 30 sources would be expected for $e > 0.5$, none are observed. Paper I interprets this as a selection effect: neutron stars in high-eccentricity systems may undergo outbursts only near periastron, making such outbursts less frequent. The orbits of such systems will then be difficult to determine. A prediction is that almost all of the Be/X-ray pulsars for which no orbit has been determined (see table) have high eccentricity, with $e > 0.5$.

Cen X-3: Detection of GeV Radiation from an Accreting Pulsar

Recently, Vestrand et al. [56,57] reported a detection of the pulsar Cen X-3 by the EGRET instrument on CGRO. This is the first detection of an accreting pulsar with EGRET, which is sensitive to gamma-rays above 30 MeV. No detections have been reported using the Comptel instrument, which is sensitive to emission above 1 MeV (W. Collmar, private communication, 1997).

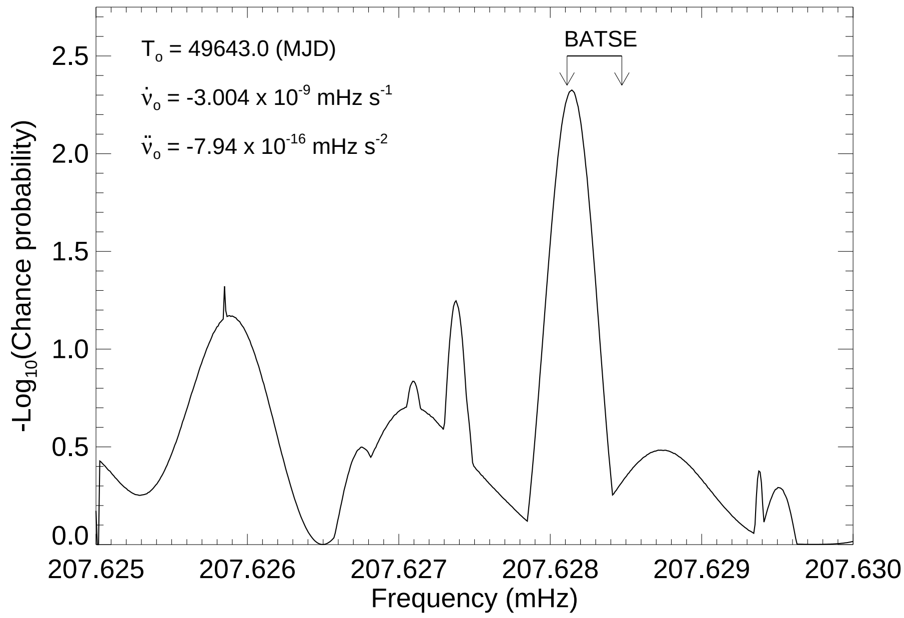

FIGURE 11. Chance probability versus the Cen X-3 spin frequency (at epoch TJD 9643) for the statistic used by Vestrand et al. (1997) to detect pulsations from Cen X-3 in the EGRET data. The 68% confidence range determined from the BATSE data is also shown.

The EGRET observations were made in October 1994 and revealed a $\sim 5\sigma$ significance source located at $l = 292.20^\circ$ and $b = 0.48^\circ$, $10.7'$ from Cen X-3 and consistent with its position. The source was not detected in earlier observations indicating that it is variable. The location in the galactic plane, and the strength of the source argue against it being an accidentally coincident blazar. Assuming a distance of 8 kpc, Vestrand et al. report a luminosity of $L_\gamma(0.1 - 10 \text{ GeV}) \sim 5 \times 10^{36}$ ergs^{-1}.

Using an ephemeris for the pulse frequency derived from BATSE data, Vestrand et al. tested for the presence of a periodic modulation of the flux from the detected EGRET source. The results are shown in Figure 11, taken from Vestrand et al. For a single harmonic, the chance probability for no modulation in the 0.1-10 GeV range at the BATSE-derived frequency is 0.47%. For two harmonics, the chance probability of no modulation is 0.16%.

Recent Observations by RXTE

The ROSSI X-ray Timing Explorer (RXTE) has observational capabilities that are an excellent complement to those of CGRO. The Proportional Counter Array (PCA) on RXTE with its 6250 cm^2 area and 1° field of view can make observations of individual systems at a much lower luminosity than BATSE. The All Sky Monitor (ASM) on RXTE does not have the timing capabilities of the BATSE detectors, but has sensitivity comparably to BATSE's (for an accreting pulsar) and can be used to determine the total X-ray flux. BATSE can make sensitive measurements of pulsed hard X-ray flux, and lower sensitivity measurements of total hard X-ray flux using Earth occultation. With both RXTE and CGRO observations, both the total and pulsed fluxes can be monitored continuously. The High-Energy X-ray Timing Experiment (HEXTE) also provides complementary capabilities, in particular good timing and spectroscopic capabilities at hard X-ray energies.

The PCA is performing accurate measurements of accreting pulsars at low luminosities, revealing some interesting new phenomena and testing ideas of about the dependence of the accretion and pulse properties on the accretion rate. The 8 day binary 4U1907+09 was observed to have dips in flux throughout its binary orbit from a luminosity of 10^{36} ergs s^{-1} to a few times 10^{35} ergs s^{-1}, during which the spectrum was substantially the same and not associated with increased column density [65]. GX 1+4 and GRO J1744-28 were observed when the pulses dropped below detection level, suggesting the possibility of propeller action of the magnetic dipole of the neutron star predicted for low accretion rates [12].

The observations of the pulse shape evolution in Her X-1 [47] confirm the complex pattern first observed in detail with Ginga and adds new details, such as transition to a quasi-sinusoidal profile at the end of the Main High state. The wealth of complex profile changes observed in Her X-1 are not associated with intrinsic luminosity variations as in transient pulsar outbursts and provide stringent constraints on pulse evolution models such as neutron star free precession or an inner disk occultation of the neutron star. The HEXTE instrument has observed Her X-1 on 3 occasions [25] and has measured the cyclotron line absorption energy of the pulsar. A power law fit with an exponential cutoff plus gaussian absorption yielded a cyclotron line energy of 39.0 keV in each observation, with statistical errors of 1% or better. There was no evidence for a harmonically spaced overtone. The line width was σ = 7.5 keV, large compared to the instrumental resolution of 3.0 keV at 39 keV. Significant residuals between 30 and 50 keV on the scale of the detector resolution indicate that the description of a Gaussian line on an exponentially cut-off continuum is now inadequate.

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