

INTERMITTENT STELLAR WIND ACCRETION AND THE LONG-TERM ACTIVITY OF POPULATION I BINARY SYSTEMS CONTAINING AN X-RAY PULSAR

L. STELLA^{1,2} AND N. E. WHITE¹
EXOSAT Observatory, European Space Operations Centre

AND

R. ROSNER
 Harvard-Smithsonian Center for Astrophysics
 Received 1985 November 21; accepted 1986 February 3

ABSTRACT

We compare the observed properties of the Population I binaries containing X-ray pulsars with the various regimes of wind accretion onto a magnetized neutron star in order to model their long-term X-ray variability properties. We point out that many of the pulsing X-ray transients in OB star systems with pulse periods of 1–10 s, when in outburst, lie close to the critical equilibrium point where the corotation radius equals the magnetospheric radius. This suggests that many of these systems usually are dormant because of the centrifugal inhibition of accretion, and that a small increase in the mass accretion rate can turn them into very luminous transient X-ray sources. If a system lies close to the equilibrium point and it is in an eccentric orbit, luminous outbursts may occur around the time of periastron passage. A correlation between the maximum X-ray luminosity and the pulsar frequency is found and interpreted as the result of centrifugal inhibition of accretion preventing low-luminosity, fast spin period magnetized neutron stars accreting.

The nontransient X-ray pulsars with periods of several hundred seconds must be far from the centrifugal equilibrium point unless there exists a correlation of pulse period with surface magnetic field strength. For the longest period systems a dependence of field strength on pulse period requires fields in excess of 10^{14} G, which we consider unlikely. If the long-period pulsars were spun down to these long periods by the interaction of the magnetosphere with the wind, then the strength of the stellar wind must have been several orders of magnitude less intense during the spin-down phase.

Subject headings: pulsars — stars: accretion — stars: winds — X-rays: binaries

I. INTRODUCTION

Most of the optically identified X-ray pulsars are in binary systems containing O- or B-type stellar companions (see, e.g., Rappaport and van den Heuvel 1982; White 1984), whose natural mass loss is in many cases capable of powering the X-ray source via gravitational capture by a magnetized neutron star (Davidson and Ostriker 1973). For the OB supergiant X-ray binaries with orbital periods of a few days, it is debatable how much extra material is provided by Roche or quasi-Roche lobe overflow (Conti 1978; Petterson 1978), but for the remainder of the systems with orbital periods of tens or hundreds of days, stellar wind accretion onto a neutron star is the only viable mechanism for producing the observed X-ray emission.

In the simple theory of direct wind accretion onto a magnetized neutron star (Davidson and Ostriker 1973; Lamb, Pethick, and Pines 1973), the (Bondi) accretion radius is, for plausible wind parameters and the canonical neutron star parameters, larger than the corotation radius, which is in turn larger than the characteristic dimensions of the magnetospheric boundary surface. The accretion rate is then set by the flow at the accretion radius, and the neutron star magnetosphere must accommodate itself accordingly. As a result of the instabilities that allow the material to penetrate the magnetosphere in a sporadic fashion, this kind of accretion model can yield time-variable emission on time scales comparable to the free-fall time scale from the magnetospheric boundary (~ 1 s; Stella *et al.* 1985). The time-averaged accretion rate (and hence the X-ray luminosity) in such a model will depend continuously on the stellar wind parameters, since the flow to the magnetosphere is controlled by conditions in the vicinity of the accretion radius.

The time variability properties of the OB star X-ray binaries on time scales from minutes to hours is characterized by aperiodic activity with a dynamic range of 2–10. This behavior is interpreted in the direct wind model as due to inhomogeneities in the stellar wind of the OB star. This view is supported by the observation of quasi-correlated absorption/intensity events from 4U 1700–37, where the wind blob responsible for the enhanced accretion event occasionally passes through the line of sight, resulting in an absorption event (White, Kallman, and Swank 1983). The longer time scale (≥ 1 day) variability properties of the persistent X-ray pulsars in OB star binaries consist of (a) irregular variations, presumably caused by corresponding overall changes in the stellar wind parameters; or (b) periodic variations associated with a moderately eccentric orbit ($e \lesssim 0.5$; e.g., 4U 1223–62; Watson, Warwick, and Corbet 1982); or both. In the second case the wind parameters at the neutron star accretion radius are modulated by the varying separation of the neutron star and the OB star companion.

¹ Affiliated to Astrophysics Division, Space Science Department of European Space Agency.

² On leave from I.C.R.A., Department of Physics "G. Marconi," University of Rome.

The variations discussed above are always limited to a dynamic range of less than 100 such that the X-ray flux does not usually drop below the detection threshold of the current generation of nonimaging X-ray instruments ($\lesssim 1 \mu\text{Jy}$). While these variations are successfully explained by the direct wind accretion model, many Be star systems are associated with X-ray transient outbursts, with a ratio of the maximum to minimum luminosity $L_x(\text{max})/L_x(\text{min})$ greater than a factor of 100 (Maraschi, Treves, and van den Heuvel 1976). For the purpose of our discussion we divide the transient activity into two different classes:

Class I, periodic transient activity.—Transient outbursts that recur periodically and have $L_x(\text{max})/L_x(\text{min}) \gtrsim 100$. For systems where a pulse-timing orbital solution is available (currently only for the shorter orbital system, with $P_0 < 50$ days), it is found that the neutron star is typically in a moderately eccentric orbit ($e \lesssim 0.5$) and that the outbursts occur close to the time of periastron passage. This suggests enhanced accretion caused by the closer proximity of the neutron star to the Be star companion. These periodic X-ray outbursts are to be distinguished from those caused simply by variations in the density of the stellar wind around an eccentric orbit. The dynamic range of typically greater than 300 (e.g., V0332+53; Stella *et al.* 1985) cannot be reconciled with the predictions of the direct wind accretion model. Even allowing for the additional modulation induced by the steepest velocity profile considered plausible for a radiatively driven stellar wind (cf. Henrichs 1980), the orbital flux variations in the direct wind accretion model are limited at most to a factor of $\lesssim 50$ (cf. Charles *et al.* 1983).

Class II, irregular transient activity.—Transient outbursts that typically last several tens of days and involve an increase in luminosity in excess of a factor of 100–1000. The timing of these outbursts is unrelated to any underlying orbital period. In cases where the orbit is known and the outburst lasts longer than the orbital period, an orbital modulation at the level predicted by the direct wind accretion model is not always seen (e.g., 4U 0115+63; Kriss *et al.* 1983).

In order to explain the large orbital modulation of the class I transients, a number of mechanisms for causing an additional surge in accretion onto the compact object have been considered. Charles *et al.* (1983) discuss the possibility that the 16 day class I outbursts seen from A0538–66 are caused by the companion star temporarily filling its Roche lobe at periastron passage, causing it to spill extra material onto the neutron star. While intermittent Roche lobe overflow might explain the outbursts of A0538–66 (the orbital eccentricity in this system is not precisely determined), in other systems where class I behavior is seen and the orbit is well known, the companion is far from filling its Roche lobe at periastron. In these cases it has been suggested (e.g., Kelley, Rappaport, and Ayasli 1983) that the neutron star orbital plane and the equatorial plane of the companion are misaligned. If the Be star is surrounded by a centrifugally supported disk (many of these stars rotate close to breakup velocity), then an outburst should be seen when the neutron star crosses the disk plane. This model predicts that two outbursts should be seen per orbit, separated in phase by at least $\Delta\phi \approx (E - e \sin E)/\pi$, where $E = 2 \arctan [(1 - e)^{1/2}/(1 + e)^{1/2}]$. However, one outburst per orbit is observed in the class I transient systems, and only by invoking special geometries such as circular orbits, or a disk that has a limited extent relative to the orbital dimensions, can this problem be avoided (Apparao 1985).

Since Be stars are in general known to undergo mass ejection (shell) episodes, this has naturally led to the suggestion that class II X-ray outbursts are the result of enhanced accretion as the shell reaches the neutron star. While to zeroth order this provides a plausible explanation, the detailed properties of the outbursts which have been studied in detail are difficult to understand in the context of such a simple picture. During an outburst from 4U 0115+63 in 1980, the optical star brightened by 1.7 mag ~ 60 days before the turn-on of the X-ray source, far longer than would be expected for the material to reach the neutron star orbit (Kriss *et al.* 1983). In another case the transient source V0332+53 was observed to display class I X-ray outbursts between 1983 November and 1984 January with a period of 34 days (Stella *et al.* 1985). However, a factor of ~ 20 brighter outburst in 1973 that lasted ~ 100 days was clearly of class II and showed no evidence for a 34 day modulation (Terrell and Priedhorsky 1984).

Mediation of the inward flow outside the neutron star magnetosphere by an accretion disk has been suggested as a reason for the optical/X-ray time delay observed from 4U 0115+63 and the failure to detect any strong orbital modulation (Kriss *et al.* 1983). The presence of an accretion disk during the class II outburst of V0332+53 in 1973, but not during the class I outbursts in 1983–1984, might also account for the difference in the properties of the 1973 and 1983–1984 outbursts. However, it is far from clear that in these stellar wind-driven systems that the stellar wind captured by the neutron star will contain sufficient angular momentum to form a disk that has a lifetime of tens of days (cf. Wang 1981).

The early discussion of the properties of magnetized neutron stars accreting from a stellar wind emphasized the importance of the interaction of the rotating magnetosphere with the inflowing material (Davidson and Ostriker 1973; Lamb, Pethick, and Pines 1973). It was pointed out that the specific angular momentum of the inflowing material may cause an accretion disk to form that will apply a torque on the neutron star. The X-ray pulsar rotation frequency will thus increase on relatively short time scales of 100–10,000 yr until an equilibrium rotation is reached where the centrifugal force acting on the wind material close to the magnetospheric boundary can prevent accretion onto the neutron star surface. Conversely, if the magnetospheric radius exceeds the corotation radius, as might be expected when the neutron star is young and rotating rapidly, then a braking torque will be applied by the magnetosphere “propelling” away the inflowing material (Illarionov and Sunyaev 1975). A mass ejection episode from the companion during the X-ray–dormant spin-down interval can cause the magnetosphere to be compressed sufficiently for the system to briefly turn on as a bright X-ray pulsar (Fabian 1975; Maraschi, Traversini, and Treves 1983).

The purpose of this paper is to investigate the full range of possible regimes for a magnetized neutron star that interacts with the stellar wind of an OB star and to compare the results with the considerable body of observational data that now exists on these systems. We emphasize how the transition to the regime in which accretion onto the neutron star is inhibited by the centrifugal drag of the rotating magnetosphere with the inflowing material can cause dramatic changes in X-ray luminosity even for a quite modest change in the stellar wind parameters. This provides the necessary sensitivity of the accretion rate onto the neutron star to the conditions in the vicinity of the accretion radius, which is required to explain the transient activity observed in so many of these systems. Our discussion will focus on explaining the X-ray properties of V0332+53, which has displayed both class I and class II behavior and, based on recent results obtained with the *Vela 5B* satellite and *EXOSAT* (Terrell and Priedhorsky 1984; Stella *et al.* 1985), provides one of the better studied Be star X-ray pulsar transients.

In § II the observed properties and system parameters for all the currently known OB star systems are summarized and a search for a correlation between the pulse periods, orbital periods, and X-ray luminosities made. Building on the earlier work outlined above, we identify in § III four different regimes where a magnetized neutron star can interact with the stellar wind. In § IV the regime where centrifugal inhibition of accretion becomes important is discussed in the context of a strong correlation found between the maximum observed luminosity from a pulsar and its pulse frequency. In § V we discuss how possible relations between the pulse period and the orbital period may be caused by the centrifugal barrier mechanism excluding accretion for a wide range of stellar wind parameters. These results are discussed in § VI and summarized in § VII.

II. THE OBSERVED PROPERTIES

a) An Overview

In Table 1 we list the known or suspected OB star X-ray binary systems and summarize some key observational properties: their pulse periods, orbital periods, maximum observed X-ray luminosities, $L_x(\text{max})/L_x(\text{min})$, eccentricity, and class of transient activity seen, and the spectral type of the optical counterpart. The pulse periods range from 69 ms to 835 s, the maximum luminosities from $\sim 10^{34}$ to $\sim 10^{39}$ ergs s^{-1} , and the orbital periods from 1.4 days to greater than several hundred days. Transient activity is exclusively confined to the Be star systems, with many of these systems not detected in quiescence. This reflects the fact that the time-averaged mass loss rate from these stars is two to four orders of magnitude lower than those of the supergiant stars in systems such as Cen X-3. It is notable that the only Be star systems that are detected in quiescence require lower wind velocities or higher mass loss rates or both than those measured or predicted by the stellar wind indicators of the Be star (White *et al.* 1982; Priedhorsky and Terrell 1983b). In the case of A0535+26 it is not yet clear whether the source is detected in quiescence, such that the $L_x(\text{max})/L_x(\text{min})$ around the orbit is only known to be greater than 10 (Priedhorsky and Terrell 1983a); we have therefore placed a question mark against the class I transient activity from the system.

In Table 1 we have also included the other OB star binary systems from which pulsations have not been detected to date. Except for the lack of a large modulation of their X-ray flux, these sources possess the same properties as the Population I X-ray pulsar systems. The failure to detect pulsations might reflect the fact that these systems contain a very slowly rotating neutron star ($P > 1000$ s) or that the magnetic dipole axis is coaligned with the rotation axis of the neutron star.

b) The Properties of V0332+53

The evolution of the outbursts of V0332+53 are shown in Figure 1. In 1973 the source underwent a giant class II outburst during which the X-ray flux rose linearly to 1.4 Crab in ~ 50 days and then decayed in a similar manner (Terrell and Priedhorsky 1984). In 1983–1984 three periodic class I outbursts were observed with EXOSAT (Stella *et al.* 1985), each with a peak flux of less than 100 millicrob. This series of observations resulted in the discovery of 4.4 s X-ray pulsations. Doppler timing allowed the determination of the orbital parameters giving a 34 day period with an eccentricity of 0.31 and the times of periastron passage coincident with the times of the three outbursts. In the decay phase of each outburst, the flux decreased abruptly within 3 days to less than 0.2 millicrob

TABLE 1
OB STAR X-RAY BINARY SYSTEMS

Source	P_s (s)	P_o (day)	$L_x(\text{max})$ (ergs s^{-1})	$\frac{L_x(\text{max})}{L_x(\text{min})}$	e	Class	Spectral type
1. A0538-66	0.069	16.7	1.2×10^{39}	$> 1.8 \times 10^4$	> 0.4	I	B2 IIIe
2. 4U 0115+63	3.6	24.3	8×10^{36}	$> 2.3 \times 10^4$	0.34	II	Be
3. V0332+53	4.4	34.2	2×10^{37}	$> 1 \times 10^4$	0.31	I + II	Be?
4. 2S 1553-54	9.3	30.6	1×10^{37}	> 30	0.09	II	?
5. A0535+26	104	111	2×10^{37}	700	0.2-0.4	II + I(?)	O9.7 IIIe
6. GX 304-1	272	133	3×10^{35}	> 25	?	...	B2 Vne
7. 4U 1145-62	292	188	6×10^{36}	250	?	II + I(?)	B1 Vne
8. X Per	835	580?	1×10^{34}	4	?	...	O9.5 (III-V)e
9. LMC X-4 ^a	14	1.4	4×10^{38}	> 20	0.0	...	O7 (III-V)
10. A1118-62	405	?	5×10^{36}	> 70	?	II(?)	O9.5 (III-V)e
11. 1E 1145-616	297	?	3×10^{36}	100	?	?	B1 I
12. SMC X-1	0.7	3.9	6×10^{38}	110	7×10^{-4}	?	B0 I
13. Cen X-3	4.8	2.1	8×10^{37}	30	8×10^{-4}	...	O6-8 fp
14. Vela X-1	283	9.0	6×10^{36}	50	0.09	...	B0.5 Ib
15. 4U 1538-52	529	3.7	4×10^{36}	10	?	...	B0 I
16. 4U 1223-62	699	41	1×10^{37}	30	0.47	...	B1.5 Ia
17. 4U 1700-37	?	3.4	3×10^{36}	40	?	...	O6.5f
18. A0114+65	?	11.6	2×10^{34}	1	?	...	B0.5 IIIe
19. γ Cas	?	?	2×10^{33}	2	?	...	B0.5 (II-V)e
20. SMC X-2	?	?	8×10^{37}	7	?	...	B1.5 Ve
21. SMC X-3	?	?	2×10^{37}	5	?	...	O9 (III-V)e

NOTES.—Data from Rappaport and Van den Heuvel 1982, Bradt and McClintock 1983, Joss and Rappaport 1984, and Corbet 1984, and references therein, except for V0332+53 (Terrell and Priedhorsky 1984; Stella *et al.* 1985); data on the optical counterpart of A0535+26 from Giangrande *et al.* 1980. The values of $L_x(\text{min})$ for the transient systems correspond to the upper limits to the (undetected) quiescence flux. We have excluded flares on time scales of hours in the evaluation of $L_x(\text{max})/L_x(\text{min})$.

^a Roche lobe overflow system.

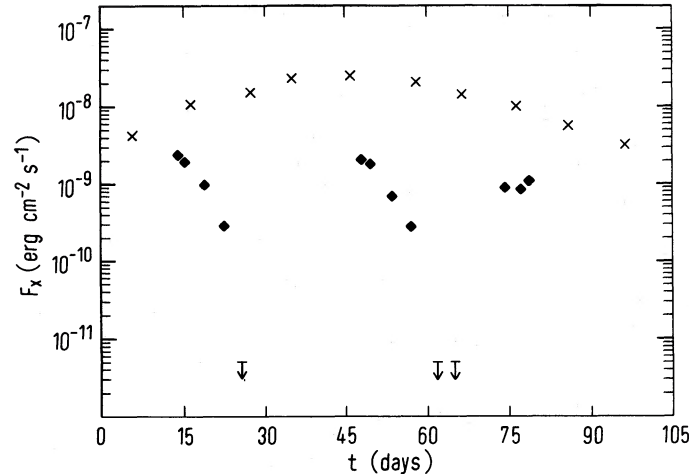


FIG. 1.—Evolution of 1973 giant outburst (*crosses*) and 1983–1984 periodic outbursts (*diamonds*) of V0332 + 53. Origin of the time axis corresponds respectively to JD 2,441,827 and JD 2,445,645, and energy range for X-ray fluxes is respectively 3–12 keV and 1–15 keV (data from Terrell and Priedhorsky 1984 and Stella *et al.* 1985). Arrows represent 3σ upper limits to the source flux during the quiescent phases between the periodic outbursts. The maximum luminosity given in Table 1 for 1.5 kpc distance has been obtained by applying a bolometric correction (derived from the *EXOSAT* X-ray spectra) to the maximum flux observed in 1973 with the *Vela 5B* satellite.

implying orbital flux variations larger than a factor of ~ 300 . An OB star was found within the *EXOSAT* $10''$ position (see Bernacca, Iijima, and Stagni 1984, and references therein).

c) General Correlations

It is evident from Table 1 that the fast X-ray pulsars ($P_s < 10$ s) display the most luminous outbursts. This is illustrated in Figure 2, where the maximum X-ray luminosity $L_x(\text{max})$ is plotted as a function of the pulsar spin period P_s . The linear correlation coefficient between the maximum X-ray luminosity and the pulsar frequency is 0.89 (corresponding to a probability of $\sim 10^{-7}$ of obtaining a larger coefficient from a random distribution). There is no clear distinction between the $L_x(\text{max}) - P_s$ relation for the supergiant (*squares*) and the Be star systems (*circles and diamonds*). For the two subsamples, coefficients of linear correlation between $L_x(\text{max})$ and the pulsar frequency of 0.947 and 0.9997 respectively are obtained.

In Figure 3 the pulse periods are plotted against the corresponding orbital periods. A correlation between the orbital period P_o

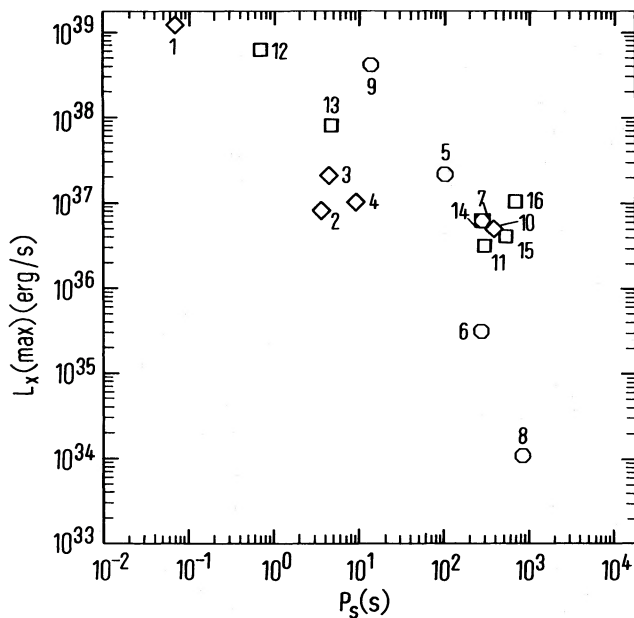


FIG. 2

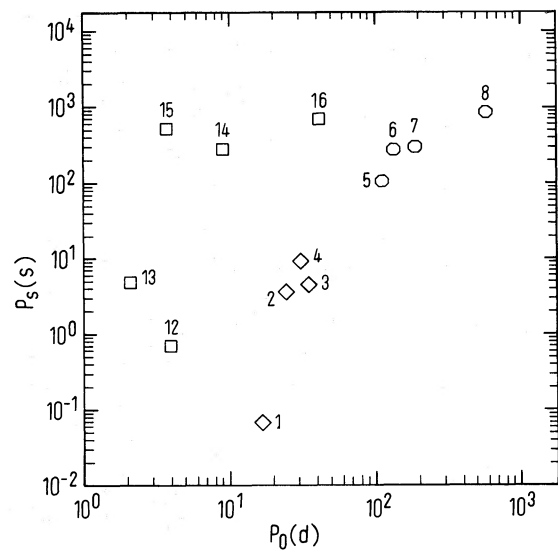


FIG. 3

FIG. 2.—Maximum X-ray luminosity of the OB star X-ray pulsar systems vs. spin period. Diamonds, circles, and squares represent respectively transients, persistent Be star systems, and supergiant star systems. The anticorrelation clearly apparent in this graph is discussed in the text. Source numbers refer to Table 1.

FIG. 3.—Spin periods P_s of the Population I X-ray pulsar systems vs. corresponding orbital periods P_o . A significant correlation between the two periods is found only for the Be star systems subsample.

and the pulsar spin period P_s limited to the Be star and transient systems has recently been noted by Corbet (1984). The pulsar spin period in the supergiant systems does not show any correlation with the orbital period. For a given orbital period, the supergiant systems possess systematically longer pulsar spin periods than the Be star systems.

III. STELLAR WIND ACCRETION

In the theory of wind accretion onto a magnetized rotating neutron star, three characteristic radii can be defined (Davidson and Ostriker 1973; Lamb, Pethick, and Pines 1973):

i) The accretion radius r_a , which from Bondi and Hoyle (1944) is approximated by

$$r_a = 4GM_x/v_0^2 \quad (1)$$

(M_x is the neutron star mass, v_0 the stellar wind velocity). This radius gives the characteristic impact parameter for the wind material to be captured by the neutron star.

ii) The magnetospheric radius r_m , obtained by equating the magnetic field pressure of the neutron star magnetosphere to the ram pressure of the accreting plasma:

$$B(r_m)^2/8\pi = \rho(r_m)v(r_m)^2, \quad (2)$$

where $B(r_m)$, $\rho(r_m)$, and $v(r_m)$ are respectively the pulsar magnetic field and the inflowing plasma density and velocity. At r_m the neutron star magnetic field begins to dominate the dynamics of the flow.

iii) The corotation radius r_c , at which the X-ray pulsar corotation velocity is equal to the Keplerian velocity,

$$r_c = (GM_x P_s^2/4\pi^2)^{1/3}, \quad (3)$$

where P_s is the X-ray pulsar spin period.

Four regimes, corresponding to the relative dimensions of these radii, can be identified.

a) Regime I: Direct Wind Accretion

When $r_a > r_m$ and $r_c > r_m$, the captured wind material flows from the accretion radius down the magnetospheric radius, where it is stopped by a collisionless shock. It then penetrates the pulsar magnetosphere, presumably in a sporadic fashion, by means of a variety of Rayleigh-Taylor and Kelvin-Helmholtz instabilities (see Lamb 1984). Although the details of the instabilities which modulate the accretion process are still highly uncertain, this will probably yield time-variable emission from the accreting material on dynamical time scales.

The time-averaged X-ray luminosity is governed by the stellar wind parameters at r_a . Combining equation (1) with Kepler's third law and assuming all the gravitational potential energy is converted into X-rays gives an expression for the X-ray luminosity L_x of:

$$L_x \approx 4 \times 10^{35} \left(\frac{R_x}{10^6 \text{ cm}} \right)^{-1} \left(\frac{M_x}{1.4 M_\odot} \right)^3 \left(\frac{M_*}{10 M_\odot} \right)^{-2/3} \left(\frac{P_o}{1 \text{ day}} \right)^{-4/3} \left(\frac{\dot{M}_*}{10^{-8} M_\odot \text{ yr}^{-1}} \right) \left(\frac{v_0}{10^8 \text{ cm s}^{-1}} \right)^{-4} \text{ ergs s}^{-1}, \quad (4)$$

where \dot{M}_* is the mass loss rate from the primary, M_* is the mass of the primary star ($M_* \gg M_x$), R_x is the neutron star radius, and P_o is the orbital period of the system. Equation (4) uses a circular orbit approximation and neglects the effects of the orbital velocity on the dynamics of accretion, as the former is always much smaller than the asymptotic wind velocity v_0 .

b) Regime II: Centrifugal Inhibition of Accretion

If $r_c < r_m < r_a$, the wind material which penetrates through the accretion radius is stopped at the magnetospheric boundary r_m and cannot penetrate any further because, as $r_m > r_c$, the drag exerted by the pulsar magnetic field is super-Keplerian. As discussed by Illarionov and Sunyaev (1975), the pulsar magnetospheric boundary assumes a prolate configuration which strongly shocks the wind material by supersonic rotation. This may eject beyond the accretion radius some or all of the material via the "propeller" mechanism. If the wind material accumulates at the magnetopause more rapidly than the ejection rate, a buildup of material outside the magnetosphere may occur (Maraschi, Traversini, and Treves 1983). This regime of inhibition of accretion has been discussed in connection with the spin-down evolution of young X-ray pulsars in binary systems (Illarionov and Sunyaev 1975).

By imposing $r_m = r_c$ we obtain a minimum luminosity at which accretion is possible.

$$L_{x,c}(\text{min}) \approx 2 \times 10^{37} \left(\frac{R_x}{10^6 \text{ cm}} \right)^{-1} \left(\frac{M_x}{1.4 M_\odot} \right)^{-2/3} \left(\frac{\mu}{10^{30} \text{ G cm}^3} \right)^2 \left(\frac{P_s}{1 \text{ s}} \right)^{-7/3} \text{ ergs s}^{-1}, \quad (5)$$

where μ is the magnetic dipole moment of the neutron star. Below this value an X-ray pulsar "turns off" as a consequence of the centrifugal mechanism discussed above. The minimum luminosity given by equation (5) is reduced by a factor of ~ 0.5 when applied to disk accretion (Wassermann and Shapiro 1983).

For any of the stellar wind accreting X-ray pulsars to go below $L_{x,c}(\text{min})$ requires a corresponding threshold in the stellar wind parameters. This gives the following relation between the pulse and orbital periods:

$$P_{s,c}(\text{min}) \approx 5.4 \left(\frac{M_x}{1.4 M_\odot} \right)^{-11/7} \left(\frac{M_*}{10 M_\odot} \right)^{2/7} \left(\frac{\mu}{10^{30} \text{ G cm}^3} \right)^{6/7} \left(\frac{P_o}{1 \text{ day}} \right)^{4/7} \left(\frac{\dot{M}_*}{10^{-8} M_\odot \text{ yr}^{-1}} \right)^{-3/7} \left(\frac{v_0}{10^8 \text{ cm s}^{-1}} \right)^{12/7} \text{ s}, \quad (6)$$

where we have used the condition $r_m = r_c$, Kepler's third law in the circular orbit case, and a free-fall approximation for the flow within r_a . For fixed values of the stellar wind parameters \dot{M}_* and v_0 and the pulsar magnetic dipole moment μ (the range of possible

values of M_* and M_x plays only a marginal role), equation (6) defines a critical line in the P_s - P_o plane below which accretion is inhibited by the drag of the pulsar magnetosphere.

The transition between the accreting and the nonaccreting regime will not occur abruptly, because even when accretion is inhibited close to the equatorial plane of the neutron star, some fraction of the magnetospheric boundary at high latitudes will still be open to the penetration of the stellar wind material, as the centrifugal drag is locally sub-Keplerian. The details of this process strongly depend on the geometry of the accretion flow close to the magnetospheric boundary and, in turn, on the distortions in the shape of the magnetospheric boundary induced by the accretion flow. In the case of disk accretion a very sharp on/off transition is likely to be generated. For a spherical accretion flow onto an undistorted dipolar magnetospheric boundary, the flow down the polar cusps will be very small (Elsner 1976). Because the magnetosphere is softest at its equator, the most extended on/off transition is obtained when the dipole axis lies in the equatorial plane of the neutron star. If the mass inflow toward the magnetospheric boundary is reduced by a factor f with respect to the critical value $\dot{M}_x(\min) = L_{x,c}(\min)R_x/(GM_x)$, the accretion onto the neutron star surface will take place only from a solid angle $\sim(1 - \sin \beta)/4\pi$, where $f^{3/7} = \cos \beta[(1 + 3 \cos^2 \beta)/4]^{1/4}$. For $f = 0.1$, the accretion rate and the X-ray luminosity will thus be reduced to 1.2% of the value given by equation (5). This example illustrates that even in a very conservative case the transition to the centrifugally inhibited regime occurs rather sharply. In the following discussion we thus assume that the condition $r_m = r_c (< r_a)$ corresponds to the onset of the "propeller" mechanism.

c) Regime III: Magnetic Inhibition of Accretion

If $r_m > r_a$, the stellar wind will flow around the obstacle presented by the neutron star magnetosphere (such as occurs in the interaction of the solar wind and terrestrial magnetosphere). In this case, very little material will penetrate the magnetosphere radius to be accreted onto the neutron star (Illarionov and Sunyaev 1975). By imposing $r_m = r_a$, we obtain the minimum X-ray luminosity below which the wind material stops penetrating through the pulsar accretion radius as a consequence of magnetic inhibition of accretion,

$$L_{x,m}(\min) \approx 2 \times 10^{27} \left(\frac{R_x}{10^6 \text{ cm}} \right)^{-1} \left(\frac{M_x}{1.4 M_\odot} \right)^{-3} \left(\frac{\mu}{10^{30} \text{ G cm}^3} \right)^2 \left(\frac{v_0}{10^8 \text{ cm s}^{-1}} \right)^7 \text{ ergs s}^{-1}, \quad (7)$$

and the corresponding maximum orbital period,

$$P_{o,m}(\max) \approx 1.5 \times 10^6 \left(\frac{M_x}{1.4 M_\odot} \right)^{9/2} \left(\frac{M_*}{10 M_\odot} \right)^{-1/2} \left(\frac{\mu}{10^{30} \text{ G cm}^3} \right)^{-3/2} \left(\frac{\dot{M}_*}{10^{-8} M_\odot \text{ yr}^{-1}} \right)^{3/4} \left(\frac{v_0}{10^8 \text{ cm s}^{-1}} \right)^{-33/4} \text{ days}. \quad (8)$$

In view of the very strong dependence on the stellar wind velocity, the above equations provide only a rough guide to $L_{x,m}(\min)$ and $P_{o,m}(\max)$.

While equations (7) and (8) are independent of the pulsar period, the mechanism of magnetic inhibition of accretion through r_a requires that the light cylinder radius $r_l = cP_s/2\pi$, beyond which the pulsar magnetic field lines cannot propagate, is larger than r_a , so that the pulsar period must be

$$P_s > 15.6 \left(\frac{M_x}{1.4 M_\odot} \right) \left(\frac{v_0}{10^8 \text{ cm s}^{-1}} \right)^{-2} \text{ s}. \quad (9)$$

In addition, for accretion onto the neutron star surface to occur, the condition $r_c > r_m$ must also be satisfied. Setting $r_c > r_a$ gives

$$P_s > 9 \times 10^3 \left(\frac{M_x}{1.4 M_\odot} \right) \left(\frac{v_0}{10^8 \text{ cm s}^{-1}} \right)^{-3} \text{ s}. \quad (10)$$

Thus only for pulse periods longer than those given by equation (10), i.e., for very slowly rotating neutron stars, will the mechanism of magnetic inhibition of accretion occur before the centrifugal barrier acts.

Equations (7) and (8) are important because they define the parameter regime at which the "propeller" mechanism and, possibly, the accumulation of material close to the magnetospheric boundary will stop because the stellar wind is deflected by the neutron star magnetosphere before it passes within the accretion radius. Even for an effectively nonrotating X-ray pulsar there exists a critical cutoff X-ray luminosity. For typical values of v_0 , the minimum luminosities involved are five orders of magnitude below the lowest observed to date. This suggests that extremely low luminosity accreting magnetized neutron stars can exist, provided they are spun down to periods longer than several thousand seconds. Such a population may become accessible to the instruments on AXAF and XMM, and a few nearby systems may also be detected in the Galactic surveys of EXOSAT and ROSAT.

d) Regime IV: Radio Pulsar Inhibition of Accretion

For very fast X-ray pulsars ($P_s \ll 1$ s), the pressure exerted by the radio pulsar on the stellar wind material provides an additional mechanism of inhibiting accretion through r_a (Illarionov and Sunyaev 1975). By imposing the condition that the radio pulsar pressure at r_a counterbalances the wind ram pressure, one obtains the minimum X-ray luminosity $L_{x,r}(\min)$ possible for accretion through r_a to take place,

$$L_{x,r}(\min) \approx 2.4 \times 10^{37} \left(\frac{\mu}{10^{30} \text{ G cm}^3} \right)^2 \left(\frac{P_s}{0.1 \text{ s}} \right)^{-4} \left(\frac{M_x}{1.4 M_\odot} \right) \left(\frac{R_x}{10^6 \text{ cm}} \right)^{-1} \left(\frac{v_0}{10^8 \text{ cm s}^{-1}} \right)^{-1} \text{ ergs s}^{-1}. \quad (11)$$

Once the rate of mass capture at the accretion radius is higher than this, the flow will continue to the neutron star until the

centrifugal barrier is reached. The centrifugal barrier will be penetrated only for pulse periods less than

$$P_s \lesssim 4.4 \times 10^{-3} \left(\frac{v_0}{10^8 \text{ cm s}^{-1}} \right)^{-3/5} \left(\frac{M_x}{1.4 M_\odot} \right) \text{ s} \quad (12)$$

will direct accretion be possible after this barrier has been penetrated, and then, if the Eddington limit is not to be exceeded by a large factor, only if $\mu \approx 10^{28} \text{ G cm}^3$. Maraschi, Traversini, and Treves (1983) have suggested that this mechanism may be relevant to the 69 ms pulsar A0538–66, but only if a buildup of material at r_m allows the centrifugal barrier to be overcome or the wind velocity is very low or both.

IV. CENTRIFUGAL INHIBITION OF ACCRETION

In Figure 4 we plot the maximum X-ray luminosity observed from these systems, together with the lines of constant $L_{x,c}(\text{min})$ corresponding to equation (5) for a variety of magnetic dipole moments. The region below the line excludes accretion onto the neutron star and provides an upper limit for μ in each system. This diagram demonstrates that for most of the persistent sources $r_c > r_m$ for $\mu = 10^{30} \text{ G cm}^3$. If we were to impose the condition $r_c = r_m$ for all these systems, magnetic field strengths of $\sim 10^{14} \text{ G}$ are required for many of the longer period pulsars. This in turn would require a strong correlation of the magnetic field strengths with the pulse period which, as discussed in § VI, does not seem plausible. At the other extreme the super-Eddington luminosity and the rapid rotation period of A0538–66 requires a lower than average field strength of $\sim 10^{10.5} \text{ G}$ for the source to turn on (see also Skinner *et al.* 1982). The proximity of many of the transient systems to the $B = 10^{12} \text{ G}$ ($\mu = 10^{30} \text{ G cm}^3$) critical line (the neutron star magnetic field indicated by cyclotron line measurements) suggests that only a small decrease in \dot{M}_* (or an increase in v_0 , or both) will cause accretion in these systems to be inhibited by magnetospheric centrifugal forces. Conversely, a small increase in \dot{M}_* (or a decrease in v_0 , or both) could turn a dormant source into a luminous X-ray transient.

By using the minimum observed X-ray luminosity before the source “turns off” as a consequence of the centrifugal inhibition of accretion (and the canonical neutron star masses and radii), equation (5) can provide an estimate of the pulsar magnetic dipole moment (Fig. 5). For V0332+53, the minimum luminosity measured just before turnoff [$L_{x(\text{min})} \approx 7 \times 10^{34} (d/1.5 \text{ kpc})^2 \text{ ergs s}^{-1}$; Stella *et al.* 1985] provides a value for μ of $3.5 \times 10^{29} (d/1.5 \text{ kpc}) \text{ G cm}^3$. This estimate depends on the uncertainty in the evaluation of the distance to V0332+53. The estimate of $\sim 1.5 \text{ kpc}$ relies on the assumption that the primary is a main-sequence Be star (cf. Bernacca, Ijima, and Stagni 1984, and references therein). Such an evaluation of the pulsar magnetic field, while not direct, is complementary to that obtained from the detection of cyclotron lines in the X-ray spectrum of Her X-1 (Trümper *et al.* 1978) and 4U 0115+63 (Wheaton *et al.* 1979; White, Swank, and Holt 1983).³ In view of the uncertainties connected with the measurement of the X-ray luminosity at turnoff, the estimate based on equation (5) cannot be more precise than a factor of 2–3. Based on their

³ It is important to realize that eq. (5) provides an estimate of the magnetic dipole moment μ of the neutron star, since any higher multipolar component is likely to be negligible at $r \approx r_m$. In the most widely accepted interpretation, the X-ray cyclotron lines provide, instead, a measurement of the magnetic field strength at the neutron star surface, which can include a significant contribution from higher multipole components. The surface magnetic field strengths derived from eq. (5) can thus be smaller than those obtained from cyclotron line measurements.

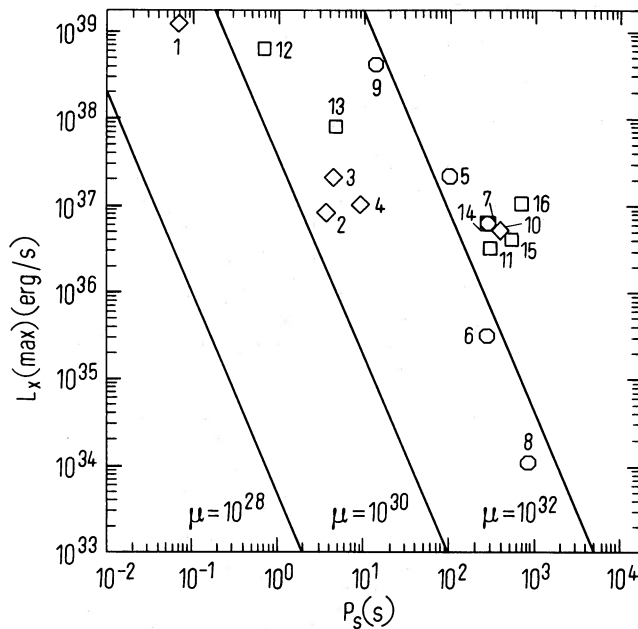


FIG. 4

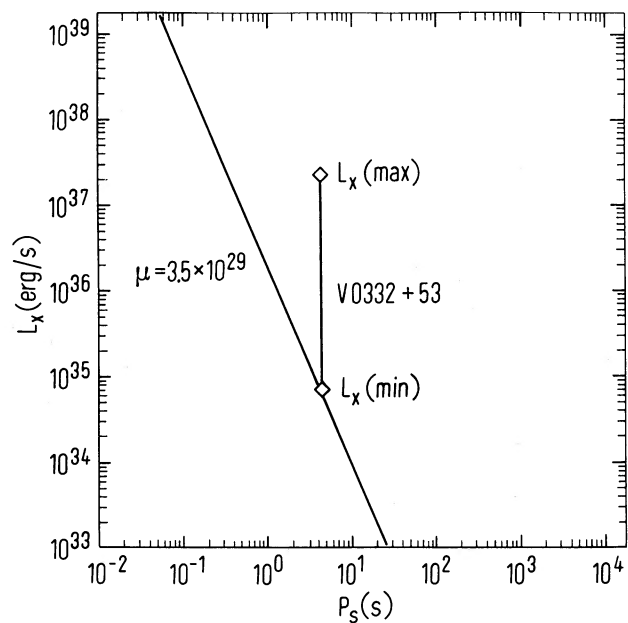


FIG. 5

FIG. 4.—Critical line below which accretion is inhibited by the centrifugal drag due to the rotating magnetosphere (cf. eq. [5]) is given for various values of μ in the $L_x(\text{max}) - P_s$ plane. Here and in the following figures we use $M_* = 10 M_\odot$, $M_x = 1.4 M_\odot$, and $R_x = 10^9 \text{ cm}$.

FIG. 5.—Evaluation of the pulsar magnetic dipole moment based on eq. (5). Dynamic range in the luminosity of V0332+53 for a distance of 1.5 kpc is indicated. $L_x(\text{max})$ refers to the 1973 giant outburst, and $L_x(\text{min})$ to the minimum detected X-ray luminosity during the 1983–1984 outbursts.

position in the $L_x(\text{max}) - P_s$ plane of Figure 4, the supergiant systems SMC X-1 and Cen X-3 are also likely candidates to undergo a transition to a dormant state, as a consequence of only a small reduction in the mass capture rate from the companion star.

The gross characteristics of the $L_x(\text{max}) - P_s$ anticorrelation that we point out in § II is naturally explained by the centrifugal barrier mechanism (cf. eq. [5]), since only those systems above a particular critical luminosity will be seen (for a given μ). If the magnetic fields were the same and if all these sources were at the critical point $r_c = r_m$, then L_x should be proportional to $P_s^{-7/3}$. The fact that the observed relation of $L_x(\text{max})$ and P_s [$L_x(\text{max}) \propto P_s^\alpha$, where $\alpha = -0.76 \pm 0.18$] is considerably less steep than $-7/3$ is likely to result both from observational selection effects and the fact that, as noted earlier, $r_c \neq r_m$. The use of $L_x(\text{max})$ [rather than $L_x(\text{min})$, as eq. (5) would require]⁴ would cause an observational bias, as this requires that all the persistent sources have the same dynamic range of luminosity, which seems unlikely. Also, if fast pulsars like A0538-66 ($P_s \lesssim 0.1$ s) are to become X-ray sources at a luminosity not strongly exceeding the Eddington limit, they must either possess low magnetic fields ($B \approx 10^{10}$ - 10^{11} G) to overcome the centrifugal barrier, or they must slow down to much longer rotation periods. The long-period pulsar with periods of several hundred seconds can accrete at much lower luminosities, so that the majority of the low-luminosity systems where $r_c \approx r_m$ would have escaped detection with the present generation of X-ray detectors.

V. THE P_s VERSUS P_o RELATION

As discussed above, the onset of the centrifugal inhibition of accretion requires a corresponding threshold in the stellar wind parameters. In Figure 6 we plot the critical lines corresponding to equation (6) for a variety of neutron star and stellar wind parameters. The wind parameters for the lines A , A' and B , B' were chosen so as to correspond to those typical of a supergiant and Be star, with $\gamma = (\dot{M}_*/10^{-8} M_\odot \text{ yr}^{-1})(v_o/10^8 \text{ cm s}^{-1})^{-4} = 1$ and 100 respectively (note that in this description the dependence on these two stellar wind parameters cannot be disentangled). It is interesting to note that most of the persistent sources occupy the upper part of the graph, well above the critical lines A and B corresponding to $\mu = 10^{30} \text{ G cm}^3$. As we have noted before, they are unlikely to undergo a transition to a nonaccreting quiescence state, unless the magnetic field strengths are substantially higher than 10^{12} G. The transient systems are usually in their dormant state, and all occupy the lower part of the P_o - P_s plane, close to the critical lines of Figure 6. As we have discussed for V0332+53, a change in the stellar wind parameters can cause these systems to suddenly "turn on." The Be X-ray transient systems may represent the tip of the iceberg of a population of dormant sources, for which an increase in the mass ejection rate from the primary star or a decrease in the wind velocity or both can cause them to briefly turn into highly luminous X-ray sources.

The effects of an eccentric orbit can be approximated in Figure 6 by indicating the equivalent range of orbital periods $P_o(1-e)^{3/2} \leq P_o(\text{eq}) \leq P_o(1+e)^{3/2}$ that corresponds to the circular orbit periods for the range of binary separations of an eccentric orbit. This is shown in Figure 7 for V0332+53; during an orbital cycle the source moves back and forth along the indicated range of equivalent orbital periods. Depending on the values of the primary star wind parameters defined by γ , three different situations can

⁴ Extensive studies of the minimum X-ray luminosity below which OB-star X-ray pulsar transient systems "turn off" have still to be carried out (using all sky monitors).

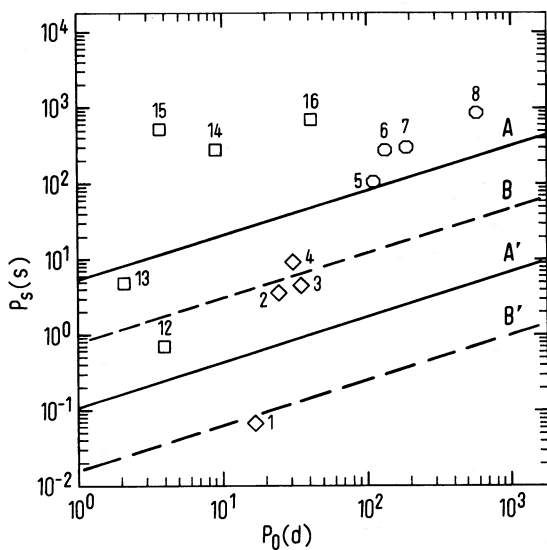


FIG. 6

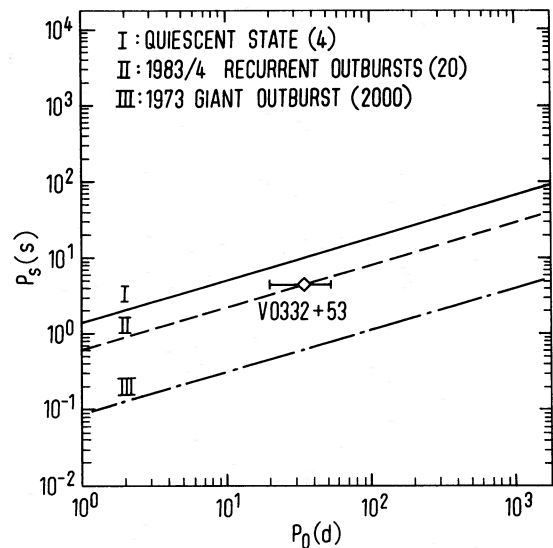


FIG. 7

FIG. 6.—Critical lines given by eq. (6) for selected values of \dot{M}_* , v_o , and μ in the spin period (P_s)–orbital period (P_o) plane. The lines A correspond to $\gamma = (\dot{M}_*/10^{-8} M_\odot \text{ yr}^{-1})(v_o/10^8 \text{ cm s}^{-1})^{-4} = 1$. The lines B are obtained by increasing γ by a factor of 100. Magnetic dipole moment is $\mu = 10^{30} (10^{28}) \text{ G cm}^3$ for the lines A and B (A' and B').

FIG. 7.—Position of V0332+53 in the orbital period (P_o)–spin period (P_s) plane. Range of equivalent orbital periods $P_o(\text{eq})$ is indicated. Critical line corresponding to eq. (6) is given for three different choices of the stellar wind parameters $\gamma = (\dot{M}_*/10^{-8} M_\odot \text{ yr}^{-1})(v_o/10^8 \text{ cm s}^{-1})^{-4} = 4, 20, 2000$, which are suitable to model respectively the quiescent state, the 1983–1984 periodic outbursts, and the 1973 giant outburst. The value of $\mu = 3.5 \times 10^{29} \text{ G cm}^3$ is obtained from Fig. 5.

occur. If the critical line defined by equation (6) lies above the range of $P_0(\text{eq})$, the X-ray pulsar will be in its dormant state. An increase of \dot{M}_* or a decrease of v_0 or both can cause the critical line to move down in the P_0 - P_s plane to intersect the segment representing the range of $P_0(\text{eq})$. In this case the X-ray pulsar can become active only in an orbital phase interval centered on periastron.⁵ For the remainder of the cycle the system is X-ray-dark. A larger increase in γ can move the critical line below the segment of $P_0(\text{eq})$, and the X-ray pulsar will thus be in its active state for all the orbital phases. This provides a very natural explanation for the large orbital modulation observed in the 1983–1984 outburst of V0332+53 (Stella *et al.* 1985) and the failure to detect a comparably strong orbital modulation during the more luminous 1973 outburst (Terrell and Priedhorsky 1984).

The peculiar behavior of the transient 4U 0115+63, for which the 1980 optical activity preceeded the X-ray outbursts by ~ 60 days, can also be understood in a similar manner. The measured surface magnetic field of $B = 10^{12}$ G (Wheaton *et al.* 1979; White, Swank, and Holt 1983) and the minimum luminosity observed during the 1972 outbursts of $\sim 10^{36}$ ergs s^{-1} (Forman, Jones, and Tananbaum 1976) imply that this system is very close to $r_m = r_c$ during that part of the outburst. The enhanced mass ejection episode from the primary probably occurred when the primary brightened by 1.7 mag, but for the first ~ 60 days was not enough to ensure $r_m < r_c$ at any orbital phase, so that the X-ray pulsar remained inactive. At a certain point in the outburst, the pressure of the inflowing material was sufficient to overcome the centrifugal barrier, and the X-ray pulsar turned on. This view is also supported by the fact that, at the end of the 1980 outburst, the X-ray flux decayed more rapidly than the optical flux (Kriss *et al.* 1983). The eccentricity of the orbit of 4U 0115+63 is similar to that of V0332+53. The fact that no strong 24 day cycle is apparent in the light curve suggests that once the barrier had been overcome, the mass flow was such as to keep the pulsar X-ray-bright around the complete binary cycle. Other outbursts from this source which are less strong may show class I behavior similar to that of the 1983–1984 outbursts from V0332+53.

Some class II outbursts tend to rise and fall in a symmetric manner (see Fig. 1), while others, such as the 1980 outburst of 4U 0115+63, begin with a sharp rise, followed by an exponential decline (Rose *et al.* 1979). The latter behavior may suggest a draining reservoir. A possible factor in the evolution of the light curve is mediation of the flow by an accretion disk. However, as noted by many authors (see Savonije 1980), the specific angular momentum captured from a stellar wind is extremely low, and only if the wind velocity is similar to or less than the orbital velocity ($\lesssim 200$ km s^{-1}) can a disk form. The observed period changes in many wind-driven X-ray pulsars directly show that the angular momentum being captured by the neutron star is well below that required to form an accretion disk (Savonije 1980; White 1984). One possibility mentioned by Maraschi, Traversini, and Treves (1983) is that prior to the X-ray turn-on, the material accumulates faster than it can be propelled away. For the interval between the optical and the X-ray outbursts of 4U 0115+63, a substantial ring may have been spun up outside the magnetosphere by the propeller mechanism. If such a ring forms, then class I behavior will only be possible if it drains (and then builds up again) on a time scale shorter than half an orbital cycle.

VI. DISCUSSION

In any binary system containing a magnetized neutron star with a companion star that has a stellar wind, the interaction of the rotating magnetosphere with any accreted material is crucial in determining the X-ray properties of the system. We have discussed four regimes where the interaction will be different. In regime I the magnetospheric radius is smaller than the corotation radius, such that the magnetosphere is open and a bright X-ray pulsar is seen. Regime II occurs when the magnetospheric radius exceeds the corotation radius but is less than the accretion radius. In this regime the inflowing material cannot penetrate the magnetosphere and is likely to be centrifugally propelled away. In regime III the magnetospheric radius exceeds the accretion radius, such that the stellar wind is simply deflected around the neutron star magnetosphere with very little accretion occurring. Finally, when the pulsar is very young and rotating very rapidly, such that radio pulsar pressure prevents the stellar wind from penetrating through the neutron star accretion radius, it is in regime IV.

The spin evolution of a neutron star after it is born, presumably as a rapidly rotating pulsar, will pass through these four regimes. The issue as to whether or not such a pulsar can be spun down on a time scale short compared to the lifetime of the companion remains controversial, and we will not repeat the discussion here (see Davies and Pringle 1981; Henrichs 1983, and references therein, for the current picture). Irrespective of the spin history of the X-ray pulsars, our results have shown that most of the long-period systems (P_s longer than several hundred seconds) must lie well away from the equilibrium point where $r_c = r_m$. The assertion by Corbet (1984) that all these systems are close to the equilibrium point requires instead (independent of any assumptions regarding the properties of the stellar wind) a correlation between pulse period and magnetic field strength, with fields as strong as 10^{14} G in the longest period systems (cf. Fig. 4). Such field strengths are excessive but not implausible. However, this would be contrary to the estimate of $\sim 10^{12}$ G obtained from the spin-down rate of radio pulsars and contrary to the measured field strengths in Her X-1 and 4U 0115+63. Moreover, if the neutron star magnetic field were to arise from dynamo action during the collapse process, slowly rotating pulsars should be born with weaker, not stronger, fields (Flowers and Ruderman 1977).

If these long-period pulsars are far from the equilibrium point, then this requires that either they were born with such periods, or that up until recently the wind parameter $\gamma (= \dot{M}_* v_0^{-4})$ was several orders of magnitude lower and these systems have yet to be spun up to the new equilibrium period. In this regard it is interesting to note that the long-period pulsars whose pulse period has been monitored for several years (e.g., Vela X-1 and GX 301–2) do not seem to be spinning up on long time scales (several years or more), but rather show random-walk variations in pulse period with temporary spin-up and spin-down episodes that may cancel out any long-term trend (e.g., Henrichs 1983; Boynton *et al.* 1984). This is in marked contrast to the higher luminosity, rapidly rotating pulsars in supergiant star systems such as Cen X-3 and SMC X-1, whose rotation periods are increasing on a time scale of 100–1000 yr. In these luminous systems it seems more likely that an accretion disk will form, either because of a more intense stellar

⁵ We note that the pulsar orbital motion, which we neglect in the present treatment, slightly increases (decreases) the wind velocity relative to the neutron star before (after) the periastron passage, and will slightly shift the outburst center after the time of periastron.

wind (cf. Bonnet-Bidaud and van der Klis 1979) or because of incipient Roche lobe overflow (Friend and Castor 1982). This indicates that once a neutron star has been spun down to very long periods, the low specific angular momentum of the wind material is insufficient to spin it back up if the wind strength increases, unless incipient Roche lobe overflow begins.

The transient X-ray pulsars with periods of a few seconds, when active, all lie close to the equilibrium point if it is assumed that they have magnetic moments close to $\sim 10^{30}$ G cm³. It is therefore encouraging that in the one case for which measurements of the surface field strength (from the detection of a cyclotron line) are available, namely 4U 0115+63, directly shows this assumption to be justified. These pulsars spend less than 10% of their lifetime in outburst, and during the remaining time they are presumably in regime II, undergoing "propeller" spin-down. Measurements of the pulse period from one outburst to the next could give some indication of the spin-down rates, although because the spin-up rates during outburst can be high, it is essential to measure the pulse period at the start of each outburst.

The ratio of the maximum to minimum luminosity of the transient outbursts from the Be star can be strongly amplified by the effects of the centrifugal barrier. If a neutron star lies just below the critical point, only a small change in the stellar wind parameter will turn it into a bright X-ray source. We have identified one system, V0332+53, where during an outburst in 1983-1984 this critical point straddled the orbit, such that for one part of the orbit the system was in regime I, and the other part in regime II. The fact that this system is so close to the equilibrium point might be related to the extraordinary level of stochastic short-term variability (~ 1 s) seen from this pulsar, which Stella *et al.* (1985) discuss in terms of a magnetospheric instability.

The origin of the correlation between the pulse and orbital periods of the Be star X-ray binaries noted by Corbet (1984) is not clear. The only Be star systems identified to date with orbital periods less than 50 days all have pulse periods of less than 100 s. The spin-down time scale for the pulsars in these systems should be somewhat quicker than the longer period systems; however, as yet no long-period pulsars have been identified in short-period binaries. This correlation suggests a connection between the birth period of the X-ray pulsar and the orbital period. However, Savonije and van den Heuvel (1977) have ruled out tidal synchronization of the helium progenitor (after core contraction), as the time scale required seems to be far too long. Nonetheless, given that the Be stars in these systems should form a homogeneous sample with respect to their age, it is not clear why long orbital periods tend to be associated with long pulse periods.

It is interesting to note that there is no evidence for any correlation of orbital and pulse periods for the supergiant systems, with three of five pulse periods being longer than 100 s. This once again suggests these systems were spun down to the centrifugal equilibrium spin period during a phase when the wind of the companion star was much less active (or that they were born with slow rotation periods). Since then, the wind has become much stronger, and the neutron star spin has not caught up with the equilibrium point. It is notable that only the two shortest orbital period supergiant systems show evidence for rapid spin-up, again supporting the view that only in the case of incipient Roche lobe overflow is a large amount of angular momentum transferred to the neutron star.

The 69 ms X-ray pulsar in A0538-66 provides direct evidence that at least in one case the pulsar was born spinning rapidly. Normally we would not expect to see such systems; however, in this case the magnetic dipole moment of the neutron star must be at least a factor of 10 lower than is normally assumed. This allows the centrifugal barrier to be overcome for accretion rates that result in luminosities up to a factor of 10 in excess of the Eddington limit. The fact that this is likely to be a young system (the highly eccentric orbit suggests this) and yet has a neutron star with a magnetic field of only $\sim 10^{11}$ G (cf. Skinner *et al.* 1982) is notable because it means either that neutron stars are born with a range of field strengths, rather than the canonical 10^{12} G that is usually assumed, or that the young neutron star has a very high multipole component that becomes dipolar as the system ages. Alternatively, this system might not be young such that the X-ray pulsar has been spun back up to its rapid period (E. van den Heuvel, private communication). Variations in the centrifugal barrier in a manner similar to that discussed for V0332+53 provides a very natural explanation for both the high $L_x(\text{max})/L_x(\text{min})$ around one orbital cycle and the long quiescent intervals seen from this source, without any need to invoke intervals of Roche lobe overflow at the time of periastron passage (see Charles *et al.* 1983).

VII. CONCLUSION

Our investigation of the possible wind regimes in Population I binary systems containing an X-ray pulsar leads to a natural explanation of the transient activity observed in many of these systems in terms of the centrifugal mechanism of inhibition of accretion. In particular, we can model the large dynamic range in the X-ray luminosity between the ON and the OFF states and the periodic or irregular character of the outbursts. The model is particularly successful in interpreting the bimodal transient activity observed in the sources (like V0332+53) which display both irregular giant outbursts and the periodic low-level outbursts close to periastron passage. In this context, the luminosity at which an X-ray pulsar transient "turns off," if it can be measured by an all-sky monitor, would provide a useful estimate of the magnetic dipole moment of the neutron star. These conclusions emphasize the need for an X-ray all-sky monitor that can monitor the activity of these systems over at least 5 yr.

We have benefited from useful discussions with J. Arons, R. Kelley, and F. Lamb. We would like to thank the European Space Agency (L. S., N. E. W.) and the National Science Foundation (R. R.) for partial support of this work.

REFERENCES

- Apparao, K. M. V. 1985, *Ap. J.*, **292**, 257.
 Bernacca, P. L., Iijima, T., and Stagni, R. 1984, *Astr. Ap.*, **132**, L8.
 Bondi, H., and Hoyle, F. 1944, *M.N.R.A.S.*, **104**, 273.
 Bonnet-Bidaud, J. M., and van der Klis, M. 1979, *Astr. Ap.*, **73**, 90.
 Boynton, P. E., Deeter, J. E., Lamb, F. K., Zylstra, G., Pravdo, S. H., White, N. E., Wood, K. S., and Yentis, D. J. 1984, *Ap. J. (Letters)*, **283**, L53.
 Bradt, H. V. D., and McClintock, J. E. 1983, *Ann. Rev. Astr. Ap.*, **21**, 13.
 Charles, P. A., *et al.* 1983, *M.N.R.A.S.*, **202**, 657.
 Conti, P. S. 1978, *Astr. Ap.*, **63**, 225.
 Corbet, R. H. D. 1984, *Astr. Ap.*, **141**, 91.
 Davidson, K., and Ostriker, J. P. 1973, *Ap. J.*, **179**, 585.
 Davies, R. E., and Pringle, J. E. 1981, *M.N.R.A.S.*, **156**, 209.
 Elsner, R. F. 1976, Ph.D. thesis, University of Illinois.
 Fabian, A. C. 1975, *M.N.R.A.S.*, **173**, 161.
 Flowers, E., and Ruderman, M. A. 1977, *Ap. J.*, **215**, 302.
 Forman, W., Jones, C., and Tananbaum, H. 1976, *Ap. J. (Letters)*, **206**, L29.

- Friend, D. B., and Castor J. I. 1982, *Ap. J.*, **261**, 293.
 Giangrande, A., Giovanelli, F., Bartolini, C., Guarnieri, A., and Piccioni, A. 1980, *Astr. Ap. Suppl.*, **40**, 289.
 Henrichs, H. F. 1980, in *Highlights Astr.*, **5**, 541.
 ———. 1983, in *Accretion Driven Stellar X-ray Sources*, ed. W. H. G. Lewin and E. P. J. van den Heuvel (Cambridge: Cambridge University Press), p. 393.
 Illarionov, A. F., and Sunyaev, R. A. 1975, *Astr. Ap.*, **39**, 185.
 Joss, P. C., and Rappaport, S. 1984, *Ann. Rev. Astr. Ap.*, **22**, 537.
 Kelley, R. L., Rappaport, S., and Ayasli, S. 1983, *Ap. J.*, **274**, 765.
 Kriss, G. A., Cominsky, L. R., Remillard, R. A., Williams, G., and Thorstensen, J. R. 1983, *Ap. J.*, **266**, 806.
 Lamb, F. K., Pethick, C. J., and Pines, D. 1973, *Ap. J.*, **184**, 271.
 Lamb, F. K. 1984, in *High Energy Transients*, ed. S. E. Woosley (New York: AIP), p. 179.
 Maraschi, L., Traversini, R., and Treves, A. 1983, *M.N.R.A.S.*, **204**, 1179.
 Maraschi, L., Treves, A., and van den Heuvel, E. P. J. 1976, *Nature*, **259**, 292.
 Petterson, J. A. 1978, *Ap. J.*, **224**, 625.
 Priedhorsky, W. C., and Terrell, J. 1983a, *Nature*, **303**, 681.
 ———. 1983b, *Ap. J.*, **273**, 709.
 Rappaport, S., and van den Heuvel, E. P. J. 1982, in *IAU Symposium 98, Be Stars*, ed. H. Haschek, and H. Groth (Dordrecht: Reidel), p. 327.
 Rose, L. A., Pravdo, S. H., Kaluzienski, L. J., Marshall, F. E., Holt, S. S., Boldt, E. A., Rothschild, R. E., and Serlemitsos, P. J. 1979, *Ap. J.*, **231**, 919.
 Savonije, G. J. 1980, *Astr. Ap.*, **83**, 375.
 Savonije, G. J., and van den Heuvel, E. P. 1977, *Ap. J. (Letters)*, **214**, L19.
 Skinner, G. K., Bedford, D. K., Elsner, R. F., Leahy, D., Weisskopf, M. C., and Grindlay, J. E. 1982, *Nature*, **297**, 568.
 Stella, L., White, N. E., Davelaar, J., Parmar, A. N., Blissett, R. J., and van der Klis, M. 1985, *Ap. J. (Letters)*, **288**, L45.
 Terrell, J., and Priedhorsky, W. C. 1984, *Ap. J. (Letters)*, **285**, L15.
 Trümper, J., Pietsch, W., Reppin, C., Voges, W., Staubert, R., and Kendziorra, E. 1978, *Ap. J. (Letters)*, **219**, L105.
 Wang, Y. M. 1981, *Astr. Ap.*, **113**, 113.
 Wassermann, I., and Shapiro, S. L. 1983, *Ap. J.*, **265**, 1063.
 Watson, M. G., Warwick, R. S., and Corbet, R. H. D. 1982, *M.N.R.A.S.*, **199**, 915.
 Wheaton, W. A., et al. 1979, *Nature*, **282**, 240.
 White, N. E. 1984, in *Proc. 1983 NATO Summer School on Interacting Binary Stars*, in press.
 White, N. E., Kallman, T., and Swank, J. H. 1983, *Ap. J.*, **269**, 264.
 White, N. E., Swank, J. H., and Holt, S. S. 1983, *Ap. J.*, **279**, 711.
 White, N. E., Swank, J. H., Holt, S. S., and Parmar, A. N. 1982, *Ap. J.*, **263**, 277.

Note added in proof.—Since completion of this work, three new X-ray pulsars have been found. The 4.2 periodically flaring persistent source X1907+097 has recently been determined to be a 437 s X-ray pulsar. Pulse-timing measurements give a moderately eccentric 8.4 day orbit ($e \approx 0.24$) with a mass function of $\sim 9 M_{\odot}$ consistent with an OB star companion (K. Makishima, N. Kawai, K. Koyama, N. Shibasaki, F. Nagase, and M. Nakagawa, *Pub. Astr. Soc. Japan*, **36**, 679 [1984]). The luminosity of $\sim 5 \times 10^{35}$ ergs s^{-1} indicates that this source is well away from centrifugal equilibrium. To date this is the only system in which two flares per orbit (at phases ~ 0.04 and ~ 0.48) have been observed. This supports the scenario involving flaring caused by equatorial mass loss from the OB star combined with an orbital axis offset from the rotation axis of the companion. However, X1907+097 is not a class I transient X-ray source, because the flaring activity is limited to a factor of ~ 10 .

The 6.4 s X-ray pulsar 1E 1048.1–5937, for which no direct evidence for binary orbital motion has yet been found, displays pronounced variability (larger than a factor of ~ 20) suggestive of transient activity (F. D. Seward, P. A. Charles, and A. P. Smale, *Ap. J.*, **305**, 814 [1986]). The luminosity of the source was constrained to be between $\sim 2 \times 10^{34}$ and $\sim 10^{36}$ ergs s^{-1} during an active state, based on a range of possible distances of 2–15 kpc. The position occupied by 1E 1048.1–5937 in the $L_x(\text{max})$ – P_s diagram of Figure 4 lies close to or below the $\mu = 10^{30}$ G cm^3 for the minimum allowed luminosity line, therefore suggesting that the system is likely to display transient activity because of centrifugal inhibition of accretion.

For the 41.2 s X-ray pulsar transient system EXO 2030+375, recently discovered with *EXOSAT*, an orbital period of 38 days, an eccentricity of 0.31, and a mass function of $\sim 5 M_{\odot}$ (consistent with the unidentified companion being an OB star) have been determined (A. N. Parmar, L. Stella, P. Ferri, and N. E. White, *IAU Circ.*, No. 4066 [1985]; N. E. White, P. Ferri, A. N. Parmar, and L. Stella, *IAU Circ.*, No. 4112 [1985]). The source decayed in intensity by a factor of ~ 5000 between 1985 May and August, with a maximum luminosity of $\sim 4 \times 10^{38}$ ergs s^{-1} (as estimated from the spin-up time scale) and a minimum detected luminosity of $\sim 10^{35}$ ergs s^{-1} . The fact that EXO 2030+375 has been observed over such a large range of accretion rates directly proves that at least in one case a relatively long period pulsar possesses a magnetic dipole moment substantially smaller than 10^{32} G cm^3 (cf. Fig. 4).

R. ROSNER: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

L. STELLA and N. E. WHITE: *EXOSAT* Observatory, ESOC, Robert Bosch Str. 5, 6100 Darmstadt, Federal Republic of Germany