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ON THE DRAMATIC SPIN-UP/SPIN-DOWN TORQUE REVERSALS IN ACCRETING PULSARS

Robert W. Nelson,[1] Lars Bildsten,[2] Deepto Chakrabarty,[3] Mark H. Finger,[4] Danny T. Koh,[5] Thomas A. Prince,[5] Bradley C. Rubin,[4,6] D. Mathew Scott,[4] Brian A. Vaughan,[5] and Robert B. Wilson[4]

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ABSTRACT

Dramatic torque reversals between spin-up and spin-down have been observed in half of the persistent X-ray pulsars monitored by the BATSE all-sky monitor on the *Compton Gamma Ray Observatory*. Theoretical models developed to explain early pulsar timing data can explain spin-down torques via a disk-magnetosphere interaction if the star nearly corotates with the inner accretion disk. To produce the observed BATSE torque reversals, however, these equilibrium models require the disk to alternate between two mass accretion rates, with $\dot{M}_{\pm}$ producing accretion torques of similar magnitude but always of opposite sign. Moreover, in at least one pulsar (GX 1+4) undergoing secular spin-down, the neutron star spins down faster during brief (~20 day) hard X-ray flares—this is opposite the correlation expected from standard theory, assuming that BATSE pulsed flux increases with mass accretion rate. The 10 day to 10 yr intervals between torque reversals in these systems are much longer than any characteristic magnetic or viscous timescale near the inner disk boundary and are more suggestive of a global disk phenomenon.

We discuss possible explanations of the observed torque behavior. Despite the preferred sense of rotation defined by the binary orbit, the BATSE observations are surprisingly consistent with an earlier suggestion for GX 1+4: the disks in these systems somehow alternate between episodes of prograde and retrograde rotation. We are unaware of any mechanism that could produce a stable retrograde disk in a binary undergoing Roche lobe overflow, but such flip-flop behavior does occur in numerical simulations of wind-fed systems. One possibility is that the disks in some of these binaries are fed by an X-ray–excited wind.

Subject headings: pulsars: general — pulsars: individual (GX 1+4)

1. SPIN-UP AND SPIN-DOWN IN ACCRETION-POWERED PULSARS

The spin evolution of an accreting magnetic star, an X-ray pulsar, magnetic CV, or T Tauri star, is thought to be regulated by torques acting between the accretion disk and the stellar magnetosphere (Rappaport & Joss 1977; Warner 1990; Konigl 1991). Because of the small neutron star moment of inertia, however, only the X-ray pulsars undergo accretion-induced changes in rotation frequency large enough to be measured on short timescales (~days). They are thus ideal laboratories for studying the dynamical interaction between a magnetic star and its accretion disk.

Accreting X-ray pulsars are rotating, highly magnetized ($B \sim 10^{12}$ G) neutron stars that accrete material from a stellar companion, either from a stellar wind or by Roche lobe overflow mediated by an accretion disk. Disks may also form in wind-fed systems if the captured material has sufficient angular momentum to circularize before reaching the neutron star magnetosphere (see King 1995). The strong magnetic field disrupts the disk and forces the accreting plasma to corotate with the star at a radius where magnetic and fluid stresses roughly balance, $r_m \sim \mu^{4/7}\dot{M}^{-2/7}(GM_x)^{-1/7} \sim 10^8$–$10^9$ cm, where $\dot{M}$ is the mass accretion rate, μ is the magnetic dipole moment, and M_x is the mass of the neutron star. Although the coupling between the disk and magnetosphere is complicated and may depend on the geometry and relative orientation of the magnetic field (Wang 1997), in the simplest picture of accretion torque (Pringle & Rees 1972; Rappaport & Joss 1977) one assumes that the specific angular momentum of material captured from the inner accretion disk is somehow transported onto the star with the accreting matter. For a Keplerian disk, the pulsar will experience a spin-up torque,

$$N = \dot{M}\sqrt{GMr_m} = 2\pi I\dot{\nu}, \tag{1}$$

where $\dot{\nu}$ is the pulsar spin frequency and $I \sim 10^{45}$ g cm^2 is the neutron-star moment of inertia. Early observations indicated that, on average, most accreting pulsars were spinning up on a timescale of $t_{su} = \nu/\dot{\nu} \sim 10^4$ yr, consistent with equation (1). This was strong evidence that X-ray pulsars must be compact stars with large magnetospheric radii (Rappaport & Joss 1977).

This simple spin-up picture had to be modified when two well-studied pulsars, Her X-1 and Cen X-3, were found to be spinning up much more slowly than predicted by equation (1). Furthermore, these pulsars sometimes underwent short episodes of spin-down (Elsner & Lamb 1977; Ghosh & Lamb 1979, hereafter GL). How could a star capturing material from a disk with the same sense of rotation actually lose angular momentum while continuing to accrete?

To explain this behavior, GL argued that the spin-up accretion torque must decrease—and eventually become negative—when the stellar rotation frequency approaches the Keplerian orbital frequency of the inner accretion disk, $\Omega_* \simeq \Omega_K(r_m) = (GM/r_m^3)^{1/2}$. Since most X-ray pulsars are in binaries much older than the pulsar spin-up timescale, GL argued that they should have reached this near-equilibrium state. In this situation, magnetic field lines that thread the disk beyond the corotation radius (where the disk rotates more slowly than the

[1] Theoretical Astrophysics, California Institute of Technology, Pasadena, CA 91125.
[2] Department of Physics and Department of Astronomy, University of California, Berkeley, Berkeley, CA 94720.
[3] Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139.
[4] Space Science Laboratory, NASA/Marshall Space Flight Center, Huntsville, AL 35812.
[5] Space Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125.
[6] Cosmic Radiation Lab, Institute of Physical and Chemical Research (RIKEN), Wako-shi, Saitama 351-01, Japan.

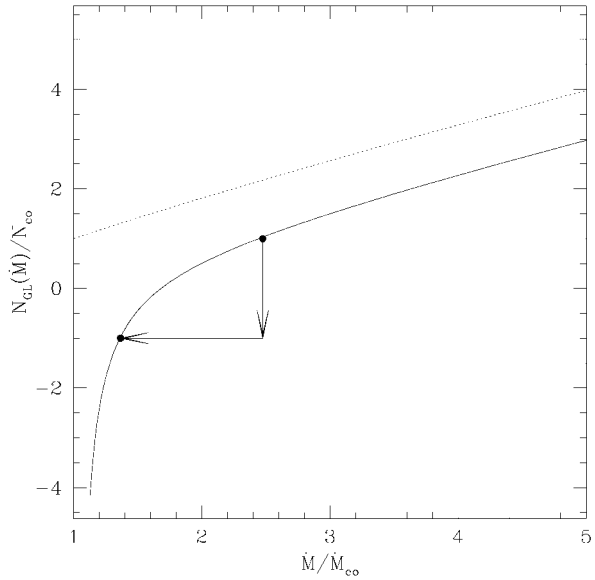

FIG. 1.—The Ghosh-Lamb accretion torque is a smooth function of mass accretion rate that passes through zero and becomes negative as $\dot{M}$ decreases and the magnetosphere approaches the corotation. Here $\dot{N}_{co} = \dot{M}_{co}(GMr_{co})^{1/2}$ and $r_m(\dot{M}_{co}) = r_{co} = (GM/\Omega_*^2)^{1/3}$. Sudden transitions between spin-up and spin-down—as occurs repeatedly for Cen X-3 (Fig. 2)—require step-function–like changes in $\dot{M}$. The dotted line corresponds to the simple spin-up torque model $N = \dot{M}(GMr_m)^{1/2}$.

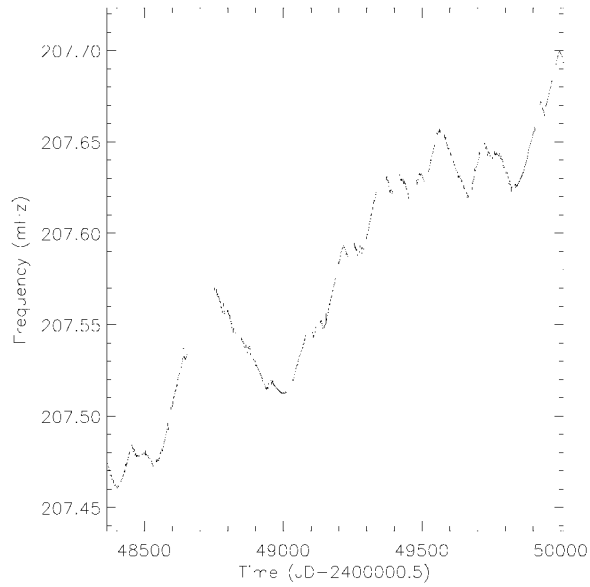

FIG. 2.—Long-term spin frequency of Cen X-3. The torque appears to be bimodal, alternating between spin-up and spin-down, with an instantaneous torque magnitude much larger than its average value.

star) are swept back in a trailing spiral and transport angular momentum outward. Stars close to equilibrium will spin up much more slowly than predicted by equation (1) and can even spin down while continuing to accrete.

GL wrote their torque as a modified form of equation (1),

$$N_{GL} = n(\omega)\dot{M}\sqrt{GMr_m}, \tag{2}$$

where $n(\omega)$ is a dimensionless function of the "fastness parameter" $\omega = \Omega_*/\Omega_K(r_m) \propto \dot{M}^{-3/7}\Omega_* B_*^{6/7}$. For most observations, Ω_* can be taken as constant, so that, in their theory, observed torque fluctuations reflect mainly the dependence of N_{GL} on $\dot{M}$. Although several functional forms have been suggested (see, e.g., Campbell 1987; Wang 1987, 1995, 1997), for our discussion it is important only that N_{GL} is a smooth and monotonically increasing function of $\dot{M}$ that crosses zero at some $\dot{M}_{crit}$ corresponding to a critical fastness parameter $\omega_{crit} \lesssim 1$. An approximate version of $N_{GL}(\dot{M})$ with $\omega_{crit} = 0.8$ is shown in Figure 1. In particular, the spin-up torque becomes negative at low accretion rates; the magnetospheric radius $r_m \propto \dot{M}^{-2/7}$ moves outward, close enough to the corotation radius $r_{co} = (GM/\Omega_*^2)^{1/3}$ that the negative magnetic torques become large. Note, however, that sudden changes in accretion torque require sudden changes in $\dot{M}$.

2. OBSERVATIONS OF TORQUE REVERSALS WITH BATSE

Prior to 1991, the spin periods of accreting pulsars were typically measured only once or twice per year by pointed X-ray telescopes (Nagase 1989 and references therein). Consequently, published measurements of accretion torque were usually long-term averages. Since the launch of the *Compton Gamma Ray Observatory* in April 1991, however, the BATSE instrument has compiled the first continuous long-term history of pulse frequencies for the majority of persistent X-ray pulsars (Bildsten et al. 1997), increasing the sampling of pulse periods by more than a factor of 100.

The frequency history of the 4.8 s pulsar Cen X-3 shown in Figure 2 is one example in which BATSE observations reveal a strikingly different picture of pulsar spin behavior than previously understood. Prior to BATSE, the long-term frequency history had been described as secular spin-up at $\dot{\nu} = 8 \times 10^{-13}$ Hz s^{-1}—a factor of ∼5 slower than predicted by equation (1)—superposed with wavy fluctuations and short episodes of spin-down. This behavior was interpreted as evidence that Cen X-3 was rotating near its equilibrium spin period with a significantly reduced torque (Elsner & Lamb 1977). In contrast, the more frequently sampled BATSE data show that Cen X-3 actually exhibits frequent transitions between states of steady spin-up and spin-down, with a short-term torque magnitude consistent with that in equation (1). The bimodal torque behavior has been confirmed quantitatively (Finger, Wilson, & Fishman 1994). The pulsar is nearly always in one of two possible torque states ($\dot{\nu} \simeq -4 \times 10^{-12}$ or $\simeq 7 \times 10^{-12}$ Hz s^{-1}) and remains in one state for ∼10–100 days before switching to the other. Transitions between spin-up and spin-down occur on a timescale more rapid than BATSE can resolve, $\lesssim$10 days. It is now evident that the reduced long-term spin-up torque inferred from the sparse pre-BATSE data is a consequence of these frequent transitions between spin-up and spin-down (Prince et al. 1994).

Interestingly, torque transitions like those seen in Cen X-3 appear to be common: at least four of the eight persistent pulsars observed by BATSE show torque reversals between steady spin-up and steady spin-down. Of the remaining four, three (GX 301−2, Vela X-1, and 4U 1538−52) are wind-fed pulsars, while Her X-1 is sampled infrequently at 35 day intervals, so we cannot measure its torque on short timescales. One of the most dramatic torque transitions took place in the 7.6 s pulsar 4U 1626−67 around 1991 (Chakrabarty et al. 1997a). After two decades of the smoothest spin-up observed in any accreting pulsar, BATSE found that 4U 1626−67 was smoothly spinning down. Most surprisingly, the spin-down torque is nearly equal

in magnitude, but opposite in sign, to the spin-up torque. A similar transition to spin-down was observed in the 120 s pulsar GX 1+4 in 1988 (Makishima et al. 1988) after more than a decade of steady spin-up. Again, the spin-down rate is close in magnitude to the spin-up rate. Finally, the 38 s disk-fed pulsar OAO 1657−415 shows torque episodes with strength and duration very close to those seen in Cen X-3 (Chakrabarty et al. 1993).

3. ACCRETION FROM RETROGRADE DISKS?

To explain the BATSE observations, the near-equilibrium models described above require the disks in systems like Cen X-3 to somehow undergo repeated step-function–like changes in the mass accretion rate (Fig. 1). Moreover, these transitions in $\dot{M}$ must always produce torques of opposite signs but with similar magnitudes. Indeed, the hypothesized change in accretion rate in 4U 1626−67 must result in a spin-down torque within 15% of its previous spin-up rate. On the other hand, if the cycle of transitions reflects physics occurring at the boundary between the disk and the magnetosphere, one would expect the characteristic time between transitions to range between the dynamical timescale, $t_d \sim \Omega_{\rm K}^{-1} \sim 1$ s, and the inner disk viscous timescale, $t_v \sim R/H(\alpha\Omega_{\rm K})^{-1} \sim 10^3$ s, where H is the disk thickness. Yet systems like GX 1+4 and 4U 1626−67 were stable for years before reversing their torques.

When the transition from spin-up to spin-down was first detected in GX 1+4, Makishima et al. (1988) instead suggested that the previous disk had dissipated and that a new disk had formed with a reversed sense of rotation. Instead of undergoing mass transfer by Roche lobe overflow, they argued that GX 1+4 is accreting from a dense, subsonic wind from its M giant companion; transient formation of alternating prograde and retrograde disks are known to occur in numerical simulations of wind-fed systems (Fryxell & Taam 1988). The formation of a retrograde disk would also explain the similar torque magnitudes in both states and obviates the need for an ultrastrong magnetic dipole field, $B \simeq 10^{14}$ G, if this slow pulsar ($P_p \sim$ 120 s) is to corotate with the inner accretion disk, $\Omega_* = \Omega_{\rm K}(r_m)$.

Chakrabarty et al. (1997b) have recently found surprising evidence, however, that supports the presence of a retrograde accretion disk in GX 1+4. While in an extended spin-down state, GX 1+4 spins down more rapidly during short-term 20–50 keV (∼20 day) flares observed with BATSE. That is, the torque is anticorrelated with the observed flux. This is opposite the prediction of standard spin-down theory (see Fig. 1.). At higher accretion rates, the magnetosphere should move inward away from corotation, reducing the magnetic spin-down torques while increasing the material spin-up torques. On the other hand, if GX 1+4 is accreting from a retrograde disk, one expects the spin-down rate to increase with luminosity. In that case the material really does carry negative angular momentum relative to the neutron star rotation.

Could the torque transitions seen in other X-ray pulsars also be due to alternating episodes of prograde and retrograde rotation? This hypothesis would naturally explain several puzzling aspects of the BATSE observations. If the disks in these systems are somehow produced with both senses of rotation, one expects the observed two-state torque behavior—the material can circulate only one way or the other. Moreover, transitions between torque states of the same sign will never occur, and for comparable mass accretion rates, the torques should have comparable magnitudes; in the simplest picture, $N \simeq \pm\dot{M}\sqrt{GMr_m}$. The time intervals between torque reversals are also consistent with the global disk viscous times in these systems, $t_v \sim R_D^2/\nu \sim$ days to years, for a fully ionized Shakura-Sunyaev disk with $\alpha \sim 0.01$–0.1. One can imagine a cycle in which a disk forms and accretes all of its material, and then a new disk forms with the opposite sense of rotation.

If these binaries undergo mass transfer by standard Roche lobe overflow, we know of no mechanism that could produce a stable retrograde disk. The specific angular momentum initially carried by the accretion stream $l \sim d^2\Omega_{\rm orb}$ (where d is the distance from the neutron star to the first Lagrangian point and $\Omega_{\rm orb}$ is the orbital frequency) is comparable to the specific orbital angular momentum of the companion star and should circularize in the prograde sense well before reaching the pulsar magnetosphere (Lubow & Shu 1975). However, transient disks with an alternating sense of rotation are known to form in numerical simulations of nonaxisymmetric wind-fed accretion (Fryxell & Taam 1988; Ruffert 1997). It may be possible that the disks in these systems are fed from a stellar wind, rather than from Roche lobe overflow as is commonly assumed. Davidsen, Malina, & Bowyer (1977) suggested that GX 1+4 accretes from a slow dense wind from its M giant companion. The massive OB-type companion of Cen X-3 is close to Roche lobe filling (van Paradijs et al. 1983; Chakrabarty et al. 1993) but should also have a strong stellar wind (Day & Stevens 1993), as should the massive companion of OAO 1657−415.

The ultracompact binary 4U 1626−67 is a more challenging case. The small upper limit on its mass function $f_x(M) < 10^{-6}\ M_\odot$ and probable 42 minute orbit is usually interpreted as indicating a very low mass hydrogen-depleted main-sequence star or degenerate He dwarf undergoing Roche lobe overflow (Verbunt, Wijers, & Burm 1990; Chakrabarty et al. 1997a). On the basis of *ASCA* detection of neon emission lines near 1 keV, Angelini et al. (1995) suggested that the companion star may be a helium-burning star with a very strong mass outflow. However, this scenario requires a very small and improbable orbital inclination ($i < 1\overset{\circ}{.}6$ for $M_c = 0.6\ M_\odot$) and high mass outflow. Alternatively, the X-ray flux from the pulsar itself may induce a self-excited wind in this system (Basko et al. 1977; Tavani & London 1993). Indeed, for a distance $D = 5D_5$ kpc, the incident X-ray flux at the companion surface is a factor of $\sim 50D_5^2$ larger than the flux incident on the companion of Her X-1, the system for which the X-ray–excited mass loss models were invented. Assuming that the companion is an $M = 0.08\ M_\odot$ main-sequence star, we estimate an induced mass outflow of $\dot{M}_w \sim 2 \times 10^{16} D_5^2$ g s^{-1} (Basko et al. 1977). This is about 5 times the inferred mass accretion rate; efficient capture of the wind is expected since the more massive neutron star dominates the binary potential well.

4. DISCUSSION

We wish to make two points in this Letter. First, the highly sampled BATSE pulsar timing data are difficult to reconcile with standard explanations of spin-down accretion torques in near-equilibrium rotators, $\Omega_* = \Omega_{\rm K}(r_m)$. According to these theories, the switching between spin-up and spin-down now seen in the majority of persistent BATSE pulsars would require repeated transitions between two mass accretion rates, with $\dot{M}_\pm$ producing torques of comparable magnitude but always of opposite sign. Moreover, in one pulsar, the observed anticorrelation between torque and 20–60 keV pulsed luminosity is opposite the predicted effect. Some bistable torque mechanism

with a switching timescale much longer than any natural time at the inner disk boundary must be at work. This timescale is more consistent with a global disk phenomenon.

Recently, Yi, Wheeler, & Vishniac (1997) have suggested that the observed torque reversals may be due to a transition from a standard Keplerian disk rotation law to a sub-Keplerian advection-dominated flow (ADF); they write the new rotation law $\Omega'(r) = A\Omega_K(r)$ with $A = 0.2$ and assume that the star is initially spinning near equilibrium. The sudden transition to ADF decreases the corotation radius, $r'_{co} = A^{2/3} r_{co}$, while the fastness parameter increases $\omega' = \omega/A \propto \dot{M}^{-3/7} B_*^{6/7}/A$. Assuming a GL-type torque (eq. [2]) in both states, it is not surprising that Yi et al. (1997) find acceptable fits to the observed transitions: for a given A, one can always adjust B_* and $\dot{M}$ to yield the observed torques before and after the transition. Their fitted parameters, however, do not agree with observational constraints. $\dot{M}$ must be near the critical accretion rates required by ADF, $\dot{M}_{crit} \sim 0.1\alpha^2 \dot{M}_{Edd} \sim 10^{15}$–$10^{16}$ g s^{-1} (Narayan & Yi 1995), yet Cen X-3, GX 1+4, and OAO 1657−415 are accreting at much higher rates, $\dot{M} \sim 10^{17}$–10^{18} g s^{-1} (Nagase 1989; Chakrabarty et al. 1993, 1997b). Moreover, the fitted magnetic field strengths are at least an order of magnitude smaller than required for these stars to be near spin equilibrium. Nevertheless, this scenario is attractive because it is consistent with the transition timescales discussed above—the ADF transition itself will occur on a fast thermal time $t_{th} \sim (\alpha\Omega_K)^{-1} \sim 10^3$ s, while the interval between torque transitions is set by slow changes in the mass transfer rate occurring on a global disk viscous timescale.

Our second point is admittedly more speculative. On the basis of the suggestion by Makishima et al. (1988) that a reversed disk formed in the binary system containing GX 1+4, the BATSE observations themselves are consistent with accretion from disks having alternating senses of rotation. This interpretation naturally explains the bimodal nature of the torques, the comparable torque magnitudes, the torque-luminosity anticorrelation seen in GX 1+4, and the timescales between torque transitions—without requiring these systems to be near spin equilibrium. Although we are unaware of any physical mechanism that could produce a reversed disk in a system undergoing Roche lobe overflow, we suggest that these binaries may be accreting from a stellar wind, possibly self-excited by the X-rays coming from the accreting neutron star.

It may be possible to test the reversed disk hypothesis with further observations. As in GX 1+4, the torque in any system undergoing secular spin-down should spin down faster with increased luminosity. Observations with the *X-Ray Timing Explorer* (*XTE*) may be able to determine the correlation between torque and luminosity in Cen X-3 while it is in a spin-down state. We estimate that a 2 day pointing of Cen X-3 with *XTE* could make of order 5 torque measurements sensitive to 10% variations at the 3 σ level. If the accretion disk is fed from an X-ray–excited wind with a flip-flop–type instability, changes in column density inferred from low-energy absorption may also reveal transitions in the structure of the accretion flow (Day & Stevens 1993).

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REFERENCES

Angelini, L., et al. 1995, ApJ, 449, L41
Basko, M. M., Hatchett, S., McCray, R., & Sunyaev, R. A. 1977, ApJ, 215, 276
Bildsten, L., et al. 1997, ApJS, in press
Campbell, C. G. 1987, MNRAS, 229, 405
Chakrabarty, D., et al. 1993, ApJ, 403, L33
———. 1997a, ApJ, 474, 414
———. 1997b, ApJ, 481, L101
Davidsen, A., Malina, R., & Bowyer, S. 1977, ApJ, 211, 866
Day, C. S. R., & Stevens, I. R. 1993, ApJ, 403, 322
Elsner, R. F., & Lamb, F. K. 1977, ApJ, 215, 897
Finger, M. H., Wilson, R. B., & Fishman, G. J. 1994, in AIP Conf. Proc. 280, Compton Gamma-Ray Observatory (New York: AIP), 304
Fryxell, B. A., & Taam, R. E. 1988, ApJ, 335, 862
Ghosh, P., & Lamb, F. K. 1979, ApJ, 234, 296
King, A. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 419
Konigl, A. 1991, ApJ, 370, L39
Lubow, S. H., & Shu, F. H. 1975, ApJ, 198, 383
Makishima, K., et. al. 1988, Nature, 333, 746
Nagase, F. 1989, PASJ, 41, 1
Narayan, R., & Yi, I. 1995, ApJ, 452, 710
Prince, T. A., et al. 1994, in AIP Conf. Proc. 308, The Evolution of X-Ray Binaries, ed. S. S. Holt & C. S. Day (New York: AIP), 235
Pringle, J. E., & Rees, M. J. 1972, A&A, 21, 1
Rappaport, S., & Joss, P. 1977, Nature, 266, 683
Ruffert, M. 1997, A&A, 317, 793
Tavani, M., & London, R. 1993, ApJ, 410, 281
van Paradijs, J., et al. 1983, A&A, 124, 294
Verbunt, F., Wijers, R. A. M. J., & Burm, H. M. G. 1990, A&A, 234, 195
Wang, Y.-M. 1987, A&A, 183, 257
———. 1995, ApJ, 449, L153
———. 1997, ApJ, 475, L135
Warner, B. 1990, Ap&SS, 164, 79
Yi, I., Wheeler, C., & Vishniac, E. T. 1997, ApJ, 481, L51