SPECTRAL TRANSITION AND TORQUE REVERSAL IN X-RAY PULSAR 4U 1626−67

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ABSTRACT

The accretion-powered, X-ray pulsar 4U 1626−67 has recently shown an abrupt torque reversal accompanied by a dramatic spectral transition and a relatively small luminosity change. The time-averaged X-ray spectrum during spin-down is considerably harder than during spin-up. The observed torque reversal can be explained by an accretion flow transition triggered by a gradual change in the mass accretion rate. The sudden transition to spin-down is caused by a change in the accretion flow rotation from Keplerian to sub-Keplerian. The X-ray pulsar 4U 1626−67 is estimated to be near spin equilibrium with a mass accretion rate $\dot{M} \sim 2 \times 10^{16}$ g s^{-1}, $\dot{M}$ decreasing at a rate $\sim -6 \times 10^{14}$ g s^{-1} yr^{-1}, and a polar surface magnetic field of $\sim 2b_p^{-1/2} \times 10^{12}$G, where b_p is the magnetic pitch. During spin-up, the Keplerian flow remains geometrically thin and cool. During spin-down, the sub-Keplerian flow becomes geometrically thick and hot. Soft photons from near the stellar surface are Compton up-scattered by the hot accretion flow during spin-down, while during spin-up such scattering is unlikely because of the small scale height and low temperature of the flow. This mechanism accounts for the observed spectral hardening and small luminosity change. The scattering occurs in a hot radially falling column of material with a scattering depth ~ 0.3 and a temperature $\sim 10^9$ K. The X-ray luminosity at energies greater than 5 keV could be a poor indicator of the mass accretion rate. We briefly discuss the possible application of this mechanism to GX 1+4, although there are indications that this system is significantly different from other torque-reversal systems.

Subject headings: accretion, accretion disks — pulsars: general — stars: magnetic fields — X-rays: stars

1. INTRODUCTION

The continuous monitoring of the accretion-powered X-ray pulsar 4U 1626−67 by BATSE (e.g., Chakrabarty et al. 1997a) has revealed that the pulsar system has recently undergone a puzzling, abrupt torque reversal from spin-up to spin-down. Similar phenomena have also been detected in other pulsar systems (e.g., Bildsten et al. 1997). The X-ray luminosity in the 1–20 keV band changes little around the torque reversal (Vaughan & Kitamoto 1997), which indicates that the reversal event is not likely to be caused by a large, discontinuous change of mass accretion rate (Yi, Wheeler, & Vishniac 1997; Yi & Wheeler 1998). This phenomenon is difficult to explain within the context of a Ghosh-Lamb magnetized disk model (Ghosh & Lamb 1979) in which the torque and mass accretion rate would be expected to change together.

Nelson et al. (1997) proposed that the torque reversal is due to a sudden change in the sense of accretion disk rotation with a nearly constant mass accretion rate. This possibility seems suspect given that the accretion flow is apparently stable up until the reversal event and then has to suddenly reverse its rotational direction. The formation of a retrograde disk is more likely in wind-fed systems in which small fluctuations due to fluctuating angular momentum are apparent observationally (e.g., Nagase 1989). Van Kerkwijk et al. (1998) have suggested an intriguing possibility in which the inner disk is warped by an irradiation instability to such an extent that the tilt angle becomes larger than 90° and the accretion flow's rotation becomes retrograde. In this explanation, there exist several out-

standing issues such as (1) the uncertain flip timescale, (2) the return mechanism from the high tilt angle back to the low tilt angle, (3) the X-ray irradiation efficiency in strongly magnetized accretion (e.g., Yi & Vishniac 1994), and (4) the severe X-ray obscuration by the tilted disk material (van Kerkwijk et al. 1998).

The observed X-ray luminosity appears to decrease slightly from spin-up to spin-down. In the 1–20 keV *Ginga* band, the X-ray luminosity decreases by about $\sim 20\%$. This flux decrease seems to be more significant at lower energies within this band (Vaughan & Kitamoto 1997). During spin-up, the phase-averaged spectrum can be modeled by a blackbody with a temperature ~ 0.6 keV (Angelini et al. 1995) together with a power-law component with a spectral index ~ 1 (Kii et al. 1986). Vaughan & Kitamoto (1997) discuss simple power-law fits to the time-averaged *Ginga* all-sky monitor count data. The strong energy dependence of the pulse profile indicates anisotropic radiative transfer within a magnetically channeled accretion column with a strong magnetic field greater than 6×10^{12} G (e.g., Kii et al. 1986). Recently, *BeppoSAX* (0.1–10 keV) detected X-ray emission during the spin-down phase (Orlandini et al. 1997; Owens, Oosterbroek, & Parmar 1997). During this phase, the spectrum is well fit by an absorbed power-law of index ~ 0.6 and a blackbody of temperature ~ 0.3 keV. The absorption column depth is $\sim 10^{21}$ cm^{-2} (Owens et al. 1997). Vaughan & Kitamoto (1997) suggest much harder spectra during spin-down with a power-law index ~ 0.41, although ~ 0.6 is within their allowed spectral index range. *Ginga* spin-up spectra are described by the power-law index of ~ 1.48, which is somewhat steeper than the index seen in the middle to late 1980's. This could well be the result of the wider energy band. A self-consistent explanation for the observed spectral transition compatible with the torque reversal is required. Absorption has been suggested as a possible explanation. The required absorption column density is, however, as high as

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$N_{\rm H} \approx 10^{23}$–$10^{24}$ cm^{-2} (Vaughan & Kitamoto 1997), which is inconsistent with the relatively low accretion rate. On the other hand, in the model of van Kerkwijk et al. (1998), as the disk tilt angle increases, absorption by the disk is expected to be too severe to account for the observed X-ray spectra.

In this Letter, we propose that the spectral change is directly related to the formation of a geometrically thick hot accretion flow during the spin-down, which Compton up-scatters the soft photons emitted near the stellar surface (Yi et al. 1997). Such a hot flow is available only during spin-down, in which the spin-down itself is the result of the sub-Keplerian rotation of the hot accretion flow (e.g., Narayan & Yi 1995).

2. TORQUE REVERSAL, MASS ACCRETION RATE, AND X-RAY LUMINOSITY

In a conventional disk-magnetosphere interaction model with a Keplerian accretion flow with the mass accretion rate $\dot{M}$, the torque exerted on the pulsar is

$$N = (7N_0/6)\,[1 - (8/7)(R_0/R_c)^{3/2}]\,[1 - (R_0/R_c)^{3/2}]^{-1}, \quad (1)$$

where $R_c = (GM_* P_*^2/4\pi^2)^{1/3}$ is the Keplerian corotation radius for a pulsar of mass $M_* = 1.4\,M_\odot$ and spin period P_* and $N_0 = \dot{M}(GM_* R_0)^{1/2}$ is the material torque at the disk disruption radius R_0, which is determined by

$$(R_0/R_c)^{7/2}\,[1 - (R_0/R_c)^{3/2}]^{-1}$$
$$= 2(2\pi)^{7/3} b_p B_*^2 R_*^5/(GM_*)^{2/3} P_*^{7/3} L_{\rm X}$$
$$= \delta. \quad (2)$$

Here b_p is a parameter of order unity that sets the pitch of the magnetic field (Wang 1995; Yi et al. 1997, and references therein). B_* is the polar surface magnetic field strength of the pulsar, and $L_{\rm X} \approx GM_*\dot{M}/R_*$ is the X-ray luminosity from the surface of the accreting pulsar with radius R_* and accretion rate $\dot{M}$. In this picture, as $\dot{M}$ varies, the pulsar spin period changes according to $\dot{P}_*/P_*^2 = -N/2\pi I_*$, where $I_* = 10^{45}$ g cm^2 is the neutron star moment of inertia. If $\dot{M}$ variation is smooth, the corresponding torque change is also smooth (e.g., Yi et al. 1997). The torque decreases in response to the decreasing $\dot{M}$. In this case, the torque should show a wide range of positive and negative values and pass through $N = 0$. This is apparently not observed in 4U 1626−67 and other similar systems (Chakrabarty 1997a; Nelson et al. 1997). The observed spin-down to spin-up transition is too abrupt to be reproduced by gradual $\dot{M}$ change in the Keplerian models. The observed event could be reproduced only if the mass accretion rate jumps by a factor of ~4 almost discontinuously (Yi et al. 1997), which is highly unlikely given the fact that the observed luminosity decreases only by about ~20% (Vaughan & Kitamoto 1997).

The model proposed by Yi, Wheeler, & Vishniac (1997) suggests that the torque reversal is due to the transition of the accretion flow from Keplerian rotation to sub-Keplerian rotation or vice versa. The transition occurs when $\dot{M}$ crosses the critical rate $\dot{M}_c$, which lies somewhere in a range ~10^{16}–10^{17} g s^{-1}. After the transition, the rotation of the accretion flow becomes sub-Keplerian because of the large internal pressure of the hot accretion flow. For sub-Keplerian rotation, $\Omega = A\Omega_{\rm K} < \Omega_{\rm K}$ [i.e., $A < 1$ and $\Omega_{\rm K} = (GM_*/R^3)^{1/2}$ is the Keplerian rotation], the new corotation radius $R_c' = A^{2/3}R_c$, and the new inner edge R_0' is determined by

$$(R_0'/R_c')^{7/2}\,[1 - (R_0'/R_c')^{3/2}]^{-1}$$
$$= 2(2\pi)^{7/3} b_p A^{-7/3} B_*^2 R_*^5/(GM_*)^{2/3} P_*^{7/3} L_{\rm X}$$
$$= \delta'. \quad (3)$$

The new torque on the star after the transition to the sub-Keplerian rotation is

$$N' = (7N_0'/6)\,[1 - (8/7)(R_0'/R_c')^{3/2}]\,[1 - (R_0'/R_c')^{3/2}]^{-1}, \quad (4)$$

where $N_0' = A\dot{M}(GM_* R_0')^{1/2}$. The reversal is simply a consequence of the change in A from 1 to less than 1 (Yi et al. 1997) as $\dot{M}$ gradually crosses $\dot{M}_c$. It has been shown that the observed torque reversals occur near spin equilibrium (i.e., $N = 0$) before and after transition (Yi et al. 1997), satisfying $b_p^{1/2} B_* \approx 7 \times 10^{11} \delta^{1/2} (L_{\rm X}/10^{36}$ ergs s$^{-1})^{1/2} (P_*/10$ s$)^{7/6}$ G, where $2A^{7/6} < \delta^{1/2} < 4A^{7/6}$ is likely to be of order unity (Yi & Wheeler 1998).

The observed spin frequency evolution is easily accounted for by $\dot{M}_c = 2.4 \times 10^{16}$ g s^{-1} and $A = 0.462$ at torque reversal with $B_* = 5.4(b_p/10)^{-1/2} \times 10^{11}$ G, which are consistent with the above criterion (Yi & Wheeler 1998). The model requires only a small change of $\dot{M}$ at a rate $d\dot{M}/dt \sim -6 \times 10^{14}$ g s^{-1} yr^{-1}, about a factor of 5 less than the required $d\dot{M}/dt$ for the Keplerian model. The observed small flux change ~20% around the torque reversal is consistent with the present model. This model has yet to explain the negative second derivative of the spin frequency before and after the reversal (Chakrabarty et al. 1997a). The truncation radius changes from $R_0 \sim 5.5 \times 10^8$ cm just before reversal to $R_0' \sim 3.7 \times 10^8$ cm right after reversal. We look for a mechanism for the spectral transition with small changes in $\dot{M}$ within the model of Yi et al. (1997). The small change in the integrated X-ray luminosity suggests a comparably small change in the mass accretion rate. In the magnetized accretion picture, if the accretion flow is truncated far away from the neutron star, most of the X-ray emission should originate in the column accretion flow near the neutron star. In this case, the X-ray luminosity is likely to reflect the mass accretion rate change. Since the observed spectra show a strong thermal emission component, it is plausible that the X-ray emission comes from the thermalized material near the accreting magnetic poles (e.g., Kaminker, Fedorenko, & Tsygan 1976; Frank, King, & Raine 1992).

When the accretion flow is Keplerian, the accretion flow is dominated by cooling and the accreted plasma remains cold until it undergoes shock heating and thermalization near the magnetic poles. In this case, the accretion column is not hot enough for significant Compton scattering. The cold accretion column is more likely to act as absorbing gas than a Comptonizing gas. The geometric thickness of the accretion column flow is much smaller than the stellar radius, so that only a small fraction of the radiation from the star will interact with the accreted material. After transition, the accretion flow is hot and its internal pressure becomes large enough to support a large scale height. The accretion flow extending from R_0' to R_* is geometrically thick and hot enough to Comptonize the thermal stellar radiation.

3. SCATTERING IN HOT ACCRETION COLUMN DURING SPIN-DOWN

The sub-Keplerian flow is advection dominated (e.g., Narayan & Yi 1995), which implies that the bulk of the viscously dissipated energy is stored within the accretion flow. Assuming that advection is the dominant channel for the viscously dissipated energy, the temperature of the accretion flow is $T_{acc} \approx 1.2 \times 10^9$ K and the electron scattering depth along the vertical direction is $\tau_{es, acc} \approx 2.8 \times 10^{-2}$ at $R = R'_0 \approx 4 \times 10^8$ cm. Here we have assumed an equipartition magnetic field and a viscosity parameter $\alpha = 0.3$ (Narayan & Yi 1995). This implies that the advection-dominated accretion flow itself has a very small scattering depth. However, the accretion flow inside the radius $R = R'_0$ is channeled by the magnetic fields lines and is a very promising site for scattering due to geometric focusing. In the conventional column accretion model (e.g., Frank et al. 1992; Yi & Vishniac 1994), if the dipole magnetic field axis is misaligned with respect to rotation axis of the star (which is assumed to be aligned with the accretion flow's rotational axis) by an angle $\pi/2 - \beta_1$, then β_2, the angle between the magnetic axis and the magnetic field lines connected to the disk plane at R'_0, is given by $\sin^2 \beta_1 = \sin^2 \beta_2 \times (R_*/R'_0)$. It can also be shown that the fraction of the polar surface area threaded by magnetic field lines connected to the accretion flow at $R \geq R'_0$ is $s \approx R_* \sin^2 \beta_2/4R'_0 \approx R_*/2R'_0$ after angle-averaging over β_2. This implies that unless β_2 is very small, the accreting fraction of the stellar surface area s is likely to be of order $\sim R_*/R'_0 \sim 10^{-2}$ to 10^{-3}. The accretion is assumed to continue to the poles without mass loss, and then the soft X-ray radiation from the polar regions is uniquely determined by the mass accretion rate derived from the torque reversal (Yi & Wheeler 1998).

The detailed emission process near the magnetic poles is complicated (e.g., Frank et al. 1992, and references therein). The existence of a thermal component at low X-ray energies implies that a significant fraction of the accretion energy is thermalized near the surface of the neutron star. If the entire accretion energy is thermalized at the stellar surface (see Kaminker et al. 1976), the anticipated blackbody temperature is $kT_* \sim 5s^{-1/4}$ keV. Since the accretion rate change is small near the torque reversal, the observed spectral transition is unlikely to be caused by the sudden change in physical conditions. If there is no scattering effect from the infalling column material, the underlying emission process is likely to remain unchanged around the torque reversal. We therefore assume that the intrinsic spectrum (before scattering and absorption) remains unchanged.

The column accretion flow follows the bent magnetic field lines. Since a detailed geometry is hard to specify, we assume that the solid angle subtended by the accretion column at the accretion poles is constant at all radii along the field lines. The radial bulk infall velocity can be parametrized as a fraction of the free-fall velocity as $v_R = -x(2GM_*/R)^{1/2}$, and we get

$$\tau_{es} \approx \frac{\sigma_T}{4\pi\mu m_p} \frac{1}{s^{1/2} x} \frac{\dot{M}}{(2GM_*R)^{1/2}}, \qquad (5)$$

where $\mu \sim 1$ is the mean molecular weight. We find that $\tau_{es} \sim 0.4\mu(R/10^6 \text{ cm})^{-1/2}$ with $s \sim 10^{-2}$, $x \sim 1$, $\dot{M} \sim 2.4 \times 10^{16}$ g s^{-1}, where the mass accretion rate is based on the torque-reversal fitting (e.g., Yi & Wheeler 1998). From the inner disk radius $R = R'_0 \sim 4 \times 10^8$ cm to the base of the accretion column near the stellar surface $R \sim 10^6$ cm, the scattering depth

is likely to range from $\tau_{es} \sim 2 \times 10^{-2}\mu^{-1}$ to $\sim 0.1\mu^{-1}$ at $R \sim 10^7$ cm to $\sim 0.4\mu^{-1}$ at $R \sim 10^6$ cm. Evidently the accretion column can have a dramatic effect on the outgoing soft radiation through scattering.

The angular momentum has to be continuously transported along the accretion column (corresponding to the torque action between the star and accretion flow). We assume that the radial infall is nearly adiabatic and that the shear dissipation is decoupled from the bulk radial motion. We take the dissipation rate per unit volume within the accretion column as $q^+ = \nu\rho R^2(d\Omega/dR)^2$, where $\nu = c_s H$ is the kinematic viscosity and $H \sim 2\sqrt{s}R$ is the cross-sectional thickness of the accretion column. We have assumed that the internal random energies, thermal and turbulent, are comparable and that the bulk radial motion is supersonic. We then obtain $q^+ \sim 18G\sqrt{s}M_* c_s\rho/4r$ or the integrated dissipation rate per unit length of the column $Q^+ \sim q^+ \times \pi D^2 \sim 9c_s|v_R|\dot{M}D^2/8R^2$. The cooling of the column material occurs via Compton up-scattering of the soft photons from the thermalized radiation near the stellar surface (e.g., Narayan & Yi 1995). Assuming that the Compton interaction occurs at a distance sufficiently far away from the stellar surface, we treat the thermal radiation as originating from a point source. Then the integrated cooling rate across the column is estimated as $Q^- \sim 4kGM_*\dot{M}D\tau_{es}T/2m_ec^2R_*R^2$. The energy balance $Q^+ = Q^-$ gives $(kT)^{1/2}\tau_{es} \sim 9m_ec^2R_*D/16(\mu m_p)^{1/2}\sqrt{s}|v_R|R^2$, which shows the expected inverse correlation between the Compton depth and the column temperature. In general, $Q^+ = Q^-$ is not guaranteed but as $\tau_{es} \to 1$ near the stellar surface (e.g., Yi & Vishniac 1994), a significant Compton cooling could lead to $Q^+ = Q^-$ (cf. Narayan & Yi 1995). In this simple picture, the column temperature remains nearly independent of R until the column material becomes optically thick and the radiation is thermalized. For parameters $s \sim 10^{-2}$ and $\dot{M} \sim 10^{16}$ g s^{-1}, we expect $kT \sim 60$ keV. This implies that the resulting Comptonized radiation is likely to show the signature of a hot plasma with this temperature. The sub-Keplerian accretion flow at $R > R'_0$ is advection dominated (e.g., Narayan & Yi 1995). At radii $R > R'_0$, the temperature difference between electrons and ions is likely to be small. After the accretion flow enters into the magnetic column, the accreted material is rapidly compressed, which justifies the single-temperature treatment of the energy balance between viscous heating and Compton cooling. The Comptonized radiation is calculated according to $E_f = \eta E_i$, where E_f is the photon energy after scattering and E_i is the incident soft energy. Here η is the energy boost parameter originally derived by Dermer, Liang, & Canfield (1991), i.e., $\eta = 1 + \eta_1 - \eta_2(E_i/kT)^{\eta_3}$, where η_1, η_2, and η_3 are defined in Narayan & Yi (1995). These functions are completely specified by τ_{es} and T for a given E_i. Therefore, given the incident photon spectrum $N_i(E_i)$, the resulting Comptonized spectrum is completely specified. The radial infall speed in the scattering region and its effects on the scattering could be significant, which is beyond the scope of this work.

Although the soft radiation is likely to be the thermalized radiation from the stellar surface, the details of the emission remains unclear. We simply assume that the soft photon spectrum remains unchanged near the torque reversal and that the unscattered soft photon spectrum during spin-down is similar to that of the spin-up period. Since during spin-up scattering is negligible, this assumption is quite plausible. We further assume that the luminosity of the source decreases according to the mass accretion rate decline. We expect the soft photon luminosity to decrease by a few times 10%, while the spectral
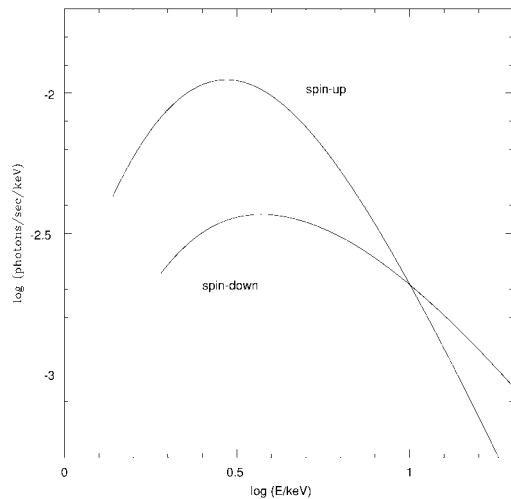
Fig. 1.—Expected X-ray photon spectra before and after torque reversal. The scattering region used in the theoretical post-reversal spectrum has $\tau_{es} = 0.3$ and $T_e = 10^9$ K. The unscattered soft radiation changes luminosity by 40%, while its spectral shape remains unchanged (see text).

shape remains unchanged. We also assume that all outgoing radiation goes through the Comptonizing accretion column. Figure 1 shows the result of the Compton scattering from a column material with $T_e = 10^9$ K and $\tau_{es} \sim 0.3$, which are close to the values we have derived above. These parameters adequately reproduce the qualitative features of the observed spectral transition. The shown spectral transition requires that the soft photon flux decrease by ~40% during spin-down, which is not far from the change required for the torque reversal (Yi et al. 1997; Yi & Wheeler 1998). Despite the uncertainties in accretion column geometry, the expected spectral change is remarkably close to the observed change. This strongly indicates that the observed spectral transition could be due to formation of the hot accretion flow during spin-down. More detailed, quantitative answers would require exact scattering geometric information and physics of thermal radiation emission near the stellar surface.

4. DISCUSSION

We have shown that Compton-scattering during spin-down could account for the sudden spectral transition correlated with the torque reversal seen in 4U 1626−67. The small luminosity change supports the possibility that the mass accretion rate varies little, as the present model indicates. The expected beat-type QPOs would be hard to detect during spin-down (Yi &

Wheeler 1998). Kommers et al. (1998) reported the detection of QPOs at a frequency of 0.048 Hz using *Rossi X-Ray Timing Explorer*, but they found that the observed QPOs are not likely to be attributable to a magnetospheric beat.

Although the spectral transition appears robust, the time-averaging of the X-ray spectra over ~30 days (Vaughan & Kitamoto 1997) could be questionable because of some changes in accretion flows near the torque reversal on short timescales. If the accretion flow transition occurs gradually over a period of days (e.g., Yi et al. 1997), the early spin-down spectra could be substantially softer than late spin-down spectra. If such a difference is not found, the accretion flow transition should occur on a timescale ≲1 day. Such a short transition timescale is still plausible within the proposed model (Yi et al. 1997), although the details of the transition process have not been addressed (Yi & Wheeler 1998). On long timescales, Owens et al. (1997) found that the X-ray flux detected by *BeppoSax* is about a factor of 2 lower than the *ASCA* flux measured 3 yr earlier (Angelini et al. 1995). This suggests that the mass accretion rate does decrease on long timescales, although the accretion rate decrease on short timescales near the reversal is not large enough to drive the torque reversal and spectral transition.

Orlandini et al. (1998) reported an absorption feature at ~37 keV, which they claim to be the cyclotron absorption line. The estimated surface field strength is $\sim 3 \times 10^{12}$ G. This field strength is substantially higher than our estimate $\sim 5(b_p/10)^{-1/2} \times 10^{11}$ G. Such a discrepancy is not unexpected given the uncertainties in the distance estimate. If the magnetic pitch b_p is as small as ~1, the Orlandini et al. (1998) estimate is largely consistent with our estimate.

GX 1+4 has shown a similar torque reversal and an unexplained torque-flux correlation, which is exactly opposite to that predicted in the conventional model (Chakrabarty et al. 1997b). A significant spectral hardening similar to that seen in 4U 1626−67 could account for the correlation. So far, such a transition has not been reported in GX 1+4. The prograde-retrograde transition (Nelson et al. 1997) could provide an explanation (van Kerkwijk et al. 1998) despite several outstanding difficulties.

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