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SIGNATURES OF ENERGETIC PROTONS IN HOT ACCRETION FLOWS: SYNCHROTRON COOLING OF PROTONS IN STRONGLY MAGNETIZED PULSARS

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ABSTRACT

The existence of hot, two-temperature accretion flows is essential to the recent discussions of the low-luminosity, hard X-ray emission from accreting neutron stars and black holes in Galactic binaries and massive black holes in low-luminosity galactic nuclei. In these flows, protons are essentially virialized and relativistic energies for nonthermal protons are likely. Observational confirmation of the energetic protons' presence could further support the two-temperature accretion flow models. We point out that synchrotron emission from nonthermal relativistic protons could provide an observational signature in strongly magnetized neutron star systems. The self-absorbed synchrotron emission from an accreting neutron star with the magnetic moment $\sim 10^{30}$ G cm^3 is expected to exhibit a spectrum $\nu I_\nu \sim \nu^2$ with the luminosity about a few times $10^{33}(L_X/10^{36}\ \mathrm{ergs\ s^{-1}})^{0.4}$ ergs s^{-1} at $\nu \sim 10^{15}$ Hz, where L_X is the X-ray luminosity from the neutron star surface. The detection of the expected synchrotron signature in optical and UV bands during the low-luminosity state of the pulsar systems such as 4U 1626−67 and GX 1+4 could prove the existence of the hot, two-temperature accretion flows during their spin-down episodes. The detected optical emission in 4U 1626−67 has a spectral shape and luminosity level very close to our predictions.

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

1. INTRODUCTION

It has recently been suggested that the accretion flows around black holes and neutron stars are very hot and two-temperatured when their luminosities are low and their spectra are hard (e.g., Narayan & Yi 1995; Rees et al. 1982, and references therein). In such flows, which are often called advection-dominated accretion flows (ADAFs), most of the viscously dissipated energy is used to heat ions and only a small fraction of the total energy is radiated by electron cooling processes. X-ray and gamma-ray emission properties in Galactic X-ray transients (see, e.g., Narayan et al. 1998b for a review) and galactic nuclei (e.g., Yi & Boughn 1998, and references therein) including Sgr A* (Manmoto, Mineshige, & Kusunose 1997; Narayan et al. 1998a) have been successfully modeled by these hot, two-temperature flows. The apparent success of these models critically relies on the existence of the two-temperature plasma in which the ion temperature is essentially the virial temperature and hence much higher than the electron temperature (Narayan & Yi 1995). Unless there is an efficient electron-ion energy exchange mechanism, the Coulomb exchange alone typically leads to the two-temperature condition (Narayan et al. 1998b).

Although the spectral signatures seen in various radiation components due to electrons at temperatures $\sim 10^9$–10^{10} K are quite plausible, the electron spectral components alone cannot prove the uniqueness of the spectral fits in the X-ray systems studied so far. Any direct observational signatures due to energetic protons could be extremely useful to confirm the presence of the protons and hence the presence of the two-temperature accretion flows. However, direct proton radiation signatures are difficult to observe since the radiation efficiencies of proton-related radiation processes are usually very low (Mahadevan 1998). There have been some recent suggestions that energetic ions could provide observable signatures through various phenomena such as pion production (Mahadevan, Narayan, & Krolik 1997; Mahadevan 1998) and nuclear spallation (Yi & Narayan 1997). It is, however, unclear how the suggested possibilities are proved to be unambiguous signatures of the energetic protons in the two-temperature plasma (Yi & Narayan 1997). It is therefore interesting to see whether there are any other signatures of the two-temperature accretion flows in which protons have relativistic energies. In this Letter, we point out that there could be such a signature produced by the proton synchrotron emission in the strong magnetic fields around neutron stars. Since electrons are rapidly cooled near the neutron stars by soft photons from the stellar surface, the electron synchrotron signature is not expected (Narayan & Yi 1995).

Within the accretion flows, since the proton gyroradius $\sim 3\gamma_2 B_8^{-1}$ cm is much smaller than the length scale of the accretion flow, the protons are likely to be tightly bound within the accretion flows in which $B_8 = B/10^8$ G is the magnetic field strength and $\gamma_2 = \gamma/10^2$ is the Lorentz factor for relativistic protons. The characteristic synchrotron loss timescale is $t_{\rm sync} \sim 5\gamma_2^{-1} B_8^{-2}$ s. The typical accretion timescale in the hot ADAFs is $t_{\rm acc} \sim 3 \times 10^{-5} \alpha^{-1} m r^{1/2}$ s, where $m = M/M_\odot$ is the stellar mass, $r = R/R_{\rm Sch}$ is the radius from the star, and $R_{\rm Sch} = 2.95 \times 10^5 m$ cm is the Schwartzschild radius (e.g., Narayan & Yi 1995; Rees et al. 1982). The energetic protons could transfer their energies to electrons on the electron-ion Coulomb exchange timescale $t_{\rm ie} \sim 9 \times 10^{-5} \theta_e^{3/2} \alpha m \dot{m}^{-1} r^{3/2}$ s, where $\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$ is the dimensionless accretion rate, $\dot{M}_{\rm Edd} = 1.39 \times 10^{18} m$ g s^{-1} is the Eddington accretion rate, $\theta_e = kT_e/m_e c^2 \lesssim$ a few is the dimensionless electron temperature, and $\alpha \sim 0.1$ is the dimensionless viscosity parameter (e.g., Frank, King, & Raine 1992). If the magnetic field has the equipartition strength, $t_{\rm sync}/t_{\rm acc} \sim 3 \times 10^3 \gamma_2^{-1} \alpha^2 \dot{m}^{-1} r^2$ and $t_{\rm sync}/t_{\rm ie} \sim 9 \times 10^2 \theta_e^{-3/2} r$, which indicates that only a very small fraction of the proton energy could be radiated by the proton

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synchrotron emission as expected. However, if there exists an external strong magnetic field such as that around a pulsar, the magnetic field strength is $B_8 \sim 4 \times 10^5 \mu_{30} m^{-3} r^{-3}$, where $\mu_{30} = \mu/10^{30}$ G cm^3 is the magnetic moment of the star (Frank et al. 1992). In this case, $t_{\rm sync} < t_{\rm acc}$ occurs at $r \lesssim 20\gamma_2^{2/11}\mu_{30}^{4/11}\alpha_{-1}^{-2/11}m^{-10/11}$ and $t_{\rm sync} < t_{\rm ie}$ occurs when $r \lesssim 50\gamma_2^{2/9}\theta_e^{1/3}\mu_{30}^{4/9}\alpha_{-1}^{2/9}m^{-10/9}\dot{m}_{-2}^{-2/9}$, where $\alpha_{-1} = \alpha/0.1$. Therefore, in the region close to the neutron star, proton synchrotron cooling could be a significant channel for proton cooling. We suggest an observational signature based on the possible proton synchrotron cooling near the strongly magnetized stars. The optical emission near 5500 Å from 4U 1626−67 (Chakrabarty 1998) appears interestingly close to the predicted synchrotron emission.

2. HIGH-ENERGY PROTONS AND PROTON SYNCHROTRON

We assume that the hot accretion flow contains an equipartition strength magnetic field (i.e., the gas pressure is equal to the magnetic pressure). The relevant physical quantities are the equipartition magnetic field $B \approx 8 \times 10^8 \alpha^{-1/2} m^{-1/2} \dot{m}^{1/2} r^{-5/4}$ G (e.g., Yi & Narayan 1997), the ion temperature $T_i \approx 1 \times 10^{12} r^{-1}$ K, and the proton number density $n_p \approx 6 \times 10^{19} \alpha^{-1} m^{-1} \dot{m} r^{-3/2}$ cm^{-3}. Although T_i and n_p quite plausibly represent the mean energy and density of the protons, they do not constrain the possible nonthermal relativistic proton population that could coexist with the nonrelativistic thermal protons.

The energy spectrum of the protons in the hot accretion flows is not well understood. Since there is not a clear thermalization process working for protons, if they are energized in nonthermal processes, their energy distribution could remain nonthermal throughout accretion (Narayan et al. 1998b). Nonthermal, power-law energy distributions for relativistic protons have been recently motivated by possible gamma-ray emission and low-frequency radio emission signatures from Sgr A* (Mahadevan et al. 1997; Mahadevan 1998). We take the number density of protons $n_p = \int n(\gamma, \theta_p) d\gamma$, where $\theta_p = kT_i/m_p c^2$. If protons have a fraction f in the nonthermal power-law tail, while $1 - f$ in the thermal nonrelativistic ($\gamma \sim 1$) protons, the fraction $f = 3(s-2)\theta_p/2$ if the mean energy of protons is kT_i and the power-law slope is given by $\propto \gamma^{-s}$. We have assumed that the thermal, nonrelativistic protons with $\gamma \sim 1$ exist as a separate proton population. Since $\theta_p \sim 0.1 r^{-1}$, $f \sim 0.2(s-2)r^{-1}$. Of the total power-law protons, protons with $\gamma \gtrsim 10$ are energetic enough for synchrotron emission. For $s = 2.5$ (e.g., Mahadevan et al. 1997) at $r \sim 1$, $f \sim 0.1$, and the fraction of protons with $\gamma \geq 10$ is $\sim 3 \times 10^{-2}$. At $r \sim 10^2$, $f \sim 10^{-3}$. Therefore, the fraction of the relativistic protons with $\gamma > 10$, ϵ, is likely to be in the range $\sim 3 \times 10^{-5}$ to $\sim 3 \times 10^{-4}$. Therefore, $\epsilon_{-4} = \epsilon/10^{-4} \sim 1$ could well represent the fraction of the relativistic nonthermal protons relevant for synchrotron emission (see also Mahadevan 1998).

The single particle synchrotron energy loss rate is (Lang 1980) $|dE/dt| = 3 \times 10^{-2} \gamma_2^2 B_8^2$ ergs s^{-1}. Using the effective number density of the relativistic protons ϵn_p, the total synchrotron energy loss rate in the entire hot accretion flow is estimated as

$$L_{\rm sync} \sim \int dR 4\pi R \, |dE/dt| \, \epsilon n_p \sim 4 \times 10^{33} \epsilon_{-4} \gamma_2^2 \alpha^{-2} m \dot{m}^2, \quad (1)$$

where we have assumed that the magnetic field is the internal equipartition field. (A more detailed luminosity estimate involving integration over γ follows below.) Since the hot accretion flows are likely to exist up to $\dot{m} \sim 0.3\alpha^2$ (Narayan & Yi 1995), the maximum synchrotron power is $L_{\rm sync,max} \sim 3 \times 10^{30} \epsilon_{-4} \gamma_2^2 \alpha_{-1}^2 m$, which is a small fraction of the total viscously dissipated energy.

On the other hand, if the magnetic field provided by a dipole-type field of the neutron star $B_8 = 4 \times 10^5 \mu_{30} m^{-3} r^{-3}$ (Frank et al. 1992), $L_{\rm sync} \sim 1 \times 10^{39} \epsilon_{-4} \gamma_2^2 \mu_{30}^2 \alpha^{-1} m^{-4} \dot{m}$ ergs s^{-1}. For the maximum accretion rate $\dot{m} \sim 0.3\alpha^2$ for the two-temperature accretion flows (Narayan & Yi 1995), $L_{\rm sync,\,max} \sim 3 \times 10^{37} \epsilon_{-4} \gamma_2^2 \mu_{30}^2 \alpha_{-1} m^{-4}$ ergs s^{-1}. The external stellar field would be more important for synchrotron cooling inside the radius $r_s \sim 4 \times 10^2 \mu_{30}^{4/7} \alpha_{-1}^{2/7} m^{-10/7} \dot{m}_{-2}^{-2/7}$, which is compared with the magnetospheric radius $r_o \sim 1 \times 10^3 \mu_{30}^{4/7} m^{4/7} \dot{m}_{-2}^{-2/7}$ (Frank et al. 1992; Yi, Wheeler, & Vishniac 1997; Yi & Wheeler 1998). Therefore, emission inside the magnetospheric radius could be dominated by the stellar field. If the accretion flows are cooled rapidly inside the magnetospheric radius, then the synchrotron luminosity could be entirely caused by the accretion flow present at $r > r_o$, which is estimated to be $L_{\rm sync} \sim 2 \times 10^{30} \epsilon_{-4} \gamma_2^2 \mu_{30}^2 \alpha_{-1}^{-1} m^{-4} \dot{m}_{-2}$. This is comparable to the synchrotron luminosity due to the internal equipartition field $L_{\rm sync} \sim 4 \times 10^{31} \epsilon_{-4} \gamma^2 \alpha_{-1}^{-2} m \dot{m}_{-2}^2$. Since the accretion flow inside the magnetospheric radius is adiabatically heated much like a spherical accretion flow, we assume that the accretion flow contains a fraction $\epsilon \sim 10^{-4}$ of energetic, relativistic protons until it hits the surface of the neutron star.

The synchrotron power at frequency ν for a single proton with the Lorentz factor γ is (e.g., Lang 1980)

$$P(\nu, \gamma) = \frac{3^{1/2} e^3 B \sin\phi}{m_p c^2} \frac{\nu}{\nu_c} \int_{\nu/\nu_c}^{\infty} dx K_{5/3}(x), \quad (2)$$

where a major fraction of the synchrotron power is produced at the characteristic frequency $\nu = \nu_c \nu_{\rm cyc} \gamma^2 = 3eB\gamma^2/4\pi m_p c$ and $\sin\phi$ accounts for the pitch angle between magnetic field and proton velocity. The emission coefficient is

$$j_\nu = \frac{1}{4\pi} \int d\gamma N(\gamma) P(\nu, \gamma), \quad (3)$$

and the absorption coefficient is

$$\alpha_\nu = -\frac{1}{8\pi m_p \nu^2} \int d\gamma P(\nu, \gamma) \frac{d}{d\gamma}\left[\frac{N(\gamma)}{\gamma^2}\right], \quad (4)$$

where $N(\gamma)$ is the distribution of protons per unit volume with the Lorentz factor γ. In our simple model for the relativistic protons, $\int d\gamma N(\gamma) = \epsilon n_p$.

Taking a power-law slope $s = 2.5$ and assuming a constant pitch angle $\sin\phi = 1/2$, we get

$$\alpha_\nu \approx 6.1 \times 10^5 \epsilon n_p B^{9/4} \nu^{-13/4} \text{ cm}^{-1}, \quad (5)$$

or for a characteristic absorption length scale which is comparable to the scale height of the hot accretion flow $H \sim R$ (e.g., Narayan & Yi 1995), the self-absorption depth $\tau_\nu \sim \alpha_\nu H \sim 6.1 \times 10^5 \epsilon n_p R B^{9/4} \nu^{-13/4}$. Using the hot accretion flow solution, $\tau_\nu \sim 2.2 \times 10^{-3} \epsilon_{-4} \alpha_{-1}^{-1} \dot{m} r^{-1/2} B_8^{9/4} \nu_{15}^{-13/4}$, where $\epsilon_{-4} = \epsilon/10^{-4}$ and $\nu_{15} = \nu/10^{15}$ Hz. The source function for the self-absorbed part of the synchrotron emission spectrum is

$$S_\nu = j_\nu/\alpha_\nu \sim 4 \times 10^{-30} B^{-1/2} \nu^{5/2} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}. \quad (6)$$

When the magnetic field is the internal equipartition field,

$$\tau_\nu \sim 9 \times 10^{-8} \epsilon_{-4} \alpha_{-1}^{-17/8} m^{-9/8} \dot{m}_{-2}^{17/8} r_1^{-53/16} \nu_{15}^{-13/4}, \quad (7)$$

where $r_1 = r/10$. The self-absorption occurs when $\tau_\nu = 1$ or at $\nu_{\rm abs} \sim 7 \times 10^{12} \epsilon_{-4}^{4/13} \alpha_{-1}^{-17/26} m^{-9/26} \dot{m}_{-2}^{17/26} r_1^{-53/52}$ Hz. The synchrotron luminosity $L_{\rm sync} = \nu L_\nu$ is estimated as

$$L_{\rm sync} \sim 4 \times 10^{26} \epsilon_{-4}^{0.79} \alpha_{-1}^{-1.43} m^{1.61} \dot{m}_{-2}^{1.43} \nu_{13}^{0.92} \text{ ergs s}^{-1}, \quad (8)$$

which could extend to $\nu = \nu_{\rm max} \sim 7 \times 10^{13} \epsilon_{-4}^{0.31} \alpha_{-1}^{-0.65} m^{-0.35} \dot{m}_{-2}^{0.65}$ Hz, where exponents have been rounded off for convenience. Therefore, such a proton synchrotron luminosity is obviously several orders of magnitude lower than the luminosity because of electron cooling for all reasonable parameters (Narayan & Yi 1995).

However, in strongly magnetized neutron star systems, the magnetic field is the stellar field of the dipole type, $B_8 = 4 \times 10^5 \mu_{30} m^{-3} r^{-3}$ (e.g., Frank et al. 1992), and the synchrotron emission could be much stronger and the emission can extend to much higher frequency. That is, the absorption depth $\tau_\nu \sim \epsilon_{-4} \mu_{30}^{9/13} \alpha_{-1}^{-1} m^{-29/4} \dot{m}_{-2} r_1^{-8} \nu_{15}^{-13/4}$ and the self-absorption occurs at

$$\nu_{\rm abs} \sim 1 \times 10^{15} \epsilon_{-4}^{4/13} \mu_{30}^{9/13} \alpha_{-1}^{-4/13} m^{-29/13} \dot{m}_{-2}^{4/13} r_1^{-32/13} \text{ Hz}. \quad (9)$$

The luminosity is estimated as $L_{\rm sync} \sim 4 \times 10^{33} \epsilon_{-4}^{0.44} \mu_{30}^{0.55} \alpha_{-1}^{0.44} m^{0.33} \dot{m}_{-2}^{0.44} \nu_{15}^{2.08}$ ergs s^{-1}. The emission could extend up to $\nu = \nu_{\rm max} \sim 2 \times 10^{16} \epsilon_{-4}^{0.31} \mu_{30}^{0.69} \alpha_{-1}^{-0.31} m^{-2.23} \dot{m}_{-2}^{0.31}$ Hz, where the exponents have again been rounded off for convenience. The expected luminosity is significant enough for possible detection (see below).

3. POSSIBLE DETECTIONS

We expect roughly $L_{\rm sync} = \nu L_\nu \propto \nu$ for black hole systems in which the magnetic fields are internal equipartition-type fields and $L_{\rm sync} = \nu L_\nu \propto \nu^2$ for neutron star systems with strong magnetic fields. Since the hot accretion flows are most likely during low-luminosity states, the above estimate for the internal field case (for black holes) suggests that in black hole systems, detection of the proton synchrotron emission is unlikely. For instance, during quiescence of A0620−00 ($M \sim 6\ M_\odot$), $\dot{m} \sim 2 \times 10^{-4}$ for $\alpha \sim 0.3$ (Yi & Narayan 1997, and references therein). Then, using the above results, we immediately get $\nu L_\nu \sim 1 \times 10^{25} \epsilon_{-4}^{0.79} \alpha_{-1}^{-1.43}$ ergs s^{-1} at $\nu = 10^{13}$ Hz and $\nu L_\nu \sim 1 \times 10^{26} \epsilon_{-4}^{0.79} \alpha_{-1}^{-1.43}$ ergs s^{-1} at $\nu = 10^{14}$ Hz. The proton synchrotron emission is too weak for detection. Even for accretion rates as high as $\dot{m} \sim 0.1$, the synchrotron emission is unlikely to be detected. In most cases, the electron synchrotron emission is expected to be much stronger, and it could have a significant contribution to the observed emission spectra (Narayan & Yi 1995).

The existence of the hot, two-temperature accretion flows in neutron star systems is hard to prove because the emission from the surface of the neutron star dominates the emission spectrum (e.g., Narayan & Yi 1995; Yi et al. 1996). The luminosity from the stellar surface $L_{\rm X} \sim GM\dot{M}/R_{\rm NS} \sim 3 \times 10^{36} \dot{m}_{-2}$ ergs s^{-1} is most likely to occur in the X-ray range (Frank et al. 1992). Therefore, the luminosity from the neutron star systems is not expected to reflect the low radiative efficiency which is often attributed to the hot, two-temperature accretion flows (Narayan & Yi 1995; Yi et al. 1996; Narayan et al. 1998b). Using the expression for $L_{\rm X}$, we get

$$L_{\rm sync} \sim 2 \times 10^{33} \epsilon_{-4}^{0.44} \mu_{30}^{0.55} \alpha_{-1}^{0.44} m^{0.33} L_{\rm X,36}^{0.44} \nu_{15}^{2.08}, \quad (10)$$

where $L_{\rm X,36} = L_{\rm X}/10^{36}$ ergs s^{-1}. However, there are a few pulsar systems that show some indication of the hot accretion flows. That is, some systems have shown puzzling torque reversals (Yi et al. 1997). The spin-down episodes could be caused by the transition of accretion flows from cool, thin accretion disk to hot accretion flows (Yi & Wheeler 1998). In the neutron star systems, the electron temperature becomes much lower than that of the black hole systems because of intense cooling of electrons by soft photons emitted at the surface of the neutron star at which the accretion flow lands. Since the electrons and ions are not strongly coupled (only weakly through Coulomb coupling), the ion temperature remains nearly unaffected. As a result, the electron temperature becomes much lower than $\sim 10^9$ K and the electron synchrotron emission is effectively quenched (Narayan & Yi 1995). As long as the protons remain hot, the proton synchrotron emission remains unaffected.

Assuming that $M = 1.4\ M_\odot$ and $R_{\rm NS} = 10$ km, we consider the pulsar systems that showed abrupt torque reversals and consider their spin-down episodes as being caused by the hot, two-temperature accretion flows. First, 4U 1626−67's torque reversal event could be accounted for by $\dot{m} \sim 2 \times 10^{-2}$ and $\mu_{30} \sim 2$ (Yi et al. 1997), which lead to $L_{\rm sync} \sim 9 \times 10^{33} \epsilon_{-4}^{0.44} \alpha_{-1}^{0.44}$ ergs s^{-1} at $\nu = 10^{15}$ Hz and $L_{\rm sync} \sim 1 \times 10^{36} \epsilon_{-4}^{0.44} \alpha_{-1}^{0.44}$ ergs s^{-1} at $\nu = 10^{16}$ Hz. The soft X-ray luminosity is expected at $L_{\rm X} \sim 6 \times 10^{36}$ ergs s^{-1}. Similarly, GX 1+4's parameters are estimated as $\dot{m} \sim 5 \times 10^{-2}$ and $\mu_{30} \sim 50$ (Yi et al. 1997; Yi & Wheeler 1998), which gives $L_{\rm sync} \sim 8 \times 10^{34} \epsilon_{-4}^{0.44} \alpha_{-1}^{0.44}$ ergs s^{-1} at $\nu = 10^{15}$ Hz and $L_{\rm sync} \sim 9 \times 10^{36} \epsilon_{-4}^{0.44} \alpha_{-1}^{0.44}$ ergs s^{-1} at $\nu = 10^{16}$ Hz. The X-ray luminosity $L_{\rm X} \sim 2 \times 10^{37}$ ergs s^{-1}. Finally, OAO 1657−415 (Yi & Wheeler 1998) has also shown an abrupt torque reversal which suggests $\dot{m} \sim 5 \times 10^{-2}$ and $\mu_{30} \sim 20$ or $L_{\rm sync} \sim 4 \times 10^{34} \epsilon_{-4}^{0.44} \alpha_{-1}^{0.44}$ ergs s^{-1} at $\nu = 10^{15}$ Hz and $L_{\rm sync} \sim 5 \times 10^{36} \epsilon_{-4}^{0.44} \alpha_{-1}^{0.44}$ ergs s^{-1} at $\nu = 10^{16}$ Hz. $L_{\rm X}$ is expected to be similar to that of GX 1+4.

It is particularly interesting that 4U 1626−67 has been detected in the optical with a luminosity of $\sim 5 \times 10^{33}$ ergs s^{-1} at 5500 Å (for an assumed distance of 8.5 kpc) and $\nu L_\nu \propto \nu^2$ (Chakrabarty 1998), which is similar to our prediction if the relativistic protons indeed have a power-law energy spectrum with index $s = 2.5$. Given the fact that $s = 2.5$ is amply motivated by the Galactic center source Sgr A*, it is quite interesting that a similar population of relativistic protons may account for the optical emission in 4U 1626−67. For the accretion parameters discussed above, if the observed optical emission is the proton synchrotron emission, we immediately get an estimate on the fraction of the relativistic protons $\epsilon \sim 5 \times 10^{-4} \alpha_{-1}^{-1}$. This fraction is not far from that assumed for the Galactic center source Sgr A*. Chakrabarty (1998) suggests that the observed optical emission may be accounted for by the X-ray irradiated accretion flow. While this possibility cannot be ruled out, it is difficult for a compact binary such as 4U 1626−67 to have the large outer radius required for the irradiation to be effective in the accretion flow (Chakrabarty 1998). It is also unclear whether the radiation from the magnetic poles can effectively heat up the outer accretion flow (e.g., Yi & Vishniac 1999). In the case of GX 1+4, the pulsar is fed through wind accretion from a giant secondary (e.g., Chakrabarty et al. 1998). It is unclear whether the torque-reversing mechanism is similar to that of 4U 1626−67 (Yi et al. 1997).

If the accretion flow at large radii is in the form of a thin disk, the optical emission from the thin disk could occur at $\nu \sim 10^{15}$ Hz with the quasi-blackbody spectra at the temperature of about a few $10^4 \dot{m}_{-2}(r_o/10^3)^{-4/3}$ K (Frank et al. 1992). The proton synchrotron luminosity at $\nu \sim 10^{15}$ Hz exceeds the quasi-blackbody emission from the thin disk if $\dot{m} \lesssim 2 \times 10^{-2}(r_o/10^3)^{1.8}$. Therefore, we conclude that the proton synchrotron emission should be seen if the accretion flow is a two-temperature, hot flow with a characteristic spectral index ∼1 (i.e., $I_\nu \sim \nu$).

4. DISCUSSIONS

We have shown that in strongly magnetized neutron star systems, the existence of energetic protons in the hot accretion flows could be confirmed by the detection of synchrotron emission from relativistic protons. Although the required number density of nonthermal protons remains highly uncertain, the detection of such a radiation signature is possible if the relativistic protons are similar to those recently discussed in the context of the gamma-ray emission from the Galactic center source Sgr A* (Mahadevan et al. 1997; Mahadevan 1998). The proton energy distribution index $s = 2.5$ makes a particularly interesting case in 4U 1626−67. A similar index is motivated by Sgr A*'s proton signatures (Mahadevan et al. 1997; Mahadevan 1998).

The existence of the two-temperature plasma around accreting black holes and neutron stars in their low-luminosity states has been shown to be very plausible. However, because of the lack of any direct test of such a possibility for relativistic protons, the spectral evidence has been the basis of the recent discussions on the low-efficiency, two-temperature flows. Therefore, nondetection of the proton synchrotron signature would imply either that the hot protons lack a relativistic component or that the neutron star systems do not have the hot accretion flows. If the former is the case, the recently suggested gamma-ray signature in Sgr A* could be questioned (Mahadevan et al. 1997).

In neutron star systems, electrons are cooled much more efficiently than in black hole systems, while protons remain nearly virialized (Narayan & Yi 1995). Since ions are not likely to be thermalized once they are produced by some nonthermal acceleration processes, the relativistic protons could be highly nonthermal. These protons could lose their energy significantly via proton synchrotron emission. In black hole systems, because of the lack of any strong fields, the synchrotron emission is much weaker. Therefore, the two-temperature accretion flows and energetic protons could be "directly" detected more easily in neutron star systems.

So far, there has not been convincing evidence for the hot accretion flows in the neutron star systems, although the abrupt torque reversal events have been attributed to the accretion flow transition between the cool, geometrically thin accretion disk and the hot, geometrically thick accretion flow. If the reversal is indeed due to the accretion flow transition, the proton synchrotron emission would be seen only during spin-down since the hot accretion flow exists only during spin-down. Interestingly, it has been noted that the torque reversal seen in GX 1+4 is much more gradual and different from the more puzzling 4U 1626−67 event (Yi et al. 1997). The detected optical emission in 4U 1626−67 shows the luminosity and the spectral slope interestingly close to the proton synchrotron emission. If the proton synchrotron is indeed responsible for the optical emission, a strong polarization signal is expected. If the GX 1+4 event is caused by some mechanism other than the accretion flow transition, then GX 1+4's spin-down phase should lack the proton synchrotron emission signature. The predicted correlation between $L_{\rm sync}$ and $L_{\rm X}$ could provide an additional test for the two-temperature accretion flow.

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