EMISSIVE MECHANISIM OF RADIO FLAT SPECTRUM ON X-RAY BINARIES

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We present that the radio emission with flat spectrum in X-ray binaries comes from the synchrotron emission of relativistic electrons in the high energy tail of hot electrons in continuous conical jet. The jet is assumed to be produced by the advection-dominated accretion flow (ADAF) and maintains ion and electron temperatures constant in the case of adiabatic steady conical expansion. The flat spectrum is result of self-absorbed synchrotron emission by relativistic thermal electrons. We find that the critical frequency at which the radiation becomes optically thin declines along the jet. The emission observed at higher frequencies originates at smaller distance, closer to the base of the jet. The highest cut-off frequency of the flat spectrum is at the base of the jet, and is determined by the physics of the ADAF and the position of the jet formation. We assert that it is a characteristic of the ADAF in black hole X-ray binaries that a continuous steady outflow is formed and causes the observed flat spectrum in the low/hard state. The observed synchrotron emission consists of the flat spectral component from the jet and the steep spectral component from the ADAF. The flat spectral component extends from infrared to radio wavelengths, while the steep spectral component with the 2/5 spectral slope extends from infrared to shorter wavelengths, it will be dominated by the thermal emission from companion star.

\textit{Subject headings:} accretion, accretion disks: stars—binaries: close—ISM: jets and outflows—radiation mechanisms—radio continuum: stars
1. INTRODUCTION

Radio emission is observed from 20% of X-ray binaries (e.g. Hjellming & Han 1995). In many cases of persistent or repetitive radio emission, there appears to be an underlying flat-spectrum component in low/Hard X-ray state (Fender 2000 and references therein). This spectral component is usually considered to originate in partially self-absorbed synchrotron emission from conical jets, of same genre as those originally considered for Active Galactic Nucleus (AGNs) (Marscher & Gear 1985; Hjellming & Johnston 1988; Falcke & Biermann 1996, 1999). These models assume the nonthermal electrons with a power-law distribution to produce a flat spectrum from the jet with a variety of geometries, magnetic fields and energetics, and produce only a flat spectrum over at most three decades in frequency. The radio spectrum observed from these black hole systems in the low/Hard state is quite different, showing a flat spectrum which probably extends to very high frequencies. For example, the flat radio spectrum may extend to mm wavelengths for Cyg X-1 (Fender et al. 2000) and even to near-infrared bands for GX 339-4 (Fender 2001) and GRS 1915+105 (Fender et al. 1997; Mirabel et al. 1998; Fender & Pooley 1998, 2000). It is therefore clear that X-ray binaries have much flatter radio-mm (-infrared) spectra than the 'flat-spectrum' AGNs. They may be not relevant in jet kinematics and emissive mechanisms. The model of optically thin emission from a flatten electron spectrum (Wang et al. 1997) is not applied to X-ray binaries. The frequency-dependent time delays observed in GRS 1915+105 (Fender et al. 1997; Fender & Pooley 1998) argue against this model, as they imply significant optical depth. Another possible mechanisms are a optically thin free-free emission and a combination of free-free emission and synchrotron emission (Fender et al. 2000), but the detailed calculations are needed. Therefore the model suitable for X-ray binaries remains to be estimated.

The extremely strong correlation between the hard X-rays and the radio emission in
many X-ray binaries (e.g. GX 339-4 [Fender et al. 1999; Corbel et al. 2000], GRO J1655-40 [Harmon et al. 1995], GRS 1915+105 [Harmon et al. 1997; Fender et al. 1999], Cyg X-3 [McCollough et al. 1999], and Cyg X-1 [Brocksopp et al. 1999]) has been observed. They imply that the regions responsible for emission in the two energy regimes are strongly physically coupled. It is currently believed that the hard X-ray emission is produced by hot electrons via comptonisation, it seems likely that the high-energy electrons responsible for the radio emission are simply the high-energy tail of hot electrons.

In this letter we present that the flat spectra of the low/hard state components are produced by the high-energy tail of hot electrons in continuous conical jets. The jets are considered to arise in the advection-dominated accretion flow (ADAF) (Narayan & Yi 1995; Esin et al. 1998) or the advection-dominated inflow-outflow (ADIO) (Blandford & Begelman 1999). We study the jet kinetics and show that the hot electrons maintain constant temperature in the adiabatic steady expansion of the conical jet. The relativistic thermal electrons in the jet turn out to produce the flat spectrum by self-absorbed synchrotron emission.

2. JET KINEMATICS AND EMISSIVE MECHANISM

Assume that the jet is a one-dimensional adiabatic steady conical, which starts at the distance $z_0$ to the central black hole, with constant opening half-angle $\phi$ and constant velocity $u$. The jet follows the continuity of momentum $(p + \rho u^2)$, the energy $(\frac{1}{2} \rho u^3 + \rho u w)$, and the mass ($\rho u$) flux densities, e.g.,

$$\rho u A(z) = const, \quad (p + \rho u^2)A(z) = const, \quad (\frac{1}{2} \rho u^3 + \rho u w) = const,$$

where $A(z) = \pi (tg\phi)^2 z^2$ is the cross-section of the jet at the distance $z$, then the thermodynamic quantities of the jet as function of distance $z$ have simple form:
\[ \rho = \rho_0 \left( \frac{z}{z_0} \right)^{-2}, \quad p = p_0 \left( \frac{z}{z_0} \right)^{-2}, \quad w = w_0 \left( \frac{z}{z_0} \right)^{-2}. \]

We assume that the gas in the jet from ADAF is equipartition with an isotropically tangled magnetic field. We take \( \beta \) to be independent of \( z \), and let the total pressure \( p \) as

\[ p = p_g + p_m, \quad p_g = \beta p, \quad p_m = (1 - \beta)p, \tag{2} \]

where \( p_g \) is the gas pressure, \( p_m \) is the magnetic pressure. For the jet plasma from ADAF, we allow the ion temperature \( T_i \) and the electron temperature \( T_e \) to be different, and take the gas pressure to be given by (Narayan & Yi 1995)

\[ p_g = \frac{\rho k}{m_u} \left( \frac{T_i}{\mu_i} + \frac{T_e}{\mu_e} \right) = 6.72 \times 10^7 \rho (T_i + 1.08 T_e) = \beta p, \tag{3} \]

where the effective molecular weights of the ions and electrons are \( \mu_i = 1.23 \) and \( \mu_e = 1.14 \) which correspond to a hydrogen mass fraction 0.75. The magnetic pressure is defined as \( p_m = \frac{B^2}{8\pi} = (1 - \beta)p \). With the above relations, we find the distribution of physical quantities along the jet as follows:

\[ \rho = \rho_0 \left( \frac{z}{z_0} \right)^{-2}, \quad B = B_0 \left( \frac{z}{z_0} \right)^{-1}, \quad T_i + 1.08 T_e = \text{const.} \tag{4} \]

It is shown that the ion and electron temperatures remain constant along the jet. The temperatures of ions and electrons in ADAF are very high. The ions are close to their virial temperature \( 10^{12}K \), while the electrons are at \( 10^9K \). Therefore the electrons in the jet are also at higher temperature \( 10^9K \). Due to the assumption an equipartition magnetic field in the jet plasma, synchrotron emission from relativistic electrons in the high energy tail of Maxwellian distribution provides likely the observed flat radio emission. We now turn to take the detailed calculation of synchrotron emission from relativistic thermal electrons. The emissive coefficient of synchrotron radiation by relativistic thermal electrons is given by (Narayan & Yi 1995; Mahadevan, Narayan, & Yi 1996; Mahadevan 1997)

\[ \epsilon_s = 4.43 \times 10^{-30} \frac{4\pi n_e \nu}{K_2(1/\theta_e)} M(x_M), \tag{5} \]
where \( M(x_M) \) is given by
\[
M(x_M) = \frac{4.0505}{x_M^{1/6}} \left( 1 + \frac{0.40}{x_M^{1/4}} + \frac{0.5316}{x_M^{1/2}} \right) \exp(-1.8899x_M^{1/3}),
\]
(6)
and
\[
x_M \equiv \frac{2\nu}{3\nu_b\theta_e^2}, \quad \nu_b \equiv \frac{eB}{2\pi mec}, \quad \theta_e = \frac{kT_e}{me^2}
\]
(7)
The synchrotron photons in the jet plasma are self-absorbed and give a blackbody spectrum, up to a critical frequency \( \nu_c \). The frequency at which this occurs, at the distance \( z \), is determined by
\[
2\pi \nu^2 c kT_e A(z_0) + \int_{z_0}^{z} \varepsilon_s A(z) \, dz = 2\pi \frac{\nu^2}{c^2} kT_e A(z),
\]
(8)
where the first term in the left side of Eq(8) is the synchrotron emission getting into the jet at the distance \( z_0 \), the second term is the synchrotron emission over a volume of conical jet between \( z_0 \) and \( z \), and the first term in the right side of Eq(8) is the synchrotron emission through the cross-section at the distance \( z \). We assume the emissive coefficient \( \varepsilon_s \) to be constant, we obtain the relation from Eq(8)
\[
x_M(z) = \frac{6.15 \times 10^{-11} 4\pi n_e z}{B} \left( \frac{1}{\theta_e} \right) M[x_M(z)].
\]
(9)
From Eq(4) we find that \( 4\pi n_e z / B \) remain constant along the jet, and that \( x_M \) is also constant in the jet. Given \( x_M \), the cutoff frequency at the distance \( z \) is given by
\[
\nu_c = \frac{3}{2} \theta_e^2 \nu_b x_M = \nu_0 \left( \frac{z}{z_0} \right)^{-1}
\]
(10)
where \( \nu_0 = \frac{3eBd^2x_M}{4\pi me^2c} \) is the cutoff frequency at the base of the jet, and \( A(z) \propto \nu_c^{-2} \). At the frequency \( \nu_c \), the radiation becomes optically thin, and the luminosity is given by the Rayleigh-Jeans part of the blackbody spectrum \((h\nu/kT_e \ll 1)\)
\[
L_{\nu_c} = 2\pi \frac{\nu_c^2}{c^2} kT_e A(z) = 2\pi \frac{\nu_0^2}{c^2} kT_e A(z_0)
\]
(11)
which shows that the luminosity at the frequency \( \nu_c \) is independent of the frequency \( \nu_c \). This produces a flat spectrum, which extends from \( \nu_0 \) down to \( \nu_{\text{min}} \), where \( \nu_{\text{min}} \) is the
cutoff frequency given by setting $z = z_{\text{max}}$ in Eq(10). Beyond this distance, the jet shrinks and causes a steeper radio spectrum, as long as the electron temperature declines (below $T_e = 10^8 K$, there is no synchrotron radiation). Eq(9) shows how the cutoff frequency varies with $z$. Emission observed at higher frequencies originates at smaller distance, closer to the base of the jet. The peak frequency is at the base of the jet.

We can use the self-similar solutions of ADAF disk to estimate the peak frequency $\nu_0$ and the total luminosity $\nu L_\nu$ of a flat-spectrum source. At the base of the jet, the magnetic field is given by (Narayan & Yi 1995)

$$B_0 = 2.22 \times 10^5 m^{-1/2} \dot{m}^{1/2} \, h_1 \left( \frac{z_0}{10^3 R_s} \right)^{-5/4} G,$$

and $h_1 = (\alpha/0.3)^{-1/2}[(1 - \beta)/0.5]^{1/2}(c_1/0.5)^{-1/2}(c_3/0.3)^{1/4}$, where we scale the mass of central object in solar unit by writing $M = m M_\odot$ and accretion rate in Eddington unit, $\dot{M} = \dot{m} \dot{M}_{\text{Edd}}$, $R_s = 2GM/c^2 = 2.95 \times 10^5 m$ cm, $\alpha$ is the standard viscosity parameter (Shakura & Sunyaev 1973), and $c_1$, $c_3$ are constants as defined in Narayan & Yi (1995).

With the Eq(10) and Eq(11), the peak frequency and total luminosity are given by

$$\nu_0 = 2.68 \times 10^{13} m^{-1/2} \dot{m}^{1/2} \, h_1 \left( \frac{x_M}{10^3} \right) \left( \frac{T_e}{10^9 K} \right)^2 \left( \frac{z_0}{10^3 R_s} \right)^{-5/4} Hz,$$

$$\nu L_\nu = 1.61 \times 10^{30} m^{1/2} \dot{m}^{3/2} \, h_1^3 \Omega \left( \frac{x_M}{10^3} \right)^3 \left( \frac{T_e}{10^9 K} \right)^7 \left( \frac{z_0}{10^3 R_s} \right)^{-7/4} \text{ergs s}^{-1},$$

where $\Omega = \pi(tg\phi)^2$, and the parameter $x_M$ satisfies the Eq(9) given by

$$x_M = 1.12 \times 10^{10}(m)^{1/2}(\dot{m})^{1/2} \left( \frac{z_0}{10^3 R_s} \right)^{3/4} h_2 \frac{1}{\theta_e^2 K_2 (1/\theta_e)} M(x_M),$$

and $h_2 = (\alpha/0.3)[(1 - \beta)/0.5](c_1/0.5)(c_3/0.3)^{-1/2}$. Table 1 shows the values of $\nu_0$ and $\nu L_\nu$ for a set of temperatures $T_e$ at given $z_0 = 10^3 R_s$, $m = 10$ and $\dot{m} = 10^{-2}$, in which we have used the values of $\theta_e^2 K_2 (1/\theta_e)$ given by Mahadevan (1997).

We now estimate the total internal jet power. The power is given by

$$L_{\text{jet}} = \frac{1}{2} \rho u^3 + \rho w A(z_0),$$

(16)
where the enthalpy $w$ can be writes as $w = \frac{\gamma p}{\gamma - 1} = \frac{\gamma}{\gamma - 1} c_s^2$, $\gamma$ is adiabatic index and $c_s$ is isothermal sound speed. We take $\gamma = 5/3$ and obtain $w = 2.5c_s^2$. Assume $u < \sqrt{2w}$, e.g.,

$$u < \sqrt{5c_s(z_0)} = 2.74 \times 10^{-2} c \left( \frac{c_3}{0.3} \right)^{1/2} \left( \frac{z_0}{10^3 R_s} \right)^{-1/2},$$  \hspace{1cm} (17)

where $c$ is the speed of light, we obtain the jet power as

$$L_{jet} \simeq \frac{5}{2} \rho u c_s^2 A(z_0) = 1.30 \times 10^{34} m \dot{m} h_3 \Omega \left( \frac{u}{10^{-3} c} \right) \left( \frac{z_0}{10^3 R_s} \right)^{-1/2} \text{ergs s}^{-1},$$ \hspace{1cm} (18)

where $h_3 = (\alpha/0.3)^{-1}(c_1/0.5)^{-1}(c_3/0.3)^{1/2}$.

For a given accretion rate and matter-to-energy conversion ($\eta_{eff} = 0.1$), standard accretion disks predict a total accretion luminosity is $L_{disk} = \dot{m} c^2 \dot{M}_{Edd} = 1.25 \times 10^{39} m \dot{m} \text{ ergs s}^{-1}$. The ADAF produces a lower luminosity because most of the viscously dissipated energy is advected inward with the flow and deposited into the black hole instead of being radiated. For $\dot{m} > 10^{-3}\alpha^2$, the total luminosity of the ADAF is given by (Mahadevan 1997)

$$L_{ADAF} \simeq 2.70 \times 10^{38} m \dot{m}^2 h_4 \text{ ergs s}^{-1},$$ \hspace{1cm} (19)

where $h_4 = g(\theta_e)(\alpha/0.3)^{-2}(c_3/0.3)(\beta/0.5)(r_{min}/3)^{-1}$, and $0.5 < g(\theta_e) < 13$ for temperature ranges of interest (see Mahadevan 1997).

The thermal self-absorbed synchrotron radiation from the ADAF has a spectrum with 2/5 spectral index which extends from $\nu_p$ down to $\nu_0$, where $\nu_p$ is the cutoff frequency given by setting $r = r_{min} = 3$ in equation (13) (Mahadevan et al. 1997)

$$\nu_p = 2.85 \times 10^{15} m^{-1/2} \dot{m}^{1/2} h_1 \left( \frac{x_M}{10^3} \right) \left( \frac{T_e}{10^9 K} \right)^2 \text{Hz}$$ \hspace{1cm} (20)

Therefore the observed synchrotron emission consists of the flat spectral component from the jet and the steep spectral component from the ADAF. Since the steep spectral component extends from infrared $\nu_0$ to shorter wavelengths $\nu_p$, it will be extremely hard to detect, being more weaker than thermal emission from companion star.
3. DISCUSSION AND CONCLUSIONS

We have presented that the radio emission with flat spectrum comes from the synchrotron emission of relativistic electrons in the high energy tail of hot electrons in continuous conical jets. The jet is produced by the ADAF/ADIO and maintains ion and electron temperatures constant in the case of adiabatic steady conical expansion. The flat spectrum is result of self-absorbed synchrotron emission by relativistic thermal electrons. The critical frequency at which the radiation becomes optically thin declines with the distance $z$. The emission observed at higher frequencies originates at smaller distance, closer to the base of the jet. The highest cut-off frequency of the flat spectrum is at the base of the jet, and is determined by the physics of ADAF and the position of the jet formation. We assert that it is a characteristic of the ADAF in black hole X-ray binaries that a continuous steady outflow is formed and causes the observed flat spectrum in the low/hard state. In the high/soft state, the hot thin accretion disk may extend much closer to the black hole, the outflow is not present. The radio emission is suppressed with respect to the low/hard state. In the transition state, the ADAF may be at the stage of growth or shrink and produce discrete ejection blobs. The ejected blob will expand rapidly and strongly interact with its surrounding to cause blast waves. The blast waves then accelerate a group of thermal electrons to be relativistic and produce optically thin radio emission.

The simultaneous radio-infrared oscillations have been observed in GRS 1915+105 (Fender et al. 1997; Fender & Pooley 1998), the infrared-radio delay, as well as delays within the radio band, occurs. If a disturbance travels along the jet and cause the changes of physical parameters, the infrared-radio oscillations will be appeared. The delay between high and low frequency emissions is the natural result of self-absorbed synchrotron emission occurred at the different region of the jet. A constant electron temperature in the jet remains within the distance $r_{\text{max}}$. Beyond this distance, the electron temperature declines
as the jet shrinks, which produces a steeper radio spectra. It can explain the observed results of four systems, GS 2023+338, GRO J0422+32, GS 1354-64 and GRS 1915+105 (Fender 2001 and references therein).

It also is a characteristic of ADAF that the strong correlation between the presence of hard X-ray emission and radio emission observed in persistent black hole candidate X-ray binaries. Since the relativistic thermal electrons responsible for the radio emission in the jet arise in ADAF and directly indicates a population of hot electrons. The hard X-ray emission arises in inverse Comptonisation of soft photons by hot electrons in the ADAF and the jet. The ADAF will be significant enough to contribute in hard X-rays if the jet carries a small part of hot electrons in the ADAF. The hard X-ray spectrum is a power-law which extends to \( \nu = 3kT_e/h = 260keV(T_e/10^9K) \). The spectral index is determined by the optical depth to electron scattering and amplification factor of photon energy in one scattering (Mahadevan 1997). In the high/soft state the ADAF is not present, the hard X-ray emission is suppressed. If the jet has larger velocity, it will be a significant power output channel for the ADAF and affect the evolution of the ADAF in the low/hard and transition state.

The observed synchrotron emission consists of the flat spectral component from the jet and the steep spectral component from the ADAF. The flat spectral component extends from infrared \( \nu_0 \) to radio wavelengths, while the steep spectral component with the 2/5 spectral slope extends from infrared \( \nu_0 \) to shorter wavelengths \( \nu_p \), it will be dominated by the thermal emission from companion star.
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Table 1: The peak frequency and total luminosity for the electron temperature range of interest.

| $T_e$ ($10^9 K$) | $x_M$ | $\nu_0$ ($10^{12} Hz$) | $\nu L_\nu$ ($10^{29} ergs s^{-1}$) |
|-----------------|------|------------------------|--------------------------|
| 1.00            | 3.230| 2.74E+00               | 1.72E+00                 |
| 1.50            | 2.269| 4.32E+00               | 1.02E+01                 |
| 2.00            | 1.800| 6.10E+00               | 3.80E+01                 |
| 2.50            | 1.516| 8.03E+00               | 1.08E+02                 |
| 3.00            | 1.321| 1.01E+01               | 2.56E+02                 |
| 3.50            | 1.177| 1.22E+01               | 5.34E+02                 |
| 4.00            | 1.065| 1.44E+01               | 1.01E+03                 |
| 4.50            | 0.975| 1.67E+01               | 1.76E+03                 |
| 5.00            | 0.901| 1.91E+01               | 2.91E+03                 |
| 5.50            | 0.838| 2.15E+01               | 4.56E+03                 |
| 6.00            | 0.784| 2.39E+01               | 6.88E+03                 |
| 6.50            | 0.738| 2.64E+01               | 1.00E+04                 |
| 7.00            | 0.696| 2.89E+01               | 1.20E+04                 |
| 7.50            | 0.660| 3.14E+01               | 1.95E+04                 |
| 8.00            | 0.627| 3.40E+01               | 2.63E+04                 |
| 8.50            | 0.598| 3.66E+01               | 3.48E+04                 |
| 9.00            | 0.571| 3.92E+01               | 4.53E+04                 |
| 9.50            | 0.546| 4.17E+01               | 5.79E+04                 |
| 10.0            | 0.524| 4.44E+01               | 7.32E+04                 |