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Observational signatures of the magnetic connection between a black hole and a disk

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Abstract. We use a simple model to demonstrate the observational signatures of the magnetic connection between a black hole and a disk: (1) with the existence of the magnetic connection, more energy is dissipated in and radiated away from regions close to the center of the disk; (2) the magnetic connection can produce a very steep emissivity compared to the standard disk accretion; (3) the observational spectral signature of the magnetic connection can be robust. These signatures can be identified by the observations of *Chandra* and *XMM-Newton*. In fact, the steep emissivity index for the Seyfert 1 galaxies MCG–6-30-15 and Mrk-766 inferred from the recent *XMM-Newton* observations is very difficult to be explained with a standard accretion disk but can be easily explained with the magnetic connection between a black hole and a disk.

Key words. black hole physics – accretion disks – magnetic fields – galaxies: active – galaxies: Seyfert

1. Introduction

A magnetic field connecting a black hole to a disk has important effects on the balance and transfer of energy and angular momentum (Blandford 1999, 2000; Li 2000, 2001, 2002; Li & Paczyński 2000, and references therein). When the black hole rotates faster than the disk, energy and angular momentum are extracted from the black hole and transferred to the disk. The energy deposited in the disk by the black hole can be dissipated by the internal viscosity of the disk and radiated away to infinity (Li 2000, 2002). Thus, the rotational energy of the black hole provides an energy source for the radiation of the disk in addition to disk accretion.

A disk powered by a black hole through magnetic connection shows interesting features different from that of a standard accretion disk (Li 2001, 2002). The energy radiated by the disk comes from regions closer to the center of the disk; the radiation flux decreases more rapidly with radius, which approaches $r^{-3.5}$ at large radii (compared to r^{-3} for a standard accretion disk). This implies that the radiation spectrum of a disk with magnetic connection observed by a distant observer will also be different from that of a standard accretion disk.

Interestingly, the most recent *XMM-Newton* observation of the nearby bright Seyfert 1 galaxy MCG–6-30-15 reveals an extremely broad and red-shifted Fe Kα line indicating its origin from the very most central regions of the accretion disk (Wilms et al. 2001). To explain the observed spectrum a very steep emissivity profile with index $\alpha = 4.3{-}5.0$ is required. A steep emissivity for the same galaxy and Mrk-766 is also reported by Branduardi-Raymont et al. (2001). Such a steep emissivity is very difficult to be explained within the framework of a standard accretion disk (Wilms et al. 2001). However, the magnetic connection between a black hole and a disk may provide a simple and natural explanation (Li 2001, 2002).

In this paper we use a simple model to demonstrate the observational signatures of the magnetic connection between a black hole and a disk. We assume that an axisymmetric magnetic field connects a black hole to a non-accretion disk from the inner boundary of the disk to a circle with radius $r_{\rm b}$. As in the case of a standard accretion disk, the inner boundary of the disk is assumed to be at the marginally stable orbit with radius $r_{\rm ms}$. We will calculate the radiation flux, the emissivity index of the disk, and the radiation spectrum observed by a distant observer, for various distribution of the magnetic field between $r_{\rm ms}$ and $r_{\rm b}$ on the disk. We will compare the results to that of a standard accretion disk and look for the robustness of the observational signatures of the magnetic connection.

2. The model and the radiation flux

The magnetic connection produces an angular momentum flux transferred between the black hole and the disk (Li 2002)

$$H = \frac{1}{8\pi^3}\left(\frac{{\rm d}\Psi_{\rm HD}}{{\rm d}r}\right)^2 \frac{\Omega_{\rm H}-\Omega_{\rm D}}{-r{\rm d}Z_{\rm H}/{\rm d}r}, \tag{1}$$

where $\Psi_{\rm HD}$ is the magnetic flux connecting the black hole to the disk, $\Omega_{\rm H}$ is the angular velocity of the horizon of the black hole, $\Omega_{\rm D}$ is the angular velocity of the disk, and $Z_{\rm H}$ is the resistance of the black hole which is mapped to the disk surface by

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the magnetic connection. We assume that H has a power-law distribution from $r = r_{ms}$ to $r = r_b$

$$H = \begin{cases} Ar^n\,, & r_{ms} < r < r_b \\ 0\,, & r > r_b \end{cases}\,, \tag{2}$$

where A is a constant. In our model we allow n to vary from $n = 1$ to $n = -9$. The case $n = 1$ roughly corresponds to a uniform magnetic field between r_{ms} and r_b. As n decreases the magnetic field becomes more concentrated toward the center of the disk.

In a steady state, the radiation flux of a non-accretion disk is (Li 2001, 2002)

$$F = \frac{1}{r}\left(-\frac{d\Omega_D}{dr}\right)(E^+ - \Omega_D L^+)^{-2}\int_{r_{ms}}^{r}(E^+ - \Omega_D L^+)\,Hr\,dr, \tag{3}$$

where E^+ and L^+ are respectively the specific energy and the specific angular momentum of a particle on a Keplerian orbit around the black hole (Page & Thorne 1974). For the H given by Eq. (2), we have

$$F = \frac{A}{r}\left(-\frac{d\Omega_D}{dr}\right)(E^+ - \Omega_D L^+)^{-2}\int_{r_{ms}}^{\min(r,r_b)}(E^+ - \Omega_D L^+)\,r^{n+1}dr, \tag{4}$$

For a canonical Kerr black hole with $a = 0.998\ M_H$, where M_H is the mass of the black hole and a is the specific angular momentum of the black hole (Thorne 1974; throughout the paper we use the geometrized units $G = c = 1$), we have calculated the radiation flux for n ranging from $n = 1$ to $n = -9$. The results are shown in Fig. 1. The position of $r = r_b$, which is chosen to be $2r_{ms}$, is shown with an upward arrow. For comparison, in Fig. 1 we also show the radiation flux of a standard accretion disk (SAD, the short-dashed curve) and the radiation flux of a disk with a limiting magnetic connection (LMC, the long-dashed curve) where the magnetic field touches the disk at the inner boundary. The radiation flux is normalized to give the same luminosity for all models. We see that, with the presence of the magnetic connection, more energy is radiated from regions close to the inner boundary of the disk. This trend becomes more prominent as n decreases i.e. as the magnetic field becomes more concentrated toward the center of the disk. In the limiting case when the magnetic field touches the disk at the inner boundary, the radiation flux peaks at the inner boundary. Outside $r = r_b$, the radiation flux of a disk with magnetic connection declines faster than that of a standard accretion disk.

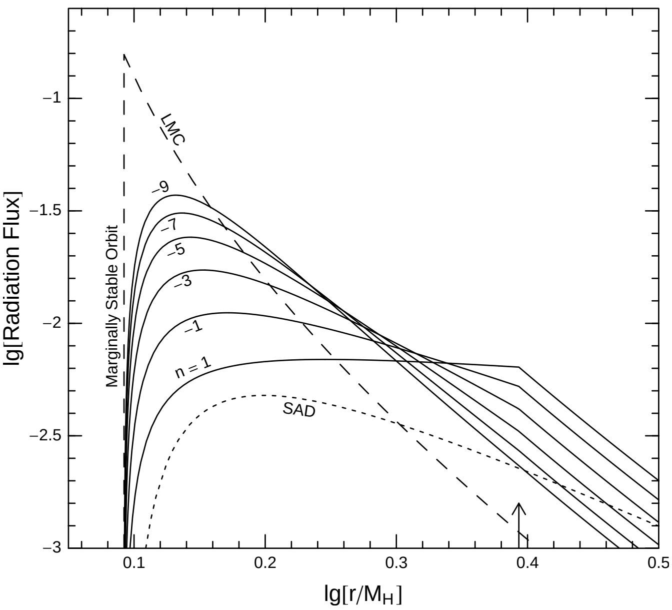

Fig. 1. The radiation flux of a non-accretion disk magnetically connected to a rapidly rotating black hole. The magnetic field is assumed to connect a canonical Kerr black hole ($a = 0.998\ M_H$) to a thin Keplerian disk rotating around it in the annular region bounded by $r = r_{ms}$ and $r = r_b = 2r_{ms}$ (r_b is indicated by the upward arrow). The distribution of the magnetic field on the disk is specified by the resultant angular momentum flux H which is assumed to be $\propto r^n$ inside r_b. We allow n to vary from $n = 1$ (roughly corresponding to a uniform magnetic field) to $n = -9$. As n decreases, the magnetic field becomes more concentrated toward the center of the disk. For comparison, we also show the radiation flux of a standard accretion disk (SAD, the short-dashed curve) and the radiation flux of a disk with limiting magnetic connection (LMC, the long-dashed curve) where the magnetic field touches the disk at the inner boundary (the marginally stable orbit). The radiation flux is normalized to give the same luminosity for all models.

3. The emissivity index and the radiation spectrum

We define the emissivity index by

$$\alpha \equiv -\frac{d\ln F}{d\ln r}, \tag{5}$$

which mimics $F \propto r^{-\alpha}$ locally. For the radiation flux given by Eq. (4) we have calculated the emissivity index and the results are shown in Fig. 2 for the same models in Fig. 1. The emissivity index produced by a standard accretion disk is shown with the short-dashed curve. The emissivity index produced by a limiting magnetic connection is shown with the long-dashed curve. The emissivity index for the Seyfert 1 galaxy MCG–6-30-15 inferred from the recent *XMM-Newton* observation (Wilms et al. 2001) is shown with the shaded region. From Fig. 2 we see that, inside r_b the emissivity index sensitively depends on the distribution of the magnetic field, while outside r_b the emissivity index is independent of the distribution of the magnetic field inside r_b. The emissivity index of a standard accretion disk increases with radius and approaches to 3 as $r \to \infty$, which is always smaller than that inferred from the observation of MCG–6-30-15. The emissivity index of a non-accretion disk with magnetic connection increases to a maximum at some radius and then decreases with radius and approaches to 3.5 as $r \to \infty$. Inside r_b, to be consistent with the observation of MCG–6-30-15, a very large $-n$ is required.

We have also calculated the radiation spectrum seen by a remote observer who is at rest relative to the central black hole, by using the transfer function provided by Cunningham (1975). The disk is assumed to radiate like a black-body and the observer is assumed to be at polar angle $\theta = \pi/3$ from the axis of the black hole. The results are shown in Fig. 3 where the radiation flux is normalized to give the same luminosity for all models. We see that, the magnetic connection tends to harden the radiation of the disk. As n decreases the amplitude of the

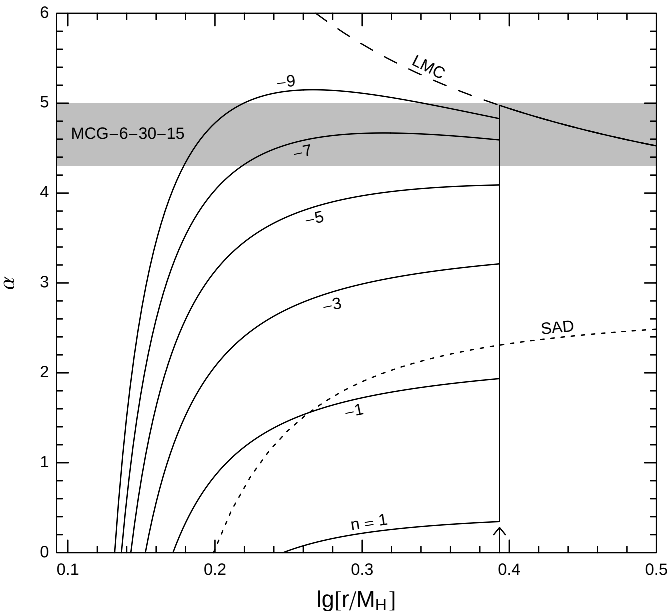

Fig. 2. The emissivity index $\alpha \equiv -\mathrm{d}\ln F/\mathrm{d}\ln r$ for the same models in Fig. 1. The emissivity index of the Seyfert 1 galaxy MCG–6-30-15 inferred from the observation of *XMM-Newton* is shown with the shaded region.

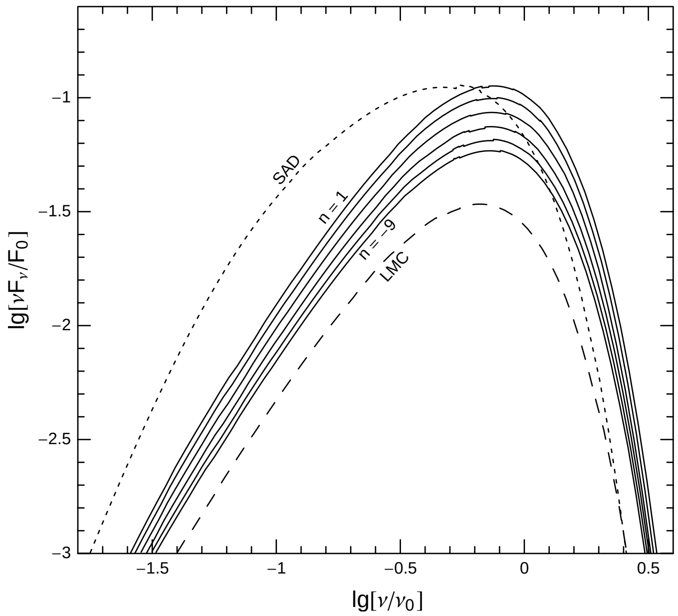

Fig. 3. The spectra seen by a distant observer at distance D from the black hole and polar angle $\theta = \pi/3$ from the axis of the black hole, for the same models in Figs. 1 and 2. The disk is assumed to radiate like a black-body. The radiation frequency is in units of $\nu_0 \equiv (k_\mathrm{B}/h)\left[L/(\sigma M_\mathrm{H}^2)\right]^{1/4}$, where k_B is the Boltzmann constant, h is the Planck constant, L is the luminosity of the disk, and σ is the Stephan-Boltzmann constant. The quantity νF_ν, where F_ν is the specific radiation flux seen by the observer, is in units of $F_0 \equiv L/(4\pi D^2)$. As in Fig. 1, the radiation flux is normalized to give the same luminosity (thus the same ν_0 and F_0) for all models.

observed spectrum goes down, this is caused by the fact that for smaller n the magnetic field becomes more concentrated toward the center of the disk and thus the radiation is more focused to the plane of the disk (Bardeen 1970). Though the shape of the radiation flux curve (Fig. 1) is very sensitive to the distribution of the magnetic field inside r_b, the radiation spectrum is not so, especially at the high frequency end. This indicates that the spectral signature of the magnetic coupling can be robust.

4. Discussion and conclusions

Ever since Penrose (1969) proposed the first gedanken-experiment for extracting energy from a rotating black hole, many people have looked for more practical ways that may work in astronomy. Among many alternatives, the Blandford-Znajek mechanism (Blandford & Znajek 1977; Macdonald & Thorne 1982; Phinney 1983) has been thought to be promising for powering extragalactic jets. The magnetic connection between a rapidly rotating black hole and a disk, as a variant of the Blandford-Znajek mechanism, is more efficient in extracting energy from the black hole (Li 2000). The energy extracted from the black hole is deposited into the disk, dissipated by the internal viscosity of the disk, and subsequently radiated away to infinity (Li 2002). Such a disk can radiate without accretion, then the power of the disk comes from the rotational energy of the black hole.

The magnetic connection not only increases the radiation efficiency of the disk (i.e., increases the ratio of radiated energy to accreted mass), but also produces observational signatures. With the presence of the magnetic connection, more energy is dissipated in and radiated away from regions closer to the center of the disk, which in turn produces a steep emissivity profile. The spectral signature produced by the magnetic connection is also significantly different from that produced by the standard accretion. The recent *XMM-Newton* observations of soft X-ray emission lines from two Narrow Line Seyfert 1 galaxies MCG –6-30-15 and Mrk 766 reveal an extreme steep emissivity profile, which has been suggested to indicate that most of the line emission originates from the inner part of a relativistic accretion disk (Branduardi-Raymont et al. 2001; Wilms et al. 2001). From Figs. 1 and 2 we see that these features are just predicted by the magnetic connection between a rapidly rotating black hole and a disk.

Another kind of observations which may be relevant to the magnetic connection between a black hole and a disk are the kilohertz quasi-periodic oscillations (kHz QPOs) in X-ray binaries, which has been suggested to originate from the inner edge of a relativistic accretion disk (van der Klis 2000, and references therein). The magnetic connection between a Kerr black hole and a disk provides an interesting model for kHz QPOs. In the case of strong coupling, Blandford (1999) has proposed to associate QPOs with the radial oscillation produced by the magnetic connection. There is yet another possibility: QPOs may be produced by a non-axisymmetric magnetic field connecting a black hole to a disk (Li 2001, 2002). Suppose a bunch of magnetic field lines connect a black hole to a disk and the feet of the magnetic field lines on the disk surface are concentrated in a small region, then a hot spot will be produced on the disk surface if the black hole rotates faster than the disk. Since the disk is perfectly conducting, the magnetic field is frozen to the disk so the hot spot will co-rotate with the disk and show a periodic oscillation.

While the model presented in this paper is so simple that it cannot be directly applied to comparison with observations, it demonstrates some interesting observational signatures of the magnetic connection between a black hole and a disk. With *Chandra* and *XMM-Newton* telescopes it becomes possible to probe the inner region of a disk around a black hole, so the observational signatures of the magnetic connection may be identified.

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