Slim Disk Model for Narrow-Line Seyfert 1 Galaxies

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Abstract

We argue that both the extreme soft X-ray excess and the large-amplitude variability of narrow-line Seyfert 1 galaxies (NLS1s) can be explained in the framework of the slim disk model. When the disk luminosity approaches the Eddington luminosity, the disk becomes a slim disk, exhibiting a multi-color blackbody spectrum with a maximum temperature, $T_{\rm bb}$, of $\sim 0.2(M/10^5 M_\odot)^{-1/4}$keV, and size of the X-ray emitting region, $r_{\rm bb}$, of $\sim r_{\rm S}$ (the Schwarzschild radius). Furthermore, magnetic energy can be amplified up to a level exceeding radiation energy emitted from the disk, causing substantial variability in X-rays by consecutive magnetic flares.

Key words: Accretion, accretion disks; black holes, magnetohydrodynamics

1 Introduction

It has been recently established that NLS1s are characterized by extreme soft excesses and extreme variability (1), although the origin still remain a puzzle. Since these features are quite reminiscent of those of Galactic black hole candidates during the very high state, i.e. the state in which the luminosity is comparable to the Eddington luminosity, $L_{\rm E}$, it is natural to assume that NLS1s have a systematically large disk luminosity, L (e.g. (2)). In such a case, the disk is known to become a slim disk (3). What, then, is the observational signature of the slim disk?

2 Spectra of slim disks

It will be useful to quickly review disk theory. The standard disk model was constructed using energy balance between viscous heating and radiative cool-

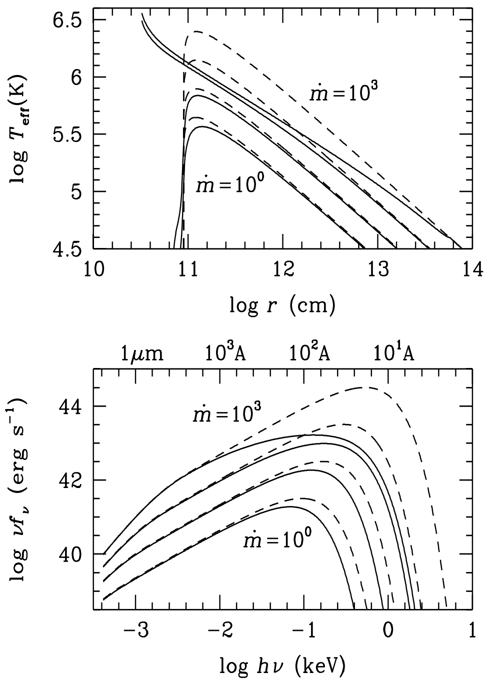

Fig. 1. The temperature profiles (upper) and the emergent spectra (lower) of accretion disks for various mass-flow rates; from the bottom, $\dot{m}[\equiv L/(L_{\rm E}/c^2)] = 10^0, 10^1, 10^2$, and 10^3. The black-hole mass is fixed at $M = 10^5 M_\odot$ ($r_{\rm S} \sim 10^{10.5}$cm). As $\dot{m}$ increases, the regions with a flat temperature profile expand to larger radii and the disk spectra become flatter around the peak. For comparison, we plot the temperature profiles expected from the standard-disk relation (upper) and their emergent spectra (lower) using dashed lines (see (4)).

ing with advective energy transport assumed negligible. Hence, accretion energy can be efficiently converted to radiation energy. This contrasts with the case of the advection-dominated flow, in which viscous heating is balanced by advective cooling; that is, accretion energy is stored in the accreting gas or trapped photons within the flow and is finally swallowed by the black hole. The slim disk corresponds to the optically thick, advection-dominated flow.

The slim disk exhibits rather unique temperature profiles. We calculate the disk structure, taking into account the advection, and plot in Figure 1 the effective temperature distribution (upper) and spectra (lower), together with those of standard disks (see (4) for details). When the mass-flow rate is relatively small, $\dot{m} \equiv \dot{M}/(L_{\rm E}/c^2) = 10$, the disk resides in the standard-disk regime. When it increases up to ~ 100, the two disk models give distinctly different results. First, the slim disk exhibits a flatter temperature profile, $T_{\rm eff} \propto r^{-1/2}$, in contrast with $T_{\rm eff} \propto r^{-3/4}$ for the standard disk. Second, substantial radiation arises from inside the marginally stable last circular orbit at $r = 3r_{\rm S}$. This reflects the fact that, although the accretion velocity is large, near the speed of light close to a black hole, substantial material exists there

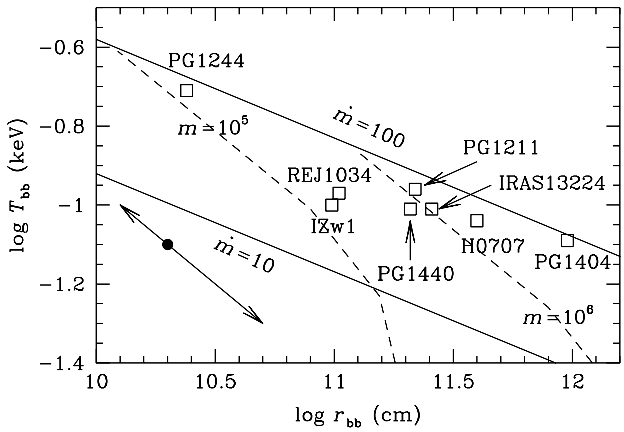

Fig. 2. The $r_{\rm bb}$–$T_{\rm bb}$ diagram of the observational data from NLS1s. The loci of $\dot{m}$ = 10 and 100 (solid lines) and those of $m(\equiv M/M_\odot) = 10^5$ and 10^6 (dotted lines) obtained from the slim disk model are also shown. The arrow pointed in the upper-left (or lower-right) direction from the filled circle in the lower-left corner indicates the direction of the correction for that point to remove Compton and general relativistic effects in the case of a face-on (nearly edge-on) disk (see (4)).

because of the large $\dot{M}$. Third, compared with the standard disk, the slim disk produces higher energy photons, but the number of photons is fewer. If we fit the spectra with a blackbody, we find small sizes for the emitting region, $r_{\rm bb} \lesssim r_{\rm S}$, and high temperatures, $T_{\rm bb} \gtrsim 0.2(M/10^5 M_\odot)$ keV.

In Figure 2 we plot the theoretical values of $r_{\rm bb}$ and $T_{\rm bb}$ as functions of $\dot{m}$ and $m(\equiv M/M_\odot)$, together with the ASCA data for NLS1s (see (4) for details). From these plots, we can safely conclude that all NLS1s plotted here fall into the regions above $\dot{m} = 10$. This justifies our assumption of large $L/L_{\rm E}$ in NLS1s. Also, the derived black-hole masses are relatively small.

3 Variability of Slim Disks

A further issue is the variability. We pay special attention to the following characteristics of the variability: (i) fluctuation light curves seem to be composed of numerous flares (or shots); (ii) shot amplitudes and durations do not have typical values but are smoothly distributed; (iii) occurrence of flares is nearly random. Power spectra of such light curves show a $1/f^\alpha$ decline (with $\alpha = 1-2$ in normal Seyferts) at high frequencies. NLS1s exhibit a more peaked profile and thus α is smaller.

It is often suggested that variability is due to magnetic reconnection leading to flares, as is the case in solar flares. To investigate this magnetic-flare model, we have examined the 3D MHD simulation data (5), finding (i) spatial fractals in the j/ρ distribution (where j and ρ are current and matter densities, respec-

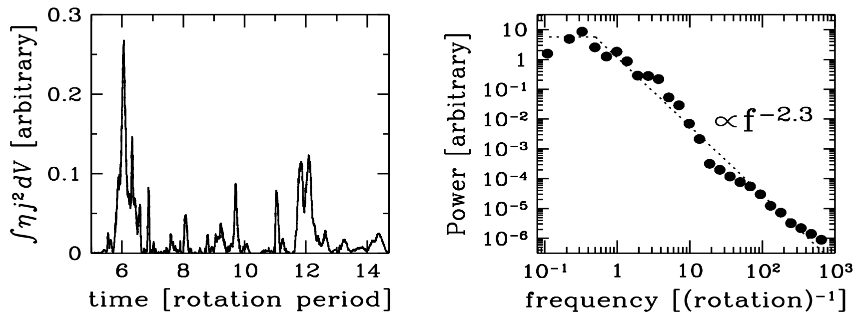

Fig. 3. A typical light curve (left) and its power-spectral density (right) of the simulated MHD disk. Here, we assume that the radiation is predominantly due to field dissipation by magnetic reconnection; thus we plot the temporal variation of Ohmic dissipation integrated over the whole disk (see (6)).

tively) and (ii) temporal $1/f^\alpha$ fluctuations in the Ohmic dissipation, $\int \eta j^2 dV$ (where η is resistivity, see Figure 3). These two are closely related. When reconnection occurs in fractal magnetic fields, a variety of flare amplitudes arise, yielding $1/f^\alpha$ fluctuations (see (6) for a more detailed discussion).

If fluctuations are of a magnetic origin, large-amplitude fluctuations indicate a relatively large field energy compared with the radiation energy. In the standard-type disk, cooling is efficient. Since the emitted radiation energy is comparable to the gravitational-energy release, the internal energy of the gas should be much less than the gravitational energy, which the magnetic field energy cannot exceed. Hence, the magnetic field energy is much less than the emitted radiation energy, leading to rather small fluctuations.

In the slim-disk case, on the other hand, radiative cooling is inefficient. It is the trapped photons that contain large energy comparable to gravitational energy, which greatly exceeds the emitted radiation energy. Magnetic energy can grow to overcome the emitted radiation energy. Thus, large fluctuations are inevitable in radiation from slim disks, consistent with the observations of NLS1s. A more detailed discussion is presented elsewhere (4).

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