An accretion disk-corona model for X-ray spectra of active galactic nuclei

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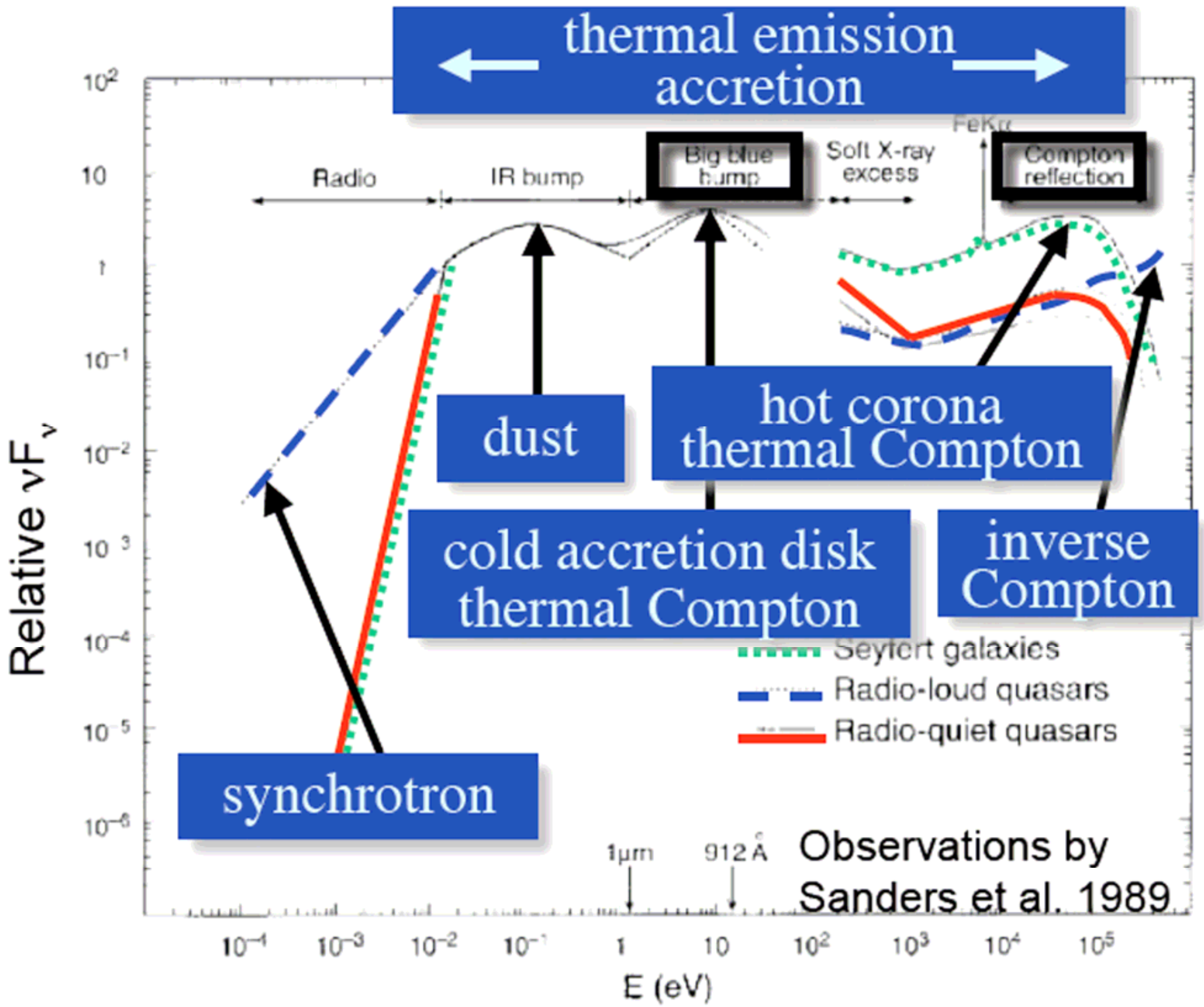
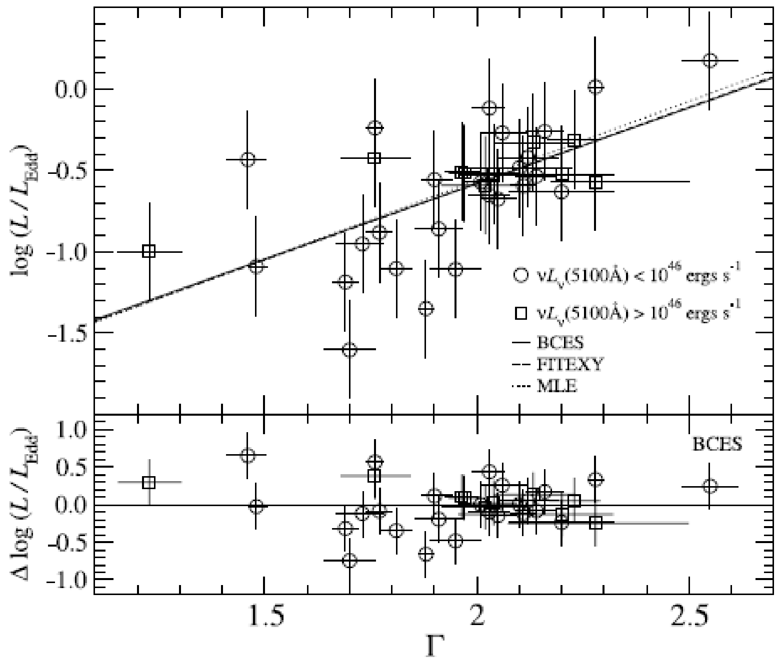
Typical SED of AGN



X-ray observations as constraints on accretion disk-corona models

1. **correlation between photon spectral index Γ (2-10keV) and $L_{\rm bol}/L_{\rm Edd}$.**
2. **Anti-correlation between $L_{\rm bol}/L_{\rm Edd}$ and $L_{2-10{\rm keV}}/L_{\rm bol}$.**



Shemmer, Brandt, Netzer, Maiolino, & Kaspi, 2008, ApJ, 682, 81

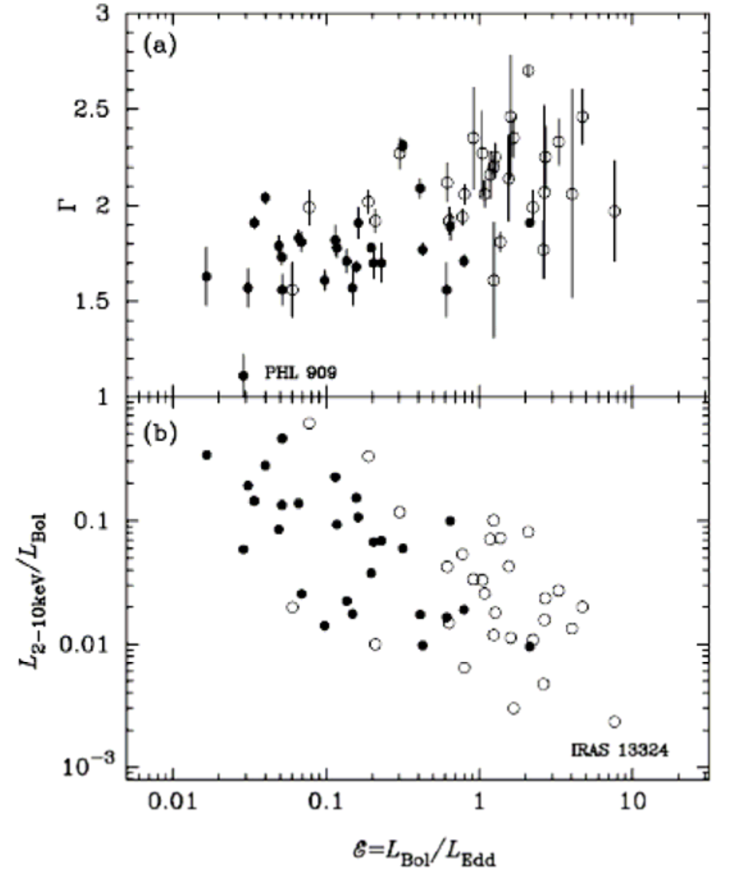


Fig. 1.—Plots of the hard X-ray spectrum index and the ratio of *ASCA* luminosity to bolometric luminosity vs. the Eddington ratio. The open and filled circles represent the NLS1s (FWHM Hβ < 2000 km s^{-1}) and the BLS1s, respectively. The object IRAS 13324−3809 is an NLS1 with FWHM(Hβ) = 620 km s^{-1} and 2–10 keV luminosity 10^{43} ergs s^{-1} much fainter than its $M_B = -24.2$ (Véron-Cetty & Véron's catalog), with $m_{\rm BH} = 10^{6.95}$, the ratio $L_{2-10\,{\rm keV}}/L_{\rm Edd} \sim 10^{-3}$, and $L_{\rm bol}/L_{\rm Edd} \sim 10^{0.88}$.

Wang, Watarai, Mineshige, 2004, ApJ, 607, L107

3. Correlation between hard X-ray spectral index Γ and Compton reflection R

$R = \Omega / 2\pi$, where Ω is the solid angle of the reflector ($\Omega = 1$ for the reflection from a semi-infinite plane).

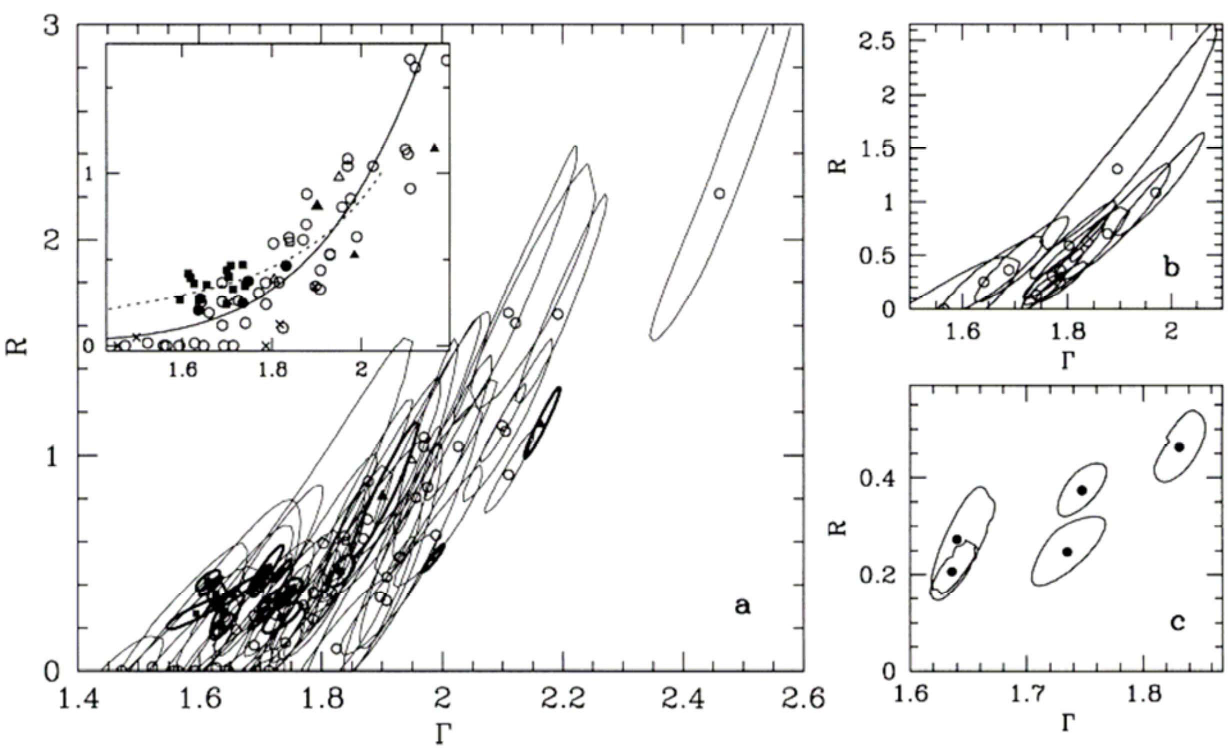


Figure 1. The $R(\Gamma)$ correlation in Seyferts and X-ray binaries in the hard state. Panel (a) shows the data and models (curves in the inset); see Sections 2 and 4, respectively. Examples of the correlation for NGC 5548 and GX 339-4 are shown in panels (b) and (c) respectively.

Zdziarski A. A., Lubinski P., Smith D. A., 1999, MNRAS, 303, L11

Accretion disk-corona model

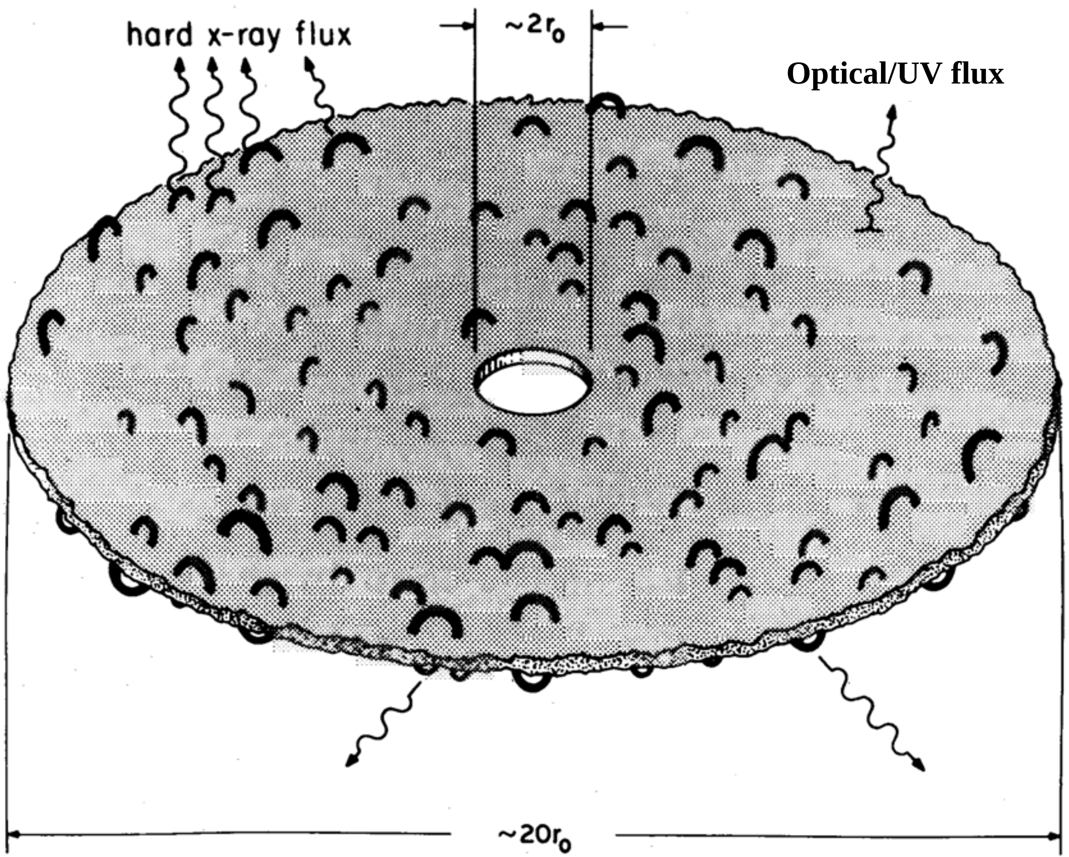
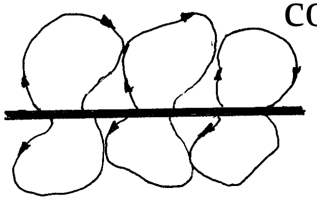
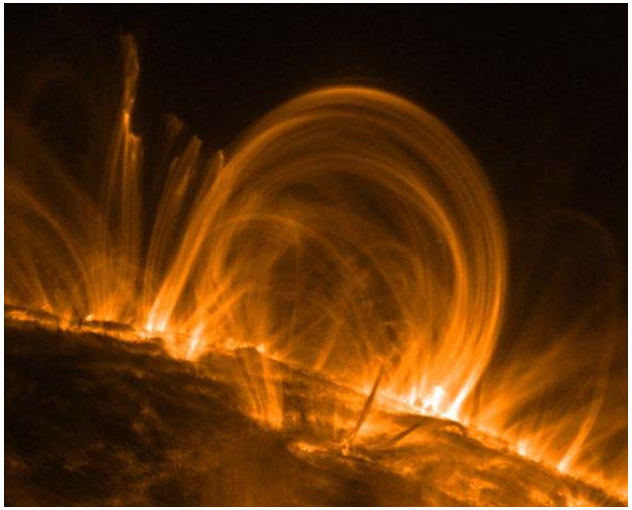


FIG. 3.—Schematic drawing of the inner accretion disk coronal geometry,





Growing loops around a sunspot.

Taken from Galeev A. A., Rosner R., Vaiana G. S., 1979, ApJ, 229, 318.

In the disk-corona model, the magnetic fields generated in the cold disc are strongly buoyant, and a substantial fraction of magnetic energy is transported vertically to heat the corona above the disc with the reconnection of the fields (e.g., Di Matteo 1998).

The key point for constructing a disk-corona model is:

the strength of the magnetic fields, which determines the efficiency of the energy transportation from the disk to corona.

Magnetic fields in the disks

Possible options for magnetic stress tensor:

a. $\tau_{r\varphi} = \frac{B^2}{8\pi} = \alpha p_{\rm tot}, (p_{\rm tot} = p_{\rm gas} + p_{\rm rad})$ **is adopted in standard thin disk model (Shakura & Sunyaev 1973), which is thermal unstable.**

b. $\tau_{r\varphi} = \frac{B^2}{8\pi} = \alpha p_{\rm gas}$ **, the modified alpha-viscosity, which is thermal stable.**

c. $\tau_{r\varphi} = \frac{B^2}{8\pi} = \alpha \sqrt{p_{\rm gas} p_{\rm tot}}$**, which is initially suggested by Taam &Lin (1984) based on the viscosity being proportional to the gas pressure while the size of turbulence being limited by the disk thickness (given by the total pressure). It's thermal stable.**

$\tau_{r\varphi} = \frac{B^2}{8\pi} = \alpha \sqrt{p_{\rm gas} p_{\rm tot}}$ **is also supported by the analysis on the local dynamical instabilities in magnetized, radiation-pressure-supported accretion disks (Blaes & Socrates 2001).**

The disk-corona model

The gravitational power released in the disk is (in unit surface area)

$$Q^{+}_{\rm dissi} = \frac{3}{8\pi}\dot{M}\Omega_K(R)^2\left[1-\left(\frac{R_{\rm in}}{R}\right)^{1/2}\right]$$

The power transported from the cold disk to the corona is

$$Q^{+}_{\rm cor} = p_{\rm m}v_{\rm p} \approx \frac{B^2}{8\pi}v_{\rm A}$$

The energy equation for the cold disk:

$$Q^{+}_{\rm dissi} - Q^{+}_{\rm cor} + \frac{1}{2}(1-a)Q^{+}_{\rm cor} = \frac{4\sigma T^4_{\rm disk}}{3\tau},$$

where the reflection albedo $a = 0.1 - 0.2$, and τ is the optical depth of the cold disk.

The equations describing the cold disk:

Continuity:

$$-4\pi R H_{\mathrm{d}}(R)\rho(R)v_{\mathrm{R}}(R) = \dot{M}$$

Equation of state:

$$p_{\mathrm{tot}} = p_{\mathrm{gas}} + p_{\mathrm{rad}} = \frac{\rho k T_{\mathrm{disk}}}{\mu m_{\mathrm{p}}} + \frac{1}{3} a T_{\mathrm{disk}}^{4}$$

Angular momentum:

$$\dot{M}\Omega_{\mathrm{K}}(R)\left[1+\left(\frac{R_{\mathrm{in}}}{R}\right)^{1/2}\right] = 4\pi H_{\mathrm{d}}\tau_{r\varphi}$$

The magnetic stress tensors:

$$\tau_{r\varphi} = p_{\mathrm{m}} = \begin{cases} \alpha p_{\mathrm{tot}} \\ \alpha p_{\mathrm{gas}} \\ \alpha\sqrt{p_{\mathrm{gas}} p_{\mathrm{tot}}} \end{cases}$$

The ratio of the power radiated from the corona to the total (bolometric luminosity) for the disk-corona system is

$$\langle f \rangle = \frac{\int Q_{\mathrm{cor}}^{+} 2\pi R \mathrm{d}R}{\int Q_{\mathrm{dissi}}^{+} 2\pi R \mathrm{d}R}$$

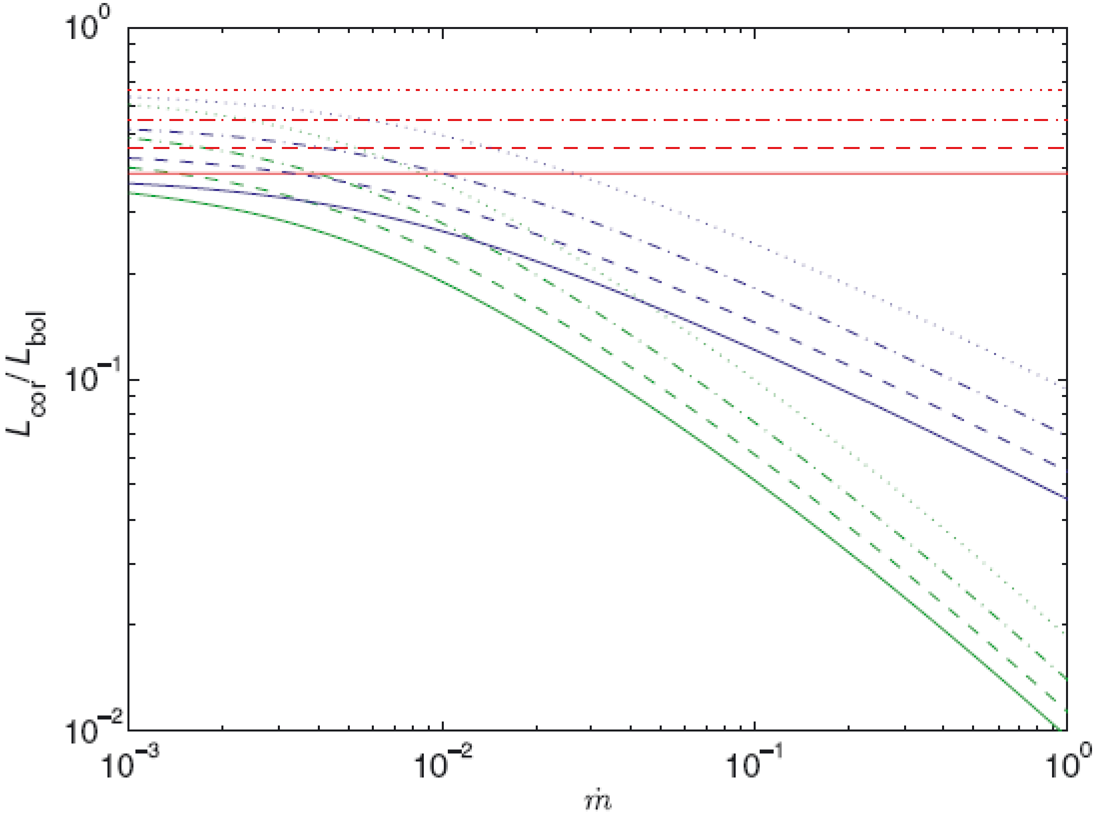


Figure 1. The ratios $L_{\rm cor}/L_{\rm bol}$ as functions of accretion rate $\dot{m}$ predicted by the models with different magnetic stress tensors. The red lines represent the results calculated with the magnetic stress tensor $\tau_{r\varphi} = \alpha p_{\rm tot}$ (green lines: $\tau_{r\varphi} = \alpha p_{\rm gas}$; blue lines: $\tau_{r\varphi} = \alpha\sqrt{p_{\rm gas} p_{\rm tot}}$). The different line types represent the different values of viscosity parameter α adopted (solid lines: $\alpha = 0.2$; dashed lines: $\alpha = 0.3$; dash–dotted lines: $\alpha = 0.5$ and dotted lines: $\alpha = 1$).

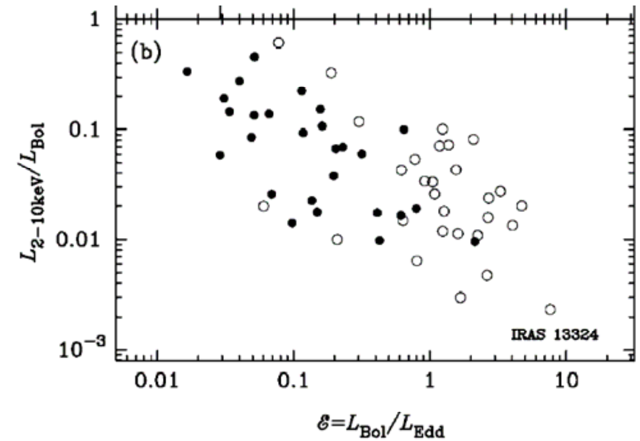


FIG. 1.—Plots of the hard X-ray spectrum index and the ratio of *ASCA* luminosity to bolometric luminosity vs. the Eddington ratio. The open and filled circles represent the NLS1s (FWHM Hβ < 2000 km s^{-1}) and the BLS1s, re-

Ruled out!

red: $\tau_{r\varphi} = \alpha p_{\rm tot}$

green: $\tau_{r\varphi} = \alpha p_{\rm gas}$

blue: $\tau_{r\varphi} = \alpha\sqrt{p_{\rm gas} p_{\rm tot}}$

Calculation of the spectrum of the corona

The equations of the corona:

Equation of state: $$p_{\mathrm{cor}} = \frac{\rho_{\mathrm{cor}} k T_{\mathrm{i}}}{\mu_{\mathrm{i}} m_{\mathrm{p}}} + \frac{\rho_{\mathrm{cor}} k T_{\mathrm{e}}}{\mu_{\mathrm{e}} m_{\mathrm{p}}} + p_{\mathrm{cor,m}}$$

Energy equation: $$Q_{\mathrm{cor}}^{+} = Q_{\mathrm{cor}}^{\mathrm{ie}} + \delta Q_{\mathrm{cor}}^{+} = F_{\mathrm{cor}}^{-},$$

where the cooling rate $F_{\mathrm{cor}}^{-} = F_{\mathrm{syn}}^{-} + F_{\mathrm{brem}}^{-} + F_{\mathrm{Comp}}^{-}$, and $Q_{\mathrm{cor}}^{\mathrm{ie}}(T_{\mathrm{i}}, T_{\mathrm{e}}, \rho_{\mathrm{cor}})$ is the energy transfer rate from the ions to electrons via Coulomb collisions.

$$Q_{\mathrm{cor}}^{\mathrm{ie}} = 1.5 \sum_{Z} \frac{m_{\mathrm{e}}}{m_{\mathrm{p}} A_Z} Z^2 n_{\mathrm{e}} n_Z H_{\mathrm{cor}} \sigma_{\mathrm{T}} c \frac{kT_{\mathrm{i}} - kT_{\mathrm{e}}}{K_2(1/\Theta_{\mathrm{e}}) K_2(1/\Theta_Z)} \ln \Lambda$$
$$\times \left[\frac{2(\Theta_{\mathrm{e}} + \Theta_Z)^2 + 1}{\Theta_{\mathrm{e}} + \Theta_Z} K_1 \left(\frac{\Theta_{\mathrm{e}} + \Theta_Z}{\Theta_{\mathrm{e}} \Theta_Z} \right) + 2 K_0 \left(\frac{\Theta_{\mathrm{e}} + \Theta_Z}{\Theta_{\mathrm{e}} \Theta_Z} \right) \right],$$

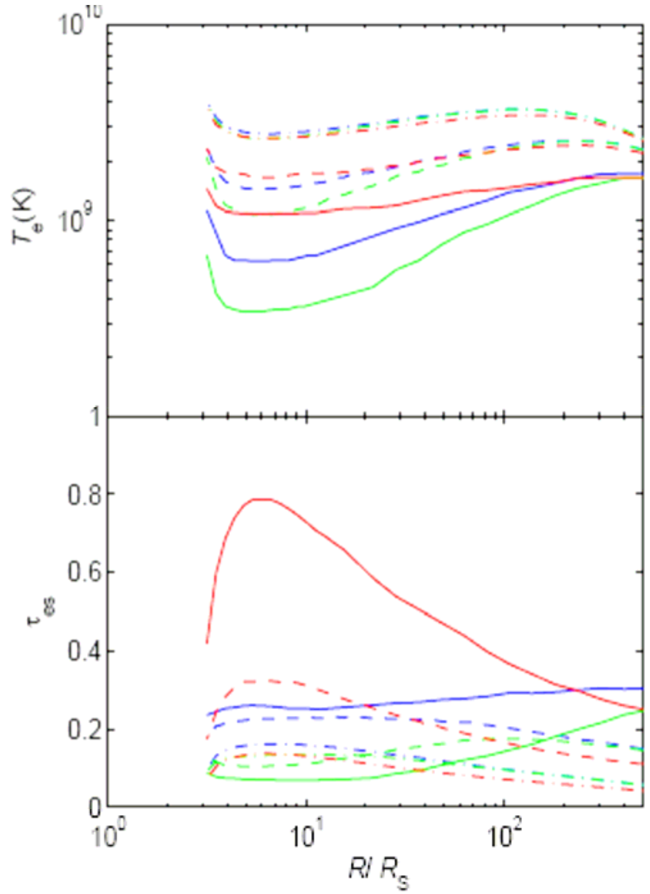


Figure 2. The upper panel: the temperature of the electrons in the corona as functions of disc radius R. The colours represent the models with different magnetic stress tensors, which are the same as those in Fig. 1. The solid lines represent the results calculated for $\dot{m} = 0.5$, while the dashed and dash-dotted lines are for $\dot{m} = 0.05$ and 0.005, respectively. The viscosity parameter $\alpha = 0.5$ is adopted for all the model calculations. In the lower panel, we plot the optical depth for the Compton scattering of the electrons in the vertical direction of the corona.

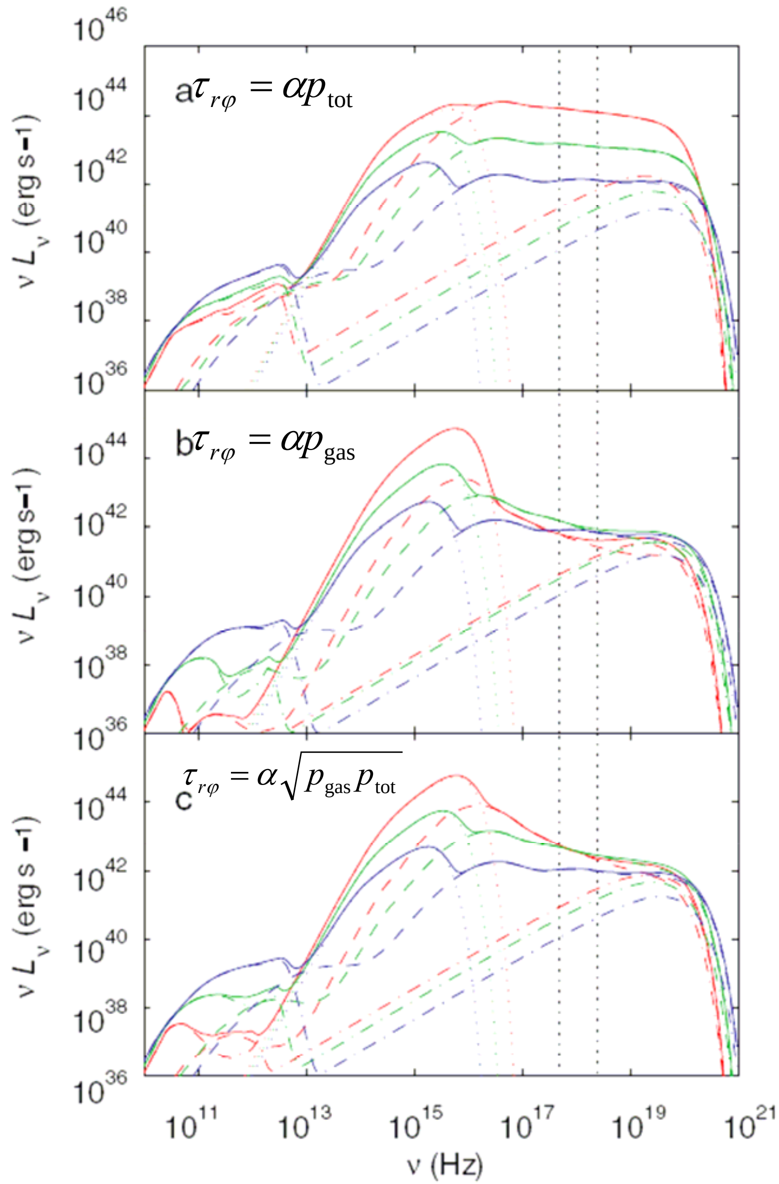


Figure 3. The spectra of the disc-corona systems with different magnetic stress tensors (a: $\tau_{r\varphi} = \alpha p_{\rm tot}$; b: $\tau_{r\varphi} = \alpha p_{\rm gas}$; c: $\tau_{r\varphi} = \alpha\sqrt{p_{\rm gas}p_{\rm tot}}$). In all the calculations, $\alpha = 0.5$ is adopted. The dotted lines represent the

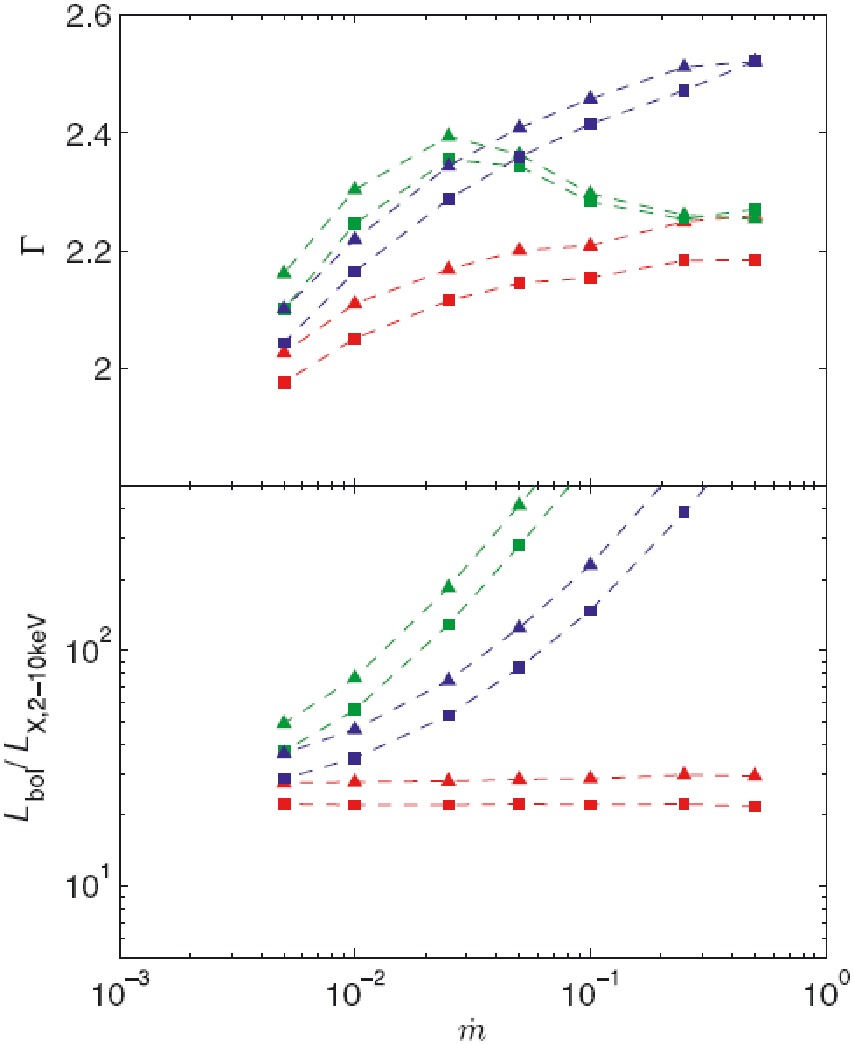
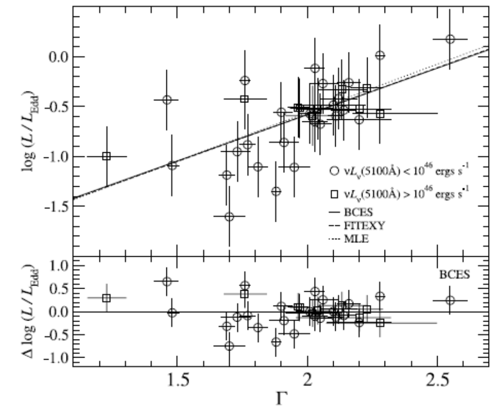
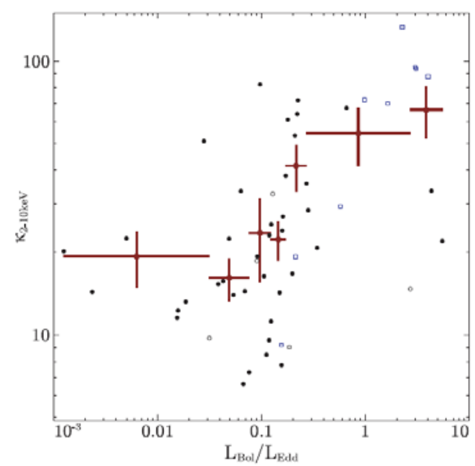


Figure 4. The upper panel: the photon spectral indices as functions of accretion rate $\dot{m}$ for different magnetic stress models (red: $\tau_{r\varphi} = \alpha p_{\rm tot}$; green: $\tau_{r\varphi} = \alpha p_{\rm gas}$; blue: $\tau_{r\varphi} = \alpha\sqrt{p_{\rm gas} p_{\rm tot}}$). The squares represent the results calculated with $\alpha = 0.5$, while the triangles are for $\alpha = 0.3$. The





Vasudevan R. V., Fabian A. C., 2007, MNRAS, 381, 1235

red: $\tau_{r\varphi} = \alpha p_{\rm tot}$ → ***Ruled out!***

green: $\tau_{r\varphi} = \alpha p_{\rm gas}$ → ***Ruled out!***

blue: $\tau_{r\varphi} = \alpha\sqrt{p_{\rm gas} p_{\rm tot}}$

Summary

1. $\tau_{r\phi} = \alpha(p_{gas} p_{tot})^{1/2}$ **is roughly consistent with the X-ray observations, while the other two are not.**

2. $L_{\rm cor} / L_{\rm bol}$ **decreases with increasing** $L_{\rm bol} / L_{\rm Edd}$**. It means more soft photons supplied by the cold disk for high-**$L_{\rm bol} / L_{\rm Edd}$ **cases, and the corona is therefore cooled down more efficiently, which leads to lower electron temperatures and then softer X-ray spectra.**

3. **Our spectral calculations show that the X-ray spectrum is too softer when the accretion rate is as low as 0.01.**

   We suggest that the ADAF+disk/corona model may resolve this issue, because the photon spectral index of an ADAF can be as low as ~1.5.

4. The transition radius of the outer disk-corona to inner ADAF increases with decreasing accretion rate, which also predicts a correlation between the Compton reflection and X-ray photon spectral index.

Narayan, Mahadevan & Quataert: *Advection-Dominated Accretion* 23

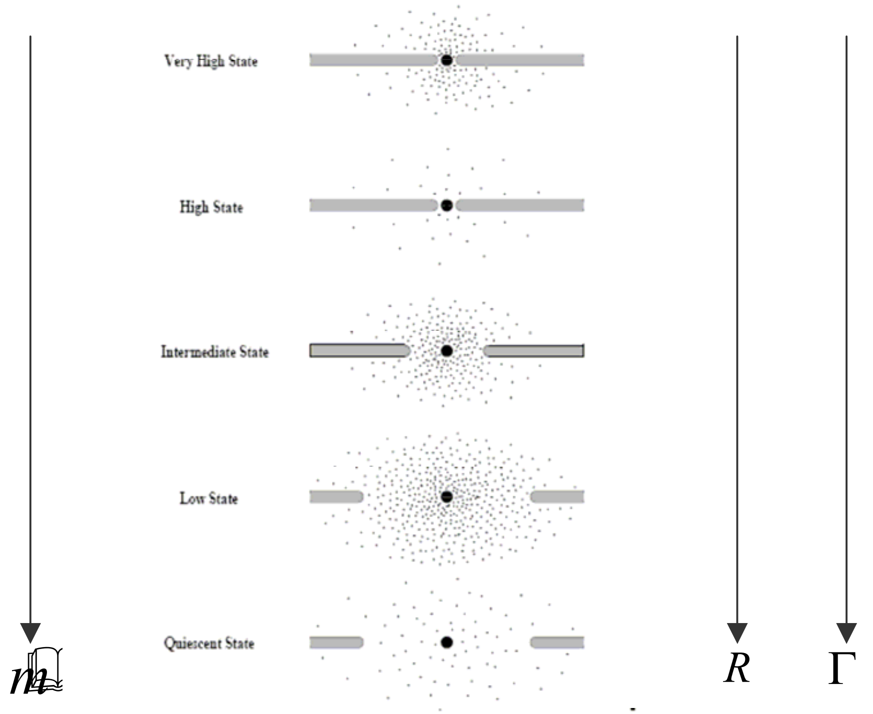
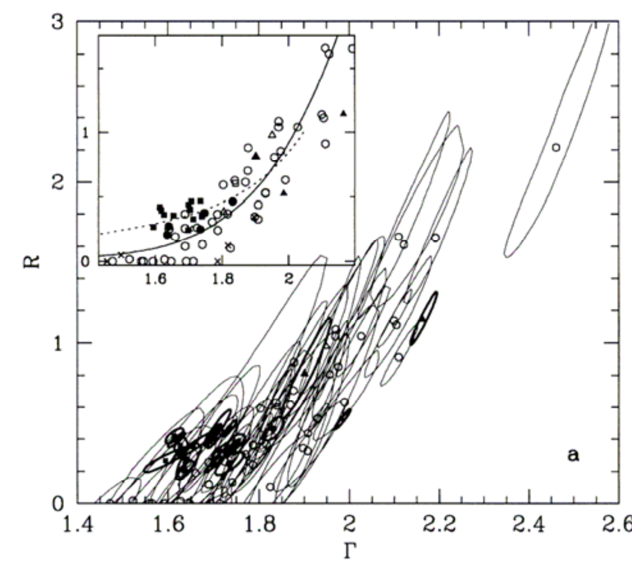


FIGURE 11. The configuration of the accretion flow in di... ically as a function of the total mass accretion rate $\dot{m}$ (f... indicated by dots and the thin disk by the horizontal ba... the quiescent state which corresponds to a low mass accre... density) and a large transition radius. The next panel



It is still ongoing, and will be reported in our future work.

Thank you!