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CONSTRAINING THE MAGNETIC FIELD IN THE ACCRETION FLOW OF LOW-LUMINOSITY ACTIVE GALACTIC NUCLEI

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ABSTRACT

Observations show that the accretion flows in low-luminosity active galactic nuclei (LLAGNs) probably have a two-component structure with an inner hot, optically thin, advection dominated accretion flow (ADAF) and an outer truncated cool, optically thick accretion disk. As shown by Taam et al. (2012), within the framework of the disk evaporation model, the truncation radius as a function of mass accretion rate is strongly affected by including the magnetic field. We define the parameter β as $p_{\rm m} = B^2/8\pi = (1-\beta)p_{\rm tot}$, (where $p_{\rm tot} = p_{\rm gas} + p_{\rm m}$, $p_{\rm gas}$ is gas pressure and $p_{\rm m}$ is magnetic pressure) to describe the strength of the magnetic field in accretion flows. It is found that an increase of the magnetic field (decreasing the value of β) results in a smaller truncation radius for the accretion disk. We calculate the emergent spectrum of an inner ADAF + an outer truncated accretion disk around a supermassive black hole by considering the effects of the magnetic field on the truncation radius of the accretion disk. By comparing with observations, we found that a weaker magnetic field (corresponding to a bigger value of β) is required to match the observed correlation between $L_{\rm 2-10keV}/L_{\rm Edd}$ and the bolometric correction $\kappa_{\rm 2-10keV}$, which is consistent with the physics of the accretion flow with a low mass accretion rate around a black hole.

Key words: accretion: accretion disks— Black hole physics — galaxies: active — X-rays: galaxies

1. INTRODUCTION

Observations show that the accretion flows in low-luminosity active galactic nuclei (LLAGNs) are consistent with a two-component structure for the accretion flow, i.e., an inner hot, optically thin, advection dominated accretion flow (ADAF) plus an outer cool, optically thick truncated accretion disk (Ho 2009 and the references therein). The evidence for the presence of an inner ADAF in LLAGNs is inferred from the very low luminosity and the very low radiative efficiency estimated from the available mass supply rate (Ho 2009). The evidence for the truncation of the accretion disk in LLAGNs is inferred from the lack of a 'big blue bump', instead of a 'big red bump' (Nemmen et al. 2014). The very weak or absent broad iron K_α line, which is attributed to X-ray fluorescence from an optically thick accretion disk extending down to a few Schwarzschild radii of a luminous AGNs, also supports the truncation of the accretion disk at larger radius ($\sim 100-1000$ Schwarzschild radii) from the black hole in LLAGNs (Nandra et al., 2007).

In this work, based on the prediction by Taam et al. (2012) for the truncation of the accretion disk, the emergent spectrum of a two-component structure with an inner ADAF and an outer truncated accretion disk around a supermassive black hole is calculated. As shown by Taam et al. (2012), the truncation radius of the accretion disk is very sensitive to β, which consequently affects the emergent spectrum. Our calculations show that the equipartition of gas pressure to magnetic pressure, i.e., $\beta = 0.5$, fails to explain the observed anti-correlation between $L_{\rm 2-10keV}/L_{\rm Edd}$ and the bolometric correction $\kappa_{\rm 2-10keV}$ (with $\kappa_{\rm 2-10keV} = L_{\rm bol}/L_{\rm 2-10keV}$). The emergent spectra for larger values of $\beta = 0.8$ or $\beta = 0.95$ can explain the observed $L_{\rm 2-10keV}/L_{\rm Edd}$-$\kappa_{\rm 2-10keV}$ correlation well. In Section 2, we briefly introduce the disk-evaporation model. The observational constrains for the magnetic field parameter β in LLAGNs are presented in Section 3. Section 4 is the conclusion.

2. THE DISK-EVAPORATION MODEL— THE EFFECTS OF β ON THE TRUNCATION RADIUS OF THE ACCRETION DISK

In the disk-evaporation model, due to the effect of evaporation, mass is accreted to the central black hole partially through the corona (evaporated part) and partially through the disk (the remaining part of the mass). The inflow and outflow of mass, energy, and angular momentum between neighboring zones were included in models by Meyer-Hofmeister & Meyer (2003). The effect of the viscosity parameter α was investigated by Qiao & Liu (2009), and the effect of the magnetic parameter β was studied by Qian et al. (2007). The spectral features of an inner ADAF and an outer truncated accretion disk predicted by the disk evaporation model in stellar-mass black holes were investigated by Qiao & Liu (2010, 2012, 2013). The model we used here is based on Liu & Taam (2009), in which the structure of the corona and the evaporation features are determined by the equation of state, equation of continuity, and equations of momentum and energy. The calculations show that the evaporation rate increases with decreasing distance in the outer region of the accretion disk, reaching a maximum value and then dropping towards the central black hole. Taam et al. (2012) generalized the results of the disk evaporation model for black hole X-ray binaries by including the effect of viscosity parameters α and magnetic parameter β in accretion disks around a supermassive black hole.

If the mass supply rate is less than the maximum evaporation rate, the matter in the inner region of the disk will be fully evaporated to form a geometrically thick, optically thin accretion inner region, which is generally called advection-dominated accretion flow (ADAF). The truncation radius of the disk can be generalized as (Taam et al., 2012),

$$r_{\rm tr} \approx 17.3\dot{m}^{-0.886}\alpha^{0.07}\beta^{4.61}, \quad (1)$$

where $\dot{m}$ is the mass supply rate from the most outer region of the accretion disk. If α, β and $\dot{m}$ are specified, we can self-consistently obtain the two-component structure of the accretion flow with an inner ADAF and an outer truncated accretion disk.

3. CONSTRAINING β FROM $L_{2-10\rm keV}/L_{\rm Edd}$-$\kappa_{2-10\rm keV}$ CORRELATION

We collected a sample composed of 10 LLAGNs, including NGC 1097, NGC 3031, NGC 4203, NGC 4261, NGC 4374, NGC 4450, NGC 4486, NGC 4579, NGC 4594 and NGC 6251 with 2-10 keV luminosity $L_{2-10\rm keV}$ measurements and bolometric luminosity measurements from Ho (2009). The bolometric luminosity was obtained by integrating the interpolated SEDs shown in Ho (1999) and Ho et al. (2000). The black hole masses were also collected by Ho (1999) and Ho (2000). The bolometric correction $\kappa_{2-10\rm keV}$ as a function of $L_{2-10\rm keV}/ L_{\rm Edd}$ is plotted with the $\diamondsuit$ sign in Figure 1. Ho (2009) conservatively estimated that the errors of $L_{\rm bol}/L_{2-10\rm keV}$ for the sources in the sample should be within 0.3 dex. The best-fitting linear regression for the correlation between $\kappa_{2-10\rm keV}$ and $L_{2-10\rm keV}/ L_{\rm Edd}$ is plotted with the dotted-line in Figure 1.

We calculate the emergent spectra predicted by a disk evaporation model for a two-component structure composed of an inner ADAF and a truncated accretion disk around a supermassive black hole with mass M when the parameters, including $\dot{m}$, α and β, are specified. In the calculation, we fix the central black hole mass at $M = 10^8 M_\odot$, assuming a viscosity parameter of $\alpha = 0.3$, as adopted by Taam et al. (2012) for the spectral fits to LLAGNs. By integrating the emergent spectrum, we calculate the 2-10 keV luminosity $L_{2-10\rm keV}$ and the bolometric luminosity $L_{\rm bol}$, with which we can calculate $\kappa_{2-10\rm keV}$ and $L_{2-10\rm keV}/ L_{\rm Edd}$.

Fixing $\beta = 0.8$, taking $M = 10^8 M_\odot$ and assuming $\alpha = 0.3$, for $\dot{m} = 0.01, 0.005, 0.003, 0.001$, $\kappa_{2-10\rm keV}$ as a function of $L_{2-10\rm keV}/L_{\rm Edd}$ is plotted with a solid red line in Figure 1. In order to check the effect of the black hole mass on the $L_{2-10\rm keV}/L_{\rm bol}$ - $\kappa_{2-10\rm keV}$ correlation, we take different black hole masses for comparisons. For $M = 10^6 M_\odot$, $\kappa_{2-10\rm keV}$ as a function of $L_{2-10\rm keV}/L_{\rm bol}$ is plotted with a solid black line in Figure 1. For $M = 10^9 M_\odot$, $\kappa_{2-10\rm keV}$ as a function of $L_{2-10\rm keV}/L_{\rm bol}$ is plotted with a solid blue line in Figure 1. It can be seen that the effect of the black hole mass on $L_{2-10\rm keV}/L_{\rm Edd}$ - $\kappa_{2-10\rm keV}$ the correlation is very weak. As an extreme example, we also plot $L_{2-10\rm keV}/L_{\rm Edd}$ - $\kappa_{2-10\rm keV}$ correlation for $\beta = 0.95$ in Figure 1. The red long-dashed, black long-dashed, blue long-dashed lines are for $M = 10^8 M_\odot$, $M = 10^6 M_\odot$ and $M = 10^9 M_\odot$ respectively.

Fixing $\beta = 0.5$, taking $M = 10^8 M_\odot$ and assuming $\alpha = 0.3$, for $\dot{m} = 0.01, 0.005, 0.003, 0.001$, $\kappa_{2-10\rm keV}$ as a function of $L_{2-10\rm keV}/L_{\rm Edd}$ is plotted with a red short-dashed line in Figure 1. The bolometric correction $\kappa_{2-10\rm keV}$ as a function of $L_{2-10\rm keV}/L_{\rm Edd}$ for $M = 10^6 M_\odot$ is plotted with a black short-dashed line in Figure 1, and for $M = 10^9 M_\odot$ is plotted with a blue short-dashed line in Figure 1.

From Figure 1, it is clear that the bolometric correction strongly depends on β. The $L_{2-10\rm keV}$ $/L_{\rm bol}$ - $\kappa_{2-10\rm keV}$ correlation predicted by $\beta = 0.8$ or $\beta = 0.95$ can explain the observations well, while the prediction by $\beta = 0.5$ severely deviates from the observations. Although our model for larger β can roughly interpret the $L_{2-10\rm keV}$ $/L_{\rm bol}$ - $\kappa_{2-10\rm keV}$ correlation, a few sources still lie below the model line. This may be because, in this work, for simplicity, we assume that outside the truncation radius the accretion flow exists in the form of a pure standard accretion disk. However, according to the disk evaporation model, outside the truncation radius the matter should be in the form of a "disk+corona", but not a pure stand accretion disk. The emission from the corona will result in an increase of the X-ray emission, which will make the bolometric correction decrease. Consequently, the model-predicted $\kappa_{2-10\rm keV}$ will systematically shift downward. We also need to keep in mind that, due to the inner ADAF dominating the X-ray emission, the emission contribution from the outer corona to the bolometric correction will be very small, so the data still support a bigger value of $\beta = 0.8$ or $\beta = 0.95$.

4. CONCLUSIONS

We calculated the emergent spectrum of an inner ADAF + an outer truncated accretion disk around a supermassive black hole by considering the effect of the magnetic field on the truncation radius of the accretion disk. As shown by Taam et al. (2012), the truncation radius of

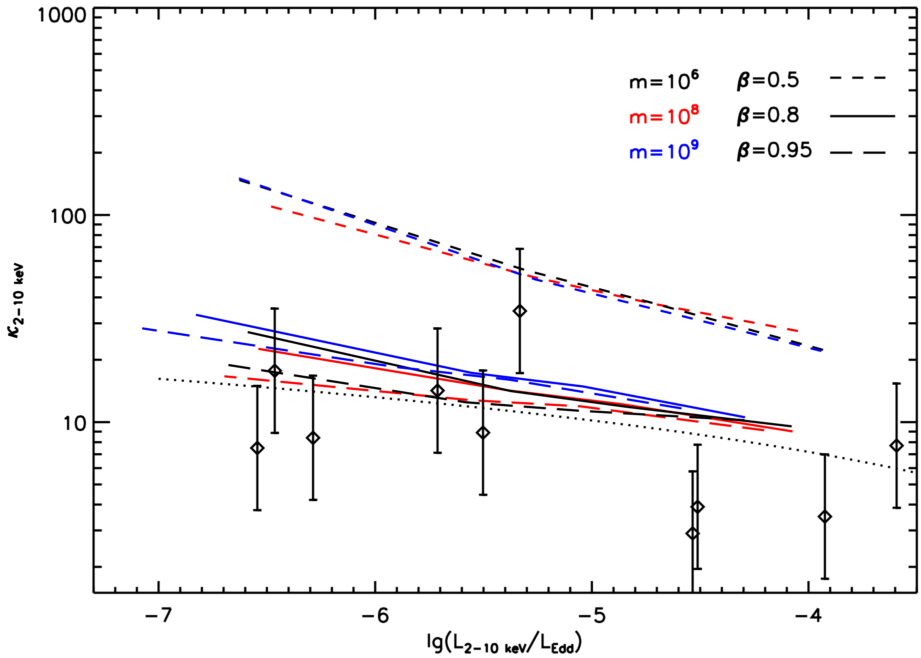

Figure 1. Bolometric correction $\kappa_{2-10\mathrm{keV}}$ as a function of $L_{2-10\mathrm{keV}}/L_{\mathrm{Edd}}$. The short-dashed line is for $\beta = 0.5$, the solid line is for $\beta = 0.8$ and the long-dashed line is for $\beta = 0.95$. The black line is for $M = 10^6 M_\odot$, red line is $M = 10^8 M_\odot$ and the blue line is for $M = 10^9 M_\odot$. In all the calculation, $\alpha = 0.3$ is adopted. The sign ◇ is the observed data, including NGC 1097, NGC 3031, NGC 4203, NGC 4261, NGC 4374, NGC 4450, NGC 4486, NGC 4579, NGC 4594 and NGC 6251 with 2-10 keV luminosity $L_{2-10\mathrm{keV}}$ measurement and bolometric luminosity measurement from Ho (2009).

the accretion disk is sensitive to the magnetic parameter β, which consequently affects the emergent spectrum. Our calculations show that the equipartition of gas pressure to magnetic pressure, i.e., $\beta = 0.5$, failed to explain the observed anti-correlation between $L_{2-10\mathrm{keV}}/L_{\mathrm{Edd}}$ and the bolometric correction $\kappa_{2-10\mathrm{keV}}$. The resulting spectra for larger values of $\beta = 0.8$ or $\beta = 0.95$ can better explain the observed $L_{2-10\mathrm{keV}}/L_{\mathrm{Edd}}$-$\kappa_{2-10\mathrm{keV}}$ correlation. We conclude that a weak magnetic field is preferred in the accretion flow of LLAGNs, which is reasonable for accretion with a low mass accretion rate. Coulomb heating is the dominant heating mechanism for the electrons only if the magnetic field is strongly sub-equipartition, which is roughly consistent with observations.

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