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Radiative feedback of low-$L_{\rm bol}/L_{\rm Edd}$ AGNs

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Abstract. AGN feedback, through either radiation or kinematics by expelled medium, plays a crucial role in the coevolution of supermassive black hole (SMBH) and its host galaxy. The nuclei spend most of their time as low-luminosity AGNs (LLAGNs), whose spectra are distinctive to bright AGNs, and the feedback is the hot mode (also named kinetic mode). We thus investigate the radiative heating in the hot mode. We calculate the value of "Compton temperature" $T_{\rm C}$, which defines the heating capability of the radiation at given flux, and find that $T_{\rm C} \sim (5-15) \times 10^7$ K, depending on the spectrum of individual LLAGNs. This work provides a cheap way to include the radiative heating of LLAGNs in the study of AGN feedback.

Keywords. galaxies: Seyfert — galaxies: evolution — accretion, accretion disks

1. Introduction

The co-evolution of the supermassive black hole and its host galaxy is now widely believed to be due to the feedback by the active galactic nuclei (AGNs) (for reviews, Fabian 2012; Kormendy & Ho 2013; Heckman & Best 2014). Accretion onto the supermassive black hole in the galactic center will possibly produce three ingredients, i.e. jet, wind and radiation. These outputs will interact with the interstellar medium (ISM) in the host galaxy, by transferring their momentum and energy to the ISM. The gas will then be heated up or pushed away from the black hole. On one hand, the changes in the temperature and density of the gas will affect the star formation and galaxy evolution. On the other hand, they will also affect the fueling of the black hole by changing the accretion rate, thus the radiation and matter output of accretion and the growth of the black hole mass.

Two feedback modes have been identified, which correspond to two accretion modes (Fabian 2012; Kormendy & Ho 2013; Yuan *et al.* 2018). One is called the cold mode (or more commonly the radiative mode), which operates when the black hole accretes at a significant fraction of the Eddington rate. In this case, the accretion flow is a cold geometrically thin disk and the corresponding AGNs are luminous. The other mode is called the hot mode (or more commonly the kinetic mode), when the black hole accretes at a low accretion rate. In this case, the accretion flow is described by a hot accretion flow (Yuan & Narayan 2014). The corresponding AGNs are called low-luminosity AGNs (LLAGNs). This is directly analogy with the soft and hard states of black hole X-ray binaries (BHBs), where the boundary between the two modes is $L_{\rm bol} \sim (1-2)\% L_{\rm Edd}$, where $L_{\rm bol}$ is the bolometric luminosity and $L_{\rm Edd}$ is the Eddington luminosity.

In the hot mode of feedback, all three types of output exist. Among them, jet is perhaps most widely considered in the study, mainly because observationally jets are most evident (e.g., Ho 2008). The wind is also considered (e.g., Ciotti *et al.* 2010), which helps to rapid reddening of moderately massive galaxies without expelling too many baryons (Weinberger *et al.* 2017).

The radiative heating in hot feedback mode of LLAGNs is ignored by most previous work (but see, e.g., Ciotti & Ostriker 2001; Ciotti *et al.* 2010; Ostriker *et al.* 2010; Gan *et al.* 2014, 2019). However, we argue it is an oversimplification based on the following reasons. First, the luminosity of a hot accretion flow covers a very wide range depending on the accretion rate and can be moderately high. For example, the radiative efficiency of hot accretion flow can be fairly high (Xie & Yuan 2012), with the highest luminosity of hot accretion flow can be $L_{\rm bol} \sim (2{-}10)\%\ L_{\rm Edd}$ (e.g., Done *et al.* 2007 for the case of BHBs in hard state). Second, the spectrum of LLAGNs is distinctive to that of luminous AGNs (Ho 2008), i.e. LLAGNs lack the big blue bump and LLAGNs are more prominent in X-rays. LLAGNs are thus expected to be more effective in radiative heating than bright AGNs (assuming the same bolometric luminosity), see Equation 1.1 below.

Radiative heating mainly includes two processes, one is through photoionization and the other (the focus of this work) is through Compton scattering. The Compton heating rate per unit volume can be evaluated as,

$$q_{\rm Comp} = n^2 \ \frac{n_e}{n} \ \frac{k\sigma_T}{\pi m_{\rm e} c^2} \ \frac{L_{\rm bol}}{nR^2} \ (T_{\rm C} - T_{\rm e}). \tag{1.1}$$

Here all the symbols are of their normal meanings, $L_{\rm bol}/4\pi R^2$ is the radiative intensity at distance R. The "Compton temperature" $T_{\rm C}$ is determined by the energy-weighted average energy of the emitted photons from LLAGNs (Sazonov *et al.* 2004). The Compton temperature of typical luminous AGNs is $T_{\rm C} \approx 2 \times 10^7$ K (Sazonov *et al.* 2004).

We calculate the value of $T_{\rm C}$ of LLAGNs. For this aim, we in §2 combine the data from the literature to obtain the broadband spectral energy distribution (SED) of LLAGNs. Special attention will be paid to the hard X-ray spectrum since this is the most important part in the spectrum for heating. The Compton temperature and its applications are given in §3. The final section is devoted to discussions and a short summary.

2. Broadband SED of LLAGNs

It is quite challenging to obtain the "average" broadband SED of LLAGNs. Various sample selection and normalization methods have been developed in literature (e.g. Ho 2008; Winter *et al.* 2009; Eracleous *et al.* 2010). As shown in Fig. 1, we adopt the composite SED of LLAGNs from Ho (2008), which has a relatively broad coverage in photon energy, i.e. from radio to soft X-rays ($E \lesssim 10\,$keV). We include three sets of SEDs with different ranges of Eddington ratio $\lambda \equiv L_{\rm bol}/L_{\rm Edd}$, i.e. $\lambda < 10^{-3}$, $10^{-3} < \lambda < 10^{-1}$, and $10^{-1} < \lambda < 1$. For comparison, the composite SED averaged over Type 1 and Type 2 AGNs compiled by Sazonov *et al.* (2004) is also shown here by the black solid curve.

The spectrum from the hard X-ray to soft γ-ray regime ($E = h\nu > 10\,$keV, where ν is the frequency), crucial for the evaluation of $T_{\rm C}$, is absent in these composite SED data. We thus complete the SED of this energy range through a power law with an exponential cutoff (named the "cutoff PL"), i.e. $F_E \propto E^{1-\Gamma} \exp(-E/E_{\rm c})$, where Γ is the photon index and $E_{\rm c}$ is the cutoff energy. Γ is better constrained. Both hot accretion theory and observations suggest that the X-ray emission becomes softer as it becomes fainter, i.e. LLAGNs follow a negative $\Gamma - L_{\rm X}/L_{\rm Edd}$ correlation, see Emmanoulopoulos *et al.* 2012; Soldi *et al.* 2014; Yang *et al.* (2015); Connolly *et al.* (2016).

The cutoff energy $E_{\rm c}$, on the other hand, is poorly constrained. This is because the sensitivity of most existing hard X-ray telescopes/instruments are not high enough to probe the low-luminosity AGNs. There are only limited sources with such measurements, where a negative $E_{\rm c} - L_{\rm X}/L_{\rm Edd}$ relationship is reported (for BHBs in hard state, see e.g., Miyakawa *et al.* 2008; for LLAGNs, see e.g., Ursini *et al.* 2016; Xie *et al.* 2017; Ricci *et al.* 2018). The game changer is *NuSTAR*, whose spectral resolution is also sufficiently high. Recent measurement on $E_{\rm c}$ by *NuSTAR* includes Pahari *et al.* (2017); Zoghbi *et al.* (2017);

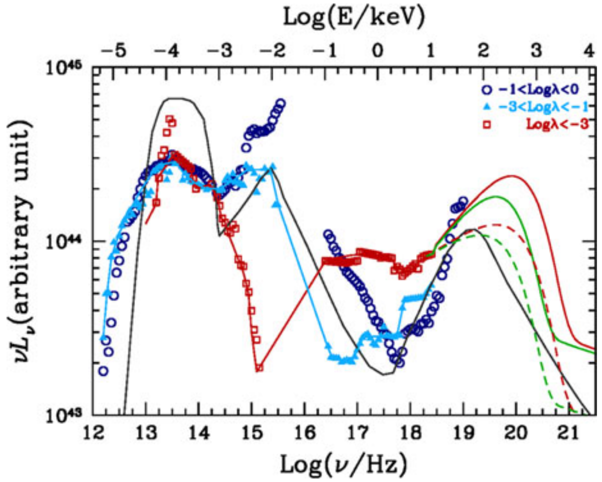

Figure 1. Composite SED of LLAGNs. We include three sets of SEDs with different ranges of Eddington ratio, i.e. $\lambda < 10^{-3}$ (red), $10^{-3} < \lambda < 10^{-1}$ (sky blue), and $10^{-1} < \lambda < 1$ (blue). For comparison, the composite SED averaged over Type 1 and Type 2 AGNs compiled by Sazonov *et al.* (2004) is also shown by the black solid curve. Above 10 keV the SED is completed by a power-law with exponential cutoff. Taken from Xie *et al.* (2017).

Rani *et al.* (2019); Younes *et al.* (2019). With existing data, we may crudely suggest that LLAGNs have $E_{\rm c}$ $300-500$ keV. Note that this value is somewhat smaller than that adopted in Xie *et al.* (2017). We complete the SED of this energy range through the cutoff PL (normalized at $E = 10$ keV), based on our knowledge of Γ and $E_{\rm c}$. Additional weak tail due to jet emission above $2E_{\rm c}$ is also taken into account. The final SED used in this work is shown in Figure 1.

One additional key uncertainty in the composite SED is the origin of infrared (IR) emission, i.e. it may come from the dusty torus, the circum-nuclear star formation, the central AGN (including the accretion disk, the jet, and sometimes the narrow-line emission clouds), or their combination. It is obviously difficult to discriminate the possible contaminations. Observations with high spatial resolution and sufficient sensitivity are crucial. Over past decades, extensive efforts have been made through infrared interferometric techniques (e.g., Asmus *et al.* 2011, 2014; González-Martí *et al.* 2015, 2017), but the contaminations are still difficult to constrain (e.g. Asmus *et al.* 2011, 2014).

One key progress in IR observations is that, the nuclear IR flux derived from arcsecond-scale resolution observations (e.g. typical resolution in mid-IR of *Spitzer* is $\sim 4''$) may be accurate within a factor of $\lesssim 2-8$, and the fraction of nuclei IR emission decreases with decreasing Eddington ratio λ (Asmus *et al.* 2011, 2014; González-Martí *et al.* 2017). This result is fairly robust.

3. Compton temperature of LLAGNs

In general, the photon energy from AGNs and/or the electrons to be scattered can be comparable to or even larger than $m_e c^2$. In this case, the Compton scattering process becomes complicated, and simplified Comptonization model may result in estimations that are inaccurate by orders-of-magnitude. Moreover, because of the strong coupling between electrons and photons, there is no exact definition of Compton temperature. We thus follow Guilbert (1986) to derive the accurate Compton heating rate and then use Equation 1.1 to evaluate the "effective" $T_{\rm C}$.

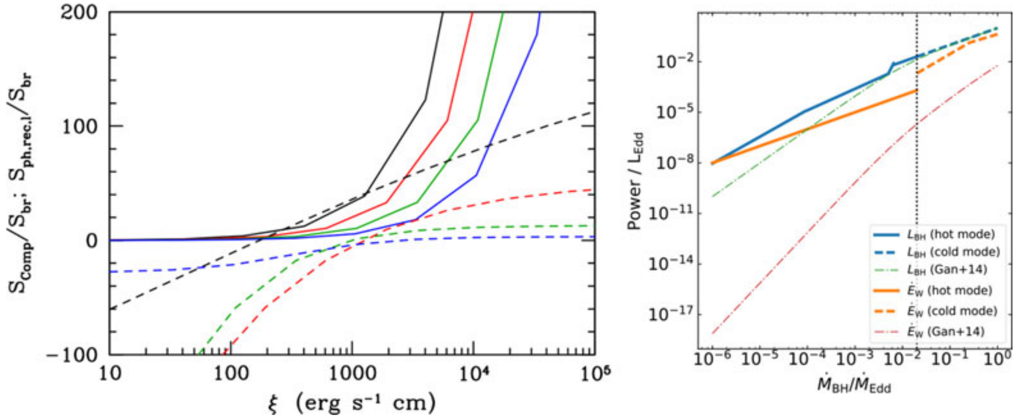

Figure 2. *Left panel:* Radiative heating/cooling versus ionization parameter ξ (solid for $S_{\rm comp}/S_{\rm br}$; dashed for $S_{\rm ph,rec,l}/S_{\rm br}$), from Xie *et al.* (2017). We set $T_{\rm C}=1\times10^8$ K. The color of each curve represents the temperature of electrons, i.e. $\log(T_{\rm e})=4.5$ (black), 5.0 (red), 5.5 (green), and 6.0 (blue). *Right panel:* Power of feedback of different components, taken from Yuan *et al.* (2018).

We first test our calculations for the $T_{\rm C}$ of the composite SED of bright AGNs by Sazanov et al. (2004), where good consistency is observed. We then apply our numerical calculations to other composite SEDs by Ho (2008), and find that $T_{\rm C}\approx(5{-}9)\times10^7$ K. Obviously, harder spectrum will higher $E_{\rm c}$ will result in higher $T_{\rm C}$. The dependence on electron temperature is weak, as long as these electrons are non-relativistic.

If we further consider the case of reducing IR emission by a factor of 10, then we have $T_{\rm C}\approx(1{-}2)\times10^8$ K, i.e. approximately a factor of $\sim$2 higher than that of normal IR case. Note that this value should be applied for the gas heating within the torus (i.e. at a distance $\lesssim 1$ kpc to the SMBH).

4. Summary and applications

The Compton scattering in principle plays a heating or cooling role, depending on the comparison between the photon energy and electron temperature of the gas. We adopt the composite SED of LLAGNs with different luminosities and calculate the "Compton temperature" $T_{\rm C}$. We find that $T_{\rm C}$ of LLAGNs is $\approx(5{-}9)\times10^7$ K outside of torus and $\approx(1{-}2)\times10^8$ K within it. This value is about 3−10 times that of bright AGNs.

In general there are three radiation sources. Among them, the Compton scattering ($S_{\rm Comp}$) usually plays a heating role, and the bremsstrahlung ($S_{\rm br}$) is always a cooling term. The photo-ionization, recombination and lines ($S_{\rm ph,rec,l}$), on the other hand, can be either a heating or a cooling term, depending on both the temperature and the ionization parameter ξ ($\xi=\frac{L_{\rm ion}}{nR^2}$, where the ionization luminosity is for photon energy between 13.6 eV and 13.6 keV.). In a given galaxy, ξ decreases with R (e.g., Tombesi *et al.* 2013). The left panel of Figure 2 illustrates these heating/cooling terms as a function of ξ, where we find that, depending on the electron temperature $T_{\rm e}$, the Compton heating dominates for $\xi\gtrsim3\times10^2\,{\rm erg\,s^{-1}\,cm}$.

The new measurement of $T_{\rm C}$ for the Compton heating has been applied in numerical simulations of AGN feedback in isolated elliptical galaxies over cosmic time (e.g., Yuan *et al.* 2018; Gan *et al.* 2019; Yoon *et al.* 2018), or in the investigation of AGN heating on small scales (e.g., Bu & Yang 2019a,b). In order to understand its relative importance, we show in the right panel of Figure 2 the power of different mechanisms as a function of accretion rate. The radiative heating ($L_{\rm BH}$ in the plot) dominates over the kinematic power ($\dot{E}_{\rm w}$ in the plot) in the hot accretion mode (Yuan *et al.* 2018; Gan *et al.* 2019; Yoon *et al.* 2019).

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