Radiative Heating in the Kinetic Mode of AGN Feedback

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Abstract

AGN feedback is now widely believed to play a crucial role in the co-evolution between the central black hole and its host galaxy. Two feedback modes have been identified, namely the radiative and kinetic modes, which correspond to the luminous AGNs and low-luminosity AGNs (LLAGNs), respectively. In this paper, we investigate the radiative heating in the kinetic mode. This process is potentially important because (1) the radiation power of LLAGNs is higher than the jet power over a wide parameter range, (2) the spectral energy distribution of LLAGNs is such that the radiative heating is more effective compared to that of luminous AGNs with the same luminosity, and (3) most of the time in the lifecycle of an AGN is spent in the LLAGNs phase. In this paper, adopting the characteristic broadband spectral energy distributions of LLAGNs, we calculate the value of “Compton temperature” ($T_C$), which determines the radiative heating by Compton scattering. We find that $T_C \sim (5–15) \times 10^7$ K, depending on the spectrum of individual LLAGNs and at which distance from the black hole we evaluate the heating. We also compare this heating process with other radiative heating and cooling processes such as photoionization/recombination. Our result can be used for an accurate calculation of the radiative heating in the study of AGN feedback.

Key words: accretion, accretion disks – galaxies: active – galaxies: Seyfert

1. Introduction

There is considerable observational evidence for the co-evolution of the supermassive black hole and its host galaxy, and the co-evolution is now widely believed to be due to active galactic nuclei (AGNs) feedback (e.g., Magorrian et al. 1998; Gebhardt et al. 2000; Fabian 2012; Kormendy & Ho 2013; Heckman & Best 2014). Accretion onto the supermassive black hole in the galactic center will produce both radiation and outflows. These outputs will interact with the interstellar medium (ISM) in the host galaxy, near or far from the black hole, by transferring their momentum and energy to the ISM. The gas will then be heated up or pushed away from the black hole. The changes in the temperature and density of the gas, on one hand, will obviously 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.

While this field is still relatively young and there are many unsolved problems, a consensus has been reached. Two feedback modes have been identified, which correspond to two accretion modes (Fabian 2012; Kormendy & Ho 2013; Heckman & Best 2014). One is called the radiative or quasar mode. This mode operates when the black hole accretes at a significant fraction of the Eddington rate. In this case, the accretion flow is in the standard thin disk regime (Shakura & Sunyaev 1973) and the corresponding AGNs are very luminous. The other mode is called the kinetic mode, radio mode, or maintenance mode, when the black hole accretes at a low accretion rate. In this case, the accretion flow is described by a hot accretion flow (Narayan & Yi 1994; Yuan & Narayan 2014). The corresponding AGNs are called low-luminosity AGNs (LLAGNs). By analogy with the soft and hard states of black hole X-ray binaries (BHBs) (see Belloni 2010 for the classification of states in BHBs), the boundary between the two modes is $L_{\text{bol}} \sim (1–2)\%L_{\text{Edd}}$, where $L_{\text{bol}}$ is the bolometric luminosity and $L_{\text{Edd}} \approx 1.3 \times 10^{36}(M_{\text{BH}}/10^9 M_\odot)$ erg s$^{-1}$ is the Eddington luminosity.

The output of black hole accretion generally includes three components, i.e., radiation, jet, and wind. The difference between the latter two is that the jet has relativistic speed and is well-collimated, while wind is sub-relativistic and has a much larger solid angle. In the radiative mode of feedback, i.e., the standard thin disk case, there is no jet. In addition to the radiation, which is obviously strong, we also have observational evidence of wind, e.g., in the case of broad-absorption-line quasars (see Crenshaw et al. 2003 for a review of the observations). These winds may be driven by the radiation line force (e.g., Murray et al. 1995; Proga et al. 2000).

In the kinetic 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). However, it is still under active debate whether jets at large scales should be described by a hydrodynamic- (e.g., Guo 2016), magnetohydrodynamic- (e.g., Gan et al. 2017 and references therein), or cosmic-ray-dominated one (Guo & Mathews 2011), and more importantly, how efficient the jet can deposit its energy into the ISM or intergalactic medium because of its very small solid angle and rather high velocity (e.g., Vernaleo & Reynolds 2006).

In the study of black hole accretion, wind from hot accretion flow is one of the most important progresses in recent years. Here we only briefly summarize the main development and readers are referred to the recent review by Yuan (2016) for more details. In the pioneering work of Narayan & Yi (1994), it has been speculated that strong outflow should be easily formed because of the positive Bernoulli parameter of the hot accretion flow. Blandford &
Begelman (1999) proposed an analytical model by emphasizing the wind. Since wind in the accretion flow is intrinsically a multi-dimensional physical process, the proper study of wind can only be achieved through numerical simulations. Stone et al. (1999) has performed the first global numerical simulation of black hole accretion and found that the mass accretion rate decreases with decreasing radius. By analyzing the numerical simulation data, including analyzing the convective instability of an MHD accretion flow, Yuan et al. (2012) convincingly showed that such a decrease in accretion rate must be caused by strong wind rather than convection (see also Narayan et al. 2012; Li et al. 2013). By using a “virtual particle trajectory” approach, Yuan et al. (2015) have carefully studied the properties of wind. They find that the mass flux of wind is generally much larger than the accretion rate and fluxes of energy and momentum are also much larger than that of the jet in the case of accretion onto a Schwarzschild black hole.4 Because the wind gas is fully ionized, it is very difficult to detect wind from observing absorption lines. Still, more and more observations confirm the existence of wind in both LLAGNs (Crenshaw & Kraemer 2012; Tombesi et al. 2014; Cheung et al. 2016) and the hard state of BHBs (Homan et al. 2016), where a hot accretion flow is believed to operate. In many works, winds have been included, though without explicitly emphasizing the mode of feedback (e.g., Ciotti et al. 2010; Ostriker et al. 2010; Eisenreich et al. 2017). Achieving a sufficiently rapid reddening of moderately massive galaxies without expelling too many baryons has been challenging for simulations of galaxy formation. Most recently, by invoking the kinetic feedback effect from winds in the regime of low accretion rates (i.e., the kinetic feedback mode), Weinberger et al. (2017) has successfully solved this problem.

In this work, we focus on another mechanism in the kinetic mode, i.e., the radiative heating. This feedback mechanism is ignored sometimes in previous works (but see, e.g., Ciotti & Ostriker 2001; Ostriker et al. 2010; Choi et al. 2012; Gan et al. 2014; Eisenreich et al. 2017), perhaps because it is thought that the radiation of the hot accretion flow is too weak. However, based on the following reasons, it is necessary to study its potential role in feedback. First, the luminosity of a hot accretion flow covers a very wide range depending on the accretion rate and can be moderately high. Taking the BHB as an example, the hard and soft states are described by the hot accretion flow and the thin disk, respectively (McClintock & Remillard 2006; Remillard & McClintock 2006; Done et al. 2007). The highest luminosity of the hard state can be $L_{\text{rad}} \sim (2-10) \times L_{\text{edd}}$ (e.g., McClintock & Remillard 2006; Remillard & McClintock 2006; Done et al. 2007). Theoretically, the high luminosity of a hot accretion flow is due to (1) the radiative efficiency being a function of the accretion rate, and thus it increases with the increasing accretion rate (Xie & Yuan 2012), and (2) the highest accretion rate of a hot accretion flow being $\gtrsim 10^{-3} M_{\text{edd}}$ (Yuan & Narayan 2014). Compared to the power of a jet, the power of radiation will be larger when the X-ray luminosity $L_X \gtrsim 4 \times 10^{-3} L_{\text{edd}}$ (or roughly the bolometric luminosity $L_{\text{bol}} \gtrsim 6 \times 10^{-4} L_{\text{edd}}$; Fender et al. 2003). Second, the spectrum emitted by a hot accretion flow is different from that emitted by a thin disk. As summarized by Ho (1999, see also Ho 2008), the main difference of the spectrum of LLAGNs from luminous AGNs is the lack of the big blue bump. This means that for a given luminosity, there will be more hard photons. This results in more effective radiative heating, as we will see later from Equations (8) or (9). Finally, galactic nuclei spend most of their time in the LLAGN phase rather than in the active phase (e.g., Haehnelt & Rees 1993; Kauffmann & Haehnelt 2000; Martini & Weinberg 2001). Thus the cumulative effect of radiative heating in the kinetic mode may be significant.

Radiative heating mainly includes two processes. One is heating by Compton scattering; the other is heating by photoionization. We will see that the former is typically determined by the spectrum of the LLAGNs; the dependence on the properties of the ISM is very weak. On the other hand, the latter is a strong function of the ionization parameter $\xi$, which is sensitive to the local properties of the ISM. Moreover, the calculation of the latter is relatively straightforward. Because of these reasons, in this paper, we focus on the Compton heating. In principle, Compton scattering can be either a heating or a cooling process, depending on the energy contrast between the photons and electrons; but, in practice, we will see that it is usually a heating process. We will evaluate the Compton heating rate by using “Compton temperature” ($T_C$), following the approach of Sazonov et al. (2004). Physically, Compton temperature means the gas temperature at which net energy exchange by Compton scattering between photons and electrons vanishes, and it is determined by the energy-weighted average energy of the emitted photons from LLAGNs, see Equation (8) below. Sazonov et al. (2004) calculated the Compton temperature of typical luminous AGNs and found $T_C \approx 2 \times 10^7$ K. The main aim of the present work is to calculate the value of $T_C$ of LLAGNs. For this aim, in Section 2, we combine the data from the literature to obtain the broadband spectral energy distribution 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. We then calculate the corresponding Compton temperature in Section 3. In Section 4, we compare the Compton heating with the other heating and cooling processes, such as photoionization heating, recombination and line cooling, and bremsstrahlung cooling, to see the relative importance of Compton heating. The final section is devoted to discussions and a short summary.

### 2. Broadband Spectrum of LLAGNs

In the kinetic feedback mode, i.e., when the luminosity of the AGNs is $\lesssim (1-2)\% L_{\text{edd}}$, the broadband spectrum of the AGNs has qualitative differences from that of a luminous AGN, with the most significant one being the absence of the “big blue bump” that is present in the spectrum of luminous AGNs (Ho 1999, 2008). Theoretically, this is because in luminous AGNs a standard thin disk extends to the innermost stable circular orbit, while in LLAGNs it is truncated at a transition radius and replaced by a hot accretion flow within this radius (Yuan & Narayan 2014). Another notable feature is that since the luminosity of LLAGNs covers a large range, the spectrum at a different luminosity regime is also different. In this section, we investigate the broadband spectrum of LLAGNs at various luminosity regimes. For the calculation of Compton heating, the spectrum in the hard X-ray band is crucial, so we first discuss the hard X-ray spectrum of LLAGNs.

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4 In this case, of course there is no Blandford & Znajek (1977, BZ) jet. However, simulations have shown that there exists a “disk-jet,” which is powered by the rotating accretion flow. The differences between the disk-jet and BZ-jet are discussed in Yuan & Narayan (2014) and Yuan et al. (2015).
2.1. Hard X-Ray Spectrum of LLAGNs: Photon Index and Cutoff Energy

The hard X-ray and Gamma-ray emission of LLAGNs are of crucial importance to determine their Compton temperatures. In practice, the X-ray spectrum can be well described by a power law with an exponential cutoff,

\[ F_{\gamma} \propto E^{-\Gamma} \exp(-E/E_c), \]

where \( \Gamma \) is the photon index of the hard X-ray spectrum, \( E \equiv h\nu \) is the photon energy, and \( E_c \) is the exponential cutoff energy (or the e-folding energy). Additionally, there may also exist a reflection component in energy band 10–50 keV. Observationally, the X-ray photon index \( \Gamma \) is now measured fairly well. The value of \( \Gamma \) in LLAGNs generally locates in the range \( \Gamma \approx 1.5–1.9 \), and it anti-correlates with the X-ray luminosity \( L_X/L_{\text{Edd}} \) (e.g., Emmanoulopoulos et al. 2012; Yang et al. 2015; Connolly et al. 2016).

The cutoff energy \( E_c \) on the other hand, remains poorly constrained. Only dozens of AGNs have such measurements, mainly thanks to recent advances in hard X-ray studies. In addition, there may also exist a reflection component in energy band 10–50 keV. Observationally, the X-ray photon index \( \Gamma \) is now measured fairly well. The value of \( \Gamma \) in LLAGNs generally locates in the range \( \Gamma \approx 1.5–1.9 \), and it anti-correlates with the X-ray luminosity \( L_X/L_{\text{Edd}} \) (e.g., Emmanoulopoulos et al. 2012; Yang et al. 2015; Connolly et al. 2016).

The cutoff energy \( E_c \) on the other hand, remains poorly constrained. Only dozens of AGNs have such measurements, mainly thanks to recent advances in hard X-ray (\( E \geq 30–50 \text{ keV} \)) telescopes and instruments, i.e., CGRO/OSSE (e.g., Maitre et al. 1999; Zdziarski et al. 1999, 2000; Gonidakis et al. 1996), BeppoSAX/PDS (e.g., Perola et al. 2002; De Rosa et al. 2007; Dadina et al. 2008), Integral/IBIS/ISGR (e.g., Beckmann et al. 2005, 2009; Malizia et al. 2008, 2012, 2014; Panessa et al. 2008; Molina et al. 2009; Lubiński et al. 2010, 2016; Beckmann et al. 2011; Molina et al. 2013), Swift/BAT (e.g., Winter et al. 2009; Burlon et al. 2011; Molina et al. 2013), and NuSTAR (e.g., Brenneman et al. 2014; Marinucci et al. 2014; Matt et al. 2015; Ursini et al. 2015, 2016; Fürst et al. 2016). Statistically, from BeppoSAX observations Dadina (2008) found that the nearby (\( z < 0.1 \)) Seyfert galaxies (105 objects in total), on average, have photon index \( \Gamma \sim 1.8 \) and cutoff energy \( E_c \sim 290 \text{ keV} \). A similar result has also been obtained by Beckmann et al. (2005) based on Integral observations. However, we note that most of the sources currently explored are moderately bright (in Eddington unit) and belong to the luminous AGN category. Besides, a reliable measurement of \( E_c \) requires broadband spectral studies, which implies that ideally both low- and high-energy X-ray spectra have to be observed and modeled simultaneously, employing spectra with high statistical quality such as those acquired. This difficulty further limits the number of sources with reliable measurements of \( E_c \).

Compared to luminous AGNs, the e-folding cutoff energy \( E_c \) of LLAGNs is much more difficult to constrain, because of their systematically lower X-ray flux. Considering the uncertainties, we gather from the literature (mainly selected from Molina et al. 2009; Malizia et al. 2012, 2014, see Table 1 for references of individual sources) LLAGNs that satisfy \( L_X \lesssim 4 \times 10^{38} L_{\text{Edd}} \). There are nine sources in total, as summarized in Table 1. We include in this table the source name, AGN classification, black hole mass, distance, X-ray luminosity, photon index, and cutoff energy. As noted in the table, the black hole mass \( M_{\text{BH}} \) is calculated through various methods. Besides, as noted in Table 1, there are redshift-independent distance measurements on the distance for several nearby sources, while for the rest the distance is calculated from redshift in a flat cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1}, \Omega_M = 0.27, \Omega_L = 0.73 \). Due to the lack of sensitive instruments in the 200–800 keV energy band, most of the LLAGNs only have a lower limit constraint on \( E_c \).

One of the best \( E_c \) measurement comes from LLAGN NGC 7213 (Emmanoulopoulos et al. 2012), which is classified as a low-ionization nuclear emission-line region (LINER). An anti-correlation between \( \Gamma \) and \( L_X/L_{\text{Edd}} \) (the so-called “harder when brighter” behavior) is observed in this source (Emmanoulopoulos et al. 2012). The cutoff energy is constrained to be \( E_c > 350 \text{ keV} \) by Suzaku and Swift/BAT (lobban et al. 2010), or \( E_c > 140 \text{ keV} \) by NuSTAR (Ursini et al. 2015).

Another example is NGC 5506, which is classified as either a Seyfert 1.9 or a narrow-line Seyfert 1 galaxy. The X-ray photon index, with a typical value \( \Gamma \approx 1.9 \) (Bianchi et al. 2004; Matt et al. 2015), also anti-correlates with the X-ray luminosity (Soldi et al. 2014). From simultaneous XMM-Newton/BeppoSAX observations, Bianchi et al. (2004) found that the cutoff energy is \( E_c = 140^{+40}_{-30} \text{ keV} \). However, as recently pointed out by Matt et al. (2015), this value suffers large systematic uncertainties due to ambiguities during the spectral modeling. Indeed, the NuSTAR observation on this source found that \( E_c = 720^{+130}_{-190} \text{ keV} \) (Matt et al. 2015). Even allowing for systematic uncertainties, they confirm the \( 3\sigma \) lower limit of the cutoff to be \( E_c > 350 \text{ keV} \).

According to Table 1, we may set \( E_c = 400–800 \text{ keV} \) for LLAGNs. Besides, the value of \( E_c \) might anti-correlate with the X-ray luminosity \( L_X/L_{\text{Edd}} \), as indicated by observations of one LLAGN (NGC 4593, Ursini et al. 2016) and BBHs in their hard state (among others see e.g., GX 339-4, cf. Figure 7 in Miyakawa et al. 2008), and expected by theory of hot accretion flows.

2.2. Composite Broadband SED of LLAGNs

Obtaining the broadband spectrum of LLAGNs is challenging. Various sample selection and normalization methods have been developed (e.g., Ho 1999, 2008; Malizia et al. 2003; Winter et al. 2009; Eracleous et al. 2010). As shown in Figure 1, we here 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 \( (E \lesssim 10 \text{ keV}) \). We include three sets of SEDs with different ranges of Eddington ratio \( \lambda \equiv L_{\text{bol}}/L_{\text{Edd}} \) from Ho (2008), 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.

We caution that the origin of the nuclear infrared (IR) emission is rather complicated, 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. Spatial resolution is thus of crucial importance to discriminate the contaminations, and extensive efforts have been made through infrared interferometric techniques (e.g., Gandhi et al. 2009; Tristram et al. 2009; Asmus et al. 2011, 2014; González-Martín et al. 2015, 2017). However, these contaminations are still difficult to constrain (e.g., Asmus et al. 2011, 2014). 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 \( \lesssim 2–8 \) (Asmus et al. 2011, 2014; González-Martín et al. 2017).

The spectrum from the hard X-ray to soft \( \gamma \)-ray regime (10 keV \( \lesssim E \lesssim 2 E_c \)) is absent in these composite SED data.
Table 1

LLAGNs with Observational Constrains on $E_c$

| Name          | Class | Distance (Mpc) | $M_{BH}$ ($M_\odot$) | Notes on $M_{BH}$ | $L_X/L_{Edd}$ | $\Gamma$ | $E_c$ (keV) | References on X-ray Properties ($L_X/L_{Edd}$, $\Gamma$, $E_c$) |
|---------------|-------|----------------|-----------------------|------------------|---------------|----------|-------------|------------------------------------------------------------------|
| M 87          | LINER | 16.7           | $3.5 \times 10^7$     | Dyn (W13)        | $8.1 \times 10^{-8}$ | 2.17 ± 0.01 | >1000       | Wilson & Yang (2002)                                              |
| NGC 4151      | Sy 1  | 19             | $3.8 \times 10^7$     | Dyn (O14)        | $2.0 \times 10^{-3}$ | 1.77 ± 0.08 | 307 ± 235   | Molina et al. (2009)                                             |
| NGC 4953      | Sy 1  | 43.5           | $1.0 \times 10^7$     | RM (D06)         | $4.7 \times 10^{-3}$ | 1.92 ± 0.01 | >222        | Molina et al. (2009)                                             |
| NGC 6814      | Sy 1.5| 22.6           | $2.4 \times 10^7$     | $M_{BH}-\sigma$  | $3.2 \times 10^{-5}$ | 1.84 ± 0.01 | >640        | Ursini et al. (2016)                                             |
| MCG-06-30-15  | Sy 1.2| 37.4           | $1.2 \times 10^8$     | $M_{BH}-\sigma$  | $3.2 \times 10^{-4}$ | 1.81 ± 0.01 | >1325       | Lubisibski et al. (2010)                                        |
| NGC 7213      | LINER | 21.2           | $1 \times 10^8$       | $M_{BH}-\sigma$  | $1.5 \times 10^{-4}$ | 1.85       | >350        | Emmanoulopoulos et al. (2012), Lobban et al. (2010)              |
| NGC 5506      | Sy 1  | 29.1           | $2 \times 10^8$       | $M_{BH}-\sigma$  | $3.4 \times 10^{-4}$ | 1.84 ± 0.03 | >140        | Ursini et al. (2015)                                             |
| Cen A         | radio gal.| 3.8   | $5 \times 10^7$       | Dyn (N07)        | $1.2 \times 10^{-4}$ | 1.67       | >700        | Burke et al. (2014)                                              |

Note. (1) The distance of M87 is derived from the Tully–Fisher relationship (Neill et al. 2014), that of NGC 4151 is from the parallax method (Honig et al. 2014), and that of Cen A is the best-estimate based on various redshift-independent distance measures (Harris et al. 2010). The distance of rest sources, on the other hand, is derived from redshift, assuming a flat cosmology. (2) Various methods are adopted to measure/estimate the black hole mass, i.e., stellar or gas dynamics (marked by “Dyn”), the reverberation-mapping (marked by “RM”), or the $M_{BH}-\sigma$ relationship (marked by “$M_{BH}-\sigma$,” with formulae taken from Kormendy & Ho (2013) and the velocity dispersion from http://leda.univ-lyon1.fr). References on $M_{BH}$ measurements. W13: Walsh et al. (2013), O14: Onken et al. (2014), D06: Denney et al. (2006), N07: Neumayer et al. (2007).

Therefore, we complete the SED of this energy range through Equation (1) (normalized at $E = 10$ keV), based on our discussions on $\Gamma$ and $E_c$ in Section 2.1. Due to the uncertainties of $\Gamma$ and $E_c$, we choose different values of $\Gamma$ and $E_c$. As shown in Figure 1, solid curves have relatively hard spectra, with $\Gamma = 1.60$, while the dashed curves have relatively soft spectra, with $\Gamma = 1.80$. Different colors indicate different $\epsilon$-floding cutoff energies, i.e., dark green and dark red are for $E_c = 400$ keV and $E_c = 800$ keV, respectively. Moreover, since the jet in LLAGNs are likely be relatively strong, we assume its emission to be significant at $E \gtrsim 2 E_c$. We take the blazar spectrum from Sazonov et al. (2004); normalization is assumed to be 10% the flux from hot accretion flow at 2 $E_c$ to consider the $\gamma$-ray emission in LLAGNs. Such an artificial jet emission in the $\gamma$-ray band will affect the resultant Compton temperature in a minor way, i.e., less than 3%–5%.

3. Compton Temperature of LLAGNs

3.1. Method and Equations

Consider the scatter between photons with energy $\epsilon$ ($\epsilon \equiv h\nu/m_\epsilon c^2$) and electrons with temperature $T_e$ ($\theta_e \equiv kT_e/m_\epsilon c^2$). The heating or cooling rate of electrons is described by the following exact formulae, which are valid for any photon energy and electron temperature (Guilbert 1986),

$$q_{\text{Comp}} = n_e \sigma_T \int \frac{\epsilon - \langle \epsilon \rangle}{\epsilon} F_\epsilon \, d\epsilon$$

$$\equiv n_e \sigma_T K_{\text{Comp}},$$

(2)

where $F_\epsilon$ is the radiation flux at energy $\epsilon$, $K_{\text{comp}}$ the kernel of the Compton heating rate. The cross-section for Compton scattering process has the form (Guilbert 1986),

$$\frac{\sigma(\epsilon, \theta_e)}{2\epsilon} = \frac{2\epsilon}{\Gamma(1/\theta_e)} \int_{-\infty}^{\infty} g_\epsilon(e^{\bar{\phi}}) e^{2\bar{\phi}} \exp \left( -\frac{\cosh \bar{\phi}}{\theta_e} \right) d\bar{\phi}.$$

(3)

The average photon energy after scattering is (Guilbert 1986),

$$\langle \epsilon \rangle = \epsilon + \frac{\sigma_T}{2\epsilon (1/\theta_e)} \int_{-\infty}^{\infty} \left( \theta_e + \sinh \phi - \epsilon \right) \exp \left( -\frac{\cosh \phi}{\theta_e} \right) d\phi.$$

(4)

Here $K_2(x)$ is the second order modified Bessel function, $G(\epsilon) \equiv g_\epsilon(\epsilon) - g_\epsilon(\epsilon)$ and

$$g_\epsilon(y) = \frac{3}{8} \int_0^y \left( t(t-2) + 1 + ty + \frac{1}{1+ty} \right) \frac{dt}{(1+ty)^{y+2}}.$$

(5)

In the Thompson limit ($h\nu \ll m_\epsilon c^2$ and $kT_e \ll m_\epsilon c^2$), Equations (3) and (4) take their usual simple forms,

$$\sigma(\epsilon, \theta_e) \approx \sigma_T, \quad \langle \epsilon \rangle \approx \epsilon + (4\theta_e - \epsilon).$$

(6)

In this case, by defining a “Compton temperature” $T_C$, Equation (2) can be simplified as

$$q_{\text{Comp}} = n_e \frac{4\pi \sigma_T}{m_\epsilon c^2} F (T_C - T_e)$$

$$= n^2 \frac{n_e \pi \sigma_T}{m_\epsilon c^2} \frac{L_{\text{bol}}}{nR^2} (T_C - T_e),$$

(7)
where $F \equiv \int F_\nu d\nu \equiv \frac{L_{\text{bol}}}{4\pi R^2}$ is the radiative flux at distance $R$. The Compton temperature $T_C$ is defined as

$$\frac{kT_C}{m_e c^2} \equiv \frac{1}{4} \int \epsilon F_\nu d\nu,$$

where the correction factor $b(\epsilon)$ is unity for photon energy below 10 keV and decreases significantly above 10 keV. With the evaluation of $T_C$, the Compton heating rate can be calculated easily by Equation (7).

### 3.2. Numerical Results of $T_C$

We now calculate the Compton temperature of LLAGNs based on the SEDs shown in Figure 1. We consider two SEDs with different luminosity values, one being $10^{-3} < \lambda < 10^{-1}$ and another $\lambda < 10^{-3}$. They are simply represented as $\lambda \sim 10^{-2}$ and $\lambda < 10^{-3}$ in Table 2. As discussed in Section 2.1, the photon index and the cutoff energy of the X-ray spectrum of LLAGNs are currently poorly constrained.

In the general case, the photon energy from AGNs can be comparable to or even larger than $m_e c^2$ and/or electrons can be relativistic; there is no exact definition of Compton temperature due to the strong coupling between electrons and photons. In this case, for the convenience of the calculation of Compton temperature, we combine the exact Compton heating rate (Equation (2)) with its simplified version (Equation (7)) and define an “effective” Compton temperature as (see also Sazonov et al. 2004)

$$T_C = T_e + \frac{m_e c^2}{k} \int b(\epsilon) F_\nu d\nu \approx T_e + \frac{m_e c^2}{k} \int_{10\text{keV}}^{\infty} F_\nu d\nu,$$

where $F_\nu$ is the uncorrected flux at frequency $\nu$.
Notes.

4 The IR data, i.e., $\nu < 3 \times 10^{14}$ Hz, in this case is reduced by a factor of 10.

5 The two photon indexes shown in bold, i.e., $\Gamma = 1.59$ and $\Gamma = 1.69$, are for cases with $L_{bol}/L_{Edd} = 10^{-2}$ and $10^{-3}$, respectively, where they are estimated from the $\Gamma - L_{{c}}/L_{Edd}$ relationship reported in Yang et al. (2015; see their Equation (5)), with $L_{{c}} = 1/16 L_{bol}$ (Ho 2008).

5 When the temperature of ISM is very low, e.g., the black hole is fueled by strong cooling flow, the Bondi radius $R_{Bondi} = 2GM_{{BH}}/c_s^2 \approx 0.1$ kpc($M_{{BH}}/10^9 M_{{\odot}}$) ($T_{{c}}/10^7$ K)$^{-1}$; this is because the properties of the gas in this region determines that the black hole accretion rate, which subsequently determines the total output of the AGN (radiation, jet, and wind strength) and the growth of the black hole mass. So Compton heating in this “inner” region is most important. If the IR emission originates far away from this region, their effect on the calculation of Compton temperature should not be included. Based on these considerations, we have also considered the “reduced-IR case,” in which the IR flux shown in Figure 1 is artificially reduced by a factor of 10 (Asmus et al. 2011, 2014; González-Martín et al. 2017). Due to the reduction in both the bolometric luminosity and the Compton cooling from IR photons, this will make the Compton temperature higher by a factor of $\sim 2-3$.

All of these models and their Compton temperatures are listed in Table 2. From this table, the main results can be summarized as follows.

1. The Compton temperature will be higher when the X-ray spectrum is harder or the cutoff energy is higher. For given $\Gamma$ and $T_{{c}}$, $T_{{C}}$ for cases with $E_{{c}} = 800$ keV is a factor of $\sim 1.4$ higher than that for cases with $E_{{c}} = 400$ keV. The impact of $\Gamma$ is more evident, i.e., changing $\Gamma$ from 1.80 to 1.60 will result in a factor of $\sim 1.8$ increase in $T_{{C}}$. This is because a harder spectrum and a higher $E_{{c}}$ implies that there will be relatively more hard photons, which can heat the electrons more efficiently than soft photons.

2. The value of $T_{{C}}$ is not sensitive to the temperature of ISM, $T_{{e}}$, as expected.

3. For reasonable parameter choices, the Compton temperature of LLAGNs with “normal” IR flux lies in the range of (5–9) \times 10^7 K.

### Table 2

Compton Temperature of LLAGNs

| $\lambda$ ($\equiv L_{{bol}}/L_{Edd}$) | $\Gamma$ | $E_{{c}}$ (keV) | $T_{{c}}/10^7$ K |
|---|---|---|---|
| | | | Normal Case | Reduced-IR Case$^a$ |
| | | | ($T_{{e}} = 10^4$ K) | ($T_{{e}} = 10^5$ K) | ($T_{{e}} = 10^6$ K) | ($T_{{e}} = 10^4$ K) | ($T_{{e}} = 10^5$ K) | ($T_{{e}} = 10^6$ K) |
| $\sim 10^{-2}$ | 1.50 | 300 | 4.66 | 4.66 | 4.65 | 9.40 | 9.40 | 9.38 |
| | | 400 | 5.64 | 5.64 | 5.62 | 11.4 | 11.4 | 11.4 |
| | | 500 | 6.52 | 6.52 | 6.50 | 13.2 | 13.2 | 13.2 |
| | | 600 | 7.29 | 7.29 | 7.27 | 14.7 | 14.7 | 14.7 |
| | | 700 | 8.00 | 7.99 | 7.98 | 16.1 | 16.1 | 16.1 |
| 1.59$^b$ | 300 | 3.44 | 3.44 | 3.43 | 6.95 | 6.95 | 6.93 |
| | | 400 | 4.10 | 4.10 | 4.09 | 8.28 | 8.28 | 8.26 |
| | | 500 | 4.68 | 4.68 | 4.67 | 9.45 | 9.45 | 9.43 |
| | | 600 | 5.19 | 5.19 | 5.18 | 10.5 | 10.5 | 10.5 |
| | | 700 | 5.64 | 5.64 | 5.63 | 11.4 | 11.4 | 11.4 |
| 1.70 | 300 | 2.41 | 2.41 | 2.40 | 4.87 | 4.87 | 4.85 |
| | | 400 | 2.82 | 2.82 | 2.82 | 5.70 | 5.70 | 5.68 |
| | | 500 | 3.17 | 3.17 | 3.16 | 6.41 | 6.41 | 6.40 |
| | | 600 | 3.48 | 3.48 | 3.47 | 7.03 | 7.03 | 7.02 |
| | | 700 | 3.75 | 3.75 | 3.74 | 7.58 | 7.58 | 7.57 |
| $< 10^{-3}$ | 1.60 | 400 | 7.36 | 7.36 | 7.34 | 14.1 | 14.1 | 14.1 |
| | | 500 | 8.37 | 8.37 | 8.35 | 16.1 | 16.1 | 16.0 |
| | | 600 | 9.27 | 9.27 | 9.25 | 17.8 | 17.8 | 17.8 |
| | | 700 | 10.1 | 10.1 | 10.1 | 19.4 | 19.4 | 19.3 |
| | | 800 | 10.8 | 10.8 | 10.8 | 20.8 | 20.8 | 20.7 |
| 1.69$^b$ | 400 | 5.65 | 5.65 | 5.63 | 10.9 | 10.8 | 10.8 |
| | | 500 | 6.37 | 6.36 | 6.35 | 12.2 | 12.2 | 12.2 |
| | | 600 | 6.99 | 6.99 | 6.97 | 13.4 | 13.4 | 13.4 |
| | | 700 | 7.54 | 7.54 | 7.52 | 14.5 | 14.5 | 14.4 |
| | | 800 | 8.04 | 8.04 | 8.02 | 15.4 | 15.4 | 15.4 |
| 1.80 | 400 | 4.16 | 4.16 | 4.15 | 7.99 | 7.99 | 7.96 |
| | | 500 | 4.63 | 4.63 | 4.62 | 8.89 | 8.88 | 8.86 |
| | | 600 | 5.03 | 5.03 | 5.02 | 9.66 | 9.65 | 9.63 |
| | | 700 | 5.38 | 5.38 | 5.37 | 10.3 | 10.3 | 10.3 |
| | | 800 | 5.69 | 5.69 | 5.68 | 10.9 | 10.9 | 10.9 |
Table 3

| Sources          | $L_X/L_{Edd}$ | $T_C/10^9$ K |
|------------------|---------------|--------------|
|                  | ($T_c = 10^4$ K) | ($T_c = 10^5$ K) | ($T_c = 10^6$ K) |
| NGC 4579         | $3.0 \times 10^{-4}$ | 25.9 | 25.9 | 25.9 |
| NGC 6251         | $5.0 \times 10^{-5}$ | 9.85 | 9.85 | 9.85 |
| NGC 4203         | $1.8 \times 10^{-5}$ | 16.1 | 16.1 | 16.1 |
| NGC 315          | $1.5 \times 10^{-6}$ | 5.23 | 5.23 | 5.21 |
| NGC 4296         | $1.3 \times 10^{-6}$ | 8.91 | 8.90 | 8.89 |
| NGC 4594         | $1.2 \times 10^{-7}$ | 9.80 | 9.80 | 9.78 |

Note. Observational data and theoretical modeling are taken from Yuan et al. (2009). We caution that the hard X-rays and soft $\gamma$-rays in these sources are actually from SED modeling because there are no direct observations at these energy bands.

4. For the “reduced-IR” case, which is more favorable to us, the Compton temperature $T_C \approx (1-1.5) \times 10^8$ K.

Besides this statistical investigation of $T_C$ for LLAGNs, we have also calculated the Compton temperature of several individual LLAGNs. Such an investigation is a little too ambiguous, since most of these sources lack the hard X-ray and soft $\gamma$-ray observations to constrain the value of $E_C$. So we use the theoretical SED results for such information, which is obtained by the accretion flow modeling to the sources (see Yuan & Narayan 2014 for details of the accretion model of LLAGNs). We select several representative sources from Yuan et al. (2009). The results are shown in Table 3. Again, we have tried three different electron temperatures. The Compton temperature is systematically higher than the “normal case” shown in Table 2, but more consistent with the results of the “reduced-IR” case. The reason is that the IR flux calculated from the theoretical model is significantly weaker than that shown in Figure 1, since we only consider the radiation from accretion flow and the jet. In other words, the Compton temperature derived here is applicable to the regions close to the black hole, as we argue above.

4. The Total Radiative Heating and Cooling in LLAGNs

In addition to Compton scattering, there are several additional radiative processes that can heat or cool the gas. In this section, we compare their relative magnitude. One process is the bremsstrahlung radiation ($q_{br}$ and $S_{br}$), which always plays a cooling role. The other processes relate to the atomic energy-level transition, i.e., the photoionization/recombination and line emission ($q_{ph,rec,1}$ and $S_{ph,rec,1}$). The total radiative heating/cooling rate per unit volume can be expressed as (e.g., Proga et al. 2000; Sazonov et al. 2005)

$$ q_{\text{rad}} = q_{\text{Comp}} + q_{\text{ph,rec,1}} - q_{\text{br}} $$

$$ = n n_e S_{\text{Comp}} + n n_e S_{\text{ph,rec,1}} - n^2 S_{\text{br}} $$

$$ = n^2 \left[ \frac{\rho}{n} (S_{\text{Comp}} + S_{\text{ph,rec,1}}) - S_{\text{br}} \right] $$

Here $n = \rho/m_p$ and $n_e$ are the number density of hydrogen atoms and electrons, respectively. For hot gas (i.e., temperature $\geq 10^4$ K) with solar abundance, $n_e \approx n$. Consequently, the radiative heating/cooling rate can be expressed as

$$ q_{\text{rad}} \approx n^2 (S_{\text{ph,rec,1}} + S_{\text{Comp}} - S_{\text{br}}). $$

The value of $S_{\text{ph,rec,1}}$ depends on both the metallicity (fixed to solar abundance in this work) and the ionization parameter $\xi$. The definition of $\xi$ is

$$ \xi = \frac{L_{\text{ion}}}{n R^2} = 27.3 \text{ erg s}^{-1} \text{ cm} \left( \frac{f_{\text{ion}}}{0.2} \right) \left( \frac{\lambda}{10^{-2}} \right) \left( \frac{M_{\text{BH}}}{10^8 M_\odot} \right) \left( \frac{n}{0.1 \text{ cm}^{-3}} \right)^{-1} \left( \frac{R}{1 \text{ kpc}} \right)^{-2}. $$

Here $R$ is the distance to the central black hole, $L_{\text{ion}} = \int_{3.6 \text{ keV}} 13.6 \text{ keV} L_E \, dE$ is the ionization luminosity, and $f_{\text{ion}} \equiv L_{\text{ion}}/L_{\text{bol}}$ is the ionization luminosity factor. As shown in Figure 2, we derive the ionization luminosity factors, i.e., $f_{\text{ion}} \approx 0.42, 0.10, 0.20$, respectively, for the composite SEDs shown in Figure 1 with $\lambda < 10^{-3}, 10^{-3}-10^{-1}$ and $10^{-1}-1$. Detailed formulae of $S_{\text{ph,rec,1}}$ is provided in the Appendix (see Equation (17)). It is a heating (cooling) term when $\xi$ is large (small).

Figure 3 provides the values of $S_{\text{Comp}}/S_{\text{br}}$ and $S_{\text{ph,rec,1}}/S_{\text{br}}$ as a function of $\xi$. In this figure, we set $T_C = 1 \times 10^8$ K, and considered four different electron temperatures, i.e., log $T_e = 4.5$ (black), 5.0 (red), 5.5 (green), and 6.0 (blue). For this given electron temperature range, the Compton scattering plays a heating role. The total radiative process, on the other hand, will play a cooling (heating) role for $\xi$ below (above) $\sim 10^2$ erg s$^{-1}$ cm. When $\xi \gtrsim 10^4$ erg s$^{-1}$ cm, we have $S_{\text{Comp}} > S_{\text{ph,rec,1}}$.

5. Summary

This paper investigates the radiative heating in the kinetic mode of AGN feedback. This process is sometimes ignored in the AGN feedback study and people usually pay more attention to the kinetic feedback by the jet and wind. However, this may be over-simplified. Previous work in the case of the hard state of BHBs, in which we believe a hot accretion flow is operating just like in the kinetic mode, has shown that whenever the...
X-ray luminosity from the black hole $L_X \gtrsim 4 \times 10^{35}L_{\text{edd}}$ (or roughly the bolometric luminosity $L_{\text{bol}} \gtrsim 6 \times 10^{34}L_{\text{edd}}$), the power of luminosity is larger than that of the jet (Fender et al. 2003). Depending on the accretion rate, the highest luminosity of the hot accretion flow in the kinetic mode can be as high as (2-10)\%$L_{\text{edd}}$. Moreover, compared to the AGN spectrum in the radiative mode, the spectral energy distribution of the LLAGNs in the kinetic mode is such that there are relatively more hard photons, which makes the radiative heating more effective. Based on these reasons, it is necessary to study systematically the radiative heating in the kinetic mode of AGN feedback.

This paper focuses on Compton scattering. This process can in principle play a heating or cooling role, depending on the comparison between the photon energy and electron temperature of the gas. For this aim, we adopt the broadband spectral energy distribution of LLAGNs with different luminosities. Based on this information, we have calculated the “Compton temperature” $T_C$, which characterizes the heating or cooling rate, and is the gas temperature at which the net energy exchange by Compton scattering between photons and electrons vanishes. Using this quantity, the Compton heating rate can be conveniently derived by Equation (7) (see also Equations (14) and (15) in the Appendix).

The results of $T_C$ are shown in Table 2, which gives $T_C \sim (5-15) \times 10^9$ K. This value is higher than the typical electron temperature of the gas in galaxies, so it implies that in most cases, Compton scattering plays a heating role to the gas. This value is several times higher than the $T_C \approx 2 \times 10^9$ K value of luminous AGNs in the case of the radiative mode of AGN feedback. The uncertainties in the $T_C$ of LLAGNs comes from two aspects. One is that the photon index and especially the cutoff energy of the hard X-ray spectrum of LLAGNs are poorly constrained. The other is that the exact value of the IR luminosity and more importantly, the distance at which we are evaluating the radiative heating is not well constrained. If we are considering the heating at a distance very far away from the black hole or accretion flow, we should adopt the lower value of $T_C \approx 5 \times 10^8$ K. However, if we are interested in the heating not far away from the accretion flow, $T_C \approx 1.5 \times 10^8$ K should be adopted. We have also compared the Compton heating with the photoionization heating. We find that when the ionization parameter $\xi \gtrsim 10^4$, Compton heating is larger than photoionization heating.

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Appendix
Numerical Formulae for the Radiative Heating/Cooling Terms

Here we provide the numerical formulae for all three radiative heating/cooling terms. The first is the Compton scattering. From Equation (7), we have (see also Proga et al. 2000; Sazonov et al. 2005),

$$S_{\text{Comp}} = 3.6 \times 10^{-35} \frac{L_{\text{bol}}}{nR^2} \frac{(T_C - T_e)}{\xi} \text{ erg s}^{-1} \text{ cm}^{-3} \quad (14)$$

where

$$\xi = \frac{\sqrt{\frac{1}{1.5T_e^{-0.5}} + \frac{1.5}{T_e^{12}} - \frac{2}{T_e^{25}}} + 4 \times 10^{10}}{\frac{\log T_e - 4.35}{\log T_e - 6.5} + \log T_e} \text{ erg s}^{-1} \text{ cm}^{-3}, \quad (18)$$

and

$$a = -\frac{18}{e^{25} (\log T_e - 4.35)^2} - \frac{80}{e^{5.5} (\log T_e - 5.2)^2} - \frac{17}{e^{3.6} (\log T_e - 6.5)^2}. \quad (19)$$

and

$$b = 1.7 \times 10^4 T_e^{-0.7}, \quad (20)$$

and

$$c = 1.1 - \frac{1.1}{e^{T_e/18} \times 10^2} + \frac{4.5 \times 10^{15}}{T_e^4}. \quad (21)$$

Another simplified version, which is not adopted in this work, is from Proga et al. (2000; note the difference in the
definition of the Compton temperature, i.e.,

\[
S_{\text{ph,rec}} = 1.5 \times 10^{-21} \xi^{2} 4\pi T_{e}^{-2} \left(1 - \frac{T_{e}}{4T_{C}}\right)
\]

\[
- \delta \left(10^{-24} + 1.7 \times 10^{-18} \xi^{-1} T_{e}^{-1/2} e^{-1.3 \times 10^{5}/T_{e}}\right) \times \text{erg s}^{-1} \text{cm}^{-3}
\]

(22)

Here parameter \( \delta \) takes into account the effect of optical depth of lines; i.e., \( \delta = 1 \) represents the optically thin line cooling case, and \( \delta < 1 \) represents the case in which the line cooling is reduced when the lines become optically thick.

References

Asmus, D., Gandhi, P., Smette, A., Höning, S. F., & Duschl, W. J. 2011, A&A, 536, 36
Asmus, D., Höning, S. F., Gandhi, P., Smette, A., & Duschl, W. J. 2014, MNRAS, 439, 1648
Beckmann, V., Jean, P., Lubiński, D., Gandhi, P., Smette, A., Hönig, S. F., & Duschl, W. J. 2011, A&A, 502, 457
Brenneman, L. W., Madejski, G., Fuerst, F., et al. 2014, ApJ, 788, 61
Burke, M. J., Jourdain, E., Roques, J. P., & Evans, D. A. 2014, ApJ, 787, 50
Burlon, D., Ajello, M., Greiner, J., et al. 2011, ApJ, 728, 58
Crenshaw, D. M., & Kraemer, S. B. 2012, ApJ, 753, 75
Crenshaw, D. M., Kraemer, S. B., & George, I. M. 2003, ARA&A, 41, 117
Czerny, B., & Elvis, M. 1984, ApJ, 279, 498
Eisenreich, M., Naab, T., Choi, E., Ostriker, J. P., & Emsellem, E. 2017, MNRAS, 468, 751
Emmanoulopoulos, D., Papadakis, I. E., McHardy, I. M., et al. 2012, MNRAS, 424, 1327
Eracleous, M., Huang, J. A., & F phoenix, H. M. L. 2010, ApJS, 187, 135
Fabian, A. C. 2012, ARA&A, 50, 455
Fender, R. P., Gallo, E., & Jonker, P. G. 2003, MNRAS, 343, 199
Furst, F., Müller, C., Madsen, K. K., et al. 2016, ApJ, 819, 150
Gandhi, P., Horst, H., Smette, A., et al. 2009, A&A, 502, 457
Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJL, 539, L13
Gonidakis, D., Zdziarski, A. A., Johnson, W. N., et al. 1996, MNRAS, 282, 646
Guo, F., & Mathews, W. G. 2011, ApJ, 728, 121
Hachnell, M. G., & Rees, M. J. 1993, MNRAS, 263, 168
Harris, G. L. H., Rejkuba, M., & Harris, W. E. 2010, PASA, 27, 457
Heckman, T. M., & Best, P. N. 2014, ARA&A, 52, 589
Ho, L. C. 1999, ApJL, 516, 672
Ho, L. C. 2008, ARA&A, 46, 475
Homan, J., Neilsen, J., Allen, L. J., et al. 2016, ApJL, 830, L5
Honig, S. F., Watson, D., Kishimoto, M., & Jhorth, J. 2014, Natur, 515, 528
Kauffmann, G., & Hachnelt, M. 2000, MNRAS, 311, 576
Kormendy, J., & Ho, L. C. 2013, ARA&A, 51, 511
Li, J., Ostriker, J. P., & Sunyaev, R. 2013, ApJ, 767, 105
Lobban, A. P., Reeves, J. N., Porquet, D., et al. 2010, MNRAS, 408, 551
Magorrian, J., Tremaine, S., Richstone, D., et al. 1998, AJ, 115, 2285
Malizia, A., Bassani, L., Bazzano, A., et al. 2012, MNRAS, 426, 1750
Malizia, A., Bassani, L., Bird, A. J., et al. 2008, MNRAS, 389, 1360
Marinucci, A., Matt, G., Cara, E., et al. 2014, MNRAS, 440, 2347
Martini, P., & Weinberg, D. H. 2001, ApJ, 547, 12
Matt, G., Baloković, M., Marinucci, A., et al. 2015, MNRAS, 447, 3029
McClelland, J. C., & Remillard, R. A. 2006, in Compact Stellar X-ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), 157
Miyakawa, T., Yamakoa, K., Homan, J., et al. 2008, PASI, 60, 637
Morin, M., Bassani, L., Malizia, A., et al. 2009, MNRAS, 399, 1293
Morin, M., Bassani, L., Malizia, A., et al. 2013, MNRAS, 433, 1687
Murray, N., Chiang, J., Grossman, S. A., & Voit, G. M. 1995, ApJ, 451, 498
Narayan, R., Sadowski, A., Penna, R. F., & Kulkarni, A. K. 2012, MNRAS, 426, 3241
Narayan, R., & Yi, I. 1994, ApJ, 428, 13
Neil, J. D., Seibert, M., & Tully, R. B. 2014, ApJ, 792, 129
Neumayer, N., Cappellari, M., Reunanen, J., et al. 2007, ApJ, 671, 1329
Narayan, R., & Yi, I. 1995, ApJL, 438, L63
Onken, C. A., Valluri, M., Brown, J. S., et al. 2014, ApJ, 791, 37
Ostriker, J. P., Choi, E., Ciotti, L., et al. 2010, ApJ, 722, 642
Ostriker, J. P., Choi, E., Ciotti, L., et al. 2010, ApJ, 754, 125
Perola, G. C., Matt, G., Cappi, M., et al. 2002, A&A, 389, 151
Perola, G. C., Matt, G., Cappi, M., et al. 2002, A&A, 389, 802
Proga, D., Stone, J. M., & Kallman, T. R. 2000, ApJ, 543, 688
Remillard, R. A., & McClintock, J. E. 2006, ARA&A, 44, 49
Sazonov, S. Y., Ostriker, J. P., Ciotti, L., & Sunyaev, R. A. 2005, MNRAS, 358, 168
Sazonov, S. Y., Ostriker, J. P., & Sunyaev, R. A. 2004, MNRAS, 347, 144
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 426, 324
Walsh, J. L., Barth, A. J., Ho, L. C., & Sarzi, M. 2013, ApJ, 770, 86
Weinberger, R., Springel, V., Herquist, L., et al. 2017, MNRAS, 465, 3291
Wilson, A. S., & Yang, Y. 2002, ApJ, 568, 133
Winter, L. M., Mushotzky, R. F., Reynolds, C. S., & Tueller, J. 2009, ApJ, 690, 1322
Xie, F. G., & Yuan, F. 2012, MNRAS, 427, 1580
Yang, Q. X., Xie, F. G., Yuan, F., et al. 2015, MNRAS, 447, 1692
Yuan, F. 2016 in Astrophysics of Black Holes (Berlin: Springer), 153
Zdziarski, A. A., Johnson, W. N., & Wu, M. 2012, ApJ, 761, 130
Zdziarski, A. A., Johnson, W. N., Done, C., Smith, D., & McNaron-Brown, K. 1995, ARA&A, 53, 157

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