POSSIBLE ORIGIN OF RADIO EMISSION FROM NONTHERMAL ELECTRONS IN HOT ACCRETION FLOWS FOR LOW-LUMINOSITY ACTIVE GALACTIC NUCLEI

HU LIU AND QINGWEN WU
School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China; qwwu@hust.edu.cn
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ABSTRACT

The two components of radio emission, above and below 86 GHz, respectively, from the Galactic center source Sgr A* can be naturally explained by the hybrid of thermal and nonthermal electrons in hot accretion flows (e.g., radiatively inefficient accretion flow; RIAF). We further apply this model to a sample of nearby low-luminosity active galactic nuclei (LLAGNs), which are also believed to be powered by RIAF. We selected LLAGNs with only compact radio cores according to high-resolution radio observations, and sources observed with jets or jet-like features are excluded. We find that the radio emission of LLAGNs is severely underpredicted by the pure RIAF model, but can be naturally explained by the RIAF model with a hybrid electron population consisting of both thermal and nonthermal particles. Our model can roughly reproduce the observed anticorrelation between the mass-corrected radio loudness and Eddington ratio for the LLAGNs in our sample. We further model the spectral energy distributions of each source in our sample and find that roughly all sources can be well fitted if a small fraction of the steady-state electron energy is ejected into the nonthermal electrons. The size of the radio emission region of our model is around several thousands of gravitational radii, which is also roughly consistent with recent high-resolution VLBI observations for some nearby LLAGNs.

Key words: accretion, accretion disks – black hole physics – galaxies: active – radiation mechanisms: non-thermal

1. INTRODUCTION

Active galactic nuclei (AGNs) produce very high luminosities in extremely compact volumes. It was found that some local galaxies show similarities to bright AGNs, but with relatively weaker broad-line emission and multiwavelength radiative cores (e.g., Ho et al. 1997, 2001; Falcke & Markoff 2000; Nagar et al. 2002; Maoz 2007). These low-luminosity active galactic nuclei (LLAGNs) are very common in the local universe, which may be the scaled-down-luminosity version of bright AGNs (see Ho 2008 for a recent review). Actually, the AGN might only spend a small fraction of its lifetime in the highly luminous, QSO-like phase, and much more time is spent in a weakly accreting state (LLAGNs or normal galaxies; e.g., Hopkins & Hernquist 2006). Both bright AGNs and LLAGNs are believed to be powered by the matter falling onto a super massive black hole (BH). The observational properties of LLAGNs are quite different from those of bright QSOs, which are thought to be driven by different accretion modes. The optical/UV bumps observed in QSOs can be naturally interpreted as multi-temperature blackbody emission from a cold, optically thick, and geometrically thin standard disk (SSD; Shakura & Sunyaev 1973). However, most LLAGNs lack the evident optical/UV bump of bright AGNs. The possible physical reason is that the standard thin accretion disk is absent in these LLAGNs. A hot, optically thin, geometrically thick radiatively inefficient accretion flow model has been developed in the last few decades (RIAF; an “updated” version of the original advection-dominated accretion flow model; ADF; e.g., Ichimaru 1977; Narayan & Yi 1994, 1995; Abramowicz et al. 1995; see Katoh et al. 2008; Narayan & McClintock 2008; Yuan & Narayan 2013 for reviews). The RIAF model can successfully explain most observational features of nearby LLAGNs (e.g., Quataert et al. 1999; Cao & Rawlings 2004; Nemmen et al. 2006; Wu et al. 2007; Wu & Gu 2008; Gu & Cao 2009; Yuan et al. 2009a, 2009b; Xu & Cao 2009; Ho 2009; Cao 2010; Yu et al. 2011; Nemmen et al. 2012; see Yuan 2007 and Ho 2008 for recent reviews).

The AGNs are traditionally divided into radio loud (RL) and radio quiet (RQ), and the origin for this dichotomy is still a matter of debate. The distinction between the RL and RQ objects is normally based on a radio-loudness parameter, which was defined as the ratio of the monochromatic flux density at 5 GHz and optical B band at 4400 Å ($R_o = F_{5\text{GHz}}/F_B$). The loudness $R_o = 10$ is usually taken as the division between RQ and RL AGNs (particularly in QSO studies; e.g., Kellermann et al. 1994). Terashima & Wilson (2003) introduced a new definition of the radio loudness parameter by comparing the 5 GHz radio luminosity to the 2–10 keV luminosity, $R_X = L_{5\text{GHz}}/L_{2–10\text{keV}}$, and proposed that log $R_X = -4.5$ should be the barrier separating RL and RQ AGNs, which roughly correspond to $R_o = 10$. The use of X-ray luminosity with respect to the optical one should largely help avoid extinction problems that normally occur in the optical band. However, most of the traditionally RQ LLAGNs become RL according to either the criterion $R_o = 10$ or log $R_X = -4.5$ if using their nuclear emission at the radio and optical/X-ray waveband (e.g., Ho 2002; Panessa et al. 2006). Panessa et al. (2006) redefined the boundary for the RL and RQ LLAGNs as log $R_X \sim -2.8$ based on a sample of low-luminosity Seyferts and Fanaro–Riley type I radio galaxies (FR Is). In the last decade, there has been great progress in estimating the BH mass in both normal galaxies and AGNs (e.g., Gebhardt et al. 2000; Kaspi et al. 2005). The measurements of BH mass help us to further understand the issue of radio loudness. Ho (2002) found that the loudness parameter increases with the decrease of the Eddington ratio. Sikora et al. (2007) investigated the radio loudness of a total of 199 sources, which include broad-line radio galaxies (BLRGs), RL QSOs, Seyferts, low-ionization nuclear emission-line region galaxies (LINERs), FR Is, and Palomar–Green QSOs (PGQs), and found that there are two distinct, approximately parallel tracks on the radio-loudness–Eddington-ratio plane. They further proposed a quantitative definition for the radio-loudness parameter that is dependent on the Eddington ratio (see their Equation (5)), where the RL sources include BLRGs, RL QSOs, and FR Is,
while RQ sources are comprised of Seyferts, LINERs, and PGQs (hereafter we use this criterion to distinguish the RL/RQ).

The radio emission of RL AGNs is believed to originate in relativistic jets, where many large-scale radio jets have been observed directly. Compared with RL AGNs, the origin of nuclear radio emission from RQ objects is still not well understood, since RQ AGNs are much fainter radio sources, and most of them only show a compact radio core. The radio variability of RQ QSOs confined the radio emission to \( < 0.1 \) pc (e.g., Barvainis et al. 2005), and the high-resolution VLBI observations show that the region of the radio emission in RQ LLAGNs should be \( \lesssim 10^{-4} \) to \( \lesssim 10^{-2} \) pc (e.g., Ho & Ulvestad 2001; Nagar et al. 2002; Giroletti & Panessa 2009). Several possibilities have been proposed to explain the radio emission in these RQ AGNs. The first explanation is that RQ AGNs are scaled-down versions of RL AGNs where a weak, small-scale jet exists (e.g., Miller et al. 1993; Falcke et al. 1996). A small fraction of RQ objects shows core-jet or linear structures at parsec-scale or sub-parsec-scale, which supports the weak-jet scenario (e.g., Ho & Ulvestad 2001; Ulvestad et al. 2005; Leipski et al. 2006). The accretion-jet model is frequently used to model the multiwavelength spectral energy distribution (SED) of AGNs (particularly in LLAGNs; e.g., Yuan et al. 2009a; Yu et al. 2011; Nemmen et al. 2012). However, this scenario cannot answer the bimodality of the RL/RQ distribution of AGNs (e.g., Kellermann et al. 1994; Sikora et al. 2007). The second possibility is that the radio emission of the RQ AGNs come from the hot optically thin plasma in the disk winds, where the plasma is completely ionized and has a density high enough for bremsstrahlung emission to make a significant contribution to the observed compact radio core (e.g., Blundell & Kunic 2006; Steenbrugge et al. 2011). In this model, the mass-loss rate in the winds is significant and the observed luminosities of radio emission from quasars imply that they should accrete at super-Eddington rates. However, most RQ AGNs are accreting at sub-Eddington rates, where the radio core emission should not dominantly come from the disk winds. The third possibility is that the radio emission also comes from the accretion flows (e.g., RIAF or disk corona). Laor & Behar (2008) found that the tight correlation between the radio and X-ray luminosities in RQ QSOs is similar to that of active stars (\( L_{\text{R}} \sim 10^{-2} L_{\odot} \)). They therefore proposed that both the radio and X-ray emission from the nuclei of RQ AGNs may be dominated by the magnetic-reconnection-heated corona. Wu & Cao (2005) found that the radio emission of most nearby LLAGNs is higher than that predicted from radiation from pure thermal electrons in the RIAF, and their radio emission should have another origin (e.g., nonthermal electrons in RIAF or jet). The radio spectrum of Sgr A*, a supermassive BH in our galaxy, consists of two components, which dominate below and above 86 GHz. Yuan et al. (2003) found that the component above 86 GHz can be well explained by the thermal electrons from the RIAF, while low-frequency radio spectrum can be explained if there exists a small fraction of nonthermal electrons in the RIAF (see also Özel et al. 2000).

It is natural that both the thermal and nonthermal electrons exist in the hot plasma (RIAF or disk corona), since turbulence, magnetic reconnection, and weak shocks can accelerate electrons and generate a nonthermal tail at high energies in the distribution function of thermal electrons. Sgr A* provides an excellent observational evidence for the existence of the hybrid of thermal and nonthermal electrons in accretion flows (e.g., RIAF), since no evident radio jet was observed up to now and therefore its radio emission may be dominated by other mechanisms. It is interesting to note that there is also independent observational evidence for nonthermal electrons in accretion flows. McConnell et al. (2000) reported a high-energy tail in the hard state of the X-ray binary, Cygnus X-1, extending from 50 keV to ~5 MeV. The data at MeV energies, collected with the COMPTEL instrument of the Compton Gamma-Ray Observatory, can be explained by a power-law distribution of nonthermal electrons in the RIAF/corona (e.g., Romero et al. 2010). In this work, we try to explore whether the nonthermal electrons in RIAF can explain the radio emission of nearby LLAGNs, which always have only compact radio cores.

2. SAMPLE

To examine whether the radio emission of nearby LLAGNs with only compact cores can be explained by nonthermal electrons in RIAF, we search the literature for high-resolution radio and X-ray data to ensure that their emission is from the nuclei of the sources. In the radio band, we only selected the sources that have been observed by high-resolution radio telescopes (e.g., VLA, MERLIN, VLBA, and VLBI), and which are mainly chosen from Ho & Ulvestad (2001), Filho et al. (2006), and Nagar et al. (2005); all these works tried to give a complete radio imaging survey of all nearby LLAGNs given in the Palomar spectroscopic survey (Ho et al. 1997). For the purpose of our study, we exclude the sources with observed radio jet or even linear radio structures where the radio emission may mainly originate from the jets/outflows. The 5 GHz nuclear radio luminosities are shown in Table 1, where two sources observed at other wavebands (NGC 1097 at 8.4 GHz and NGC 4736 at 15 GHz) were converted to 5 GHz by assuming \( F_{\nu} \propto \nu^{-0.5} \) as given in Ho et al. (2001) for LLAGNs. In the X-ray band, we only selected the sources that have compact X-ray cores, which were observed by the high-resolution telescopes of Chandra and/or XMM-Newton. Several sources with high-resolution optical data from the Hubble Space Telescope are also included in building the SEDs (Eracleous et al. 2010 and references therein). Maoz et al. (2005) gave lower limits for the intrinsic AGN optical emission for a sample of LINERs, which were constrained from their optical variabilities. We also include the lower limits of the intrinsic AGN optical emission for three sources (NGC 3998, NGC 4594, and NGC 4736; Maoz 2007). We estimate the BH mass from the velocity dispersion \( \sigma \) of the host bulges for LLAGNs in our sample using the relation given by Tremaine et al. (2002). Most velocity dispersions are selected from the Hyperleda database\(^1\) with one exception, NGC 1097, which is from Eracleous et al. (2010). We find that the velocity dispersion of most LLAGNs in our sample is consistent with that reported in Ho et al. (2009). Our sample includes 20 LLAGNs (see Table 1).

3. MODEL

In this work, we consider the RIAF model proposed by Yuan et al. (2003), which can be considered to be an updated version of the original ADAF (e.g., Narayan & Yi 1995), where both outflows and the possible existence of nonthermal electrons are considered. We briefly summarize the model as follows.

A more accurate global structure and dynamics of the accretion flow is calculated numerically to obtain the ion and electron temperature and density at each radius. In particular,

\(^1\) http://leda.univ-lyon1.fr
we employ the approach suggested by Mannmoto (2000) for calculating the structure of the RIAF in the general relativistic frame, which allows us to calculate the structure of the accretion flow surrounding either a spinning or a nonspinning BH. In this work, we calculate the global structure of the accretion flows surrounding massive Schwarzschild BHs. Instead of using a constant accretion rate, we assume that the accretion rate is a function of radius, e.g., $M = M_{\text{out}}(R/R_{\text{out}})^{\delta}$ (e.g., Blandford & Begelman 1999; Stone et al. 1999; Igumenshchev & Abramowicz 1999; Stone & Pringle 2001; Li & Cao 2009; Yuan & Bu 2010), where $R_{\text{out}}$ is the outer radius of the RIAF and $M_{\text{out}}$ is the accretion rate at $R_{\text{out}}$. The global structure of the RIAF can be calculated with proper outer boundaries, if the parameters $\dot{m}$, $\alpha$, $\beta$, and $\delta$ are specified (see Mannmoto 2000 for more details). All radiation processes (synchrotron, bremsstrahlung, and Compton scattering) are included self-consistently in the calculations of the RIAF structure. The parameter $\dot{m} = M/M_{\text{Edd}}$ is the dimensionless accretion rate, where the Eddington accretion rate is defined as $M_{\text{Edd}} = 1.4 \times 10^{18} M_\odot / R_g$ g s$^{-1}$. For the viscosity parameter $\alpha$ and magnetic parameter $\beta = P_B / P_{\text{out}}$ (defined as the ratio of the gas to the total pressure (sum of gas and magnetic pressure)), we adopt typical values of $\alpha = 0.3$ and $\beta = 0.9$, which are widely used in RIAF models. There is obviously a degeneracy between $\dot{m}_{\text{out}}$ and $s$ when the accretion rate at the innermost region of the RIAF is concerned. We adopt $s = 0.3$ in this work, which is well constrained from the observation of our Galactic center BH, Sgr A* (Yuan et al. 2003; but see also Yuan et al. 2012 for the slightly higher value of $s \sim 0.4–0.5$ from simulations). We fix the outer boundary at 5000 $R_g$ ($R_g = GM_{\odot}/c^2$ is the gravitational radius), which is roughly consistent with the prediction of the disk–corona evaporation model for the LLAGNs with very low Eddington ratios (e.g., $10^{-7} \lesssim L_{2–10\text{keV}} / L_{\text{Edd}} \lesssim 10^{-4}$; Liu & Taam 2009). The most poorly constrained parameter is $\delta$, which describes the fraction of the turbulent dissipation that directly heats the electrons in the flow. Sharma et al. (2007) found that the parameter $\delta$ may be in the range of $\sim 0.01–0.3$ based on the simulations, depending on the model details. In this work, we adopt $\delta = 0.1$ because we find that the X-ray spectra of most LLAGNs in our sample can be fitted well with this fixed $\delta$ value.

Following Yuan et al. (2003), we assume that the injected energy in the nonthermal electrons is equal to a fraction $\eta$ of the energy in thermal electrons, where we take $\eta$ to be independent of the radius. The thermal electrons are assumed to have the relativistic Maxwell–Boltzmann distribution, while the nonthermal electrons are assumed to be the power-law tail of the thermal electrons, which can be described by the parameter $p (n(y) \propto y^{-p}$, where $y$ is the electron Lorentz factor). The number density of the nonthermal electrons can be obtained if $\eta$ is given. Özelt et al. (2000) proposed that the parameters $p$ and $\eta$ describing the nonthermal electrons are degenerate in the radio waveband in our model. Therefore, we adopt a fiducial value of $p = 3.0$ and allow the parameter $\eta$ to be free.

After determining the distribution of thermal and nonthermal electrons, we calculate their radiation. The synchrotron emission from both thermal and nonthermal electrons is calculated (e.g., Yuan et al. 2003). The Comptonization of seed photons from both thermal and nonthermal electrons are considered, which was calculated by the method proposed by Coppi & Blandford (1990). In spectral calculations, the gravitational redshift effect...
Figure 1. Top panel shows the typical spectrum of the RIAF with both thermal and nonthermal electrons for \( M_{\text{BH}} = 10^8 M_\odot \), \( \dot{m}_{\text{out}} = 10^{-2} \), \( \eta = 1\% \), and \( p = 3.0 \) at \( R_{\text{out}} = 5000 R_g \), where the short-dashed, long-dashed, and solid lines are the radiation from the thermal electrons, nonthermal electrons, and their sum, respectively. The dotted lines represent the radiation of the nonthermal electrons in the RIAF with different outer radii at 3000 \( R_g \), 1000 \( R_g \), and 500 \( R_g \) (from top to bottom), respectively. The bottom panel shows the spectrum from the nonthermal electrons with \( p = 2.5, \eta = 0.5\% \) (solid line); \( p = 3.0, \eta = 1\% \) (dashed line); and \( p = 3.5, \eta = 5\% \) (dotted line), respectively, where the other parameters are the same as above.

is considered, while the relativistic optics near the BH is neglected. More details about the spectrum calculation can be found in Yuan et al. (2003 and references therein).

In summary, our model has only two free parameters, \( \dot{m}_{\text{out}} \) and \( \eta \), in fitting the SED of LLAGNs.

4. RESULTS

We present the typical spectrum of the RIAF with a population of hybrid electrons in Figure 1 (top panel), where the short-dashed, long-dashed, and solid lines represent the emission from the thermal electrons, nonthermal electrons, and their sum, respectively, where typical parameters \( M_{\text{BH}} = 10^8 M_\odot \), \( \dot{m}_{\text{out}} = 10^{-3} \), and \( \eta = 1\% \) are adopted for a given outer radius \( R_{\text{out}} = 5000 R_g \). In this model, the X-ray emission mainly comes from the Comptonization of seed photons produced by both thermal electrons and nonthermal electrons. We find that the low-frequency radio emission is dominated by the self-absorbed synchrotron emission from the nonthermal electrons, which is normally 2–3 orders of magnitude higher than that from thermal electrons in RIAF. Our results are similar for other parameters if the typical parameter \( \eta \) of \( 5\% \) is adopted, such as that used in Sgr A* (Yuan et al. 2003, 2006). The high-energy X-ray emission dominantly comes from the inner region of the accretion flows (e.g., within several tens of gravitational radii). However, we find that the region of the radio emission is much larger. The dotted lines in Figure 1 (top panel) show the spectrum from the nonthermal electrons with outer boundary \( R_{\text{out}} = 3000 R_g, 1000 R_g \), and 500 \( R_g \), respectively, for the other parameters given above. We find that the radiation region of the low-frequency radio emission at several GHz can be up to several thousands of gravitational radii, where the radio emission at \( \geq 3000 R_g \) is negligible. The bottom panel of Figure 1 shows the spectrum of nonthermal electrons with \( p = 2.5, \eta = 0.5\% \) (solid line); \( p = 3.0, \eta = 1\% \) (dashed line); and \( p = 3.5, \eta = 5\% \) (dotted line), where the other parameters remain the same as above. It can be found that \( p \) and \( \eta \) are degenerate for radio emission (e.g., \( \geq 10 \) GHz; see also Özel et al. 2000). Therefore, it should be impossible to determine \( p \) and \( \eta \) from the observational low-frequency radio emission alone.

Our calculations show that the X-ray emission from the RIAF is almost proportional to the BH mass for a given \( \dot{m} \), and it scales as \( \dot{m}^q \) with \( q \simeq 2 \) for a given BH mass (see also Wu & Cao 2006; Merloni et al. 2003). In this work, we further explore the possible relation between the radio luminosity and BH mass/accretion rate for the RIAF model with both thermal and nonthermal electrons, where the radio emission originates dominantly from the nonthermal electrons. Figure 2 (top panel)
shows the relation between radio luminosity and BH mass for $m_{\text{out}} = 10^{-2}$ and $m_{\text{out}} = 10^{-4}$ with $\eta = 1\%$, respectively, where we find that the radio emission is roughly proportional to $M_{\text{BH}}^{0.4}$ (solid lines). The bottom panel of Figure 2 shows the relation between the radio luminosity and dimensionless accretion rate for given BH masses $M_{\text{BH}} = 10^7$ and $10^9 M_\odot$, respectively, where we find that the radio emission is roughly proportional to $m^\eta$ with $\eta \approx 0.8$ for both cases. To explore the radio emission for a sample of LLAGNs with different BH masses as a whole, we define the mass-corrected radio-loudness as $R_m = R_X/M_{\text{BH}}^{0.4}$ and the Eddington-scaled X-ray luminosity, $L_{2-10\,\text{keV}}/L_{\text{Edd}}$, where $R_X = L_{5\,\text{GHz}}/L_{2-10\,\text{keV}}$. The solid points represent the LLAGNs in our sample, and the solid lines represent the model prediction with the parameter $\eta = 10\%$, 1\%, 0.1\%, 0.01\%, and 0\% (from top to bottom), respectively.

![Figure 3: Relation between the mass-corrected radio loudness, $R_m = R_X/M_{\text{BH}}^{0.4}$, and the Eddington-scaled X-ray luminosity, $L_{2-10\,\text{keV}}/L_{\text{Edd}}$, where $R_X = L_{5\,\text{GHz}}/L_{2-10\,\text{keV}}$. The solid points represent the LLAGNs in our sample, and the solid lines represent the model prediction with the parameter $\eta = 10\%$, 1\%, 0.1\%, 0.01\%, and 0\% (from top to bottom), respectively.](image)

In this work, we explore the hybrid thermal–nonthermal synchrotron emission from the hot accretion flows of the RIAF. Such hot accretion flows are expected to exist in sources with low-mass accretion rates (e.g., LLAGNs). We calculate the spectrum of the global RIAF model with hybrid electrons and find that synchrotron emission from the nonthermal electrons can be up to 2–3 orders of magnitude greater than that from the purely thermal electrons even with only a few percent of the electron thermal energy injected into the nonthermal electrons. This model has explained the multi-wavelength spectrum of Sgr A* very well (Yuan et al. 2003), and we further extend this model to other nearby LLAGNs, which have only a compact radio core and have no evidence of the jet. Our model can roughly reproduce the observed anticorrelation between the mass-corrected radio loudness and Eddington ratio as found in the LLAGNs. We further perform the detailed modeling of the SED for 20 LLAGNs in our sample from the radio to X-ray waveband. We find that the SED of LLAGNs can be well described by our model, where the X-ray emission is produced predominantly by the inverse Compton scattering of the seed synchrotron photons produced by both thermal and nonthermal electrons in the RIAF, while the radio emission mainly comes from the nonthermal electrons.

It is now established that RQ AGNs are not radio-silent and do emit radio emission at some level. Ho & Ulvestad (2001) found that 85\% of nearby Seyfert nuclei show nuclear radio emission at 5 GHz, and their typical radio morphology is a compact core (either unresolved or slightly resolved). Anderson et al. (2004) observed six nearby LLAGNs with high-resolution VLBA, and found that the radio emission is still unresolved even at the milliarcsecond scale, which roughly corresponds to several to tens of thousands gravitational radii. Therefore, contrary to the RL AGNs that have been directly observed with jet or core-jet structures, the physical origin of the radio emission in RQ AGNs is less clear. The most popular model is that there may exist a scaled-down version of the jet in RQ AGNs. The coupled RIAF–jet model has been explored to fit the multiwavelength spectrum of LLAGNs (e.g., Wu et al. 2007; Yuan et al. 2009a; Yue et al. 2011; Nemmen et al. 2012). We note that it is reasonable to apply the RIAF–jet model to the sources with observed jet structures (e.g., FR Is), while it is still controversial whether the same model can be used for LLAGNs with only compact radio cores, where these sources have no evident jet structure even at the scale of several thousands of gravitational radii. Another possibility is that the radio emission in RQ AGNs also originates in the hot plasma (e.g., RIAF in LLAGNs and disk-corona in bright AGNs), where the turbulence, weak shocks, and/or magnetic reconnection events may occasionally accelerate a fraction of the electrons to a harder power-law tail. The synchrotron emission from these nonthermal power-law electrons may account for the radio emission from the compact cores of these LLAGNs. The hybrid thermal–nonthermal synchrotron emission from the RIAF has reproduced well the two components of the radio spectrum and also the X-ray flares observed in Sgr A* (e.g., Yuan et al. 2003). We confirm the result that pure RIAF always underpredicts the radio emission for nearby LLAGNs (Wu &
Figure 4. Models for the SEDs of LLAGNs. The solid points represent the observed emission, and the empty circles denote the lower limit for the intrinsic AGN optical emission derived from the variability of the optical emission. The short-dashed and long-dashed lines represent the emission from the thermal and nonthermal electrons of the RIAF, respectively, while the solid line shows the radiation from both components.

Cao 2005). However, the low-frequency radio emission of the compact cores in LLAGNs can be accounted for if only a small fraction of the viscous dissipation energy in the accretion flow goes into accelerating electrons to a nonthermal power-law distribution (see Figures 4 and 5). It is well established that magnetic reconnection is unavoidable and play an important role in converting the magnetic energy into particles (e.g., Hawley & Balbus 2002; Goodman & Uzdensky 2008). Both the magnetic
reconnection itself (e.g., Ding et al. 2010) or the diffusive shock caused by the violent plasma motions in the magnetic reconnection region (e.g., Spruit 1988) can naturally accelerate a small fraction of the electrons to a power-law distribution. A small fraction of the power-law electrons present in the RIAF will not affect the global structure of the RIAF (e.g., Özel et al. 2000). Therefore, our work provides the possibility that the radio emission of nearby LLAGNs may originate in the nonthermal electrons of the hot accretion flow. It may be similar for other bright RQ AGNs, where the radio emission is dominated by
the nonthermal electrons in the corona. Laor & Behar (2008) found similarities of the radio/hard X-ray correlation in RQ AGNs and magnetically active stars, which support the fact that the radio emission of RQ AGNs also dominantly comes from the corona as in active stars. We will further test this issue in a subsequent work for bright RQ AGNs considering the possible physical mechanism for the production of thermal and nonthermal electrons in the corona above the SSD.

Ho (2002) found a strong anticorrelation between the radio loudness and Eddington ratio for the LLAGNs (see also Sikora et al. 2007; Panessa et al. 2007; Younes et al. 2012). We investigate the dependence of the mass-corrected radio loudness, \( R_{M} = R_{M} / M_{BH}^{1.4} \), on the Eddington ratio, \( L_{2-10\, keV} / L_{Edd} \), where the scaling of \( M_{BH}^{1.4} \) is derived from our model as \( L_{X} \propto M_{BH} \) and \( L_{R} \propto M_{BH}^{1.4} \). We find that the mass-corrected radio loudness is still anticorrelated with the Eddington ratio, where both quantities are not affected by the mass term. It is interesting to note that the dependence of the radio emission on the BH mass, \( L_{R} \propto M_{BH} \), in our model is similar to that of the jet model (e.g., Heinz & Sunyaev 2003) and that derived from the observed fundamental plane of BH activity (Merloni et al. 2003; Falcke et al. 2004). Therefore, we should be cautious in concluding that the origin of the radio and X-ray emission is similar for the stellar-mass BH X-ray binaries (XRBs) and the supermassive BH AGNs based only on the fundamental plane equation of the BH activity, since the dependence of the radio emission on the BH mass is similar for our model and the jet model. We find that the relation between the radio luminosity and X-ray luminosity is \( L_{R} \propto L_{X}^{3.0} \) at a given BH mass in our model based on \( L_{R} \propto m_{i}^{0.8} \) and \( L_{X} \propto m_{i}^{2.0} \). Our model prediction for the radio–X-ray correlation is much shallower than that observed in XRBs (e.g., Gallo et al. 2003; Corbel et al. 2003) or that predicted by the accretion-jet model (e.g., Yuan & Cui 2005), where \( L_{R} \propto L_{X}^{0.7} \). Our results provide a diagnostic that can distinguish the possible origin of the radio emission in LLAGNs by investigating the radio–X-ray correlation for LLAGNs with the same or similar BH masses. However, our present sample is still limited, which prevents us from further testing this issue.

From a theoretical perspective, there are still some uncertainties in the current RIAF model with hybrid thermal and nonthermal electrons. The dependence of the spectrum on the model parameters have been explored in former works (e.g., Quataert & Narayan 1999; Özel et al. 2000). The RIAF spectrum is not sensitive to some parameters (e.g., \( \alpha, \beta \)); we adopt the typical values \( \alpha = 0.3 \) and \( \beta = 0.9 \), which are constrained from observations and/or simulations. The wind parameter \( s = 0.3 \) is adopted directly, which is constrained from observations of Sgr A*. We adopt the radius \( R_{out} = 5000 R_{g} \) as the outer boundary. We find that the X-ray emission mainly comes from the innermost region of the accretion flow, which is less affected by the outer boundary condition if it is larger than several tens of gravitational radii. However, we find that the low-frequency radio emission comes from the much larger regions from several tens to several thousands of gravitational radii. The LLAGNs in our sample have very low Eddington ratios (\( 10^{-4} \lesssim L_{2-10\, keV} / L_{Edd} \lesssim 10^{-1} \)), and the whole accretion may be through RIAF. Liu & Taam (2009) proposed that the truncation radius should be around one thousand to several tens of thousands of gravitational radii (if the possible outer SSD is present) for \( m \sim 10^{-4} \) to \( 10^{-2} \) as adopted when the SED of the LLAGNs was fit in our sample. Therefore, the assumption of the outer boundary \( R_{out} = 5000 R_{g} \) should be reasonable and will not affect our main results. The region of the radio emission from the nonthermal electrons in RIAF is more or less consistent with the size of the compact radio cores as observed by the VLBI for some nearby LLAGNs (e.g., Wroblewski & Ho 2006). We neglect the contribution of the emission from the possible outer SSD (if present) in our SED fits, since we still do not know whether or not the outer SSD still exists in LLAGNs with extremely low Eddington ratios, and the optical emission also easily suffers from contamination from the host galaxies or is contaminated by the nuclear starbursts. For example, Storchi-Bergmann et al. (2005) reported an evidence of recent starburst formation in the nucleus of NGC 1097, and its optical/UV emission may be dominated by stellar contribution. We find that our model prediction on the optical emission is slightly lower than the observed emission but higher than the lower limits of the possible intrinsic AGN optical emission derived from optical variabilities. Therefore, the observed optical emission of LLAGNs is roughly consistent with our model predictions even without considering the possible contribution from the outer SSD (e.g., Figures 4 and 5). The parameter \( \delta \), which describes the fraction of turbulent dissipation that directly heats the electrons in the flow, is still unclear and may be in the range of several percent up to several tens of percent based on recent simulations (e.g., Sharma et al. 2007) and/or model fitting of the Sgr A* (Yuan et al. 2003, 2006). We find that most LLAGNs in our sample can be better fitted if \( \delta = 0.1 \) is adopted (see Figures 4 and 5). It should be noted that the adopted \( \delta = 0.1 \) is slightly smaller than that used in Sgr A* (\( \delta = 0.3 \); Yuan et al. 2003), which may be caused by different microphysics since the accretion rate in Sgr A* is much smaller than that used in our work. Our results will be roughly unchanged even if we use \( \delta = 0.3 \), such as that used in Sgr A* (e.g., Yuan et al. 2006), but the model fitting of the X-ray emission is less perfect as that with \( \delta = 0.1 \). The values of \( p \) and \( \eta \) that describe the nonthermal electrons are not strongly constrained, but are degenerate for low-frequency radio emission (e.g., Özel et al. 2000). We fix the typical value of \( p = 3.0 \), and then adjust the parameter \( \eta \) to fit the radio emission of LLAGNs in our sample. We find that only a small fraction of the energy in nonthermal electrons is sufficient to produce the radio emission at low frequencies. The value of \( \eta \) can even be smaller if the parameter \( p \) is also smaller. Our fitting results show that the value of \( \eta \) in these LLAGNs of our sample is more or less consistent with that constrained for Sgr A* (e.g., \( \sim 1\% \) in Yuan et al. 2003, 2006) and that derived from the gamma-ray background (e.g., \( \sim 4\% \) in Inoue et al. 2008).

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REFERENCES

Abramowicz, M. A., Chen, X., Kato, S., Lasota, J.-P., & Regev, O. 1995, ApJ, 438, 37
Anderson, J. M., Ulvestad, J. S., & Ho, L. C. 2004, ApJ, 603, 42
Barvainis, R., Lehar, J., Birkinshaw, M., Falcke, H., & Blundell, K. M. 2005, ApJ, 618, 108
Blandford, R. D., & Begelman, M. C. 1999, MNRAS, 303, L1
Blandell, K. M., & Kuncic, Z. 2006, ApJ, 668, 103
Cao, X. 2010, ApJ, 724, 855
