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Ivan Almeida – Universidade de São Paulo
Rodrigo Nemmen – Universidade de São Paulo
Ka-Wah Wong – Minnesota State University
Qingwen Wu – Huazhong University of Science and Technology
Jimmy A. Irwin – University of Alabama

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The multiwavelength spectrum of NGC 3115: hot accretion flow properties

Ivan Almeida,[1★] Rodrigo Nemmen,[1] Ka-Wah Wong,[2,3] Qingwen Wu[4] and Jimmy A. Irwin[5]

[1] *Universidade de São Paulo, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Departamento de Astronomia, São Paulo, SP 05508-090, Brazil*
[2] *Eureka Scientific, Inc., 2452 Delmer Street Suite 100, Oakland, CA 94602-3017, USA*
[3] *Department of Physics and Astronomy, Minnesota State University, Mankato, MN 56001, USA*
[4] *School of Physics, Huazhong University of Science and Technology, Wuhan 430074, China*
[5] *Department of Physics and Astronomy, University of Alabama, Box 870324, Tuscaloosa, AL 35487, USA*

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ABSTRACT

NGC 3115 is the nearest galaxy hosting a billion solar mass black hole and is also a low-luminosity active galactic nucleus (LLAGN). X-ray observations of this LLAGN are able to spatially resolve the hot gas within the sphere of gravitational influence of the supermassive black hole. These observations make NGC 3115 an important test bed for black hole accretion theory in galactic nuclei since they constrain the outer boundary conditions of the hot accretion flow. We present a compilation of the multiwavelength spectral energy distribution (SED) of the nucleus of NGC 3115 from radio to X-rays. We report the results from modelling the observed SED with radiatively inefficient accretion flow (RIAF) models. The radio emission can be well-explained by synchrotron emission from the RIAF without the need for contribution from a relativistic jet. We obtain a tight constraint on the RIAF density profile, $\rho(r) \propto r^{-0.73^{+0.01}_{-0.02}}$, implying that mass-loss through subrelativistic outflows from the RIAF is significant. The lower frequency radio observation requires the synchrotron emission from a non-thermal electron population in the RIAF, similarly to Sgr A*.

Key words: accretion, accretion discs – black hole physics – galaxies: individual: NGC 3115.

1 INTRODUCTION

NGC 3115 is a nearby lenticular galaxy (Menezes, Steiner & Ricci 2014, distance of 9.7 Mpc) hosting the nearest $>10^9\ \mathrm{M}_{\odot}$ black hole (Kormendy et al. 1996; Emsellem, Dejonghe & Bacon 1999). Its central supermassive black hole (SMBH) is accreting at low rates with a Bondi accretion rate of $\dot{M}_{\mathrm{B}} = 2 \times 10^{-4} \dot{M}_{\mathrm{Edd}}$ (Wong et al. 2014), where $\dot{M}_{\mathrm{Edd}} = 10 L_{\mathrm{Edd}}/c^2$ is the Eddington mass accretion rate and hosts a low-luminosity active galactic nucleus (LLAGN). As such, the SMBH in NGC 3115 is thought to be accreting in the radiatively inefficient accretion flow (RIAF) mode (for a comprehensive review see Yuan & Narayan 2014).

Thanks to the Megasecond *Chandra* X-ray Visionary Project observation of NGC 3115's SMBH (PI: Irwin), Wong et al. (2011) placed the first direct observational constraints on the spatially and spectroscopically resolved structures of the X-ray emitting gas inside the Bondi radius (R_{B}) of a black hole. Wong et al. (2011, 2014) measured the temperature and density profiles of the hot gas from a fraction out to tens of the Bondi radius (R_{B} = 2.4–4.8 arcsec = 112–224 pc). The density profile is broadly consistent with $\rho \propto r^{-1}$ similarly to the case of Sgr A* and M87 for which emission within R_{B} can also be resolved with *Chandra* (Wang et al. 2013; Russell et al. 2015). The observed density profile is in stark contrast with the $\rho \propto r^{-3/2}$ profile expected from Bondi accretion and simple RIAF models (Narayan & Yi 1994).

These *Chandra* observations give us an unprecedented level of details on the gas surrounding the SMBH in NGC 3115, providing us with an unique characterization of the outer boundary conditions of an underfed SMBH in a nearby galaxy. Therefore, NGC 3115 is one of the best test beds for the theory of low-density plasmas and hot accretion in the vicinity of compact objects.

The goal of this paper is to compile the broad-band, multiwavelength spectral energy distribution (SED) of the accreting SMBH in the nucleus of NGC 3115, and model the observed SED with radiative RIAF models – as appropriate for LLAGNs – assessing along the way whether theory reproduces observations.

The structure of this paper is as follows. In Section 2, we describe the SED data compiled from previous observations. Section 3 describes the physical model that we adopted in order to interpret and fit the SEDs and the modelling results. In Section 4, we contextualize our results given what is currently known from the observational

★ E-mail: ivan.almeida@usp.br

Table 1. SED data.

ν (Hz)	νL_ν (erg s^{-1})	$\Delta\nu L_\nu$ (erg s^{-1})	Resolution
1.40E+09[a]	6.92E + 34	3.45E+34	5.9 arcsec
5.00E+09[b]	<1.86E + 35		5 arcsec
8.50E+09[a]	3.10E + 35	1.33E+35	0.17 arcsec
5.55E+14[c]	<1.80E + 40		∼0.1 arcsec
6.82E+14[d]	<3.66E + 38		∼8 arcsec
4.84E+17[d]	<5.51E + 38		25 arcsec
(1.2-14.5)E+17[e]	<4.4E + 37		0.5 arcsec

References: [a]Wrobel & Nyland (2012) [b]Fabbiano, Gioia & Trinchieri (1989) [c]Lauer et al. (2005) [d]Wu & Cao (2005) [e]Wong et al. (2014).

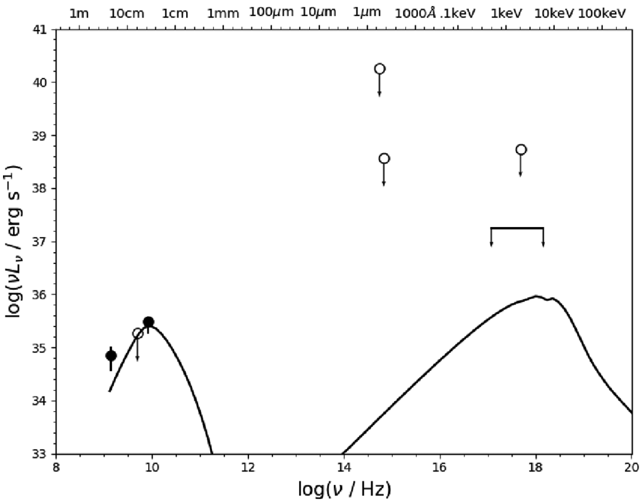

Figure 1. SED of NGC 3115 with Table 1 data. The plot is the best thermal obtained fit, with $s = 0.77$ and $\delta = 0.095$.

and theoretical side of LLAGNs and black hole accretion theory. We conclude by presenting a summary of our results in Section 5.

2 OBSERVATIONS

We compiled the multiwavelength observations of NGC 3115 previously available in the literature, in order to gather the SED and proceed with the modelling. The data we were able to find cover from radio to X-rays energies; the observations were obtained with the Very Large Array (VLA), *Spitzer*, *GALEX*, and *Chandra*. All the SED data points are presented in Table 1 and displayed in Fig. 1 . We adopted the same distance for computing all luminosities.

We treat the two observations that comprise the optical-ultraviolet portion of the SED as upper limits, since there is not enough information to infer the true emission of the LLAGN – our primary interest in this work – and thus these data points may potentially include considerable contamination by host galaxy emission (Lauer et al. 2005).

3 SED MODELLING

Given that NGC 3115 hosts a sub-Eddington LLAGN, presumably accreting in the RIAF mode, we use a semi-analytical approach to treat the radiation from this system in which the accretion flow is considered stationary assuming a α-viscosity and a pseudo-Newtonian gravity, and the radiative transfer is treated in considerable detail, taking into account synchrotron, inverse Compton scattering, and bremsstrahlung processes (e.g. Nemmen et al. 2006; Yu, Yuan & Ho 2011; Nemmen, Storchi-Bergmann & Eracleous 2014).

We do not consider the contribution to the emission by an optically thick, geometrically thin accretion disc for two reasons. First, at the low accretion rates in NGC 3115, we do not expect a coherent thin disc (Yuan & Narayan 2014); secondly, there are not enough observational constraints in the SED in the near-Infrared and optical in order to meaningfully constrain the presence of the thin disc. Furthermore, given that NGC 3115 displays only compact radio emission and shows no evidence for the presence of extended jets, we do not incorporate the contribution of a relativistic jet.

Our model for the RIAF emission follows Nemmen et al. (2014) (cf. also e.g. Yu et al. 2011). We now describe the main parameters of this model. RIAFs are characterized by the presence of outflows or winds, which prevent a considerable fraction of the gas that is available at large radii from being accreted on to the black hole (see Yuan & Narayan 2014, for a review on recent analytical and computational advances). In order to take this mass-loss into account, we introduce the parameter s to describe the radial variation of the accretion rate as $\dot{M}(R) = \dot{M}_{\rm o}\,(R/R_{\rm o})^s$ (or $\rho(R) \propto R^{-3/2+s}$), where $\dot{M}_{\rm o}$ is the rate measured at the outer radius $R_{\rm o}$ of the RIAF (Blandford & Begelman 1999).

The other parameters that describe the RIAF solution are the black hole mass M; the viscosity parameter α; the modified plasma β parameter, defined as the ratio between the gas and total pressures, $\beta = P_{\rm g}/P_{\rm tot}$; the fraction of energy dissipated via turbulence that directly heats electrons δ; and the adiabatic index γ.

Following Nemmen et al. (2014), in our calculations, we adopt the typical choice of parameters $\alpha = 0.3$, $\beta = 0.9$, $\gamma = 1.5$, and $R_o = 10^4 R_S$. Traditional RIAF models adopted δ to be small ($\delta \lesssim 0.01$; e.g. Yuan & Narayan 2014).

Given considerable observational efforts to constrain the properties of the accreting black hole in NGC 3115, important empirical priors are available for our modelling leaving very little freedom in the SED model. We adopt the black hole mass $M = 2\times10^9\,{\rm M}_\odot$ as estimated by Kormendy et al. (1996). Using $M = 10^9\,{\rm M}_\odot$ gives essentially the same results. We fix the outer accretion rate as $\dot{M}_o = \alpha\dot{M}_{\rm B} = 6\times10^{-5}\dot{M}_{\rm Edd}$, where we take into account the appropriate RIAF outer boundary conditions (Narayan & Yi 1995) and the Bondi rate constrained by Wong et al. (2014).

We end up with only two free parameters in the modelling: The s parameter that sets the RIAF density profile and δ. We allow only s to vary within the limits obtained from *Chandra* X-ray constraints on the density profile within 3 arcsec (140 pc) by Wong et al. (2014), roughly $s \approx 0.6$–1.26. Given the theoretical uncertainty related to the value of δ, we allow it to vary over the range $0.01 \le \delta \le 0.5$ (Sharma et al. 2007; Howes 2010).

In this work, we adopted a iterative procedure where we changed individually the parameters, keeping the others fixed, until we find the set of values that best reproduces visually the observations (Nemmen et al. 2014). With only two free parameters, this task is made immensely more convenient.

In Fig. 1, we show the observations and the best model fit. The solid line is the predicted spectrum of the accretion flow for NGC 3115 with $s = 0.77$ and $\delta = 0.095$. The model is consistent with all observations except the lower frequency radio point at 1.4 GHz, which is underpredicted. We estimated a rough uncertainty of 0.02 in the value of s in order to fit the radio data. Keeping all parameters fixed to the above values and varying only δ, we estimate that a rough uncertainty on 0.01 in δ is consistent with the observations.

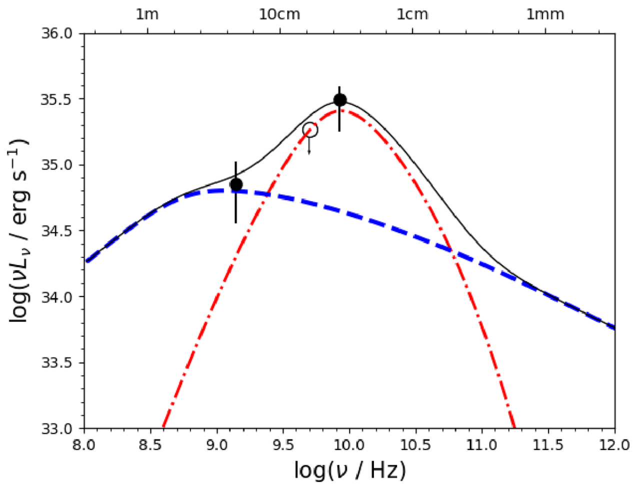

Figure 2. Similar to Fig. 1, but with emission from non-thermal electrons included in the model. The dashed line represents emission from the non-thermal electrons and the dash-dotted line represents the thermal emission. The solid line is the sum of the two components.

It is known that the compact radio emission in LLAGNs is underpredicted by models which only account for synchrotron emission from a thermal distribution of electrons in the RIAF. In the case of radio-loud LLAGNs, the excess radio emission is naturally explained by the relativistic jet (e.g. Wu, Yuan & Cao 2007; Yu et al. 2011; Nemmen et al. 2014). Liu & Wu (2013) modelled a sample of LLAGNs where they excluded the sources which display evidence of resolved radio jets; they found that the compact radio emission for this sample is well-explained by an alternative model where the synchrotron emission includes the contribution of a non-thermal electron distribution in the RIAF – in addition to a thermal component, similar to Sgr A* (Yuan, Quataert & Narayan 2003). In these models, the origin of the non-thermal electron component is due to a non-specified particle acceleration process such as *Fermi* first order process (e.g. Sironi, Keshet & Lemoine 2015).

We incorporate the non-thermal electron distribution following the approach of Liu & Wu (2013). The thermal electrons are assumed to follow a relativistic Maxwell–Boltzmann distribution and the non-thermal electrons follow a power-law tail $n_{\rm e} \propto \gamma^{-p}$, where $n_{\rm e}$ is the number density of non-thermal electrons and γ is the electron Lorentz factor. Assuming the energy in non-thermal electrons is a fraction η of the energy in thermal electrons, the number density of non-thermal electrons can be derived. The synchrotron emission from thermal electrons and non-thermal electrons can be calculated with the above thermal and non-thermal electron distributions.

The RIAF SED model incorporating non-thermal electrons successfully explains the 1.4 GHz data point, as can be seen in Fig. 2. This figure shows the best-fit non-thermal model where we fixed all parameters shared with the thermal-only model. The resulting values for the free parameters in this case are $s = 0.76$, $\delta = 0.1$, and $\eta = 3$ per cent, where we adopted a typical value of $p = 3$ for power-law index for the non-thermal electron distribution.

4 DISCUSSION

In our modelling of the SED, we obtained a rough constraint on the fraction of the turbulent energy that heats the electrons as $\delta = 0.095 \pm 0.01$; δ-values outside this range – for a fixed value of s – considerably underpredict or overpredict the radio emission. The resulting value of 0.095 is comfortably within the range of values $\sim$0.01–0.5 predicted by more sophisticated models for the electron heating in RIAFs (Bisnovatyi-Kogan & Lovelace 1997; Quataert & Gruzinov 1999; Sharma et al. 2007; Howes 2010; cf. Xie & Yuan 2012 for an overview).

Chandra X-ray observations of the hot diffuse gas on scales of $\sim$100 pc (2 arcsec) placed constraints on the density profile of $s \approx 0.72 - 1.11$ ($\rho(r) \propto r^{-(0.39\,-\,0.78)}$) (Wong et al. 2014). The results of our modelling place much tighter constraints on the inner density profile for the accretion flow in NGC 3115. We found the resulting range $s = 0.76$–0.79; the higher s-values are from the SED models including only thermal electrons, whereas the lower-end s-values come from the models with non-thermal electron contribution. Apart from Sgr A* (Yuan et al. 2003; Yuan, Shen & Huang 2006), this is the best constraint for the density profile – and correspondingly mass-loss ratio – in a LLAGN.

The above constraint on s should provide valuable input to studies of the dynamics of RIAFs. For instance, they suggest that the amount of mass-loss through winds in RIAFs is not as extreme as proposed by some authors. For example, Begelman (2012) revised the adiabatic inflow-outflow solution (ADIOS) model and proposed that s should be one. This is disfavoured by our results; on the contrary, this seems to give support to the numerical simulations of Yuan, Wu & Bu (2012a) and Yuan, Bu & Wu (2012b). Yuan et al. (2012a) performed 2D numerical hydrodynamical simulations of RIAFs with a large dynamical range; they found $s \approx 0.5$–0.7. Our results are more consistent with Yuan's work.

Related to the non-thermal electron RIAF model, the parameters η and p are degenerated in reproducing the low-frequency radio spectrum (e.g. Özel, Psaltis & Narayan 2000), where η will be lower for smaller p. For a typical value $p = 3$, we obtain $\eta \sim 3$ per cent in NGC 3115, which is quite consistent with the constraints obtained from nearby LLAGNs and Sgr A* (e.g. $\eta \sim 1$ per cent; Yuan et al. 2003; Liu & Wu 2013).

It is worth comparing our results with those of Shcherbakov (2014) who also modelled the gas accretion in NGC 3115. The main difference in their approach is that they take into account gas injection by stars in the nuclear star cluster and the effect of energy injection by supernova explosions, electron heat conduction, and Coulomb collisions – among other effects – and do not include viscosity and rotation. They compared their model with the spatially resolved X-ray observations and from their fits obtained an upper limit to the mass accretion rate on to the SMBH of $\dot{M} = 2 \times 10^{-3}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$. From our best-fitting RIAF model, $\dot{M}(R_{\rm o}) = 3 \times 10^{-3}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ at the RIAF outer radius $R_{\rm o}$. Given the considerable amount of mass-loss in the accretion flow, $\dot{M}(3R_S) = 5 \times 10^{-6}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ at the innermost stable circular orbit for a Schwarzschild black hole; this is consistent with the Shcherbakov (2014) accretion rate upper limit. Furthermore, they estimate a shallow density profile ρ r^{-1} over a large dynamic range. Therefore, their estimated radial dependency of the density is roughly in agreement with our results.

One model that remains to be better explored in the future for NGC 3115 is the chaotic cold accretion (CCA; Gaspari, Ruszkowski & Oh 2013; Gaspari, Temi & Brighenti 2017b) flow. The CCA model takes into account cooling effects and associated thermal instabilities as the gas flows from the larger galactic scales down to the SMBH, which could lead to the condensation of cold clouds. Interestingly enough, the CCA model predicts $\rho(r) \propto r^{-(0.7\,-\,1)}$ (Gaspari, private communication), which is in agreement with our results. The cold and chaotic mode of accretion in the CCA model boosts the SMBH accretion rate to levels of up to $100\dot{M}_{\rm B}$; this is in stark contrast with our work, where we fix the outer accretion rate to $\dot{M}(R_o) \sim 0.1\dot{M}_B$ according to RIAF theory expectations (Section 3). It will be worth in the future to test the CCA model with, for example, Integral Field Unit observations (Gaspari et al. 2017a) of NGC 3115.

We should now point out some of the limitations in our model. The dynamical structure of the flow is based on the solution to stationary, height-integrated, one-dimensional equations describing a RIAF in a pseudo-Newtonian potential (Narayan & Yi 1995; Yuan, Ma & Narayan 2008) adopting an α-prescription for the viscosity (Shakura & Sunyaev 1973). The radiative transfer is carried out on top of this simplified flow structure with considerable detail (Yuan, Cui & Narayan 2005; Nemmen, Storchi-Bergmann & Eracleous 2014). Nowadays, there is considerable interest in treating in more details the dynamics and radiation spectra of RIAFs using multidimensional, general relativistic radiative magnetohydrodynamics (GRRMHD) numerical simulations (e.g. Chan et al. 2015; Ryan, Dolence & Gammie 2015; O'Riordan, Pe'er & McKinney 2016; Ryan et al. 2017). We should stress that 1D stationary RIAF spectral models are still very useful even though sophisticated 3D GRRMHD simulations are available. The 1D models are much computationally faster for generating SED models to compare with observations, whereas in the case of 3D simulations this is not usually practical. Furthermore, 1D models can provide useful insights to understand the physics, something which is harder to get from 3D GRRMHD simulations.

One may wonder how the resulting SED and radiative efficiency from our simplified models compare with those of more advanced, numerical simulations. Recently, Ryan et al. (2017) performed a GRRMHD simulation of an RIAF including a detailed treatment of the electron thermodynamics and evolving a two-temperature plasma and a frequency-dependent radiative transport. This simulation is able to predict multiwavelength SEDs and the behaviour of the radiative efficiency $\epsilon \equiv L/(\dot{M}c^2)$ as a function of $\dot{M}$. We estimate the accretion rate at the black hole from our SED models as $\dot{M} = (R_S/R_o)^s \approx 10^{-7}\dot{M}_{\rm Edd}$; the corresponding radiative efficiency in our model is $\epsilon \approx 10^{-4}$ (Xie & Yuan 2012). Satisfyingly, Ryan et al. (2017) computed $\epsilon = 2.6 \times 10^{-4}$ from their GRRMHD model for a comparable accretion rate. This is a neat consistency check of our calculations.

5 CONCLUSIONS

NGC 3115 is the only galactic nucleus besides Sgr A* and M87 for which the sphere of gravitational influence of the black hole – the Bondi radius – can be spatially resolved in X-rays. Due to the well-determined Bondi accretion rate from *Chandra* observations, there are only two free parameters in the SED modelling, which are related to the density profile and the electron heating rate in the accretion flow, i.e. the global dynamics and the electron thermodynamics. We have analysed the broad-band, multiwavelength SED of NGC 3115 in order to obtain information about the physics of the massive black hole in its low-luminosity AGN. Our main conclusions are the following:

(i) NGC 3115 does not require a relativistic jet in order to account for the radio emission: it is well-explained by synchrotron emission from the hot accretion flow.

(ii) The lower frequency (1.4 GHz) radio observation is underpredicted by a thermal synchrotron emission from the RIAF. This suggests that a small fraction of non-thermal electrons is required to account for this observation, similar to Sgr A*.

(iii) We obtained an independent constraint $\rho \propto r^{-0.73^{+0.01}_{-0.02}}$ or $\dot{M} \propto r^{0.77^{+0.02}_{-0.01}}$ on the inner density profile. This result implies that mass-loss through subrelativistic outflows from the RIAF is significant in this accreting system. This is also consistent with previous *Chandra* estimates as well as theoretical RIAF expectations about the role of winds.

(iv) We constrain the fraction of viscous energy that directly heats electrons as $\delta \approx 0.095$. This is consistent with theoretical studies of dissipation in collisionless plasmas, which suggest that electrons receive a significant fraction of the viscously dissipated energy in the flow.

(v) The radiative efficiency from our stationary, one-dimensional model, $L/(\dot{M}c^2) \approx 10^{-4}$, is very similar to the corresponding efficiency resulting from a recent general relativistic radiative MHD numerical simulation for a comparable accretion rate.

The fact that this source lacks an extended relativistic jet suggests that the central black hole is slowly spinning, otherwise a stronger jet would be produced via the Blandford–Znajek mechanism (e.g. Blandford & Znajek 1977; Tchekhovskoy, Narayan & McKinney 2011). Since the size and shape of a rapidly spinning SMBH is markedly different from that of a Schwarzschild hole, the slowly-spinning hypothesis could, in principle, be tested with Event Horizon Telescope (EHT) observations (Doeleman et al. 2012) resolving the shadow cast by the SMBH in NGC 3115. The predicted size of the event horizon shadow for a Schwarzschild black hole is $2\sqrt{27}GM/c^2 \approx 10\mu$as (Bardeen 1973; Luminet 1979), which could be resolvable with the EHT at mm-wavelengths (Falcke & Markoff 2013). However, NGC 3115's LLAGN flux is only 10^{-7} of Sgr A*'s flux; it will be very hard to even detect any radio emission at all – and much less a SMBH shadow – with the EHT sensitivity for this faint LLAGN.

There are only a few high-angular-resolution observations of the NGC 3115's nucleus; most of the measurements were obtained with low angular resolution and are contaminated by galactic emission (e.g. stellar populations, dust) as a consequence. More high-angular-resolution observations for this source in the mm to X-rays range will be instrumental in order to better test the physics of accretion flows and collisionless plasmas in LLAGNs.

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