AN ACCRETION-JET MODEL FOR M87: INTERPRETING THE SPECTRAL ENERGY DISTRIBUTION AND FARADAY ROTATION MEASURE

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ABSTRACT

M87 is arguably the best supermassive black hole (BH) to explore jet and/or accretion physics, due to its proximity and fruitful high-resolution multi-waveband observations. We model the multi-wavelength spectral energy distribution (SED) of the M87 core that observed at a scale of 0.4 arcsec ($\sim 10^7 R_g$, $R_g$ is gravitational radius), as recently presented by Prieto et al. Similar to Sgr A*, we find that the millimeter bump as observed by the Atacama Large Millimeter/submillimeter Array can be modeled by the synchrotron emission of the thermal electrons in an advection-dominated accretion flow (ADAF), while the low-frequency radio emission and X-ray emission may predominantly come from the jet. The millimeter radiation from ADAF predominantly comes from the region within $10 R_g$, which is roughly consistent with the recent very long baseline interferometry observations at 230 GHz. We further calculate the Faraday rotation measure (RM) from both ADAF and jet models, and find that the RM predicted from the ADAF is roughly consistent with the measured value, while the RM predicted from the jet is much higher if jet velocity close to the BH is low or moderate (e.g., $v_j \lesssim 0.6 c$). With the constraints from the SED modeling and RM, we find that the accretion rate close to the BH horizon is $\sim (0.2-1) \times 10^{-3} M_\odot$ yr$^{-1}$ ($M_\odot$ is Bondi accretion rate), where the electron density profile, $n_e \propto r^{-3}$, in the accretion flow, is consistent with that determined from X-ray observation inside the Bondi radius and recent numerical simulations.

Key words: accretion, accretion disks – black hole physics – galaxies: individual (M87) – galaxies: jets

1. INTRODUCTION

The giant radio galaxy M87 is one of the well-known radio-loud low-luminosity active galactic nuclei (AGNs). It is an excellent laboratory for investigating the accretion and jet physics because of its proximity, with a distance of $D = 16.7 \pm 0.6$ Mpc (Jordán et al. 2005; Blakeslee et al. 2009) and a large estimated black hole (BH) mass of $(3-6.6) \times 10^9 M_\odot$ (Macchetto et al. 1997; Gebhardt et al. 2011; Walsh et al. 2013). The bolometric luminosity of the core is estimated to be $L_{bol} \sim 2.7 \times 10^{42}$ erg s$^{-1}$, $\sim 3.6 \times 10^{10} L_\odot$ ($L_\odot$ is Eddington luminosity, Prieto et al. 2016), which is several orders of magnitude less than those of Seyferts and quasars. The quite low Eddington ratio in M87 suggests that it most likely accretes through a radiatively inefficient accretion flow (see Yuan & Narayan 2014 for a recent review and the references therein). Recent high spatial resolution Chandra X-ray observations have resolved the Bondi radius, $R_{Bondi} \approx 0.2 kpc \approx 8 \times 10^5 R_g$, where $R_g = GM_\odot/c^2$ is the gravitational radius (Russell et al. 2015). In combination with the inferred gas density at the Bondi radius being about 0.3 cm$^{-3}$, the Bondi accretion rate is estimated to be $\dot{M}_B \approx 0.2 M_\odot$ yr$^{-1}$ (e.g., Russell et al. 2015), which indicates that either the radiative efficiency of the accretion flow is very low ($\eta \sim L_{bol}/\dot{M}_B c^2 \approx 10^{-4}$) or most of the matter at the Bondi radius is not captured by the BH, or both.

The Galactic center BH (Sgr A*) and the supermassive BH in the center of the Virgo cluster (M87), are the two largest BHs on the sky, with putative event horizons subtending $\sim 53$ and 38 $\mu$as, respectively (e.g., Ricarte & Dexter 2015). The Event Horizon Telescope (EHT), a planed Earth-sized array at millimeter (mm) and submillimeter (submm) wavebands, provides well-matched horizon-scale resolution for Sgr A* and M87 (e.g., Doeleman et al. 2009), which greatly help to study the accretion and/or jet physics in both sources (e.g., Doeleman et al. 2008; Huang et al. 2009; Mościbrodzka et al. 2009; Dexter et al. 2010; Broderick et al. 2011; Fish et al. 2011; Li et al. 2009; Yuan et al. 2009; Nemmen et al. 2014; Mościbrodzka et al. 2016), where the radio emission is produced by the jet in both models while the millimeter/submillimeter and X-ray emission can either come from the jet or ADAF.

Apart from the continuum spectrum, linear polarization can be a diagnostic of the relativistic jets and accretion flows...
associated with BH systems. In particular, millimeter/submillimeter polarimetry serves as an important tool for studying the magnetized plasma near a BH through the Faraday rotation of the polarized light. It was found that the accretion rate close the BH ($\lesssim 10 R_g$) is several orders of magnitude lower than the accretion rate at a Bondi radius ($R_B \sim 10^{-6} R_g$) in Sgr A* based on the Faraday rotation measure studies (RM). This is consistent with the product of the thermal electron density and the magnetic field component which is in line with Sgr A* based on millimeter polarimetry. Moreover, it is an important tool for studying the BH structure. In this work, we simply set the Bondi radius is not really accreted by the BH.

Abramowicz et al. (1995; Narayan & Yi 1995; Yuan et al. 2003; Wu, Feng, & Lu, 2016 October 10). Kuo et al. (2014) presented the first constraint on the Faraday RM at millimeter wavelengths for the nucleus of M87 and found that the best fit RM is $-2.1\pm1.8 \times 10^2$ rad m$^{-2}$ (1σ uncertainty). Using the same method as used for Sgr A* (Marrone et al., 2006). Kuo et al. (2014) found that the accretion rate should be below $9.2 \times 10^{-4} M_\odot$ yr$^{-1}$ at a distance of 21 Schwarzschild radii from the BH, which suggests that most of the matter at the Bondi radius is not really accreted by the BH.

Recently, Prieto et al. (2016) presented a high-resolution quasi-simultaneous multi-waveband SED at a scale of ~0.4 arcsec for M87, which is very helpful for exploring the accretion-jet physics. In particular, the evident millimeter bump in the SED of M87 is quite similar to the submm bump of Sgr A* (e.g., Yuan et al. 2003), which may be contributed by the synchrotron emission from the thermal electrons in ADAF. If this is the case, it can be used to constrain the accretion rate near the BH, since for most former works it is believed that the multi-waveband emission of M87 core is dominated by the jet, which prevents us from learning about the underlying accretion physics. Furthermore, the recently reported Faraday RM will put another constraint on the accretion and jet model. The ADAF-jet model in Section 2, and show the main results in Section 3. A discussion and our conclusions are given in Section 4. Throughout this work, we adopt a BH mass of $6.6 \times 10^9 M_\odot$ and a distance of 16.7 Mpc, where $1~\text{mas} = 0.08~\text{pc} = 280~R_g$.

2. ACCRETION-JET MODEL

Due to the low Eddington ratios of M87, we adopt the ADAF model that is widely used in modeling the SED of the quiescent and low-luminosity AGNs (e.g., Ichimaru 1977; Abramowicz et al. 1995; Narayan & Yi 1995; Yuan et al. 2003; Wu & Cao 2006; Wu et al. 2007, 2013; Liu & Wu 2013; Cao et al. 2014). The global structure and dynamics of the accretion flow in general relativistic frame are calculated numerically to obtain the density and temperature of the ion and electron, respectively, at each radius, since the BH may be fast-rotating in M87. The accretion rate at each radius is $M = M_{\text{out}}(R/R_{\text{out}})^{\delta}$, where $M_{\text{out}}$ is the accretion rate at the outer radius, $R_{\text{out}}$, of the ADAF, and $\delta$ is the wind parameter. In this work, we simply set $R_{\text{out}} = R_B$ and $M_{\text{out}} = M_B$. The global structure of the ADAF can be calculated if the parameters $\alpha$, $\beta$, and $\delta$ are specified, where $\alpha$ is viscosity parameter, $\beta$ is the ratio of gas to total pressure (sum of gas and magnetic pressure), and $\delta$ describes the fraction of the turbulent dissipation that directly heats the electrons in the flow (see Mannodo 2000, for more details). For $\alpha$, we adopt typical values of 0.3 as widely used in ADAF models. The value of $\beta$ is typically $0.5-0.9$ (Yuan & Narayan 2014), where $\beta = 0.5$ corresponds to the equipartition between magnetic energy and thermal energy. Similar to modeling of Sgr A*, we adopt $\delta = 0.3$ (e.g., Yuan et al. 2006), which is roughly consistent with simulations by Sharma et al. (2007). We keep $s$ as a free parameter, which can be constrained in SED fitting if other parameters are fixed. We take into account three processes of the radiative cooling, i.e., the synchrotron radiation, the bremsstrahlung, and the multi-Comptonization of soft photons, where the general description of cooling processes and relevant formulae have been presented by Narayan & Yi (1995) and Mannodo (2000) in a more handy way. For calculation of the Comptonization, we adopt the program given by Coppi & Blandford (1990). In spectral calculations, the effect of the bending of light and the gravitational and the Doppler shift of the energy of the photons should be considered. In this work, we consider the gravitational and the Doppler shift of the energy of the photons, while the effect of the bending of light was neglected for simplicity (see more details in Mannodo 2000), which does not affect our main conclusion.

The mechanisms of the jet formation, collimation, acceleration, and dissipation are very unclear. In this work, we adopt a phenomenological jet model due to above uncertainties. We assume that a small fraction of the material in the ADAF is transferred into the vertical direction to form a jet, since the velocity of the accretion flow is supersonic near the BH and a standing shock should occur at the bottom of the jet because of bending. From the shock-jump conditions, we calculate the properties of the post-shock flow, such as the electron temperature $T_e$ (e.g., Yuan & Cui 2005). With high-resolution VLBI observations, Asada & Nakamura (2012) found that the collimation profile of the M87 jet is parabolic on scales up to $\sim 5 \times 10^5 R_g (Z \propto R_g^{0.75 \pm 0.05})$ and then transits to a conical shape beyond that. We adopt this observational parabolic shape in our model. For the jet radiation, we mainly adopt the internal shock model, which is widely used for interpreting gamma-ray burst (GRB) afterglows (e.g., Piran 1999; Spada et al. 2001), the multi-waveband SEDs of XRBs (e.g., Xie & Yuan 2016), and AGNs (e.g., Wu et al. 2007). The internal shock scenario is that the central power engine produces energy that is channeled into jets in an intermittent way, where the faster shells catch up with slower ones, and internal shocks are formed in the jet at a scale of $\sim 10^2 R_g$ ($\Gamma$ is Lorentz factor). These shocks accelerate a fraction of the electrons, $\xi_e$, into a power-law energy distribution with an index $p$. The radiative cooling is also considered self-consistently for the distribution of the accelerated electrons, where the power-law electrons should be truncated at higher energies due to cooling. In this work, we adopt a typical value of $\xi_e = 0.01$ and allow the $p$ to be a free parameter that can be constrained from observations (see Yuan & Cui 2005 for more details and references therein). The energy density of accelerated electrons and amplified magnetic fields are determined by two parameters, $\epsilon_e$ and $\epsilon_B$, which describe the fraction of the shock energy that goes into electrons and magnetic fields, respectively. Obviously, $\epsilon_e$ and $\xi_e$ are not independent. In calculations of the jet spectrum, the emission and absorption of both the thermal electrons and non-thermal electrons are considered. It should be noted that only synchrotron emission is included in calculations of the jet spectrum, where the synchrotron self-Compton in the jet is several orders of magnitude less than the synchrotron emission in the X-ray band (see Wu et al. 2007 for more discussions). The jet inclination angle of $15^\circ$ is adopted (e.g., Wang & Zhou 2009). We treat the mass-loss rate, $\dot{M}_{\text{out}} = M_{\text{jet}}/\dot{M}_{\text{feed}}$, and jet velocity, $v_{\text{jet}}$, as free parameters. In Figure 1, we show a cartoon picture of our model.
sensitive to the jet velocity, as it is roughly unchanged for different jet velocities if we adjust the outflow rate simultaneously (e.g., $m_{\text{jet}} \sim 10^{-7} \text{--} 10^{-5}$ for $v_{\text{jet}} = 0.3 \text{--} 0.9 \, c$, see Table 3). The steep IR to optical data cannot be well reproduced with our ADAF-jet model.

In Figure 3, we present the 230 GHz intensity distribution from the ADAF and jet with the parameters obtained from the above SED modeling. We find that the 230 GHz emission in the ADAF predominantly comes from the region within 10$R_g$ (top panel). However, the 230 GHz emission in the jet comes mainly from the region much larger than 10$R_g$ (bottom panel). Doeleman et al. (2012) found that the 230 GHz emission predominantly comes from a very compact region within $\sim$10$R_g$, which prefers that the millimeter emission come from the thermal electrons in ADAF rather than the synchrotron emission in the jet of our ADAF-jet model.

3.2. Constraints from Faraday RM

The possible contribution to the observed RM includes both the ADAF surrounding the BH and the jet that is possibly perpendicular to the disk. The RM has been used to constrain the accretion rate in ADAF or the outflow rate in the jet for Sgr A* and M87, respectively (e.g., Yuan et al. 2003; Kuo et al. 2014; Li et al. 2015). The RM depends on the distribution of the electron density and magnetic field, which is

$$\text{RM} = 8.1 \times 10^5 \int \log \frac{\gamma_e(z)\delta}{2\gamma_e(z)} n_e(z) B_\parallel dl \text{ rad m}^{-2},$$

where $\gamma_e = \kappa T_e / m_e c^2$ is the electron Lorentz factor, $n_e$ is the electron density in units of cm$^{-3}$, the path length $dl$ in units of pc, and the magnetic field along LOS $B_\parallel$ in units of Gauss. The factor $\log \gamma_e(z)/\gamma_e^2(z)$ is the relativistic correction (Quataert & Gruzinov 2000; Huang & Shcherbakov 2011).

Our SED modeling suggests that the mm emission mainly originates from the inner region of ADAF (e.g., within several $R_g$), which is roughly consistent with recent observations (e.g., Doeleman et al. 2012). The RM that is provided in Kuo et al. (2014) is also inferred from the polarization observation in this waveband. Therefore, the RM may be mainly contributed by the hot plasma in the inner region of the ADAF. Instead of assuming the spherical accretion flow in Kuo et al. (2014), we calculate the RM from our ADAF along the line of sight (LOS; see LOS-1 in Figure 1), where the ADAF is a thick disk ($H/R < 1$). When calculating the RM, we need to know the distribution of electron density and magnetic field. Here, we simply assume $B_\parallel \simeq B_{\text{ADAF}}$ since a large-scale magnetic field is normally needed in the formation of a collimated, relativistic jet. The real RM should be a little bit lower, due to the inclination angle between the magnetic field line and the LOS-1. The observational value of RM is $\sim -2.1 \pm 1.8 \times 10^5 \text{ rad m}^{-2}$, which was derived at $\sim$230 GHz (Kuo et al. 2014). In this work, we calculate the RM along the LOS-1 from $R = 10R_g$ (see Figure 1), where most of the millimeter emission originates from a compact region (Doeleman et al. 2012). For the case of $a_\ast = 0.9$, $\text{RM} = 3.3 \times 10^5 \text{ rad m}^{-2}$ and $7.5 \times 10^5 \text{ rad m}^{-2}$ for $\beta = 0.5$ and 0.9, respectively. For a non-rotating BH with $a_\ast = 0$, $\text{RM} = 1.5 \times 10^6$ and $4.0 \times 10^6 \text{ rad m}^{-2}$ for $\beta = 0.5$ and 0.9, respectively, for slightly higher accretion rates (or weaker wind) near the BH are needed to reproduce the millimeter bump in the SED when compared to the case of $a_\ast = 0.9$ (see Table 2). It should be noted that the RM may be decreased by a factor of 2 if

![Figure 1](image_url). A picture of our ADAF-jet model, where a geometrical thick, optically thin ADAF and parabolic shape of jet are considered. The jet inclination angle is assumed to be 15°, and the disk is perpendicular to the jet. Here, we consider the two possibilities where the polarized emission passes through ADAF itself along LOS-1 and the polarized emission of ADAF passes through the plasma in the jet along LOS-2 (the thick solid lines).
Table 1
M87 Core SED in Quiescent Phase with Aperture Radius of ~0.4

| Frequency (Hz) | Flux (Jy) | Telescope | Date                  | References |
|---------------|-----------|-----------|-----------------------|------------|
| 5.0 × 10^9    | 3.10 ± 0.06 | VLA-A     | 1999 Sep              | 1          |
| 8.4 × 10^9    | 3.02 ± 0.02 | VLA-A     | 2003 Jun and 2003 Aug | 2          |
| 8.4 × 10^9    | 3.15 ± 0.16 | VLA-A     | 2004 Dec              | 2          |
| 15.0 × 10^9   | 2.7 ± 0.1   | VLA-A     | 2003 Jun and 2003 Aug | 2          |
| 22.0 × 10^9   | 2.0 ± 0.1   | VLA-A     | 2003 Jun              | 2          |
| 93.7 × 10^9   | 1.82 ± 0.06 | ALMA      | 2012 Jun              | 2          |
| 108.0 × 10^9  | 1.91 ± 0.05 | ALMA      | 2012 Jun              | 2          |
| 221.0 × 10^9  | 1.63 ± 0.03 | ALMA      | 2012 Jun              | 2          |
| 252.0 × 10^9  | 1.42 ± 0.02 | ALMA      | 2012 Jun              | 2          |
| 286.0 × 10^9  | 1.28 ± 0.02 | ALMA      | 2012 Jun              | 2          |
| 350.0 × 10^9  | 0.96 ± 0.02 | ALMA      | 2012 Jun              | 2          |
| 635.0 × 10^9  | 0.43 ± 0.09 | ALMA      | 2012 Jun              | 2          |
| 2.6 × 10^{10} | (1.3 ± 0.2) × 10^{-2} | Keck   | 2000 Jan 18         | 3          |
| 2.8 × 10^{10} | (1.67 ± 0.09) × 10^{-2} | Gemini | 2001 May             | 4          |
| 1.37 × 10^{11} | (3.3 ± 0.6) × 10^{-3} | HST    | 1998 Jan 16         | 2          |
| 1.81 × 10^{11} | (3.1 ± 0.8) × 10^{-3} | HST    | 1999 Jan 16         | 2          |
| 2.47 × 10^{11} | (2.06 ± 0.18) × 10^{-3} | HST   | 1997 Nov 10         | 2          |
| 3.32 × 10^{11} | (1.38 ± 0.01) × 10^{-3} | HST   | 2003 Jan 19         | 2          |
| 3.70 × 10^{11} | (9.5 ± 1.9) × 10^{-4} | HST   | 2003 Nov 29         | 2          |
| 4.99 × 10^{11} | (6.33 ± 0.63) × 10^{-4} | HST   | 2003 Nov 29         | 2          |
| 6.32 × 10^{11} | (4.13 ± 0.12) × 10^{-4} | HST   | 2003 Nov 29         | 2          |
| 8.93 × 10^{11} | (2.10 ± 0.04) × 10^{-4} | HST   | 2003 May 10         | 2          |
| 8.93 × 10^{11} | (2.16 ± 0.04) × 10^{-4} | HST   | 2003 Mar 31         | 2          |
| 1.11 × 10^{12} | (1.55 ± 0.03) × 10^{-4} | HST   | 2003 May 10         | 2          |
| 1.27 × 10^{12} | (1.05 ± 0.03) × 10^{-4} | HST   | 2003 Jul 27         | 2          |
| 1.36 × 10^{12} | (1.33 ± 0.04) × 10^{-4} | HST   | 2003 Nov 29         | 2          |
| 2.06 × 10^{12} | (4.73 ± 0.47) × 10^{-5} | HST   | 1999 May 17         | 2          |
| 2–10 keV      | (0.70 ± 0.04) × 10^{-12} erg cm^{-2} s^{-1} | Chandra | 2000 Jul 30      | 5          |

References. (1) Nagar et al. (2001), (2) Prieto et al. (2016), (3) Whysong & Antonucci (2004), (4) Perlman et al. (2001), (5) Russell et al. (2015).

Table 2
Model Results from ADAF

| α_0 | β | s | M (10 R_g) (M_⊙ yr^{-1}) | RM (rad m^{-2}) |
|-----|---|---|--------------------------|-----------------|
| 0.9 | 0.5 | 0.52 | 5.8 × 10^{-4} | 2.3 × 10^{6} |
| 0.9 | 0.9 | 0.48 | 9.0 × 10^{-4} | 7.5 × 10^{4} |
| 0.9 | 0.5 | 0.40 | 2.2 × 10^{-3} | 1.5 × 10^{6} |
| 0.9 | 0.9 | 0.37 | 3.1 × 10^{-3} | 4.0 × 10^{5} |

Note. The RMs are calculated from the radius of 10 R_g in the accretion flow from the line of sight.

Table 3
Model Results from Jet

| v_jet (c) | M_jet (M_⊙ yr^{-1}) | P_\gamma (erg s^{-1}) | RM (rad m^{-2}) |
|----------|----------------------|-----------------------|-----------------|
| 0.3      | 1.5 × 10^{-3}       | 4.4 × 10^{42}         | 1.6 × 10^{9}    |
| 0.6      | 2.2 × 10^{-4}       | 4.1 × 10^{42}         | 5.4 × 10^{7}    |
| 0.9      | 1.5 × 10^{-5}       | 2.6 × 10^{42}         | 3.6 × 10^{6}    |
| 0.99     | 1.5 × 10^{-6}       | 3.8 × 10^{42}         | 7.5 × 10^{5}    |

Note. The RMs are calculated from the height of 10 R_g in the jet along the line of sight.

the LOS-1 is along a smaller radius (e.g., R = 2R_g), which is suppressed by the relativistic effect due to higher electron temperature (see Equation (1)). Our main results are unchanged.

The other possible contribution to the observed RM, in addition to the ADAF, may come from the jet. Due to the jet emission at 230 GHz being much larger than the observational size (see bottom panel of Figure 3 and Doeleman et al. 2012), we consider the possibility of the jet as an external origin of the RM, where the polarized emission in the disk passes through the jet along LOS-2 (see Figure 1). We calculate the RM along LOS-2, where the LOS-2 intersects with the jet axis at the point of Z ~ 10R_g in the jet axis due to the millimeter observations being quite compact (e.g., within several R_g, Doeleman et al. 2012). In the jet model, we also assume B_j ~ B_{jet} if the poloidal magnetic field dominates near the BH horizon. The RM = 1.6 × 10^{9} rad m^{-2},
The multi-wavelength SED of M87 has been widely modeled in the literature by the ADAF model (Reynolds et al. 1996; Di Matteo et al. 2003; Wang et al. 2008; Li et al. 2005; Markoff et al. 2008; Maitra et al. 2009 respectively). The millimeter bump, we find that the ADAF cannot reproduce the X-ray emission simultaneously, while the X-ray emission and low-frequency radio emission are better explained by the jet. This conclusion is similar to Yuan & Cui (2005), Wu et al. (2007), and Yuan et al. (2009), where the X-ray emission should be dominated by the jet, not the ADAF, if the Eddington ratio is less than a critical value. It should be noted that our ADAF-jet model cannot explain the optical-UV emission, which may be contributed by the host galaxy (Nemmen et al. 2014; de Jong et al. 2015), and the multi-waveband flux variations may help to test this issue. We find that different BH spin parameters ($a_\ast = 0–0.99$) and magnetic parameters ($\beta = 0.5–0.9$) yield an equivalent fit of the SED, but the accretion rate has to be decreased if high BH spin and stronger magnetic field (lower $\beta$) are adopted. The jet velocity also cannot be constrained from our SED modeling, and we find that it will not affect our above conclusion since that it is degenerated with $m_{\text{jet}}$, where the different jet velocity parameters will lead to different Doppler factors. In the ADAF model, the density profile is $\rho \propto r^{-1.5}$, and $\rho \propto r^{-1}$ for $s \sim 0.4–0.5$, which is quite consistent with that determined by Chandra within the Bondi radius for M87 (Russell et al. 2015). It was also found that the density profile is quite shallow, $\rho \propto r^{-(0.5–1)}$ in Sgr A* and NGC 3115 (e.g., Wang et al. 2013; Wong et al. 2014), which is much shallower than that predicted in “old” ADAF model ($\rho \propto r^{-1.5}$). These results suggest that only a small fraction of the material captured at the Bondi radius reaches the SMBH, which is quite consistent with the recent numerical simulations of the hot flows (e.g., Yuan et al. 2012 and the references therein).

The Faraday RM has been used to constrain the accretion rate in both Sgr A* and M87 (Marrone et al. 2006; Kuo et al. 2014), where they simply assumed a spherical accretion flow surrounding the BH. It may be no problem for Sgr A* due to our LOS possibly being close to the ADAF plane; however, the disk-like ADAF is roughly perpendicular to our LOS in M87 if assuming the jet is perpendicular to the disk (see Figure 1). For this case, the RM cannot be calculated using the same method as Sgr A*. We calculate the RM along the LOS-1 based on the disk-like ADAF (see Figure 1). We find that the RM is around $(0.8–15) \times 10^7$ rad m$^{-2}$, with different parameters of $a_\ast$ and $\beta$, where the wind parameter $s \simeq 0.4–0.5$ has been constrained from SED modeling. Our result is roughly consistent with the observed value of $\sim(2.1 \pm 1.8) \times 10^7$ rad m$^{-2}$ if, in particular, the BH is fast-rotating (e.g., $a_\ast \sim 0.9$) in M87 (e.g., Wu et al. 2007). It should be noted that our above conclusion will not change if the RM is calculated along the LOS-1, even in a smaller radius of ADAF (e.g., $2R_g < R < 10R_g$), where the RM values will decrease by a factor of 2. Besides the ADAF model, we also explore the possibility of a jet, due to the jet emission at the mm waveband being much larger than that of the observations (see Figure 3). Therefore, we only consider the case of a jet as an external origin of the RM (e.g., a polarized source passes through the jet). The RM should be $<7.5 \times 10^7$ rad m$^{-2}$ if the jet velocity is $>0.99c$, where the lower $m_{\text{jet}}$ is needed for modeling the SED with a higher jet velocity. The intrinsic velocity of a core jet in M87 is still not known, where the jet may have complex structure, e.g., a fast spine surrounded by a slower layer, and the observed low-velocity is measured from the slower layer (e.g., Giroletti et al. 2008; Gracia et al. 2009; Xie et al. 2012; Nagai et al. 2014; Wang et al. 2014; Mościbrodzka et al. 2016). Furthermore, the RM will
become lower if the magnetic field is strongly dominated by a toroidal field in the innermost part of the jet or the magnetic field undergoes many reversals along the LOS. In our model, the ADAF model can naturally reproduce the observed RM and we cannot exclude the possibilities of the jet model. Future constraints on the intrinsic velocity of the spine jet (if the jet is spine-layer structure) will help us to further understand this issue.

Similar to Sgr A* (Yuan et al. 2003), we model the millimeter bump of M87 using a thermal disk component. It should be noted that the millimeter/submillimeter bump of both M87 and Sgr A* can also be reproduced by the jet component associated with the jet launching region close to the BH (so-called “jet nozzle,” Falcke & Markoff 2000; Prieto et al. 2016). In this work, we use a simple jet model, with the shape constrained from the observations directly, which do not include such a nozzle. Recently, Li et al. (2015) calculated the RM of Sgr A* based on the jet nozzle model of Falcke & Markoff (2000) and found that the predicted RM is two orders of magnitude less than the observed value, which suggests that this model cannot explain the observed RM, even if it can reproduce the submillimeter bump. It is still unknown whether or not this model can explain the RM of M87, which is beyond our scope.

5. SUMMARY

Using the multi-waveband observational data at a scale of ~0.4 arcsec, we model the multi-wavelength SED of M87 using a coupled ADAF-jet model, where this model is widely adopted for modeling the SEDs of low-luminosity AGNs. The main results are summarized as follows.

(1) We find that the millimeter bump can be naturally reproduced by the synchrotron emission from the thermal electrons in a hot accretion flow of the ADAF, where the radio, optical, and X-ray emission may still dominantly come from the jet.

(2) The millimeter and submillimeter emission of ADAF mainly comes from the inner region of the accretion flow (e.g., \( < 10R_g \)), which is roughly consistent with the recent 230 GHz observations. The density profile of the ADAF \( (n_e \propto r^{-1}) \) is quite consistent with that determined by Chandra within the Bondi radius and the recent numerical experiments.

(3) Based on the analysis of the RM, we find that the RM calculated from the ADAF with the parameters constrained from the SED modeling is roughly consistent with the measured values.

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Note added in proof. After the submission of this manuscript, another work appeared as a preprint (Li et al. 2016), which is similar in content and reaches a very similar conclusion about the accretion and Faraday rotation of M87.

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