The Possible Submillimeter Bump and Accretion-jet in the Central Supermassive Black Hole of NGC 4993

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Abstract

NGC 4993, as a host galaxy of the electromagnetic counterpart of the first gravitational-wave detection of a binary neutron-star merger, was observed by many powerful telescopes from radio to γ-ray wavebands. The weak nuclear activities of NGC 4993 suggest that it is a low-luminosity active galactic nuclei (LLAGNs). We build the multiwaveband spectral energy distributions (SEDs) of NGC 4993 from the literature. We find that the radio spectrum at ~100–300 GHz is much steeper than that of the low-frequency waveband (e.g., 6–100 GHz), where this break was also found in the supermassive black holes (SMBHs) in our galaxy center (Sgr A*), and in some other nearby AGNs. The radio emission above and below this break may have different physical origins, which provide an opportunity to probe the accretion and jet properties. We model the multiwaveband SEDs of NGC 4993 with an advection-dominated accretion flow (ADAF) jet model. We find that the high-frequency steep radio emission at the millimeter waveband is consistent with the prediction of the ADAF, while the low-frequency flat radio spectrum is better fitted by the jet. Furthermore, the X-ray emission can also be simultaneously explained by the ADAF model. From the model fits, we estimate important parameters of the central engine (e.g., the accretion rate near the horizon of the black hole and the mass-loss rate in the jet) for NGC 4993. This result strengthens the theory that the millimeter, submillimeter, and deep X-ray observations are crucial to understanding the weak or quiescent activities in SMBH systems. Further simultaneous millimeter and X-ray monitoring of this kind of LLAGN will help us to better understand the physical origin of multiwaveband emission.

Key words: accretion, accretion disks – black hole physics – galaxies: individual (NGC 4993) – galaxies: jets

1. Introduction

It is now widely believed that most, if not all, galaxies harbor a supermassive black hole (SMBH) with a mass of $10^6$–$10^{10} M_\odot$. Different levels of nuclear activity are found in different types of galaxies, ranging from the most active and luminous active galactic nuclei (AGNs), to the less active low-luminosity AGNs (LLAGNs), to the quiescent normal galaxies, such as our own. The activities of different types of galaxies mainly determined and coevolved with the activities of the central SMBH. The most luminous AGNs (e.g., quasars and narrow-line Seyfert Is) host SMBHs accreting at sub-Eddington rates through the standard disk or even with a super Eddington rate through the slim disk (e.g., Shakura & Sunyaev 1973; Abramowicz et al. 1988; Wang et al. 2014). For nearby LLAGNs or even quiescent normal galaxies (e.g., weak Seyfert, LINERs), the central SMBHs normally accreting through advection-dominated accretion flow (ADAF), where most of the gravitational energy released by accreting matter is advected into the central BH when the accretion rate is less than a critical value of ~0.1% of the Eddington rate (e.g., Abramowicz et al. 1995; Narayan & Yi 1995; Yuan & Narayan 2014). The strongly evolved accretion processes are also found in stellar-mass BH X-ray binaries (XRBs), where the X-ray spectra also strongly evolved during outburst (e.g., Wu & Gu 2008) and show similar features as those in AGNs (e.g., Wang et al. 2004; Gultekin et al. 2009).

Compact radio cores and/or weak jets are widely observed in nearby LLAGNs (e.g., Falcke & Markoff 2000; Ho 2002). The radio emission is normally much higher than the radiation of the thermal electrons in ADAF and is normally more consistent with a jet/wind origin or emission from nonthermal electrons in ADAF (e.g., Yuan et al. 2003; Liu & Wu 2013). This phenomenon is also found in XRBs, where the radio emission is stronger in the low/hard state, while it becomes weaker or disappears in the high/soft state (e.g., Abramowicz et al. 1995). Due to the appearance of the jet in LLAGNs and low/hard state XRBs, the origin of their multiwaveband emission is always under debate. Markoff et al. (2005, 2008) proposed that most of the radiation from radio to X-rays may be dominated by the jet in the low accretion regime. However, both ADAF and jet contribution are considered in modeling the multiwaveband spectral energy distribution (SED) of LLAGNs (e.g., Wu et al. 2007; Yu et al. 2011; Nemmen et al. 2014), where the radio emission is always dominated by the jet, while the X-ray emission is either dominated by the ADAF or by the jet depending on the Eddington ratio (e.g., Yuan & Cui 2005). The millimeter excess was found in both nearby LLAGNs and also in some bright Seyferts (e.g., An et al. 2005; Doi et al. 2005, 2011; Behar et al. 2015; Doi & Inoue 2016; Prieto et al. 2016). This excess suggests the possible different physical origins compared the low-frequency radio emission. Doi et al. (2011) suggested that the millimeter emission should come from the AGN cores, where the other possibilities are also discussed, but is unlikely. The synchrotron emission from the hot thermal electrons in ADAF radiate at the submillimeter waveband, which was used to constrain the accretion flow in Sgr A* and M87 (e.g., Yuan et al. 2003; Feng et al. 2017). Behar et al. (2015) suggested that the high-frequency excess in the millimeter waveband should be correlated to the accretion flow (e.g., corona produced by the magnetic activity around the accretion disk) based on a 95 GHz observation on a sample of...
radio-quiet AGNs. Baldi et al. (2015) found that the millimeter variability is similar to that of X-ray emission in NGC 7469, which further supports that they may have the same origin (e.g., associated with the accretion disk corona).

NGC 4993 is a nearby S0 galaxy, which is the host galaxy of the EM counterpart for the GW170817A (Abbott et al. 2017). It has a redshift of $z = 0.009873$, corresponding to a distance of $\approx 40$ Mpc (Levan et al. 2017). The weak [O III], [N II], and [S II] emission lines are presented in the nuclear, and the relatively high ratio of [N II]λ6583/Hα is suggestive of LLAGNs rather than star formation (which may also be driven by some hot post-AGB stars or shocks, e.g., Levan et al. 2017). The nuclear activities are also clearly detected at other wavebands (e.g., radio, submillimeter, and X-rays; Haggard et al. 2017; Kim et al. 2017), which suggests that the central BH still shows weak activities and has not fully gone into the quiescent state.

The accretion-jet physics has been widely explored in LLAGNs, where the radio and X-ray wavebands are normally used to constrain the models (e.g., Wu et al. 2007; Yuan et al. 2009; Nemmen et al. 2014). The millimeter observations also play an important role in helping us to understand the BH activities. However, the millimeter observations, particularly high-resolution observations such as ALMA, are still rare for BH sources. Fortunately, many ground- and space-based telescopes observed and monitored the event of GW170817A because it was the first electromagnetic counterpart of the gravitational wave (Abbott et al. 2017). The observational data, including the millimeter observations by ALMA, of its host galaxy were also fruitful, which can help us to explore the SMBH activities. In this work, we explore the accretion-jet process for the SMBH in NGC 4993 based on the most recent multiwavelength observations, where the submillimeter and deep Chandra observations can help us to understand the accretion-jet properties for the SMBH in the weak or quiescent state.

### 2. Data

The GW170817A and its host galaxy were observed by the Very Large Array (VLA) and Atacama Large Millimeter/submillimeter Array (ALMA) from August 18 (approximately a half day after the GW event) to September 25. The radio emission of the host galaxy is unresolved in both VLA and ALMA observations at a resolution of $\sim0\prime\prime.1$–1$\prime\prime$ (corresponding to $<20$–200 pc at a distance of 40 Mpc). During the above observations, for approximately one month, both VLA and ALMA observations show $\sim20\%$ variations, which suggest the activities of the central BH (Alexander et al. 2017). The imaging from the Very Long Baseline Array (VLBA) also find an unresolved core or a marginally resolved source on a scale smaller than the VLBA synthesized beam ($2.5 \times 1.0$ mas) with a 9$\sigma$ flux density of $0.22 \pm 0.04$ mJy and a brightness temperature of $1.6 \times 10^{6}$ K (Deller et al. 2017). Haggard et al. (2017) presented two deep Chandra observations on September 1–2, where both the GW counterpart and its host galaxy are detected. The compact X-ray source is consistent with the nucleus of the galaxy with a hard X-ray spectrum (photon index $\Gamma = 1.5 \pm 0.4$). This X-ray emission is most likely due to a weak LLAGN. We also include the Hubble Space Telescope (HST), 2MASS, Spitzer, Pan-STARRS (PS1), GALEX, WISE, and Very Large Telescope (VLT) observations, where the photometry has been measured using Kron apertures or 1$\prime$ apertures centered on the host galaxy.
3. The ADAF and Jet Model

Due to the weak activities in NGC 4993, the SMBH should accrete the surrounding material through the ADAF. We simply introduce the model as below, and more details can be found in Yuan & Cui (2005), Wu et al. (2007), and Feng et al. (2017).

We numerically solve the global structure of the ADAF, where the ion and electron temperature, density, angular momentum, and radial velocity at each radius can be obtained. The accretion rate is \( M = M_{\text{out}}(R/R_{\text{out}})^q \), where the possible wind is considered \( (s = \text{the wind parameter}) \) and \( M_{\text{out}} \) is the accretion rate at the outer radius, \( R_{\text{out}} \). In this work, we simply set \( R_{\text{out}} = 10^4 R_g \) \( (R_g \text{ is gravitational radius}) \), and the wind parameter \( s = 0.4 \) as constrained in Sgr A* and M87 (e.g., Yuan et al. 2003; Feng & Wu 2017). For other parameters in ADAF, we adopt the typical values that are widely used in modeling LLAGNs and XRBs, where the viscosity parameter of \( \alpha = 0.3 \), the ratio of gas to total pressure \( \beta = 0.5 \), and the fraction of the turbulent dissipation that directly heats the electrons in the flow \( \delta = 0.1 \) (see Mammoto 2000; Liu & Wu 2013; Yuan & Narayan 2014 for more details). The radiation of synchrotron, bremsstrahlung, and Compton scattering are considered consistently in our calculations, where synchrotron photons are Compton scattered by the hot electrons and produce the radiation in the optical to X-ray waveband. At a sufficiently low \( \dot{m} \), Comptonization becomes much weaker and the X-ray spectrum may be dominated by bremsstrahlung emission. The \( M_{\text{out}} \) is set as a free parameter.

Compared to the accretion processes, the physics in the jet is very unclear (e.g., jet formation and jet acceleration; Cao 2016a, 2016b). We assume that a small fraction of the accreting material was transferred into the jet (outflow rate \( M_{\text{out}} \)). The shock will occur due to the collision of shells with different velocities in the outflow. We adopt the internal shock scenario that has been used to explain the broadband SEDs of XRBs, AGNs, and afterglow of gamma-ray bursts (e.g., Piran 1999; Yuan & Cui 2005; Wu et al. 2007; Nemmen et al. 2014; Xie & Yuan 2016). These shocks accelerate a fraction of the electrons, \( \xi_e \), into a power-law energy distribution with an index \( p \). In this work, we fix \( \xi_e = 0.01 \) and allow the \( p \) to be a free parameter that can be constrained from observations (e.g., Yuan & Cui 2005). The energy density of accelerated electrons and amplified magnetic field 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. Only synchrotron emission is considered in the calculation 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). We set the size of the jet as \( \sim 10^5 R_g \), which is derived from the VLBA observations. The jet viewing angle and jet velocity are unclear, we simply set \( \theta_j = 20^\circ \) and \( v_{\text{jet}} = 0.6c \) in our calculations, where the subrelativistic velocity is adopted as in most of the nearby LLAGNs (e.g., Wu et al. 2007; Nemmen et al. 2014; Feng & Wu 2017). The free parameters are \( M_{\text{jet}}, \epsilon_e, \epsilon_B, \) and \( p \) in the jet model.

![Figure 1. Multi-waveband spectrum for NGC 4993, where the solid circles represent the radio data observed by VLA, the open squares represent the radio data observed by the VLBA, the solid squares represent the submillimeter emission observed by AMLA, open circles represent the infrared-optical data observed by Spitzer/VLT/HST, respectively. The bow tie is the X-ray observations. The dotted, dashed, and solid lines represent the ADAF, jet, and their total spectrum, respectively.](image-url)

4. Result and Discussion

We find that the radio spectrum cannot be simply described by a single power-law function \( F_\nu \propto \nu^{-\beta} \), where a break seems to exist at \( \sim 100 \text{GHz} \) (see Figure 1). For the radio observations at 6–100 GHz, the power-law spectral index is \( k \approx 0.14 \), which is a slightly inverted spectrum. However, the spectral index is \( k \approx -1.3 \) at 97.5–338.5 GHz that observed by ALMA, which is much steeper than that of the low-frequency radio spectrum. This feature is also found in nearby LLAGNs (e.g., An et al. 2005; Doi et al. 2005, 2011; Doi & Inoue 2016; Prieto et al. 2016) and even in some Seyferts (e.g., Behar et al. 2015). In particular, the submillimeter bumps are very evident in the two best studied nearby SMBHs, Sgr A* and M87 (e.g., An et al. 2005; Prieto et al. 2016). This feature implies that they come from two different components. The X-ray spectrum is quite hard with \( \Gamma = 1.5 \pm 0.4 \), which is consistent with other nearby LLAGNs. The mid-infrared to ultraviolet emission is much higher than those of other wavebands, which is measured with a large aperture (e.g., \( \sim 1' \)) and may dominantly come from the host galaxies.

The central velocity dispersion is \( \sigma_v \approx 170 \text{ km s}^{-1} \) for NGC 4993 (Levan et al. 2017), the BH mass \( M_{\text{BH}} \approx 8 \times 10^7 M_\odot \) can be obtained from the \( M_{\text{BH}} - \sigma_v \) relations (Gultekin et al. 2009). We present our SED modeling for NGC 4993 in Figure 1. The steeper radio spectrum at \( \sim 100–300 \text{GHz} \) is roughly consistent with that prediction of ADAF, where the ADAF can also explain the hard X-ray spectrum as observed by Chandra (the dotted line). The accretion rate at \( 10^5 R_g \) is \( M_{\text{out}} = 5.3 \times 10^{-3} M_{\text{edd}} \) and the accretion rate at the inner region of the accretion flow \( M(R_g) = 3.3 \times 10^{-4} M_{\text{edd}} \). We note that most of the radiation comes from the accreting matter in the inner region of the accretion flow near the BH horizon (e.g., within \( 10 R_g \)), which is not sensitive to the accretion rate at the outer boundary \( (M_{\text{out}}) \). The low-frequency radio emission is much higher than the prediction of the ADAF and can be better explained by the jet model, where \( M_{\text{jet}} = 1 \times 10^{-6} M_{\text{edd}} \), \( \epsilon_e = 0.06 \), \( \epsilon_B = 0.02 \), and \( p = 2.4 \). It should be noted that there is degeneracy in jet parameters (e.g., jet speed, outflow rate, magnetic field, etc.), which will not affect our
main conclusion on the origin of the radio emission. It is difficult for the jet model to explain the hard X-ray spectrum, where the jet emission can contribute at the soft X-ray waveband at some level. Based on our modeling results, we find that the ratio of the mass-loss rate in the jet to the accretion rate estimated at $5 R_g$, $M_{\text{jet}}/M(5R_g) \approx 4 \times 10^{-3}$. In other words, only a small fraction of 0.4% of the mass that ultimately accreted by the BH is channeled into the jet. As expectation, the IR bump in the SED, measured with a larger aperture cannot be fitted by the ADAF-jet model, which should dominantly come from the old stellar population in the host galaxy (e.g., Nemmen et al. 2014). The detailed SED modeling of NGC 4993 allows us to put an independent constraint on the mass accretion rate into the BH and the jet mass-loss rate.

The origin of the multiwaveband emission in LLAGNs and, particularly, in quiescent galaxies, is always under debate. For the low-frequency radio emission in NGC 4993, the unresolved emission is much higher than the prediction from star formation as constrained from the SED modeling of the host galaxies, where the radio spectrum is also much shallower than that observed in star-forming galaxies (e.g., Blanchard et al. 2017). The compact radio emission (mas scale or pc scale) detected by VLBA in the central region of NGC 4993 with a brightness temperature exceeding $10^6$ K and $\sim 20\%$ of radio variability further suggests the presence of an LLAGN, and the radio emission should not be seriously contaminated by the host galaxy (e.g., Alexander et al. 2017; Andreoni et al. 2017). The low-frequency radio emission (e.g., up to several tens GHz) is much higher than the prediction of the pure ADAF and the flat spectrum with $k \sim 0.1$ being more consistent with the jet (e.g., Figure 1).

The high-resolution submillimeter observations on the nearby LLAGNs are still very limited, where a possible submillimeter bump is found in the two most well studied LLAGNs of Sgr A* and M87. The ALMA observations of NGC 4993 provide us with valuable information on the submillimeter waveband, due to the fact that NGC 4993 is the host galaxy of the gravitational-wave event GW170817A. The possible millimeter-wave excess (not the full submillimeter bump) is also found in some of the nearby LLAGNs and Seyferts (e.g., Doi et al. 2005, 2011; Behar et al. 2015; Doi & Inoue 2016). Doi & Inoue (2016) discussed the different physical origins of the high-frequency excess component based on the Seyfert galaxy NGC 985, where they found that the excess may originate from the free–free emission of the cloud in the broad emission line region, synchrotron jet free–free absorbed by a circumnuclear photoionized region and/or self-absorbed nonthermal synchrotron from disk corona, and rule out the possibilities of the dust emission at the Rayleigh–Jeans regime, compact jets under synchrotron self-absorption, or thermal synchrotron from ADAF. For NGC 4993, there are no far-infrared observations and we cannot constrain the possible contribution of millimeter emission from the dust even though it is not important, as was found in NGC 985 (e.g., Doi & Inoue 2016). The free–free or bremsstrahlung emission is considered in our ADAF model, which may contribute at the radio to X-ray wavebands. However, our calculations show that the radio and X-ray radiation from the free–free emission are much less than those from the Synchrotron and inverse-Compton radiation, respectively, for the same population of hot electrons in ADAF. Therefore, the free–free emission from the ADAF cannot explain the radio to millimeter emission in NGC 4993. The free–free emission from the possible broad-line region clouds should also not be important, since there is no optical evidence of broad lines in NGC 4993. The steep millimeter emission should also not originate from the synchrotron self-absorption, where the spectral peak at $\geq 300$ GHz is much larger than that of young radio galaxies (e.g., O'Dea 1998). The mild variability ($\sim 20\%–30\%$) at 97.5 GHz within a half-month further suggests that millimeter emission of NGC 4993 should mainly come from the BH activities, not from the host (e.g., Alexander et al. 2017). Markoff et al. (2008) proposed that the millimeter bump, including the other multiwaveband spectra, can be explained by the pure jet emission, where the millimeter emission was attributed to the quasi-thermal distribution of electrons in the nozzle at the base of the jet. It should be noted that the synchrotron emission from the quasi-thermal electrons from the nozzle of the jet should be more or less similar to that of ADAF. In our jet model, we did not include this nozzle since we naturally include the hot electrons in accretion flow. Doi & Inoue (2016) found that the synchrotron emission from ADAF is insufficient for the millimeter excess in NGC 985, which may be caused by the adoption of the old self-similar ADAF solution and an important fraction of gravitational energy in the accretion flow can heat electrons directly in the updated ADAF model (e.g., $\delta = 0.1–0.5$, see also Section 3). It should be noted that the property of corona in bright AGNs should be more or less similar to that of ADAF (e.g., optically thin hot plasma with $T_e \sim 10^7$ K), and, therefore, the millimeter excess in both LLAGNs and bright AGNs may be related to the hot plasma either in ADAF or corona (e.g., ADAF/coronal outflow/wind, or a not well collimated subrelativistic jet; Behar et al. 2015). The multiwaveband correlation in variability may help us to distinguish their possible origins.

It was suggested that the X-ray emission should be dominated by the ADAF and jet for the Eddington-scaled X-ray luminosity larger and less a critical value (e.g., Yuan & Cui 2005; Wu et al. 2007; Yuan et al. 2009). Based on Yuan & Cui (2005), the critical X-ray luminosity is $L_{2-10\, \text{keV}} \sim 2 \times 10^{46} \text{erg s}^{-1}$ for the BH mass of $\sim 10^8 M_\odot$, and the observed X-ray luminosity of NGC 4993 is $L_{0.3-8\, \text{keV}} \sim 10^{39} \text{erg s}^{-1}$, which roughly corresponds to the critical luminosity. Our fitting result roughly supports this scenario, where the X-ray emission is consistent with the Comptonization emission from ADAF and just slightly higher than that predicted by the synchrotron emission from the jet. The ratio $L_R/L_X \sim 5 \times 10^{-3}$ in NGC 4993 suggest that it may be similar to other mildly radio-loud AGNs (e.g., Behar et al. 2015). The multiwaveband emission, including the submillimeter waveband, may be fully dominated by the jet if the Eddington ratio is much less than this critical value, since the ADAF emission ($L \propto M$) decreases faster compared that of the jet ($L \propto M$) with the decrease of the accretion rate. The jet emission may be more and more important in weak-activity BH sources. The radio emission, X-ray emission, and BH mass of NGC 4993 follow the so-called “fundamental plane” of BH activities, which suggest that both the radio and X-ray emission should be dominated by the supermassive BH activities and was not seriously contaminated by the host galaxy (e.g., Merloni et al. 2003).
5. Conclusion

Based on the most recent multiwaveband observations of the BH activities in NGC 4993, we find that the radio emission in the millimeter waveband is much steeper than that of the low-frequency radio band, in which the break is also found in the central BH of Sgr A* and M87, where the BH mass of NGC 4993 is more than one order of magnitude larger, and smaller, than that in Sgr A*, and M87, respectively. We model the SEDs of NGC 4993 with a coupled ADAF-jet model, and find that the steep millimeter radio spectrum and hard X-ray spectrum can be explained by the ADAF model, while the low-frequency radio emission may come from the jet. The ratio of the outflow and inflow is ~0.4%, which suggests that only a small fraction of the accreting matter is channeled into the jet if it exists. The submillimeter bump may exist in SMBHs at different scales (e.g., $10^6-10^8 M_\odot$) in the low accretion regime, we suggest that the submillimeter and deep X-ray observations will be very helpful in allowing us to understand the central engines of nearby LLAGNs.

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