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# Accretion models for LLAGNs: model parameter estimation with M87 as an example

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**Resumen** / El Telescopio de Horizonte de Eventos (EHT por sus siglas en inglés) brinda una oportunidad única para explorar la física de los agujeros negros supermasivos por medio de la interferometría de muy larga base (VLBI por sus siglas en inglés), incluyendo la existencia del horizonte de eventos y los procesos de acreción así como la formación de chorros. Hemos construído un modelo teórico que incluye un flujo de acreción dominado por advección (ADAF por sus siglas en inglés) y un flujo en chorro de radio simple. La distribución espectral de energía (SED por sus siglas en inglés) predicha por este modelo se puede comparar con observaciones para obtener las mejores estimaciones de los parametros del modelo. Además, los perfiles de emisión radial predichos por el modelo en diferentes bandas de frecuencia, pueden ser usados para predecir la posibilidad de resolver el flujo de entrada con el EHT u otros telescopios. En esta publicación aplicamos el modeo a la radio galaxia M87 como ejemplo.

**Abstract** / The Event Horizon Telescope (EHT) provides a unique opportunity to probe the physics of supermassive black holes through Very Large Baseline Interferometry (VLBI), such as the existence of the event horizon, the accretion processes as well as jet formation in low luminosity AGN (LLAGN). We build a theoretical model which includes an advection-dominated accretion flow (ADAF) and a simple radio jet outflow. The predicted spectral energy distribution (SED) of this model can be compared to observations to get the best estimates of the model parameters. Additionally, the model-predicted radial emission profiles at different frequency bands, can be used to predict whether the inflow can be resolved by the EHT or other telescopes. In this proceeding we demonstrate this process using M87 as an example.

*Keywords* / Galaxies:active, Accretion:accretion disks, Black hole physics, Relativistic processes

## 1. Introduction

Active Galactic Nuclei (AGN) are among the brightest sources in the sky, with a central engine consisting of a compact object with accreting gas surrounding it. The accretion process is expected to be the primary power source illuminating the AGN. The existence of a highly massive compact object in the center of our galaxy (Sgr A*) has been confirmed from observations of stellar motions near the center (Meyer et al., 2012). Based on the predictions of General Relativity, the compact object is assumed to be a black hole, i.e. an object with an event horizon, from which not even light can escape. To rule out the existence of a surface for the compact object in Sgr A* and M87 (CD galaxy in the Virgo cluster), Broderick et al. (2009, 2015) pursued a comparison of the observed fluxes in the central regions with the expected fluxes in the presence of a putative surface. They have shown that, for realistic accretion rates, the existence of such a surface is highly implausible. However, this still presents an indirect argument. The detection of the shadow of the black hole would provide direct and firm evidence of the existence of an horizon. Imaging the shadow of the supermassive black holes in Sgr A* and M87, thus detecting their horizons, is one of the main goals of the Event Horizon Telescope (EHT) which has a resolution of 15-20 $\mu$arcsec. In addition, the EHT will study the accretion of supermassive black holes in other nearby Low-Luminosity AGN (LLAGN). While the Global 3-mm VLBI Array (GMVA) and the European VLBI Network (EVN) observe at lower frequencies and offer lower resolutions (50-70 $\mu$arcsec), observing nearby LLAGN with them will enable the characterization of emission from a greater part of the accretion disk. Our primary aim is to build a simple theoretical framework to predict, for a large sample of LLAGN, the spectrum and the morphology of the emitting region when varying the model parameters. In this work we demonstrate this process with M87 as an example.

## 2. Model Description

### 2.1. Dynamical Equations

The accretion disks in LLAGN can be described by an advection dominated accretion flow (ADAF), which is a sub-Eddington accretion flow (Shapiro et al., 1976; Ichimaru, 1977; Rees et al., 1982). The accretion rate is much smaller than the Eddington rate and the gas

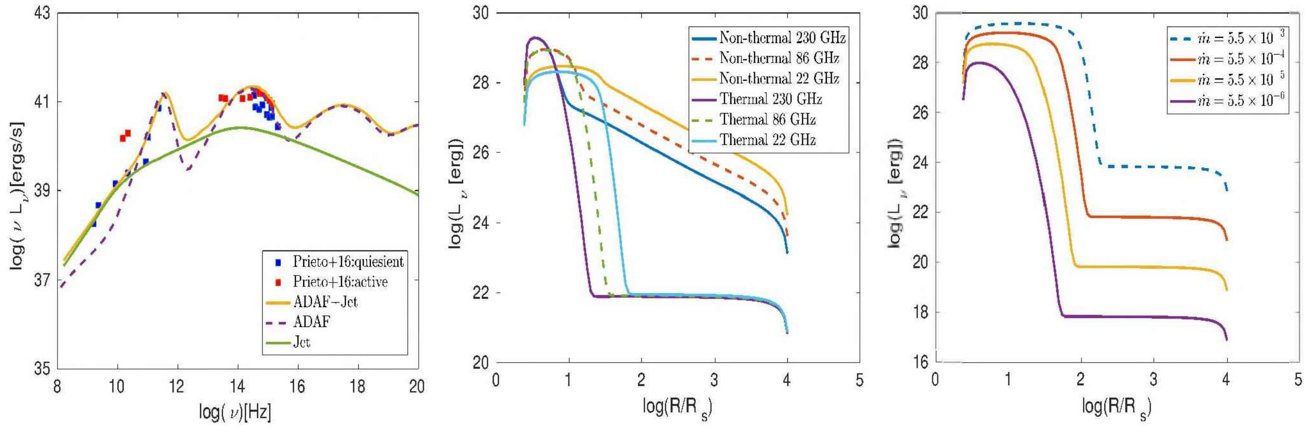


Figure 1: *Left Panel*: We show the best fit ADAF+JET model SED for M87 (yellow line) and compare the result with the observational data given in Prieto et al. (2016). The individual components are ADAF (purple dashed) and JET (green line). *Middle Panel*: The radial profile for emission at 22 GHz, 86 GHz and 230 GHz with the ADAF disk models in cases with and without the inclusion of non-thermal electrons. Here $R_s$ is the Schwarzschild radius. *Right Panel*: Variation in the radial profile of emission at 22 GHz for different accretion rates. Here $\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$ *i.e.* the ratio of true accretion rate to the Eddington rate.

reaches its virial temperature. Such disks are geometrically thick but optically thin, and are often accompanied by outflows. The small accretion rate leads to a low density in the disk. The excess heat generated due to viscous dragging is unable to escape due to inefficient radiative cooling, and is advected into the black hole. As a consequence of low opacity, a two-temperature plasma forms, where the ions are much hotter than the electrons. We investigate the evolution of the dynamical equations in an ADAF model tailored to LLAGN (Yuan et al., 2005). From the laws of conservation of mass, radial momentum, angular momentum and energy, we set up the following dynamical equations (Yuan & Narayan, 2014):

$$\dot{M}(R) = \dot{M}_{\rm R_{out}} \left(\frac{R}{R_{\rm out}}\right)^{s} = 4\pi\rho R H|v| \quad (1)$$

$$v\frac{dv}{dR} - \Omega^2 R = -\Omega_K^2 R - \frac{1}{\rho}\frac{d}{dR}(\rho c_s^2) \quad (2)$$

$$\frac{d\Omega}{dR} = \frac{v\Omega_K(\Omega R^2 - j)}{\alpha R^2 c_s^2} \quad (3)$$

$$\rho v\left(\frac{de_i}{dR} - \frac{p_i}{\rho^2}\frac{d\rho}{dR}\right) = (1-\delta)q^{+} - q^{ie}$$

$$\rho v\left(\frac{de_e}{dR} - \frac{p_e}{\rho^2}\frac{d\rho}{dR}\right) = \delta q^{+} + q^{ie} - q^{-} \quad (4)$$

The variables have their usual meaning. It should be noted that Eq. 1 includes the case of outflows, while Eq. 4 is the modified energy conservation equation for two temperature plasmas. Comparing the modeled spectrum with the available SED data, allows us to constrain important model parameters like the accretion rate $\dot{M}$, the strength of the outflow parameter $s$, the relative magnetic strength $\beta$ (which is embedded in the energy equation) and the electron heating factor $\delta$ (Xie & Yuan, 2012; Chael et al., 2018b). For M87, using a black hole mass of $6.4 \times 10^9$ $\mathrm{M}_\odot$ and a distance of 14.9 Mpc, the best fit parameter values, by comparing our models with observational data (left panel of Fig. 1), are: $\dot{M}_{R_{out}} = 5.5 \times 10^{-4}\ M_{Edd}$, $\beta = 0.9$, $s = 0.1$ and $\delta = 0.09$.

## 2.2. The Jet

The accretion dynamics is more complex due to turbulence, the presence of magnetic fields, hot spots and outflows. Narayan & Yi (1994, 1995) and Blandford & Begelman (1999) postulate that hot accretion flows should have strong winds followed by the formation of jets. This is supported by observational evidence which suggests that almost all LLAGN are radio-loud (Falcke & Markoff, 2000; Nagar et al., 2000; Ho, 2002). The jet dynamics is generally assumed to arise from a combination of magnetic fields and rotation. The most accepted theoretical models are the Blandford-Znajek model (BZ, Blandford & Znajek, 1977) which states that the primary source of energy in the jet is the rotational energy of the black hole, while the Blandford-Payne model (BP, Blandford & Payne, 1982) suggests that it is due to the rotational energy of the accretion flow. Independent of the origin of the jet, it is often necessary to include a jet to explain the observed SED of most LLAGN (Nemmen et al., 2014; Li et al., 2016). The most powerful jet can be produced by a highly-magnetized version of ADAF, i.e. the magnetically arrested disk (MAD, Tchekhovskoy et al. (2011); Chael et al. (2018a)). In this work, we do not aim to explore the origin of the jet, but use a phenomenological model to describe its properties (Spada et al. 2001; Yuan et al. 2005), which is sufficient to model the 1D spectrum. Owing to the supersonic radial velocity of accretion near the supermassive black hole, the bending of the gas into the jet causes a standing shock at the bottom. Post shock properties, like the temperature and densities, are determined from the shock jump condition. The shock accelerates a fraction of the electrons yielding a power law energy distribution. These are the electrons that contribute most to the emission of the jet. The emission from the jet depends on the mass loss rate, $\dot{m}_j$, the Lorentz factor, $\Gamma_j$ and the energy densities, $\epsilon_e$ and $\epsilon_B$, for the accelerated electrons and the amplified magnetic fields respectively. For M87 we obtain: $\dot{m}_j = 1.0 \times 10^8$, $\Gamma_j = 6.0$, $\epsilon_e = 0.0006$ and $\epsilon_B = 0.001$ (left panel of Fig. 1).

### 2.3. The Spectral Energy Distribution (SED) and emission profiles

The temperature, electron density and velocity profiles of the gas, are the parameters that we obtain from the solution of the dynamical equations. Assuming the disk is isothermal in the vertical direction, the spectrum of non scattered photons at a given radius is calculated by solving the radiative transfer equation in the vertical direction of the disk, based on the two-stream approximation (Rybicki & Lightman, 1979). Since the gas near to the black hole is hot, optically thin and magnetized, the processes which significantly contribute to the emission are synchrotron and bremsstrahlung (Manmoto et al., 1997). The presence of electrons comptonizes (Coppi & Blandford, 1990) these photons to modify the total SED. Processes such as magnetic reconnection, weak shocks and turbulent dissipation can accelerate a fraction of the thermal electrons to a non-thermal, power-law distribution, which also emits via synchrotron emission (Yuan et al., 2005). The power-law electrons in the jet lead to an enhanced contribution of the synchrotron emission. In our model we have included the emission of power-law electrons from the disk (following the method of Özel et al. (2000)) which has not been included in the works of Li et al. (2016).

## 3. Discussion and Conclusion

We showed how to obtain the best fit parameter values of our model, by comparing the simulated SED with the observed dataset. As a specific example, we have calculated the SED of M87 and the expected radial profiles of the emission from the disk at three different frequencies (22 GHz, 86 GHz and 230 GHz), shown in the middle panel of Fig. 1. The radial profile changes depending on the parameter values as well as the adopted physics in the disk (mass of the black hole, Eddington ratios, presence of non-thermal electrons, etc.). Potentially allowing us to constrain the physics of the accretion disk through a comparison with observations from the EHT (230 GHz), the GMVA (86 GHz) and the EVN (22 GHz). As an example we have shown in right panel of Fig.1, the variation in the radial profile of emission from the disk at 22 GHz for different accretion rates. This analysis is the first step towards predicting the resolvability of the region in the proximity of the black hole. The summary of our analysis for M87 is as follows:

- The emission from power-law electrons in the disk is important especially to explain the Compton peak in the SED of M87.
- The radial profile of emission varies significantly when including the power-law electrons, hence showing their significant contribution to emission at low frequencies, even from the outer regions of the disk.
- For a system like M87, it is important to include the emission from the jet in order to explain the flux at lower frequencies. Any synchrotron emission from the disk will be highly self-absorbed.

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