Accretion models for LLAGNs: Model Parameter Estimation and Prediction of their Detectibility

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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. 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 is compared to observations to get the best estimates of the model parameters. Also the model-predicted radial emission profiles at different frequency bands can be used to predict whether the inflow can be resolved by the EHT.

Keywords / Accretion – ADAF, LLAGN, Jet

1. Introduction

Active Galactic Nuclei (AGN) are among the brightest sources in the sky. It is well established that the accretion processes around compact objects are the most energetic processes in the universe, with an efficiency higher than even nuclear fusion. Their central engines are therefore expected to be the primary powering source illuminating the AGN. The existence of a highly massive compact object in the center of our galaxy (Sgr A*) has been confirmed from the observations of stellar motions near the centre (Meyer et al. 2012). Based on the predictions of General Relativity, this compact object is usually 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 in the Virgo cluster CD galaxy M87, Broderick et al. (2009, 2015) pursued a comparison of the observed fluxes in the central regions and 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 based on assumptions. The detection of the shadow of the nuclear black hole would provide direct and firm evidence of the existence of a horizon. Imaging the shadow of the supermassive black holes in Sgr A* and M87, thus detecting their horizons, is thus one of the main goals of the Event Horizon Telescope (EHT)† which has a resolution of 15-20 micro-arcseconds. 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 micro-arcseconds), observing nearby LLAGN with them will enable the characterization of emission from a greater part of the accretion disk.

2. Model Description

2.1. Dynamical Equations

The accretion disks in LLAGN can be described by an advection dominated accretion flow (ADAF). These are sub-Eddington accretion flows (Shapiro et al. 1976; Ichikawa et al. 2009, 2015) which has a resolution of 15-20 micro-arcseconds. 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 micro-arcseconds), observing nearby LLAGN with them will enable the characterization of emission from a greater part of the accretion disk.

†Webpage EHT: http://www.eventhorizontelescope.org/
‡Webpage GMVA: https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/
§Webpage EVN: http://www.evlbi.org/
The accretion dynamics in reality is more complex due to turbulence, the presence of magnetic fields, hot spots and outflows. [Narayan & Yi (1994, 1995); 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 more complicated but it is accepted to arise from a combination of magnetic fields and rotation. The most accepted models are the Blandford-Znajek (BZ) model (Blandford & Znajek 1977) which states that the primary source of energy in the jet is the rotational energy of the black hole and the Blandford-Payne (BP) model (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 in order to explain the observed SED of most LLAGN (Nemmen et al. 2014; Li et al. 2016). We consider a basic jet model (Spada et al. 2001; Yuan et al. 2005) here. The radial velocity of accretion near the supermassive black hole is supersonic and hence the bending of the gas into the jet causes a standing shock at the bottom. From the shock jump condition, post shock properties like the temperature and densities are determined. The shock accelerates a fraction of the electrons yielding a power law energy distribution. It is these electrons which contribute to most of the emission in the jet. The emission from the jet depends on the jet-opening angle $\phi$, the Lorentz factor $\Gamma_j$, the energy densities $\epsilon_e$ and $\epsilon_B$ for the accelerated electrons and the amplified magnetic fields.

### 2.2. The Jet

The accretion dynamics model for LLAGNs was first introduced by [Rees et al. 1982], for which the accretion rate is much smaller than the Eddington rate and the gas 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 lower density in the disk. Such a disk is thus optically thin and the excess heat generated due to viscous dragging is unable to escape due to inefficient radiative cooling, hence it is advected onto 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]):

\[ M(R) = M_{\text{out}} \left( \frac{R}{R_{\text{out}}} \right)^s = 4\pi \rho RH|v| \] (1)

\[ v \frac{dv}{dR} - \Omega^2 R = -\Omega^2 R - \frac{d}{dR} \left( \rho c_s^2 \right) \] (2)

\[ d\Omega \left( \frac{\Omega R^2 - j}{\Omega^2 R^2 - j} \right) = \frac{v \Omega_R (\Omega R^2 - j)}{\alpha R^2 c_s^2} \] (3)

\[ \rho v \left( \frac{de_e}{dR} - \frac{p_e}{\rho^2} \frac{d\rho}{dR} \right) = (1 - \delta) q^+ - q^+ \] (4)

Here the variables have their usual meaning. It should be noted that eq. 4 takes into account the case of outflows while eq. 3 is the modified energy conservation equation for two temperature plasmas. Comparing the modeled spectrum with the available SED data allows us to constrain the 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. 2018]).

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

The temperature, density of electrons and the velocity profiles of the gas are the parameters that we obtain from the solution of the dynamical equations. Assum-
For a system like M87 it is important to include the effect of power-law electrons. This shows that the power-law electrons contribute significantly to the 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.

We plan to apply this analysis to other nearby LLAGN and estimate the detectability of their accretion flows.

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3. Discussion and Conclusion

Our primary aim in this work is to find 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), which is shown in 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.), thereby potentially allowing us to constrain the physics of the accretion disk through a comparison with observations from the EHT (230 GHz) as well as the GMVA (86 GHz) and the EVN (22 GHz). As an example we have shown in Fig. 2 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:

• Including the effect of power-law electrons is important especially to explain the Compton peak in the SED.

Figure 2: Variation in the radial profile of emission at 22 GHz for different accretion rates. Here $\dot{m} = M/M_{\text{Edd}}$ i.e. the ratio of true accretion rate to the Eddington rate.