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The Structure of Accretion Flow at the Base of Jets in AGN

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Abstract: This paper discusses the boundary layer and the emission spectrum from an accretion disk having a jet anchored at its inner radius, close to the black hole. We summarise our earlier work and apply it to the accretion disks of some blazars. We suggest that the 'accretion disk with jet' (ADJ) model could make the bridge between standard accretion disk models (suitable for quasars and FRII sources) and low-power advection dominated accretion disk models (suitable for some of the low-power BL Lacs and FRI sources).

The jet is collimated within a very narrow region close to the black hole (nozzle). In our model it is assumed that the boundary layer of the disk is the region between radius $R_{\rm ms}$ — the last marginally stable circular orbit calculated for a Kerr geometry — and the radius $R_{\rm jet}$, which gives the thickness of the 'footring', i.e. the base of the jet. We analyse the size of the boundary layer of the disk where the jet is fed with energy, mass, and angular momentum. As a consequence of the angular momentum extraction, the accretion disk beyond $R_{\rm jet}$ no longer has a Keplerian flow. A hot corona usually surrounds the disk, and entrainment of the corona along the flow could also be important for the energy and mass budget of the jet.

We assume that the gravitational energy available at the footring of the jet goes into the jet, and so the spectrum from the accretion disk gives a total luminosity smaller than that of a 'standard' accretion disk, and our ADJ model should apply for blazars with low central luminosities. Variations of the boundary layer and nozzle may account for some of the variability observed in active galactic nuclei.

Keywords: accretion, accretion disks — galaxies: jets — galaxies: active — galaxies: nuclei

1 Introduction

The family of active galactic nuclei (AGN) contains a large variety of objects from powerful radio galaxies, radio-loud quasars, radio-quiet quasars to Seyfert galaxies, blazars, LINERS, etc. Following the unification scheme of AGN it is widely accepted now that the central nucleus of an active galaxy has a Kerr black hole, a relativistic accretion disk, a molecular torus, and clouds emitting broad emission lines. The existence of radio features expanding almost perpendicular on accretion disks suggests that jets and accretion disks are strongly related regardless the size of the system, be it a massive black hole in the core of a galaxy or a small black hole in a stellar system.

Blazars are very interesting AGN having the jet axis almost directed towards the Earth to reveal emission amplified through boosting effects. The flaring states observed in these objects could be a consequence of the way in which the jet is fed with energy, mass, and angular momentum from the accretion disk. A flare could occur when a significant amount of energy has been accumulated in the inner disk and is subsequently expelled into the jet. Relativistic shocks may form in jets and could account for short time variability time scales observed in these objects. The strong emission observed during a flare could be due to an increase of the bulk Lorentz factor of the emitting material in the jet, or an increased efficiency of accelerating particles at shocks.

In this paper we shall analyse how changes in the size (physics) of the base of the jet could influence the supply of energy to the jet. The analysis is based on earlier work (Donea & Biermann 1996) in which we have shown that the jet and disk are in symbiosis, and that the energy available for the jet is the energy which would be dissipated between $R_{\rm ms}$, the last marginally stable circular orbit (in Kerr geometry) and radius $R_{\rm jet}$ (a free parameter in our model) with $R_{\rm jet} > R_{\rm ms}$ (see Figure 1). The total power of

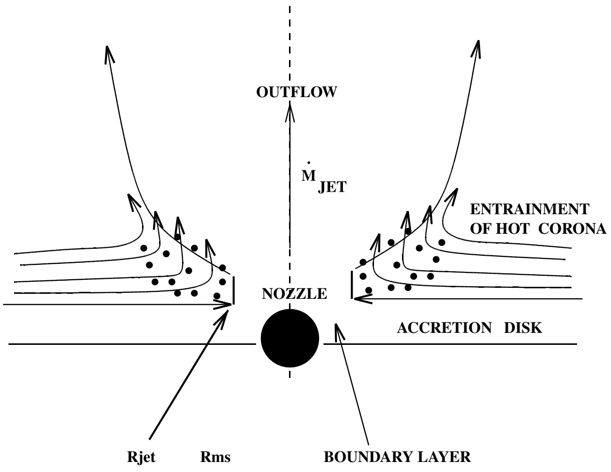

Figure 1 Structure of the region connecting the accretion disk and the jet. The entrainment of the corona creates an envelope of hot gas which could penetrate the base of the jet. The footring of the jet is identified with the boundary layer of the accretion disk, between $R_{\rm ms}$ and $R_{\rm jet}$.

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the jet depends on the parameters characterising the coupling between the jet and disk. A thick base of the jet means that more energy is expelled into the jet and, therefore, less energy is dissipated in the disk. A direct consequence of this assumption is that an accretion disk in symbiosis with a jet (ADJ models) produces a disk luminosity smaller than the luminosity of a 'standard' relativistic accretion disk (Novikov & Thorne 1973).

Many blazars do not show thermal disk emission and their spectra from radio to UV, sometimes to X-ray frequencies, are universally attributed to synchrotron emission from the relativistic jet. Therefore, it is difficult to estimate the size of the base of the jet in blazars as has been done for some quasars displaying visible UV bumps (Donea & Biermann 1996). We suggest that the ADJ models could describe the low-luminosity accretion disks in some blazars and could provide a bridge between the standard accretion disk assumed to exist in FRII sources (Reynolds et al. 1996) and the low-power advection dominated accretion disk which may be found in some FRI sources. There are several accretion models which can, in principle, produce such low luminosities: CDAF convection-dominated accretion flow (Narayan, Igumenshchev, & Abramowicz 2000), ADAF advection dominated accretion flow (Narayan & Yi 1994), ADIOS flow (Blandford & Begelman 1998), and an EDAF ejection dominated accretion flow (an ADJ with wind; Donea, Falcke, & Biermann 1999). However, a low-luminosity disk in our ADJ model could explain better the central activity of Sgr A* and some blazars and Seyfert galaxies.

In Section 2 we summarise the accretion disk with jet model. The coupling of the disk and the jet is discussed together with some of the properties of the boundary layer. In Section 3 we discuss the emission spectrum of the disk and emphasise that disk photons produced by ADJ are an important source of radiation for the Comptonisation processes, in which the electrons accelerated in the jet interact with soft photons from the 'modified' disk.

2 The Boundary Layer of an Accretion Disk with Jets

In stellar systems the boundary layer is the transition region between the accretion disk which rotates with Keplerian angular velocity, and the stellar surface which has an angular velocity typically much smaller. Because a surface of infinite redshift (the horizon) hides the image of the massive black hole it is difficult to estimate the angular velocity of the event horizon (assumed to be the 'hard' surface of the black hole). It is therefore convenient to consider the boundary layer of the ADJ as the region between $R_{\rm ms}$ and $R_{\rm jet}$ which we identify with the footring of the jet, i.e. the base of the jet. While we expect some similarities between the boundary layers in stellar systems and AGN, we assume that within $R_{\rm ms}$ and $R_{\rm jet}$ the gas follows sub-Keplerian orbits, and at R_0 ($R_{\rm ms} \le R_0 \le R_{\rm jet}$) the torque vanishes.

The rate at which the angular momentum is expelled at $R_{\rm jet}$ is

$$\dot{L}_{\rm jet} = \dot{M}_{\rm jet} u_\phi(R_{\rm jet}) = q_{\rm m} \dot{M} M^{1/2} R_{\rm jet}^{1/2} \mathcal{F}/\mathcal{C}^{1/2} \qquad (1)$$

where M is the mass of the black hole, $\dot{M}$ is the accretion mass rate into the disk, and $\mathcal{F}$ and $\mathcal{C}$ are relativistic correction factors (equation 5.4.7a, Novikov & Thorne 1973). We assumed that the jet is fed with mass by the accretion disk, and that the flow of mass into the jet per unit time $\dot{M}_{\rm jet} = q_{\rm m} \dot{M}$ is a fraction $q_{\rm m}$ of $\dot{M}$ ($q_{\rm m} \le 1$). $\dot{L}_{\rm jet,max} = \dot{M} u_\phi(R_{\rm jet})$ provides an upper limit for the rate of angular momentum going into the jet and corresponds to the case when most of the accreted mass is expelled into the jet funnel. However, we assume that this is not the case.

The jet is approximated by a thin cylinder of outer radius $R_{\rm jet}$, which can have values from $R_{\rm ms}$ and $R_{\rm out}$, the outer radius of the disk. Radio observations of the inner jets show that the jets are very well collimated into a narrow tunnel perpendicular to the accretion plane, suggesting that the free parameter $R_{\rm jet}$ cannot be too far from $R_{\rm ms}$, and that $R_{\rm jet} \ll R_{\rm out}$.

A coupled jet–disk system must obey the laws of mass and angular momentum conservation. The equation for conservation of mass includes an additional term now for the extraction of mass by the jet:

$$\dot{M} = -2\pi R \Sigma u^R + \dot{M}_{\rm jet}, \qquad (2)$$

where Σ is the surface density of mass in the disk and u^R is the radial velocity of gas at a given R. A complex equation can be written for the conservation of angular momentum. The derivation of these equations is given in Donea & Biermann (1996). The inner edge of the accretion disk with jet becomes $R_{\rm jet}$, and the disk extends out to $R_{\rm out}$.

There are many processes that we do not understand in the boundary layer which is dynamically quite complex since it is there that the jet must be created. We emphasise at this point that the ADJ model does not propose to explain how the jet is created at the innermost radii of the disk. We are interested in the consequences which the existence of the jet can have for the structure of the boundary layer, and for the accretion disk and its emission spectrum. Any contribution to the power of the jet from the black hole itself is not considered in this paper. In our model the base of the jet is characterised by sub-Keplerian gas motion and we suggest that an ADAF boundary layer may be a better description for the base of the jet with an efficient energy convertor for the jet. At $R > R_{\rm jet}$ the low-luminosity ADJ could have ADAF or EDAF characteristics, and that means a significant fraction of energy could be transported towards $R_{\rm jet}$ from larger radii of the disk and expelled into the jet.

There is a different method of obtaining some information about the size of the base of the jet, $R_{\rm jet}$. Coronal gas, together with the gas in the disk, will flow towards the nozzle of the jet where the jet entrains the coronal gas creating an envelope of hot and dense gas, denser than that of the corona (dotted region around the nozzle in Figure 1). A fraction of the coronal mass accreted ($q_c \leq 1$) may penetrate the wall of the nozzle. Hence, the mass balance of the system becomes $\dot{M}_{\rm jet} = q_{\rm m}\dot{M} + q_{\rm c}\dot{M}_{\rm c}$, where $\dot{M}$ and $\dot{M}_{\rm c}$ are the mass accretion rates of the disk and corona, respectively.

The inner region of corona is clearly relevant for the X-ray photon production in AGN. The base of the jet or/and the entrained corona region could provide a pool of thermal electrons Comptonising the UV disk/jet photons. The importance of Comptonisation is determined by the Compton parameter $y = y_{\rm nz} + y_{\rm ec}$ which has contributions from the nozzle (nz) and the entrained corona (ec). For the nozzle the Compton parameter is $y_{\rm nz} = 4k_{\rm B}T_{\rm nz}/m_{\rm e}c^2 \max(\tau_{\rm nz}, \tau_{\rm nz}^2)$, where the optical depth is $\tau_{\rm nz} = n_{\rm nz}\sigma_T R_{\rm nz}$, with $n_{\rm nz}$ the number density in the nozzle, $T_{\rm nz}$ the temperature of the hot electrons at the nozzle, $R_{\rm nz} \approx R_{\rm jet}$, and $k_{\rm B}$ Boltzmann's constant. A similar formula holds for the case of the corona.

ROSAT observations show soft X-ray emission in AGN which could be thermally Comptonised emission from the nozzle of the jet (Mannheim 1993) or from a hot corona identified as the base of the jet (Bicknell et al. 1998). Fitting of data with both models suggests that $R_{\rm jet} \approx 10R_{\rm g}$, where $R_{\rm g}$ is the gravitational radius. However, considering the dense region of entrained corona, we find that $R_{\rm jet}$ could be smaller than $10R_{\rm g}$, since the critical radius for Comptonisation is equal to $R_{\rm jet} + R_{\rm ec} \approx 10R_{\rm g}$, where $R_{\rm ec}$ is the thickness of the coronal material accumulated around the nozzle. Therefore, the disk/jet system becomes more complex when the inflow of the corona is included in the mass and energy conservation laws of the jet.

3 Emission Spectrum from a Disk with Jet

Donea & Biermann (1996) have put forward a model for an accretion disk with jets starting at the inner region of a disk, and were able to reproduce the UV bump in quasars. By fitting observed spectra we found upper limits of the size of the boundary layer. In our model, the gravitational potential energy available between $R_{\rm ms}$ and $R_{\rm jet}$ is the energy reservoir of the jet. The total power of the jet is strongly dependent on the mass and angular momentum of the black hole as well as on the size of the boundary layer. The boundary layer of an ADJ has little emission. The total power of the jet, including the rest energy of the expelled matter is

$$Q_{\rm jet} = L_{\rm disk} - L_{\rm disk}^{\rm jet} \tag{3}$$

where $L_{\rm disk}^{\rm jet}$ is the total luminosity of the disk with jet and $L_{\rm disk}$ would be the total luminosity of the standard relativistic disk if there are no conditions to drive the outflows.

We followed the standard method of calculating the emission spectrum from an accretion disk (Novikov & Thorne 1973, hereafter NT73). If there is no angular momentum and mass loss into the jet our equations for mass and angular momentum transport in the disk become the standard NT73 equations, with $R_{\rm jet} \to R_{\rm ms}$, $Q_{\rm jet} \to 0$, and $L_{\rm disk}^{\rm jet} \to L_{\rm disk}$.

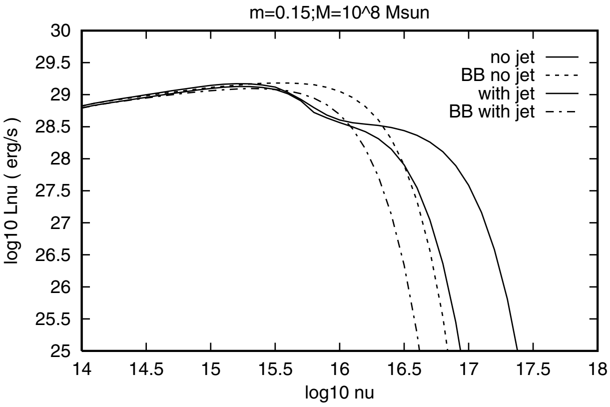

Figure 2 Disk spectra calculated with different assumptions about the jet/disk symbiosis: black-body accretion disk without jets (dashed curve), black-body accretion disk with jet (dot-dashed curve), complex accretion disk with a jet (low solid curve, $R_{\rm jet} \approx 2.5R_{\rm g}$), accretion disk without a jet (upper solid curve). Required parameters are: $\dot{M}/\dot{M}_{\rm edd} = 0.15$, $M = 10^8 M_\odot$, Kerr black hole.

Most of the UV radiation originates from the inner region of disk just outside $R_{\rm jet}$. An important result of our model is that the spectrum from a Kerr disk is cut off at high frequencies, from extreme UV to soft X-ray frequencies (see Figure 2).

As we mentioned in the introduction, an ADJ model could describe the low-luminosity accretion disks for some blazars. Due to the assumption we have made about the jet/disk coupling, ADJ provides a diluted photon radiation field with energy density

$$U_{\rm diskj} = \frac{L_{\rm disk}^{\rm jet}}{4\pi c r^2} = \xi_{\rm symb}(R_{\rm jet})\frac{L_{\rm disk}}{4\pi c r^2}, \tag{4}$$

where r is the position along the jet axis and $\xi_{\rm symb}(R_{\rm jet}) \leq 1$ is the parameter for the jet/disk connection. Some of the implications of this for interactions of accelerated electrons or protons and for energetic γ-rays are discussed in Donea & Protheroe (2002). The average energy of photons from disks with jets is smaller than the average energy of photons from 'standard' disks, since the energy dissipated in the hot region of the disk close to the black hole goes into the jet and not into radiation. This result is relevant for the inverse Compton scattering models (Sikora, Begelman, & Rees 1994) which explain the γ-ray spectra of flat spectrum radio quasars and optically violently variable quasars with external radiation from the disk. Mannheim (1995) and Protheroe (1997) have also shown that the disk radiation is relevant for the γ-ray flaring state when the main constituents of the jet are relativistic protons.

4 Conclusion

The ADJ model gives a simplified approach to the symbiosis between disk and jets. It can explain the low central activity in some blazars. The strong variability observed in blazars from radio to γ-ray frequencies could be a consequence of the feeding mechanism of the jet at the boundary layer. A local perturbation produced in the boundary layer, such as a rapid variation of $R_{\rm jet}$ or $\dot{M}$, propagates along the jet, through the nozzle causing transient phenomena. The jet extracts energy from the disk, and this diminishes the energy density of the radiation field produced by an accretion disk with jets, and so affects an important target photon field for interactions of accelerated electrons and protons along the jet.

We have shown that the power of the jet can be scaled with the size of the footring, where the gravitational potential energy of the infalling gas goes into the jet. An increase of the mass flow rate at $R_{\rm jet}$ could induce more energy to be dissipated at the footring of the jet. However, a more detailed analysis of the extraction of the angular momentum from the boundary layer is required to give more insight into the structure of the flow. A rigorous model could not neglect the possible effects of the black hole's proximity on the stability of the boundary layer/nozzle region.

We have identified three elements essential for understanding the jet/disk connection: the footring of the jet, the nozzle, and the envelope of the inner corona. The interrelation between these elements is relevant for understanding the formation of jets.

References

Bicknell, G. V., Dopita, M. A., Tsvetanov, Z. I., & Sutherland, R. S. 1998, ApJ, 495, 680

Blandford, R. D., & Begelman, M. 1998, MNRAS, 303, L1

Donea, A. C., & Biermann, P. L. 1996, A&A, 316, 43

Donea, A. C., & Protheroe, R. J. 2002, PASA, 19, 39

Donea, A. C., Falcke, H., & Biermann, P. L. 1999, in The Central Parsecs of the Galaxy, ASP Conf. Series 186, eds H. Falcke, et al. (San Francisco: ASP), 162

Mannheim, K. 1993, A&A, 269, 67

Mannheim, K. 1995, A&A, 297, 321

Narayan, R., & Yi, I. 1994, ApJ, 428, L13

Narayan, R., Igumenshchev, I. V., & Abramowicz, M. 2000, ApJ, 538, 798

Novikov, I. D., & Thorne, K. S. 1973, in Black Hole Astrophysics, Les Astres Occlus, eds C. DeWitt, & B. DeWitt (New York: Gordon & Breach), 343 (NT73)

Protheroe, R. J. 1997, in Accretion Phenomena and Related Outflows, IAU Colloquium 163, ASP Conf. Series 121, eds D. T. Wickramasinghe, G. V. Bicknell, & L. Ferrario (San Francisco: ASP), 585

Reynolds, C. S., di Matteo, T., Fabian, A. C., Hwang, U., & Canizares, C. R. 1996, MNRAS, 283, L111

Sikora, M., Begelman, M. C., & Rees, M. J. 1994, ApJ, 421, 153