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Ratio of kinetic-to-bolometric luminosity at the "cold" disk accretion onto black holes

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Abstract. In galactic nuclei (AGN), the kinetic energy flux of the jet may exceed the bolometric luminosity of the disk a few orders of magnitude. At the "cold" accretion the radiation from the disk is suppressed because the wind from the disk carries out almost all the angular momentum and the gravitational energy of the accreted material. We calculate an unavoidable radiation from such a disk and the ratio of the kinetic-to-bolometric luminosity from a super massive black hole in framework of the paradigm of the optically thick α-disk of Shakura & Sunyaev. The results confirm that the gravitational energy of the accreted material can be the only source of energy in AGNs.

Keywords. accretion disks, magnetohydrodynamics, galaxies: jets.

1. Introduction

The observations of recent years show that the power of kinetic energy of the jets in some AGN exceeds the bolometric luminosity of the disk (Körding *et al.* 2008; Ma *et al.* 2008; López-Corredoira & Perucho 2012; Daly 2016; Daly *et al.* 2016; Fernandes *et al.* 2011; Punsly 2011; Ghisellini *et al.* 2014). In this case the question about the source of the energy of the jets becomes the central one for understanding of the processes at the accretion onto SMBH (McNamara *et al.* 2011). Presently, the rotational energy of a black hole is considered as the most likely source of energy which is transformed in to the energy of jets due to the so-called mechanism of Blandford & Znajek (1977). This mechanism can provide the energy flux in the jet $\approx 3\dot{M}c^2$, where $\dot{M}$ is the accretion rate (Tchekhovskoy *et al.* 2011; Barkov & Khangulyan 2012).

It was firstly pointed out by Pelletier & Pudritz (1992) and explored by the Grenoble group (Ferreira & Pelletier 1995) that the magnetized wind from the disk can carry out a significant fraction of the angular momentum of the accreted matter rather than the viscous stresses. We call this regime of accretion as "cold" accretion because the disk appears radiationally inefficient. Starting with our first work (Bogovalov & Kelner 2010) we stressed that the "cold" accretion can be applied to the solution of the problem of high ratio of the kinetic luminosity of the jets. In this work we estimate the expected ratio of the kinetic-to-bolometric luminosity to verify can the model of the cold accretion be consistent with the current observations.

2. Physics of the "cold" accretion

The equation of conservation of the angular momentum in framework of the α-disks paradigm Shakura & Sunyaev (1973) has the following form:

$$\dot{M}\frac{\partial r V_k}{\partial r} + \frac{\partial}{\partial r}4\pi r^2 t_{r\varphi} h + r^2 < B_\varphi B_z > |_{wind} = 0, \qquad (2.1)$$

where $t_{r\varphi}$ is the tangential stress, V_k is the Keplerian velocity of rotation, $\dot{M}$ is the accretion rate, r is the cylindrical radius and h is the semi-height of the disk. B_φ and B_z are toroidal and z-components of the magnetic field at the base of the wind. The brackets $<>$ mean averaging over time.

The tangential stress in the disk $t_{r\varphi}$ is defined by the turbulent motion and by the magnetic field. According to Shakura & Sunyaev (1973)

$$t_{r\varphi} = -\alpha\rho v_s^2. \tag{2.2}$$

where v_s is the sound velocity, ρ is the matter density and α is the parameter connecting the pressure and tangential stress in the disk.

As it was pointed out by Pelletier & Pudritz (1992), the momentum loss due to the wind will dominate the losses caused by the viscous stresses provided that

$$4\pi r t_{r\varphi} h \ll r^2 < B_\varphi B_z > |_{wind}. \tag{2.3}$$

This is the condition for the "cold" accretion. In the opposite case we have the standard Shakura & Sunyaev (1973) version of the disk accretion. The heat production equals

$$Q = t_{r\varphi} h r \frac{\partial \Omega}{\partial r}. \tag{2.4}$$

The angular momentum carried out by the wind at the "cold" accretion is

$$r^2 < B_\varphi B_z > |_{wind} = 0.5 \dot{M} V_k. \tag{2.5}$$

To connect this torque at the base of the wind with $t_{r\varphi}$ we introduce a parameter

$$\theta = \frac{4\pi t_{r\varphi}}{< B_\varphi B_z > |_{wind}}. \tag{2.6}$$

Below we assume that $\theta \geq 1$ but should satisfy to the condition of "cold" accretion following from eq.(2.3)

$$\frac{\theta h}{r} \ll 1. \tag{2.7}$$

For the geometrically thin disks with $h/r \ll 1$ the "cold" disk accretion can take place even for $\theta > 1$.

3. Thermal radiation from the disk

We consider the case when the gas pressure dominates the radiation pressure. According to Shakura & Sunyaev (1973) the heat conductivity of the disk is defined by the transport of radiation and $\varepsilon = \frac{3}{4}\frac{Q\sigma u_0}{c}$, where $\sigma = 0.4$ $\mathrm{cm^2/g}$ is the Thomson opacity and $u_0 = 2\rho h$, $\varepsilon = bT^4$. Then the rate of heating of the disk equals

$$Q = \frac{3\theta \dot{M} V_k v_s}{16\pi r^2}. \tag{3.1}$$

We used here that $h = v_s/\Omega$. The sound velocity is defined as $v_s^2 = kT/m_p$, where m_p is the proton mass. Let us express $\dot{M} = \dot{m}\dot{M}_{crit}$, the radius r in $r = (3r_g)x$ and the mass M in the solar masses $M = mM_\odot$. When the Thomson scattering dominates free-free absorption we obtain

$$Q = 0.75 \cdot 10^{23} (\theta\dot{m})^{5/4} m^{-9/8} x^{-47/16} \alpha^{-1/8}, \quad \mathrm{erg/s/cm^2}. \tag{3.2}$$

$$L_{bol} = 0.84 \cdot 10^{36} (\theta\dot{m})^{5/4} m^{7/8} \alpha^{-1/8}, \quad \mathrm{erg/s}. \tag{3.3}$$

$$T = 2.5 \cdot 10^7 (\theta\dot{m})^{1/2} \alpha^{-1/4} x^{-7/8} m^{-1/4}, \quad \mathrm{K} \tag{3.4}$$

$$\rho = 0.6 (\theta\dot{m})^{1/2} m^{-3/4} x^{-13/8} \alpha^{-3/4}, \quad \mathrm{g/cm^3}. \tag{3.5}$$

The kinetic luminosity of the jets equals to the total energy release at accretion $L_{kin} = 1.4 \cdot 10^{38} m\dot{m}$, erg/s. Then, the ratio of the kinetic luminosity over the bolometric luminosity equals

$$L_{kin}/L_{bol} = 168(m\alpha)^{1/8}\dot{m}^{-1/4}\theta^{-5/4}. \tag{3.6}$$

The aspect ratio of the disk, true optical depth $\tau^* = \sqrt{\sigma \cdot \sigma_{ff}} \cdot u_0$ and surface density are

$$h/r = 3.7 \cdot 10^{-3}(\dot{m}\theta)^{1/4}x^{1/16}(\alpha m)^{-1/8}. \tag{3.7}$$

$$\tau^* = 51(\theta\dot{m})^{1/8}m^{3/16}x^{5/32}\alpha^{-13/16}. \tag{3.8}$$

$$T_s = 6 \cdot 10^6(\theta\dot{m})^{5/16}m^{-9/32}x^{-47/64}\alpha^{-1/32} \ \ \mathrm{K}. \tag{3.9}$$

where $\sigma_{ff} = 0.11 \cdot T^{-7/2}n$, cm^2/g is the free-free opacity of the disk.

At the condition $4.6 \cdot 10^{-3}(\alpha m)^{1/10}x^{23/20}(\theta\dot{m})^{-1} > 1$ the free-free absorption dominates the Thomson scattering opacity and parameters of the disk take a form

$$T = 10^7(\theta\dot{m})^{6/17}x^{-12/17}(\alpha \cdot m)^{-4/17} \ \mathrm{K}. \tag{3.10}$$

$$L_{bol} = 0.6 \cdot 10^{36}(\theta\dot{m})^{20/17}m^{15/17}\alpha^{-2/17} \ \ \mathrm{erg/s}. \tag{3.11}$$

$$\tau = 93(\theta\dot{m})^{4/17}m^{3/17}x^{1/34}\alpha^{-14/17}, \tag{3.12}$$

$$\rho = 1.2(\theta\dot{m})^{11/17}(\alpha m)^{-13/17} \cdot x^{-61/34} \ \mathrm{g/cm^3}, \tag{3.13}$$

$$h/r = 2.5 \cdot 10^{-3}x^{5/34}(\theta\dot{m})^{3/17}(\alpha m)^{-2/17}. \tag{3.14}$$

$$T_s = 5.5 \cdot 10^6(\theta\dot{m})^{5/17}m^{-19/68}x^{-97/136}\alpha^{-1/34} \ \ \mathrm{K}. \tag{3.15}$$

$$L_{kin}/L_{bol} = 228(\alpha m)^{2/17}\dot{m}^{-3/17}\theta^{-20/17} \tag{3.16}$$

4. Comparison with the fundamental plane of the black holes

The fundamental plane (FP) encapsulates the relationship between the compact radio luminosity, X-ray luminosity, and the black hole mass and provides a good description of the data over a very large range of black hole mass. In the work Daly *et al.* (2016), the position of objects of different masses in the coordinates L_{kin}/L_{bol} and L_{bol}/L_{Edd} has been collected in one FP. If this is true, the FP can be used to extract information about the dependence of θ on $\dot{m}$ and m.

Obviously, at the constant θ the theoretical predictions are not consistent with observations. θ must depend on $\dot{m}$ and m. The most natural option is to assume that θ depends on $\dot{m}$ as a power law

$$\theta = D\dot{m}^{\gamma}. \tag{4.1}$$

Our calculations are in agreement with the FP if in the Thomson and free-free regimes

$$\theta_T = 5 \cdot 10^3\dot{m}^{3/4}(\alpha m)^{1/10} \tag{4.2}$$

$$\theta_{ff} = 11.4 \cdot 10^3\dot{m}^{0.86}(\alpha m)^{1/10}. \tag{4.3}$$

For details see (Bogovalov 2018).

5. Discussion

The cold accretion onto SMBH transforms practically all the gravitational energy into the kinetic energy of jets. On this reason the disk appears radiationally inefficient. This strongly contrasts with radiationally inefficient ADAF models Esin *et al.* (1997). In the last case AGN appears very inefficient machine which transforms almost all the gravitational energy into mass and rotational energy of the SMBH. ADAF model needs an additional source of energy which is believed can be the rotational energy of SMBH.

We show that the "cold" accretion is consistent with the observations presented by FP provided that θ depends on $\dot{m}$ and m in accordance with equations (4.3). θ basically reflects the ratio of the magnetic field pressure inside and at the surface of the disk. The estimated values of θ agree with the recent calculations of the disk structure (Salvesen *et al.* 2016). The obtained ratio of kinetic-to-bolometric luminosity is close but exceeds the value obtained in (Li 2014).

At small accretion rates $\dot{m} < 10^{-2}$, the estimated value of θ is located in the region well below the line were the Shakura-Sunyaev model is valid. The magnetic pressure inside the disk appears less than the magnetic pressure estimated in the model Shakura & Sunyaev (1973). Therefore, it is quite reasonable to assume that at relatively low rates of accretion, $\dot{m} < 10^{-2}$, the accretion occurs predominantly in the regime of the "cold" accretion. At higher values of $\dot{m} > 0.1$ the accretion occurs in the regime of Shakura & Sunyaev. The transition between the regimes takes place at the value of $\dot{m}$ between 0.01 and 0.1 which well agree with location of the transition from very bright to very dim disks around SMBH with powerful outflow deduced in Churazov *et al.* (2005).

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