PROCEEDINGS OF SCIENCE

Impact of the magnetized wind on the formation of the accretion disk and the jet

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We consider the specific case of disc accretion for low viscosity and high electric conductivity of plasma. The key component in this model is magnetized wind outflowing from the accretion disc. This wind effectively carries away angular momentum of the accreting matter. Assuming variable magnetic field polarity in the disc (to avoid magnetic flux and energy accumulation at the gravitational center), this leads to radiatively inefficient accretion of the disc matter onto the gravitational center. Interestingly, that in this framework, the basic properties of the outflow (as well as angular momentum and energy flux per particle in the outflow) do not depend on the accretion disc structure. The obtained self-similar solutions prove the existence of such an accreting regime. The outflow predominantly occurs from the very central part of the disc. The accretion/outflow mechanism provides transformation of the gravitational energy of the accreted matter into the energy of the outflowing wind with efficiency close to 100%. The flow velocity can essentially exceed the Kepler velocity at the site of the wind launch

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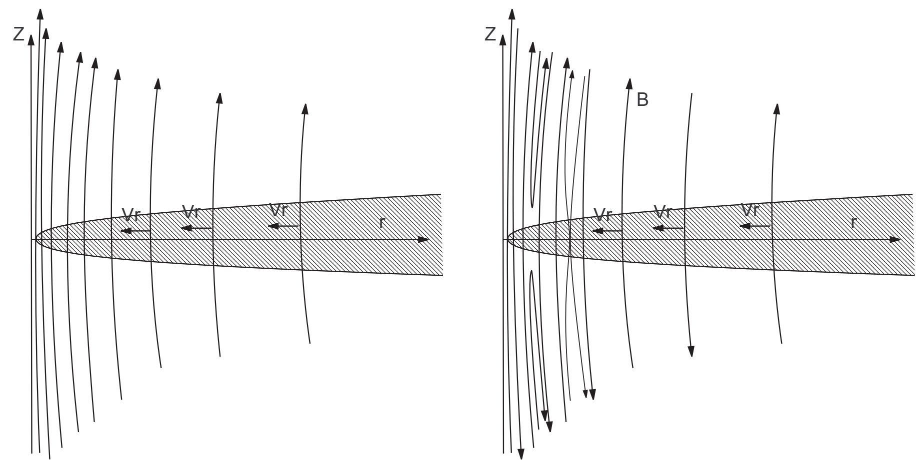

Figure 1: In [3] the matter diffuse across the magnetic field lines (left panel). Field lines do not move to the center. In our case (right panel) the magnetic field is advected to the center.

1. Main features of disk accretion due to wind outflow

Observations show that jets are strictly connected with accretion. It is reasonable to assume that the jets are directly connected with the plasma outflow from the disk and the energetics of the jets is defined by the energetics of the accretion. In some cases the mechanism of the plasma ejection appears surprisingly efficient. The total bolometric luminosity of radio galaxy M87 does not exceed 10^{42}ergs/s [4], while the kinetic luminosity of the jet is as high as 10^{44}ergs/s [5, 6]. Thus, the kinetic luminosity of the jet from M87 exceeds by two orders of magnitude the gravitational energy released at the accretion as estimated on the basis of conventional theory [2]. The conventional models of the disc accretion (Shakura & Sunyaev type or ADAFs) do not explain the existence of such objects. The example of M87 jet shows that one needs to explore new regimes of accretion.

The most evident modification of the accretion model is the incorporation of the magnetic field. In this regard, two processes are of special interest. The first one is related to the idea of Ref. [7]. It has been demonstrated that the magnetic field impact results into instability of particles in the Kepler orbits. If the angle between the magnetic field direction and the disc plane is less than 60° the particles are ejected freely from the disc by centrifugal force. The second one was proposed in [1]. They found that the loss of the angular momentum in the accretion disk can occur predominantly due to the wind outflow rather than viscous stresses like in the classical accretion disks [2]. Nevertheless, in the approach to this type of accretion developed by the Grenoble group [3] there is a difficulty. The magnetic flux is accumulated at the center of the system at the advection of the magnetic field (see Fig.1, left panel). To avoid this problem, it was assumed that due to the strong turbulence in the disk the resistivity of the plasma is reduced on a few orders of magnitude. The magnetic field lines are not advected to the center in this case. Plasma flows across the magnetic field lines.

We claim that the plasma does not flow across the magnetic field lines. The plasma advects the frozen field lines to the center. The problem with the magnetic flux accumulation is solved automatically if to take into account that the polarity of the field lines crossing the disk chaotically distributed along the disk, so that an average magnetic flux through any fraction of the disk equals to zero (see Fig.1, right panel).

2. Objectives and basic assumptions.

The objective of the work is to verify the possibility of the disk accretion at the loss of the angular momentum due to the magnetized wind when the magnetic field lines are perfectly frozen into the plasma. In this case all the dissipative processes (viscosity and finite electric conductivity) can be neglected.

Basic assumptions are following:

- The disk is cold and geometrically thin;
- The magnetic energy density is much less the energy density of the Keplerian rotation;
- The magnetic field varies with radius as a power low of r;
- The outflow is considered at the distance $z \ll R$, where R -is the radius of the disk;
- The frozen in condition
$$\mathbf{E} + \frac{1}{c}\mathbf{v} \times \mathbf{B} = 0$$
takes place in the wind zone;
- The processes of dynamo and magnetic field dissipation can take place in the disk. Nevertheless, the viscosity due to magnetic stresses is neglected.

The accretion and outflow occurs in this case in the self-similar regime.

3. Basic equations

In the wind zone the equations are

$$\frac{\partial T_{ik}}{\partial x_k} = -\rho GM \frac{R_i}{R^3}. \tag{3.1}$$

for spatial indexes i, where

$$T_{ik} = \rho v_i v_k + p\delta_{ik} - \frac{1}{4\pi}(B_i B_k - \frac{1}{2}B^2\delta_{ik}) \tag{3.2}$$

is the energy-momentum tensor. For energy flux $\vec{q}$ the equation is as follows

$$\frac{\partial q_k}{\partial x_k} = 0, \tag{3.3}$$

where

$$q_i = \rho v_i \left(\frac{v^2}{2} - \frac{GM}{R}\right) + \frac{c}{4\pi}[E \times B]_i\,. \tag{3.4}$$

4. Disk-wind connection

Dynamics of the disk is defined by the loss rate of the angular momentum, energy and matter carried out by the wind. Balances of the fluxes of these values are as follows. We have

$$\frac{\partial \dot{M}}{\partial r} - 4\pi r\rho v_z = 0, \tag{4.1}$$

for the matter,

$$\frac{\partial}{r\partial r}\left(r^2 v_\varphi \int_{-h/2}^{h/2} \rho v_r\, dz\right)_{disc} + 2\left(r\rho v_\varphi v_z - \frac{1}{4\pi} r B_\varphi B_z\right)_{wind} = 0. \tag{4.2}$$

for the angular momentum, and

$$\frac{1}{r}\frac{\partial}{\partial r}\int_{-h/2}^{h/2} r\rho v_r\, dz \left(\frac{V_k^2}{2} - \frac{GM}{r}\right)_{disc} + 2\left(\rho v_z\left(\frac{v^2}{2} - \frac{GM}{R}\right) + \frac{1}{4\pi}[E\times B]_z\right)_{wind} = 0. \tag{4.3}$$

for the energy.

The mechanism of the accretion is similar one proposed in [1] and developed in [3]. Plasma is accreted at the loss of the angular momentum carried out by the wind. It does not matter do any dissipative processes occur in the disk or not. Nevertheless, the crucial difference with [3] is in the relaxing restrictions imposed by the assumption in [3] that the plasma have to diffuse across the magnetic field lines. This means that the distribution of the poloidal magnetic field in the disk have to provide necessary rate of the diffusion. In our scenario the distribution of the poloidal magnetic field is free.

5. Analytical results

The main results were obtained for self-similar solutions. In this case λ, the ratio of the Alfvenic radius over the radius of the root of a field line at the disk, is assumed to be constant. The rate of accretion varies with radius as

$$\dot{M} = \dot{M}_{\max}\left(\frac{r}{r_{\max}}\right)^{\frac{1}{2(\lambda^2-1)}},$$

where $\dot{M}_{max}$ is the rate of accretion at the outer edge of the disk.

Velocity in the wind from the disk, density and magnetic field are scaled with r as follows

$$\begin{aligned}\mathbf{v}(r,z,\phi) &= r^{-1/2}\tilde{\mathbf{v}}(z/r,\phi)\,,\\ \rho(r,z) &= r^{-\delta}\tilde{\rho}(z/r)\,,\\ \mathbf{B}(r,z,\phi) &= r^{-\frac{1+\delta}{2}}\tilde{\mathbf{B}}(z/r,\phi)\,.\end{aligned}$$

Self-similarity index δ and λ are connected by the equation

$$\delta = \frac{3\lambda^2-4}{2(\lambda^2-1)}.$$

Thus, the self-similarity index is not free parameter as in [7]. The matter is launched from the disc with Keplerian rotational velocity and zero poloidal velocity.

6. Properties of the solution

The basic conclusion following form our work is that the magnetized plasma outflow from the accretion disk is sufficient to provide accretion of the matter onto the gravitational center. This fully confirms the idea proposed by [1]. No dissipative processes are necessary for the accretion. This is new property of the process. Therefore, no heating of the disk occurs and it's luminosity is close to zero. Almost 100% of the accretion energy is transformed into the kinetic energy of the wind. Ratio of the disk luminosity to the kinetic luminosity of the jet is low. This is ideal limiting case. In reality, turbulence in the disk inevitably provides some heating of the disk and it's luminosity [3]. Nevertheless, in this regime the hard connection between luminosity of the disk and the gravitational energy release taking place in the conventional model [2] is fully lost. Model predicts existence of strongly under luminous disks like in M87.

It is important that every particle in the wind carries energy equal to

$$W = (2\lambda^2 - 3)E_{Kepler}.$$

Low density or highly magnetized wind (big λ) is accelerated to the energy greatly exceeding Keplerian energy. Although this result has been obtained in the nonrelativistic limit it allows us to understand the mechanism how the plasma at the last Keplerian orbit with Lorentz factor ~ 1 is accelerated to the Lorentz factors ~ 10 and above.

One of the interesting result is efficient transformation of the Poynting flux into the kinetic energy flux. It is shown in Fig. 2, that the terminal velocity is close to the possible theoretical limit corresponding to transformation of the Poynting flux into the kinetic energy flux. It is interesting to point out that this transformation occurs in superafvenic but sub fast magnetosonic regime of the flow.

The wind from the disk is collimated. Fig. 3 demonstrates that the collimation dramatically depends on the dimensionless Alfvenic radius λ.

The visible mass of the jet is ejected from the central part of the disk. Fig. 4 shows the distribution of the column density in the wind which approximately reproduces the image of the jet. The inclination angle is 42^o. The integration along the line site is performed up to the Alfvenic radius.

7. Conclusion

This work demonstrate that dissipative processes like viscosity and finite electric conductivity are not necessary to provide the disk accretion. The self consistent solutions obtained for this case naturally explain the most puzzling features of the jets from AGN:high energy of bulk motion, ejection of the jets from the very central part of the system and low ratio of the disk luminosity over the kinetic energy luminosity of the jets. This supports the idea proposed in [1] that under certain conditions, which are still not clear, the angular momentum losses are provided predominately by the wind rather than by the viscous stresses.

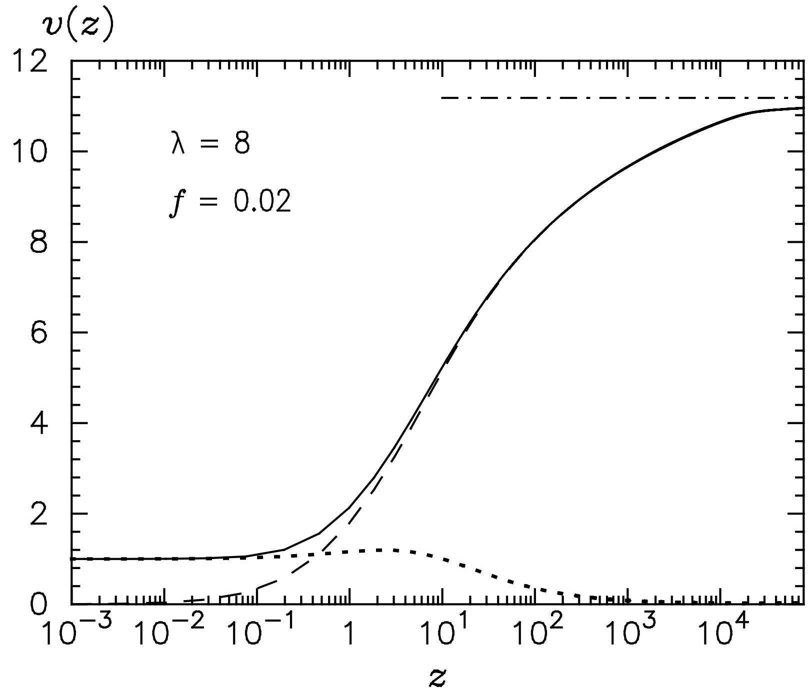

Figure 2: Variation of velocity with z for $\lambda = 8$, $f = 0.02$. Solid line - full velocity, dashed line - poloidal velocity, dotted line - azimuthal velocity. Horizontal dashed-dotted line shows the upper limit on the velocity

Acknowledgments

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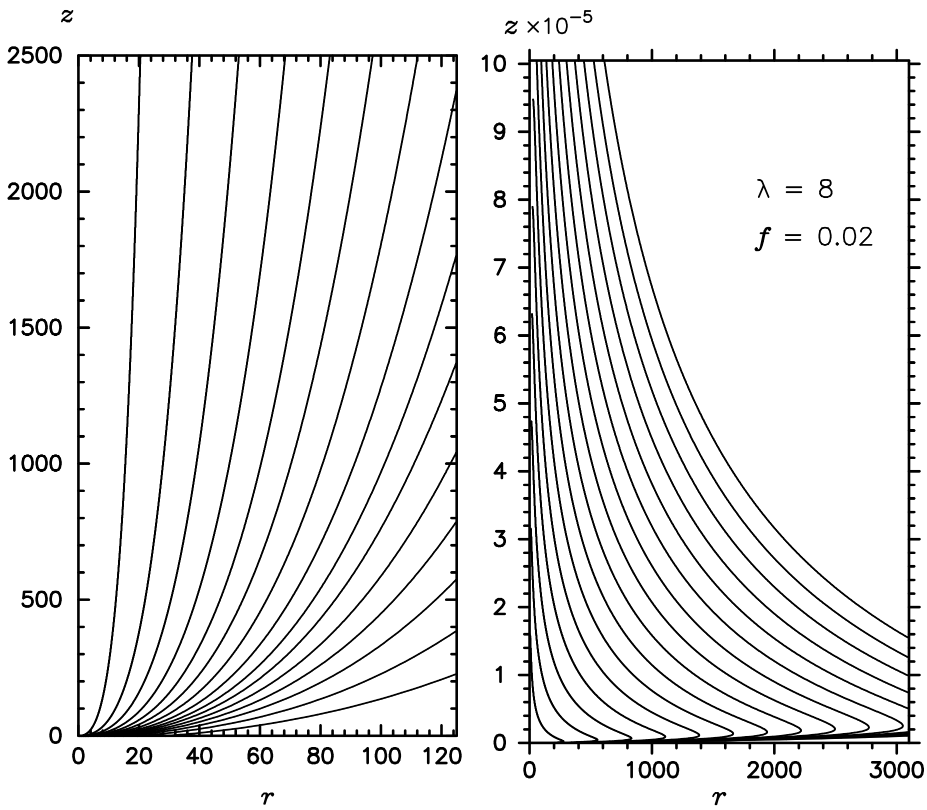

Figure 3: The field lines in the wind for $\lambda = 5$, $f = 0.01$ (left panel) and for $\lambda = 8$, $f = 0.02$ (right panel)

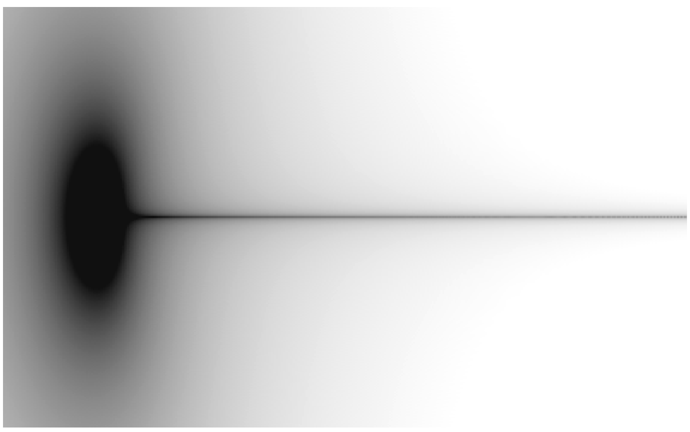

Figure 4: Distribution of column density along line of sight for the solution with $\lambda = 8$, $f = 0.02$. central part of the disk is shown. The scale of the whole disk well exceeds the scale of the figure.