

Launching Jets From the Transitive Layer of Accretion Disks by Burgers Vortex

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Abstract

Possibility of representation of a transitive (boundary) layer of an accreting disk round young stellar formations as Burgers vortex with a converging radial flow of substance, almost homogeneous rotation in nuclear area which is falling down on the hyperbolic law to periphery is considered. Physical and geometrical characteristics of a transitive layer are received. It is shown that transitive layer of Burgers, in depending of characteristics of transitive layer can both to provide formation of bipolar collimated outflow which is accelerated proportionally to the vertical coordinate accruing in due course exponentially (the active phase) and provide the capture of all accreting substance by the central body. The behavior of outflow is determined by the properties of Burgers vortex.

Keywords: *Accretion disk; Burgers vortex; outflow*

Introduction

Process of formation of stars leads to occurrence accretion disk (AD) around "young star formations" (YSO) [1]. Almost all such objects which have reached of age of an order of one millions of years possess such disk [2]. Opening of gas and dust clouds round protostars and of T Tauri stars [3] confirms this conclusion.

The mechanism of formation of stars and structures accompanying them of type accretion disks and bipolar outflows so far is not clear [4,5]. A problem of the angular momentum - the mechanism, on which accreting substance loses the angular momentum to rich a star, mechanisms causing macroscopic turbulence, and the viscosity connected with it, occurrence astrophysical, as a rule, bipolar, collimated jet eruptions from an accretion disk's central region, remain in the center of attention of many researchers. It is considered, for example, that the angular momentum is broken by a solar wind at T Tauri stage, and then broadcast to external areas of a disk by viscosity [6]. Viscosity is created by large-scale turbulence, but mechanisms causing turbulence, for the present are not completely clear... As to jet eruptions, which are observed from not relativistic HH objects [7] to relativistic micro-quasars and gamma bursts (see for example, [8,9]), and to extragalactic streams of Mpc scales from active galactic nucleus [10], though the propagation and collimation of jets it is possible to consider as rather clear [11,12], the exact mechanism of their formation remains unclear. Discussed magnetic mechanisms connect generation of jets with interaction of a rotating matter in internal areas of accretion disk with a magnetic

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field of the central star, or an external magnetic field (see for example [13-16]). In thermal (see in [17]) mechanism the stream generation is connected with interaction of accretion currents with the central star in a disk boundary layer. In hydrodynamic vortical mechanisms [18-21] the features of an outflow are defined by properties of a vortex, similar to tornado occurrence.

Other hydrodynamic mechanism has been offered by authors [22] who have noticed that assumptions for thin accretion disk approach, where orbits should be circular, are broken from certain critical radius. It leads to occurrence of a quasi-radial stream of substance in a disk and to occurrence of the jet expiration (references of earlier attempts can be found in [22]).

We recognize the importance of magnetic fields in physics of outflows from YSO. Indeed, magnetic fields of considerable magnitude were indirectly and even directly detected in the vicinity of some YSO's and also in outflows (see, e.g., [23]). Their role in collimation of outflows is evident from these observations. However, an important observational conclusion that X-ray properties YSO's were unrelated to the presence or lack of outflows [24] is pretty awesome, if outflows are determined dynamically by magnetic field is true.

In the present work we continue to develop the vortical concept, and we will try to present central regions of accretion disks in the form of Burgers vortex. This vortex is one of a few axially symmetrical exact solutions of the Navier-Stokes equation, which is often used for the description of different properties of a tornado, and also widely used in the researches devoted to turbulence occurrence, etc. (see for example [25]).

Modelling of accretion disk by Burgers vortex

The system of Navier-Stokes and continuity equations for axially symmetrical currents of the viscous environment round the central body of mass M^* in cylindrical co-ordinates r, θ, z is represented as:

$$\frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} - \frac{v_\theta^2}{r} = -\frac{1}{\rho} \frac{\partial p}{\partial r} - \frac{GM_* r}{r^2 + z^2} + \nu \frac{\partial}{\partial r} \left(\frac{\partial v_r}{\partial r} + \frac{v_r}{r} \right), \quad (1)$$

$$\frac{\partial v_\theta}{\partial t} + v_r \left(\frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} \right) = \nu \frac{\partial}{\partial r} \left(\frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r} \right), \quad (2)$$

$$\frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + v_z \frac{\partial v_z}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} - \frac{GM_* z}{r^2 + z^2} + \nu \frac{\partial^2 v_z}{\partial z^2}, \quad (3)$$

$$\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial(\rho r v_r)}{\partial r} + \frac{\partial \rho v_z}{\partial z} = 0, \quad (4)$$

where ν is kinematic viscosity, ρ is homogeneous mass density, p is the pressure. In the resulted equations because of axial symmetry of a problem the terms containing derivatives rather θ , and also derivatives v_r and v_θ with respect to co-ordinate z are omitted.

In case of homogeneous distribution of a mass the stationary continuity equation (4) allows the exact solution

$$v_r = -Ar, v_z = 2Az. \quad (5)$$

Corresponding azimuthal equation of motion (2) under the condition

$$v_{\theta} \rightarrow \begin{cases} 0, & r \rightarrow \infty \\ \omega r, & r \rightarrow 0 \end{cases} \quad (6)$$

gives following expression for azimuthal speed

$$v_{\theta} = \frac{\omega r_0^2}{r} \left(1 - e^{-r^2/r_0^2}\right), \quad (7)$$

where ω has meaningful to angular speed of homogeneous rotation of nuclear area of a vortex, and $r_0 \equiv \sqrt{2 \nu/A}$.
(8)

Formulas (5) and (7) represent one of a few exact axially symmetrical solutions of Navier-Stokes equation that is the Burgers vortex.

Azimuthal speed (7) has a maximum, $v_{\theta \max} = 0.6382 \omega r_0$, which reaches at $r_m \cong 1.12 r_0$. (8)

The characteristic size r_0 , apparently from (8) is defined by kinematic viscosity ν and a gradient of speed of radially converging stream A which simultaneously characterizes also vertical bipolar outflow of substance from nuclear area of the vortex.

Typical rotary speed of a surface of the central body of radius R_* (in terms of R_{\odot}) and cycle time P (in days), an order

$$v_{\theta*} \approx 5 \cdot 10^6 (R_*/R_{\odot}) P^{-1} \text{ cm}\cdot\text{s}^{-1} \quad (9)$$

$$v_K = \sqrt{GM_*/r} \equiv \Omega_K r, \text{ where } \Omega_K = \sqrt{GM_*/r^3}, \quad (10)$$

which on the surface of the central body, an order

$$v_K(R_*) \approx 4.4 \cdot 10^7 (M_*/R_*)^{1/2} \text{ cm}\cdot\text{s}^{-1}, \quad (11)$$

where M_* is the mass of the central body in terms M_{\odot} . The rotational velocity of the accreter is less than the Keplerian one. A difference between these speeds, generally speaking, is an order of Keplerian speed. This is an enormous burden to place on the substance, slowing down over relatively short distance to become synchronous with the surface. Therefore in this area should operate significant forces of a friction and must be released a big amount of energy.

The internal area of a disk in which occurs this transition, is transitive (boundary) layer (TL) of a disk. It is clear that in this area the crucial role played by viscosity and pressure.

In the present work we will try to provide the transitive layer in the form of Burgers Vortex. This requires that the rotational speed of the Vortex at distance $R_* \ll r$ coincided with the central body surface speed v_* :

$$v_{\theta}(R_*) \equiv v_* = \omega r_0 \frac{1 - e^{-(R_*/r_0)^2}}{R_*/r_0} \cong \omega R_*, \quad (12)$$

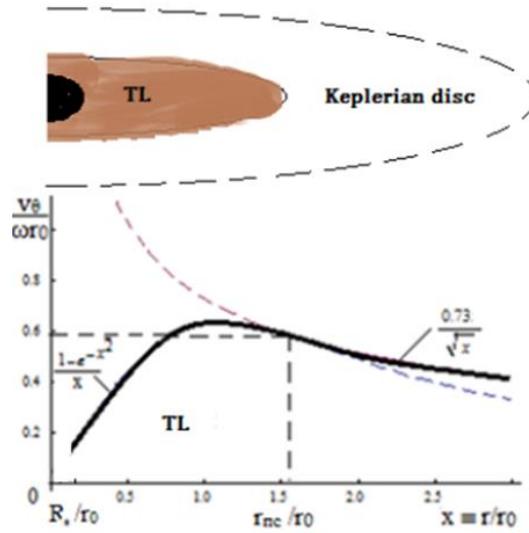


Fig.1 Rotational velocity profile of AD

that is, ω is the angular velocity of rotation of the surfaces of the central body, and on the outer border of TL the Vortex speed (7) should smoothly go into Keplerian (10). This gives

$$\sqrt{\frac{GM_*}{\omega^2 r_0^3}} \frac{1}{\sqrt{x_{TL}}} = \frac{1 - e^{-x_{TL}^2}}{x_{TL}}, \tag{13}$$

where $x_{TL} \equiv r_{TL}/r_0$.

On the schedule fig. 1 curves represent the rotational profiles of Burgers vortex (a continuous curve in the left with faltering continuation on the right) and of Kepler. The contact of these curves occurs at following value of dimensionless parameter a :

$$a \equiv \sqrt{\frac{GM_*}{\omega^2 r_0^3}} \approx 0.73, \tag{14}$$

In a point (fig.1)

$$r_{nc}/r_0 \approx 1.53, v_0(r_{nc})/v_{0max} \approx 0.92. \tag{15}$$

Hence, the disk transitive layer, modeled as Burgers vortex, represents a ring with the radial sizes $R_* \leq r \leq r_{TL} \approx 1.53r_0$. This size may vary from a few to a dozen R_* . For example, for the central body with the parameters of the Sun, the size of the transitive layer would be of order $\sim 30R_*$.

Parities (14) and (15) allow expressing the maximum speed of rotation of a vortex in mass of the central body and the characteristic size r_m :

$$v_{0max} \approx 0.64 \omega r_0 \approx 0.92 (GM_*/r_m)^{1/2}. \tag{16}$$

By integration of the radial (1) and vertical (3) equations, taking into account (5), (7) the pressure distribution in a transitive layer, under a condition $p(R_*, 0) = p_*$, we will receive

$$\frac{p(r, z)}{\rho \omega^2 r_0^2} = \frac{b^2 - 1}{2x_*} x_1^3 - \left[\frac{(1 - e^{-x^2})^2}{2x^2} + \text{ExpIntegralEi}(-2x^2) - \text{ExpIntegralEi}(-x^2) \right] \Big|_{x_1}^x \tag{17}$$

$$- \frac{1}{2} b^2 (x^2 + z^2 - x_*^2) + \frac{a^2}{\sqrt{x^2 + z^2}}, \quad x \equiv \frac{r}{r_0}; x_* \equiv \frac{R_*}{r_0}; z \rightarrow \frac{z}{r_0}$$

where $b \equiv A/\omega$, and p^*/ρ has been estimated from the Clapeyron equation:

$$p^*/\rho = \mathcal{R}T_*/\mu \approx c_s^2 \tag{18}$$

where T_* and c_{s*} are temperature and the sound speed on the surface of central body respectively, $\mathcal{R} = 8.3 \cdot 10^7 \text{ erg} \cdot \text{mol}^{-1} \text{ K}^{-1}$ is the gas constant, μ is the molar mass of gas. In (17) is used notation (14).

Surface on which the gas pressure vanishes describes by equation:

$$\frac{a^2}{\sqrt{x^2 + z^2}} - \frac{1}{2}b^2(x^2 + z^2 - x_*^2) + \frac{b^2 - 1}{2x_*}x_1^3 - \left[\frac{(1 - e^{-x^2})^2}{2x^2} + \text{ExpIntegralEi}(-2x^2) - \text{ExpIntegralEi}(-x^2) \right]_{x_1}^x = 0, \quad x_1^2 = x_*^2 - z_1^2 \tag{19}$$

The solution of this equation rather z : $z_{\text{TL}} = z(x)$, gives semi thickness of TL depending on radial co- ordinate in units r_0 .

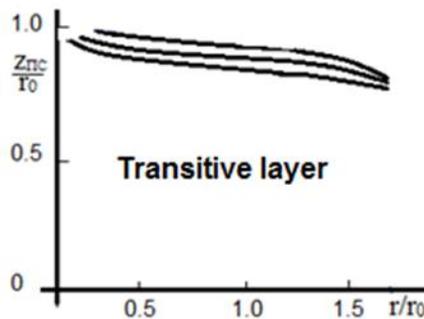


Fig. 2. Semi thickness of TL for $R_*/r_0 = 0.1, 0.2, 0.3$

3. Some properties of a disk with Burgers TL

Accretion rate - the quantity of substance radially transferred through a disk for a time unit

$$dm/dt = m - 2\pi r \rho v_r h(r), \tag{20}$$

where h is a thickness of a disk, ρ is the mass density, v_r is the speed of the radial flow of substance.

In a two-dimensional case, the joint decision of the equation of a continuity (4) and the radial equation of the angular momentum, taking into account (15), that is lawful only in area $r > r_{\text{ПC}}$, where it is possible to neglect vertical speed, gives the formula for radial speed [26]:

$$v_r = -3 v/2r. \tag{21}$$

In this case actually it is considered that the transferable all mass (20) riches to a star and increases its mass:

$$\dot{m} = \dot{M}_* = 3\pi\rho v h. \tag{22}$$

Estimations of Reynolds number show that accretion disks are turbulent. For an estimation of turbulent viscosity in them usually use α - parametrization of a disk [26]:

$$v \sim \alpha c_s h \sim \alpha c_s^2 / \Omega_K, \tag{23}$$

where α - dimensionless parameter with value from zero accretion is absent) to unit.

For an accretion rate in the Burgers transitive layer, taking into account (5) and (8) we receive

$$\dot{m} = 2\pi\rho Ar^2h. \tag{24}$$

Let's notice the important feature of Burgers TL that is how is nearer to the center of a disk, the lesser radial transfer of mass. Instead the mass transfer in a vertical direction increases significantly.

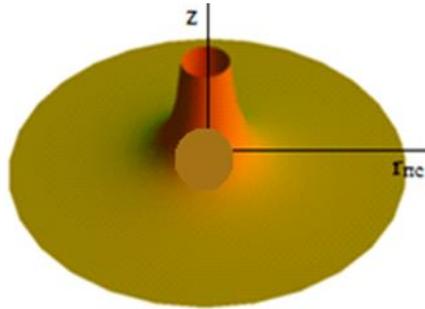


Fig.3. The surface $\psi (r, z) = \text{constant}$

Formation of a bipolar outflow

Current function of axially symmetrical vortex $\psi(r,z)$ for Burgers vortex gives

$$\psi (r, z) = Ar^2 z. \tag{25}$$

The characteristic form of a surface on which current function of the Burgers vortex has constant value, is represented on For definition of a trajectory of gas particles it is necessary to solve equations

$$dr/dt = -Ar, \quad dz/dt = 2Az, \quad d\theta/dt = \omega \frac{1 - e^{-x^2}}{x^2}. \tag{26}$$

First two equations, considering initial conditions $r(0) = r_{TL}$ and $x(0) = z_0$ give

$$r(t) = r_{TL} e^{-At}, \quad z(t) = z_0 e^{2At}. \tag{27}$$

Integrating the third equation we will receive time dependence of the azimuthal coordinate θ :

$$\theta(t) \approx \frac{\omega}{A} \left(e^{2At} \left(1 - e^{-2.34e^{-2At}} \right) - 2.34 \text{ExpIntegralEi} \left[-2.34e^{-2At} \right] \right). \tag{28}$$

On the fig. 4 the lines represent dependence of azimuthal angle from dimensionless time $2At$. In zero approach these lines can be approximated by linear function

$$\theta = 0.42 \omega/A + 0.74 \omega t. \tag{29}$$

Excluding of time from (27) and (29), we will receive the equation of a spatial curve (trajectory) by which approaches to the center of a disk gas in the Burgers transitive layer:

$$r(\theta) \approx r_{TL} e^{-1.34 \frac{A}{\omega} \theta}, \quad z(\theta) \approx z_0 e^{2.68 \frac{A}{\omega} \theta}. \tag{30}$$

Hence, gas particles come nearer to the disk center by a helicoid trajectory, which characteristic form is presented on fig.5, and create a bipolar outflow. Speed of the stream is accelerated proportionally to vertical co-ordinate z which grows in due course, and the radial co- ordinate decreases exponentially.

It is necessary to notice that formation of the bipolar outflow begins in the area, closer to the internal boundary of the transitive layer, and the behavior of jet is determined by the properties of Burgers vortex, although the parameter ω is associated with the mass of the central body.

he mass of substances falling on central body per

The mass of substances falling on central body per second can be estimated using the equation (24) on the inner border of the TL:

$$\dot{m} = 2\pi\rho AR_*^2 h_{cr} = 4\pi\rho AR_*^2 z_{cr}, \tag{31}$$

where z_{cr} is the maximal high on the border $r = R_*$, on which gas captured by the central body. Obviously

$$v_r^2 + v_*^2 + v_{z_*}^2 - 2GM/\sqrt{(R_*^2 + z^2)} \leq 0,$$

which gives for z_{cr} transcendental equation

$$\frac{2a^2}{\sqrt{x_*^2 + z_{cr}^2}} - 4b^2 z_{cr}^2 - (1 + b^2)x_*^2 = 0, \tag{32}$$

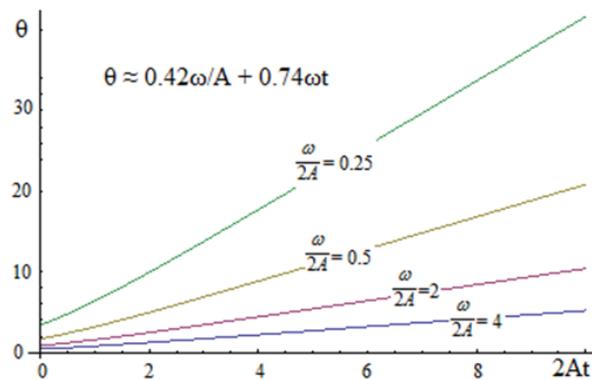


FIG. 4 Dependence of azimuthal angle from dimensionless time $2At$ for different values of $\omega/2A$

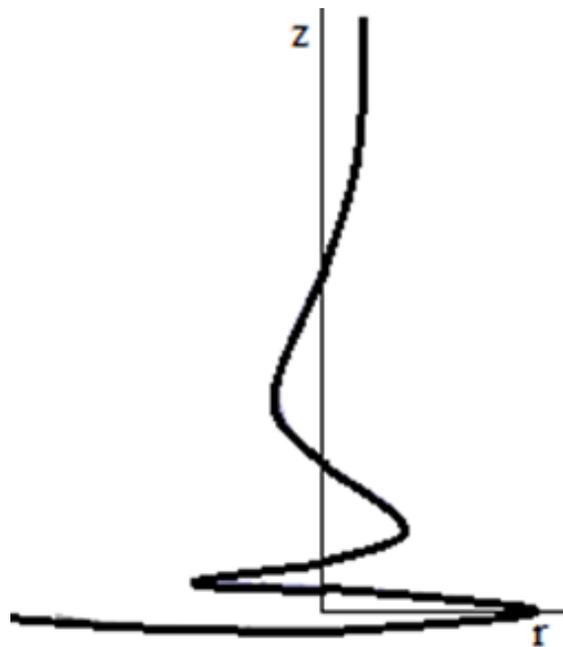


FIG.5 The characteristic form of the gas particle trajectory in central region of TL

where z_{cr} is measured in units r_0 .

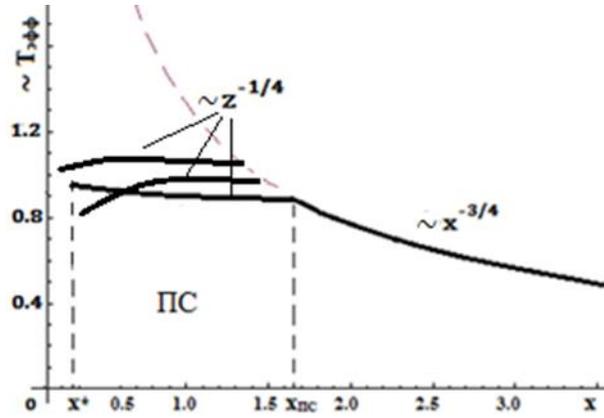


FIG. 6 Solutions of Eq. (32)

Solutions of this equation for the value $b = 0.7$ are presented in Fig. 6, which implies that $x_* = 0.1$ turns $z_{cr} = 0.81$. Whereas for the thickness of the TL equation (19), when $c_{s*} \approx 15v_*$, gives $z_{TL} = 0.99 r_0$. It follows that only 0.2 part of accreting substance comes on the formation of a bipolar outflow, the rest is captured by a central body.

Estimation of the accretion rate of the central body in this case, for $\rho \sim 10^{-12} \text{ g} \cdot \text{cm}^{-3}$, gives

$$\dot{M}_* \approx 10^{-10} \left(\frac{R_*}{R_\square} \right)^2 \left(\frac{P_*}{P_\square} \right)^{-1} \frac{M_\square}{\text{лет}}. \tag{33}$$

With the change in the values of parameters c_{s*} and (b) the proportion of mass, going on the formation of the bipolar Jet changes. For example, for constant values x_* and b , with a reduction of the speed of sound, the thickness of the TL is decreased, whereas z_{cr} does not change. This reduces the mass of the jet formation. At even smaller values c_{s*} outflow from such systems will be absent: the whole accreting mass will be captured by a central body. A similar picture can be obtained and at the same time reducing the b parameter. Consequently, in the course of evolution, the systems may have periods of "activity" with the eruption of the bipolar outflow.

Effective Surface Temperature

Energy dissipation in unit of volume of a disk for a unit time because of a viscous friction, is estimated by the formula

$$q = \rho v \left(\frac{dv_\theta}{dr} - \frac{v_\theta}{r} \right)^2. \tag{34}$$

Out of a transitive layer of a disk taking into account (16) it gives

$$q_n = \frac{9}{4} \rho v \frac{GM_*}{r^3} = -\frac{3}{4\pi} \dot{m} \frac{GM_*}{r^3}. \tag{35}$$

Considering that this energy is radiated from both edges of a disk under the black body law, we receive the well-known dependence of effective surface temperature of a disk on radial co-ordinate [27]:

$$T_{\text{eff}} = \left(\frac{3\dot{m}}{8\pi\sigma} \frac{GM_*}{r_0^3} \right)^{1/4} x^{-3/4}, \tag{36}$$

where $\sigma = 5.67 \cdot 10^{-5} \text{ erg} / (\text{s} \cdot \text{cm}^2 \cdot \text{K}^4)$ is the Stefan- Boltzmann constant.

For an estimation of temperature of a transitive layer, we will take advantage that luminosity of accretion substances in the field of gravitation of the central body is released in a optically thick transitive layer

$$L_{TL} = \frac{1}{2} \frac{GM_* \dot{m}}{R_*} = 2 \cdot 2\pi R_* h_{TL} T_{TL}^4. \tag{37}$$

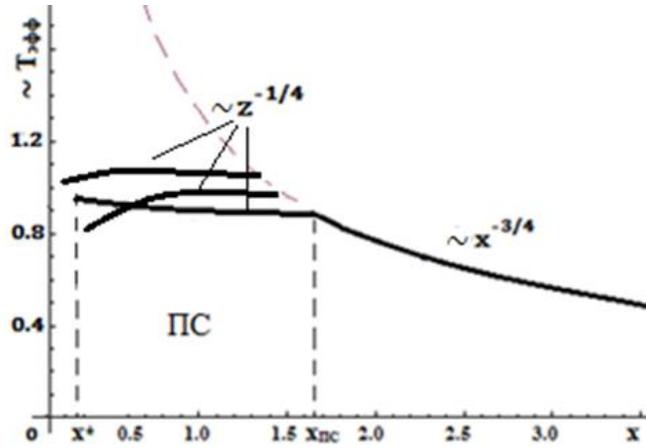


FIG. 7. The effective surface temperature distribution along the accretion disc radius for different values x_* , c_{s*} and b .

Considering that $h_{TL} = 2z(x)$, for the temperature of a transitive layer we will receive

$$T_{TL} = \frac{1}{2} \left(\frac{\dot{m}}{2\pi\sigma} \frac{GM_*}{R_*^2 r_0} \right)^{1/4} z(x)^{-1/4}. \tag{38}$$

Characteristic dependence of effective temperature of accretion disc (functions $z(x)^{-1/4}$ and $x^{-3/4}$)

from dimensionless radial co-ordinate x is presented on the schedule fig. 6, where δ dimensionless parameter is equal $(12 \cdot x^2)$. The effective temperature in a transitive layer has flat character, and crosses a curve $\sim x^{-3/4}$ in limits of TL.

These considerations only tell us about the surface temperature. The internal temperature that determines the disk thickness h and probably also the viscosity in the disk can be quite different, and depends on the mechanism transporting energy to the surface. But this transport needs to some detail for realistic disk models and when a number of additional assumptions are made...

Stability of a Disk

Let's notice that for the Burgers vortex the value $(rv_\theta)^2$ increases in a direction to periphery of a transitive layer (Reyleigh criterion for stability of axially symmetrical currents):

$$\frac{1}{r^3} \frac{d}{dr} (rv_\theta)^2 = \frac{4\omega^4}{x^2} (1 - e^{-x^2}) > 0. \tag{39}$$

Gravitational stability of differentially rotating disk is defined by the criterion of Toomre [28]

$$Q = \frac{c_s \kappa}{\pi G \Sigma} > 1, \tag{40}$$

where Σ is superficial mass density of a disk, $\kappa = 2 \Omega \sqrt{1 + \Omega r / 2\Omega}$ is epicyclic frequency. In area of Keplerian rotation (40) gives

$$Q = \frac{\Omega_K^2}{2\pi G \rho} \approx \frac{h}{r} \frac{M_*}{m_{disk}}, \quad (41)$$

which shows, that the outer edge of a disc can become unstable. Instability of outer edge is found in 2D numerical simulations of accretion discs also [29,30].

In a transitive Burgers layer for Toomre parameter we receive expression

$$Q = \frac{1.8M_*}{\pi \rho r_0^3} \zeta(x), \quad \text{where} \quad \zeta(x) \equiv \left(\frac{1 - e^{-x^2}}{x^2} \right)^2 \left(1 + \frac{2x^2 e^{-x^2}}{1 - e^{-x^2}} \right)^{1/2}. \quad (42)$$

The least value, ≈ 0.2 , the function $\zeta(x)$ accepts on external edge of TL, $r = r_{TL}$. So the considered area of a disk is stable if $1.8M_* / \pi \rho r_0^3 > 5$. If to consider r_0 an order of several radii's of the central body this condition is satisfied for transitive layers of typical accretion disks.

Conclusion

The results received in the present consideration, specify in importance of hydrodynamic vortical processes for physics of accretion disks. In particular, the description of the central transitive layer of a disk by the Burgers vortex allows explaining formation of bipolar outflows without attraction of magnetic fields, or the powerful thermal phenomena which, from our point of view, in an initial stage of star formation are not too important.

Qualitatively, vortical hydrodynamic process of formation of bipolar outflows, apparently, occurs under the following scenario. The Radially-converging stream in Keplerian disk, leads to "accumulation" of the angular momentum. Because of a viscous friction between gas blankets, the part of the angular momentum has to be transferred outside. The rest changes the character of Keplerian rotation in its central part at the expense of excessively big turbulent viscosity, energy dissipation and pressure gradient force. A transitive layer in form of a large-scale Vortex with almost uniform rotation in its nuclear area, a fact which is observed in many discs [18], is forming. Continuing to move toward the center, depending on values of the parameters of the transitive layer, a substance with excess of angular momentum and energy generates high-speed bipolar Jet, accelerating on vertical direction (active phase), and the rest of substances lost angular momentum and energy falls on the emerging central body increases its mass and speeds up the process.

The formation of the bipolar Jet begins in the area, closer to the internal border of transitive layer. However, depending on the values of the physical parameters of the system, the bipolar Jet may not occur: all the accreting mass will be captured by the central body.

In this consideration parameters of Burgers vortex are constants. The following work we plan to take into account no stationarity of transitive layer, as well as a comparison of theory with observations.

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