DIPOLE TOROIDAL VORTEXES AND WIND-ACCRETION INSTABILITY IN ACTIVE GALAXY NUCLEI

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The torus concept as an essential structural component of active galactic nuclei (AGN) is generally accepted. Here, the situation is discussed when "twisting" the torus by radiation or wind transforms it into a dipole toroidal vortex which in turn can be the source of matter replenishing the accretion disk. Thus originating instability which can be responsible for quasar radiation flares accompanied by matter outbursts is also discussed. A "matreshka" scheme for obscuring vortex torus structure that could explain the AGN variability and evolution is proposed. The model parameters estimated numerically for the luminosity close to the Eddington limit agree well with the observations.

PACS: 94.30.Tz

1. INTRODUCTION

Starting with the Antonucci and Miller's outstanding work, tori have been considered as an AGN-structure necessary element forming the basis of the AGN unified model [1]. A brilliant achievement was the first direct observation of the obscuring tori described by Jaffe and his colleagues [2]. Tori were positively confirmed existing when observed with the Hubble telescope and the MIDI IR-camera equiped VLT optical interferometer, though the efforts to reveal their structure detail and internal motion are yet to come. Many papers are devoted to tori as embodiments of thick accretion disks, and also investigate their stability defined by the orbital motion gradients. However, within the AGN structure they are mainly considered purely geometrically.

We offer to consider a torus as a dynamic object with its proper vortex motion. As is well known, a torus allows two independent rotations: "orbital" over the torus periphery and "vortical" over its inner-radius circle (our terms). This latter will be of our major interest. The vortical motion in a self-gravitating torus (see discussion in [3]) is vitally different from the orbital one, which in an oversimplified case merely means rotation of a torus as a single whole about the axis of symmetry. For the near Eddington limit luminosity $L \approx L_{Edd}$, when the gravitation is largely balanced by light pressure, this motion in AGN is not so essential. Though it is necessary to stabilize self-gravitation of a compact toroidal vortex [4], as used here, it can be quite neglected at first.

The vortical torus motion, which makes the torus the vortex, will be of most importance in the following. Originating or being sustained by the central source radiation or wind «twist» it is capable of «replenishing» the accretion disk mass, thereby adjusting the process of accretion and introducing a feedback (Fig.1). Here, the dipole structure of a toroidal vortex defined by the symmetry of radial-outflowing wind and radiation is of importance. Note that the streamline structure across such a dipole vortex resembles the structure and topology of streamlines in the well-studied hydrodynamic models, such as Hill and Lamb's vortices [5], Larichev-Reznik solitons, and others. At the same time, each component of a toroidal dipole taken separately resembles the Maxwell vortex, though with the opposite direction of rotation.

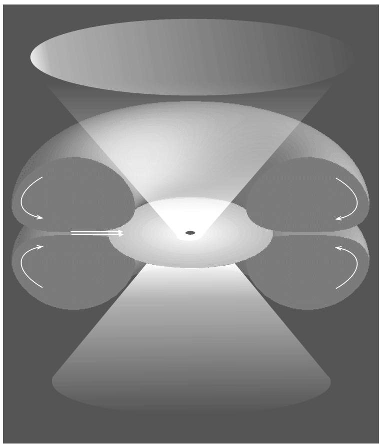

Fig.1. Dipole toroidal vortex in the center of AGN – 3D picture. Conic sections sketch out the wind and radiation

2. TWISTING A VORTEX BY RADIATION

At the torus large radius distance R, the central source emitted light pressure is $L/(4\pi cR^2)$. The equation for a vortical motion momentum takes the form:

$$\left(\frac{dp_\varphi}{dt}\right)_{twist} = \frac{L}{4\pi cR^2} 2\pi R \cdot \pi r \cdot r \cdot \varsigma(\theta), \quad (2.1)$$

where the right-hand side is the modulus of a force twisting moment with the arm of about a torus small radius r, which appears due to the radiation pressure on the inner torus surface ($\approx 2\pi R \cdot \pi r$). Factor $\varsigma(\theta) \le 1$ takes into account the torus shape effect and the radiant flux angular dependence. The momentum [3] is related with circulation and mass as $p_\varphi = M_{ring}\Gamma/2\pi$, where M_{ring} is the torus mass and $\Gamma = \oint \mathbf{v}d\mathbf{r} = 2\pi r \cdot v_\varphi$ is the torus inner circle velocity circulation. Twisting, which turns the torus into a toroidal (ring) vortex and sustains its vortical motion (the velocity circulation), by virtue of the symmetry should result in a "dipole" vortex whose "northern" and "southern" components rotate in opposite directions (Fig.2).

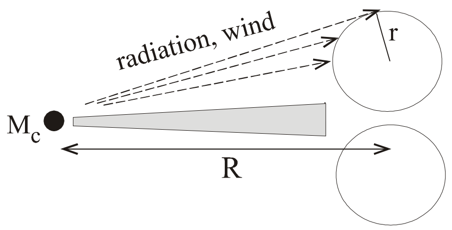

Fig.2. Schematic of a central source wind- and radiation-twisted vortex

The streamline cross-section should resemble a pair of vortices of different signs. Such a system, as is known, moves as a whole with the velocity $V_{ring} = \Gamma/(4\pi r)$. As Lamb notes [5, p.300] this motion can be interpreted as the necessity to compensate the attraction of vortices induced by the Bernoulli effect arising due to a flow of a moving vortex pair. In our case, such a flow should result from the central source wind with the velocity U_{wind}. As the torus and wind have different densities, the balance condition, as it is easy to ascertain, takes the form

$$\rho_{wind} U_{wind}^2 = \rho V_{ring}^2 . \qquad (2.2)$$

The fact that both components of a dipole-vortex torus gravitate towards each other should be taken into account too.

Using the known result for the attraction of two electrically charged rings [6], we may rewrite the gravitational force between the two rings with masses M_a and M_b, with the distance of $2r$ between them in the form:

$$F_g = \frac{G M_a M_b \cdot 2r \cdot k}{4\pi R^3} \frac{E(k)}{1-k^2},$$

where $k = R\big/\sqrt{r^2+R^2}$, $E(k)$ is the elliptic function. If $r \ll R$, then $k \approx 1 - 1/2 \cdot (r/R)^2$, $1-k^2 \approx (r/R)^2$ and in this case $E(k) \approx E(1) = 1$. The gravitational force between the two components of a dipole toroidal vortex (for $r \ll R$) takes the form

$$F_g = \frac{G M_{ring}^2}{2\pi R r}. \qquad (2.3)$$

This attraction will also be balanced by wind flow. Therefore, in the equality (2.2) an additional addend appears:

$$\rho_{wind} U_{wind}^2 = \rho V_{ring}^2 + \rho V_{esc}^2 , \qquad (2.4)$$

where $V_{esc}^2 = G M_{ring}\big/(2R)$. Below it will be shown that for the numerical parameters chosen, the gravity contribution (i.e. the second addend in the right-hand side of equality (2.4)) exceeds the hydrodynamic one and is about of the same order as the radiation twist contribution. Therefore in this work, the wind effect is neglected. At the same time it will be observed that unlike for the "unipolar" self-gravitating vortices, where the environment is not a governing factor, for the dipole toroidal vortex, according to (2.4), the environment – similar to vortices in an incompressible fluid – is required in principle. At the same time, a flow generated «lifting force» can explain the existence of «thick» cold tori that causes per se a serious problem now [7].

In the luminosity, let us single out the contribution to the accretion disk of matter from a torus and the "background" torus unrelated luminosity L_0:

$$L = L_0 + \xi \dot{M} c^2 , \qquad (2.5)$$

where $\dot{M} \equiv dM/dt$ is the accretion rate, and $\xi \sim 0.1$ means accretion related energy conversion into radiation. The magnitude L will be considered close to the Eddington limit, which is typical of the AGN luminosity. The toroidal vortex luminosity contribution is described by the second addend connected with the accretion disk vortex "twist".

3. ACCRETION DISK REPLENISHMENT BY VORTEX

For the problem considered, the vortex matter inflow into the accretion disk due to particle detachment in the region of contact of dipole components is essential. This process is similar to that considered in [3] of the origin of a jet in a compact-vortex hole. This process will be described phenomenologically by introducing the effective «height» h of a belt through which the toroidal vortex matter flows into a disk. Then the mass flow towards the disk per unity of time is equal to

$$\dot{M} = \rho v_\varphi \cdot 2\pi R \cdot h , \qquad (3.1)$$

where the vortex density ρ is

$$\rho \equiv m_H n \approx \frac{M_{ring}}{2\pi R \cdot \pi r^2}, \qquad (3.2)$$

and the vortex velocity v_φ is expressed through circulation Γ as

$$v_\varphi = \frac{\Gamma}{2\pi r}. \qquad (3.3)$$

The particle detachment parameters enter into the expression for the area $2\pi R \cdot h$ through the belt height

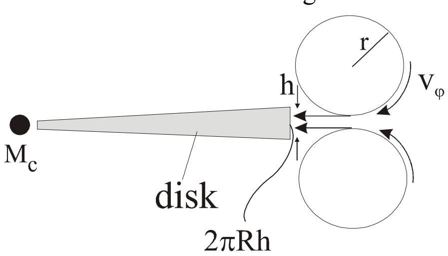

Fig.3. Schematic of a vortex fed accretion disk. The belt effective height h is amenable to particle intake in a disk

which will be taken equal to the torus minor radius part

$$h = \xi_1 r . \qquad (3.4)$$

The major and minor radii relate as [3]

$$r = \sqrt{\lambda R} , \qquad (3.5)$$

where $\lambda = \Gamma^2\big/(4\pi G M_{ring})$ is the Jeans scale. This relation is a direct consequence of coordinate dependencies of gravitational and centrifugal forces connected to a vortical motion in a torus. By substituting (3.2)-(3.5) in

(3.1) we obtain the accretion rate expression

$$\dot M = \frac{2\xi_1 G}{\pi}\frac{M_{ring}^2}{\Gamma R}. \qquad (3.6)$$

The magnitude of $\dot M$ determines the accretion rate defining the central source luminosity and connected to the replenishment from a toroidal vortex.

Generally speaking, by virtue of nonstationarity of the process under investigation, the time delay between the mass intake into a disk at the distance of a torus major radius R and its "irradiation" in the central engine (i.e. in the disk inner part) may become essential. The effect of this irradiation, as well as of the time lag between the moment of radiation and the vortex twist (due to the light and wind velocity finiteness), will be discussed more below.

Now let us substitute the accretion rate expression (3.6) into the luminosity formula (2.5)

$$L = L_0 + \frac{2\xi\xi_1 Gc^2}{\pi}\frac{M_{ring}^2}{\Gamma R}. \qquad (3.7)$$

Hence, using the relation of Γ with p_φ and taking (3.5) into account yield the following formula for the rate of momentum change (2.1) due to twisting:

$$\left(\frac{dp_\varphi}{dt}\right)_{twist} = \frac{\pi^2\zeta(\theta)L_0}{2GM_{ring}^3 c}p_\varphi^2 + \frac{\zeta(\theta)\xi\xi_1 c}{2R}p_\varphi. \qquad (3.8)$$

The torus mass loss in replenishing the disk results, however, in the loss of the momentum carried away by the escaping (pulled inward a disk) mass. The corresponding momentum losses are described by

$$\left(\frac{dp_\varphi}{dt}\right)_{repl} = -\frac{\xi_1 G}{\pi^2 R}M_{ring}^2. \qquad (3.9)$$

Actually, the momentum carried away from the torus per time unit is equal to

$$\left(\frac{dp_\varphi}{dt}\right)_{repl} = -\rho v_\varphi \cdot r v_\varphi \cdot 2\pi Rh, \qquad (3.10)$$

whence follows (3.9).

4. ACCRETION-WIND INSTABILITY

Let us first neglect the losses, assuming that the inequality providing the angular momentum growth is fulfilled:

$$\left(\frac{dp_\varphi}{dt}\right)_{twist} > \left(\frac{dp_\varphi}{dt}\right)_{repl}. \qquad (4.1)$$

Nevertheless, the time evolution of inequality depends essentially on how the torus mass M_{ring} varies. If the torus illuminated side subjects to wind and radiation, there is no radiation pressure on its shadowed side and the mass inflow is possible from a more distant environment. In particular, one of the variants of the discussed scenario corresponds to the steady-state mass inflow which allows considering $\dot M_{ring}$ as one of the slowly varying parameters for the times of "fast" variations. Substitution of (3.8) at $L_0 = 0$ and (3.9) in (4.1) yields momentum restriction from below

$$p_\varphi > \frac{4GM_{ring}^2}{\pi^2\xi\varsigma(\theta)c}. \qquad (4.2)$$

The angular momentum which satisfies it on the order of magnitude is equal to

$$p_\varphi^* \approx \frac{GM_{ring}^2}{\xi\varsigma(\theta)c}. \qquad (4.3)$$

This might be amenable to the fact that the contribution of the "background" addend with $L_0 \neq 0$ into vortex twisting can be of fundamental importance [6]. The accretion rate and luminosity magnitudes corresponding to p_φ^* are of the form

$$\dot M^* = \frac{\xi\xi_1\varsigma(\theta)M_{ring}c}{\pi^2 R},\ L^* = \frac{\xi^2\xi_1\varsigma(\theta)M_{ring}c^3}{\pi^2 R}. \qquad (4.4)$$

The possibility for AGN instability connected both with the accretion from a torus and with the central source wind (the photon wind included) is obvious from (3.8). The nature of such accretion-wind instability, as it could possibly be named, is that the growing L increases $\dot p_\varphi$, while this in turn increases $\dot M$, that again increases L, i.e.

$$\dot p_\varphi \propto L, \quad L \propto \dot M, \quad . \qquad (4.5)$$

The linear increment of accretion-wind instability at $L_0 = 0$ should result in the exponential growth with the slowly rising (due to the decrease of R) parameter α:

$$\frac{dp_\varphi}{dt} = \alpha \cdot p_\varphi, \quad \alpha = \frac{\xi\xi_1\varsigma(\theta)c}{2R}. \qquad (4.6)$$

The complete analysis of instability may appear rather complicated and is not meant here in this paper. Nevertheless, in its character and behavior the instability is similar to the observable quasar radiation bursts [8] that can testify to the discussed dynamic role of AGN toroidal vortices (see Fig.6 and discussion further in this paper).

5. THE DELAY EFFECT ON THE INCREMENT

The feedforward and feedback circuit, which causes the accretion-wind instability, has the delay which in the oversimplified case is described by the equation

$$\frac{dp_\varphi(t)}{dt} = \alpha\, p_\varphi(t-\tau), \qquad (5.1)$$

where $\tau = \tau_1 + \tau_2$ (see Fig.4).

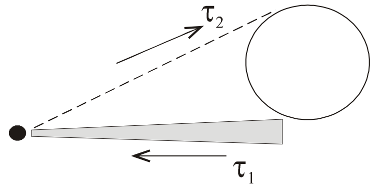

Fig.4. Schematic of time delay in a feedback circuit of accretion-wind instability, where τ_1 is the time of mass transfer along the disk radius, τ_2 is the time of centre-to-torus radiation propagation

The evolutionary differential equation with the time delay

$$\frac{dx(t)}{dt} = \alpha\, x(t-\tau) \qquad (5.2)$$

allows the exact solution and results, as earlier in the system with no delay, in the exponentially growing solution

$$x(t) = x(0)\cdot e^{-\alpha f(\alpha\tau)\cdot t}, \qquad (5.3)$$

but with the increment depending on the dimensionless delay $\alpha\tau$, where the universal function $f(\alpha\tau)$ is the solution of the transcendental equation $f = \exp(-\alpha\tau f)$ or

$$\ln f / f = -\alpha\tau\ . \qquad (5.4)$$

The form of this function is shown in Fig.5 and is obtained by the inversion of function (5.4).

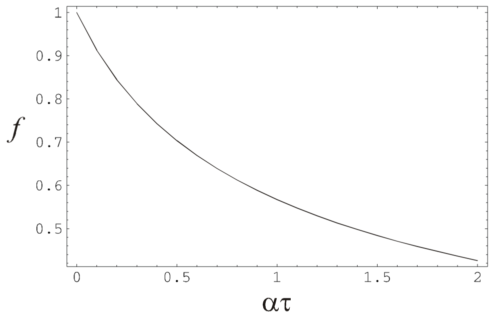

Fig.5. The dependence $f(\alpha\tau)$ *obtained as graphic solution of the functional equation* (5.4)

It is seen that $f \le 1$ (see Fig.5), $f = 1/(1+\alpha\tau)$ for the weak delay $\alpha\tau \ll 1$. Thus, the delay present reduces the increment of accretion-wind instability $\alpha \to \alpha \cdot f(\alpha\tau)$. With the vortex compression and thin-to-compact evolution, the delay becomes less important and the increment rises.

6. DISCUSSION

The aforesaid proves that in the considered system the positive feedback and related instability are possible. We have considered the instability in its simplest case with least parameters: no background radiation unconnected with a toroidal vortex, insignificant wind contribution to twisting vs. radiation, rather slow motion (compression) over the torus major radius. Then, according to (4.7), the accretion-wind instability increment is equal to $\alpha = \xi\xi_1\varsigma(\theta)c/(2R)$ and determines the characteristic time scale of its development. In case we want to compare the 3.5-year time scale of the observable burst duration in quasar 3C 345, see Fig.6 from [8], we should take the space scale $R \sim 10^{16}$ cm (1/300 light year). Here we have taken into account that $x \sim 0.1$, and ξ_1 is taken of the same infinitesimal order. The last estimation may essentially differ from reality, therefore ξ_1 should be sooner treated as a scale factor which variation may considerably change the system parameters.

As the preliminary observed data [1] point to significantly larger torus sizes, a question - which one of the answers results in the "matreshka" scheme (Fig.7) - may naturally arise. The inner toroidal vortex may be responsible for the variability of AGN, the development of instability, etc. In the shadow of a close minor-radius torus there exists a preference for the centre-falling matter because of less interfering radiation (this latter being weaker due to absorption) and of wind screened by the inner torus.

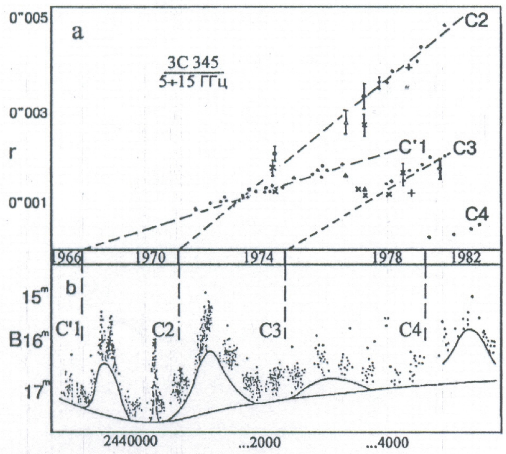

Fig.6. Correlation between the optical bursts of quasars 3C345 and arising the super luminal components of radio jet (according to [8]*)*

Therefore the interstellar gas clouds will move towards the centre in the nearby torus shadow.

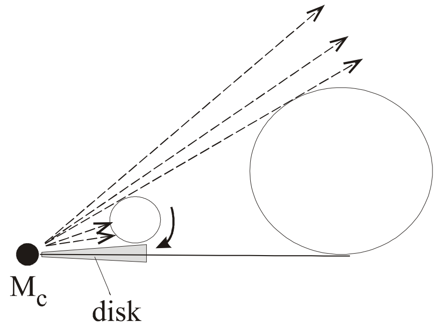

Fig7. The possible obscuring structure of AGN in the form of the "matreshka" sequence of tori

Orbital motion causes the falling clouds to flatten into tori and disks. Though the outer tori cannot add to the development of accretion-wind instability due to this latter extremely slow development at large scales (cf. the estimate (4.7)) and, in addition, being weakened by the increment-slowing delay.

Thus, the instability is determined by the inner centre-closest torus. The torus distribution increment is determined by the accretion process on the scales considerably exceeding those considered here and is beyond the discussed scenario. Detailed studying of the processes which occur in the evolution of toroidal vortices in the centres of active galaxies is a highly to intricate problem. Nevertheless, it is possible already now distinguish some features of these processes. Under the near Eddington's conditions, due to the radiation pressure compensated centre attraction, the evolution of vortices should largely resemble their evolution without the central mass [3]. At the compact vortex phase, the ejection of particles along the torus axis is possible, that might explain the correlation between the quasar optical bursts and the formation of new jet components [8].

The expressions obtained above may allow to estimate the features of the outer (obscuring) torus for the Seyfert galaxies (see Table 1) and quasars (see Table 2).

Table 1. *Obscuring torus parameters for the Seyfert galaxies*

Model parameters	Chosen values	Calculated AGN values	Obtained values
M_{BH}	$6.6\cdot10^7 M_\odot$ [9]	α	$5\cdot10^{-12}$ CGS
M_{ring}	$0.1\cdot M_{BH}$ [9]	p_φ	$3.8\cdot10^{64}$ CGS
R	1pc (see [3])	Γ	$1.8\cdot10^{25}$ CGS
r/R	0.5 (see [10])	v_φ	$2\cdot10^6$ cm/s
ξ	0.1	n	$5.4\cdot10^7$ cm^{-3}
ξ_1; ς	0.1	nV_{ring}^2	$2\cdot10^{20}$ CGS
$n_{wind}U_{wind}^2$	10^{22} CGS ($n_{wind}=10^6$ cm^{-3}, $U_{wind}=10^8$ cm/s)	nV_{esc}^2	$7.7\cdot10^{21}$ CGS
L_{Edd}	$8.6\cdot10^{45}$ erg/s	L^*	$1.2\cdot10^{48}$ erg/s (see the text)

Table 2. *Obscuring torus parameters for the quasars*

Model parameters	Chosen values	Calculated AGN values	Obtained values
M_{BH}	$10^9 M_\odot$	α	$5\cdot10^{-12}$ CGS
M_{ring}	$0.1\cdot M_{BH}$	p_φ	$8.8\cdot10^{66}$ CGS
R	1pc	Γ	$2.8\cdot10^{26}$ CGS
r/R	0.5	v_φ	$3\cdot10^7$ cm/s
ξ	0.1	n	$1.4\cdot10^9$ cm^{-3}
ξ_1; ς	0.1	nV_{ring}^2	$6.7\cdot10^{23}$ CGS
$n_{wind}U_{wind}^2$	$5\cdot10^{24}$ CGS, [11]	nV_{esc}^2	$1.8\cdot10^{24}$ CGS
L_{Edd}	$1.3\cdot10^{47}$ erg/s	L^*	$1.8\cdot10^{49}$ erg/s (see the text)

Note that in [9] the dust mass of a obscuring torus is estimated on the order of magnitude of $0.01M_{BH}$, where M_{BH} is the central black hole mass. In our estimations we assume the dust making 10% of the total torus mass.

The discrepancy between the characteristic L^* and Eddington luminosities L_{Edd} can be easily eliminated by assuming a smaller efficiency replenishment of the accretion disk by a toroidal vortex. Thus, taking $\xi_1 = 10^{-3}$ yields $L^* \sim L_{Edd} \sim 10^{47}$ erg/s for the other parameters unchanged. However, the delay affected decrease of L^* may appear to be essential as well. The luminosity L^* (4.5) can be represented as

$$L^* = 2\xi\alpha M_{ring}c^2/\pi^2, \qquad (6.1)$$

where α is the accretion-wind instability increment. As is shown above (item 5), the τ-time delay decreases the increment by a factor of *f*, where $f(\alpha\tau)$ is the solution of equation (5.4). As a matter of fact, the time delay essentiality means that the detail description needs using the theory of a nonstationary disk accretion with the "boundary conditions" determined by the interaction of a toroidal dipole vortex with a disk, that exceeds the bounds of this paper.

For the luminosity near to the Eddington one the torus mass M_{ring} have to be near to the value $M_{ring} = \eta(R)M_c$, where $\eta(R)$ is estimated from the relation $L^* < L_{Edd} = 1.3\cdot10^{38}\left(\frac{M_c}{M_\odot}\right)$ erg/s, that led to inequality $\eta(R) < 3.7\cdot10^{-6}\frac{1}{\xi_1\varsigma(\theta)}\left(\frac{R}{1pc}\right)$. In particular, in the case $R = 10^{-2}$ pc for $M_c = 10^9 M_\odot$ and $\xi_1 = \varsigma = 0.1$ we receive the value $M_{ring} \approx 4\times10^3 M_\odot$. The decrease of the torus mass with decreasing the torus radius naturally to link with a departure of the mass to the accretion disk and/or with a blowing off the part of the mass under the action of the wind.

The torus twisting by wind rather than by radiation may appear essential. In this case, the magnitude $\rho_{wind} U^2_{wind}$ will play the role of the pressure on a torus in (2.1). Closing a feedback circuit requires the knowledge about the connection between the wind parameters and the central source luminosity. The magnetic field which impacts the parameters of wind and its angular distribution, and accordingly the torus twisting, can be of importance too. Despite of these problems unsolved, the described scheme already now yields the reasonable correspondence with the data observed until recently.

A short description of some items of this work is published in authors' paper [12].

CONCLUSIONS

1) A dipole toroidal vortex may be an essential AGN-structure element which "replenishes" the accretion disk.

2) In the feedback circuit, which includes twisting the vortex by radiation and wind and replenishment of the accretion disk by a vortex, the instability causing the bursts in active nuclei may develop.

3) The presence of a "lifting force" due to wind may allow the existence of a "thick" and cold torus.

4) The "matreshka" scheme of AGN toroidal structure which may explain the evolution effects is proposed.

This work is partly supported by the Ukraine President grant ГП/Ф8/0051.

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ДИПОЛЬНЫЕ ТОРОИДАЛЬНЫЕ ВИХРИ И ВЕТРОВО-АКРЕАЦИОННАЯ НЕУСТОЙЧИВОСТЬ В ЯДРЕ АКТИВНОЙ ГАЛАКТИКИ

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Принята концепция тора как неотъемлемая структурная компонента ядра активной галактики (ЯАГ). Здесь обсуждается ситуация, когда «вращающийся» тор благодаря излучению или ветру трансформируется в тороидальный вихрь, который может быть источником вещества, пополняющего акреационный диск. Таким образом обсуждено также, что исходная неустойчивость может быть ответственна за вспышки излучения квазаров, сопровождающиеся выбросами вещества. Предложена схема "матрешка" для структуры наблюдающегося тороидального вихря, которая может объяснить изменчивость и эволюцию ЯАГ. Параметры модели оценены численно для яркости, близкой к Эддингтоновскому пределу и хорошо согласуются с наблюдениями.

ДИПОЛЬНІ ТОРОЇДАЛЬНІ ВИХОРІ ТА ВІТРОВО-АКРЕАЦІЙНА НЕСТІЙКІСТЬ У ЯДРІ АКТИВНОЇ ГАЛАКТИКИ

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Прийнята концепція тора як невід'ємної структурної компоненти ядра активної галактики (ЯАГ). Тут обговорюється ситуація, коли «твістуючий» тор завдяки випромінюванню або вітрові трансформується в тороїдальний вихор, котрий може бути джерелом речовини, що поповнює акреаційний диск. Таким чином обговорено також, що первісна нестійкість може бути відповідальна за спалахи випромінювання квазарів, які супроводжуються викидами речовини. Запропонована схема "матрьошка" для структури тороїдального вихорю, яка може пояснити змінність та еволюцію ЯАГ. Параметри моделі оцінені чисельно для яскравості, близької до Едингтонівської межі та добре узгоджуються зі спостереженнями.