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LARGE-SCALE DYNAMO OF ACCRETION DISKS AROUND SUPERMASSIVE NONROTATING BLACK HOLES

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SUMMARY: In this paper one presents an analytical model of accretion disk magnetosphere dynamics around supermassive nonrotating black holes in the centers of active galactic nuclei. Based on general relativistic equations of magnetohydrodynamics, the nonstationary solutions for time-dependent dynamo action in the accretion disks, spatial and temporal distribution of magnetic field are found. It is shown that there are two distinct stages of dynamo process: the transient and the steady-state regimes, the induction of magnetic field at $t > 6.6665 \times 10^{11} GM/c^3$ s becomes stationary, magnetic field is located near the innermost stable circular orbit, and its value rises up to $\sim 10^5$ G. Applications of such systems with nonrotating black holes in real active galactic nuclei are discussed.

Key words. Galaxies: active – Accretion, accretion disks – MHD – Magnetic fields

1. INTRODUCTION

Black hole accretion flows are the most likely central engine for quasars and active galactic nuclei (AGN) (Zeldovich 1964, Salpeter 1964). Therefore, they are the subject of intense astrophysical interest and speculation. Recent observations from XMM-Newton, Chandra, Hubble, VLBA, and other ground- and space-based observatories have expanded our understanding of the time variability, spectra, and spatial structure of AGN. Radio interferometry, in particular, has been able to probe within a few hundred gravitational radii (GM/c^2) of the central black hole, e.g. Lo et al. (1998), Junor et al. (1999), Doeleman et al. (2001). Despite these observational advances, only instruments now in the concept phase will have sufficient angular resolution to spatially resolve the inner accretion disk (Rees 2001). Thus there remain fundamental questions that we can answer only by simulating the observations through models of AGN structure.

All black hole accretion flow models require that angular momentum be removed from the flow in some way so that material can flow inwards. In one group of models, angular momentum is removed directly from the inflow by, e.g., a magneto-centrifugal wind (Blandford and Payne 1982). Here we will focus our attention on another group of models in which angular momentum is diffused outward through the accretion flow.

It has been long suspected that the diffusion of angular momentum through an accretion flow is driven by turbulence. The α model (Shakura and Sunyaev 1973) introduced a phenomenological shear stress into the equations of motion to model the effects of this turbulence. This shear stress is proportional to αP , where α is a dimensionless constant and P is the (gas or gas + radiation) pressure. This shear stress permits an exchange of angular momentum between neighboring, differentially rotating layers in an accretion disk. In this sense it is analogous to a viscosity (Lynden-Bell and Pringle 1974) and is often referred to as the "anomalous viscosity".

The α model artfully avoids the question of the origin and nature of turbulence in accretion disks. This allows useful estimates without solving a difficult, perhaps intractable, problem. Recently, however, significant progress has been made in understanding the origin of turbulence in accretion flows. It is now known that, in the magnetohydrodynamic (MHD) approximation, an accreting, differentially rotating plasma is destabilized by a weak magnetic field (Balbus and Hawley 1991, Hawley and Balbus 1991). This magneto-rotational instability (MRI) generates angular momentum transport under a broad range of conditions. Numerical work has shown that in a plasma that is fully ionized, which is likely the case for the inner regions of most black hole accretion flows, the magnetorotational instability is capable of sustaining turbulence in the nonlinear regime (Hawley and Balbus 1991, Hawley et al. 1995, Hawley 2000, Hawley and Krolik 2001).

AGN may be powered by the electromagnetic braking of a rapidly rotating black hole. The Blandford and Znajek (1977) effect (here, broadly defined as any electromagnetic way of extracting energy from a rotating black hole) is the most likely astrophysical means of extracting energy from a rapidly rotating black hole. Estimates for the nominal black hole spin in astrophysical environments give a rapid black hole spin of about $a \sim 0.92$ (Gammie 2004). Phenomenological estimates determined that the Blandford and Znajek luminosity is likely small compared to the disk luminosity (Ghosh and Abramowicz 1997, Armitage and Natarajan 1999, Livio et al. 1999).

Research on magnetized disks has now turned to global numerical models. These are possible thanks to advances in computer hardware and algorithms. Recent work by Hawley (2000), Stone and Pringle (2001), and Hawley and Krolik (2001) considers the evolution of inviscid, nonrelativistic MHD accretion flows in two or three dimensions. Some of these works use a pseudo-Newtonian, or Paczynski and Wiita (1980), potential as a model for the effects of strong-field gravity near the event horizon.

Other work on global models has considered the equations of viscous, compressible fluid dynamics as a model for the accreting plasma (Igumenshchev and Abramowicz 1999, Stone et al. 1999, Igumenshchev and Abramowicz 2000, Igumenshchev et al. 2000). The viscosity is meant to model the effect of small scale turbulence, presumably generated by magnetic fields, on the large scale flow. In light of work on numerical MHD models, this may seem like a step backwards.

The existing MHD models of accretion disks and flows, however, are computationally expensive, complicated and introduce new problems with respect to initial and boundary conditions. Therefore, there are no models today (even numerical), which are able to describe dynamics and evolution of accretion disks in account of time-dependent accretion flow regimes, hydromagnetic dynamo, large spin of a central black hole, and electromagnetic extracting of its energy. In this paper we propose analytical model of nonrotating black hole magnetosphere dynamics, based on solutions of general relativistic MHD equations, taking into account hydromagnetic dynamo effect.

2. EQUATIONS OF DYNAMO IN ACCRETION DISK

In this section we derive basic equations of GRMHD induction and find their solutions governing dynamo action in accretion disk around nonrotating Schwarzschild black hole. Doing this we are interested mainly in nonstationary solutions, which can show dynamics of accretion disk magnetic fields. We use formalism well known in general relativity where $c = G = 1$.

Let us consider two dimensional matter inflow velocities:

$$\overrightarrow{V} = V_\varphi \hat{e}_\varphi - V_r \hat{e}_r. \tag{1}$$

Matter in the inner disk regions is mainly in the plasma state. Therefore, dynamo action can take place in it. For perfect plasma with infinite conductivity we can write equations of magnetohydrodynamics in general relativity (GRMHD). Following Komissarov (1999), Shibata and Sekiguchi (2005) we have

$$\left\{ \begin{array}{rcl} \frac{\partial}{\partial t}\left(\sqrt{-g}B^i\right) & = & -\frac{\partial}{\partial x_j}\left[\sqrt{-g}\left(b^j u^i - b^i u^j\right)\right], \\ \frac{1}{\sqrt{-g}}\frac{\partial}{\partial x_i}\left(\sqrt{-g}B^i\right) & = & 0, \quad \{i,j\} = (1,2,3), \end{array} \right. \tag{2}$$

where

$$\left\{ \begin{array}{rcl} b^t & = & B^i u^\mu g_{i\mu}, \\ b^i & = & \left(B^i + b^t u^i\right)/u^t, \end{array} \right. \tag{3}$$

$\mu = (1,2,3,4)$, $B^i = F^{*it}$ — components of magnetic field vector, $u^\mu = \frac{dx^\mu}{ds}$ — 4-velocity of accretion disk matter. In (2) g is determinant of Schwarzschild metric tensor:

$$\det g_{\mu\nu} = -r^4 \sin^2\theta. \tag{4}$$

As accretion disk is assumed to be two dimensional, $\theta = \pi/2$, and $\sqrt{-g} = r^2$. System (2) can be rewritten in the form:

$$\left\{ \begin{array}{rcl} \frac{\partial}{\partial t}\left(\sqrt{-g}B^r\right) & = & -\frac{\partial}{\partial \phi}\left[\sqrt{-g}\left(b^\phi u^r - b^r u^\phi\right)\right], \\ \frac{\partial}{\partial t}\left(\sqrt{-g}B^\phi\right) & = & -\frac{\partial}{\partial r}\left[\sqrt{-g}\left(b^r u^\phi - b^\phi u^r\right)\right], \end{array} \right. \tag{5}$$

and

$$\left\{ \begin{array}{l} \frac{\partial}{\partial t}\left(\sqrt{-g}B^r\right) = \\ = -\frac{\partial}{\partial \phi}\left[\sqrt{-g}\left(B^\phi u^r/u^t - B^r u^\phi/u^t\right)\right], \\ \frac{\partial}{\partial t}\left(\sqrt{-g}B^\phi\right) = \\ = -\frac{\partial}{\partial r}\left[\sqrt{-g}\left(B^r u^\phi/u^t - B^\phi u^r/u^t\right)\right]. \end{array} \right. \tag{6}$$

In view of accretion symmetry along direction of ϕ

$$\left\{ \begin{array}{rcl} B^\phi & = & B^\phi(r,t), \\ B^r & = & B^r(r,t), \end{array} \right. \tag{7}$$

we can write:

$$\frac{\partial}{\partial t}(\sqrt{-g}B^r) = 0. \tag{8}$$

The last expression leads to $B^r\sqrt{-g} = const$. Therefore radial component of magnetic field vector does not depend on time coordinate t:

$$B^r = B_0^r\left(\frac{r_0}{r}\right)^2. \tag{9}$$

In (9) r_0 is the outer radius of the accretion disk, B_0 denotes the initial value of magnetic field, frozen in interstellar medium in the center of a galaxy. In further calculations, B_0 is assumed to be 10^{-7} G (Gaensler et al. 2004).

Our next step is to derive analytical expression for B^ϕ. Combining the result (9) with the second equation of the system (6) we have:

$$r^2\frac{\partial B^\phi}{\partial t} = -\frac{\partial}{\partial r}\left[B_0 r_0^2\frac{u_\phi}{u_t} - r^2 B^\phi\frac{u_r}{u_t}\right]. \tag{10}$$

Since $u_{\phi,r}/u_t = V_{\phi,r}$, it is possible to rewrite the last equation as:

$$\frac{\partial B^\phi}{\partial t} - \frac{\partial B^\phi}{\partial r}V_r = B^\phi\left(\frac{2}{r}V_r + \frac{\partial V_r}{\partial r}\right) - B_0\left(\frac{r_0}{r}\right)^2\frac{\partial V_\phi}{\partial r}. \tag{11}$$

The result (11) is a differential equation with partial derivatives. Its solution yields B^ϕ as a function of t and r. It is necessary to note that we always use coordinate time (not the proper one) throughout this paper. Eq. (11) is equivalent to the system of ordinary differential equations of the first order:

$$dt = -\frac{dr}{V_r} = \frac{dB^\phi}{B^\phi\left(\frac{2}{r}V_r + \frac{\partial V_r}{\partial r}\right) - B_0\left(\frac{r_0}{r}\right)^2\frac{\partial V_\phi}{\partial r}}. \tag{12}$$

The first equation of this system,

$$\frac{dB^\phi}{dt} = B^\phi\left(\frac{2}{r}V_r + \frac{\partial V_r}{\partial r}\right) - B_0\left(\frac{r_0}{r}\right)^2\frac{\partial V_\phi}{\partial r}, \tag{13}$$

has solution

$$B^\phi = B_0\left(\frac{r_0}{r}\right)^2\frac{\partial V_\phi}{\partial r}\frac{1}{2V_r/r + \partial V_r/\partial r} + \\ + C_1\exp\left(2V_r/r + \partial V_r/\partial r\right)t. \tag{14}$$

Taking into account our definition of initial velocity field (1), we should change sign in front of V_r. Therefore $V_r \longrightarrow -V_r$, and

$$B^\phi = -B_0\left(\frac{r_0}{r}\right)^2\frac{\partial V_\phi}{\partial r}\frac{1}{2V_r/r + \partial V_r/\partial r} + \\ + C_1\exp\left(-2V_r/r - \partial V_r/\partial r\right)t. \tag{15}$$

The second equation of the system (12) and its solution are:

$$dt = \frac{dr}{V_r} \Longrightarrow C_2 = r - V_r t. \tag{16}$$

In the expressions, derived C_1 and C_2 are constants which should be determined.

The general solution of (12) is an arbitrary function

$$F(\Phi_1, \Phi_2) = 0, \tag{17}$$

where

$$\begin{cases} \Phi_1 = C_1(r,t), \\ \Phi_2 = C_2(r,t). \end{cases} \tag{18}$$

We choose linear function, i.e.

$$F(\Phi_1, \Phi_2) = a_0 + a_1\Phi_1(r,t) + a_2\Phi_2(r,t). \tag{19}$$

One of the coefficients can be made equal to unity (e.g. $a_1 = 1$). Therefore, we have:

$$B^\phi = -B_0\left(\frac{r_0}{r}\right)^2\frac{\partial V_\phi}{\partial r}\frac{1}{2V_r/r + \partial V_r/\partial r} + \\ + \left[a_0 + a_2(r - V_r t)\right]e^{-(2V_r/r + \partial V_r/\partial r)t}. \tag{20}$$

During further calculations we shall express radial and time coordinate in the units of gravitational radius $R_g = GM/c^2$, i.e. $R = r/M$, and $T = t/M$, where M is mass of the central black hole. The next step is to find constants a_0 and a_2 using initial and boundary conditions. At $T = 0$ magnetic field is located at $R = R_0$, and it is equal to B_0, therefore

$$a_0 = B_0 - a_2 R_0. \tag{21}$$

Boundary condition is of the form

$$B^\phi\big|_{R=R_0} = B_0. \tag{22}$$

To find B^ϕ explicitely, we ought to derive the expression for V_r. It is impossible to find it neither theoretically nor experimentally today, so that we use estimation $V_r = \alpha V_\phi$, where α is a constant considerably smaller than unity. It is assumed herewith to be equal 10^{-6}. This corresponds to rather slow accretion and viscous disk. $V_\phi = 1/\sqrt{R}$ is Keplerian velocity of tangential motion. Therefore (22) leads to:

$$a_2 = \frac{\sqrt{R_0}}{\alpha T}B_0\left[1 + \left(\frac{1}{3\alpha} - 1\right)\exp\left\{\frac{3}{2}\alpha R_0^{-3/2}T\right\}\right]. \tag{23}$$

Combining (21), (23) with (20) we have

$$B^\phi = B_0\left(\frac{R_0}{R}\right)^2\frac{1}{3\alpha} + B_0\left[\exp\left\{-\frac{3}{2}\alpha R_0^{-3/2}T\right\} - \\ - \frac{R_0\sqrt{R_0}}{3\alpha^2 T} + \frac{\sqrt{R_0}}{3\alpha^2 T}\left(R - \frac{\alpha T}{\sqrt{R}}\right)\right] \times \\ \times \exp\left\{-\frac{3}{2}\alpha T\left(\frac{1}{R^{3/2}} - \frac{1}{R_0^{3/2}}\right)\right\}. \tag{24}$$

However, the formula (24) is not the final solution for magnetic field component B^ϕ. It is necessary to take into account the fact that the magnetic field exists only in the region where the accreted matter already arrived, i.e. in the region $R \geq R_0 - \langle V_r \rangle_r T$. More exactly, this condition should be written as

$$\int_R^{R_0} \frac{dR}{V_r} \leq \int_0^T dT \implies R^{3/2} \geq R_0^{3/2} - \frac{3}{2}\alpha T. \quad (25)$$

Expressions (9) and (24) together with condition (25) define distribution of magnetic field vector components along the plane of accretion disk and its time dependence.

3. RESULTS AND DISCUSSION

Based on results of analytical derivations in the previous section it is possible to plot spatial and temporal distribution of magnetic-field vector in the accretion disk. To do this, we ought to define some input parameters of the model. First of all, initial magnetic field is assumed to be $B_0 = 10^{-7}$ G, as pointed out in the previous section. In our model, we need to know exactly the explicit form of the expression for radial velocity in the disk. However, this is connected with great difficulties today (Bisnovatyi-Kogan and Lovelaca 2001, Poplavsky et al. 2003, Poplavsky 2005). Unfortunately, problem of viscosity in the disk, which defines radial velocity of accreted plasma, is far from its solution today. Therefore, we use the estimate for radial component of plasmas velocity $V_r = \alpha V_\phi$, where $V_\phi = R^{-1/2}$ is the Keplerian velocity of a circular orbit. The main problem of this model is to estimate dimensionless parameter α, which can be connected with viscosity process in the accretion disk. Our "viscosity parameter" α is different from α-parameter in standard accretion model (Shakura and Sunyaev 1973). We assume the value of α to be 10^{-6}. This case corresponds to rather viscous disk and slow accretion. Such a case seems to be common in real astrophysical conditions, and contemporary accretion models (e.g. Bisnovatyi-Kogan and Lovelaca 2001, Hawley 2000, Hawley and Krolik 2001) are in a good agreement with it. The last arbitrary parameter of the model is the outer radius R_0 of the accretion disk. We assume it to be equal 10 000. With this value of R_0, the disk remains thin according to the model created by Collin and Hure (2001) as the best fit of contemporary experimental data.

The resulting plots are presented in Fig. 1. As in the previous section, distance R and time T are expressed in gravitational radii R_g. Fig. 1 shows several plots with R-distribution of magnetic-field vector $\vec{B}$ ($\vec{B} \simeq B_\phi \hat{e}_\phi$, as $B_\phi \gg B_r$) for different instants of coordinate time T. It is possible to see the "wave of magnetic field" that propagates from the outer borders of the disk R_0 inwards. At the initial moment of time, $T = 0$, the magnetic field is on the outer border of the disk, where $B = B_0 = 10^{-7}$ G. In the inner parts of the disk $B = 0$, as there is no accreted plasma there. Then nonzero magnetic field is aligned with plasma motion via dynamo action. In Fig. 1 one can see different stages of dynamo process. All of them are essentially nonlinear. The most noticeable feature of the process is burst of magnetic field near the time dependent inner border of the accretion disk. In spite of large scales of the dynamo action, for the space of whole accretion disk, induced magnetic field is rather small. It rises greatly (up to $\sim 10^5$ G for $\alpha = 10^{-6}$) only when the radius of innermost stable circular orbit for Schwarzschild black hole ($R = 6$) is attained.

Analyzing the results obtained in our analytical modeling, one can notice two main stages of accretion and magnetic field induction. They are: transient regime and steady-state condition. Transition between them is realized when accreted plasma reaches the innermost stable orbit, i.e. $R = 6$. Such a transition takes place for $T > T_a$, where T_a is period of time for the matter to arrive at the innermost stable orbit:

$$T_a = -\int_{R_0}^{6} \frac{dR}{V_r} = 6.6665 \times 10^{11}. \quad (26)$$

For $T > T_a$, the steady-state regime is attained. Accretion and dynamo process become time-independent. To estimate the value of T_a, we get back to SI system. Accretion period in seconds is

$$t_a = T_a \frac{GM}{c^3}, \quad (27)$$

and, finally,

$$t_a \text{ [years]} = 0.104 \frac{M}{M_\odot}. \quad (28)$$

Fig. 2 illustrates the last formula. It shows the relation between the mass of the central supermassive black hole and the accretion period. It is possible to see that t_a achieves the value of $\sim 10^8$ years for $M/M_\odot = 10^9$. This corresponds, e.g. to active galactic nucleus of M87 (Ferrarese and Ford 2004).

The last point to be discussed is the role of Schwarzschild black holes in AGN activity. AGNs seem to contain fast spinning black holes in their centers. This is an inevitable phenomenon, when angular momentum is conserved during black hole formation in the centers of parent galaxies. Schwarzschild black holes are possible at late stages of AGN evolution when the initial Kerr black holes lose their angular momentum and become nonrotating. They also seem possible at eventual repeats of AGN activity.

Thus, main results of this paper are the following.

1. We found analytical solutions of GRMHD equations for dynamo effect in accretion disks of supermassive nonrotating black holes.

2. We showed that radial component of magnetic-field vector B_r is time independent, and $B_\phi \gg B_r$ when $V_\phi \gg V_r$.

3. We found that dynamo action consists of two regimes, transient and steady-state. During the steady-state mode magnetic field is located near the inner border of the accretion disk. It reaches up to $\sim 10^5$ G at the innermost stable circular disk orbit.

4. This value of maximum magnetic field is rather low in comparison to pulsars and magnetars.

5. The existence of such systems with non-rotating black holes is possible during late stages of AGN evolution and repeats of their activity.

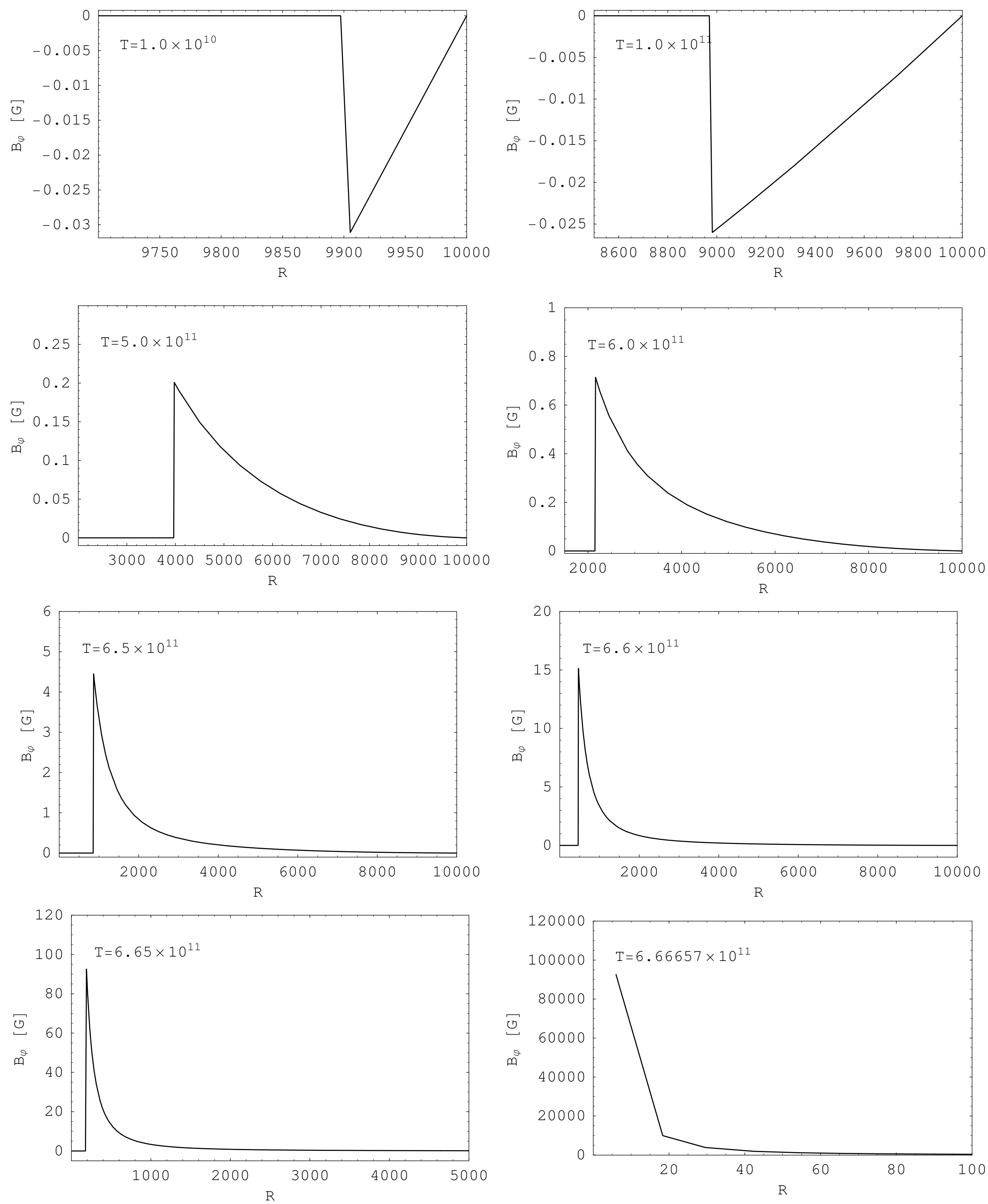

Fig. 1. *Distribution of azimuth component of magnetic-field vector along radial coordinate of the accretion disk plane. Plots correspond to the times T:* 10^{10}, 10^{11}, 5×10^{11}, 6×10^{11}, 6.5×10^{11}, 6.6×10^{11}, 6.65×10^{11}, 6.66657×10^{11} *($T = t/R_g$).*

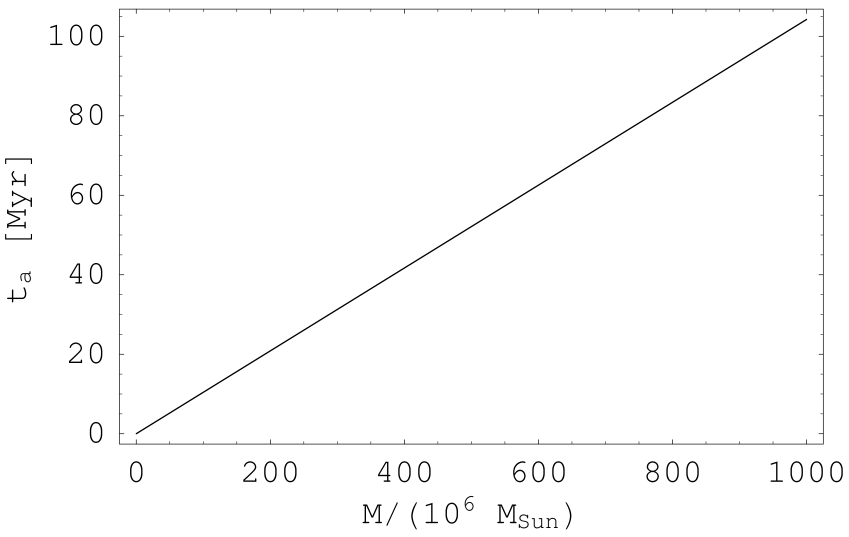

Fig. 2. *Mass of the central black hole in AGN — time of reaching the innermost stable circular orbit dependence. Value of t_a is expressed in millions of years, black hole mass M — in millions of solar masses.*

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ДИНАМО ВЕЛИКИХ РАЗМЕРА КОД АКРЕЦИОНИХ ДИСКОВА ОКО СУПЕРМАСИВНИХ НЕРОТИРАЈУЋИХ ЦРНИХ РУПА

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У овом раду је представљен аналитички модел динамике магнетосфере код акреционих дискова око супермасивних неротирајућих црних рупа у центрима активних галактичких језгара. Полазећи од једначина магнетохидродинамике у Општој теорији релативности, нађена су нестационарна решења за динамо механизам у акреционим дисковима, као и просторна и временска расподела магнетног поља. Показано је да постоје две различите етапе динамо процеса: прелазни режим и стабилни режим, да индукција магнетног поља постаје временски независна за $t > 6.6665 \times 10^{11} GM/c^3$, као и да се магнетно поље налази близу најмање стабилне кружне орбите и да његова вредност расте до $\sim 10^5$ G. Дискутоване су и примене таквих система са неротирајућим црним рупама на права активна галактичка језгра.