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PARTICLE ACCELERATION AND NONTHERMAL ENERGY RELEASE AS AN EFFECT OF MAGNETOACTIVE DISK ACCRETION ONTO GRAVITATING CENTER

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ABSTRACT

Observations of *GRO* and UHEGR show that a number of Galactic and extragalactic accreting systems release most of their energy in the ultrarelativistic energy range (more than GeV). This result contradicts one of the principal conclusions of the standard models of accretion about a predominantly thermal character of energy release. This contradiction is caused by ignoring in the standard approach the processes of generation and amplification of magnetic field in the case of accretion onto a magnetized gravitating center. A new approach taking into account the processes mentioned above is applied to disk accretion onto a nonmagnetized gravitating center, as well as onto a magnetosphere. It is shown that in both cases the accretion is strictly controlled by the magnetic field, which leads to new conditions of equilibrium and stability and turns on nonthermal processes of energy release. The resulting configuration of the magnetic field, in which the main energy release takes place in both cases, is called "Z-pinch," and is formed in the polar region of an accreting object. Effective particle acceleration occurs in it owing to the chain of MHD and resistive plasma instabilities, resulting in current discontinuity with the formation of "double layers" and generation of electric fields close to the Dreicer limit in them. The maximum energies of the accelerated particles are limited by the value 10 EeV, that coincides with the results of UHEGR observations.

Subject headings: acceleration of particles — accretion, accretion disks — gamma rays: theory — MHD

1. INTRODUCTION

Recent observations have shown that a number of accreting objects—galactic close binaries, as well as extragalactic sources of BL Lac–type (blazars)—release the predominant part of their energy in the form of particles accelerated up to ultrahigh-energy (Weekes 1992; Hartman et al. 1992). The most striking example to be given is the latest observation of the blazar 3C279, obtained with *Gamma-Ray Observatory,* which released luminosity in the energy range $E_\gamma = 1$–20 GeV exceeding by almost one order of magnitude that in the remaining spectral regions from radio up to X-rays (Hartman et al. 1992).

This fact is in obvious contradiction with the basic consequence of standard models of accretion—the thermal character of energy release, caused either by the friction of rotating layers in the accretion disc or by heating in the accretion column and at the front of its shock wave (Shakura & Sunyaev 1973; Basko & Sunyaev 1976).

We believe this contradiction to arise because of the processes of accreting plasma interaction with magnetic fields, which leads to rapid increase of the magnetic field energy up to the value $\frac{H_G^2}{8\pi} \simeq \rho V^2 \simeq \frac{\rho GM}{R}$, followed by flaring dissipation of this energy into particle acceleration and anomalous heating, processes which are ignored in the standard approach. This fundamental property of magnetic fields (and its principal role in energy release) is well known and actively investigated in laboratory plasma experiments and solar physics (Svestka 1976; Altyntsev et al. 1984). In the present paper we argue that taking into account the above-mentioned factor is necessary in the case of disk accretion onto a black hole as well as in the case of accretion onto a magnetized neutron star, since in both variants it is the basic cause of nonthermal energy release.

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2. DISK ACCRETION ONTO A NONMAGNETIZED GRAVITATING CENTER

The question of the necessity of taking into account the generation of intrinsic magnetic field in the disk was raised by Lynden-Bell (1969). This problem was later examined by Pustil'nik & Shvartsman (1974), and Galeev, Rosner, & Vaiana (1979). As has been shown in these papers, the differential character of Keplerian rotation of the disk matter ($\Omega \propto R^{-3/2}$) and the turbulence result in the rapid amplification of initial magnetic field by the dynamo-mechanism up to threshold values $H_{cr} = (8\pi\delta n_d kT_d)^{1/2}$, with $\delta = 0.2$–0.5, at which the disk is broken, by the Parker instability, into dense plasma blobs bound up one with another by field lines. A magnetic corona is formed in this process. Anomalous thermal heating of such a magnetized corona was examined in detail by Galeev et al. (1979). However, in this and subsequent papers devoted to this problem, one principal argument was omitted: the energy release of a magnetic corona must be predominantly nonthermal.

Once the disk has disintegrated into the system of blobs, the exchange of rotational momentum between them can take place only via the tension of field lines, which connect the blobs through the magnetic corona. The blobs' rotation being differential, the connecting magnetic fluxes get entangled with current layers forming at the surface of the blobs. However, owing to high coronal plasma conductivity, the dissipation of magnetic field via reconnection does not occur at this stage. On the contrary, the process of field amplification is going on, with generation of a stronger azimuthal component, H_φ, and corresponding amplification of the poloidal component, caused by extension of field lines and the self-compression of the forming structure by $H_\varphi^2/8\pi$. As a result, on the axis of accretion disk, in the region above and under the gravitating center, a configuration of the Z-pinch type is formed parallel to the disk rotation axis (Fig. 1), in which the tension of the toroidal component is balanced by the counterpressure of the disk poloidal field. The continuing Keplerian rotation of the blobs leads to further winding of magnetic lines of force round the axial Z-pinch. The value of the magnetic field strength in the Z-pinch has the upper limit $H_G = (8\pi\rho GM/R)^{1/2}$, at which the tension of the field lines becomes equal to the gravitational force and the blobs begin to move nearly radially. At this value of the field, plasma turbulence in the Z-pinch essentially reduces the effective conductivity $\sigma_{\rm eff}$ and, therefore, turns on rapid processes of nonthermal dissipation of the magnetic energy concentrated in it. Under the action of the chain of MHD and resistive instabilities (sausage and screw modes ⟹ tearing modes ⟹ plasma turbulization with current discontinuity and formation of "double layers") powerful electric fields accelerating the particles are generated (Kondoh & Hirano 1978). Hence, in the framework of this scheme, the basic energy release occurs not in the accretion disk, but in the axial Z-pinch.

Thus, our consistent account of effects accompanying the generation of magnetic field in the accretion disk leads us to the conclusion that it is possible to realize a nonthermal mode of energy release, with the great bulk of energy being released in the form of anomalous field dissipation in the axial Z-pinch under the action of plasma instabilities. The efficiency of nonthermal energy release in the process of pinch disruption by plasma instabilities was investigated in the numerous plasma experiments and appeared to be high enough (Altyntsev, Krasov, & Tomosov 1984 p. 99; Kondoh & Hirano 1978).

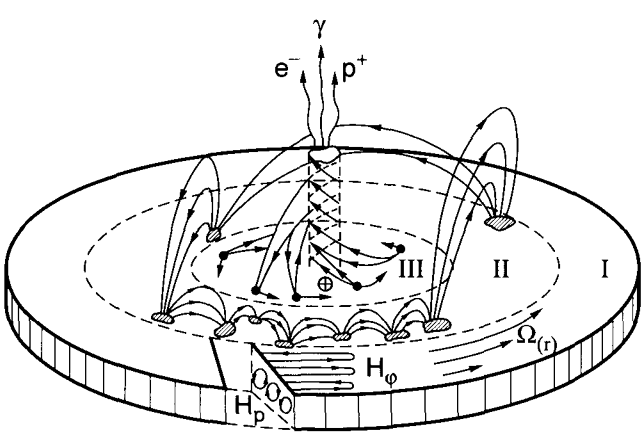

FIG. 1.—Structure of a magnetized accretion disk: I, region of α-disk; II, intermediate region of Parker instability; III, central region of the polar Z-pinch.

3. DISK ACCRETION ONTO A MAGNETIZED GRAVITATING CENTER

As has been shown by Ikhsanov & Pustilnik (1993), the character of disk accretion onto a magnetosphere (m-sphere) essentially depends on the effective conductivity of disk plasma $\sigma_{\rm eff}$. Three different regimes of accretion might be distinguished in accordance with this. In the case of two traditional approximations: $\sigma_{\rm eff} = \infty$ (Lipunov 1978) and $\sigma_{\rm eff} \approx \sigma_0 \rightarrow 0$ (Ghosh & Lamb 1979), the fraction of nonthermal energy release is negligibly small. However, in the third intermediate case: $0 \leftarrow \sigma_0 \ll \sigma_{\rm eff} \neq \infty$, the nonthermal mode of energy release becomes comparable or even predominant in efficiency. This is the case of "squeeze" accretion (s-accretion) (Ikhsanov & Pustil'nik 1993), in which one takes into account the effect of the azimuthal field component generated in a thin skin layer of the disk.

In the regime of s-accretion, the disk is screened from the external magnetic field and squeezed between the external magnetic field lines of a central component. The disk keeps all principal parameters of an α-disk.

At the boundary between disk plasma and external magnetic field, a diffusion skin layer (d-layer) from the disk with the thickness δ_m is formed. Plasma from the disk diffusing into the d-layer possesses high rotational momentum $2\pi\rho\delta_m R^2 V_\varphi$. Therefore the magnetic lines in the d-layer stretch in the azimuthal direction and a toroidal magnetic winding H_φ is generated. Hence, we get a configuration analogous to the Z-pinch in a skin layer with longitudinal magnetic field (Kadomtsev 1963). The poloidal field of the central object counteracts the tension of the toroidal magnetic winding, providing the equilibrium of the m-sphere. According to Ikhsanov & Pustil'nik (1993), the equilibrium configuration in this case is intermediate between a sphere and a dipole, being convex everywhere and stable with respect to instabilities of interchange type: the shear of the magnetic field in the d-layer stabilizes long-wavelength perturbations, and "ballooning," the saturated flute mode, stabilizes short-wavelength ones. In the case of noncoaxial rotator, the interaction of the accretion disk with the m-sphere leads to the inner part of the disk leaving the Keplerian regime, to accretion flow streaming of the m-sphere and to a plasma polar vortex being formed in the region of magnetic poles (see Fig. 2) (Ikhsanov & Pustil'nik 1993).

The principal feature of s-accretion is the conservation of a significant part of the rotational momentum of the plasma, captured by the polar vortex. This rotational momentum leads to formation of a skin layer of Z-pinch–type structure right up to the regions close to the surface of a central component, or $3r_g$. Plasma rotating in the polar vortex forms a d-layer with azimuthal field

$$H_\varphi = (8\pi\rho GM_*/3r_*)^{1/2}$$

in the inner magnetosphere and central magnetic tube. This is equivalent to the exciting of a current with the density $|j|$ in the d-layer:

$$|j| = (c/4\pi)|\text{rot } H| = cH_\varphi/4\pi\delta \ .$$

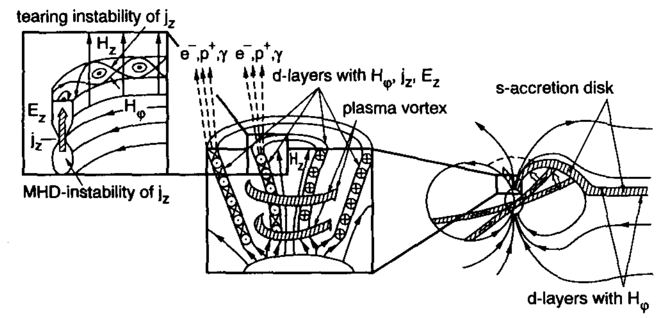

FIG. 2.—Structure of the *s*-accretion onto magnetosphere: *I*, external region of "squeezing" accretion disk; II, polar whirlwind structure; III, structure of a currents and fields in the polar *d*-layer.

This current layer is unstable with respect to a dissipative tearing-mode on the characteristic timescale of instability $\tau \approx \tau_d^{1/2}\tau_A^{1/2}$–$\tau_d^{1/3}\tau_A^{2/3}$. As a result, the surface current is disrupted into separate magnetic islands. Within the islands grow the characteristic pinch modes ($m = 0$, sausage mode; and $m = 1$, screw mode) and arise "double layers" (Alfvén 1981, chap. 11.6) with extremely high electric fields in the region of current discontinuity:

$$E = \frac{c}{4\pi}\frac{\Delta H}{\delta_m}\frac{4\pi\nu_{\rm eff}}{\omega_0 e},$$

where $\nu_{\rm eff}$ is the effective collision frequency of current-carrying electrons with ions and plasma waves. Under the conditions in the vicinity of a neutron star surface, the electron-cyclotron modes dominate, and therefore $\nu_{\rm eff} = \zeta\omega_{H_e}$, ($\zeta < 1$), and the equilibrial electric field has the upper limit, estimated by Dreicer (1959, 1960):

$$E_d = m_e V_{T_e}\nu_{\rm eff}/e\ .$$

This corresponds to the maximum energy of particles, accelerated in the current layer, being estimated as

$$\epsilon_{\rm max} = eE_d r_* = 10^{19} H_{12} r_6 T_8 \zeta\ {\rm eV}$$

that coincides with the results of UHE gamma-ray observations (Weekes 1992).

4. CONCLUSIONS

Our principal change of the picture of energy release involves the generation of toroidal component of the magnetic field due to plasma rotation in the process of disk accretion. First, this opens the effective nonthermal channel of magnetic energy dissipation in the current layer. Second, it localizes the zone of energy release; if the gravitating center has no magnetic field, the zone is in the region of the disk rotation axis; and otherwise in the region of magnetic poles for a magnetized neutron star. This allows to use the mechanism presented for generation of relativistic and subrelativistic jets and to explain the cause of nonthermal energy release dominating in a number of Galactic and extragalactic accreting systems.

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