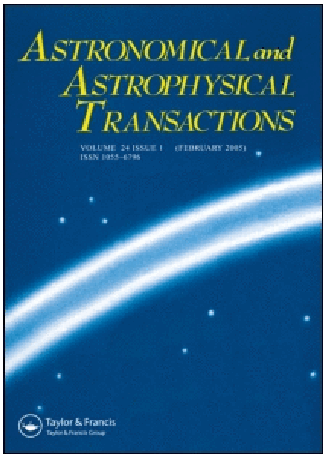

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THE NON-THERMAL MODE OF DISC ACCRETION ONTO THE MAGNETOSPHERE OF A NEUTRON STAR

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A new regime of the disc accretion onto a magnetosphere is considered: the "squeezing" accretion. The magnetosphere surface is shown to be concave, essentially non-spherical and stable with respect to interchange-type instabilities, with the accretion flow streaming around it and forming a plasma vortex near the magnetic poles. In this case the instability of a current layer on the boundary "plasma-magnetic field" leads to an efficient particle acceleration and non-thermal energy release. The estimates obtained corresponds well to the observational data on UHE gamma-quanta from X-ray binaries.

KEY WORDS Accretion, plasma instability, particle acceleration, high-energy astronomy

1. INTRODUCTION

One of fundamental consequences of the standard approach to disc accretion by magnetized neutron stars is the thermal character of energy release (Lipunov, 1978; Ghosh and Lamb, 1979). The hot plasma of the accretion column is the basic source of radiation in these models. The contribution of non-thermal radiation and, moreover, the portion of UHE gamma-quanta are negligibly small in the standard approach. But, however, this postulate is in contradiction with the latest observational data, in particular, with the registration of UHE gamma-rays from a great number of classical X-ray pulsars (including Her X-1, Vela X-1, LMC X-4) (Ramana Murthy and Wolfendale, 1986; Weekes, 1988).

These facts make us to suppose that in the standard models they disregard a very important group of processes which determine the non-thermal character of the energy release.

In the present paper we reexamine the traditional approach to disc accretion onto the magnetosphere (m-sphere) and argue that it is possible to consider the regime when a great deal of energy is released in a non-thermal form, in particular, by generation of particles, accelerated up to UHE.

2. REGIME OF S-ACCRETION

Disc accretion onto the m-sphere is usually considered using one of the following approximations (see Table 1): either that of an infinite-conductive disc-plate

Table 1 The models of disc accretion onto the magnetosphere of a neutron star

$\sigma = \infty$ (Lipunov, 1978)	$\infty > \sigma \gg \sigma_0 \cong 0$ (Ikhsanov and Pustil'nik, 1992)	$\sigma = \sigma_0 \cong 0$ (Ghosh and Lamb, 1979)
Infinite-conductive accretion disc-plate in the dipole field	Accretion disc of high but finite conductivity	Low-conductive accretion disc in the dipole field
a) potential field with a singular point; b) the interchange instability of the m-sphere boundary; c) plasma flowing into the accretion column with heating and emission.	a) accretion disc transition from the α-regime to the s-regime; b) generation of azimuthal field in the skin layer and the m-sphere relaxation to the equilibrium and stable configuration; c) rotation of the accretion ring and formation of the polar vortex; d) conversion of the rotational energy into azimuthal fields and surface currents; e) disruption of the current layer by tearing and pinching modes, plasma turbulization, double layers, anomalous heating and particle acceleration in the current layer.	a) plasma diffusion into the accretion disc into the outer region; b) deceleration of Keplerian rotation in the transition layer; c) plasma flowing in the accretion column with heating and emission.

interacting with the dipole-type m-sphere (solution in the form of a potential field with singular points) (Lipunov, 1978), or a low-conductive disc which easily diffuses through the magnetospheric field and weakly perturbs it (Ghosh and Lamb, 1979). The second one is more popular, and it is based on the comparison (Ghosh and Lamb, 1979) of the time of the plasma radial motion in the disc, $\tau_D = d^2/D_t$, and that of the field reconnection in such a disc, $\tau_h = \xi(d/V_a)$, where d is the thickness of the disc, D_t is the turbulent diffusivity and V_a is the Alfvén velocity. The result obtained by Ghosh and Lamb, $t_r = 10^3 \max(\tau_D, \tau_h)$, implies that the magnetic field penetrates the disc just at the radius $R \gg R_a$ (the Alfvén radius). However, this conclusion is based on the upper limits for the diffusion, $V_D = 0.1c_s$, and reconnection, $V_h = 0.1V_a$, velocities, where c_s is the sound velocity. These are overestimations, which can be illustrated by the fact that the lifetime of the solar active regions, derived from them, is 10^3 sec, i.e., by three orders of magnitude less than observed. In their model, Ghosh and Lamb also ignored the existence of the hot chromosphere and corona of the disc (McClintock *et al.*, 1982; White and Holt, 1982), which result in the diffusion length larger by an order of magnitude and the diffusion time, by two orders.

Thus, using the standard models, one ignores the existence of the third intermediate case, when the conductivity of the disc plasma is finite, but on the other hand, it is high enough to screen the accretion disc from the magnetospheric field. In this case, the disc itself continually moves in the radial direction without diffusing through the magnetic field and squeezes in between its lines of force drawing them and keeping all the basic properties of the α-disc (however, the structure of the resulting disc may differ essentially form the Shakura-Sunyaev model (1973)). The general picture of the regime of squeezing accretion (the s-accretion) appears to be radically different from the commonly adopted one and makes us to look on "well-known" XRB in a new way.

3. EQUILIBRIUM AND STABILITY OF THE MAGNETOSPHERE IN THE REGIME OF S-ACCRETION

For the sake of clarity, we consider here a somewhat simplified model with the axis of the neutron star rotation being parallel to its magnetic axis and inclined to the orbital axis of the system.

The formation of the *m*-sphere by the accretion disc is determined by the following two physical processes: 1) the angular momentum transfer along the disc from its inner radius by α-friction; 2) the generation of magnetic field toroidal component in a thin diffusion skin-layer (hereafter the *d*-layer) at the boundary "disc plasma-dipole magnetic field". The former controls the radial motion of the disc plasma. The role of the second process becomes essential for the regime of *s*-accretion. Consider it in detail.

Due to a high but finite conductivity of the disc plasma, a diffusion skin layer (*d*-layer) is formed (by the classical or Bohm diffusion) at the boundary "disc plasma-magnetic field". Plasma in the *d*-layer possesses rotational momentum $2\pi\rho\delta_m R^2 V_\phi$, where δ_m is the thickness of *d*-layer. This leads to the magnetic line stretching in the aximuthal direction and the generation of toroidal magnetic field H_ϕ, caused by the radial gradient of $V_\phi(r)$ $(dH_\phi/dt = H_p\, dV_\phi/dr)$ during the time $t_\phi \simeq R_r/V_\phi \simeq \Omega^{-1}$. The situation arising is analogous to the skinned Z-pinch with longitudinal magnetic field well-known in plasma physics (Kadomtsev, 1963). Indeed, the generation of H_ϕ leads to the current of the density

$$|j_z| = c/4\pi|\text{rot}\, H| \cong cH_\phi/4\pi\delta_m \tag{1}$$

flowing to the poles along the *m*-sphere surface. Hence, under the condition $\rho V_{\phi0}^2 \geq nkT + H_p^2/8\pi$ (where $V_{\phi0} = R(\omega_{ns} - \omega_{\phi d})$, $\omega_{\phi d}$ is the frequency of plasma rotation at radius R in the disc and ω_{ns} the frequency of neutran star rotation) the tension of the toroidal magnetic field $H_\phi^2/4\pi$ begins to compress the *m*-sphere along the whole surface from its equator to the poles. The equilibrium configuration of the *m*-sphere can be estimated (from below) using the conservation of the total current. Indeed, the current generated in the region of the dipole intersection by the disc, $I = 2\pi r\delta_m j_z \simeq (c/2)rH_\phi$ (where $r = R\cos\lambda$, λ is the magnetic latitude), must be conserved along the *m*-sphere surface. This means that the strength of the toroidal magnetic field is $H_\phi \propto 1/R\cos\lambda$ and the pressure, acting on the poloidal field of the inner *m*-sphere by magnetic winding, is $H_\phi^2 \propto 1/R^2\cos^2\lambda$. The form of the *m*-sphere surface, if the pressure varies as $1/R^2$, was culculated by Elsner and Lamb (1977) with the use of the conformal mapping techniques. It essentially differs from the spherical one and, by the curvature of the resulting field line, is intermediate between a sphere and a dipole. Evidently, if the *m*-sphere is compressed by toroidal winding, the form of its surface differs from that obtained by Elsner and Lamb (1977), namely it is more flattened in the region of magnetic poles, "deviating" from a sphere to a dipole configuration.

Taking into account the toroidal field leads to another important conclusion about the stability of the *m*-sphere surface for all types of MHD instabilities considered in the standard models. The following factors result in the *m*-sphere stability (Mikhailovskii, 1977):

a) Long-wavelength perturbations with $k_{\parallel} < k_{max} = (\Theta/\delta_m)$ are stabilized by the shear of magnetic field in the d-layer ($\Theta = \delta_m(d\phi/dX)$—is the shear thickness, depending on the angle of field lines turn along the transition layer);

b) Short-wavelength perturbations with $k_{\parallel} > k_{min} = \Gamma/\delta_m$ are stabilized by the effect of "bubbling" of the flute mode, where

$$\Gamma = [(g_{eff}\delta_m)/V_a^2]^{1/2} \cong [(\delta_m\beta)/h]^{1/2}$$

determines the stabilization of the flutes due to the tension of magnetic field lines of finite length, $h = c_s^2/g_{eff}$ is the height of homogeneous atmosphere and $\beta = 8\pi nkT/H^2$. Since, in our model, $\Theta\Gamma \ll 1$ everywhere, we obtain $k_{min} \gg k_{max}$ and, hence, the stabilization of the m-sphere surface.

Finally, we conclude, that the accreting plasma cannot penetrate into the magnetic field region via instabilities on the Alvfén surface. The picture of s-accretion becomes essentially different from the standard scheme.

4. THE POLAR VORTEX (α-CONE)

The non-spherical form of the m-sphere surface and its stability with respect to plasma penetrating into the magnetic field, leads to the accretion flow streaming around the m-sphere and plasma with rotational momentum is captured in the polar region. At the Alfvén radius, due to the α-friction, the inner part of the disc becomes non-Keplerian. Physically, this means that non-zero gravity directed to the compact object arises in this region. Since the m-sphere is non-spherical, the tangential component of this force differs from zero and is directed to the pole. Its action on the non-Keplerian region of the disc is equivalent to that of the pair of forces towards the poles. Because of rotation, the corresponding ring squeezes in between the field lines, dividing them into the systems of inner and outer (closed on the light cylinder) lines of force. Physical conditions in the plasma of this rotating ring are determined by the pressure of concave magnetic field: $H^2/8\pi = n_r kT_r$.

Due to the fact that the strength of a dipole magnetic field depends on magnetic latitude, the departure of the disc from a Keplerian one at the inner radius leads to the inner orbit deflection from a spherical one (the m-sphere is flattened in the region of disc intersection with the magnetic equator). This results in additional effective momentum transport from the accretion ring at the inner radius of the disc because of the streaming of non-spherical body by rotating flow.

The motion of a test particle in the non-Keplerian rotating ring along the surface of axissymetric m-sphere in the central field of gravity can be approximately described by the Lagrangian (Landau and Livshitz, 1959)

$$L = m\dot{r}^2/2 + M_z^2/2mr^2 \sin^2\alpha + GM/r \qquad (2)$$

with effective potential $U_{eff} = M_z^2/2mr^2 \sin^2\alpha - GM/r$. This is a finite rotation (about the magnetic axis) with oscillations between r_1 and r_2 ($r_1 \leq r_2$). Here $M_z^2 = mr^2 \sin^2\alpha\, d\phi/dt$ and α is the opening angle of the cone. In particular, at the minimum of the potential energy ($r_1 = r_2$) plasma rotates around the magnetic axis

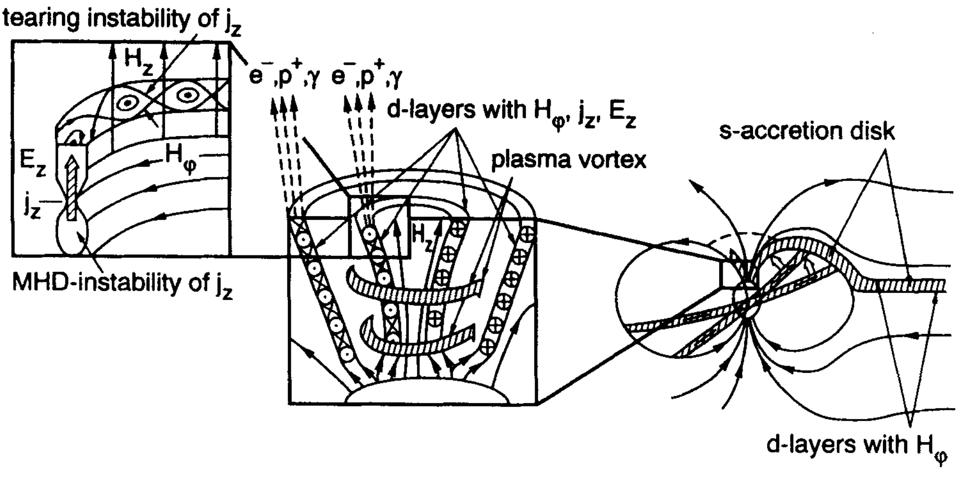

Figure 1

at the velocity $V_\phi = (2GM/3r)^{1/2}$, an analogue of the Keplerian velocity. The relaxation of the system to the minimum state is caused by friction: the line of apsides rotation leads to a fast dissipation of all the momentum components except the azimuthal one, P_ϕ.

As a result, the rotating ring is divided into two rings which, in accordance with (2), rapidly relax to the rotation around the axis and continue to squeeze along the m-sphere surface towards the poles. The final configuration of the polar region forming in the processes discussed above is shown in Figure 1. The plasma rotating in the thin polar vortex separates the system of closed field lines—the inner m-sphere–from the central magnetic tube system of open lines (lines closed on the light cylinder)—the outer m-sphere. Plasma by itself continually moves in the polar cone in the radial direction because of friction and forms the plasma α-cone. The α-cone plasma penetration into the magnetospheric field through the d-layer is determined by the anomalouse diffusion, as well as by the development of the drift-dissipative instabilities of the tearing mode type and some other in the skin layer. As a result, plasma flow from the accretion vortex occurs in the lower part of the α-cone, with the whole system going over to a stationary regime.

5. ENERGY RELEASE AND ACCELERATION IN THE POLAR VORTEX

Plasma rotating in the polar vortex diffuses into the m-sphere skin layer, generating the azimuthal field component $H_\phi = (8\pi\rho GM/3r_*)^{1/2}$ and the corresponding current density j_s in the d-layer. The current layer arising is unstable with respect to dissipative tearing mode on the characteristic timescale $\tau_t \simeq$

$(\tau_d\tau_A)^{1/2} \div \tau_d^{1/3}\tau_A^{2/3}$. As a result, the current surface is disrupted into separate magnetic "islands" with consequent growth of characteristic pinch-modes and formation of "double-layer" in them (Alfvén, 1981) with extremely high electric fields in the region of current discontinuity:

$$E = (c/4\pi)(\Delta H/\delta_m)(4\pi v_{ef}/\omega_{oe}^2), \tag{3}$$

where v_{ef} is the effective frequency of current electrons collisions with ions and plasma waves. In particular, under the conditions on the magnetized neutron star surface ($H = 10^{12}G$, $\omega_{He} \gg \omega_{oe}$), the cyclotron-electron modes dominate, and therefore, $v_{ef} = \zeta\omega_H$, where $\zeta \leq 1$. Then the equilibrium electric field has the upper limit estimated by Dreicer (1959, 1960):

$$E_d = m_e V_{T_e} v_{ef}/e, \tag{4}$$

that allows to evaluate the maximum energy of particles accelerated in the vicinity of the neutron star surface:

$$E_{\max} = eEr_* = 10^{19} H_{12} r_6 Y_8 \zeta eV, \tag{5}$$

coinciding with observational limits.

As for the efficiency of such non-thermal regime of energy release in the current layer disrupted by the drift-dissipative instability, we can point out that the investigations of these processes in the solar flares (Svestka, 1976) and laboratory plasma experiments (Altyntsev *et al.*, 1984) demonstrate the existence of situations when the major part of energy is released in a non-thermal form of accelerated particles. This fact allows us to conclude that the current layer of the polar vortex can be a powerful source of accelerated particles and non-thermal radiation, comparable (or exceeding) in efficiency the radiative losses of the thermal plasma.

6. CONCLUSIONS

The general picture arising from our analysis is as follows. In the standard models, the rotational momentum of accreting plasma dissipates in the magnetic field of the outer m-sphere, the accretion takes place in the form of plasma flowing along the m-sphere field lines and the gravitational energy is converted into heat and the emission of the hot plasma. In our model, plasma is accreting with conserving its rotational momentum just up to the innermost polar regions. Due to this fact, a part of gravitational energy is converted into the energy of plasma rotation in the vortex, which, in turn, is transformed into the energy of azimuthal magnetic fields generated by the vortex, the corresponding currents and electric fields, with the final conversion into particle acceleration up to ultrarelativistic energies.

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