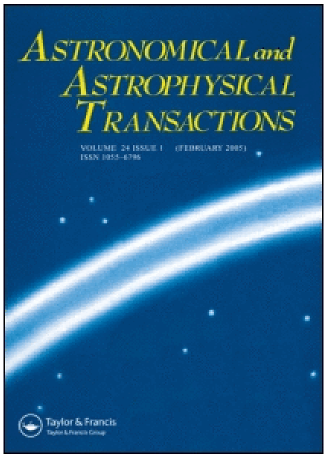

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STABILITY OF ACCRETION MODELS

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Critical analyses of the standard accretion models is presented. We consider the model stability of the theory of disc accretion on to black holes and of the theories of spherical/disc accretion on to a magnetosphere. We take into account the real physical processes and geometry (inner magnetic field in an accreted plasma, finite conductivity, finite length of the field lines, finite rotation of the accreted object and magnetic shear on the boundary between the magnetosphere and the accreted plasma). We show that the influence of these factors leads to radical change in both the pattern of accretion as a whole and the character of the energy release in the accreted system. A strong current sheet and Z-pinch-like structure have to arise over the polar region of the accreted object. Particle acceleration in the electric fields of current discharges in these regions may be a source of effective energy conversion into non-thermal particles and emission observed from many accreted objects.

KEY WORDS Accretion, instabilities, acceleration of particles, theory of gamma rays, MHD

1 INTRODUCTION AND SOME GENERAL STATEMENTS

1.1 This article is part of the work devoted to critical analyses of widely accepted accretion models. We consider the standard approaches from the point of view of their "instability" in accounting for real physical processes and geometrical factors.

The main reason of this work is the existence of very strong "hidden" assumptions in the basis of the "classical" accretion models. The origin of these assumptions is evident – it was made many years (sometimes, tens of years) ago for the attainment of computability of the proposed models. If the authors of these original models remembered their assumptions and discussed some limitations of the models they use, their disciples conceived this model as a classical element of the astrophysical building. Now at the stage of "disciples of their disciples" these models are "holy cows" and most of the astrophysical community uses them without any suspicion of the models' correctness. However, the assumptions which were made at the beginning limit the use of these models in real situations. Very often any attempt to take into account neglected factors are enough to stir some element of the theoretical basis with tragic consequences for a global theoretical construction – it loses its equilibrium and "falls to pieces". In some general considerations of stability criteria we may talk about application of the theory of catastrophe to theoretical model building.

We would like to illustrate this general statement on the example of accretion theory by analyses of the "theoretical stability" for the most popular and used accretion models: (a) spherical or disc accretion on to a magnetosphere boundary, and (b) disc accretion on to a gravitated centre without boundary (a "black hole" for example). We will attempt to shake these models by taking into account the "hidden" factors and will test the "model stability" to the influence of real factors (dimensions of the geometry, magnetic field–plasma interaction, instability/stability effects, finite conductivity, etc.).

1.2 The history of the development of accretion theory may be considered (in some sense) as the history of successive neglect of the real physics (if you ask me "what do you neglect", and I will say you, "what do you want to obtain in reality"). In this way authors have an effective mechanism for overcoming standard tests by comparing with observational data. It is a way of multiparameter fitting, when the fit of numerous model parameters (number of sources, their energy spectrum and individual input, etc.) gives fine agreement between theoretical conclusions and observed data. The art of best fitting algorithms is the reason for the mysterous agreement of absolutely different (sometimes opposite) models with the same observational data. This situation with the success of the fitting art raised the necessity of direct observational tests based on "first principles" (limits on energy, time variability, polarization level). As an example of a similar "first principles test" we may remember here the recent results of the EGRET and UHE Cherenkov system observations of ultrarelativistic gamma ray emission in numerous accreted objects (Hartman *et al.* 1992; Weeks 1992). These results ruled out from the list of possible energy sources classical α-accretion disc or plasma penetration into an unstable magnetosphere so far as these models are based on the "thermal" paradigm and are not able to release any essential energy into high-energy particles with energy greater than $\varepsilon_0 = m_p c^2 \approx 1$ Gev. An other example is the well-known test on the minimal time of variability (Shvartsman *et al.*, 1996) with its direct estimation of the brightness temperature and particle energy as a non-thermal one. Another example of a direct test is the registration of high-level linear and/or circular polarization. Unfortunately, this method, very effective in the optical and radio wave-range, may not be realized in the gamma range (at least in this century).

2 CLASSICAL APPROACHES TO ACCRETION AND BASIC ASSUMPTIONS

We may describe existing theoretical models in the frame work of a chain of consecutive neglect of uncomfortable processes or factors. It is possible to construct a scheme (similar to the known periodical table of the chemical elements) with properties of a concrete model (element) given by its place in the multidimensional space of neglected parameters.

(1) The first parameter, which find its model position in this space is doubtless the rotation moment L.

All theoretical models divide into two main groups by taking into account this factor: *spherical accretion with* $L = 0$ *and disc accretion with* $L \neq 0$.

(2) The second parameter for division of models into groups is the existence of any surface on the accreted object. This will divide accretion models in the second dimension into two groups: *accretion on to a magnetosphere or solid surface* ($R_{\mathrm{surf}} \gg R_g$) *and accretion on to a black hole* without any surface ($R_{\mathrm{surf}} \leq R_g$).

The next step in the model's development is connected with some concrete assumption about the dominant processes both in the accreted plasma and in the boundary between the accreted plasma and the accreted object. Here some "hidden" assumptions with far-reaching consequences were made. We consider some of them for the most popular model of disc accretion on to a black hole (the α-disc of Shakura–Sunyaev, 1973) and for accretion on to a magnetosphere both for spherical (Arons and Lea, 1976; 1980; Elsner and Lamb, 1977; 1984) and for disc accretion (Ghosh and Lamb, 1979) states.

3 STABILITY OF α-DISC ACCRETION MODEL

Numerous speculations on the disc accretion theme are based on the model of disc accretion (Shakura and Sunyaev, 1973), later named the α-disc model. The authors proposed considering processes in the accretion disc as gas-dynamical motion of an almost Keplerian rotating gas. They described the processes of friction between differencially rotated layers by the parameter

$$\alpha = \frac{\rho v_t^2 + H_\varphi H_r/4\pi}{\rho c_s^2},$$

where v_t, c_s are the turbulence and sound velocities, and H_φ, H_r are azimuthal and radial components of the inner disc field. As a result they succeeded in obtaining a closed form system of equations for the description of disc accretion (balance of mass and moment of motion, thermal equilibrium, inner state, radiation). As a result they obtained all the plasma and disc parameters (T, n, P, h, etc.) as a function of radius. The final dependences contain as parameters: the α-value (friction efficiency); $\dot{M}$, the accretion rate; M the central mass similar to $X = A\alpha^i r^k M^l \dot{M}^n$ with different values for the constants A, i, k, l, n in different regions of the accreted disc (depending on the ratio of gas pressure/radiation pressure and on the character of the opacity). This result was very comfortable for subsequent analyses of emission properties from the accretion disc and other manifestations. It allowed authors and numerous users to fit the model's conclusions (frequency spectrum, variability effects) to observational results with necessary accuracy.

In reality, this comfortable and popular approach has on this basis one hidden assumption: "the inner magnetic field doesn't increase anywhere more than the gas pressure limit". But as it was shown for different accreted systems (Lynden–Bell, 1969; Shvartsman, 1971; Galeev *et al.*, 1979) this assumption means an extremely fast magnetic field dissipation in the disc (in other words it means a very low effective conductivity in the accreted plasma $\sigma_{\rm eff} \approx 0$). Critical consideration argued that in a rotating accretion disc, the situation had to be opposite: $\sigma_{\rm disc-eff} \neq 0$ and this fact led to the fast exponential dynamo of the inner magnetic field up to the gas-dynamical pressure limit $H_g \approx \sqrt{8\pi nkT}$ during certain rotation times.

Why is this field generation so criminal for the α-disc model? Why can't we take into account this field as an additional correction $\beta = \frac{8\pi nkT}{H^2} \rightarrow 1$ to the α-disc equation with an influence on the α-value and the pressure expression?

The main reason for the dramatic consequences of fast magnetic field generation is the Parker instability (Parker, 1967) which leads to disc disruption before the gas-dynamical limit ($\beta_{\rm cr} \approx 0.1 \div 0.2$). As a result of the Parker instability the disc disintegrates into numerous compact and dense clouds of plasma embedded into the rarefied intercloud medium and connected directly by magnetic fields through an extended "magnetic corona" over the disc plane. This situation has a physical analogue in the very inhomogeneous interstellar medium of our Galaxy with numerous clouds and, in some aspects, with the solar "cold photosphere–hot magnetic corona–solar flares" state.

The concrete consequences of this dramatic failure of the α-disc model depend on the effective conductivity of the coronal plasma $\sigma_{\rm cor-eff}$.

(a) If it is so low ($\sigma_{\rm cor-eff} \approx 0$) that the reconnection process dominates in comparison with the magnetic field intersection and confusing with rotational time, we will have effective heating of the coronal plasma and will obtain the two-component model Galeev *et al.* (1979) similar to the solar "cold photosphere–hot corona" state.

(b) If the situation is opposite ($\sigma_{\rm cor-eff} \neq 0$) and the magnetic field hasn't had time to dissipate in the corona we have another result (Pustil'nik, 1995; Ikhsanov and Pustil'nik, 1994a, 1994b), the generation of a coronal Z-pinch like structure over the central accreted object with conversion of azimuthal magnetic field energy (generated by the Kepler motions of random clouds) into effective acceleration of ultrarelativistic particles. These processes are a result of current discharges and anomolous magnetic field reconnection. In the physical sense this situation is like effective magnetic field energy conversion into accelerated high-energy particles observed in solar flares (see the last review of Chump, 1996).

We have to understand that in reality all three components of the accretion plasma exist in the disc simultaneously and dominate in the different regions: the α-disc (or its modification) in the external region with the weak inner disc field, the "clouds" – "intercloud medium" – "hot magnetic corona" in the intermediate region of the Parker instability, and the "hot corona" – "flare Z-pinch structure" in the central region. Since most of the gravitational energy converts to plasma motion–magnetic field–"heating-acceleration" in the inner region ($W_G \propto 1/r$) it is natural to wait the dominant input of the "inner corona–accelerated particles" emission in the global energy output.

We see from this demonstration of the α-accretion disc "model instability" that taking into account the real processes of a turbulent dynamo in a differentially rotating disc ($\sigma_{\mathrm{disc-eff}} \neq 0$), and the Parker instability of the generated fields ($\frac{\beta}{\beta_{\mathrm{cr}}} \approx 1$), the magnetic energy accumulation in coronal current structures ($\sigma_{\mathrm{cor-eff}} \neq 0$) leads to the hot corona and polar Z-pinch formation with possible acceleration of high-energy particles. These regions are not so comfortable in the model's fit to observations as in the case of the α-disc, but they are only able to explain "uncomfortable" observational facts such as the hard X-ray tail formation (by Compton scattering of the "cold" emission of the α-disc on to the "hot" plasma of the magnetic corona) and non-thermal ultrarelativistic emission with energy up to 30–1000 Gev dominating in some accreted objects (the last fact is absolutely impossible for a thermal α-disc).

4 STABILITY OF MODELS WITH ACCRETION ON TO MAGNETOSPHERE ($R_{\mathrm{surf}} \gg R_g$)

Our next example of the model's instability in accretion physics is connected with accretion on to the magnetosphere surface. This group of models may be divided in two subgroups: spherical accretion with $L = 0$ and disc accretion with $L \neq 0$.

4.1 The last case of *disc accretion on to the magnetosphere* has some specific features connected with the interaction of a magnetospheric magnetic field with an accreted disc in the external region. At the present time this task has been considered in two opposite limits of the relative effective conductivity of the disc plasma:

(a) The conductivity of the disc is very low ($\sigma_{\mathrm{disc-eff}} \approx 0$) and the plasma of the disc percolates through the magnetic field of the magnetosphere almost free by Ghosh and Lamb (1979) up to the boundary. The magnetic field in these models has time to dissipate the rotational moment but doesn't affect the slower radial motion. The resulting state on the boundary is similar to the situation with spherical accretion and was considered similarly (see below).

(b) The conductivity of the disc is very high ($\sigma_{\mathrm{disc-eff}} \approx \infty$) and the disc doesn't percolate through the magnetic field, but distorts it similarly to a rigid superconductive plate with a central hole compressing the magnetic field of the central dipole (Lipunov, 1978). It is suggested that near the magnetospheric boundary this plate loses its superconductive properties, loses its rotational moment and comes into a state similar to case (a).

Both these model lead to comfortable parametric solutions of the disc–magnetosphere interaction, and both these models are able to agree their conclusions on the deceleration dependence and final plasma emission with observation by fitting of free parameters in spite of their opposite physical basis (one more illustration of "fitting illusion").

As shown by Ikhsanov and Pustil'nik (1994a, 1996) correctly taking into account the turbulent conductivity of the disc plasma changes its value to an intermediate value ($0 \ll \sigma_{\text{disc-eff}} \ll \infty$). Penetration of this plasma through the magnetospheric magnetic field is not percolation as in (Ghosh and Lamb, 1979) or compression as in (Lipunov, 1978), but is more similar to squeezing with pulling apart of the broad magnetic field lines and the singular point of Y-type formation. The main difference between "squeezing" accretion and the previous cases (a) and (b) is the ability of the disc plasma to conserve the main part of the rotational moment up to the magnetosphere boundary and later, during streaming along it in the polar region. These conclusions change radically the sign of the basic statement about stability of the magnetosphere boundary relative interchange MHD modes similar to Raleigh–Taylor flute disturbances (see below).

4.2 The next case of *spherical accretion on to the magnetosphere* is the most transparent from the physical point of view and we will discuss its model's stability in more detail.

The classical analysis of this process was made by Arons and Lea (1976, 1980) with the fundamental conclusion: the accreted magnetosphere is not stable to interchange ("flute") disturbances; the plasma will penetrate into it and then diffuse into the magnetic fields. The penetrated plasma will fall down on to the magnetic poles and form there a cone–like column of hot thermal plasma ("hole cone"-like, too).

This fundamental conclusion about magnetospheric instability is based on the assumptions (partly "open", partly "hidden"). The first one is the assumption about the effective Compton cooling of the hot plasma beside the "standing shock wave" decelerated accreted plasma. Actually, if we estimate the effective acceleration of the force, which act on the particles in the boundary region,

$$g_{\text{eff}} \approx \frac{GM}{r^2} - \frac{V_{T_i}^2}{\rho}$$

(where the first term is the gravitation of the central mass and the second is the centrifugal acceleration of the hot particles in the curved field of the magnetosphere) we obtain for the initial hot plasma with

$$V_{T_i} \approx V_{\text{ff}} \approx \sqrt{\frac{GM}{r}}$$

that the magnetosphere boundary is absolutely stable! It is a sequence of stability conditions $g_{\text{eff}} \cdot \boldsymbol{n} \leq 0$, where $\boldsymbol{n}$ is the normal to the magnetosphere surface. This situation is well known in thermonuclear plasma confinement, where the interchange instability is suppressed by the external field salient into the plasma similar to the dipole field.

However, taking into account the fast Compton cooling of the hot plasma reduces the second term in the acceleration to a negligible amount in comparison with the first one. As a result the authors obtained their basic conclusion about the abihly of the accreted plasma to penetrate into the magnetosphere by interchange mode. This result about the principal instability of the magnetosphere boundary was used later in the models of disc accretion on to the magnetosphere and is their basis, too.

Unfortunately in this basic work the authors (and after them the next generation of investigators) made one "hidden" assumption – they neglected the possible relative motion between the accreted plasma and the rotating magnetosphere, i.e. they assumed $\Omega_m \approx 0$. Since we observe real rotation of the central object in real accreted systems we have to test the relative stability of the spherical accretion model taking into account the finite rotational velocity $\Omega_m \neq 0$ and estimate the critical value of the rotational period necessary for the correctness of the classical models with an unstable magnetosphere.

The main result of the interaction between a rotating magnetosphere and an accreted plasma is the generation in the skin layer of a strong azimuthal magnetic field. As a result the direction of the local field is strong on the radius in the transition layer and changes from almost polloidal within to almost azimuthal outside of the boundary. It leads to the generation of a strong shear of the magnetic field in the boundary region $\Theta = \frac{\partial(H_\varphi/H_\vartheta)}{\partial r} \neq 0$. It is well known from plasma confinement investigations that strong magnetic shear suppresses very effectively all long-wavelength disturbances. This suppression is caused by the fact that these disturbances are forced to cross a net of aligned field lines during their development in depth, to disturb it and to lose initial energy. The condition for the shear stability is quite transparent: $\lambda_{||} \geq \lambda_{\rm cr}^{(1)} = a/\Theta$. For instability it is necessary that the disturbance is so short, that the deviation of the field line direction on the depth of the transition layer for this disturbance will not be significant.

On the face of it this limitation doesn't seem so essential for instability of the magnetosphere boundary (at least short flutes may penetrate into the magnetosphere!) but our next consideration of the "balloon mode" (Michailovskii, 1974; Cap, 1976) stabilization by longitudinal tension of field lines in short-wavelength disturbances leads to a radical change of the global pattern. Actually, consideration of the interchange instability by Arons and Lee means one more "hidden" assumption about the infinite length of the field lines ($\lambda_{||} = \infty$). It allowed workers to neglect the magnetic field tension stabilization effects (well known in plasma confinement "stabilization by conductive ends" (Kadomtsev, 1963; Connor *et al.*, 1979)). For disturbances with a finite longitudinal wavelength this assumption is not correct and the maximal increment is

$$\gamma_{g_{\rm eff},k_{||}} = \sqrt{\frac{g_{\rm eff}}{a} - k_{||}^2 V_A^2}$$

(where $k_{||} = 2\pi/\lambda_{||}$, $V_A = \sqrt{H^2/4\pi\rho}$ is the Alven velocity). From this we find that all disturbances with wavelength shorter than $\lambda \leq \lambda_{\rm cr}^{(2)} = \sqrt{V_A^2 \cdot a/g_{\rm eff}}$ will be stabilized (so-called "balloon mode stabilization" (Mikhailovskii, 1974)). As shown in our article (Ikhsanov and Pustil'nik, 1996) joint consideration of both stabilization factors (stabilization by magnetic shear, $\Theta \neq 0$, and by tension of magnetic field lines $k_{\|} \neq 0$) leads to the limitation on the rotational period of the accreted magnetosphere: for penetration of the accreted plasma into the magnetosphere by interchange mode it is necessary to have very slow relative rotation of the accreted objects with a period depending on the diffusion process rate through the boundary. For classical diffusion with $D_{\rm cl} \approx \frac{c^2}{4\pi\sigma} \approx 7 \times 10^{12} T_e^{-3/2}$ we have

$$P_{\rm unstable-cl} = \frac{2\pi}{\Omega} \gg P_{\rm cr}^{\rm (cl)} \approx 3 \times 10^4 \mu_{30}^{13/14} L_{37}^{-13/28} R_6^{-13/28} m^{-1/7} T_{(e)8}^{3/8}\, sec.$$

For the extreme case of fast Bohm diffusion, $D_B \approx \chi_B \frac{ckT_i}{16eB}$, of a turbulent plasma we have

$$P_{\rm unstable-Bohm} \gg P_{\rm cr}^{\rm (Bohm)} \approx 4 \times 10^2 \chi_B^{-1/4} \mu_{30}^{3/4} L_{37}^{-1/4} R_6^{-1/4} m^{-1/4} m^{-1/4} T_{(i)10}^{-1/4}\, sec.$$

This limit shows that the magnetosphere of most (and probably all) accreted X-ray pulsars is absolutely stable relative to interchange modes.

What does change stability of the accreted magnetosphere? First of all, the accreted plasma loses the possibility of penetrating into the magnetosphere in the equatorial region. The accreted plasma is forced to move down along the magnetosphere surface into the polar cusp region (with a free-fall velocity for spherical accretion and a component of this velocity for disc accretion). The final state of this process is the accumulation of the accreted plasma in the polar magnetic cusp region out of the magnetospheric magnetic field (in some sense it is similar to Michel's (1977) description). The interaction between the rotating magnetosphere and the accreted plasma leads to plasma rotation over the polar cusp region and stops its sinking down (similar to a side-show with a motor-cyclist on the vertical wall). The accreted plasma will be accumulated here and will interact with the surrounded magnetic field with the formation of currents sheets in the skin layer. At the final stage of this evolution the accreted plasma from the polar cusp column will penetrate to the surrounded magnetic field as a result of gradient instabilities (tearing mode, gradient-dissipative modes, etc.). This process occurs more slowly than interchange modes, but faster then the standard diffusion rate (even with the Bohm coefficient). During this process much local tearing of the current structure in the boundary takes place with an effective particle acceleration in the induced electric field of numerous generated "electrostatic double-layers" (see Pustil'nik, 1996). But this is the theme of other work (in preparation). As result we have an accretion scheme with an effective conversion of accretion energy into high-energy particle acceleration, impossible for classic models.

We see that critical analyses of the standard accretion models (both for spherical or disc accretion on to the magnetosphere and for disc accretion on to a black hole) leads to similar conclusions: taking into account "hidden" neglected process results in a radical change of accretion behaviour from the standard "thermal" approach. At the end of a new chain of processes we have the formation of metastable current structures in the immediate neighbourhood of an accreted centre and the accumulation there of accretion energy. This structure (Z-pinch for disc accretion on to a black hole or boundary current sheets for accretion on to a magnetosphere) may perform the duties of an effective engine for energy release into the high-energy non-thermal component of particles and emission.

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