NATURE OF TURBULENCE: GOVERNING FACTOR OF ACCRETION DISK DYNAMICS

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It has long been suggested that turbulence provide viscous torques to transport angular momentum outward and flow mass inward in accretion disks (von Weizsäcker 1948, Shakura & Sunyaev 1973). Recent advances in subject of understanding of accretion disk turbulence are mach linked with magnetised disks (cf. Vishniac & Diamond 1992, Balbus, Gammie & Hawley 1994, Brandenburg *et al.* 1995, Stone *et al* 1996). However, not all the disks are magnetically coupled (see Balbus, Hawley & Stone 1996). Two different sources that are able to sustain turbulence in not magnetised accretion disk are the following:

(i) superadiabatic temperature gradients in the direction normal to the disk plane;
(ii) differential rotation of the disk matter (shear flow).

Existence of superadiabatic temperature gradients leads to a powerful (exponential in time) amplification of perturbations and maintenance of turbulent state by a thermal convection, and yet it does not certainly solves accretion disk enigma. Firstly, such temperature gradients may exist only in particular cases and in definite parts of accretion disks. Secondly, it have not been clarified yet the direction of momentum transport (inward or outward) via this type of turbulence (cf. Ryu & Goodman 1992, Lin, Papaloizou & Kley 1993, Stone & Balbus 1996).

The second source of turbulence sustenance – *shear flow* – is universally present in accretion disks. However, shear flow phenomena are characterised by peculiar features and are still not completely understood. In fact, not all types of shear flows passed even an analysis of linear processes. Canonical linear theory (modal approach) has been successful in explaining of instability genesis in some kinds of shear flows. However, in some quite simple but important kinds (*e. g.* Couette and Poiseuille) of smooth shear flows (the similar are the considered disk flows) it meets significant problems evoked by the non-normal character of the operators describing the linear dynamics of perturbations in these flows (cf. Reddy, Schmid & Henningson 1993).

Impressive progress in the understanding of shear flow phenomena has been enforced by an extensive usage of the so-called nonmodal approach since 1990s. The nonmodal analysis implicates a change of independent variables from a laboratory to a moving frame and a study of temporal evolution of *spatial Fourier harmonics* (SFH) of perturbations without spectral expansion in time. This approach greatly simplifies the mathematical description and helps to grasp phenomena that are overlooked in the framework of a widely used modal approach. The nonmodal approach has already yielded some unexpected results on time evolution of both vortices (cf. Criminake & Drazin 1990, Lominadze, Chagelishvili & Chanishvili 1988, Reddy & Henningson 1993, Farrell & Ioannou 1993) and acoustic waves (see Chagelishvili, Rogava & Segal 1994, Chagelishvili *et al* 1997a) in shear flows. This approach has also been successfully applied to the study of MHD waves (cf. Balbus & Hawley 1992, Chagelishvili *et al* 1997b). It has led to the discovery of a new linear mechanism of transformation of perturbations in shear flows (see Chagelishvili & Chkhetiani 1995, Chagelishvili, Rogava & Tsiklauri 1996, Rogava Mahajan 1997, Chagelishvili *et al.* 1997b). Finally, it has helped to formulate a new conjecture of transition to turbulence and its maintenance (see Broberg & Brosa 1988, Chagelishvili, Chanishvili & Lominadze 1988, Chagelishvili *et al* 1993, Gebhardt & Grossmann 1994, Henningson & Reddy 1994, Bagget, Driscoll & Trefethen 1995), that differs fundamentally from previously existing models and takes priority in hydrodynamical society. This conception of turbulence (based on an interplay between transient linear growth of vortical perturbations and nonlinear energy conserving mixing) may be applied for not magnetised convectively stable

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accretion disks. However, it should be taken properly into account that this model of turbulence is developed for smooth parallel flows with low shear rates. In distinction, Keplerian accretion disk flow is considerably influenced by rotational Coriolis and buoyancy forces and is characterised by a large shear rate ($r\partial_r ln\Omega = -3/2$). These circumstances significantly change the linear dynamics of perturbations and turbulence features. Therefore the model of turbulence should be somewhat modified for accretion disk flows.

The purpose of this report is to describe the statistical characteristic (helicity) of two different types of turbulence in accretion disks of black holes and to outline manifestations of this characteristic in accretion dynamics. In accordance with all the above these two types of turbulence are: **(i)** convective turbulence, caused by a superadiabatic temperature gradients (when the latter exists) and **(ii)** shear turbulence, caused by differential rotation of matter in the disks. Both kinds of turbulence can create an anomalous viscosity. But effect of turbulence in disks is not only the creation of anomalous viscosity; Turbulence, depending on originating forces, can have gyrotropic nature. The latter leads to the existence of an average helicity and is the cause (together with the differential rotation) of generation of large-scale magnetic fields in disks. And the known dynamical activity of magnetic fields may appreciably change the accretion physics. Therefore, depending on the nature of the turbulence (gyrotropic or not) accretion in disks would proceed in a different ways. For instance, shear turbulence, having a non-gyrotropic nature, promotes monotonous axisymmetric accretion (without formation of any macroscopic structures) and a "high" state of disk radiation.

Accretion disk (or its considerable region) may become convectively active with variation of accretion rate and convective turbulence may be developed. This type of turbulence has gyrotropic nature, closes the cycle of turbulent dynamo and promotes generation of large-scale, quadruple (mainly azimutal) magnetic field. Magnetic forces give rise to Parker instability. As a result magnetic flux tubes, emerging in the region of the main energy release, are heated, forming a hot, optically thin arcs (coronas). The latter are required for the explanation of a power law spectrum of X-ray photons in the "low" state of the accreting black holes. Time variation (millisecond variation and quasi periodic oscillations) of the spectrum in this state may be explained by geometry of magnetic arcs and dynamics of their formation.

Shear turbulence is mainly two dimensional and has not gyrotropic character, while convective turbulence is especially three-dimensional and obtains gyrotropic character. Therefore, convective turbulence in a differentially rotating accretion disks generates helicity and leads to amplification of large-scale magnetic-fields (Chagelishvili, Lominadze, and Sokhadze 1986). Thus, unlike shear turbulence, convective turbulence may make an accretion disk magnetically active – but only if there exists a strong large-scale magnetic seed field. On this property of convective turbulence alone, the bimodal accretion model for Cyg X-1 (Chagelishvili, Chanishvili, and Lominadze, 1986, 1988) is founded. It predicts, for a "low" state, the formation of hot magnetic arcs – the inhomogenouties that are able to create millisecond variation (MV) of this source.

The model assumes (Chagelishvili, Chanishvili and Lominadze 1986, 1988) a variation of the accretion rate $\acute{M}$ in a certain interval $(\acute{M}_1, \acute{M}_2)$ and the existence of some critical rate $\acute{M}_{cr}$ in it. (Here $\acute{M}_{cr}$ has nothing in common with the critical Eddington accretion rate.) Shear turbulence definitely exists in the whole accretion disk (Chagelishvili, Chanishvili and Lominadze 1988), but convective turbulence is only inherent to the inner radiation-dominated region of the accretion disk and is always absent in the outer regions. Thermal convection is also absent in the middle region if $\acute{M} > \acute{M}_{cr}$, and for $\acute{M} < \acute{M}_{cr}$ the parameters of the region are such that it becomes unstable against thermal convection, that is, the middle region grows convectively active.

This is circumstance that makes the accretion disk magnetically active and switches Cyg X-1 to the "low" state. But how does it actually happen?

Originally magnetic field is carried by the matter coming from the optical component of the binary system. A part of this field, being large-scale, may be considered as a seed field for the processes described by the turbulent dynamo equations (Moffat 1978). In the outer region where helical turbulence is absent (there is no thermal convection), the large-scale magnetic field is decreased because of the turbulent diffusion brought on by the shear turbulence. If thermal convection in the middle region is still absent ($\acute{M} > \acute{M}_{cr}$), the decrease of the large-scale field transported in through by the matter from the outer region of the disk continues. In this case, the matter is not able to supply the inner region of the disk with a sufficiently strong large-scale magnetic field. As a result, despite of the fact that the large-scale magnetic field is generated in the inner, convectively active region of the disk, estimations show (Chagelishvili, Chanishvili and Lominadze 1986) that it does not have time to increase up to perceptible values, and accretion goes on without large-scale magnetic field, mainly in accordance with the standard model. Thus, we can say that when $\acute{M} > \acute{M}_{cr}$, Cyg X-1 is in a "high state.

When $\acute{M} < \acute{M}_{cr}$, thermal convection appears in the middle region of the disk and the generation of a large-scale magnetic field has already begun here – long before the matter comes to the inner region. It should be emphasised that the generated large-scale magnetic field is virtually azimuthal (Chagelishvili, Lominadze, and Sokhadze 1986). Under such conditions, the magnetic forces become stronger in the region of the main energy release of the disk and have a real influence on the matter dynamics. Namely they give rise to a Parker instability – rather, stretched parts of some magnetic tubes emerge out of the main volume of the disk, forming arcs of decreased density above it. At the same time the greater part of the magnetic tube matter sinks toward the central plane, forming a kind of clots, situated between the arcs. The study of Parker instability in the inner region of a accretion disk made in Chagelishvili, Lominadze and Sokhadze (1988) shows that in the process of instability development, mainly perturbations (with maximum growth rate) which have no $Z \to -Z$ reflection symmetry are amplified.

The action of Parker instability described above must be conceived as a quasi-periodic process. Really, we assume that magnetic flux tubes emerging in the region of the main energy release are heated, forming a hot, optically thin corona. The latter is made up of several magnetic arcs which are connected with the main disk and are sweeping inward in the process of matter accretion. Then the magnetic flux tubes emerge once again, and the cycle continues. At any subsequent time, the magnetic flux tubes, may emerge at a different distance from the black hole. It may by understood that number of generated magnetic arcs may vary in time. It may be shown that *three to five* magnetic arcs may be situated in the region of the main energy release in Cyg X-1 during the development of Parker instability (Chagelishvili, Lominadze and Rogava 1990).

The characteristic radial length scale (bellow all the scales are given in unites of Schwartshilds radius) of inhomogeneutes (l_r) is connected with the radial extension of the region of the main energy release, because the latter is the upper limit for the former (The region of the main energy release is rather narrow and extends to $r = 6.5$ Chagelishvili, Lominadze and Rogava 1988). Thus we can consider l_r to be ≤ 4, which is essentially less than the extension of the same region in azimuthal direction. For the azimuthal scale we have $l_\phi \approx 30$. Taking into account the noticeable difference between l_r and l_ϕ, it becomes clear that for $n = 3$ each arc in the region of the main energy release will be stretched considerable in the azimuthal direction. It is also evident that with increasing n, this stretching will weak.

Thus we propose that a number of these magnetic arcs of decreased density form, due to heating, the hot, optically thin corona so necessary for explaining the power-low spectrum of Cyg X-1 in the "low" state. Such a spectrum is generated in the arcs by Comptonization of soft X-ray photons emitted by dense clusters of relatively cold plasma between and under the arcs in the vicinity of the equatorial plane of the disk (for details see Chagelishvili, Lominadze and Rogava 1988). The corona made up of these magnetic arcs will cover only a part of the colder "core", which, in fact, is indirectly confirmed by some observations of Cyg X-1 (Sunyaev and Trümper 1979).

We hold that macroscopic magnetic arcs rapidly rotating in the region of the main energy release are very "hot spots" necessary to explain MV phenomena in a "low" state.

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