Plasmas in galaxies and galaxy clusters

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Development of the theory of instabilities of differentially rotating plasma with astrophysical applications

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Abstract. Instabilities of nonuniform flows is a fundamental problem in dynamics of fluids and plasmas. This presentation outlines atypical dynamics of instabilities for unmagnetized and magnetized astrophysical differentially rotating flows, including, our efforts in the development of general theory of magneto rotation instability (MRI) that takes into account plasma compressibility, pressure anisotropy, dissipative and kinetic effects. Presented analysis of instability (transient growth) processes in unmagnetized/hydrodynamic astrophysical disks is based on the breakthrough of the hydrodynamic community in the 1990s in the understanding of shear flow non-normality induced dynamics. This analysis strongly suggests that the so-called bypass concept of turbulence, which has been developed by the hydrodynamic community for spectrally stable shear flows, can also be applied to Keplerian disks. It is also concluded that the vertical stratification of the disks is an important ingredient of dynamical processes resulting onset of turbulence.

Keywords. Astrophysical disks, transient growth, MRI, turbulence.

1. Introduction

Nonuniform flows are ubiquitous in astrophysical rotating (stars, protoplanetary disks, galaxies, etc.) and plane flows (e.g. solar wind). Consequently, the appearance of complex dynamics of these systems is often a manifestation of nonuniform kinematics. For instance, the structure and dynamical appearance (such as turbulence) of astrophysical disks are largely defined by the differential character of the disk matter rotation. This concerns to both, unmagnetized and magnetized astrophysical disks – objects of our interest.

The consequent development in understanding the physics of turbulence in astrophysical disks has been irregular and has taken considerable time. Substantial progress has been achieved in the nineties with the discovery of a linear instability in magnetized disks, so called magneto rotation instability (MRI) (Balbus & Hawley, 1991; Balbus & Hawley, 1992; Hawley & Balbus, 1991; Hawley & Balbus, 1992; Hawley *et al.*, 1995; Stone *et al.*, 1996). Behind the frameworks of this theory were the papers Velikhov (1959) and Chandrasekhar (1960), showing that the nondissipative Couette flow, i.e., the flow of an ideally conducting fluid between rotating cylinders can be destabilized by an axial magnetic field. As a whole, MRI and related instabilities became a focus point of astrophysical studies dealing with accretion disks around a compact object in binary systems. These studies were summarized in the review Balbus & Hawley (1998). These studies were mostly concerned with hydrodynamic regimes when standard MHD is applicable. On other hand, there are many astrophysical objects where regimes different from standard MHD occur. In a series of recent papers, the MRI theory has been extended taking into account finite plasma compressibility, pressure anisotropy, dissipative and kinetic effects thereby allowing applications to various of astrophysical objects. We aim to present these recent developments.

In contrast to the magnetized disks, the solution of the turbulence problem in the unmagnetized/hydrodynamic case has not yet reached sufficient maturity. Moreover, the very occurrence of turbulence in hydrodynamic disks has been questioned by Balbus *et al.* (1996) and Balbus & Hawley (1998). However, there is irrefutable observational evidence that such disks have to be turbulent. Due to this apparent contradiction, disk turbulence is often considered as some sort of mystery. The reason for this situation is that cylindrical flows with Keplerian profile belong to the class of smooth shear flows, i.e. which present no inflection point; it is well known that these flows are spectrally stable, although they may become turbulent in the laboratory. This dilemma, that existed also in laboratory/engineering flows, has been solved by the hydrodynamic community in the 90s of the last century, where a breakthrough was accomplished in the comprehension of turbulence in spectrally/asymptotically stable shear flows (e.g. in the plane Couette flow). We also aim to outline the breakthrough of the hydrodynamic community and its application to unmagnetized/hydrodynamic astrophysical disks.

2. Generalization of MRI

The incompressible case studied in Balbus & Hawley (1991) corresponds to the high-β plasma (β- ratio of the plasma and the magnetic field pressures) and can be called the simplest MRI in the simplest astrophysical situation. In Mikhailovskii *et al.*, (2008), it was suggested that the MRI can be treated as a plasmaphysical phenomenon. The electrodynamic approach to the MRI problem has been formulated within a framework of an appropriate plasma permittivity tensor. One more step in the MHD theory of MRI has been done in Kim & Ostriker (2000) and Blaes & Socrates (2001) taking into account compressibility. Thereby, the analysis of Balbus & Hawley (1991) has been generalized to the case of an arbitrary-β plasma. It was also pointed out that, in addition to one-fluid MRI theory, a kinetic theory is needed for a collisionless plasma with anisotropic pressure, and the axisymmetric modes in the simplest astrophysical configuration were analyzed in Quataert *et al.* (2002) and Sharma *et al.* (2003) where the basic kinetic theory of the MRI in the isotropic plasma and the related instabilities in the presence of pressure anisotropy were studied. In Mikhailovskii *et al.*(2008a) a family of hybrid instabilities due to the differential plasma rotation was found: the so-called rotational-firehose and rotational-mirror instabilities.

Electrodynamic theory for a larger part of the phenomena was developed in Mikhailovskii *et al.*, (2008b). The dynamics can be described by either the one-fluid MHD or the kinetic theory. We have shown that the local dispersion relation for all these situations and for both approaches in terms of the permittivity tensor has the universal form. We have developed four versions of electrodynamic theory: one-fluid theory for the simplest astrophysical plasma, kinetic theory for the simplest astrophysical plasma, one-fluid theory for the case with both the gravitation force and the pressure gradient present and kinetic theory for this case. These versions differ from each other by the permittivity tensor components. These equations show that the nonaxisymmetric modes are less dangerous than the axisymmetric being, first, stronger stabilized by the magnetoacoustic effect, and, second, because of the overstable effect. The dispersion relation describes two instabilities: the MRI and the Convective Instability. The latter induced by the pressure gradient together with the density gradient.

The kinetic treatment reveals the pressure anisotropy effects on the instabilities. It is known that the plasma pressure anisotropy may be a drive of the collisionless plasma instabilities (Mikhailovskii, 1975). Three varieties of the pressure anisotropy-driven instabilities in the nonrotating plasma (Kitsenko & Stepanov, 1960; Rudakov & Sagdeev, 1958; Vedenov & Sagdeev, 1958; Chandrasekhar, Kaufman & Watson, 1958; Parker, 1958) are known: the mirror instability (Kitsenko & Stepanov, 1960; Rudakov & Sagdeev, 1958; Vedenov & Sagdeev, 1958) and two kinds of firehose instabilities, one related to the Alfven oscillation branches (Kitsenko & Stepanov, 1960; Chandrasekhar, Kaufman & Watson, 1958; Parker, 1958), other to the magnetoacoustic ones (Kitsenko & Stepanov, 1960; Rudakov & Sagdeev, 1958; Vedenov & Sagdeev, 1958). Initially, the rotation effect has been included into firehose instability theory in Sharma *et al.*, (2006) and Ferriere (2006). The rotational-firehose and rotational-mirror instabilities have been found in Mikhailovskii *et al.* (2008a) for the simplest astrophysical plasma with axisymmetric perturbations. The axisymmetry is a restriction of Mikhailovskii *et al.* (2008a), Sharma *et al.* (2006) and Ferriere (2006). In general, the technique developed in Mikhailovskii *et al.* (2008b) allows to obtain a broader view of the rotation effect on the pressure-anisotropy-driven instability. Comparison shows that, in contrast to the one-fluid approach, the axisymmetric MRI in the collisionless laboratory plasma is not affected by the Velikhov or the plasma density gradient effects. Predictions of the one-fluid MHD and the kinetics are different since the MHD implies a coupling of the perpendicular and parallel plasma motions. Behavior of the axisymmetric and nonaxisymmetric modes in the kinetic laboratory plasma model is similar. The main difference between them comes from the overstable effect for nonaxisymmetric modes. In addition to the local dispersion relations, in Mikhailovskii *et al.* (2008b) is derived a series of electrodynamic mode equations. These can be used for the development of the electrodynamic theory of nonlocal instabilities complementing the MHD theory of such instabilities (Mikhailovskii *et al.*, 2008c).

Our electrodynamic theory is developed for the pure plasma, similar to MHD theory. It can be generalized to the case of the dusty plasma, which can be an alternative to the MHD theory of instabilities in the rotating dusty plasma (Mikhailovskii *et al.*, 2008b; Mikhailovskii *et al.*, 2008d). Both the one-fluid and kinetic regimes considered here concern the magnetized plasma with the ion cyclotron frequency larger than the oscillation frequency and the plasma rotation frequency. A weak magnetization implies the so-called Hall regime which was broadly analyzed in astrophysics (Wardle, 1999; Urpin & Rudiger, 2005; see also Mikhailovskii *et al.*, 2007; Mikhailovskii *et al.*, 2008e), with both the MHD and electrodynamic approaches. Then the axisymmetric modes only have been studied. It seems that our technique can be applied for the electrodynamic theory of nonaxisymmetric modes. According to Krolik & Zweibel (2006), in some cases the electron inertia should be allowed for in astrophysics. The electrodynamic theory of axisymmetric modes with the electron inertia has been developed in Mikhailovskii *et al.* (2007a) and Mikhailovskii *et al.* (2008e). With our technique, this can be extended to the nonaxisymmetric modes. An important area of application of our technique is the electromagnetic instabilities in the rotating plasma in the approximation of unmagnetized electrons. A first step in this direction has been made in Mikhailovskii *et al.* (2007a) in the framework of electron hydrodynamics allowing for the collisionless parallel viscosity. However, the effects of electron pressure anisotropy leading to the Weibel-type instabilities (Weibel, 1959; Shukla & Shukla, 2007) were problematic in this topic. It seems that electrodynamic treatment can allow one to fill the gap in the theory. We have restricted ourselves to the linear approximation. It seems that inclusion of the three-wave interaction, as in Lindgren, Larsson & Stenflo (1982), and nonlinear zonal flow generation, as in Mikhailovskii *et al.*, (2007b), may be important generalization of our theory.

3. Hydrodynamic Keplerian disk flows

The breakthrough of the hydrodynamic community (see Chagelishvili *et al.* (2003), for details). Traditional stability theory followed the approach of Rayleigh (1880) where the instability is determined by the presence of exponentially growing modes that are solutions of the linearized dynamic equations. Only recently has one become aware that operators involved in the modal analysis of plane shear flows are not normal, hence that the corresponding eigenfunctions are non-orthogonal and would strongly interfere (Reddy *et al.*, 1993). For this reason, the emphasis was shifted in the 90s from the analysis of long time asymptotic flow stability to the study of short time behavior. It was established that asymptotically/Rayleigh stable flows allow for linear transient growth of vortex and/or wave mode perturbations (cf. Gustavsson, 1991; Butler & Farrell, 1992; Reddy & Henningson, 1993; Trefethen *et al.*, 1993). This fact incited a number of fluid dynamists to examine the possibility of a subcritical transition to turbulence, with the linear stable flow finding a way to bypass the usual route to turbulence (via linear classical/exponential instability). On closer examination, the perturbations reveal rich and complex behavior in the early transient phase, which leads to the expectation that they may become self-sustaining when there is nonlinear positive feedback.

Based on the interplay of linear transient growth and nonlinear positive feedback, a new concept emerged in the hydrodynamic community for the onset of turbulence in spectrally stable shear flows and was named bypass transition (cf. Boberg & Brosa (1988), Butler & Farrell (1992), Farrell & Ioannou (1993), Reddy & Henningson (1993), Gebhardt & Grossmann (1994), Henningson & Reddy (1994), Baggett *et al.* (1995), Grossmann (2000), Reshotko (2001), Chagelishvili *et al.* (2002), Chapman (2002)). The bypass scenario differs fundamentally from the classical scenario of turbulence. In the classical model, exponentially growing perturbations permanently supply energy to the turbulence and they do not need any nonlinear feedback for their self-sustenance, so the role of nonlinear interaction is just to reduce the scale of perturbations to that of viscous dissipation. In the bypass model, nonlinearity plays a key role. The nonlinear processes are conservative, but in the case of positive feedback, they ensure the repopulation of perturbations that are able to extract energy transiently from the mean flow. The self-sustenance of turbulence is then the result of a subtle and balanced interplay of linear transient growth and nonlinear positive feedback. Consequently, thorough examination of the nonlinear interaction between perturbations is a problem of primary importance, and the first step is to search and to describe the linear perturbation modes that will participate in the nonlinear interactions.

Transient dynamics of hydrodynamic disk flows. Described above linear transient growth is also at work in rotating hydrodynamic disk flows; however, the Coriolis force causes a quantitative reduction of the growth rate there which delays the onset of turbulence. Keplerian flows are therefore expected to become turbulent for Reynolds numbers a few orders of magnitude higher than for plane subcritical flows (see: Longaretti (2002), Tevzadze *et al.* (2003)). The possibility of an alternate route to turbulence gave new impetus to the research on the dynamics of astrophysical disks (Lominadze *et al.* (1988), Richard & Zahn 1999, Richard (2001), Ioannou & Kakouris (2001), Tagger (2001), Longaretti (2002), Chagelishvili *et al.* (2003), Tevzadze *et al.* (2003), Klahr & Bodenheimer (2003), Yecko (2004) 2004, Afshordi *et al.* (2004), Umurhan & Regev (2004), Umurhan & Shaviv (2005), Klahr (2004) 2004; Bodo *et al.* (2005), Mukhopadhyay *et al.*

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(2005), Barraco & Marcus (2005), Johnson & Gammie (2005), Umurhan (2006)). By adapting the progress of the hydrodynamic community to the disks flow, this research is promising for solving the disks' hydrodynamic turbulence problem.

But it remains to be seen whether this route to turbulence actually applies to astrophysical disks. Compared to plane shear flows, these possess two additional properties: differential rotation and vertical stratification. Separate studies of these factors show that each exerts a stabilizing effect on the flow: these include numerical calculation of the stability of unstratified flows by Shen *et al.* (2006), experiments on Keplerian rotation without stratification by Ji *et al.* (2006), estimates of the growth rates with stratification by Brandenburg & Dintrans (2006). However, it appears that the combined action of differential rotation and stratification introduces a new degree of freedom that may influence the flow stability and lead to turbulence at a high enough Reynolds number. The study of the linear perturbations in strato-rotational flow in the local limit can be found in Tevzadze *et al.* (2003) and Tevzadze et al. (2008) where it is shown the following:

The combined action of vertical gravity and Coriolis forces in 3D case results the conservation of the potential vorticity that indicates the existence of a vortex/apperiodic mode in the perturbation spectrum of the system. This vortex mode is the primary in the transient amplification phenomenon. In the absence of any one of these (vertical gravity or Coriolis) forces vortex mode degenerates into the trivial solution of the system – it disappears.

In 3D hydrodynamic disks with vertical gravity the density-spiral wave mode (which is internal gravity wave modified by the disk rotation) does not extract the energy of differential rotation efficiently, but is linearly coupled with the vortex mode. This coupling indicates the importance of the density-spiral waves along with the vortices in the overall dynamics of the system. The linear dynamics of small scale perturbations can be analyzed by a single spatial Fourier harmonic: a leading Fourier harmonic of 3D vortex mode gains background shear flow energy and are transiently amplified by several orders of magnitude. Reaching the point of maximal amplification and switching to the trailing, it gives rise to the corresponding harmonic of the density-spiral wave due to the shear flow induced coupling. The generated wave maintains the energy of perturbations. In fact, overall energetic dynamics is similar to that occurred in the plane parallel constant shear flow (see Fig. 2 of Tevzadze *et al.* (2003)). So, these investigations strongly suggest that the linear dynamics in vertically stratified 3D hydrodynamic Keplerian disks matches requirements of the bypass concept developed for the plane-parallel flows. This conjecture may be confirmed by appropriate numerical simulations that take the vertical stratification and consequent mode coupling into account in the high Reynolds number regime.

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