THE MECHANISM OF ANGULAR MOMENTUM TRANSFER IN ACCRETION STELLAR DISKS BY LARGE VORTICAL STRUCTURES

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ABSTRACT. Large-scale vortical flows arising in shear flows of stellar accretion disks with Keplerian azimuthal velocity distributions is investigated. The two reasons of the development of large-scale instability is shown: hydrodynamical instability and magnetorotational instability (MRI). The presence of large-scale structures leads to angular-momentum redistribution in the disk.

Key words: accretion disk, instability, magnetic field, angular momentum transfer, large-scale vortical flows

Introduction

The mechanism of removing of angular momentum from matter in an accretion disk is the most important factor determining the rate of disk accretion onto a compact object. Reasons of the removal of angular momentum in an accretion disk have long been of interest to researchers all over the world. There are a lot of mechanisms of angular momentum transfer (Shakura 1972, Shakura et al. 1973, Sawada et al. 1986, Fridman et al. 2003, Gribov et al. 1972, Bisnovatyi-Kogan et al. 1976, Balbus et al. 1991, Winters et al. 2003, Goodman 1993, Li et al. 2000) but all these mechanisms meet with some difficulties in attempts to explain the properties of accretion disks (Papaloizou et al. 1995, Balbus 2003). One widespread and well known means to transport momentum is the magnetorotational instability (MRI) (Velikhov 1959), but observations demonstrate that there exist systems which don't have magnetic field. It was first shown in (Velikhov et al. 2007, Lugovskii A.Yu. et al. 2008) that large vortical structures arising in shear flows of the accretion disk with a non-Keplerian velocity distribution, which develop and lead to a redistribution of angular momentum in the disk, could provide a mechanism for angular-momentum transport.

Here, we consider two options of the appearance and development of large-scale instability in an accretion disk with a Keplerian azimuthal-velocity distribution: hydrodynamical instability and MRI. In both cases we consider the redistribution of the angular momentum due to occurrence of large vortical structures in shear flows of the disk.

Case of hydrodynamical instability

In first case the problem is considered in a two-dimensional geometry in polar coordinates (r, □) in the domain $\Omega = (R1 \le r \le R2) \times (0 \le □ < 2\pi)$. The physical-mathematical model of the matter flows in a stellar accretion disk is given in (Velikhov et al. 2007), where a system of equations and techniques for their solution are presented. Here, we change the initial state, choosing an azimuthal-velocity distribution that is close to the observed one; i.e., we will assume an equilibrium state with a Keplerian velocity distribution. An analytical solution for the equilibrium configuration of a gas cloud near a gravitating center in the case of a Keplerian azimuthal-velocity distribution $V(r) = 1/\sqrt{r}$ was constructed in (Abakumov et al. 1996).

The behavior of the system with time in case of introducing small symmetric perturbation is considered. It was shown that at the initial time the vortical structures form in the region where the perturbations are specified; these structures, in turn, lead fairly quickly to the formation of spiral vortical structures in the entire disk (Fig. 1a). Thus, small perturbations specified in a narrow band develop into large-scale structures covering the whole disk and the flow pattern does not change qualitatively for a long time, retaining its symmetry. A considerable redistribution of the angular momentum has occurred with time, compared to the initial distribution.

These studies show that large vortical structures forming in the disk lead to a redistribution of angular momentum in the disk and a removal of matter and angular momentum through the outer boundary, but the accretion arising as a result of the angular momentum loss leads to

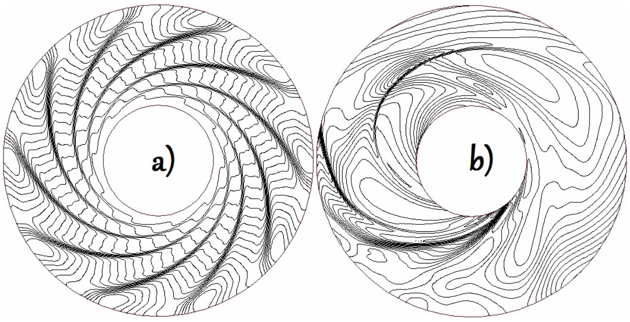

Figure 1: Flow pattern in the form of density contours for the disk with the Keplerian velocity distribution at time corresponding to t = 160 (five disk revolutions) (a) and t = 700 (twenty disk revolutions)

an inflow of the matter and,hence, an increase of the angular momentum. This quasi-stationary behavior of the system causes the observed pulsations of the parameters of the disk matter (Fig. 2).

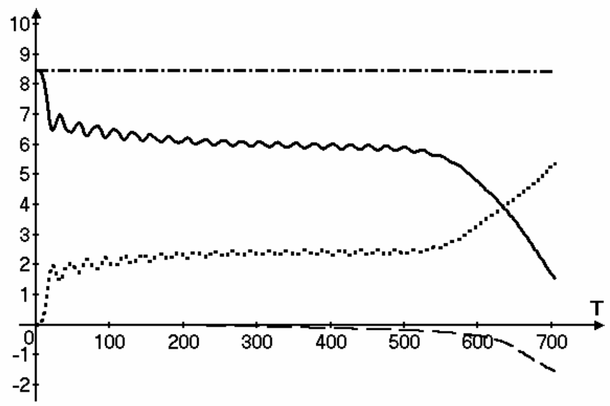

Figure 2: Time dependence of the mass in the computational domain (solid line), the total mass flux through the outer boundary (dotted line), the total mass flux through the inner boundary (dashed), and the sum of the masses in the computational domain and leaving the computational domain (dash–dotted line)

Further study of the system's evolution shows that, with time, the flow starts to lose its symmetry, leading to a qualitative change of the flow pattern — the joining and enlargement of the vortices (Fig. 1b). The flow has undergone considerable reconstruction and separate asymmetrical larger vortical structures have formed. Such two-spiral structures due to different physical processes occur fairly often in flow modeling in various stellar accretion disks.

The results obtained agree with those obtained earlier in (Belotserkovskii O.M. et al. 2000, Belotserkovskii O.M. et al. 2003), where the evolution of perturbations in various types of plane shear flows is considered and it is shown that perturbations develop, vortical structures are formed, the flow loses its symmetry, and several larger vortical structures are formed.

As was already noted above, the system is in a quasi-stationary state for a fairly long time. From the time of the symmetry loss by the flow ($t \approx 550$, 18 revolutions) and the onset of the growth of the vortical structures, the removal of angular momentum and disk matter through the outer boundary begins to occur. As a result, the rate of inward accretion increases strongly, and matter begins to flow out actively through the inner boundary (Fig. 2). Thus, large vortical structures provide a mechanism for the outward transport of the angular momentum of the disk matter, leading to matter accretion through the inner boundary of the computational domain towards the central gravitating body.

The results of our modeling of the flow in a Keplerian accretion stellar disk coincide qualitatively with the results for a non-Keplerian disk obtained in (Velikhov et al. 2007, Lugovskii A.Yu. et al. 2008).

Case of MRI

We investigate the role of the magnetic field in the collapse of a gas–dust cloud into a massive gravitating object. It is known that in the presence of a weak magnetic field, the shear flow may be subject to the development of strong instability, first discovered in (Velikhov 1959). This phenomenon, which has been called the magnetorotational instability (MRI), occurs for certain distributions of the rotational angular velocity of the matter and magnetic-field strengths. In (Balbus et al. 1991) first considered the appearance of local instability of shear flows in astrophysical disks in the presence of magnetic fields. They showed that a weak magnetic field can provide a means of angular-momentum transport in accretion disks by destabilizing the flow in the disk. The accretion of matter onto the star in the presence of a magnetic field has been considered in many studies and it was shown that the magnetic field can appreciably influence the structure of the accretion flow. We consider the development of large-scale vortical flows in a gas–dust disk in the presence of a magnetic field.

The physical-mathematical model of the matter flows in a stellar accretion disk with magnetic field is given in (Velikhov et al. 2012). All the computations were carried out in a two dimensional formulation and assuming azimuthal symmetry. Since the most "dangerous" perturbation modes in the development of MRI have azimuthal wave number $m = 0$ (Velikhov 1959), this assumption essentially does not impose any constraints on the linear stage of the development of the MRI. We used a spherical computational domain with its center cut out to model the collapse of a gas–dust cloud into a star. The protostar located inside the central region creates a spherically symmetrical gravitational potential. At the initial time, a uniform magnetic field oriented along the rotation axis is specified in the region. We adopt as the initial configuration an equilibrium distribution of the density and Keplerian rotational angular velocity of the matter.

A linear analysis of the perturbations carried out for local MRI in an accretion disk enabled us to establish the maximum increment and the characteristic size of small perturbations. The results obtained for the local model agree well with the initial growth stage of perturbations observed in numerical simulations. The critical magnetic field that stabilizes the flow was determined in (Velikhov 1959). In the problem considered here, the criterion for the strong magnetic field stabilizing the flow is the ratio of the gas and magnetic pressures. Figure 3 shows that MRI develops in regions where the matter density (gas pressure) appreciably exceeds the magnetic pressure. The characteristic size of the perturbations grows with increasing magnetic field.

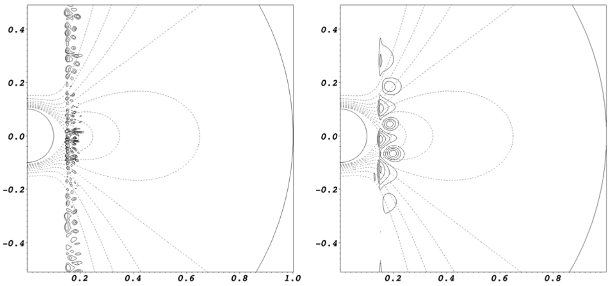

Figure 3: Perturbations of the rotational angular velocity of the matter for ratios of the gas and magnetic pressures near the equator of the inner region Pgas/Pmagn = 4000 (left) and Pgas/Pmagn = 40 (right).

Rotational shear flows can also be unstable in the absence of a magnetic field. In our current study, the initial state of the disk was chosen so that small perturbations do not appreciably disrupt the flow pattern in the absence of a magnetic field. The development of instability occurs in the presence of a fairly weak but non-zero vertical magnetic field.

At late stages in the development of the instability, the flow acquires a strongly non-linear character. As expected, the appearance of chaotic flows leads to the transport of angular momentum to the periphery of the computational domain. As it loses angular momentum, the matter near the central object begins to move into lower orbits, giving rise to accretion.

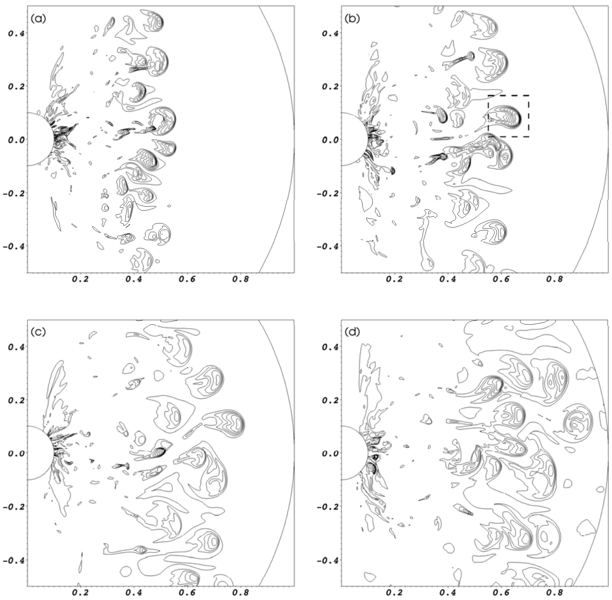

Figure 4: Positive perturbations of the angular momentum at times (from left to right, from top to bottom).

The angular momentum grows at large distances and decreases at small distances from the rotation axis with time. The magnetic field is amplified the chaotic motion of the fluid by several orders of magnitude relative to its initial magnitude. With the development of MRI, the characteristic scale for the chaotic flows becomes larger compared to the scale for the perturbations at the initial stage of development of the instability. Angular momentum is carried away by characteristic large-scale “bubbles”, whose sizes are comparable to the disk thickness. (Fig. 4).

Conclusions

Our computations have shown that the development of hydrodynamical or magnetorotational instability in an astrophysical accretion disk can lead to large-scale turbulence. Large vortical structures arising in the disk lead to a redistribution of the angular momentum of the disk matter; further, the enlargement of vortical structures leads to the more active removal of angular momentum from the disk matter, leading to considerable accretion. Thus, the larger the arising vortical structures, the more actively they remove angular momentum and the more intensively the disk matter begins to accrete.

The results indicate that large-scale turbulent flows that can lead to a considerable redistribution of the angular momentum of the disk matter and an increase in the inward accretion can arise in stellar accretion disks. In addition, quasi-periodic pulsations of the matter parameters giving rise to a non-stationary accretion rate are obtained for various accretion disks under various conditions. This accretion can explain the observed quasi-periodic pulsations of radiation during accretion onto the central body.

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