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BRIEF OVERVIEW OF SOME RECENT DEVELOPMENTS IN THE THEORY OF NON–AXISYMMETRIC ACCRETION DISCS

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Abstract

This overview considers the recent status of accretion disc theory in the cases of non-axisymmetric flows around compact objects with stellar masses. Examples of the absence of circular symmetry may be not only the discs' elliptical shape, but also the spiral density waves, the non-circular gaps in the discs and the density clumps (protoplanets). The overview is based on papers in the field published during the last four years. The implications concerning the observational appearances are also discussed. The considered problem of non-axisymmetry is examined both from theoretical and observational point of view. The former approach also includes numerical simulations of accretion flows. This review touches upon problems related with such astrophysical objects which need to be resolved.

Introduction

The present investigation of non-circular accretion discs is bounded preferably to the cases of stationary Keplerian discs, orbiting around stellar mass compact objects in close binary systems. The normal components in these systems supply the matter which is needed for discs to exist in a (quasi)stationary state. They also tidally affect accretion flows, causing in such a way their elliptical shape. It would be stressed that the elliptical orbits of the disc particles may arise not only due to the external factors, but also as a consequence of internal instabilities inherent to the accretion discs alone. To some extent, the structure of the outermost parts of accretion discs may be affected by the infalling flows of matter coming from the star orbiting around the compact object (the so called “bright spot”). Observational data, when there is a possibility for high spatial/angular and spectral resolutions of circumstellar discs, are consistent (as a rule) with the existence of Keplerian rotating gaseous discs. For example, the massive star R Mon has a clearly established Keplerian disc [1]. But there are also some exceptions, as we shall see later [3]. Such high-quality observations of the stellar accretion discs, however, are not numerous. In the lack of great amount of direct (spatially resolved) observations of discs, theoretical physics has tried to provide reasonable analytical and numerical models with varying degrees of success. This is due to the uncertainties which still exist in accretion disc theory (even with respect to some basic equations). In this situation, progress may be made, if the investigations are restricted to particular object cases hoping that the results are likely to have in some sense direct impact on the understanding of other objects.

With respect to numerical experiments, it may be definitely said that the use of modern powerful computers allows performing of 3D smoothed particle hydrodynamics calculations with high spatial and temporal resolution and more realistic viscosity and sound-speed prescriptions. Such approach may be successfully applied to the modelling of eccentric instability, which underlies the superhump phenomena in nova-like binaries such as SU Ursae Majoris variables [2]. Comparison of 2D and 3D results leads to the conclusion that 3D simulations are an indispensable requirement to obtain reasonable description of the disc’s dynamics. Numerical simulations reveal that it is necessary to run computations of very long durations to achieve eccentric equilibrium, and that saturation depends on the mass ratio of the stars in the binary system.

Another problem arises when the description of the disc’s dynamics is limited only to the Newtonian case. As a rule, the inner part of the accretion disc is affected by the very strong gravitation of the compact object. Consequently, the general relativistic effects must be taken into account. In some particular cases, when the modelling is limited to a stellar mass black hole accreting at a low rate, the disc close to the central object cannot survive and is evaporated. This is in agreement with earlier theoretical and observational results for low accretion rates [3]. In the other cases of high accretion rates onto the compact object, the advection processes most probably determine the inner disc structure, and therefore, a Keplerian motion of the accreted material is not a good approximation.

There is also an important factor, which in many situations cannot be neglected when the disc dynamics is a subject of computations. In stellar accretion discs, especially in their high temperature inner regions, the gas is highly ionized plasma. Consequently, there are strong magnetic fields with complex spatial and temporal structure of their magnetic lines. Simulations and analytical arguments indicate that the turbulence driven by magnetorotational instability in accretion discs can amplify the azimuthal component of the magnetic field to a point at which the magnetic pressure exceeds the combined “gas + radiation” pressure in the disc. Examination of the properties of these magnetically dominated discs shows that, in such manner, a number of outstanding problems in accretion disc theory are resolved [4]. These investigations show that the discs would be thicker than the standard Shakura-Sunyaev discs [22] at the same radius r and accretion rate. They would also tend to have higher colour temperature. If such accretion flows, transport angular momentum according to an α-prescription, they would be stable against the thermal and viscous instabilities that were found in the standard disc models. Other studies concerning the viscous evolution of protoplanetary discs include the combined action of magnetohydrodynamic turbulence (generated by magnetorotational instability), self-gravity torques (parametrized in terms of an effective viscosity) and also an additional viscous agent (of unspecified origin) [5]. It was generally found that accretion discs rapidly evolve towards a configuration where the intermediate regions of the radii r between a fraction of an astronomical unit and a few astronomical units are stable against magnetorotational instability due to their low ionization degree. When an additional source of viscosity was assumed to operate in these regions, it was obtained that the subsequent evolution of the disc was eruptive, i.e., highly nonstationary. Namely, brief episodes of high mass accretion rate ensure satisfaction (though for a short time) of the criterion for development of magnetorotational instability in the regions of low ionization. These theoretical investigations reveal that the radial distribution of mass and temperature in the accretion disc may be considerably different from the disc models with constant α-parameter or layered accretion models. Although magnetic fields are widely believed to play a crucial role in the transport of angular momentum, in the models of ionized atmospheres of accretion discs their contribution to the vertical hydrodynamic support has been generally neglected. Simulations of magnetorotational turbulence in a vertically stratified geometry show that the magnetic pressure support can be dominant in the upper layers of the discs. It generically produces a vertically more extended disc atmosphere with a larger density scale height. This feature acts to harden the emitted spectrum of accretion flows compared to the models where the vertical magnetic pressure support has been neglected [6].

Obviously, the great variety of accretion disc geometries, initial conditions, different simplifications introduced into the models, etc., do not permit analytical treatment of all these combinations, and in some cases, even the self-consistency of the parameters of the concrete models may not be ensured. In such complicated situations it is useful to apply numerical methods to solve the problems. Of course, this approach does not mean that the universal prescription has been found. The two commonly used techniques of grid and smoothed particle hydrodynamics show striking differences in their ability to model processes that are important across many areas of astrophysics. For example, Eulerian grid-based methods are able to resolve and treat Kelvin-Helmholtz and Rayleigh-Taylor dynamical instabilities, but these processes are poorly or even not at all resolved by the existing techniques based on the smoothed particle hydrodynamics methods [7]. The reason for this is that in the latter case the standard implementation of the smoothed particle hydrodynamics introduces spurious pressure forces on particles in regions where there are steep density gradients. Another serious problem encounters in numerical simulations is taking into account the vertical structure of the accretion flow, i.e. its 3D nature. Even at a resolution of one million particles, the vertical structure in the disc simulations may not be accurately reproduced inside 10 astronomical units, where the midplane densities drop well below their analytical values. The erroneously low densities may lead to enhanced fragmentation in those regions, even if the structure is accurately modelled further out [8]. It should be mentioned that the resolved and unresolved parts of the disc are not isolated from each other. When waves or other perturbing structures propagate through the disc their subsequent evolution will be apparently influenced by the change in resolution. Hence, the evolution of the perturbations throughout the entire simulation becomes suspect.

In numerical simulations of accretion flows it is important to quantify what changes in the behaviour of the models occur as a function of gravitational softening; for example, in order to be able to sort out real and artificial effects. That is, it must be possible to decide which effects are to be considered to be numerically induced rather than due to physical processes.

Often, such a situation arises when the reality of fragmentation events must be checked. The authors of paper [9] conclude that the ability of the accretion disc to remain in a self-regulated and self-gravitating state (without fragmentation) is partly dependent on the thermal history of the disc, as well as on its current state of cooling. An important implication of their work is that self-gravitating discs can enter into the fragmentation regime via secular evolution and it is not necessary to invoke rapid/impulse events to trigger fragmentation. Another investigation [8] shows that fragmentation will be enhanced in under-resolved simulations or (more importantly) in real physical systems. Simulations which are performed with different systems of initial conditions, different resolutions in time and space, different approximations etc., may lead to similar results about the fragmentation, which occurs in each numerical accomplishment. In other words, the simulations may be in fact converged to the same results. This conclusion may be actually true, but nevertheless there is no guarantee that it may be also seriously misleading. Due to uncertainties in their design, numerical simulations are also able to tend to converge to incorrect results. The interpretation of these results, in terms of the physical behaviour of accretion flows and the importance of the other correctly implemented physical processes, becomes difficult or even impossible [8]. Sometimes, the results and their invalidity can be clearly and/or easily established, but the same statement may not be true in other simulations, where the results could be more difficult to verify. Another investigation [10] examined whether accretion discs around the massive stars are likely to fragment due to self-gravity. It was established that the rapid accretion and the high angular momentum push these discs towards fragmentation. Oppositely, viscous heating and high protostellar luminosity tend to stabilize them. Generally speaking, for a broad range of protostellar masses and for reasonable accretion times, the massive discs larger than 150 astronomical units are prone to fragmentation. The discs are marginally prone to fragmentation around stars of about 4÷15 solar masses, even for conservative estimates of the disc’s radii and tendency to fragment. The discs around more massive stars are progressively more likely to fragment and there is a sharp drop in the stability of disc accretion at very high accretion rates, which are expected for accretion flows around very high stellar masses: 110 solar masses and more. The conclusion made in paper [10] is that fragmentation may starve accretion in massive stars, especially above the latter's mass limit and is likely to create swarms of small coplanar dense condensations.

As follows from the extensive researches devoted to the evolution of the fragments in accretion discs, the appearance of planet systems is a common phenomenon. The latter circumstance may affect appreciably the structure of accretion discs. The most striking appearance of such kind is the formation of gaps in the discs cleared by the planets. One such observational evidence of the existence of gaps is the spectral energy distribution of some T Tauri stars which display a deficit of near-infrared flux. A possible explanation of this event is that it could be a consequence of an embedded Jupiter-mass planet, partially clearing an inner hole in the circumstellar disc [11]. In this paper, it was shown that the pressure gradient at the outer edge of the gap (cleared by the planet) acts as a filter. Namely, particles, smaller than a critical size, pass through the gap to the inner disc, and the larger ones are held back in the outer disc. This process leads to discontinuous grain population across the planet's orbital radius, with small grains in the inner disc and larger grains in the outer disc. This type of dust population was found qualitatively consistent with the spectral energy distribution in the models of stars that have optically thin inner holes in their circumstellar discs. Edgar et al. [12] consider the minimum mass of the planet as a function of its orbital radius that is capable to open a gap in an α-accretion disc. They estimate that a planet with a ½ Jupiter mass can open a gap in a disc with accretion rate corresponding to viscosity parameter $\alpha = 0.01$ and central star with solar mass and solar luminosity. It was established that, if a gap-opening planet cuts off disc accretion, allowing formation of a central hole or clearing a ring in the disc, then the clearing radius would be approximately proportional to the stellar mass.

Theoretical and observational evidence of globally non-axisymmetric accretion discs

Let us denote by M_1 the mass of the compact stellar object around which the accretion flow rotates, and by M_2 – the mass of the companion star. Respectively, $q = M_2/M_1$ is the mass ratio of the components of the binary stellar system. By means of numerical simulations, analysis of the dynamics and geometry of accretion discs in binary systems with $q < 0.1$ was performed. This investigation refers to ultracompact X-ray binaries, AM CVn stars and cataclysmic variables with very short periods. It was found that the steady state geometry of the disc in the binary reference frame may be quite different from the geometry expected for higher mass ratio $q > 0.1$. For $q = 0.1$, the disc takes on the usual elliptical shape, with the major axis aligned perpendicular to the line of centres of the two stars. However, at smaller mass ratios ($q < 0.1$), the elliptical gaseous orbits in the outer regions of the disc are rotated in the binary plane. For much smaller values of q ($q = 0.01$; i.e. an order of magnitude smaller), the major axes of these orbits are aligned almost parallel to the line of centres of the two stars [13]. The steady-state geometry at low mass ratio q has not been found to be predicted by an inviscid, restricted three-body model of gaseous orbits. Instead, it is related to the effects of tidal-viscous truncation of the accretion disc near the Roche lobe boundary. Numerical investigations of Amand Smith et al. [2] also confirm the conclusion that the global structure of accretion discs may essentially depend on the mass ratio q. The latter authors have found that for $q > 0.24$, the high-resolution 3D models of the discs do not show development of superhumps/superoutbursts. It turns out that this property agrees with the analytical expectations.

The non-axisymmetric structure of accretion discs in Be/X-ray binaries was studied in [14] by performing three-dimensional smoothed particle hydrodynamics simulations for a system with a short orbital period and a moderate orbital eccentricity. It was found that the pressure due to the phase-dependent mass transfer from the disc of the Be star excites a one-armed, trailing spiral structure in the accretion disc around the neutron star. The numerical simulations established that the spiral wave was a transient event. It was excited around the periastron passage, when the material was transferred from the Be-disc and it was gradually damped afterwards. These investigations demonstrated that the accretion disc changes its morphology from circular to eccentric with the development of the spiral wave, and then from eccentric to circular with the decay of the wave during the orbital period. Another numerical study also gives similar conclusions about the evolution of the accretion disc's structure. Vorobyov and Theis [15] have studied the time-dependent evolution of stellar discs in the linear regime and partially in the non-linear one. They have established that in the earlier linear phase, the very centre and the large scales are characterized by growing one-armed and bisymmetric positive density perturbations, respectively. But in the late linear phase, the overall appearance is dominated by a two-armed spiral structure localized within the outer Lindblad resonance. During the non-linear evolutionary phase, radial mass redistribution due to the gravitational torques of spiral arms produces an outflow of mass, which forms a ring at the outer Lindblad resonance, and also an inflow of mass, which forms a transient central bar. As a final result, a compact central disc and a diffuse ring at the outer Lindblad resonance are formed. In [2] it was concluded that the disc models reveal a complex standing wave dynamics, which repeats (in the inertial frame) the disc precession period. This picture of the disc motions can be described as a superposition of different spiral modes. The authors of paper [2] characterize the eccentricity distribution in their accretion disc models and show that the entire body of the disc has its contribution which must be taken into account when evaluations of disc eccentricity have to be made.

The instabilities of non-axisymmetric gaseous discs are also subject of investigation in [16], where a perturbation theory for studying of these phenomena is presented. For such discs, the amplitude and the phase angle of the travelling waves are functions of both the radius r and the azimuthal angle φ, because of the interaction of different wave components in the response spectrum. It was demonstrated that wave interaction in unstable discs (with small initial asymmetries) can develop dense clumps during the phase of exponential growth of instabilities. Such events are relevant to the formation of planet systems around the accreting stars. Namely, local clumps, which occur on the major spiral arms, may play the role of seeds of gas giant planets in accretion discs.

Special cases of accretion flows are the circumbinary accretion discs orbiting around binary stars (i.e., the latter being in the centres of the discs). There are studies of two-dimensional thin, viscous, locally isothermal corotating discs, which investigate the structure of the discs after multiple viscous times. One of them is presented in paper [17], where a numerical modelling of a flow, moving in the orbital plane of two equal mass point masses (rotating along a fixed circular orbit) is performed. The binary system maintains a central hole in the viscosity relaxed disc with hole radius equal to about twice the binary semimajor axis. The model shows that the disc surface density Σ within the hole is reduced by orders of magnitude relative to the density in the disc bulk. The initially circular disc becomes elliptical and after that, eccentric. Disturbances in the disc contain a component that is stationary in the rotating frame in which the binary star is at rest and this component is a two-armed spiral density wave.

Returning to the effects of planets on accretion discs, the paper of Hosseinbor et al. [18] should be mentioned, where such an investigation is performed for a planet moving along an eccentric orbit. The planet acts on a two-dimensional low-mass gaseous disc. The authors find that the disc morphology differs from that exhibited by a disc containing a planet in a circular orbit. An eccentric gap is created with eccentricity that can exceed the planet eccentricity and precesses with respect to the planet orbit. It is established that a more massive planet is required to open a gap, when the planet is on an eccentric orbit. In [18], this behaviour is attributed to spiral density waves excited at corotation resonances by the eccentric planet orbit. These act to increase the disc's eccentricity and exert a torque opposite in sign to the one exerted by the Lindblad resonances. Another group of collaborators also investigates the interaction between a giant planet and a viscous circumstellar disc by means of high-resolution, 2D hydrodynamic simulations [19]. They also find that a planet can cause eccentricity growth in a disc region adjacent to the planet orbit, even if the latter is circular. Moreover, disc-planet interactions lead to increase of planet orbital eccentricity. The accretion rate towards a planet depends on both the disc and the planetary orbital eccentricity and is pulsed over the orbital period of the planet. Similar accretion modulation occurs in the flow at the inner disc boundary, which represents the accretion towards the star [19]. A concrete example of the planet-disc interactions is discussed in paper [20], where it is suggested that a planet just interior to the ring edge causes the eccentricity and sharpness of the edge of Fomalhaut's disc. The collision time-scale is evaluated as being long enough that spiral density waves could not be able to be driven near the planet. It is also found that the ring edge has eccentricity, caused by secular perturbations from the planet and its eccentricity, equal to 0.1 (the same as of the planet orbit).

The role of magnetic fields on accretion disc structure

Here we shall consider in some details the influence of large scale organized magnetic fields. Such fields may play a major role in understanding the dynamical and spectral properties of X-ray binary stars. Although most of the models are computed for discs with circular orbits of their gaseous flows, the results have also implications on elliptical accretion discs. It is important to note that numerical simulations of turbulent, magnetized, differentially rotating flows, driven by the magnetorotational instability, are often used to calculate the effective values of α-viscosity that is invoked in the analytical models. The authors of paper [21] show that the angular momentum transport in magnetorotational instability-driven accretion discs cannot be described by the standard model of Shakura and

Sunyaev [22] for shear viscosity. The former demonstrate that turbulent magnetorotational stresses are not linearly proportional to the local shear and vanish identically for angular velocity profiles that increase outwards [21]. The properties of a geometrically thin, steady magnetically torqued accretion disc model is computed in [23] for a flow around a central rotating magnetized star. The magnetosphere in these calculations is assumed to entrain the disc over a wide range of radii. The solution for angular velocity profile tends to corotation close to the central star and smoothly matches a Keplerian curve at a radius where the viscous stress vanishes. It was also found that for rapid rotators the accretion disc might be powered mostly by the spin-down of the central star. These results are independent on the viscosity prescription in the disc. Another investigation [24] deals with the role of disc magnetization on the hysteresis behaviour of X-ray binaries. The precisely worked out model contains a transition radius below which a jet-emitting disc is settled. The latter drives self-collimated non-relativistic jets. But beyond the transition radius, no jets are produced and a standard accretion disc is established, despite the presence of magnetic fields. The radial distribution of disc magnetization adjusts itself to any change in the disc accretion rate, thus modifying the established transition radius. This property opens the possibility for the transitions between standard accretion disc and jet-emitting disc and their reverse transitions to occur locally at different magnetization. This bimodal behaviour of the accretion disc may explain the hysteresis cycles observed in X-ray binary stars during outbursts. It is well known that such events are closely related to the elliptical shape of the accretion disc.

Concluding remarks

The evolution of astrophysical discs is dominated by instabilities of gravity perturbations, including those produced by spontaneous disturbances. A hydrodynamic theory of non-resonant Jeans instability in the gaseous component of a disc has been developed [25], in which it is shown analytically that gravitationally unstable systems (such as, in particular, protoplanetary discs) are efficient at transporting mass and angular momentum. Already on a timescale of the order of 2 or 3 rotational periods, the unstable accretion flow has a large portion of its angular momentum transferred outward and mass transferred both inward and outward.

As already mentioned, the true estimations of the values of the viscosity parameter α are of essential importance when the dynamics of accretion flows must be determined. This is valid both for discs with circular and elliptical orbits of their particles. For accretion discs, the height scale is a constant whenever hydrostatic equilibrium and the subsonic turbulence regime hold. In order to have a variable height scale, an extra term must be added to the continuity equation, due to processes of specific physical nature. Such a contribution makes the viscosity parameter α much greater in the outer region and much smaller in the inner region of the disc [26]. Under these circumstances, the hydrodynamical turbulence is the presumable source of viscosity in the disc. There is no need to include magnetic fields in the considerations. The way disc structure is affected by the values of α is demonstrated by Liu et al. [27], where the condensation of matter from a corona to a cool, optically thick inner disc is investigated. They give a description of a simple model for the exchange of energy and mass between corona and disc taking into account the effect of Compton cooling of the corona by photons from underlying disc. It is established that the inner disc can be present in the low/hard state for a range of luminosities that depends on the magnitude of the viscosity parameter. For $\alpha \approx 0.1 \div 0.4$, such an inner disc can exist for solar luminosities within the range $0.001 \div 0.02$. This example illustrates how essential the precise evaluation of the viscosity parameter α may be, when the global structure of accretion flows must be derived.

Astronomical observations of binary stars with accretion discs (both photometric and spectroscopic) enable us to check the validity of the theoretical models based on numerical or analytical approaches. Another method is the investigation of the evolution of protostellar discs around T Tauri stars that have formed self-consistently from the collapse of molecular cloud cores. Numerical studies of such objects demonstrate that the discs settle into a self-regulated state with low-amplitude non-axisymmetric perturbations persisting for at least several million years [28]. The global effect of gravitational torques due to such perturbations is to produce disc accretion rates that are of the correct magnitude to explain observed accretion onto T Tauri stars. An important development of accretion disc theory makes references to the formation of planet systems. Closely related to this problem is the process of disc fragmentation. In paper [29], the effects of eccentricity on the fragmentation of gravitationally unstable accretion discs are considered using numerical hydrodynamics. It is found that the eccentricity does not affect the overall stability of the disc against fragmentation, but significantly alters the manner in which such fragments accrete gas. Variable tidal forces around an eccentric orbit slow down the accretion process and suppress the formation of weakly bound clumps. The "stellar" mass function resulting from the fragmentation of an eccentric disc is found to have a significantly higher characteristic mass than that from a corresponding circular disc. The application of the worked out model to massive stars at 0.1 parsecs from the Galactic center shows that the fragmentation of an eccentric accretion disc (due to gravitational instability) is a viable mechanism for the formation of these systems [29].

It is often a matter of discussion what is the range of applicability of the standard accretion disc model. As it would be expected, the limitations of its use would be the same for discs with elliptical orbits of their particles. Shaffe et al. [30] consider a simple Newtonian model of a steady accretion disc around a black hole. They use height-integrated hydrodynamic equations, α-viscosity prescription and a pseudo-Newtonian potential. The results reveal that as the disc's thickness or the value of α increases, the hydrodynamic model exhibits increasing deviations from the standard thin disc model [22]. However, these results must be taken with a caution, because they have been obtained with a viscous hydrodynamic model. More accurate quantitative estimates need to be received by magnetohydrodynamic simulations of radiatively cooled thin discs.

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КРАТЪК ПРЕГЛЕД НА НЯКОИ ОТ СЪВРЕМЕННИТЕ РАЗРАБОТКИ В ТЕОРИЯТА НА НЕОСЕСИМЕТРИЧНИТЕ АКРЕЦИОННИ ДИСКОВЕ

Д. Димитров

Резюме

Този обзор разглежда съвременното състояние на теорията на акреционните дискове в случаите на неосесиметрични потоци около компактни обекти със звездни маси. Примери за отсъствието на кръгова симетрия могат да бъдат не само елиптичната форма на дисковете, но също спиралните вълни на плътността, имащите некръгова форма празнини в дисковете и плътните сгъстявания от вещество (протопланети). Обзорът включва статии по тази тематика от последните четири години. Дискутирани са също следствията, отнасящи се до наблюдателните прояви. Разглежданият проблем на отсъствие на осева симетрия е проучван както от теоретична, така и от наблюдателна гледна точка. Първият подход също включва числени моделирания на акреционните потоци. Този обзор засяга и проблемите, които трябва да бъдат решени за такива астрофизични обекти.