Mem. S.A.It. Vol. 83, 562

Memorie della

Accretion processes in intermediate polars with asynchronous rotations of white dwarfs

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Abstract. Using results of 3D MHD numerical simulations we investigate how the asynchronous rotation of the accreting star influences flow pattern and accretion processes in intermediate polars. We also discuss main features of the flow structure in "accretor", "propeller" and "super propeller" regimes.

Key words. Stars: cataclysmic variables – Stars: intermediate polars – Stars: accretion disks – Stars: 3D MHD simulations

1. Introduction

It is accepted now that gas dynamics of a non-magnetic close binary system is determined by presence of a stream from the L_1 point, quasi-elliptical accretion disk, circumdisk halo and circumbinary envelope (see e.g. Boyarchuk et al., 2002; Bisikalo et al., 2003, 2004, 2005; Bisikalo & Matsuda, 2007; Fridman & Bisikalo, 2009). The classification of the main elements of the flow pattern is based on their physical properties: 1) if gas motion is not governed by gravity of the accretor the gas forms a circumbinary envelope that fills space between the components; 2) if gas moves around the accretor and then mixes with the matter of the stream from the L_1 point it does not belong to the disk and forms a circumdisk halo; 3) the accretion disk is formed from the matter of the stream that, being captured by gravity of the accretor, does not interacts any more with the stream, but loses its angular momentum and moves toward the accretor.

There are a large number of close binaries where magnetic field plays a significant role in processes of mass transfer and accretion. These systems are, above all, magnetic cataclysmic variables and X-ray binaries. In the magnetic cataclysmic variables the accretor is a white dwarf having the induction of magnetic field of $\sim 10^4$–10^8 G on its surface. In X-ray binaries the accretors are neutron stars with proper magnetic fields in a range $\sim 10^{12}$–10^{13} G. Simple estimates show that dipole magnetic moments of white dwarfs in magnetic cataclysmic stars and neutron stars in X-ray binaries are approximately the same (10^{30} G cm^3). It means that radii of the magnetospheres of the white dwarf and neutron star are equal. Their values determine how much the magnetic field influences the flow structure in the close binary system. However in cataclysmic variables binary separations are tens and even hundreds times shorter than in X-ray binaries. So the dimensionless radius of the

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magnetosphere r_m/A in cataclysmic variables can exceed the analogical value in X-ray binaries. Thus, in cataclysmic variables magnetic field influences processes of the mass transfer and the structure of accretion disks much stronger than in X-ray binaries.

There are two main types of magnetic cataclysmic variables, intermediate polars and polars. In polars the white dwarf possesses a strong magnetic field ($\sim 10^7$–10^8 G on the surface). Results of observations show that polars demonstrate relatively short orbital periods ranging from 1 to 5 hours. No accretion disks are observed in such systems and their components rotate synchronously (Norton et al., 2004). It is believed that in polars the matter that flows from the donor star forms a collimated stream that moves onto the magnetic poles of the accretor along the field lines (see e.g. Warner, 2003; Campbell, 1997).

Intermediate polars are binary systems where accretors have relatively weak magnetic fields ($\sim 10^4$–10^6 G on the accretor's surface). They occupy an intermediate position between polars (systems of AM Her type) and non-magnetic cataclysmic variables. Intermediate polars are characterized by a great variety of orbital periods ranging from several hours to several tens of hours. The spin periods of accretors in these systems are significantly shorter than orbital periods (tens, hundreds and even thousands times). In the DQ Her subtype this difference is even higher. The rest of the systems are divided into regular intermediate polars (EX Hya type) and systems with almost synchronous rotation. The asynchronous rotation of white dwarfs in intermediate polars can be explained by the interaction of the accretor's magnetic field and the matter of the disk that takes place in the vicinity of the magnetosphere. This interaction results in the regime of the equilibrium rotation where the co-rotation radius is equal to the radius of the magnetosphere (see e.g. Warner, 2003; Campbell, 1997).

Investigation of MHD-flows in binary systems is a complicated task, since even in the simplest case the flow structure can be "significantly three-dimensional". However this task is of great interest, since all the observed phenomena in binary systems are due to accretion of matter onto one of the components. The accretion onto a compact object possessing a magnetic field can lead to a number of observational effects like the radiation of the accretion columns, variability concerned with hot spots on the surface of the accretor, high-frequency quasi-periodic oscillations of the X-ray radiation, etc.

A detailed description of the 3D numerical model used to calculate the flow structure in magnetic close binaries one can find in Zhilkin & Bisikalo (2009, 2010a, 2010b, 2010c). In our approach we use a complete system of the MHD-equations that allows us to describe all the main dynamic effects caused by magnetic field. In the model we take into account effects of the radiative heating and cooling, diffusion of the magnetic field due to dissipation of currents in turbulent vortices, magnetic buoyancy and the wave MHD-turbulence. It is important to note that in the developed model an accretion disk forms "by nature" due to the process of the mass transfer through the inner Lagrangian point L_1. So, we have pioneered a self-consistent description of the MHD flow structure in close binaries. These results can be used to interpret observations of magnetic cataclysmic variables.

In this work we focus on the influence of the accretor's spin on the flow structure in magnetic cataclysmic variables.

2. Problem setup

To describe the flow structure in a binary system we use a Cartesian coordinate frame (x, y, z) that is set up as follows. The origin of the frame is in the center of mass of the accretor, $\boldsymbol{r}_a = (0, 0, 0)$. The center of mass of the donor is located on the x-axis at a distance A from the center of the accretor $\boldsymbol{r}_d = (-A, 0, 0)$. The z-axis is directed along the rotation axis of the system $\boldsymbol{\Omega} = (0, 0, \Omega)$. The accretor's spin rotation is asynchronous and can be described by the angular velocity $\boldsymbol{\Omega}_a$ in the chosen coordinate frame.

As a rule magnetic field of a white dwarf in a polar and intermediate polar can be described rather accurately as a dipole field. Let us de-

Table 1. Parameters of the calculated models of systems with the asynchronous rotation of the accretor. The prototypes correspond to the accepted classification of intermediate polars (Norton et al., 2004).

Model	Prototype	P_{spin}/P_{orb}	r_c/r_m	Regime
1	Synchronous	1	∞	"accretor"
2	EX Hya	0.1	1.48	"accretor"
3	Regular	0.033	1.00	equilibrium rotation
4	DQ Her	0.01	0.66	"propeller"
5	AE Aqr	0.001	0.31	"propeller"

note the inclination of the $\boldsymbol{d}$ vector with respect to the z-axis as θ_d. The angle between the projection of the $\boldsymbol{d}$ vector to the xy plane and the x-axis we denote as $\phi_d = \Omega_a t + \phi_{d0}$. This angle is time-dependent and ϕ_{d0} is its initial value. Thus, the magnetic field of the accretor is not stationary

$$\frac{\partial \boldsymbol{B}_a}{\partial t} = \nabla \times (\boldsymbol{v}_a \times \boldsymbol{B}_a). \tag{1}$$

Here $\boldsymbol{v}_a = \boldsymbol{\Omega}_a \times (\boldsymbol{r} - \boldsymbol{r}_a)$ is the velocity of the field lines of the accretor's magnetic field. We should note that in the case when $\Omega_a = 0$ (synchronous rotation of the accretor) and $\theta_d = 0, \pi$ (the magnetic axis coincides with the rotation axis) the magnetic field of the accretor does not vary in time.

The influence of the accretor's spin rotation velocity on the structure of the MHD flow in a close binary system can be characterized by the ratio of the radius of the magnetosphere r_m and co-rotation radius r_c. The radius of the magnetosphere is equal to (see e.g. Campbell, 1997):

$$r_m = \left(\frac{B_a^4 R_a^{12}}{8GM_a\dot{M}_a^2}\right)^{\frac{1}{7}}. \tag{2}$$

Here R_a is the radius of the accretor, M_a – its mass, and $\dot{M}_a$ is the accretion rate. The corotation radius is a distance at which the velocity of the rotation of the field lines is equal to the velocity of matter rotating in the accretion disk. If we suppose that the rotation of the field lines is of the solid-body type with the angular velocity Ω_a and the angular velocity of matter is equal to the Keplerian velocity ω_K we find:

$$r_c = \left(\frac{GM_a}{\Omega_a^2}\right)^{1/3}. \tag{3}$$

If the accretor rotates slowly ($r_c > r_m$) then the velocity of the magnetic field rotation at the boundary of the magnetosphere is lower than the Keplerian velocity at the same radius. So, matter can be captured by the magnetic lines and can freely fall onto the surface of the accretor. This regime can be called the "accretor" regime. If the accretor rotates rapidly ($r_c < r_m$) a centrifugal barrier occurs at the boundary of the magnetosphere. This barrier prevents matter from falling onto the accretor's surface. This regime is known as the "propeller" regime. In this regime accretion is significantly non-stationary (Romanova et al., 2004, 2005; Ustyugova et al., 2006). In case of the equilibrium rotation a relation $r_c = r_m$ works. Analysis performed in Lipunov (1992) shows that the interaction between the magnetosphere and disk makes the system evolve toward the equilibrium rotation.

This classification is in agreement with the observed distribution of intermediate polars over the spin period of the accretor (see Tab. 1). The vast majority of these systems are in the state of the equilibrium rotation (regular intermediate polars). The systems that are in the "accretor" regime can be divided into synchronous intermediate polars ($P_{spin} \approx P_{orb}$) and EX Hya systems ($P_{spin} \approx 0.1P_{orb}$). Systems with the rapid spin rotation of the accretor can be grouped into two classes: DQ

Her systems ($P_{spin} \approx 0.01 P_{orb}$); and AE Aqr systems ($P_{spin} \approx 0.001 P_{orb}$). In DQ Her type systems an accretion disk forms but the "propeller" regime works. In AE Aq systems the accretor rotates so rapidly that no accretion disk is formed. This regime, hence, is called "super propeller".

To investigate how the asynchronous rotation influences the flow structure in a magnetic close binary we performed 3D numerical simulations for models with different values of the P_{spin}/P_{orb} ratio. Parameters of these models are shown in Tab.1. The parameters are taken for the SS Cygni system (see., e.g., Giovannelli et al., 1983). The donor-star (red dwarf) in this system has a mass $M_d = 0.56 M_\odot$ and effective temperature 4000 K. The accreting star (white dwarf) has a mass $M_a = 0.97 M_\odot$ and temperature 37000 K. The orbital period of the system P_{orb} = 6.6 h, and the binary separation $A = 2.05 R_\odot$. The inner Lagrangian point L_1 is located at the distance $0.56A$ from the center of the accretor. The system has been observed for more than a century, so much information on it has been gathered. Nonetheless, many questions on its physical properties still remain unanswered. In accordance with morphological criteria SS Cygni is related to U Gem stars. However, there are a number of features that allow us to suppose that SS Cygni is an intermediate polar with the value of the magnetic filed of $B_a = 10^4$–10^6 G (Fabbiano et al., 1981; Kjurkchieva et al., 1999).

3. Results and discussion

Models that we consider correspond to the types of intermediate polars discussed above (see Tab.1). For all the models we accepted the value of the surface induction of the magnetic field equal to 10^5 G and the inclination of the magnetic axis with respect to the rotation axis is $\theta_d = 30°$. We should note that the Model 1 (synchronous rotation) and Model 3 (equilibrium rotation) do not differ from the Model 2 ("accretor", EX Hya systems). Further we will consider the Model 2 as a typical solution for a system that is in the "accretor" regime.

Let us consider specific features of the flow patterns of the Models 2 and 4 corresponding to the "accretor" and "propeller" regimes. The morphology of the flow in the considered systems is shown in Fig. 1. In the top diagram one can see distributions of the density and velocity vectors in the equatorial plane of the system for the Model 2 ("accretor") and in the bottom diagram - for the Model 4 ("propeller"). In both the diagrams of this Figure flow lines that edge the accretion disk are shown (bold black line). The solutions shown correspond to the moment when the stationary flow is established (about 20 orbital periods).

In the Model 2 the flow structure is similar to that calculated for the synchronous rotation (Zhilkin & Bisikalo 2010a, 2010b, 2010c). It is seen that in such models an accretion disk forms. This disk has a specific features of the flow structure: the "hot line", tidal spiral shocks, precessional spiral density wave, etc. The radius of the calculated region of the magnetosphere is in good agreement with estimates of the inner radius of the accretion disk in SS Cygni that was obtained from analysis of observed Doppler tomogramms (Bisikalo et al., 2008; Kononov et al., 2008). A significant difference between solutions with the synchronous and asynchronous rotation is in the decrease of the accretion rate and formation of the more powerful "tail" of the matter outflowing through the Lagrangian point L_3. The power of the "tail" is higher with the higher spin rotation velocity of the accretor (degree of asynchronicity).

Analysis of the solution in the Model 4 shows that the flow structure has qualitative differences from the solution of the "accretor" regime. The accretion disk becomes larger. The flow line that edges the accretion disk even crosses the Roche lobe. A powerful tail of the matter that outflows through the Lagrangian point L_3 and replenishes the outer envelope of the binary is clearly seen. In inner regions of the disk a magnetospheric cavity forms. Its radius is $(0.05$–$0.1)A$. At the boundary of this cavity the Kelvin - Helmholtz instability develops. The spiral waves that occur as a result of the instability tend to become shock-waves.

Since in the magnetospheric cavity there is almost no gas, the accretion rate in the Model 4 is close to zero. On the other hand the mass

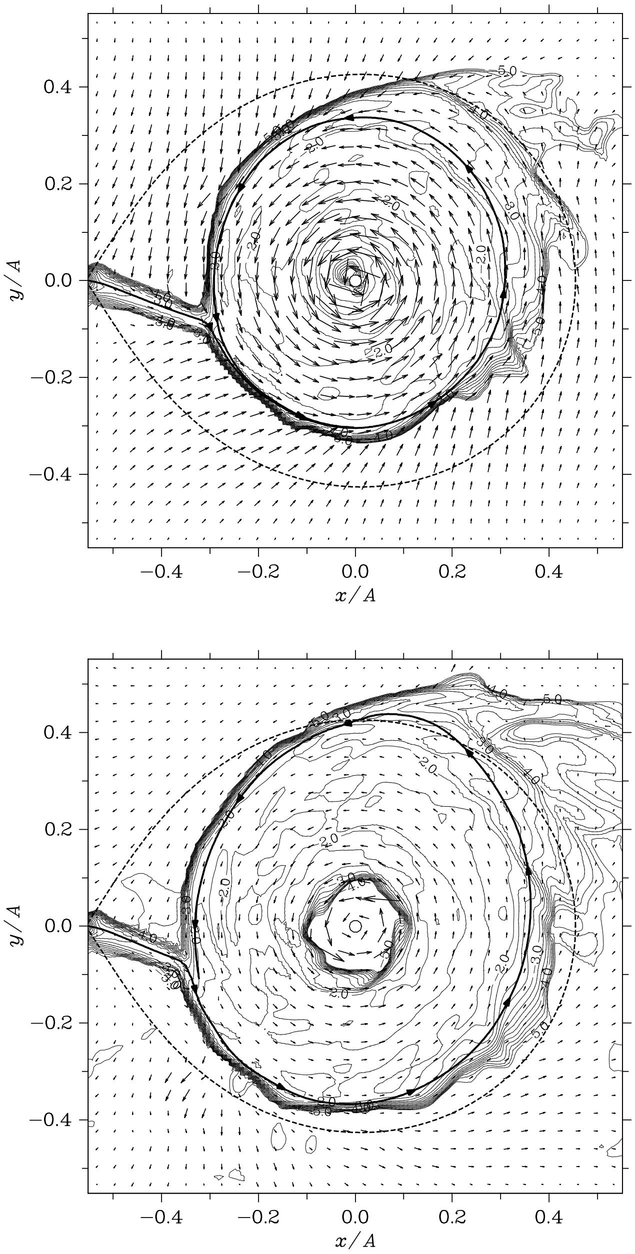

Fig. 1. Distributions of the density and velocity in the equatorial (*xy*) plane for Models 2 ("accretor", top panel) and 4 ("propeller", bottom panel). The flow lines edging the accretion disk are shown by bold solid lines. The Roche lobes are depicted by the dashed line.

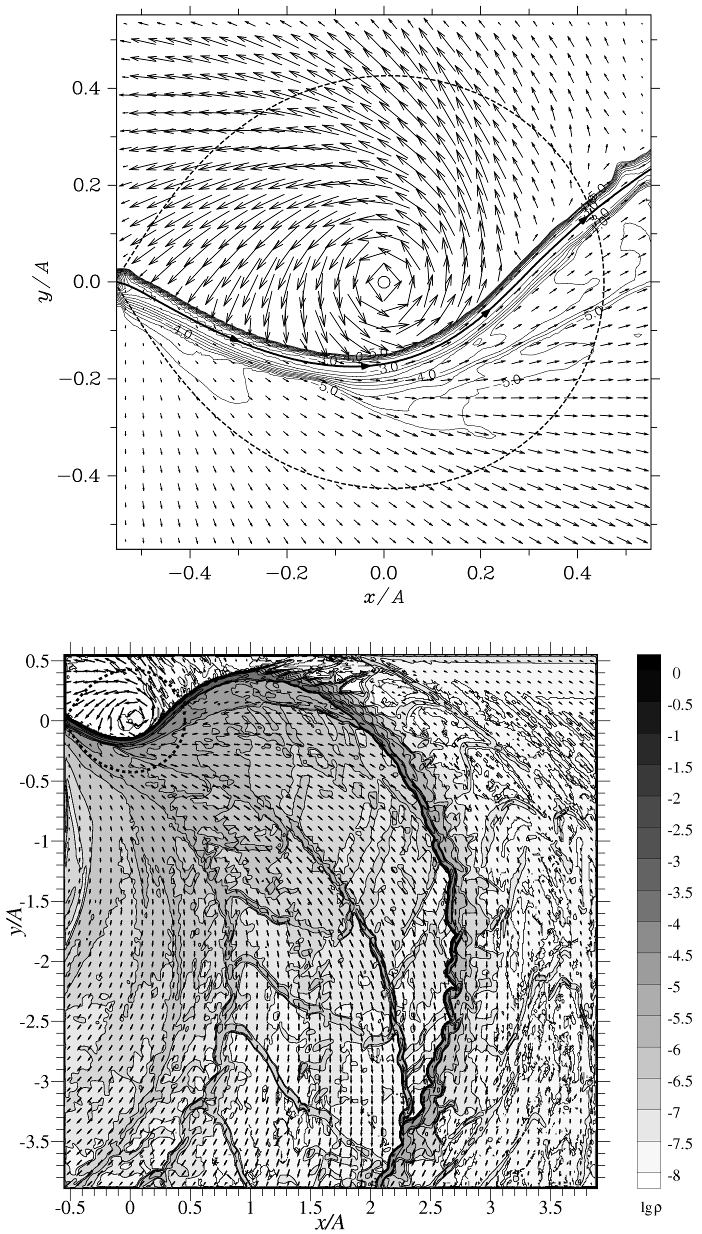

Fig. 2. Distributions of the density and velocity for the Model 5 ("superpropeller") in the different regions of the equatorial plane.

transfer in the binary star continues and the mass of the accretion disk grows with time. At a certain moment the density at the boundary of the cavity becomes so high that matter can push the magnetosphere in and be accreted on the surface of the star. When the exceeding mass has been released the system gets back to the "propeller" regime. The described mechanism can be considered as an explanation of the periodic dwarf novae outbursts observed in DQ Her systems.

Let us now consider a solution for the system in the "superpropeller" regime. In Fig. 2 we show density and velocity distributions in the equatorial (xy) plane of the system for the Model 5 that corresponds to intermediate polars of the AE Aqr type. In this "superpropeller" model we suppose that $P_{spin} = 0.001P_{orb}$. From the Fig. 2 one can see that the spin rotation of the accretor is so rapid that no disk is formed. The matter that flows from the donor's surface through the inner Lagrangian point L_1 is captured by the rapidly rotating magnetosphere, obtains additional angular momentum and is ejected from the Roche lobe. It is seen that the matter ejected from the Roche lobe of the accretor forms a long tail that flows around the system as a spiral. Further this matter forms a circumbinary envelope of the system. In the bottom panel of the Fig. 2 it is clearly seen that the Kelvin - Helmholtz instability develops along the spiral tail. One also can see several additional tails less powerful than the main spiral. It is interesting that some of them are connected by "bridges". The flow pattern we have obtained in the Model 5 is in good agreement with results of Wynn et al. (1997), and Ikhsanov et al. (2004) obtained using the method of quasi-particles. It also should be noted that analysis of Doppler maps of the AE Aqr system (Wynn et al., 1997; Ikhsanov et al., 2004) shows that the flow pattern in this system is indeed similar to the result we have obtained.

4. Conclusions

It is found that asynchronous rotation of the accreting star strongly influences the flow structure in magnetic close binary systems.

If the accreting star rotates slowly ($P_{spin} > 0.033P_{orb}$, "accretor" regime) the flow structure is not very different from the solution with the synchronous rotation.

If the rotation is rapid ($P_{spin} < 0.033P_{orb}$, "propeller" regime) a magnetospheric cavity forms close to the accretor and the accretion rates falls almost down to zero. Since the mass of the disk grows gradually and finally matter pushes the magnetic field in the cavity and gets accreted. It leads to a sharp jump of the accretion rate. In accordance with results of the simulations this mechanism can be an explanation of quasi-periodic dwarf nova outbursts observed in DQ Her type systems.

When the accretor rotates very rapidly ($P_{spin} \approx 0.001P_{orb}$) no accretion disk is formed. Matter is ejected from the magnetosphere and forms a tail that twists around the binary system as a spiral. Such a flow pattern is observed in AE Aqr type systems.

5. Discussion

ELENA PAVLENKO How does the expected light curve for a polar with several current sheets look like?

DMITRY BISIKALO The presence of current sheets in accretion disks of intermediate polars significantly change the thickness of the disk, so it could change the light curve of the system. We have not constructed synthetic light curves yet, but it is a good issue and I'll try to answer it soon.

ODED REGEV What is Re, Re_m in your simulations?

DMITRY BISIKALO The values of both Re and Re_m are rather high. They have different values in different regions of the disk but the mean value is above unity.

GIORA SHAVIV What is the boundary condition at the center?

DMITRY BISIKALO We use the free outflow condition at the surface of the white dwarf. In this case all the gas falling onto the accretor will be accepted by the star.

CHRISTIAN KNIGGE You showed that accretion rates depend on things like magnetic field. But since input mass transfer rate is fixed by donor, what happens to the excess of mass when the accretion rate is less than the mass transfer rate?

DMITRY BISIKALO This matter will leave system through the vicinity of the L_3 point and form a circumbinary envelope. This is a very interesting part of the flow structure containing a lot of details. Our simulations show that the circumbinary envelope can significantly change observational manifestations of the system (Sytov et al., 2007, 2009a, 2009b).

Acknowledgements. This work was supported by the Basic Research Program of the Presidium of the Russian Academy of Sciences, Russian Foundation for Basic Research (projects 09-02-00064, 11-02-00076), Federal Targeted Program "Science and Science Education for Innovation in Russia 2009-2013".

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