Part 8
Hydrodynamic Simulations of Exoplanets and Mass Transfer in Interacting Binaries

From Interacting Binaries to Exoplanets: Essential Modeling Tools
Proceedings IAU Symposium No. 282, 2011
Mercedes T. Richards & Ivan Hubeny, eds.

doi:10.1017/S1743921311028286

Flow Structure in Magnetic CVs

Dmitry V. Bisikalo* and Andrey G. Zhilkin

Institute of Astronomy of the Russian Acad. of Sci., 48 Pyatnitskaya str., Moscow, Russia
*email: bisikalo@inasan.ru

Abstract. We present a review of the modern concept of physical processes which go on in magnetic CVs with the mass transfer between the components. Using results of 3D MHD simulations, we investigated variations of the main characteristics of accretion disks depending on the value of the magnetic induction on the surface of the accreting star. In the frame of a self-consistent description of the MHD flow structure in close binaries, we formulate conditions of the disk formation and find a criterion that separates two types of flows corresponding to intermediate polars (intermediate magnetic field) and polars (strong field).

The influence of asynchronous rotation of the accretor on the flow structure in magnetic close binaries is also discussed. Simulations show that the accretion instability arising in binaries with rapid rotation of accretor ("propeller" regime) can explain the mechanism of quasi-periodic dwarf nova outbursts observed in DQ Her systems.

Keywords. binaries: close, MHD, accretion disks

1. Introduction

Magnetic cataclysmic variables (CVs) are close binary stars where the matter of the donor-star (low-mass late-type star) flows through the inner Lagrangian point L_1 onto a white dwarf (see e.g. Warner 2003). There are two main types of magnetic CVs, intermediate polars and polars. In polars (AM Her type), the white dwarf possesses a strong proper magnetic field ($\sim 10^7 - 10^8$ G on the surface). There are no accretion disks observed in such systems. The rotation of components in polars is synchronized. It is accepted that in polars the matter flowing from the donor-star forms a collimated stream that moves along the field lines onto one of the magnetic poles of the accretor (Campbell 1997; Warner 2003). Intermediate polars are binary systems with a relatively weak magnetic field ($\sim 10^4 - 10^6$ G on the accretor's surface). They occupy an intermediate stage between polars and non-magnetic cataclysmic variables. Intermediate polars demonstrate a great variety of orbital periods ranging from several hours to tens of hours. Proper rotations of accretors in such systems are, as a rule, much faster (ten to thousands times) than orbital rotations of the systems (Norton *et al.* 2004). The asynchronous rotation in intermediate polars is explained by the interaction of the dwarf's magnetic field with the matter of the accretion disk that takes place near the boundary of the magnetosphere (Campbell 1997; Warner 2003).

The first numerical studies of the influences of a magnetic field on the flow structure were made in the early 1990s. However, since the problem is very complicated, the investigations have been performed either in the frame of simplified models (King 1993; Wynn & King 1995; Wynn *et al.* 1997; King & Wynn 1999; Norton *et al.* 2004; Ikhsanov *et al.* 2004; Norton *et al.* 2008), or in a limited region of the stellar magnetosphere (Koldoba *et al.* 2002; Romanova *et al.* 2003, 2004a, 2004b). Only over the last few years, the authors have managed to develop a comprehensive 3D numerical model to calculate the flow structure in close binaries (Zhilkin & Bisikalo 2009, 2010a, 2010b, 2010c). In our approach, we use a complete system of MHD equations that allows one to describe all the main dynamic effects concerned with the magnetic field. In the numerical model, we take into account the following phenomena: radiative heating and cooling and diffusion of the magnetic field due to dissipation of currents in turbulent vortexes, magnetic buoyancy, and wave MHD turbulence. It is important to note that in the developed model the disk formation and evolution happen in a natural way due to the mass transfer through the inner Lagrangian point. Thus, we have pioneered a self-consistent description of the MHD flow structure in close binary systems that may be used to interpret observations.

2. Morphology of the flow pattern

Let us investigate how magnetic field influences the flow structure using as an example a close binary star with parameters of SS Cyg (see, e.g., Giovannelli *et al.* 1983). The donor-star (red dwarf) in this system has a mass $M_d = 0.56M_\odot$ and effective temperature of 4000 K. The mass of the accretor (white dwarf) is $M_a = 0.97M_\odot$ and the temperature is of 37000 K. The orbital period of the system is $P_{orb} = 6.6$; the separation is $A = 2.05R_\odot$. According to morphological properties, some scientists refer this star to the U Gem subtype. However, there are a number of features allowing one to consider this system as an intermediate polar with the value of magnetic field $B_a = 10^4 - 10^6$ G (Fabbiano *et al.* 1981; Kjurkchieva *et al.* 1999). For the first approach, we assume that the accretor's rotation is synchronous, i.e. $P_{spin} = P_{orb}$.

Fig. 1 (left panel) demonstrates the morphology of the flow pattern in the considered system. In this figure, one can see the distribution of the surface density (in units of $\rho(L_1)* A$) and velocity vectors in the equatorial plane of the system. Shock waves forming in the disk are seen in the figure as condensations of the density isolines. The condensations of the isolines near the edge of the disk correspond to the sharp drop of the gas density from the values common for the disk to the density of the circumbinary envelope gas. The tidal influence of the donor-star leads to occurrence of a spiral shock wave. This wave has two arms located in outer regions of the disk. One can see in the presented results that the interaction of the circumdisk halo and the stream from the L_1 point has all the features of an oblique collision of two flows. A structure consisting of two shocks and tangential discontinuity between them that occurs due to this collision has a complex shape. Outer regions of the circumdisk halo have low density and the shock caused by the interaction between them and stream is located along the edge of the stream. As the gas density increases, the shock curves and, finally, locates itself along the disk edge. The formed shock is rather extended and may be called a "hot line".

In inner regions of the disk which do not undergo gas dynamical perturbations, particle orbits demonstrate retrograde precession due to the gravitational influence of the donor star. Since flow lines cannot intersect each other in a gas dynamical disk, the equilibrium forms with time and all the flow lines start to move with the same angular velocity, i.e. the precession becomes of quasi solid-body type. Since the velocity of the precession depends on the specific size of the orbit, gas more distant from the accretor flow lines must be turned by a larger angle in the direction opposite to the motion of matter, since the precession is retrograde. The precession velocity is in a range between the velocities of the outer (fast) and inner (slow) orbits. Formation of spiral structures in accretion disks was considered in Lyubarskij *et al.* (1994), Ogilvie (2001), and Bisikalo *et al.* (2004). Analysis of the results of the 3D numerical simulations shown in Fig.1 (left panel) completely proves the hypothesis that a spiral density wave can form in inner regions of a cold accretion disk. The results of the calculations show that the wave has a low velocity in the observer's frame. In the non-inertial frame rotating with the binary, the period of its rotation is a little larger than the orbital one. We should note that the precession

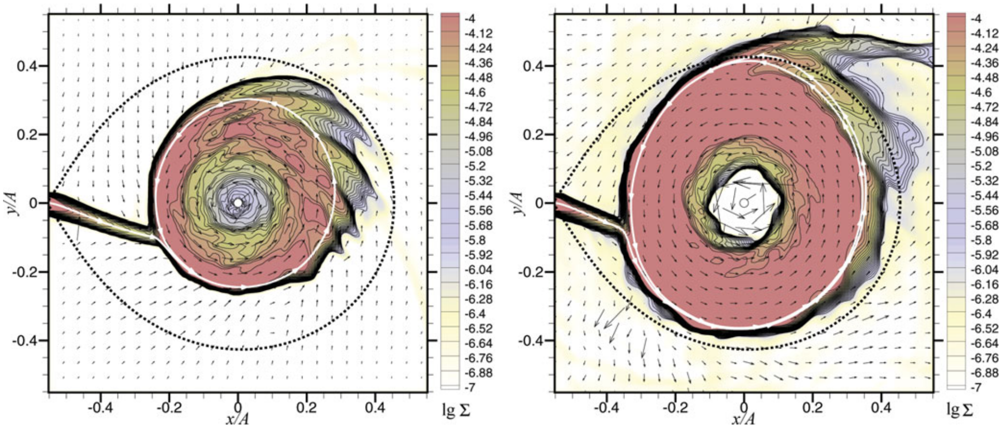

Figure 1. The surface density distribution and velocity vectors in the equatorial plane of the system with synchronous (Left panel) and asynchronous (Right panel) rotation. The flow lines edging the accretion disk are shown by white solid lines. The Roche lobes are depicted by the dashed line.

wave found in the simulations is a density wave. Nonetheless, its presence in the disk leads to significant redistribution of the angular momentum. The accretion rate caused by the increase of the radial flux behind the precessional wave grows approximately by an order of magnitude, compared to a solution with no wave. Despite the significant role of the magnetic field, all the main features of the flow structure found in the purely gas dynamic solution (see e.g. Bisikalo & Matsuda 2007) exist in the "magnetic" case. It may be explained in the way that formation of these structures is mainly due to gravitational effects.

Let us note the most essential differences of MHD solutions in comparison with HD case. The magnetosphere is formed near the accretor and the accretion goes on through the funnel flows. Besides, due to magnetic braking of rotation in the disk, the accretion rate approximately doubles in comparison with the purely HD case where it was about 20-30% from the mass transfer rate.

3. Changes in the flow structure with increasing of the magnetic field

To investigate how the value of the magnetic field influences the flow structure, we have performed calculations with various values of B_a in a range from 10^5 to 10^8 G (Zhilkin & Bisikalo 2010c). Let us consider seven models, with values of the magnetic induction equal to: 10^5 G (model 1), 5×10^5 G (model 2), 10^6 G (model 3), 5×10^6 G (model 4), 10^7 G (model 5), 5×10^7 G (model 6), and 10^8 G (model 7). These models can be divided into two groups. The first group contains models 1, 2 and 3 with relatively low magnetic fields and accretion disks formed. These models correspond to the case of intermediate polars. The second group consists of models 4, 5, 6 and 7 with strong fields. There are no disks formed in these models. They correspond to polars.

The 3D flow structure of intermediate polars (model 3) is shown in Fig. 2 (left panel). This figure demonstrates isosurfaces of the decimal logarithm of the density $log\rho = -4.5$ (in units of $\rho(L_1)$) and field lines which start from the surface of the accretor. In the case of $B_a = 10^5$ G (model 1), the flow pattern corresponds to that described in the previous section. If $B_a = 5 \times 10^5$ G (model 2), the outer radius of the accretion disk becomes much smaller (about $0.15A$). The efficiency of the magnetic braking and angular momentum transfer increases. The magnetosphere becomes larger. The accretion columns become more distinguishable near the magnetic poles of the accretor. Finally, in the case of $B_a = 10^6$ G (model 3, Fig. 2 left panel), the accretion disk almost disappears. The matter makes only 1-2 rounds before falling onto the accretor. To describe such a structure, the term "spiralo-disk" is appropriate, since the velocity in this structure is significantly non-Keplerian. The outer radius of this "spiralo-disk" is about $0.1A$. It is almost entirely in the region of the magnetosphere. A significant portion of this disk includes the accretion columns. We can conclude that this variant is the ultimate case of intermediate polars. It is necessary to note that the numerically calculated size of the magnetosphere is well correspondent with that estimated analytically.

Fig. 2 (right panel) demonstrates isosurfaces of the decimal logarithm of the density $log\rho = -5$ (in units of $\rho(L_1)$) and field lines for the model 5. In models 4-7, we observe no disk formed and the flow structure is the funnel flow. In model 7, the magnetic field is so strong that it controls the flow structure over the entire Roche lobe of the accretor. Matter is captured by the magnetic field very close to the inner Lagrangian point. It starts to move along the field line toward the magnetic poles of the star forming a powerful southern stream and a weaker northern stream. In this case, the magnetosphere is larger than the Roche lobe of the accretor and partially penetrates into the envelope of the donor.

Thus, in our simulations of the flow structure in a close binary system whose parameters correspond to those of SS Cyg, in models where the value of magnetic field $B_a \leqslant 10^6$ G, we observe accretion disks formed. If the field is stronger, no disks are formed. To explain this result, we propose the following simple ideas. The matter motion in the stream issuing from the inner Lagrangian point is supersonic, therefore, the stream can be investigated in a ballistic approach with no pressure and magnetic field taken into account (Boyarchuk *et al.* 2002; Fridman & Bisikalo 2008). The analysis of the trajectories (Lubow & Shu 1975) shows that the stream approaches close to the surface of the accretor at a minimal distance $R_{min} = 0.0488\, q^{-0.464} A$. If R_{min} is larger than the radius of the magnetosphere $r_m = [(B_a^4 \times R_a^{12})/(8 \times G \times M_a \times \dot{M}_a^2)]^{(1/7)}$, the magnetic field will have no strong influence on the matter motion. If R_{min} is smaller than the radius of the magnetosphere, then in a certain region of its trajectory the stream will be strongly influenced by the magnetic field. Electromagnetic forces acting in this zone brake the stream and make it lose its angular momentum. As a result, the stream will not be able to round the star and form an accretion disk. So a "boundary" between intermediate polars (with accretion disks) and polars (without disks) is determined by the expression $r_m = R_{min}$. If we use parameters of SS Cyg to calculate R_{min}, we obtain a corresponding value of the magnetic field $B_a \approx 10^6$ G that separates these two regimes. However, this estimate of the "boundary" induction of the magnetic field separating cases of intermediate polar and polars is rather common, since in cataclysmic variables q varies only a little and is equal approximately to 0.5.

Let us consider the accretion rate $\dot{M}_a$ as a function of the magnetic field induction B_a on the surface of the accretor. The main feature of this function is that it is non-monotonic. For $B_a < 10^6$ G, the accretion rate grows when the magnetic field grows; while the amplitude of the variations decreases. At the point $B_a = 10^6$ G, the maximal value of the accretion rate is achieved. If the magnetic field induction continues to grow, the accretion rate decreases. This dependence is completely correspondent to the ideas we described above. If $B_a < 10^6$ G, an accretion disk forms and the accretion rate is determined by processes of the angular momentum transfer in the disk. An increase in the magnetic field leads to increasing efficiency of the magnetic braking in the disk. Thus, while $B_a < 10^6$ G, the function $\dot{M}_a(B_a)$ grows. When the value of the magnetic field is above $B_a = 10^6$ G, no disk is formed and a funnel flow takes place. In this case, the

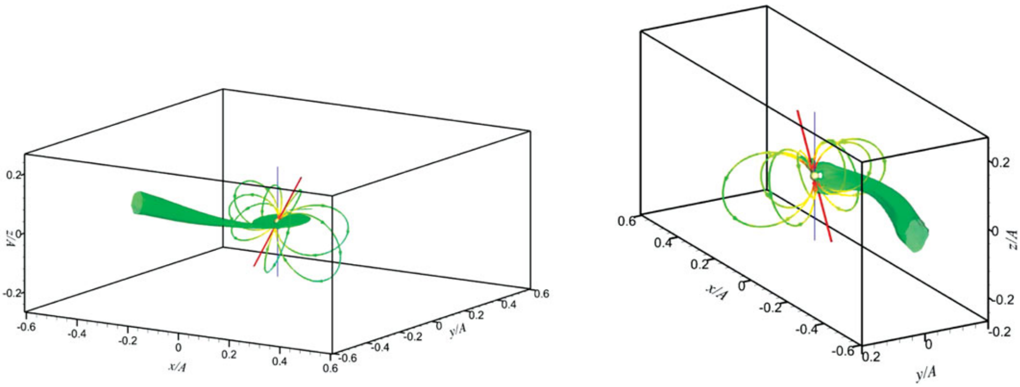

Figure 2. The isosurfaces of the decimal logarithm of the density and field lines which start from the surface of the accretor for the model 3 (Left panel, $lg\rho = -4.5$ in units of $\rho(L_1)$) and for the model 5 (Right panel, $lg\rho = -5.0$ in units of $\rho(L_1)$). The rotation (straight thin line) and magnetic (bold tilted line) axes of the accretor are also shown.

accretion rate is determined by the throughput capacity of the stream. If the magnetic field induction grows, the cross-section of the stream decreases and the accretion rate decreases as well.

4. Asynchronous rotation of the accretor

The influence of the proper rotation velocity of the accretor on the MHD flow structure may be specified by the ratio between the magnetosphere radius r_m and corotation radius r_c. The corotation radius is the distance where the rotation velocity of the magnetic lines coincides with the velocity of matter motion in the accretion disk. If we assume the rotation of the magnetic lines to be of solid-body type with the angular velocity Ω_* and the angular velocity of matter to be ω_K, then (according to Lipunov 1987): $r_c = (G \times M_a/\Omega_*^2)^{1/3}$.

If the accretor rotates slowly ($r_c > r_m$), the velocity of the magnetic field rotation on the boundary of the magnetosphere is lower than the Keplerian one. Thus, matter can freely fall onto the surface being captured by the field lines. This regime may be called a regime of "accretor". If the rotation of the accretor is fast ($r_c < r_m$), a centrifugal barrier occurs on the boundary of the magnetosphere that prevents matter from falling onto the surface. This regime is known as the "propeller regime". In this regime, the accretion process is very non-stationary (Romanova *et al.* 2004b, 2005; Ustyugova *et al.* 2006). In the equilibrium rotation, the condition $r_c = r_m$ is satisfied. Analysis shows (Lipunov 1987) that the interaction of the disk and magnetosphere makes the system evolve toward the equilibrium rotation.

To investigate how the asynchronous rotation of the accretor influences the flow structure in the magnetic close binary, we have performed 3D numerical simulations with different ratios P_{spin}/P_{orb}. In Fig. 1 (right panel), we show distributions of the density and velocity in the equatorial plane for models "propeller" by the moment when the stationary flow regime has been achieved (in about 17 orbital periods). In the "accretor" model, the flow structure is similar to the structure observed in the case of synchronous rotation (see Fig. 1, left panel). The rotation of the accretor leads to a more powerful tail of the matter outflowing through the L_3 point. However, in the "propeller" model, the flow structure has significant differences. The accretion disk is larger. A flow line issuing

https://doi.org/10.1017/S1743921311028286 Published online by Cambridge University Press

from the L_1 point at a certain region even crosses the Roche lobe boundary. A powerful tail of the matter ejected to the outer envelope of the system through the L_3 point is well seen. A magnetospheric cavity with a radius of $0.05 - 0.1A$ is formed in inner regions of the disk. The Kelvin-Helmholtz instability develops on the boundary of this cavity. Spiral waves that occur due to this process tend to turn into shock waves. The matter from the circumbinary envelope is accreted mainly not onto the star but onto the disk.

Since there is almost no matter in the magnetospheric cavity, the rate of accretion onto the star in the "propeller" model is almost zero. On the other hand, the mass transfer goes on and the mass of the disk will grow with time. At a certain moment, the density on the boundary of the cavity can increase so much that matter can break through the magnetosphere and be accreted onto the surface. When the excess mass is released, the system comes back into the "propeller" state. The described mechanism can probably explain quasi-periodic dwarf nova outbursts observed in DQ Her stars. It is notable, that the SS Cygni system demonstrates outbursts approximately every 200 orbital periods. The amplitude of the outbursts reaches 4.5^m. If one assumes that most of the flux from the system is due to accretion, then the increase of the system brightness observed during outbursts corresponds to the increase of the accretion rate by about 60 times. The flow structure in SS Cyg during an outburst was investigated in Kononov et al. (2008) using observed spectra and Doppler tomograms.

In the "superpropeller" model (AE Aqr systems), very rapid rotation of the accretor prevents the disk from formation. The matter issuing from the L_1 point is captured by the magnetosphere, acquires additional angular momentum, and is ejected from the Roche lobe. It leads to formation of a long tail twisting around the system and forming its common envelope.

5. Conclusions

The main results of the work may be summarized as follows.

1. It is found that in models with a relatively weak magnetic field, $B_a \leqslant 10^6$ G, an accretion disk is formed in the system. The disk has all the specific features: "hot line" shock, tidal spiral shocks, precessional wave etc. When B_a grows, the disk radius becomes smaller and the size of the magnetosphere increases. These types of flow correspond to intermediate polars.

In models where $B_a > 10^6$ G, no accretion disk is formed. The flow is a funnel flow starting from the L_1 point and ending on the magnetic poles of the accretor. These types of flow, in accordance with morphology, correspond to polars.

A value $B_a = 10^6$ G that separates two types of flows is determined by the ratio of R_{min}, a minimal distance at which the stream approaches the accretor, and r_m a radius of the magnetosphere. An accretion disk is formed when $R_{min} > r_m$. Otherwise, the stream undergoes strong influence of the magnetic field and no disk is formed. This estimate of the magnetic field induction is rather common, since it is not strongly dependent on the parameters of a system.

2. The flow structure in magnetic close binaries is strongly influenced by asynchronous rotation of the accretor. If the rotation is slow ($P_{spin} > 0.033 P_{orb}$, "accretor" regime), the structure is similar to that formed when the rotation is synchronous.

If the rotation is rapid ($P_{spin} < 0.033 P_{orb}$, "propeller" regime), a magnetosphere cavity is formed near the accretor and the accretion rate falls down to almost zero. Subsequent growth of the mass of the disk leads to a break of matter through the magnetosphere and sharp jump in the accretion rate. In accordance with the results of the simulations, this mechanism can be used to explain quasi-periodic dwarf nova outbursts observed in DQ Her systems.

If the accretor rotates very rapidly ($P_{spin} \approx 0.001 P_{orb}$), no accretion disk in the system is formed. The matter is pushed by the rapidly rotating magnetosphere ejected from the accretor's Roche lobe and forms a tail spiraling around the system. This type of flow ("superpropeller") is observed in AE Aqr systems.

Acknowledgements

This work has been supported by the Basic Research Program of the Presidium of the Russian Academy of Sciences, Russian Foundation for Basic Research (projects 09-02-00064, 09-02-00993, 11-02-00076, 11-02-01248), Federal Targeted Program "Science and Science Education for Innovation in Russia 2009-2013".

References

Bisikalo, D. V., Boyarchuk, A. A., Kaigorodov P. V., Kuznetsov, O. A., & Matsuda T. 2004, *Astron. Rep.*, 48, 449

Bisikalo, D. V. & Matsuda, T. 2007, W. I. Hartkopf, E. F. Guinan & P. Harmanec (eds.), *Proceedings of IAU Symposium 240 Binary Stars as Critical Tools & Tests in Contemporary Astrophysics* (Cambridge: Cambridge University Press), p. 356

Boyarchuk, A. A., Bisikalo, D. V., Kuznetsov, O. A., & Chechetkin, V. M. 2002, *Mass transfer in close binary stars*, Taylor and Francis, London

Campbell, C. G. 1997, *Magnetohydrodynamics in binary stars* Dordrecht: Kluwer Acad. Publishers

Fridman, A. M. & Bisikalo, D. V. 2008, *Phys. Usp.*, 51, 551

Fabbiano, G., Hartmann, L., Raymond, J., Branduardi-Raymont, G., Matilsky, T., & Steiner, J. 1981, *ApJ*, 243, 911

Giovannelli, F., Gaudenzi, S., Rossi, C., & Piccioni, A. 1983, *AcA*, 33, 319

Ikhsanov, N. R., Neustroev, V. V., & Beskrovnaya, N. G. 2004, *A&A*, 421, 1131

King, A. R. 1993, *MNRAS*, 261, 144

King, A. R. & Wynn, G. A. 1999, *MNRAS*, 310, 203

Kjurkchieva, D., Marchev, D., & Ogloza, W. 1999, *Ap&SS*, 262, 53

Koldoba, A. V., Romanova, M. M., Ustyugova, G. V., & Lovelace, R. V. E.. 2002, *ApJ*, 576, L53

Kononov, D. A., Kaigorodov, P. V., Bisikalo, D. V., Boyarchuk, A. A., Agafonov, M. I., Sharova, O. I., Sytov, A. Y.u., & Boneva, D. 2008, *Astron. Rep.*, 52, 835

Lipunov, V. M. 1992, *Astrophysics of Neutron Stars* Heidelberg: Springer

Lubow, S. H. & Shu, F. H. 1975, *ApJ*, 198, 383

Lyubarskij, Yu.E., Postnov, K. A., & Prokhorov, M. E. 1994, *MNRAS*, 266, 583

Norton, A. J., Wynn, J. A., & Somerscales, R. V. 2004, *ApJ*, 614, 349

Norton, A. J., Butters, O. W., Parker, T. L., & Wynn, G. A. 2008, *ApJ*, 672, 524

Ogilvie, G. I. 2001, *MNRAS*, 325, 231

Romanova, M. M., Ustyugova, G. V., Koldoba, A. V., Wick, J. V., & Lovelace, R. V. E.. 2003, *ApJ*, 595, 1009

Romanova, M. M., Ustyugova, G. V., Koldoba, A. V., & Lovelace, R. V. E. 2004a, *ApJ*, 610, 920

Romanova, M. M., Ustyugova, G. V., Koldoba, A. V., & Lovelace, R. V. E. 2004b, *ApJ*, 616, L151

Romanova, M. M., Ustyugova, G. V., Koldoba, A. V., & Lovelace, R. V. E. 2005, *ApJ*, 635, L165

Ustyugova, G. V., Koldoba, A. V., Romanova, M. M., & Lovelace, R. V. E. 2006, *ApJ*, 646, 304

Warner, B. 2003, *Cataclysmic Variable Stars* Cambridge: Cambridge Univ. Press

Wynn, G. A. & King, A. R. 1995, *MNRAS*, 275, 9

Wynn, G. A., King, A. R., & Horne, K. 1997, *MNRAS*, 286, 436

https://doi.org/10.1017/S1743921311028286 Published online by Cambridge University Press

Zhilkin A. G. & Bisikalo, D. V. 2009, *Astron. Rep.*, 53, 436
Zhilkin A. G. & Bisikalo, D. V. 2010a, *Advances in Space Research*, 45, 437
Zhilkin A. G. & Bisikalo, D. V. 2010b, *Astron. Rep.*, 54, 840
Zhilkin A. G. & Bisikalo, D. V. 2010c, *Astron. Rep.*, 54, 1063

Discussion

W. Kley: To calculate the light curve (e.g., OY Car), you need the surface temperature. How is this determined in your model?

D. Bisikalo: In our gas dynamic model, the radiative heating and cooling processes are taken into account in an approximate manner. We just add the heating and cooling terms in the energy equation. Parameters of these terms are chosen for the equilibrium temperature to correspond to the observed temperature ($T \sim 10^4$ K). However, relative temperature variations over the disk (e.g. due to shock waves) are calculated in an accurate manner. So, the shape of the synthetic light curve takes into account all the features of the solution and may be used to interpret observations.

V. Trimble: What would count as an exotic mechanism in this context?

D. Bisikalo: I have talked about models which are used to analyze light curves but they do not take into account results of numerical simulations of gas dynamics of the matter in the close binary. I call them exotic since, as a rule, they even do not take into account well known facts of classical physics.

R. Wilson: I have a simple question about terminology. All mentions of “precessional” spiral waves on your slides have “precessional” in quotes, so apparently you do not really mean precession. Of course, precession involves two planes that slide around in a conical motion (of their normals), as in the precession of a gyroscope, but here there is only one plane. Would it be fair to call the phenomenon rotational or rotating waves? Or perhaps another name as a replacement for “precession”? Often, we see a similar usage of “precession” for the periastron motion of planet Mercury and other orbiting bodies, which of course is not precession.

D. Bisikalo: You are absolutely right. Indeed, the motion of the wave, I talked about, is the counter-clockwise rotation of the apsidal lines of the elliptic flow lines. Their apastrons form the wave. I agree that the term “rotating density wave” is more appropriate.

P. Harmanec: It is interesting to note that what you called “a pre-eclipse” dip in the light curves of cataclysmic variables, i.e. another light minimum seem near phase 0.75 (counted from the primary minimum), is also observed in the light curves of some Be binaries. For the examples, see Harmanec and Křiž (1976, in IAU Symp. 70 on Be and Shell Stars, ed. A. Slettebak), and maybe R Arae shown in the poster here might be another example. Our qualitative explanation at that time was basically the same as what your hydrodynamic solution shows.

D. Bisikalo: Great! This is one more example of how one can formulate an adequate conceptual model using the main physical facts in a proper way. It is evident that if one uses more sophisticated gas dynamical calculations, he will only prove (or improve) this model.