Accretion disks and envelopes in close binary stars

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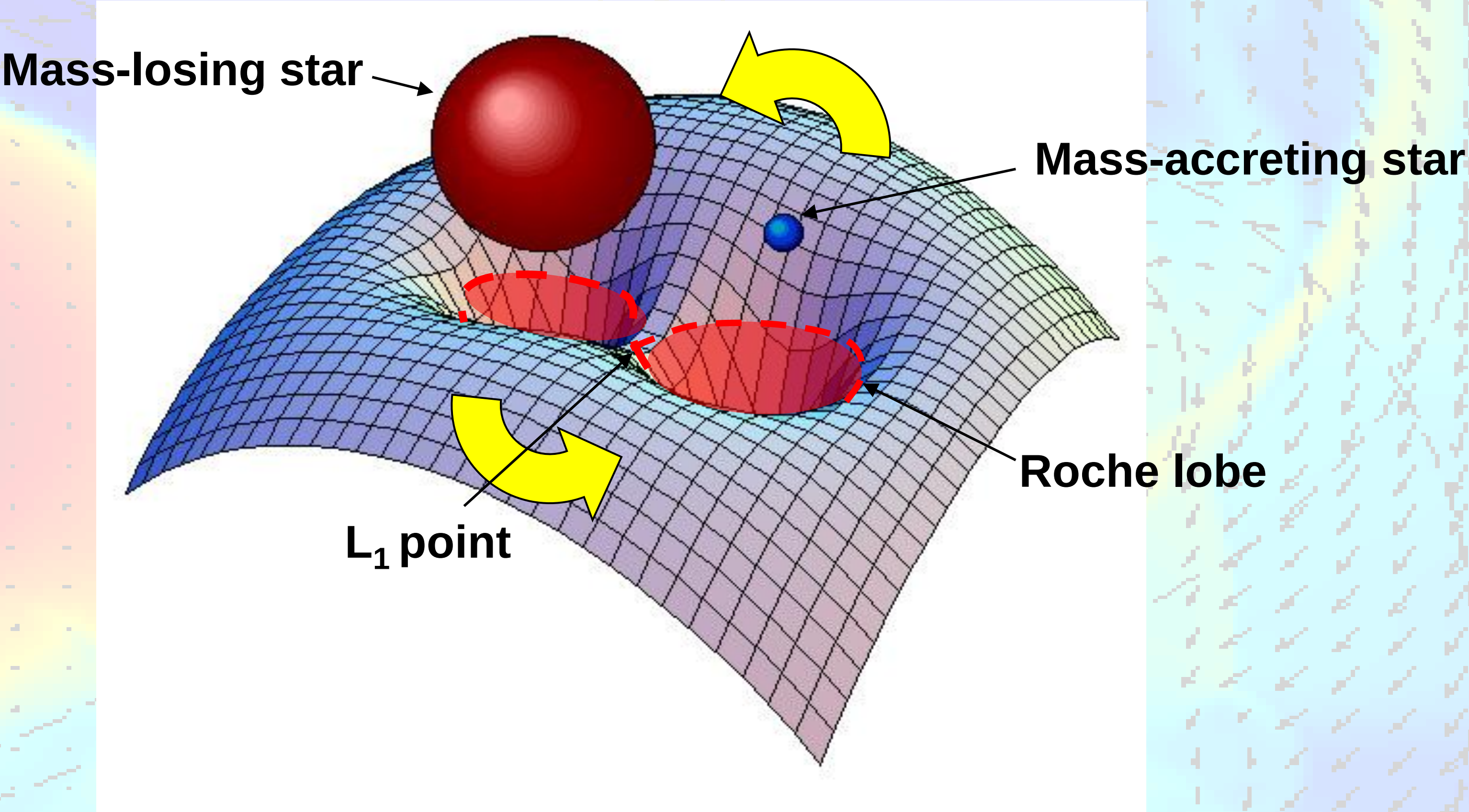
Introductory remarks

$$\Phi_R(\boldsymbol{r}) = -\frac{GM_1}{|\boldsymbol{r}-\boldsymbol{r}_1|} - \frac{GM_2}{|\boldsymbol{r}-\boldsymbol{r}_2|} - \frac{1}{2}(\boldsymbol{\omega}\times\boldsymbol{r})^2$$

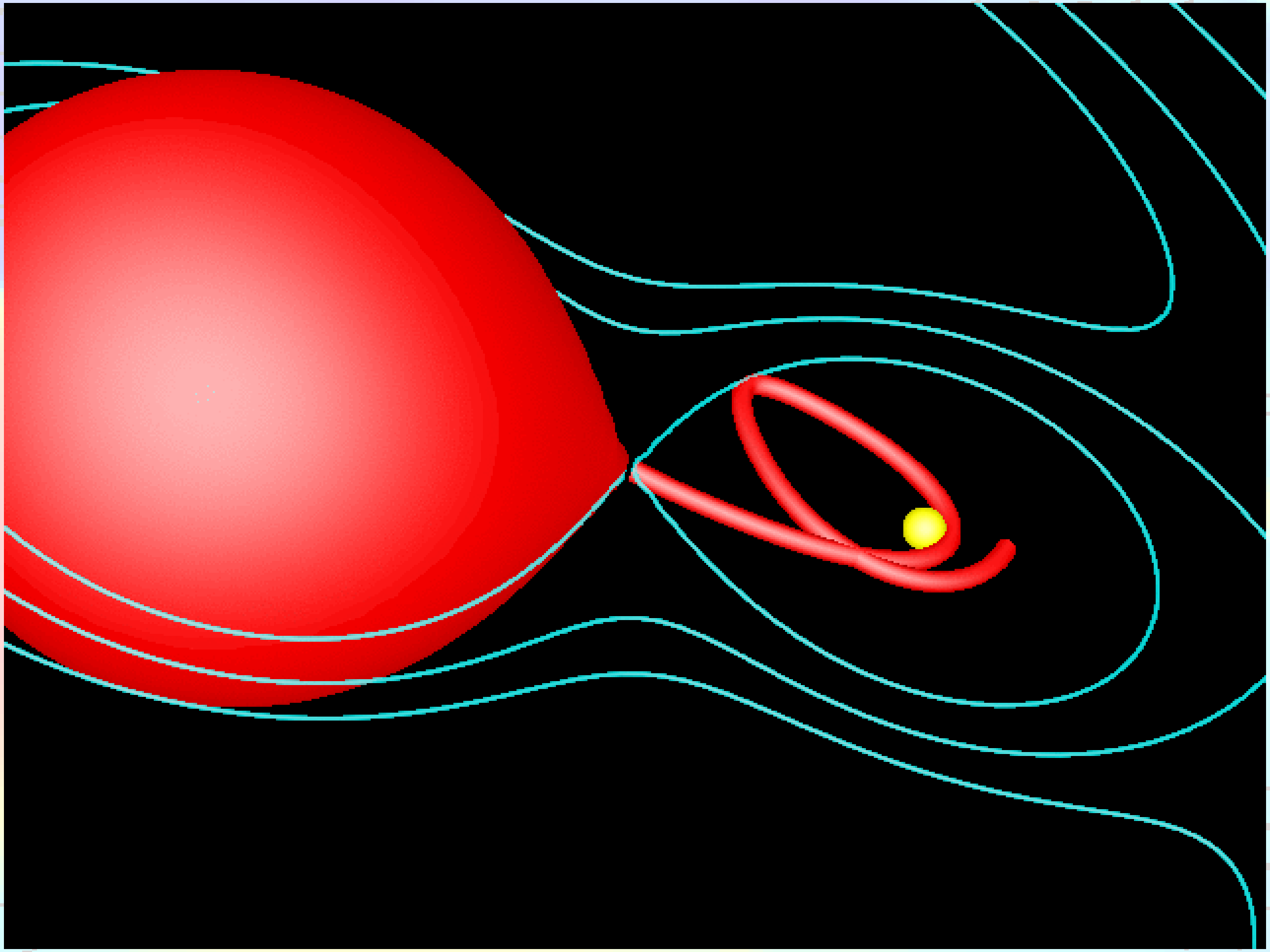


Mass-losing star

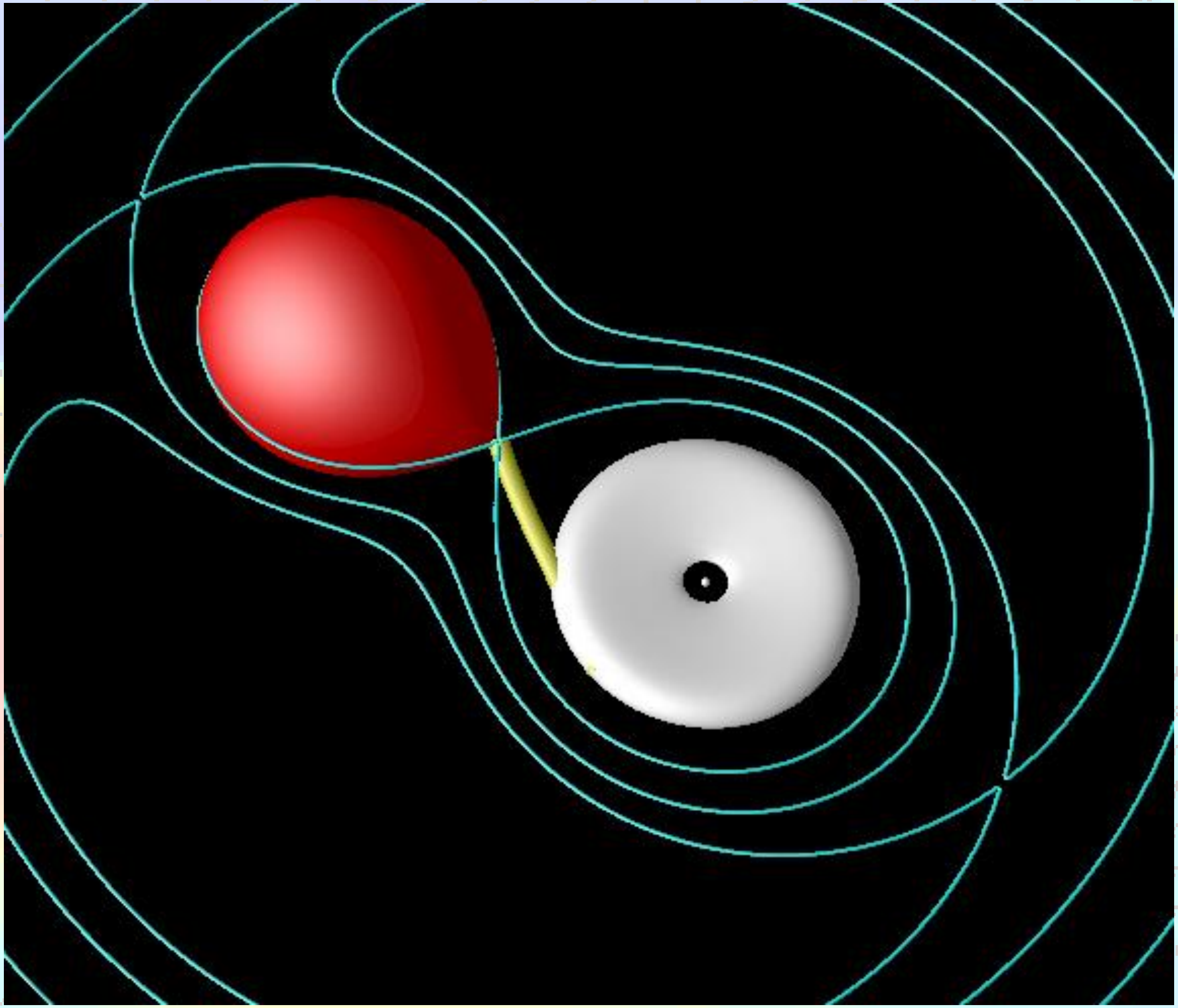
Mass-accreting star

Roche lobe

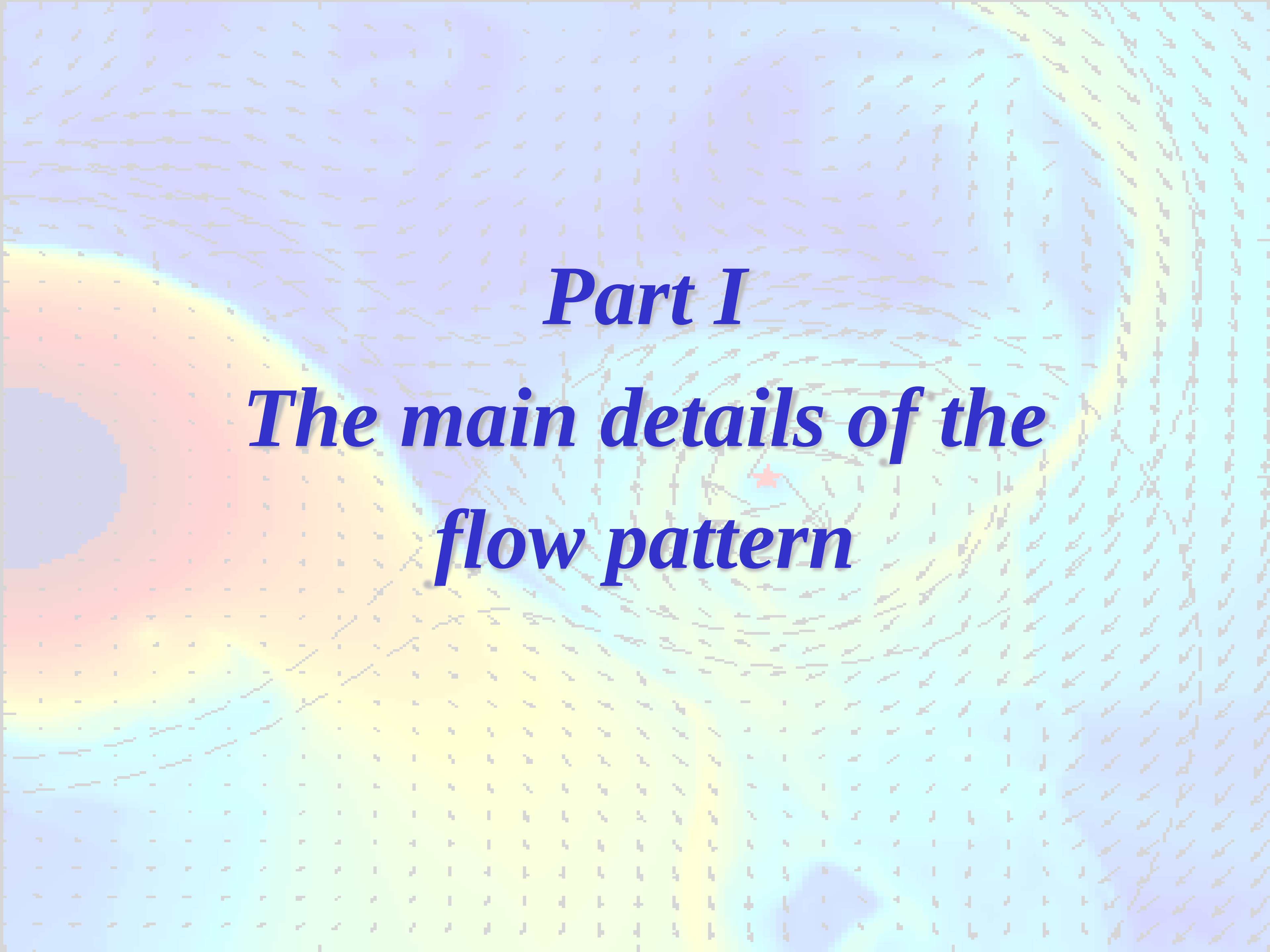
L_1 point



The situation will change drastically if the size of the accretor is small (WD, NS, BH). In this case the gas of the stream will revolve around the gravitational center and form a dense ring.

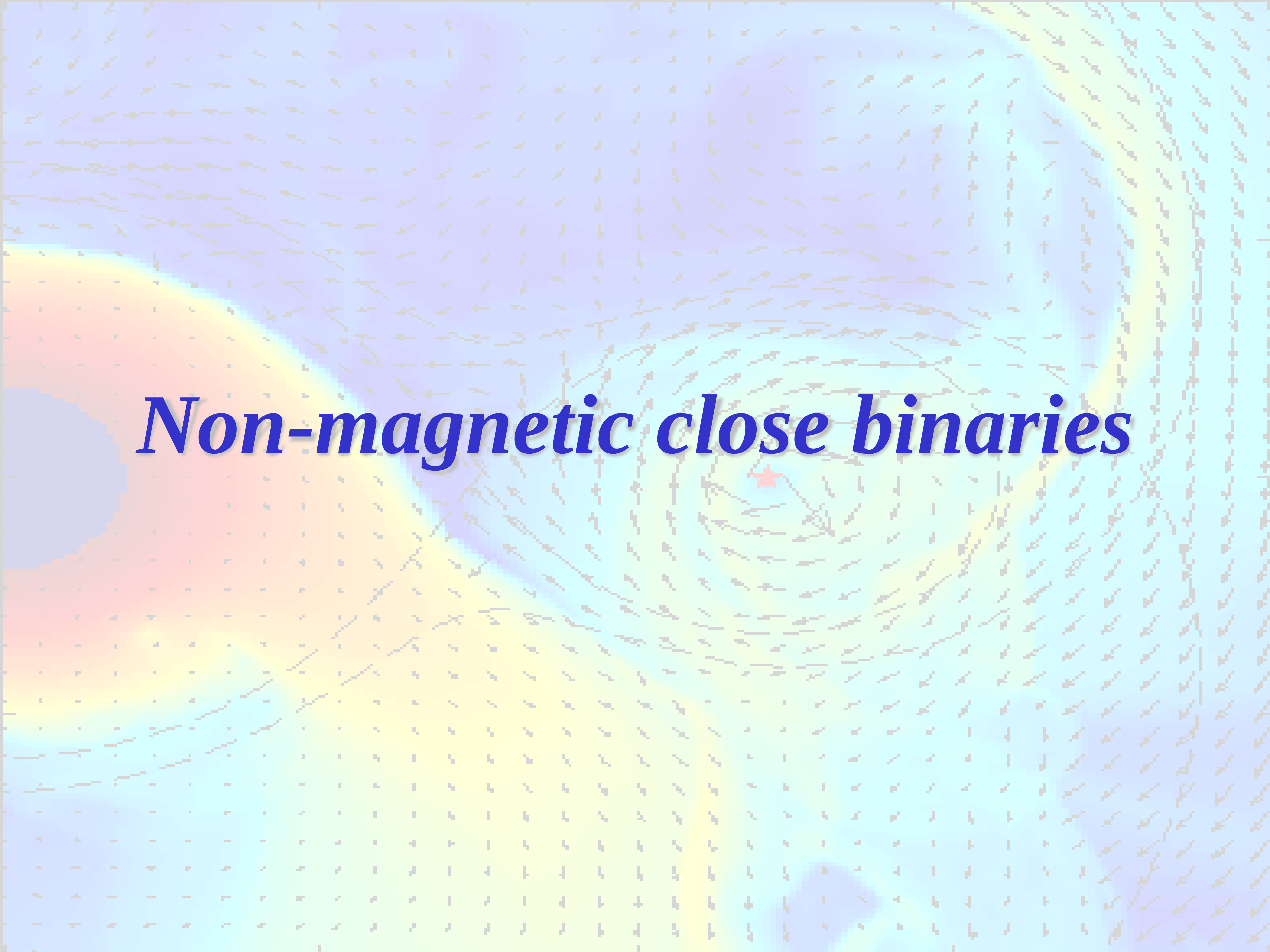


Under action of dissipation processes this ring will expand and form an accretion disc. Further redistribution of the angular momentum in the disc leads to gas accretion.



Part I

The main details of the flow pattern



Non-magnetic close binaries

3D gas dynamic equations

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}+\frac{\partial \rho w}{\partial z}=0$$

Momentum equation:

$$\frac{\partial \rho u}{\partial t}+\frac{\partial (\rho u^2+P)}{\partial x}+\frac{\partial \rho uv}{\partial y}+\frac{\partial \rho uw}{\partial z}=-\rho\frac{\partial \Phi}{\partial x}+2\Omega v\rho$$

$$\frac{\partial \rho v}{\partial t}+\frac{\partial \rho uv}{\partial x}+\frac{\partial (\rho v^2+P)}{\partial y}+\frac{\partial \rho vw}{\partial z}=-\rho\frac{\partial \Phi}{\partial y}-2\Omega u\rho$$

$$\frac{\partial \rho w}{\partial t}+\frac{\partial \rho uw}{\partial x}+\frac{\partial \rho vw}{\partial y}+\frac{\partial (\rho w^2+P)}{\partial z}=-\rho\frac{\partial \Phi}{\partial z}$$

Energy equation:

$$\frac{\partial \rho E}{\partial t}+\frac{\partial \rho uh}{\partial x}+\frac{\partial \rho vh}{\partial y}+\frac{\partial \rho wh}{\partial z}=-\rho u\frac{\partial \Phi}{\partial x}-\rho v\frac{\partial \Phi}{\partial y}-\rho w\frac{\partial \Phi}{\partial z}$$

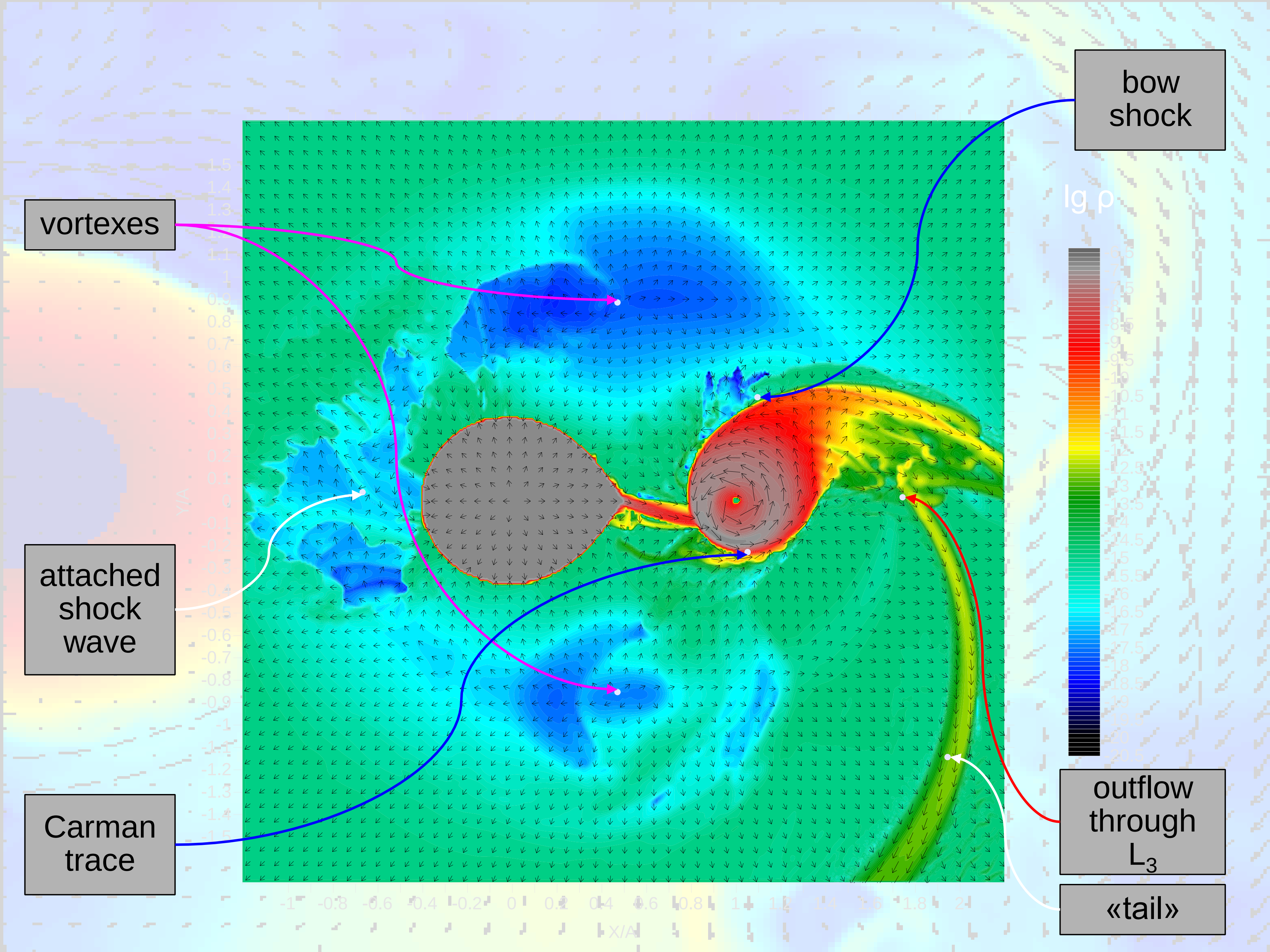
Equation of state:

$$P=(\gamma-1)\rho\varepsilon$$

Roche potential:

$$\Phi(\mathbf{r})=-\frac{GM_1}{\sqrt{x^2+y^2+z^2}}-\frac{GM_2}{\sqrt{(x-A)^2+y^2+z^2}}-\tfrac{1}{2}\Omega^2\left((x-A\frac{M_2}{M_1+M_2})^2+y^2\right)$$

Binary system in corotational frame



vortexes

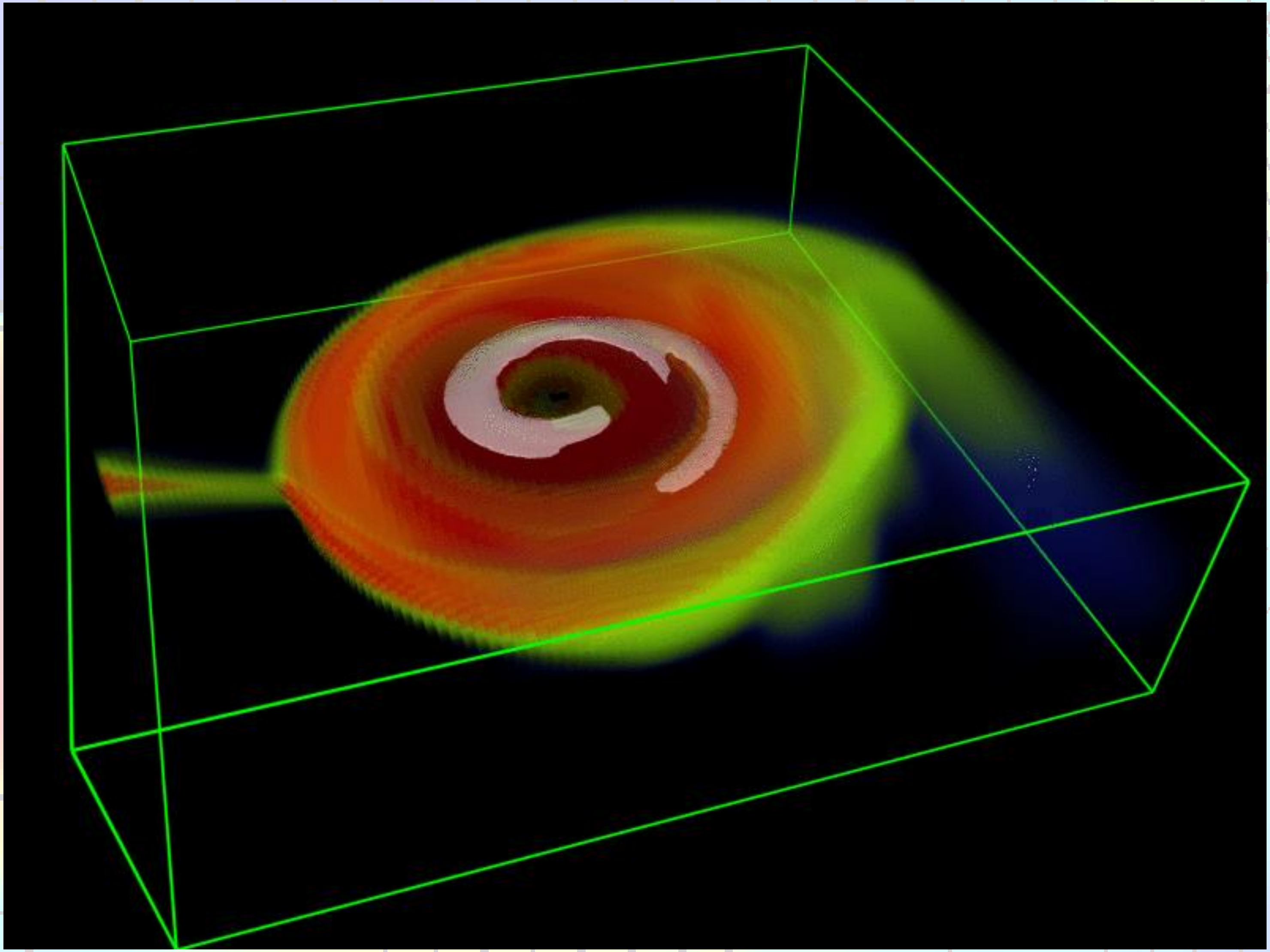
bow shock

attached shock wave

Carman trace

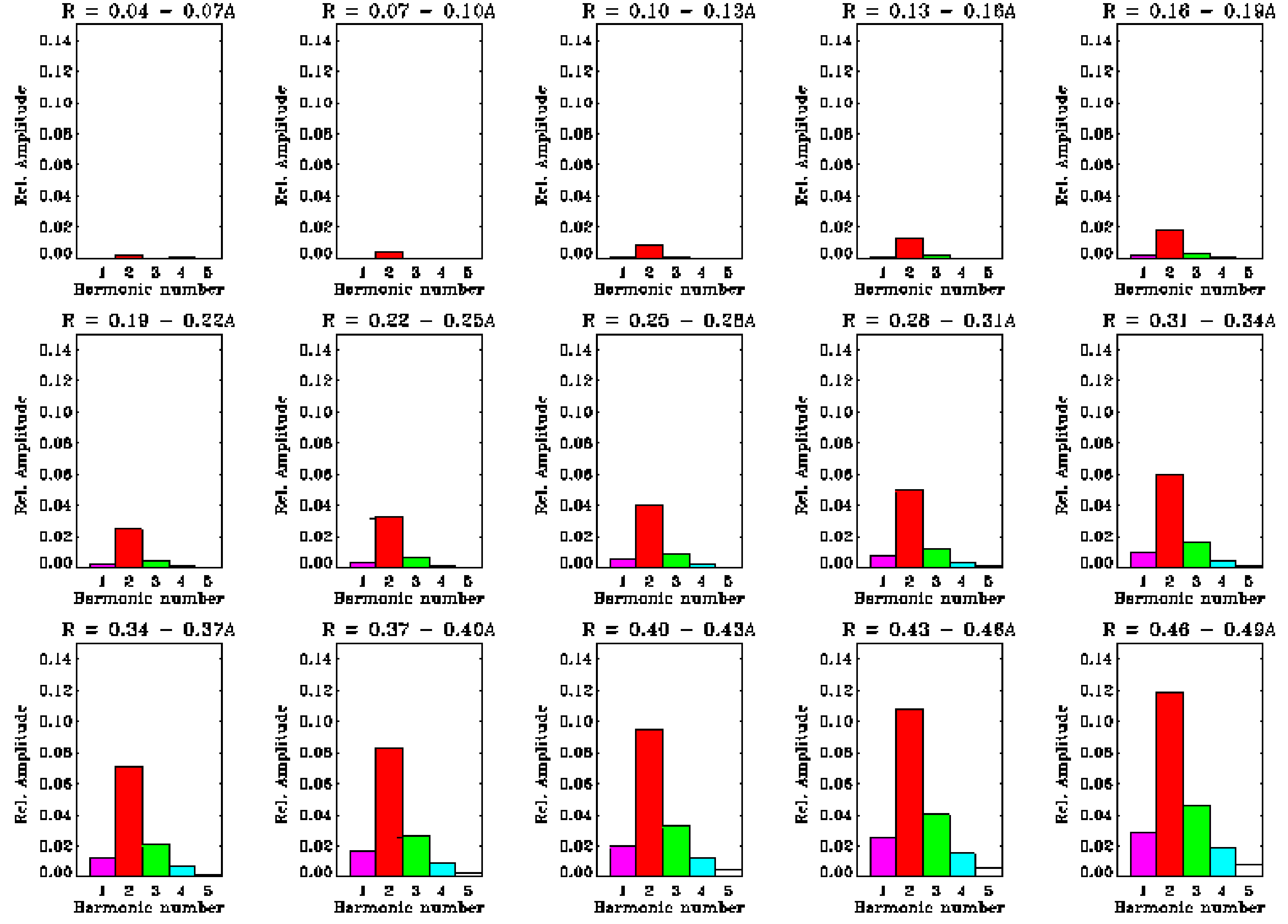
outflow through L_3

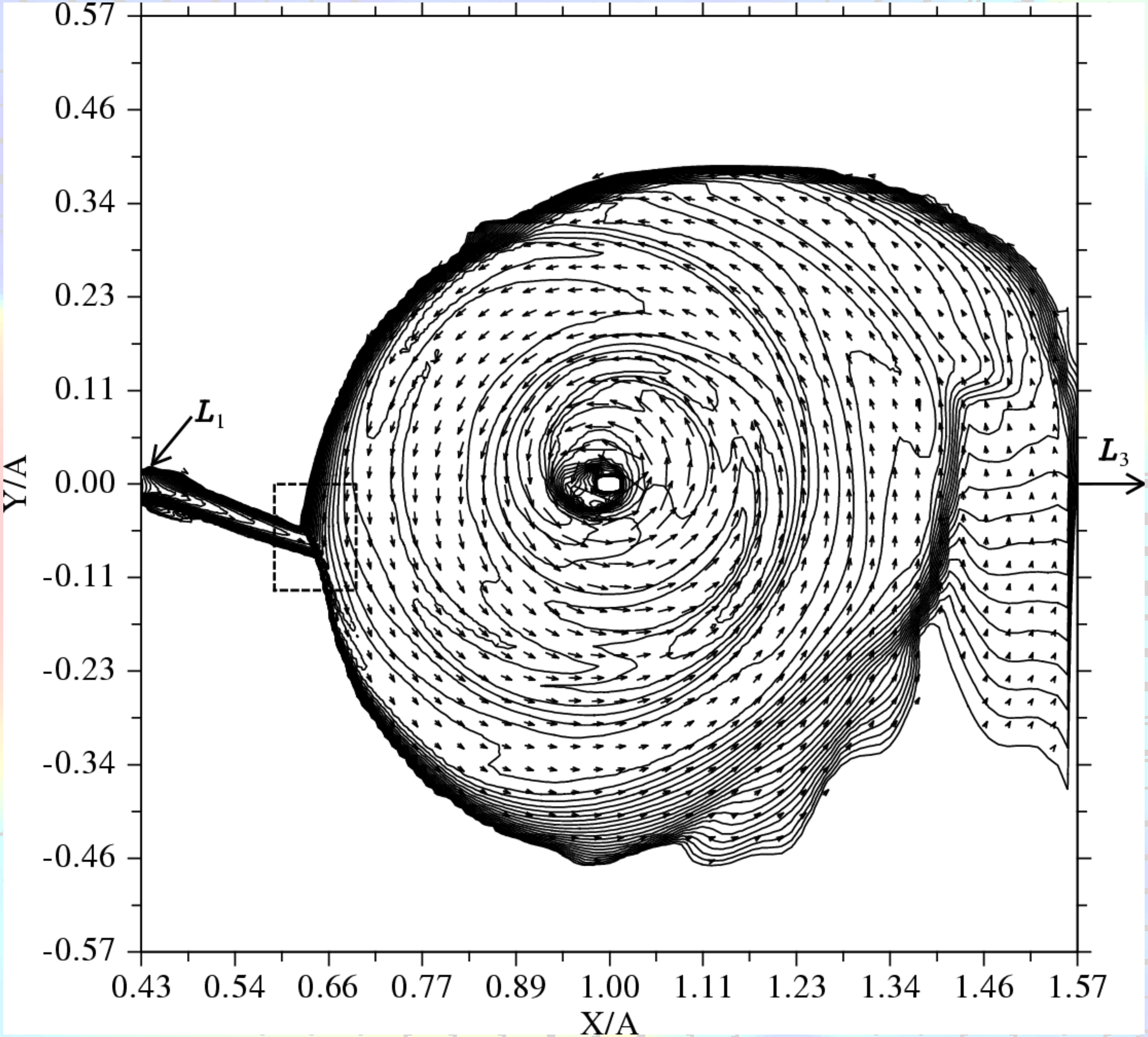
«tail»



Analysis of the results allows us to reveal some features of the flow structure. The matter of the stream splits into three parts.

Amplitudes of Fourier harmonics of the non-axisymmetric part of the Roche potential




0.57
0.46
0.34
0.23
0.11
0.00
-0.11
-0.23
-0.34
-0.46
-0.57
Y/A
L_1
L_3
0.43
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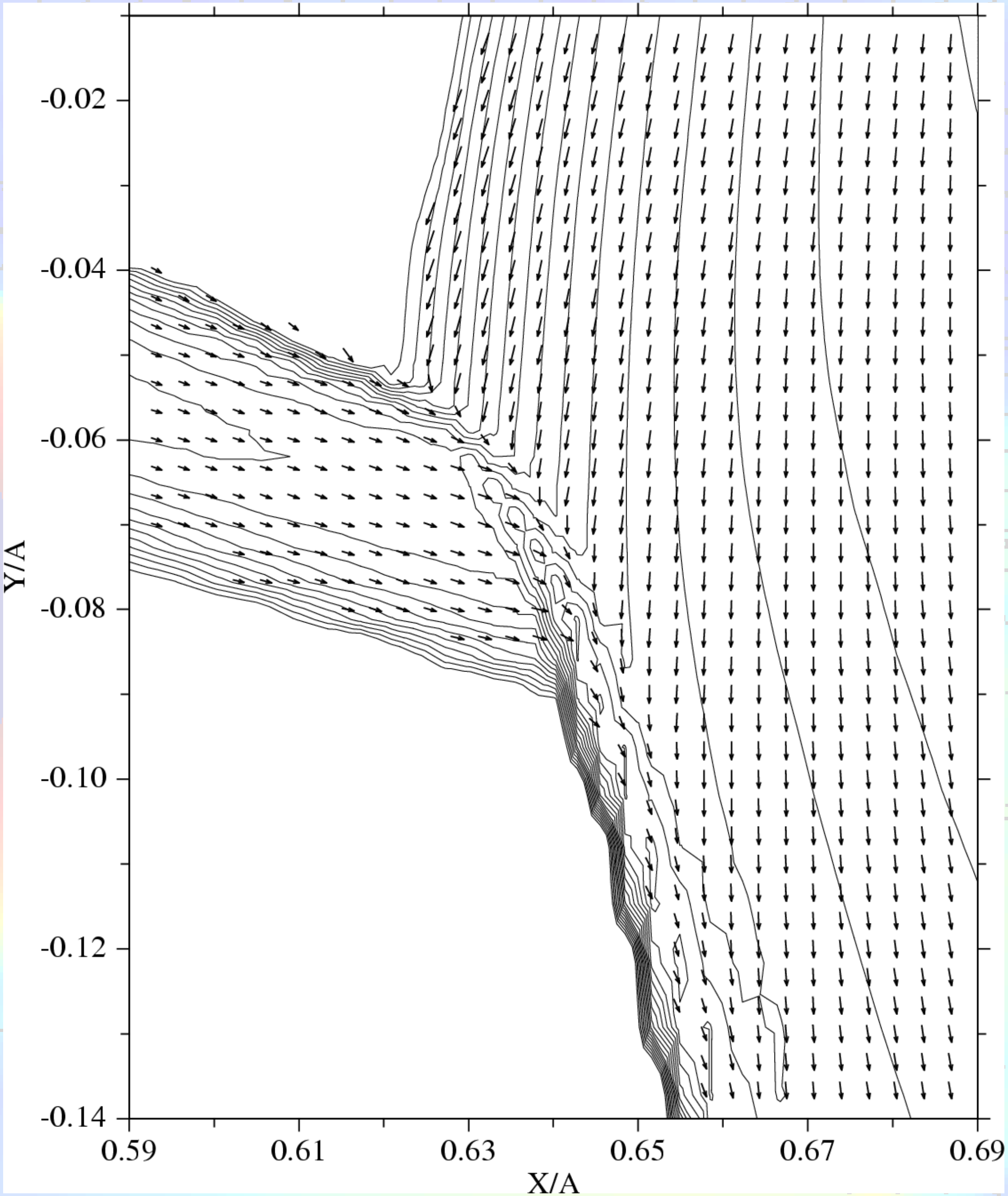
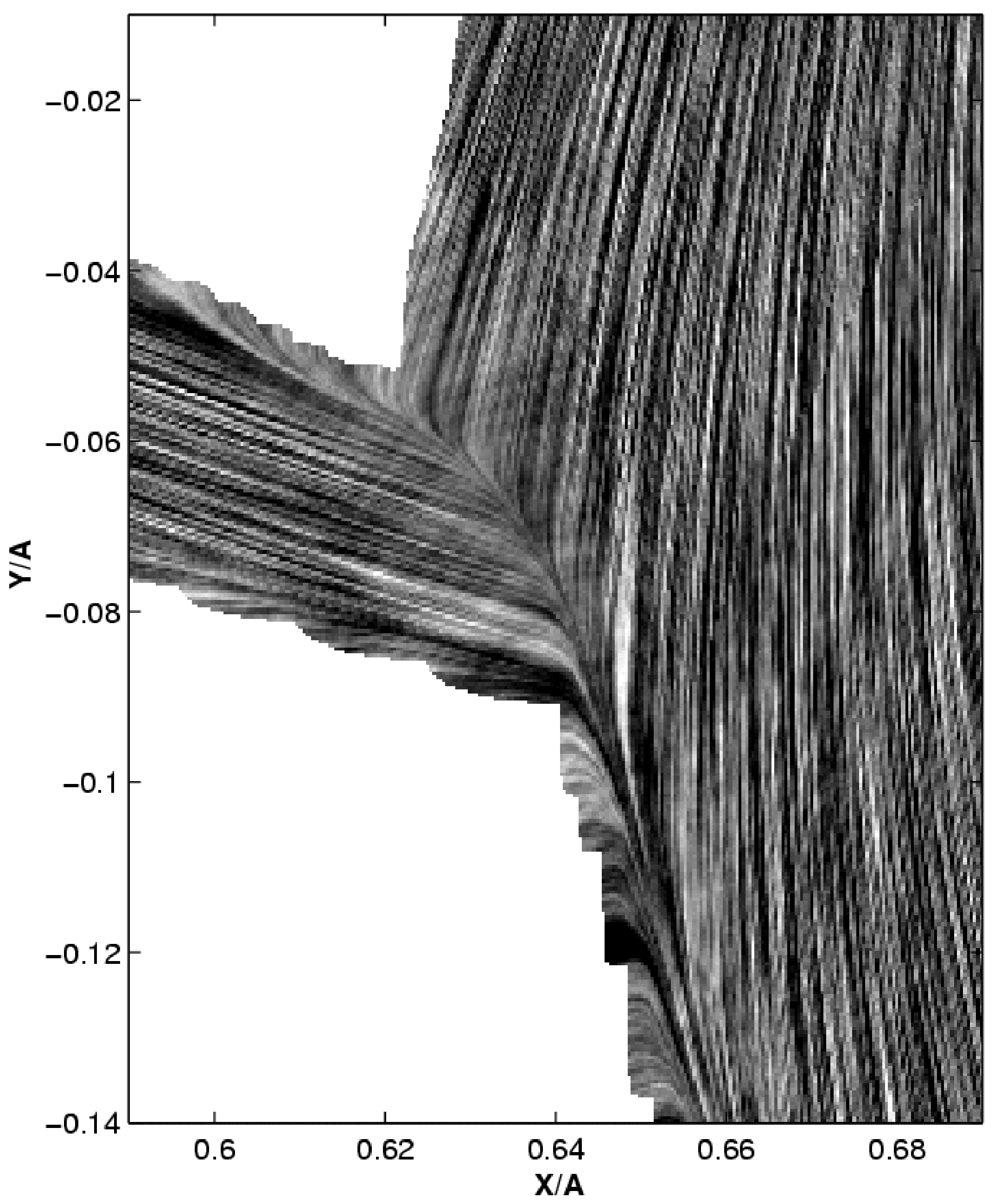
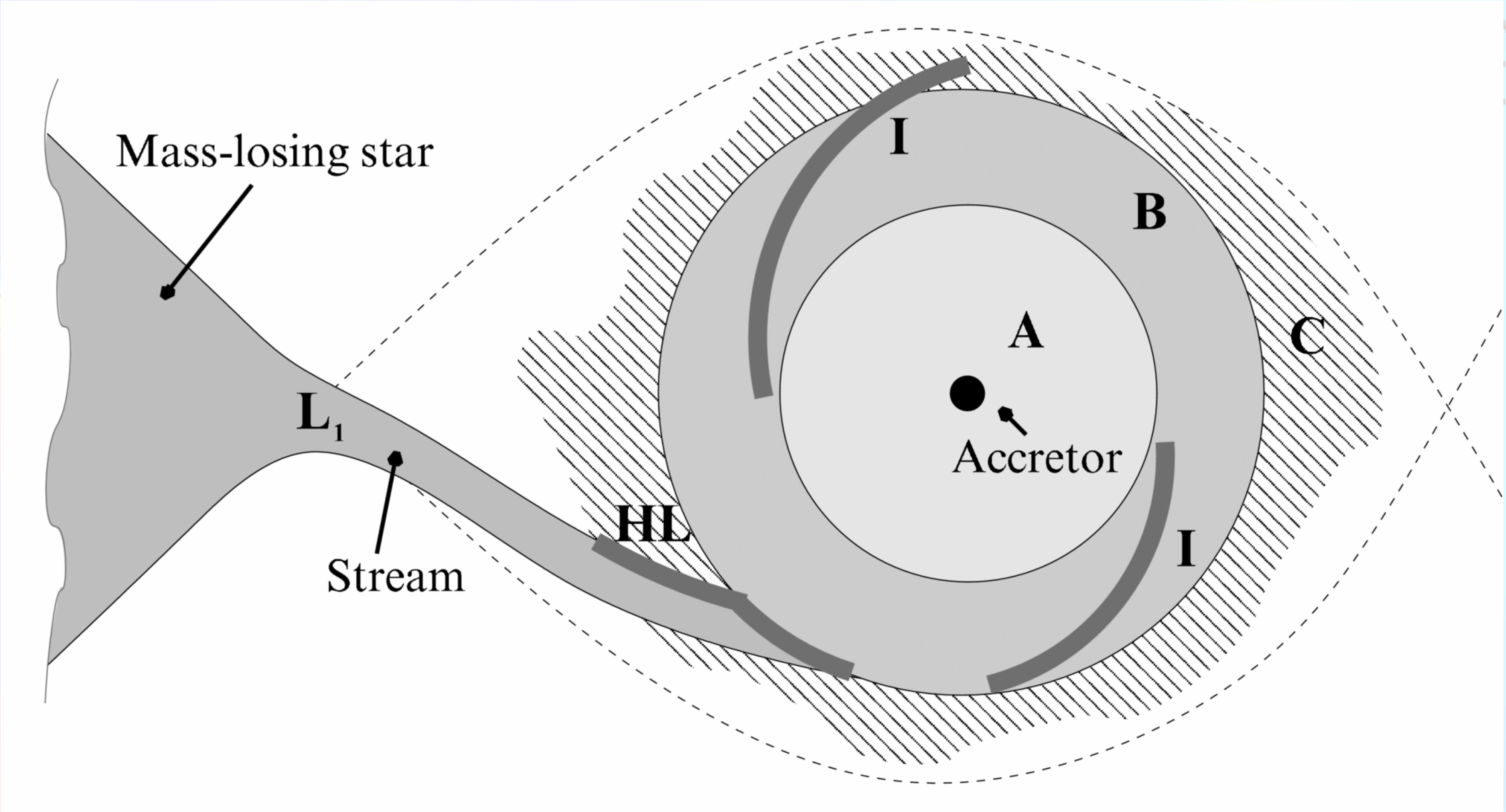


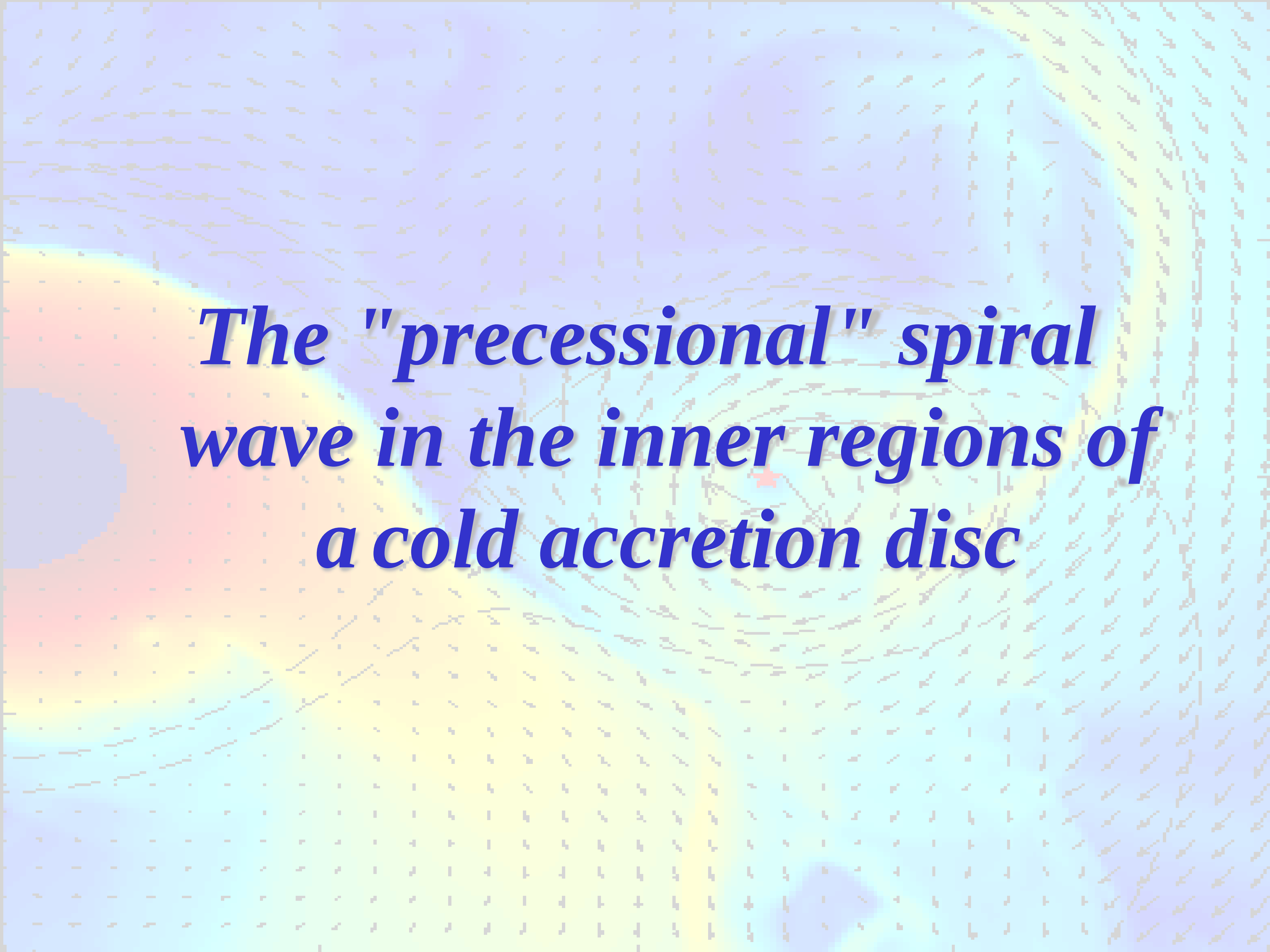
Interaction between the stream and "disc halo" has all features of an oblique collision of two flows. The formed structure includes two shocks separated by a contact discontinuity.



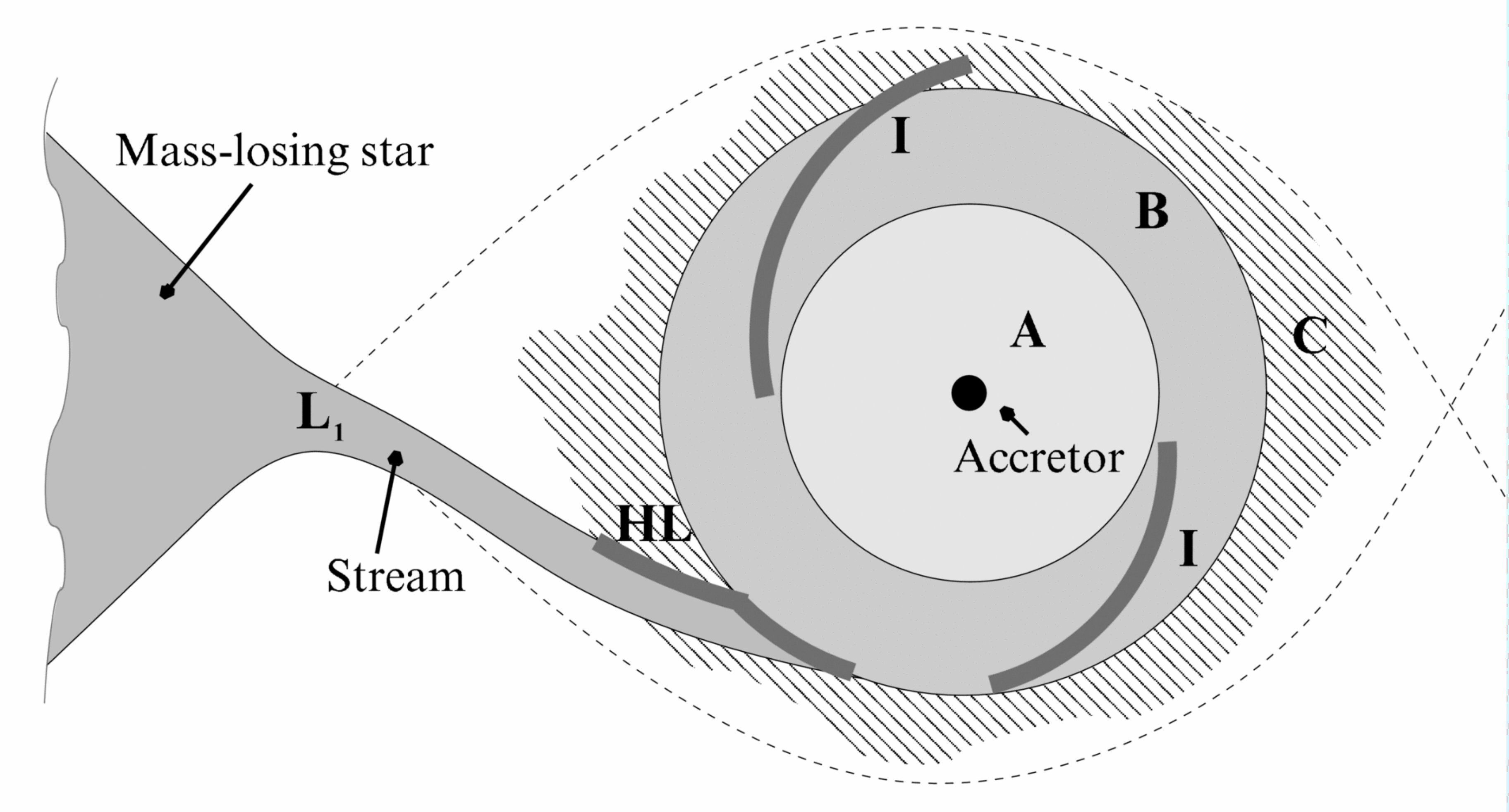
The gas of the “halo” and gas of the stream pass through their own shocks and mix. The mixed matter moves along the contact discontinuity between two shocks. Finally, this matter will form the disc itself, halo, and circumbinary envelope.



Analysis of these results has revealed that in the self-consistent model the flow structure in non-magnetic close binaries is formed by the stream of matter from L_1, accretion disc, “disc halo”, and circumbinary envelope.



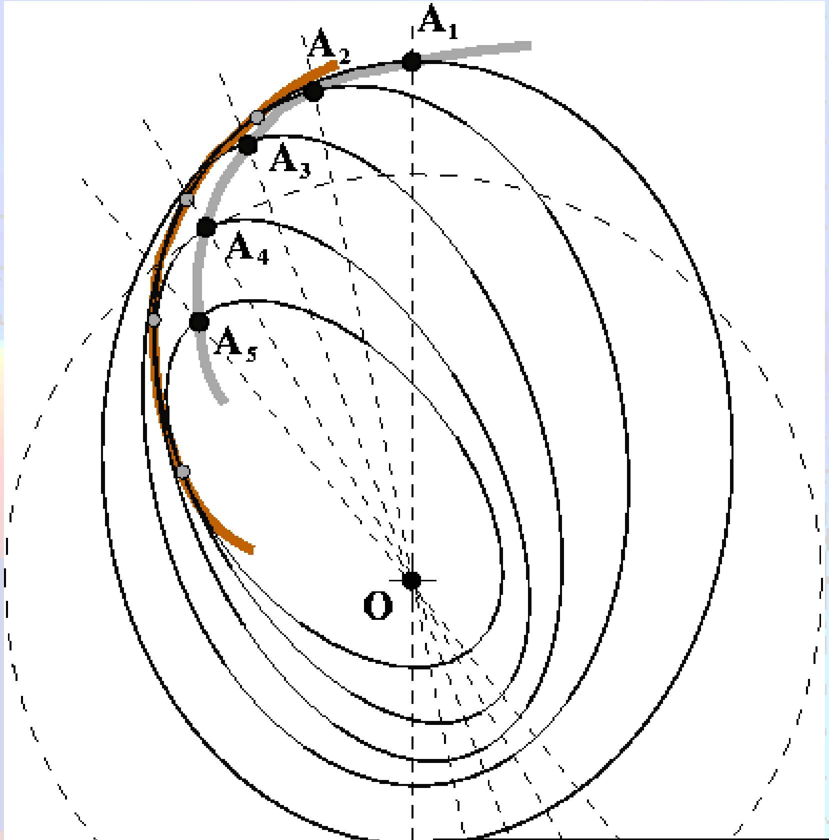
The "precessional" spiral wave in the inner regions of a cold accretion disc

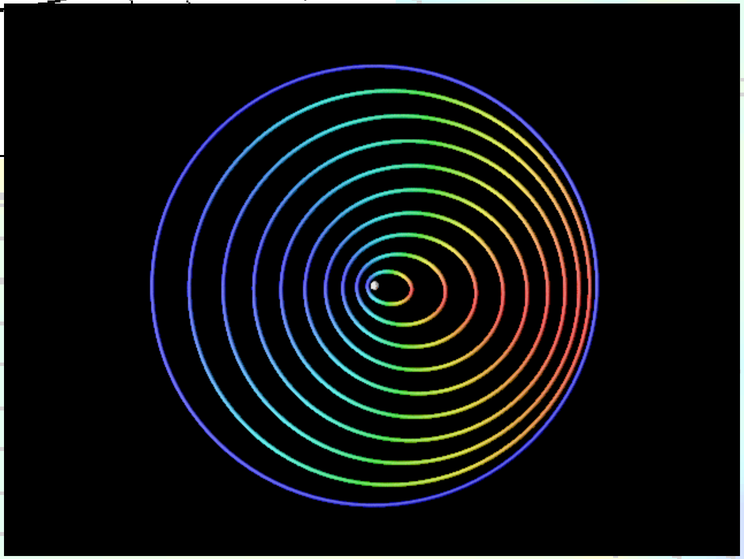


In the obtained solution a new element of the flow structure can be introduced – this is the inner region of accretion disc where gas dynamic perturbations are negligible.

Let us consider the flow of matter in inner parts of the disc. It is known that the influence of the companion star results in the retrograde precession of the particle's orbit; and the precession rate is the following function of the orbit radius:

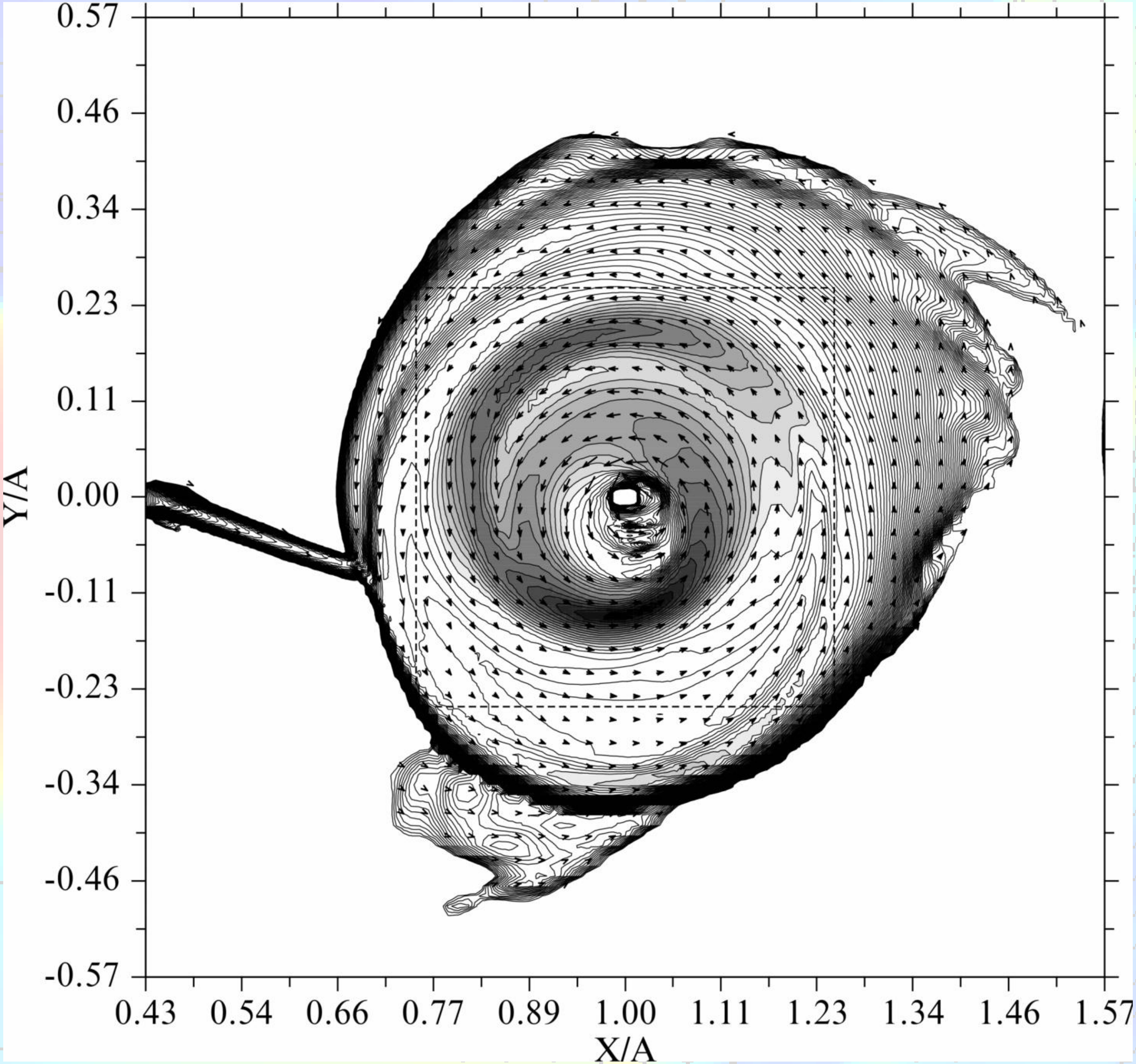
$$\frac{P_{pr}}{P_{orb}} \approx \frac{3}{4} \cdot \frac{(1+q)^{1/2}}{q} \cdot \left(\frac{r}{A} \right)^{-3/2}$$





In the gas dynamic approach we should consider flowlines instead of orbits.

The precession of flowlines more distant from the accretor is faster, so they will overtake the flowlines with shorter semimajor axes. It is obvious that such a solution should contain spiral structures.


0.57
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Y/A
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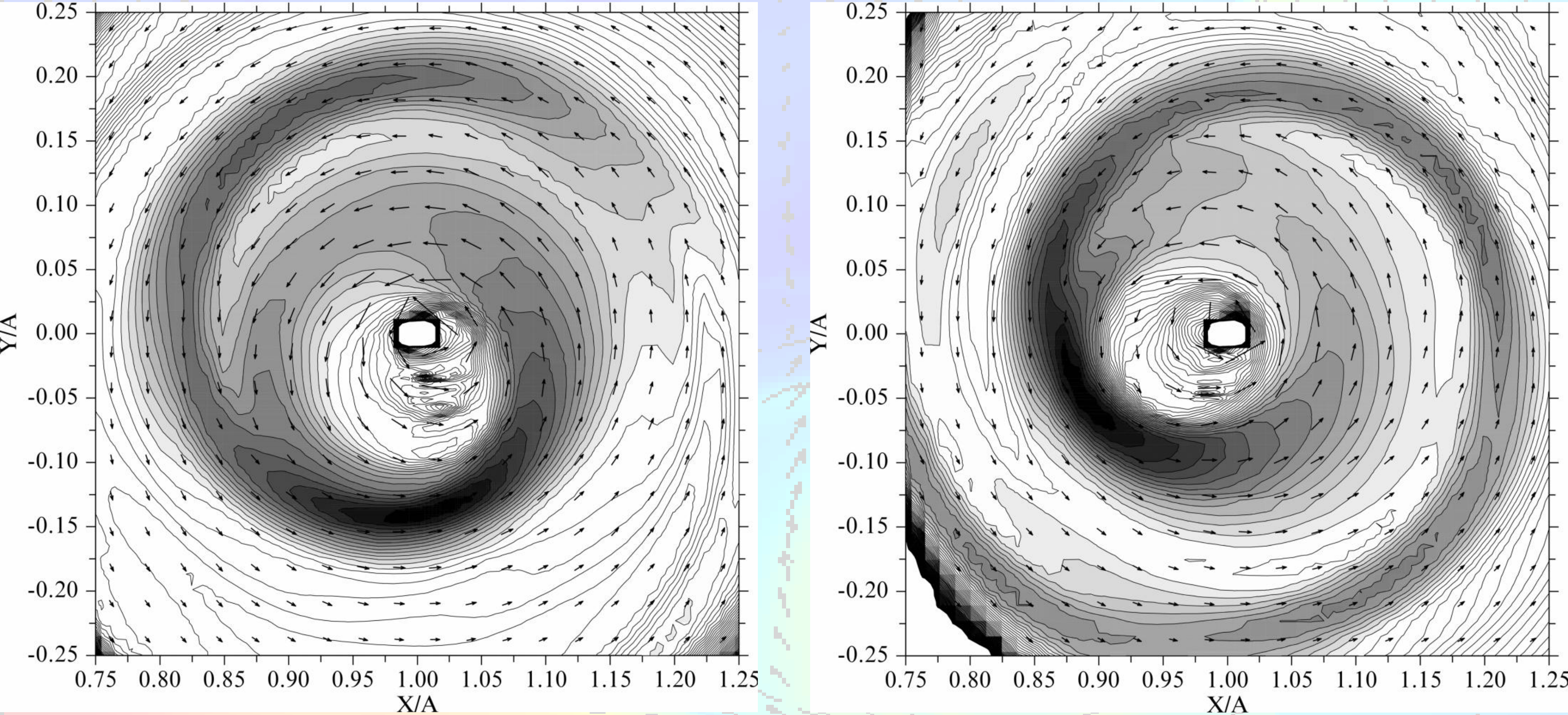
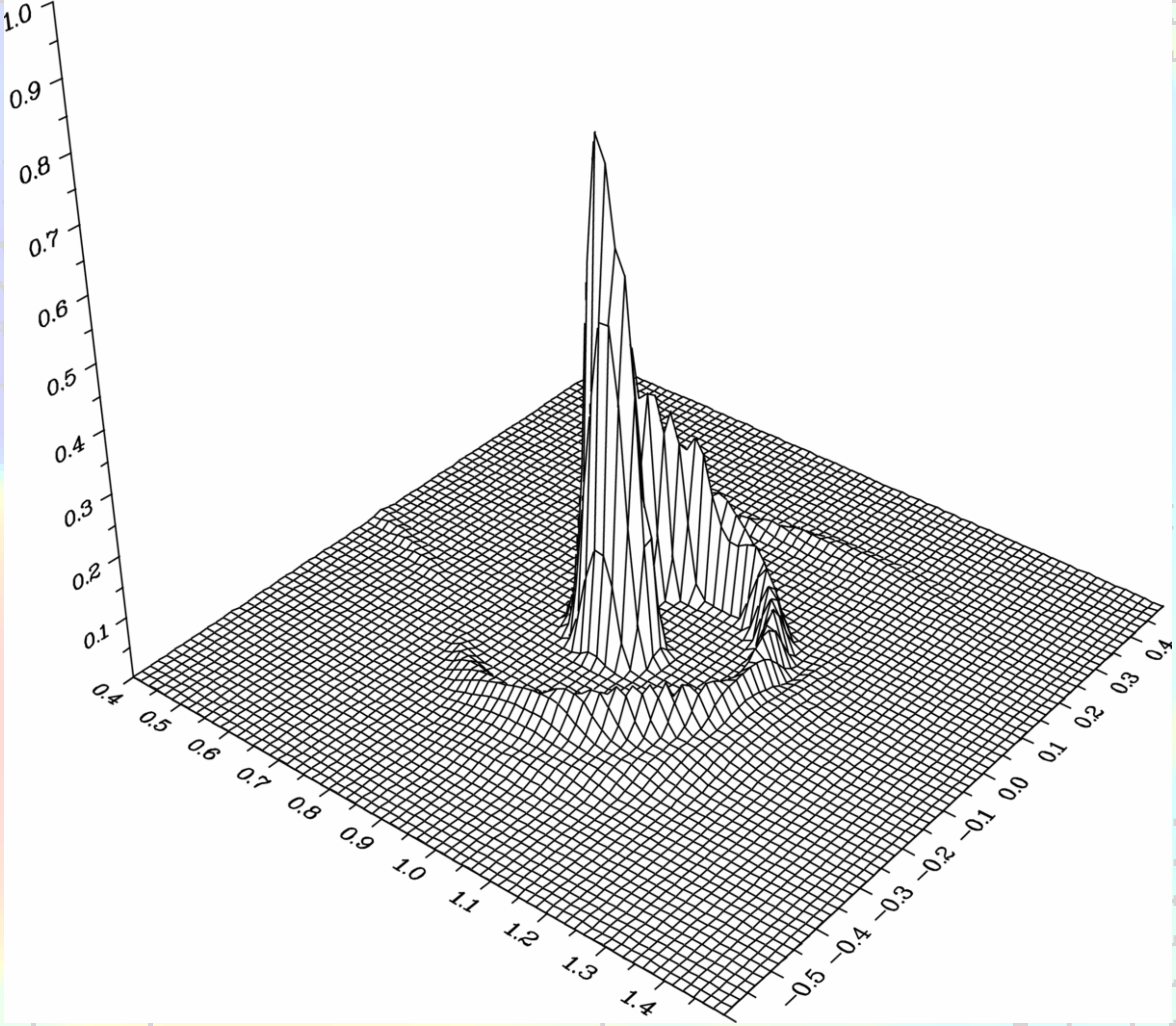
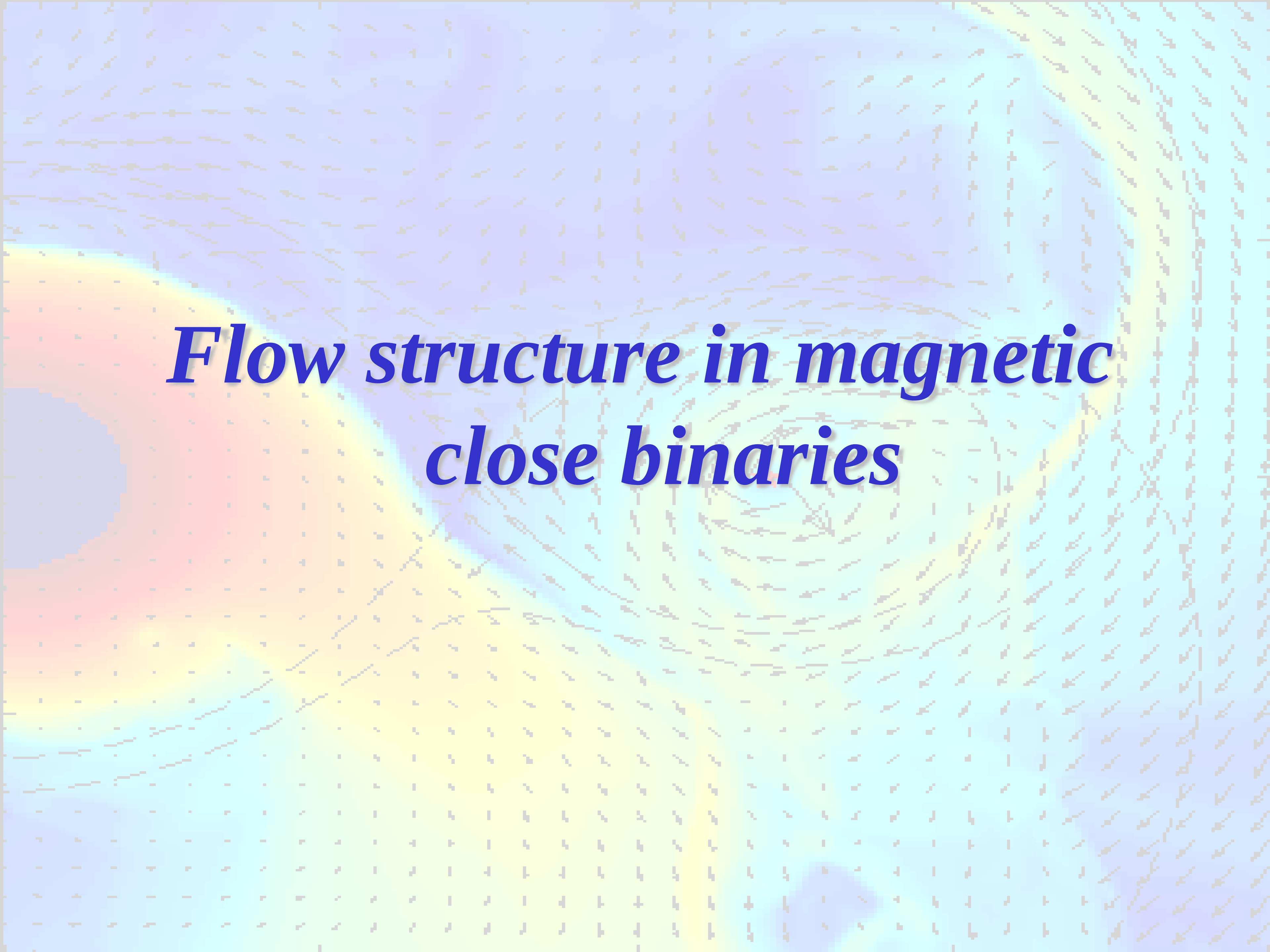


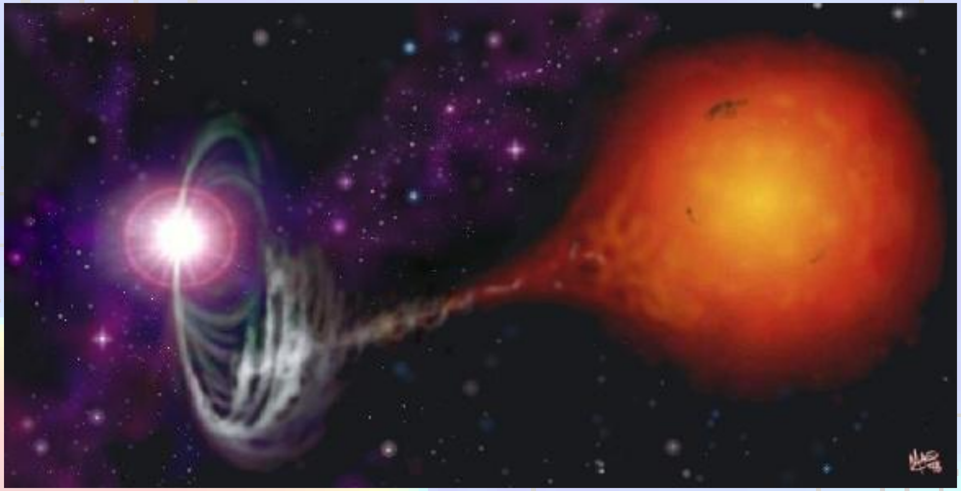
This figure shows a zoom of the density distribution and velocity vectors in the inner part of the disc for two moments of time. It is seen that the inner spiral wave rotates in the retrograde direction. Analysis of computational results shows that the wave moves in a rigid body mode with the period that is dozens times longer than the orbital one.

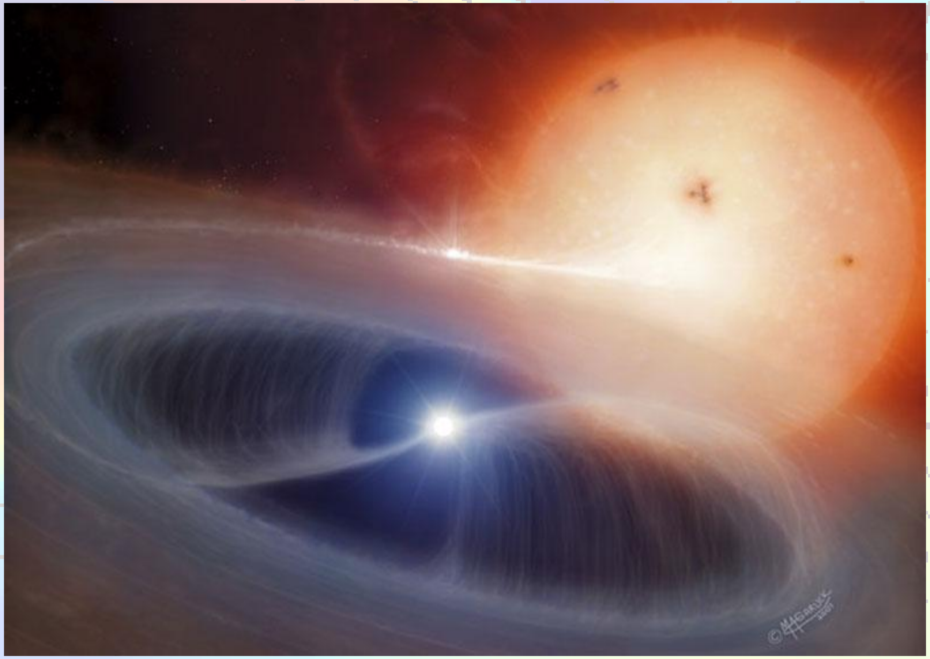


This figure shows a bird-eye view of the distribution of the radial flux of matter in the equatorial plane. Increase of the radial flux of matter behind the “precessional” density wave results in growth of the accretion rate up to the order of magnitude comparing to the wave-free solution.



Flow structure in magnetic close binaries





Depending on the magnetic field value, binary systems where accretor is a magnetized white dwarf are divided into two classes: polars (or AM Her stars) and intermediate polars (or DQ Her stars). In a polar the magnetic field is so high ($B \sim 10^7 - 10^8$ G) that it prevents from formation of the accretion disc and matter from the donor star falls directly onto the primary star along the accretion column. In intermediate polars the magnetic field is not so strong ($B \sim 10^4 - 10^6$ G) and the accretion disc forms.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{\nabla P}{\rho} - \frac{1}{4\pi\rho}\left(\mathbf{B} \times (\nabla \times \mathbf{B})\right) + 2(\mathbf{v} \times \mathbf{\Omega}) - \nabla \Phi$$

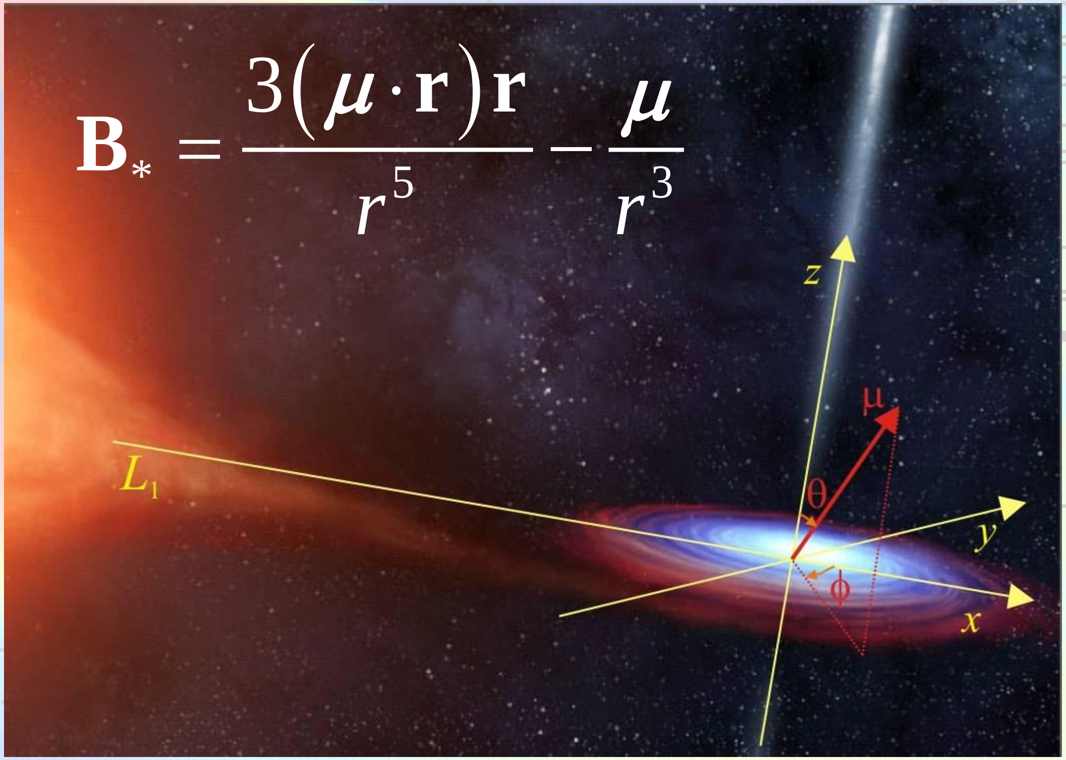
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{v} \times \mathbf{B} - \eta(\nabla \times \mathbf{B})\right), \quad \nabla \cdot \mathbf{B} = 0$$

$$\rho T\left(\frac{\partial s}{\partial t} + (\mathbf{v} \cdot \nabla) s\right) = n^2 (\Gamma - \Lambda) + \frac{\eta}{4\pi}(\nabla \times \mathbf{B})^2$$

$$s = c_V \ln\left(P/\rho^\gamma\right)$$

A developed numerical model takes into account the turbulent diffusion of the magnetic field that is determined by the magnetic reconnections and electric currents dissipation in turbulent vortexes as well as by the magnetic flux tubes buoyancy.

SS Cyg: M_{wd}=0.97 M_{sun}, M_{sec}=0.56 M_{sun}, P=6.6h, A=2.05 R_{sun}, c_s=7.4 km/s, M_{ar}=10^{-9} M_{sun}/yr



$$\mathbf{B}_* = \frac{3(\mu\cdot\mathbf{r})\mathbf{r}}{r^5} - \frac{\mu}{r^3}$$

The magnetic field of the accretor is considered to be a dipole type field. Here **μ** is the vector of the magnetic moment. We take the value B_* = 10^5 G for the magnetic induction on the surface of the compact primary star. We assume that the dipole moment is inclined to the rotation axis at the angle 30º.

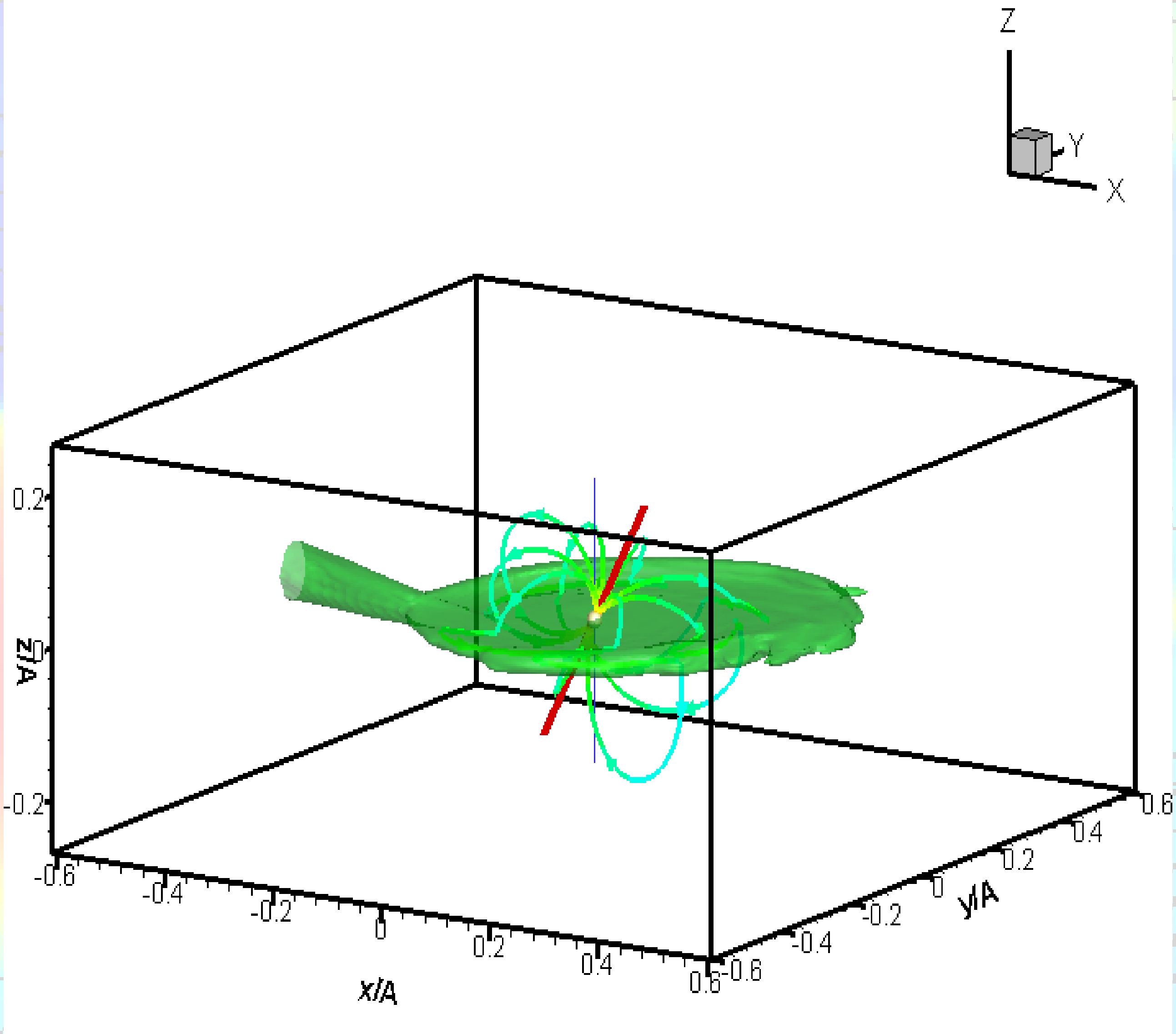
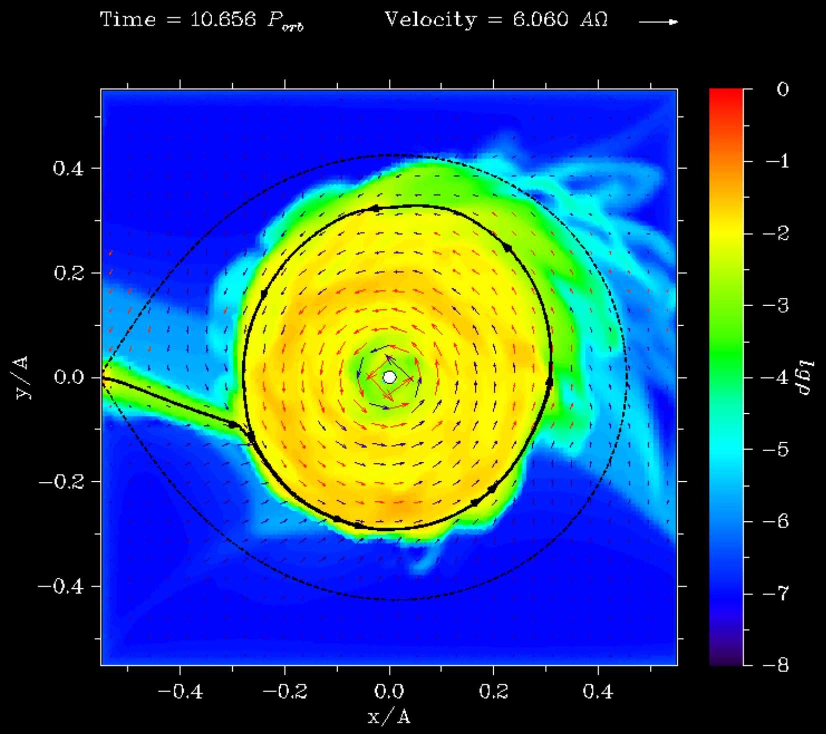


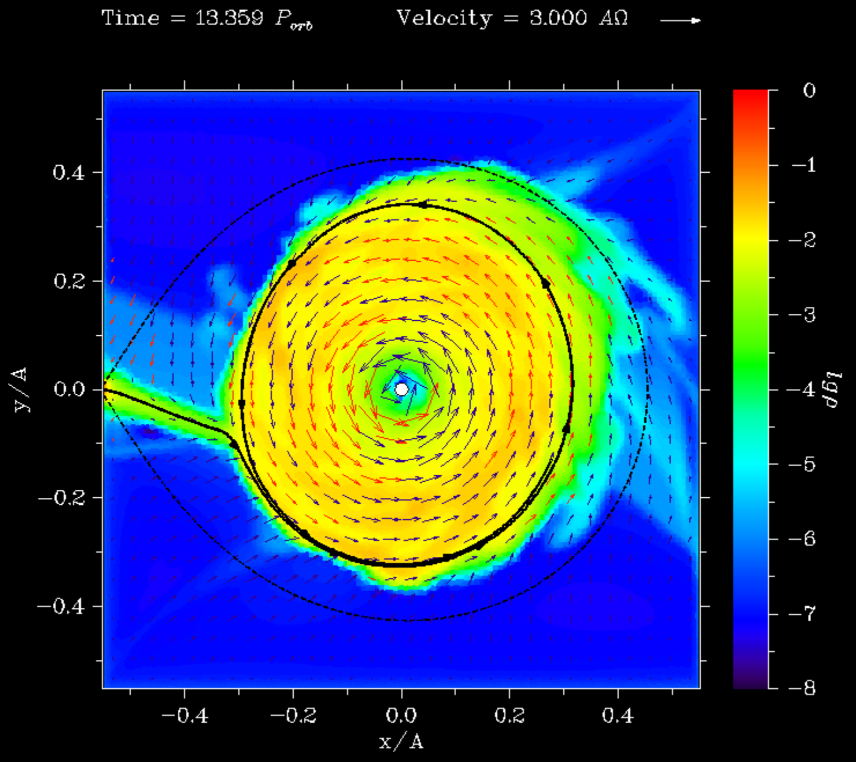
Figure shows the density isosurface. The blue line is the accretor rotation axis. The red line is the magnetic axis. The color along the magnetic field lines represents the strength of the field.

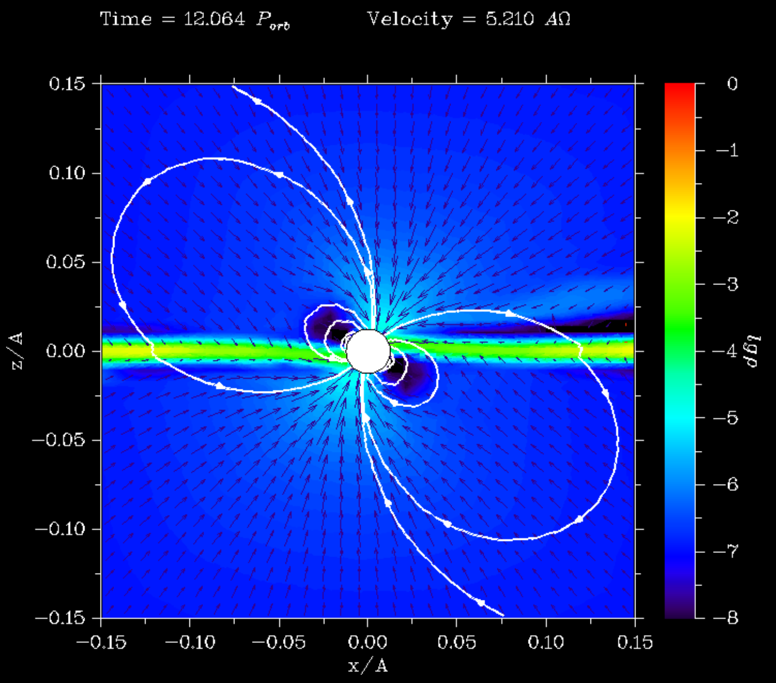


It was found out that in the MHD model the flow structure has the same qualitative features as in the pure HD solution: (i) magnetized accretion disc forms in the system;

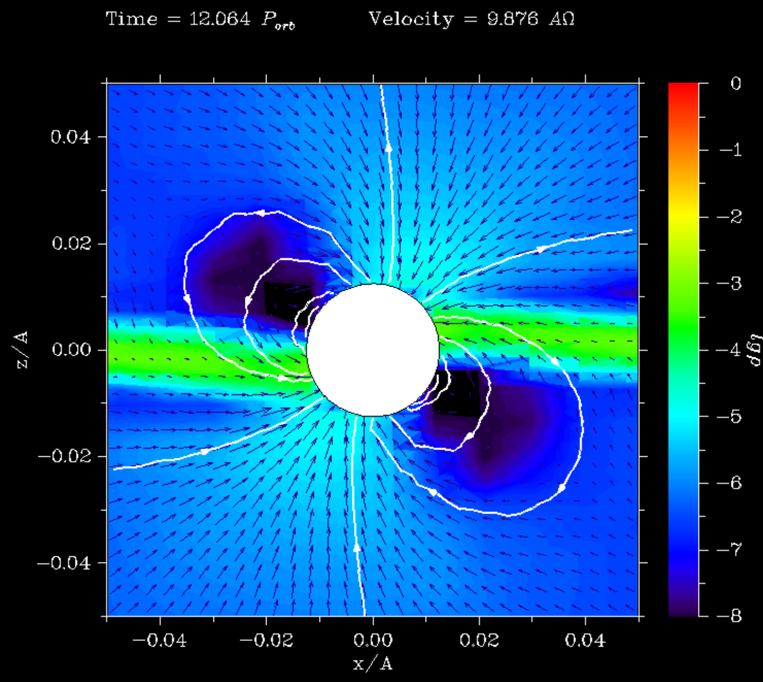
(ii) all previously discovered waves still exist in the disc:

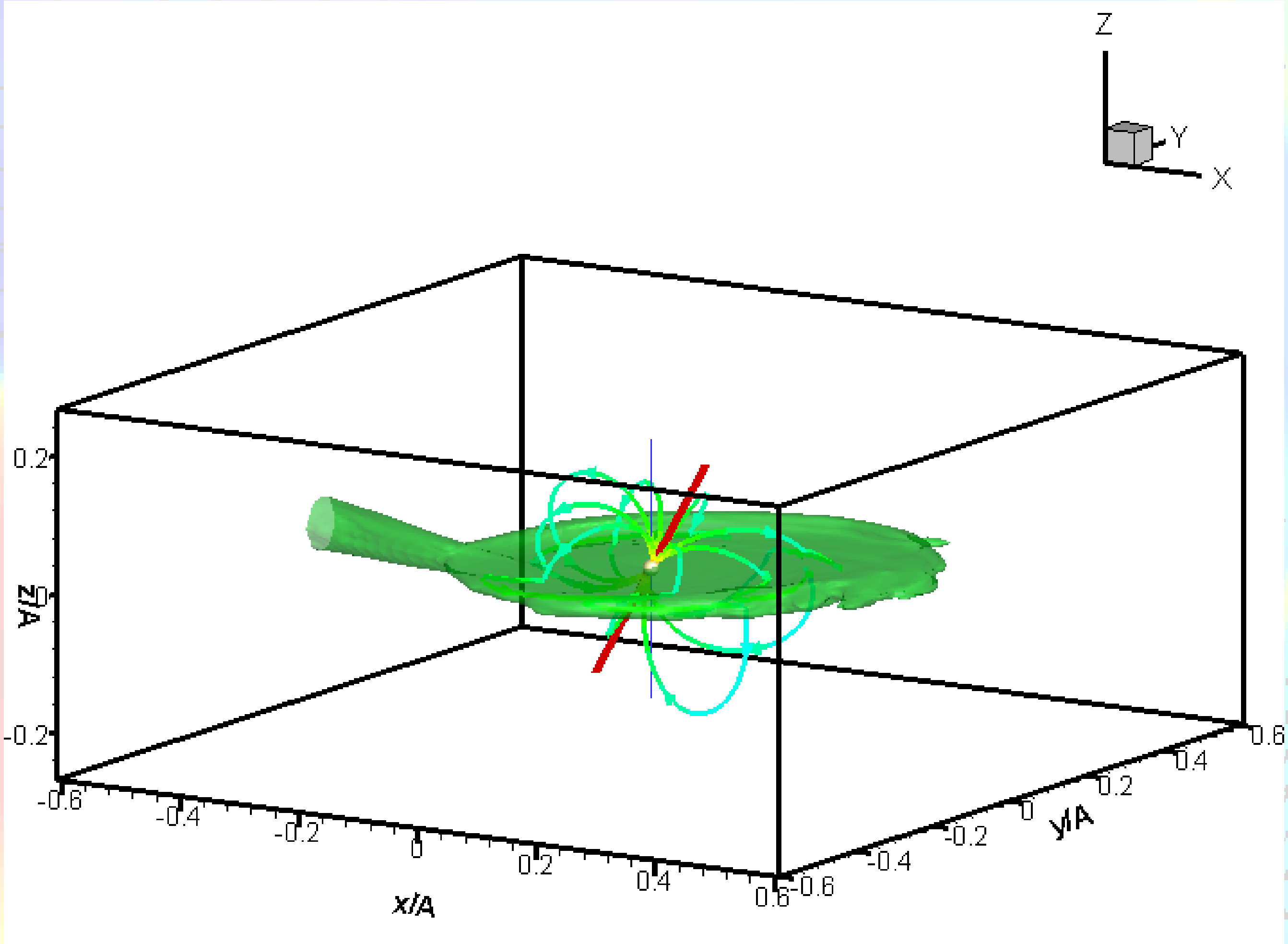
- bow shock;
- “hot line”;
- tidal shock;
- precessional wave.





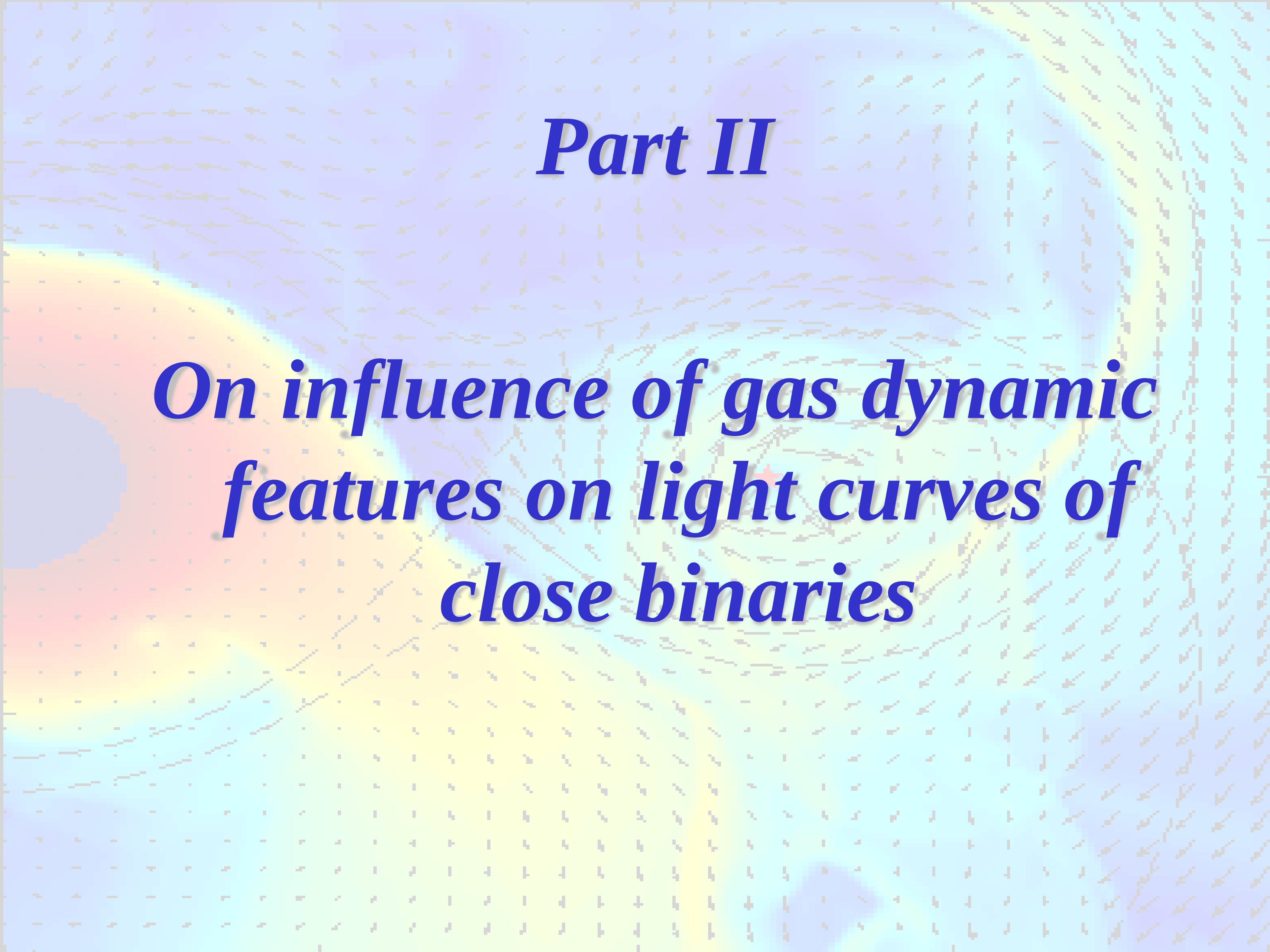
Presence of the magnetic field leads to formation of the magnetosphere and funnel flows near the magnetic poles of the primary star.





The moderate magnetic field of the accretor does not destroy the flow structure, **while basic characteristics of the accretion disc change. For example, the accretion rate approximately doubles, the characteristic density decreases by roughly an order of magnitude, and thickness of the disc increases by factor of 2.**

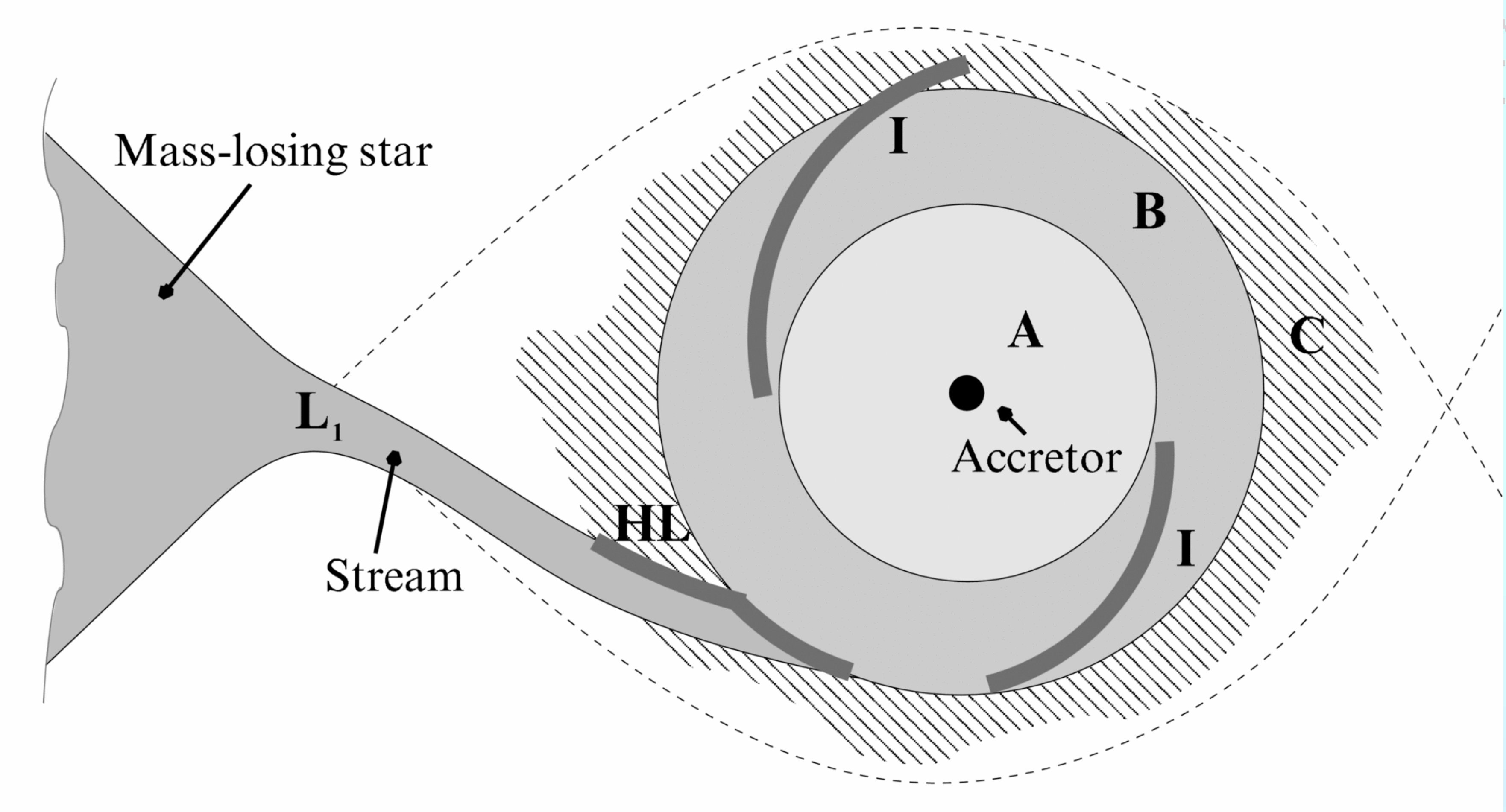
- *In close binary stars the flow structure is very complicated. It is formed by the stream from the L_1 point, accretion disc, circumdisc halo, circumbinary envelope as well as by features caused by their interaction.*
- *The **bow shock** is formed in the system due to motion of the disc in the circumbinary envelope.*
- *In the accretion disc a number of shock waves exist: "**hot line**" formed due to the interaction between the circumdisc halo and stream from the inner Lagrange point L_1, and two arms of the **spiral tidal shock**.*
- *The **"precessional" spiral wave** is formed in inner regions of a cold accretion disc.*
- *The moderate magnetic field of the accretor ($B<10^6$G) does not destroy the flow structure; meanwhile new elements appear: the magnetosphere region becomes distinguishable, and the matter is accreted via funnel flows.*



Part II

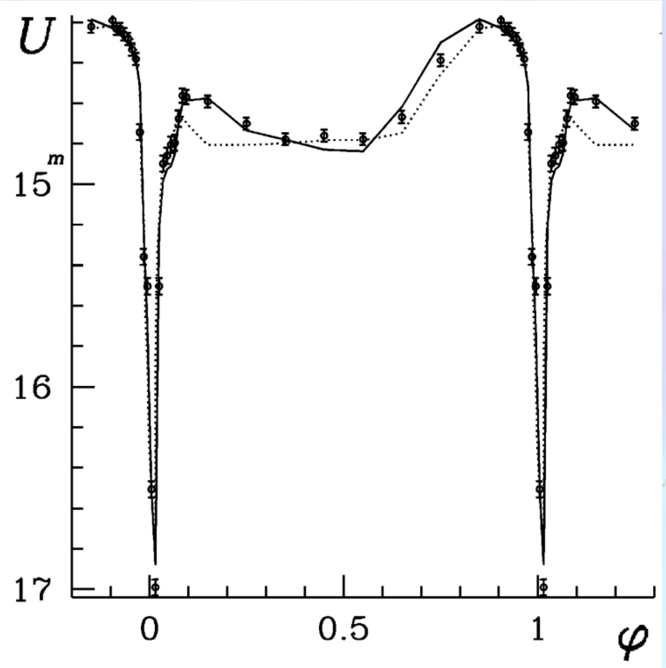
On influence of gas dynamic features on light curves of close binaries

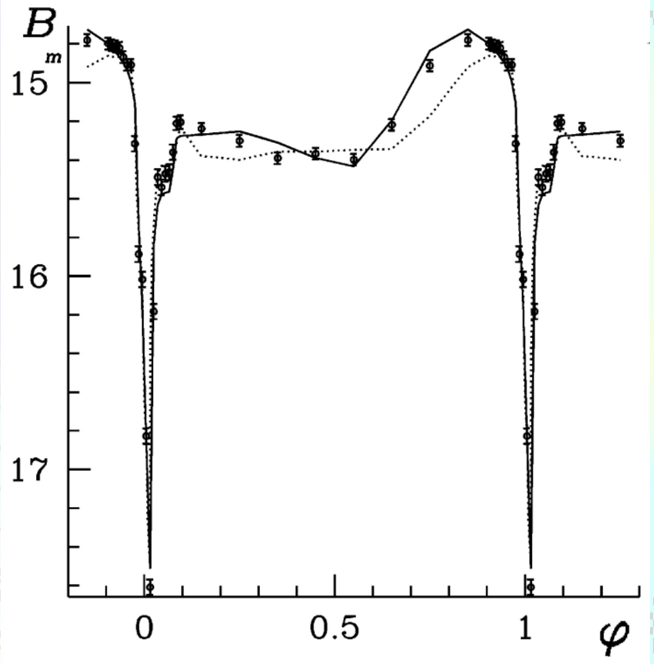
The accretion disc



The most significant contribution into the total brightness of the system comes from the accretion disc, and shock waves (“*hot line”, spiral tidal shock,* and *bow shock*). These shocks are at rest in a coordinate frame rotating with the orbital period of the binary, and they should be seen with the same period.

OY Car


U
15^m
15
16
17
0
0.5
1
φ


B
m
15
16
17
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0.5
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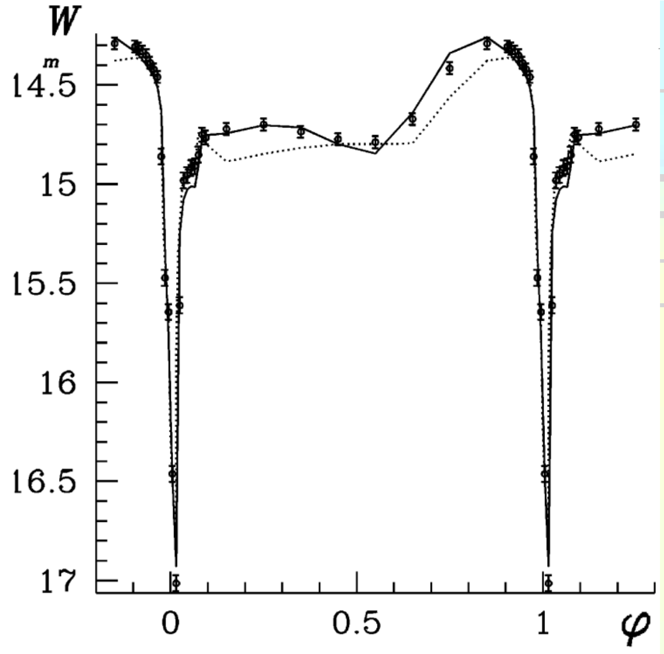
φ


W
m
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16
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17
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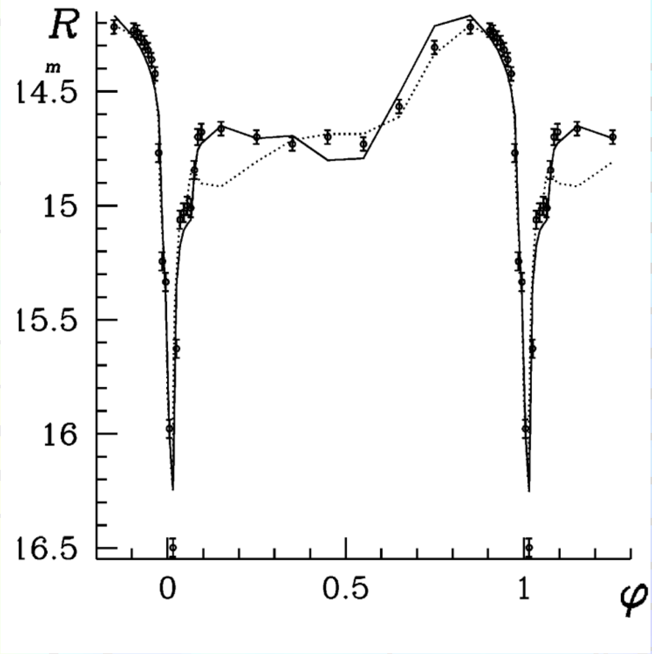
0.5
1
φ


R
m
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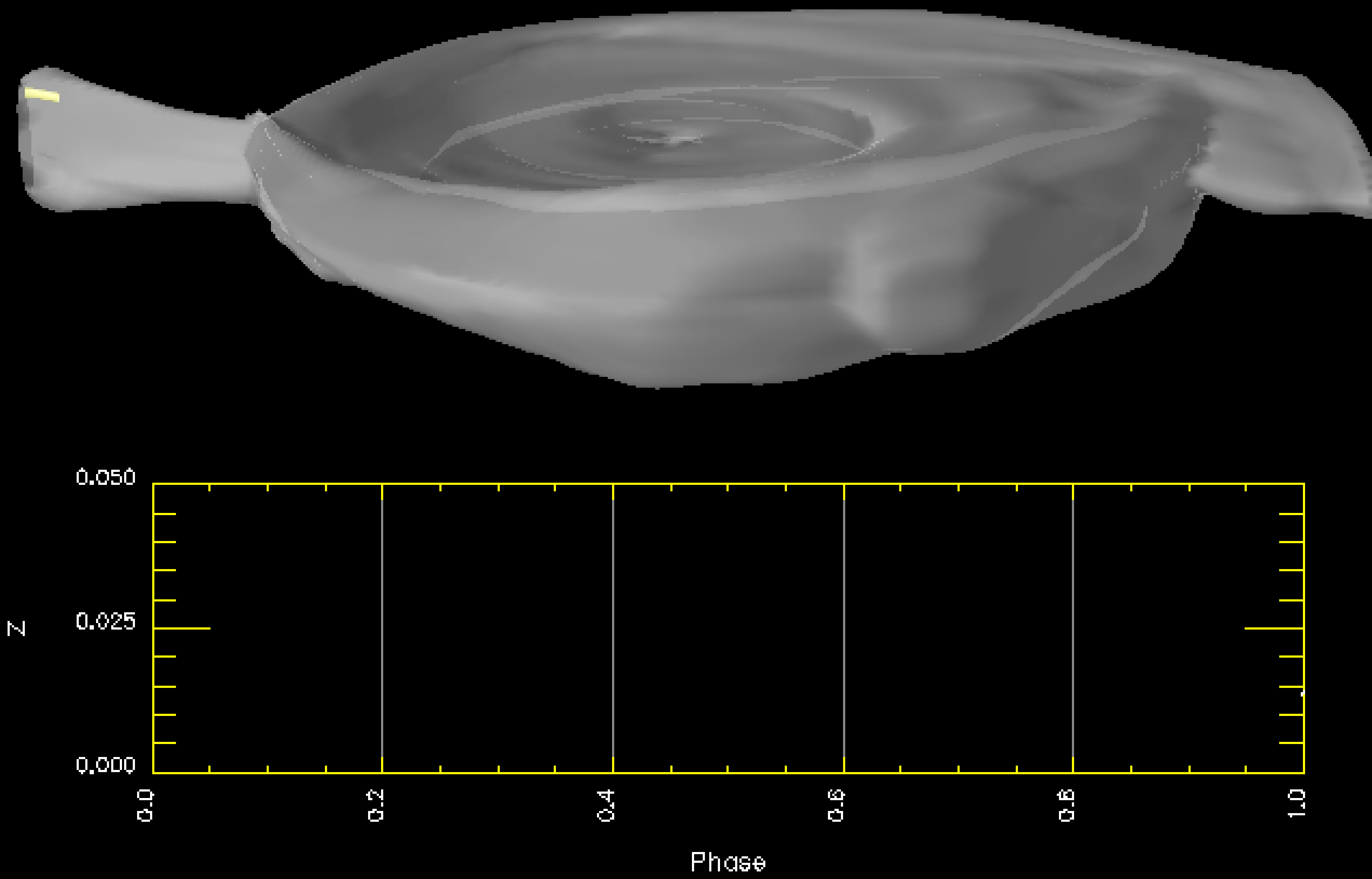
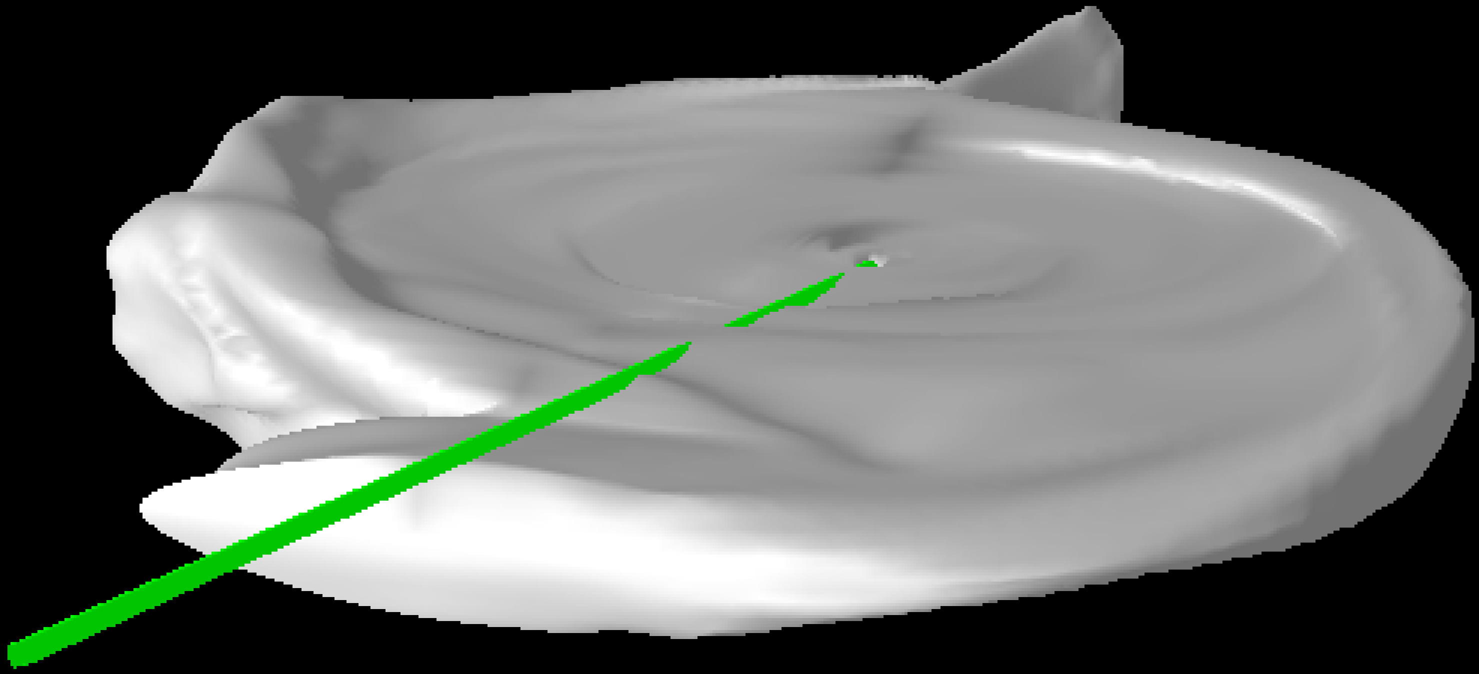
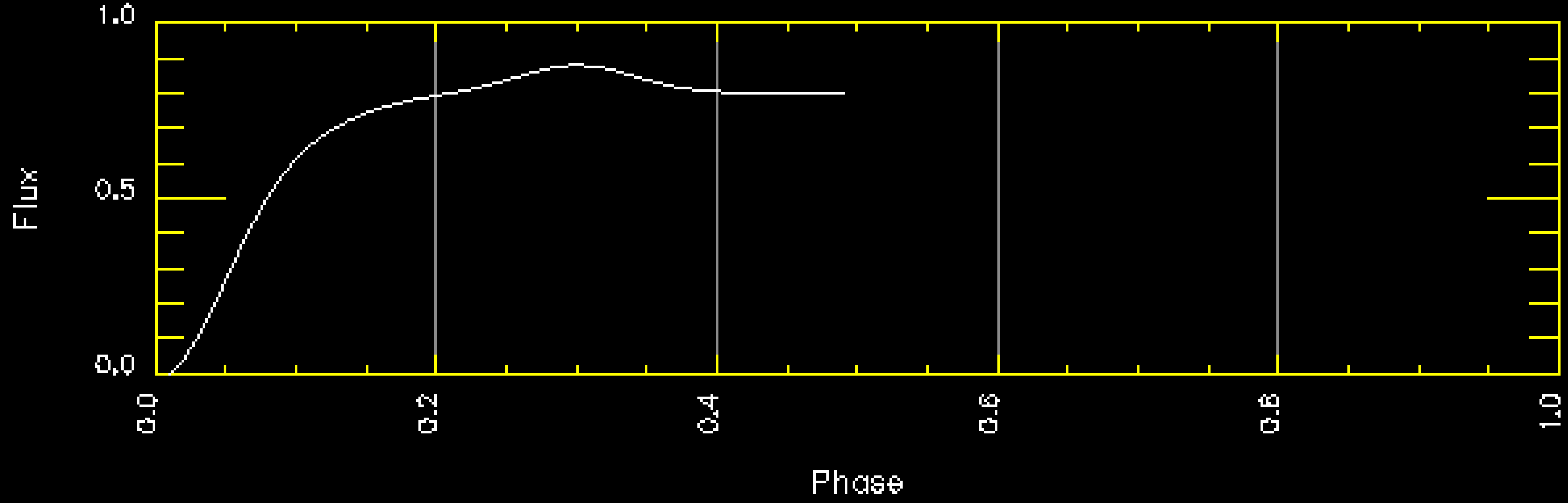
φ

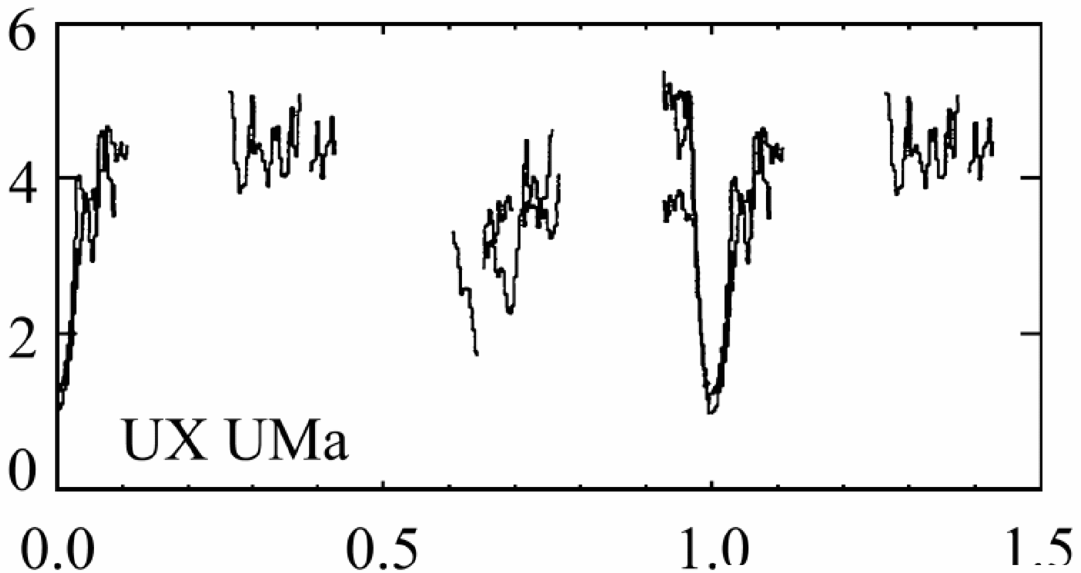

0.050
0.025
0.000
Z
0.0
0.2
0.4
0.6
0.8
1.0
Phase

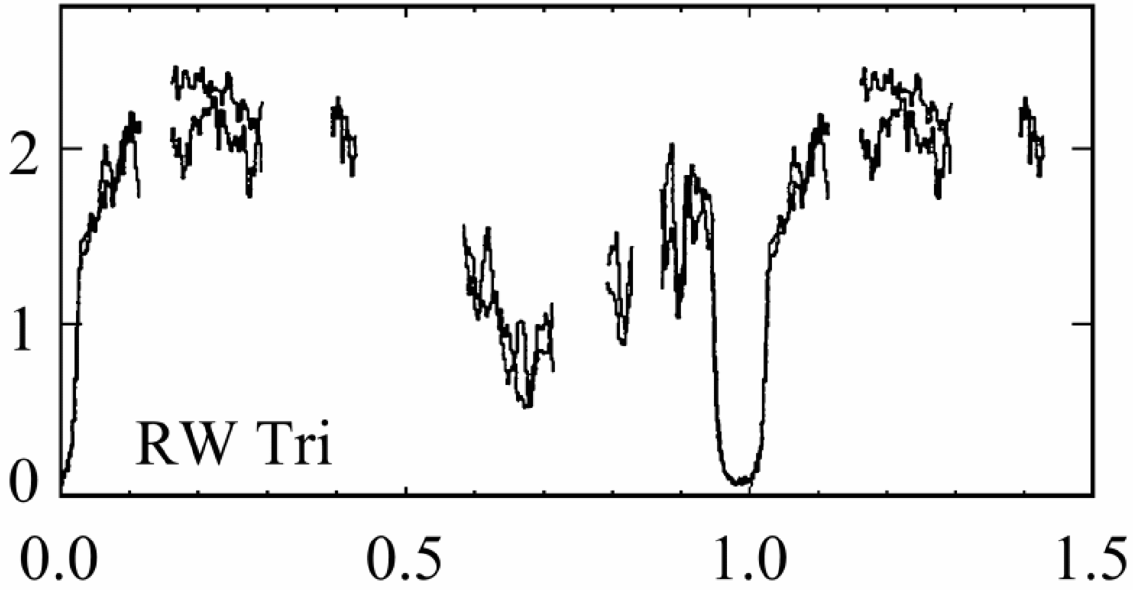




Flux
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Phase

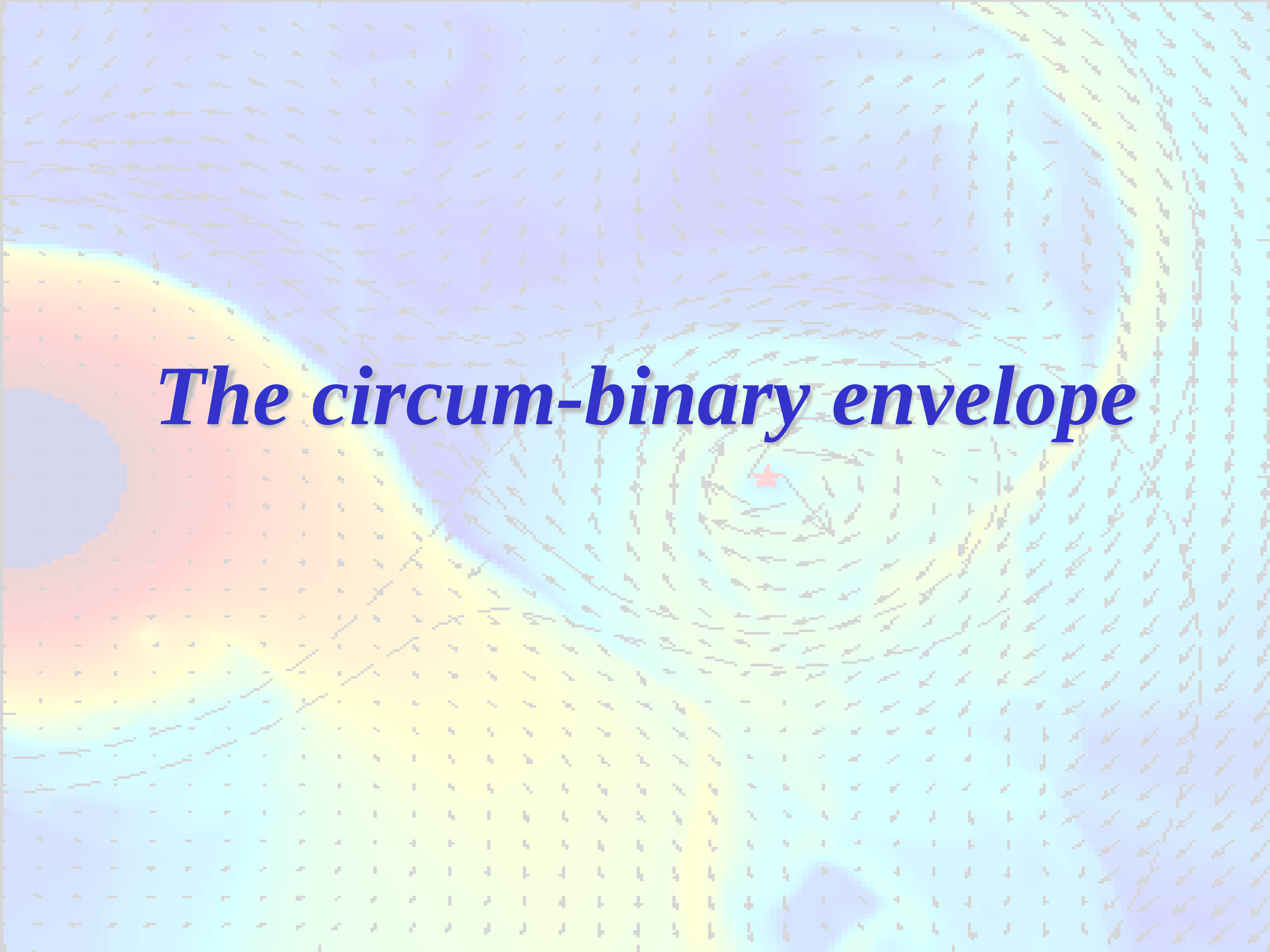
Indeed, observations of the eclipsing nova-like variables reveal pre-eclipse dips in their light curves.





Hubble Space Telescope, Mason, Drew, and Knigge (1997)

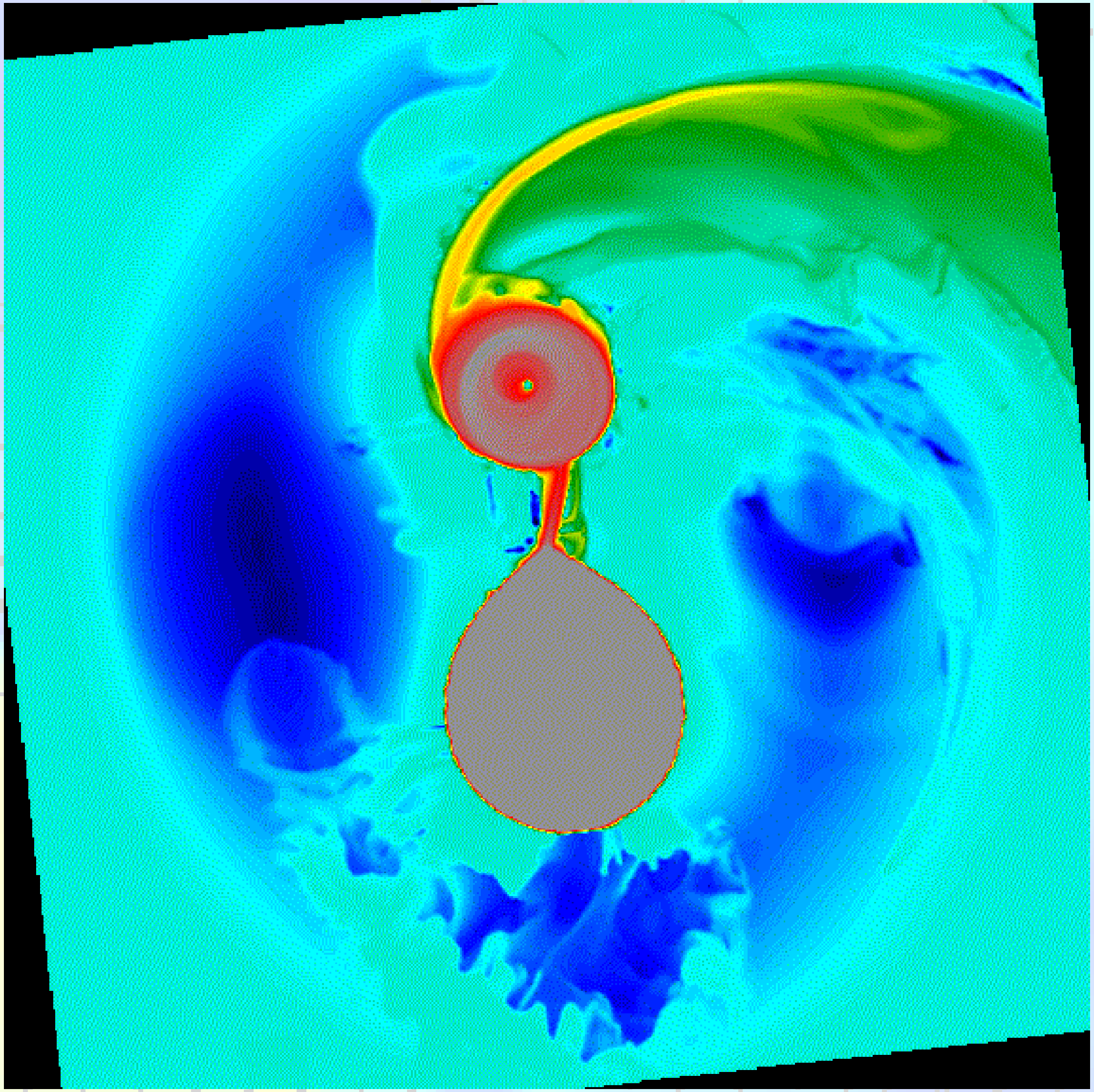
The circum-binary envelope

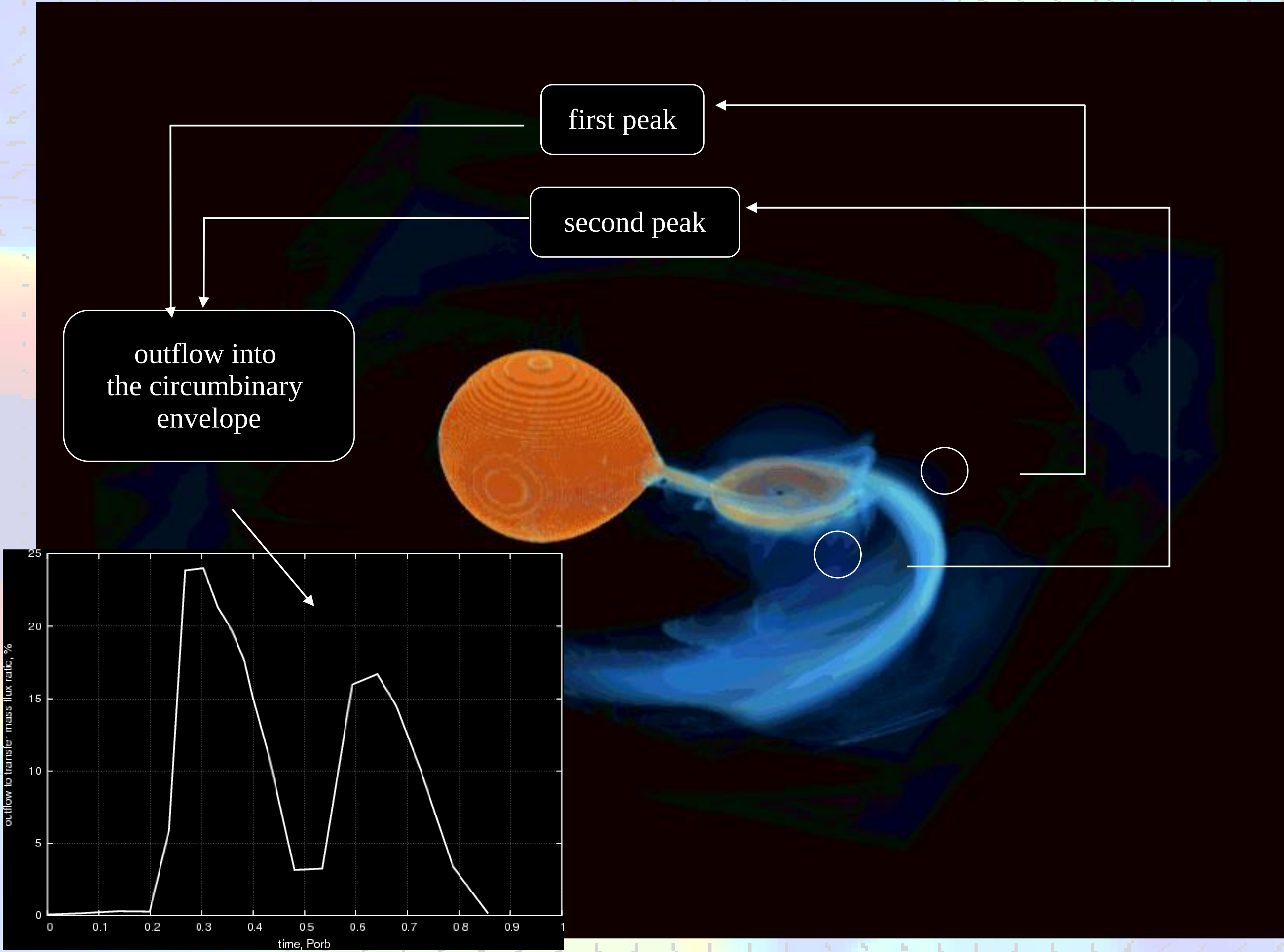


Binary system in observer reference frame

Presence of the precessional wave in the disc specifies its elliptical shape. In the observer's frame, the wave (and therefore a substantial part of the disc) will be essentially stationary, while the position of the other elements of the flow will vary due to the orbital rotation of the system.

The outer parts of the circumbinary envelope are replenished due to periodic ejections of matter from the accretion disc and circum-disc halo through the vicinity of the L_3 point.

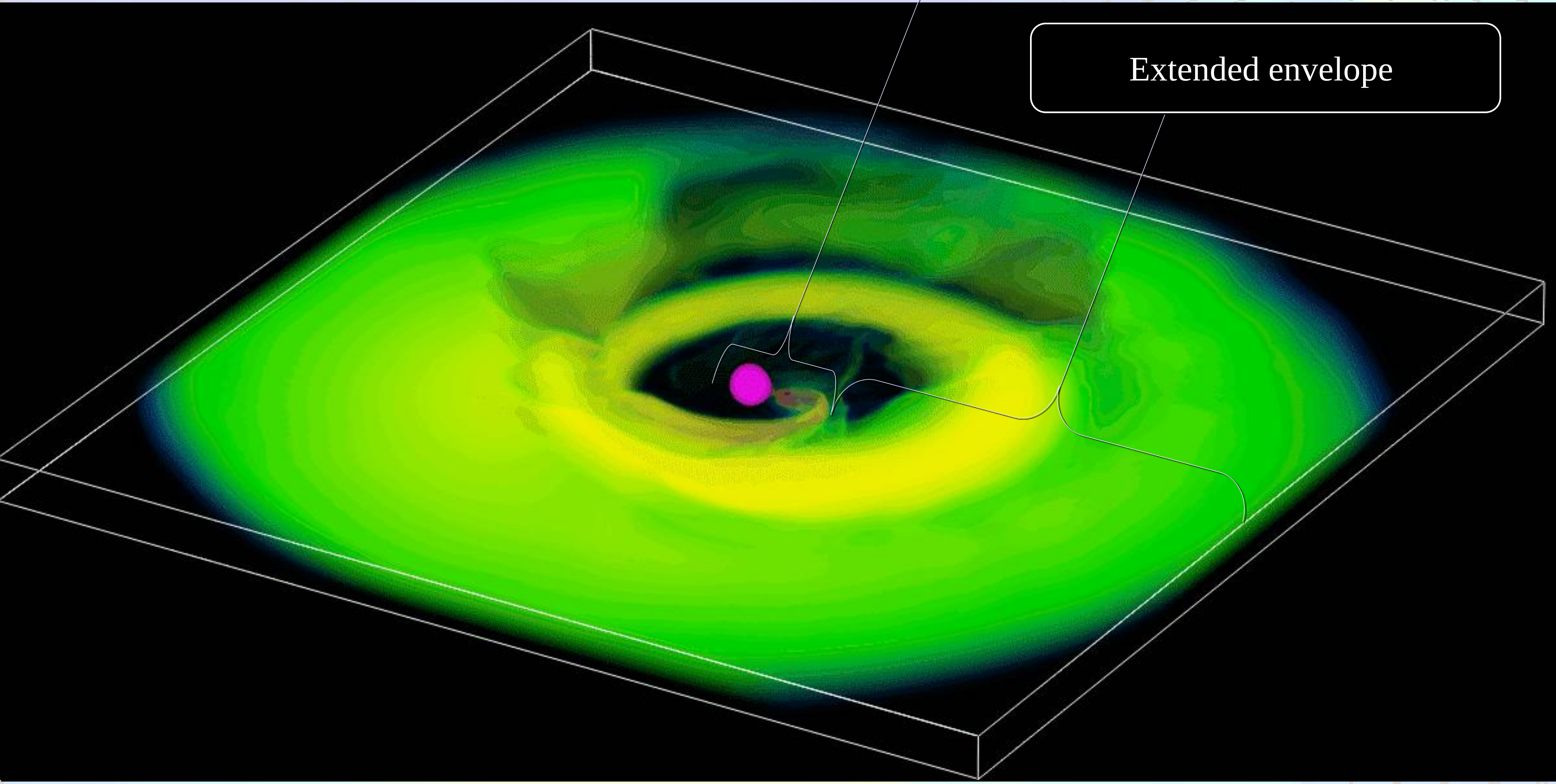




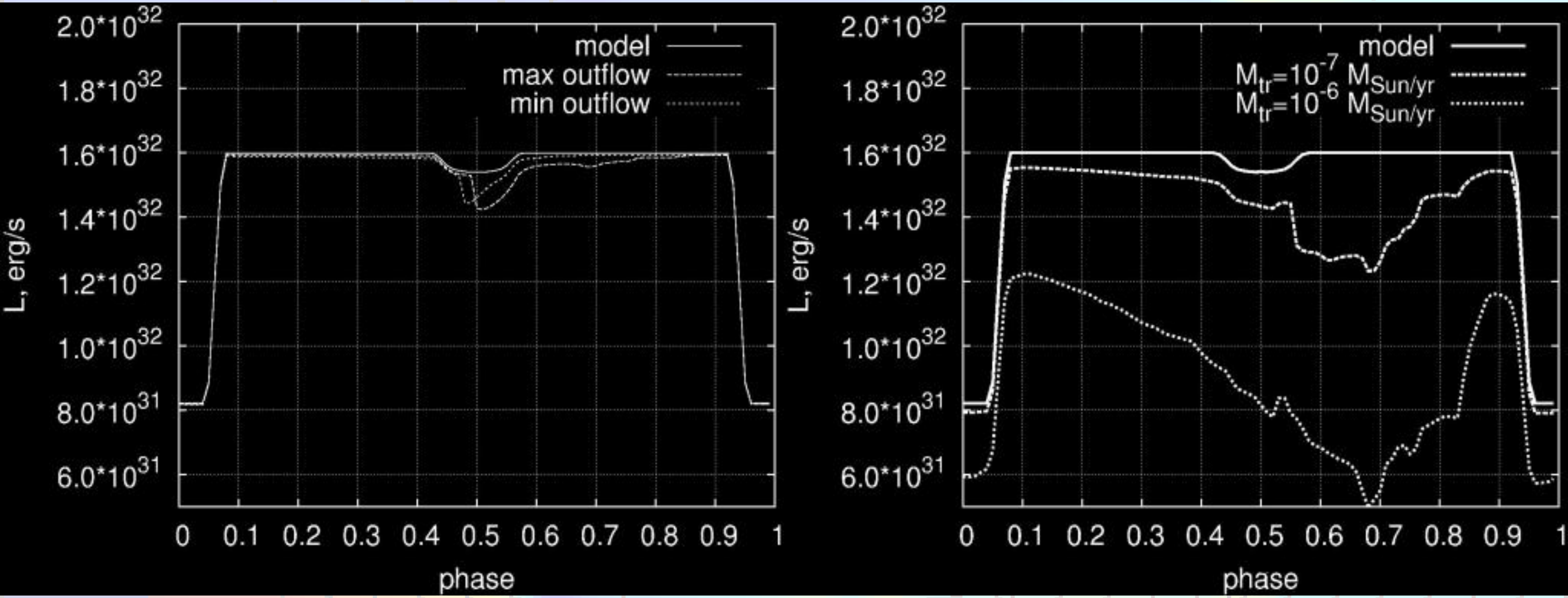
first peak

second peak

outflow into
the circumbinary
envelope


Central source

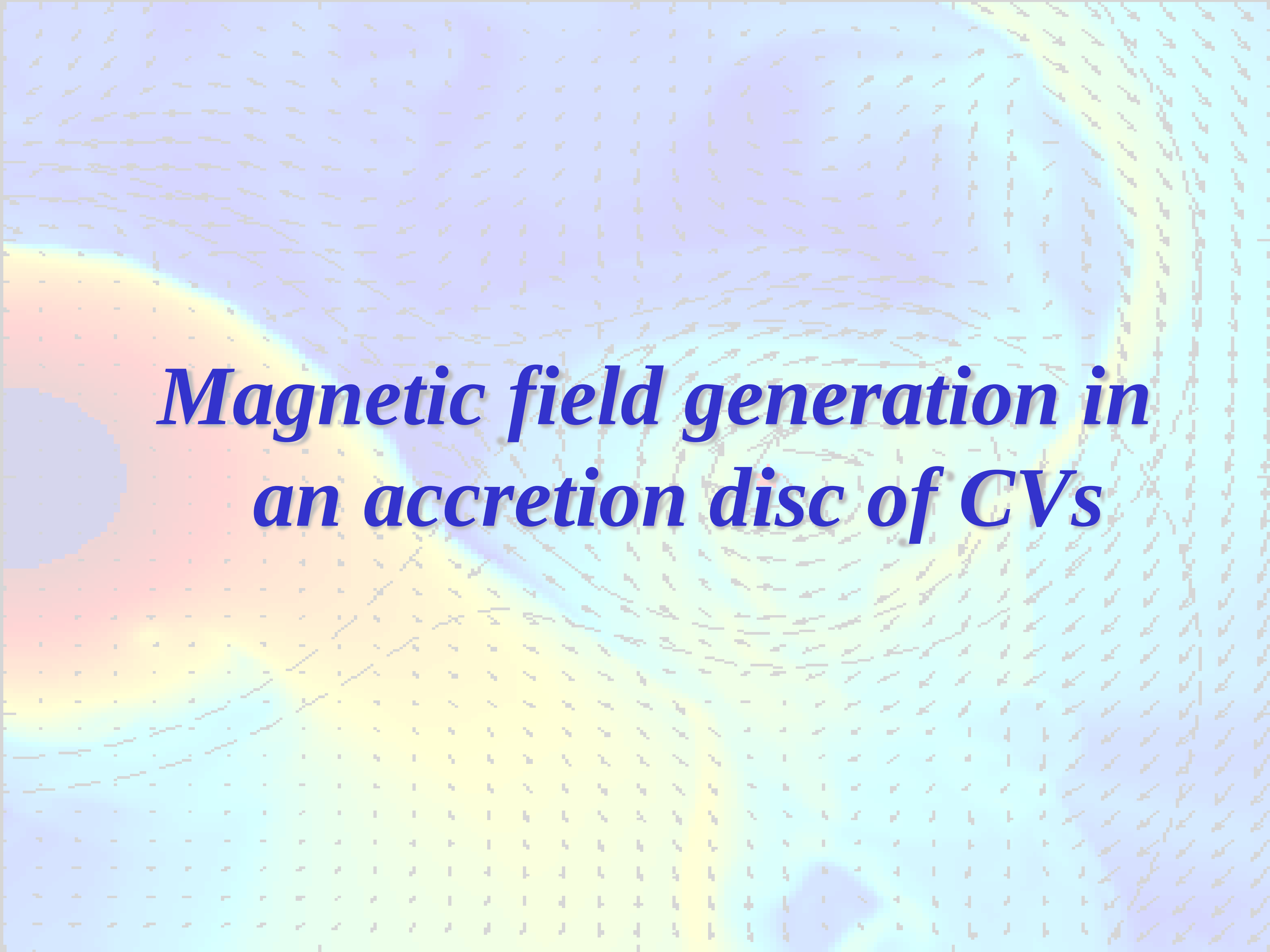
Extended envelope

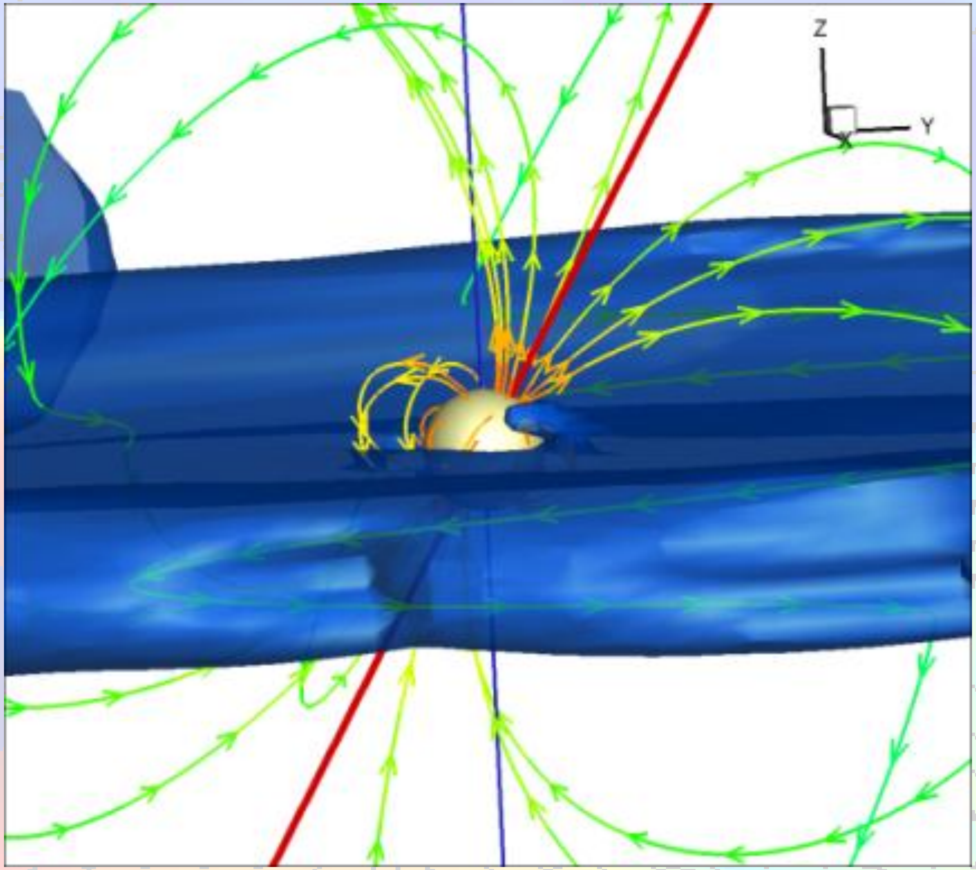


Periodic variations of positions of the disc and bow shock result in variations in both the rate of the angular-momentum transfer to the disc and flow structure near the Lagrangian point L_3. As a consequence, outer parts of the circumbinary envelope are replenished by periodic ejections from the accretion disc and circum-disc halo through the vicinity of the Lagrangian point L_3 .

Results of simulations show that the matter distribution in the envelope is substantially non-uniform in phase and in time. As a consequence the radial concentration of gas will vary depending on the phase, and this should be seen as variations of the system brightness.

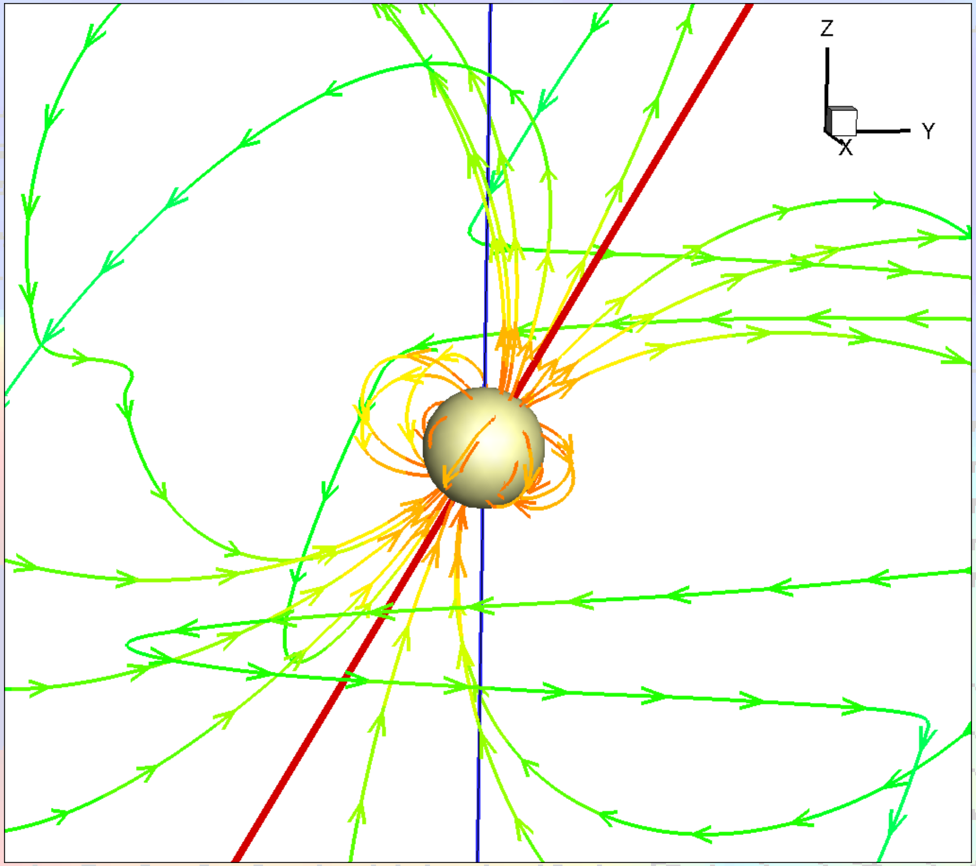
Magnetic field generation in an accretion disc of CVs





3D structure of the magnetic field around an accreting star. The color of the magnetic field lines corresponds to the value of the magnetic induction.

The magnetic field of the compact object can increase due to the differential rotation, radial movements and dynamo. The diffusion, turbulent dissipation and magnetic buoyancy can decrease the magnetic field. As a result of these effects some complex structures of the magnetic field can be formed, because a particular effect can dominate in different regions of the disc .



3D structure of the magnetic field around an accreting star. The color of the magnetic field lines corresponds to the value of the magnetic induction.

Near the surface of the star the magnetic field is close to a dipole type field. But at a large distance the magnetic field is distorted by the toroidal field generation. Near the surface of the star the magnetosphere and funnel flow are formed.

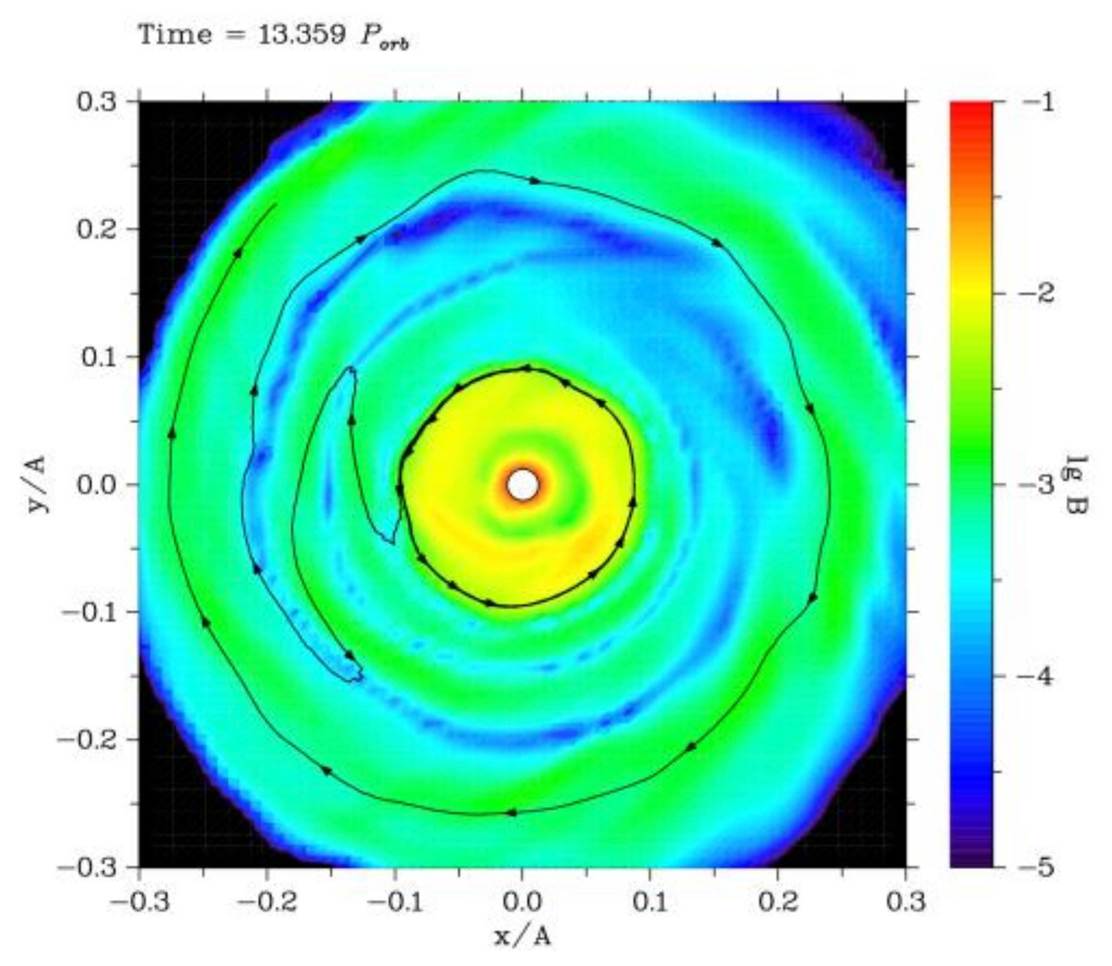
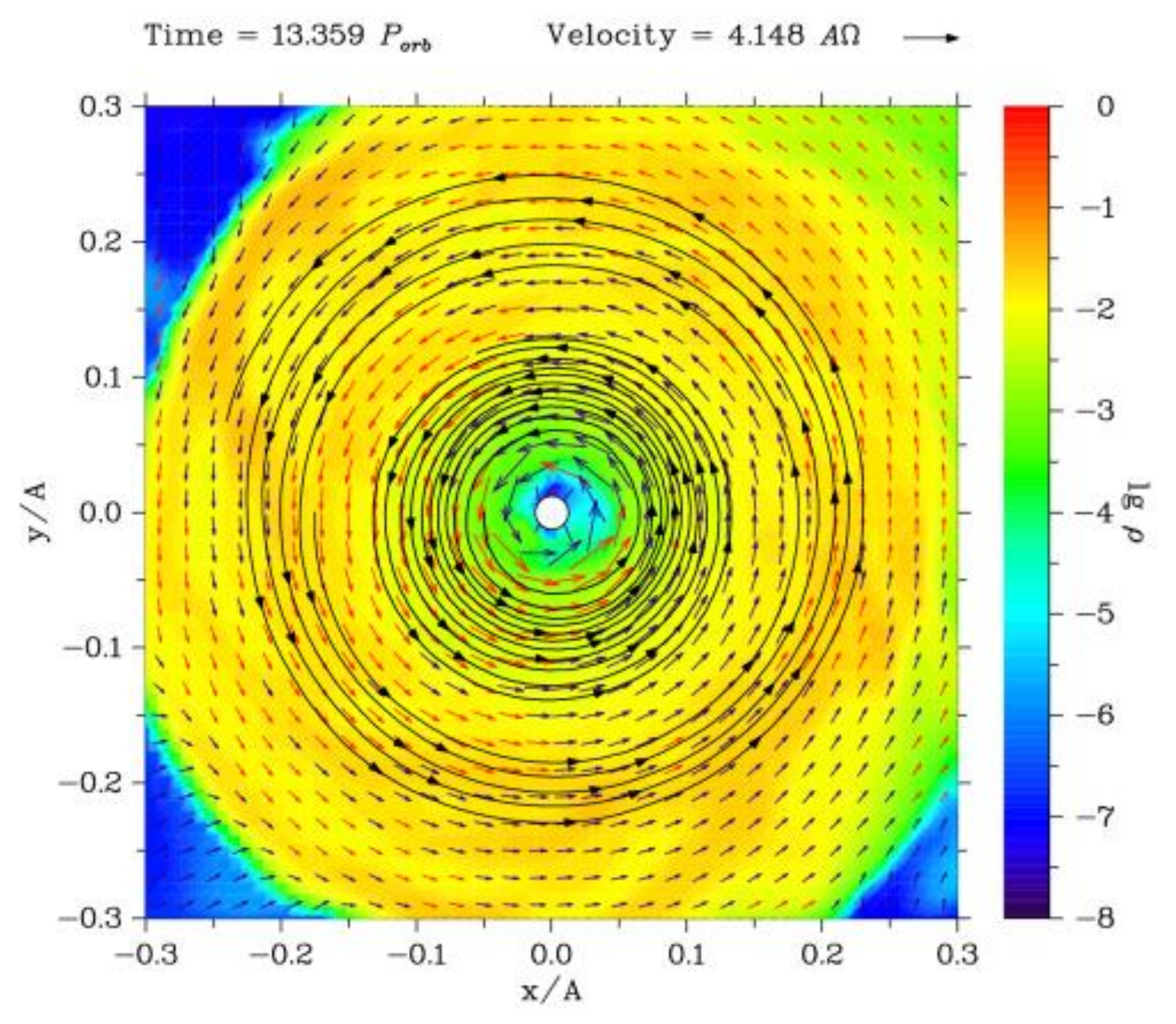


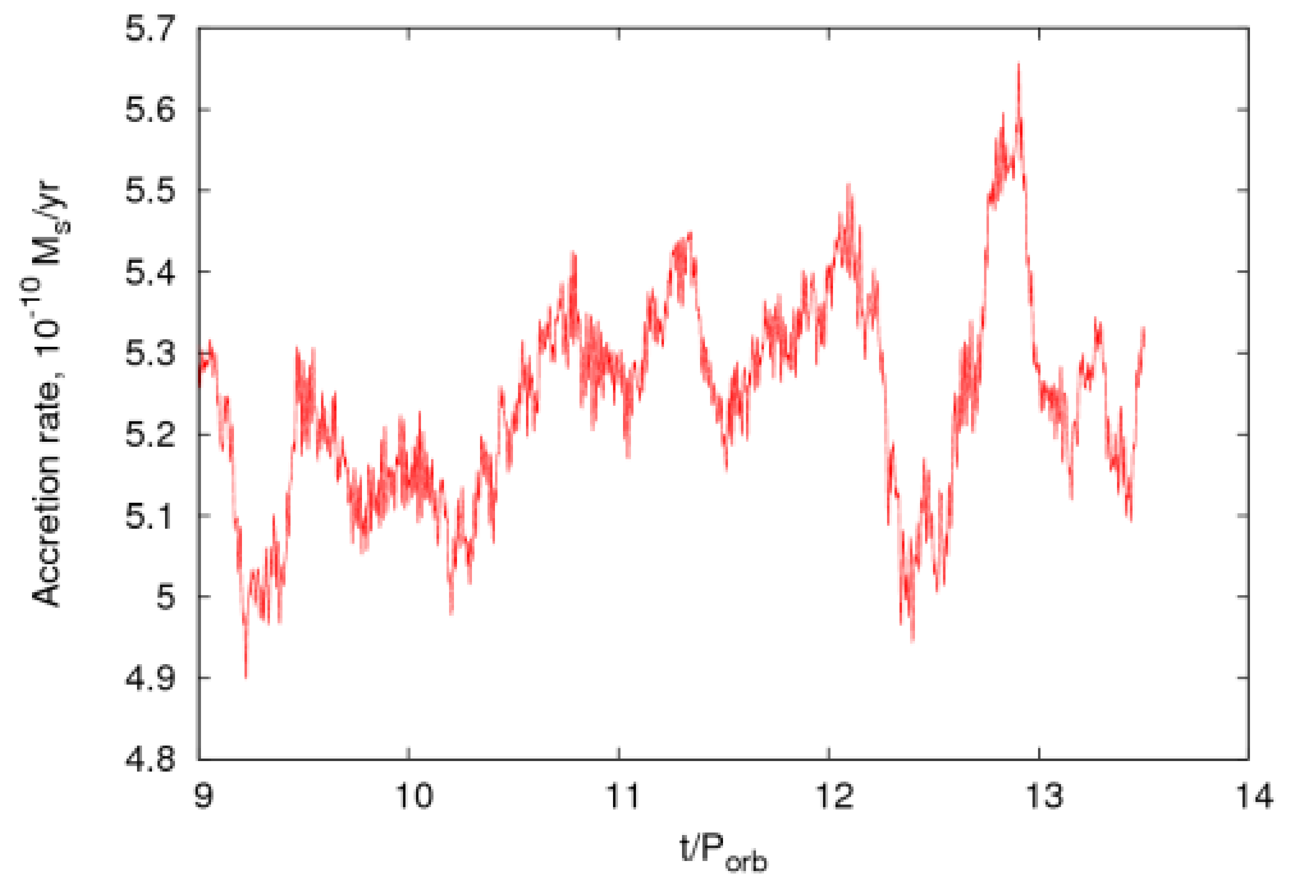
Figure shows the distribution of the magnetic induction in the equatorial plane of the disc. The magnetic field line changes its direction when it passes through the current sheet.

The current sheet is formed in the inner zone due to variations of the rotation law near the stellar magnetosphere. Further, the formed current sheet is moved outwards because of the decretion of matter. At its place the new current sheet is formed in a while. Thus in the intermediate zone several current sheets can exist simultaneously.



Distribution of density and velocity in the equatorial plane of the disc.

Forming current sheets move outwards through the disc due to decretion. Analysis of the flow lines shows that the alternation of accretion and decretion regimes occurs in the disc (especially in its inner parts).



The alternation of the accretion and decretion regimes in inner regions of the disc is concerned with the generation of the magnetic field. When the field is generated, the radial gradient of the toroidal magnetic field pressure increases and finally stops the accretion. Then the field flows outwards; the magnetic pressure decreases and accretion starts again.

The average amplitude of the accretion rate variations is about 15-25 %

Conclusions

There are a variety of different physical processes in close binaries. They are interesting both from theoretical and observational points of view and in particular they can lead to observed variability on different time scales.

To interpret the CB light curves it is necessary firstly to consider known physical processes, and draw some exotic mechanism only in case if classical physics fails.