Tilted disc formation in intermediate polars

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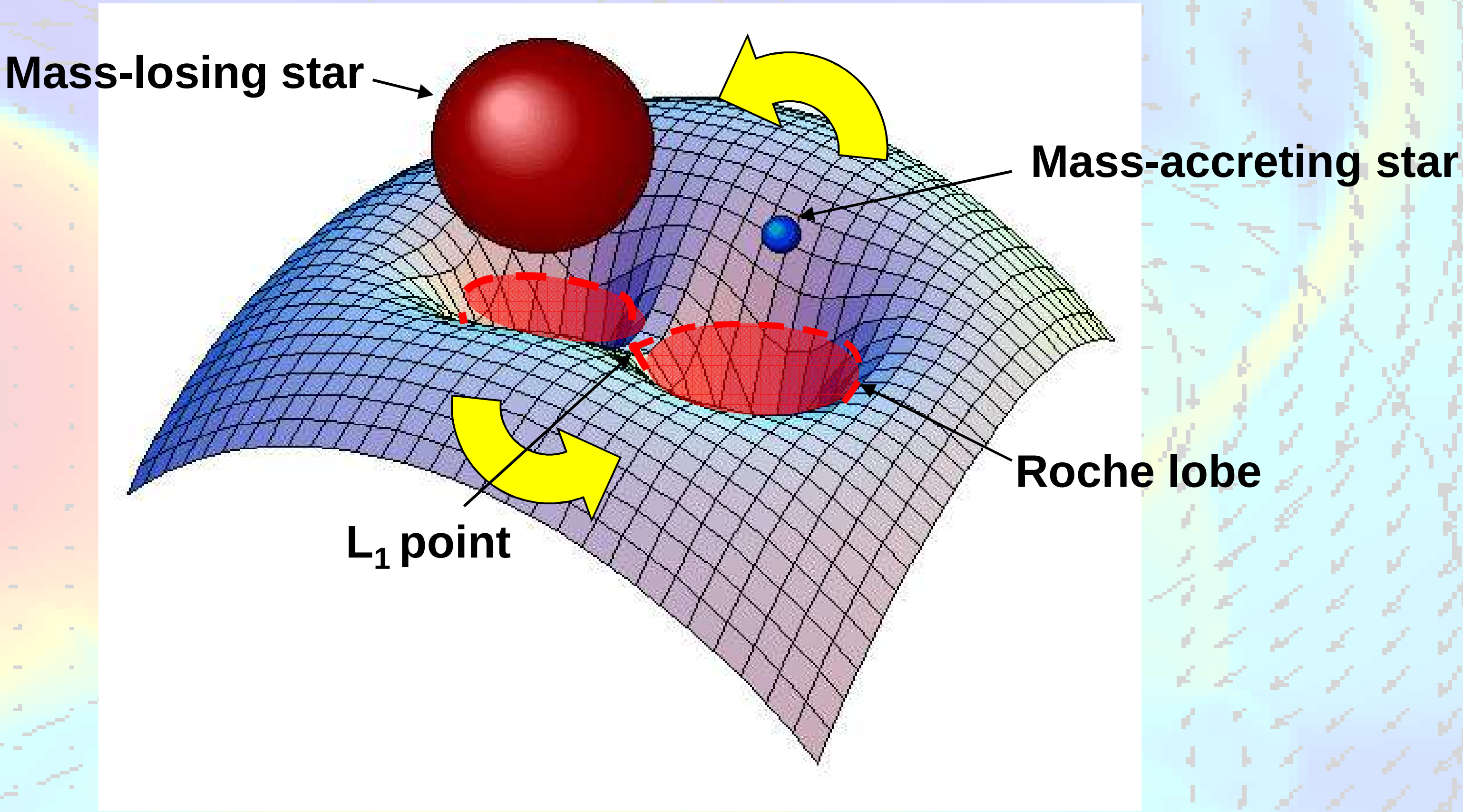
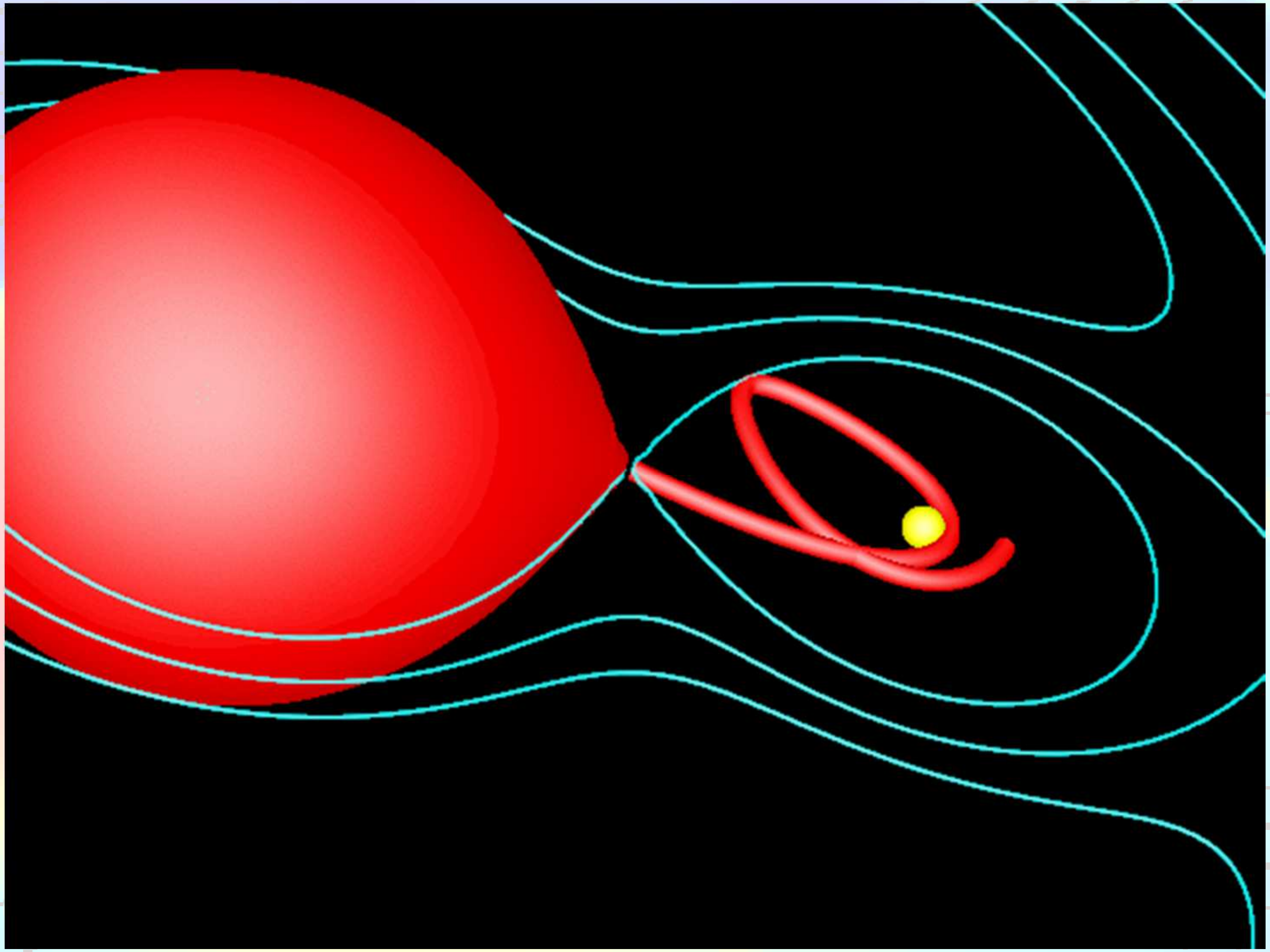
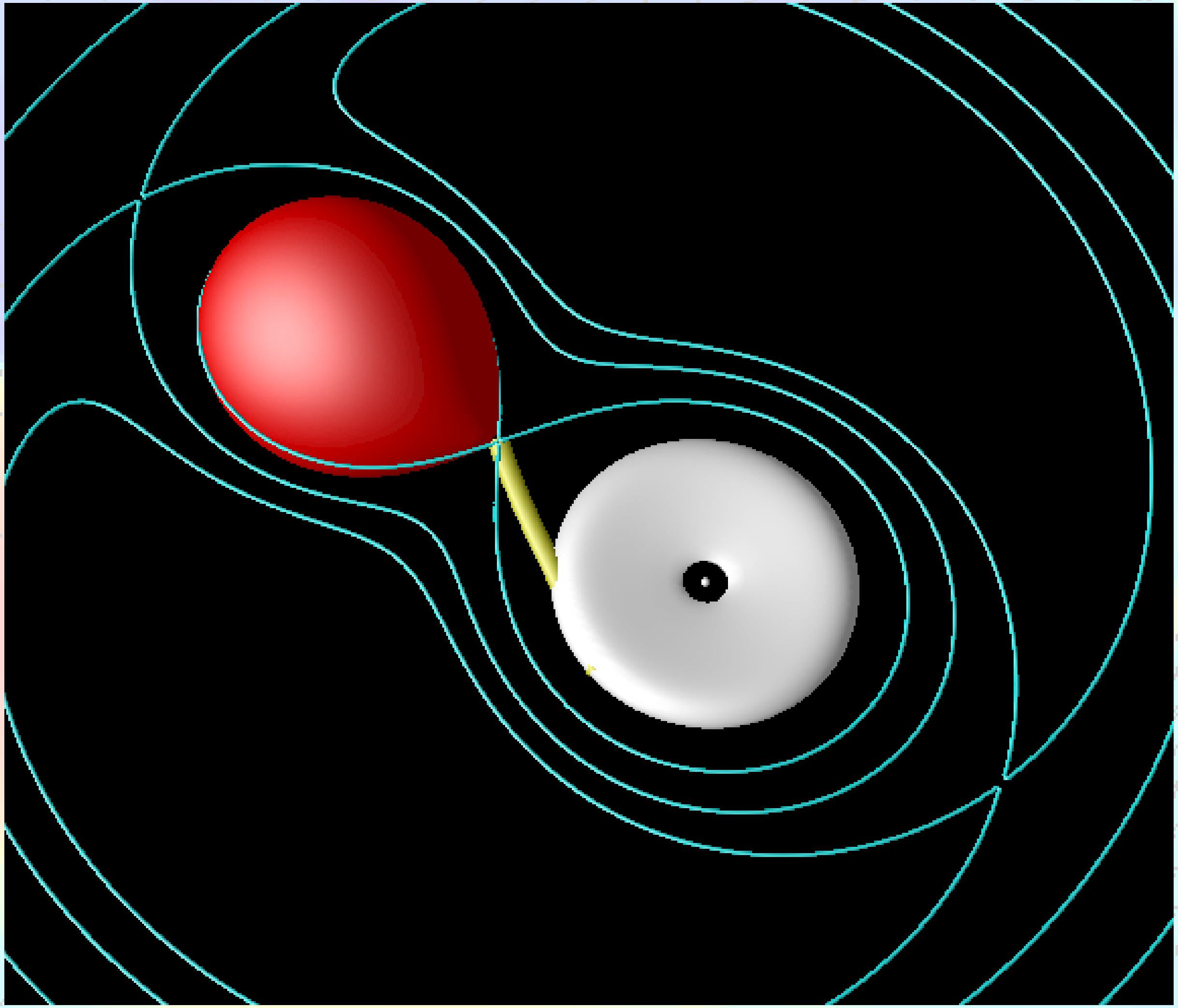
Introductory remarks

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

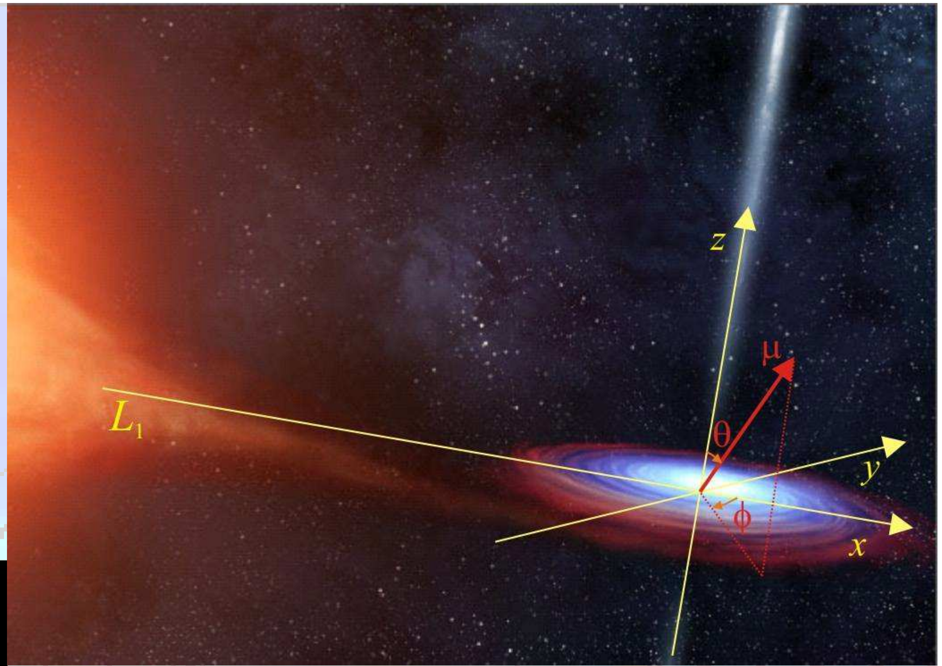


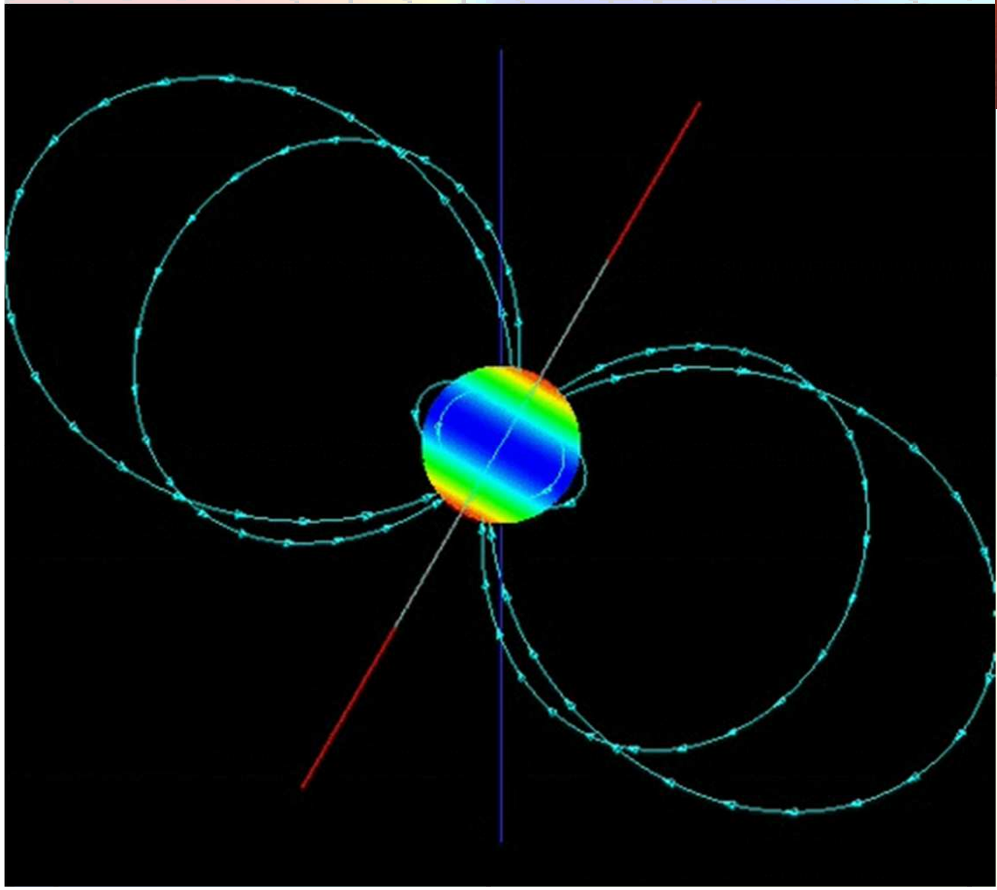


If the size of the accretor is small (WD) the gas of the stream will revolve around the gravitational center and form a dense ring.

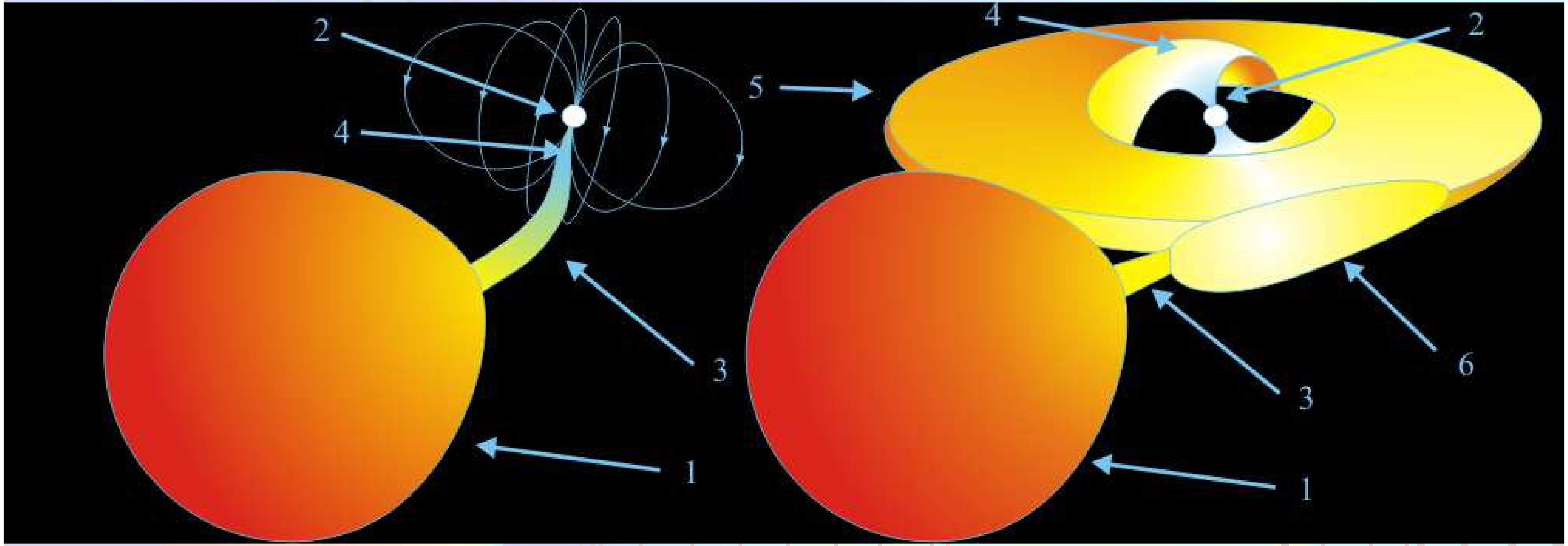


Under action of dissipation processes this ring will expand and form an accretion disc. Further redistribution of the angular momentum in the disc leads to gas accretion.





For a significant part of CVs there are observational proofs of existence of magnetic field in the system. Accretor's proper magnetic fields should change the solution significantly.

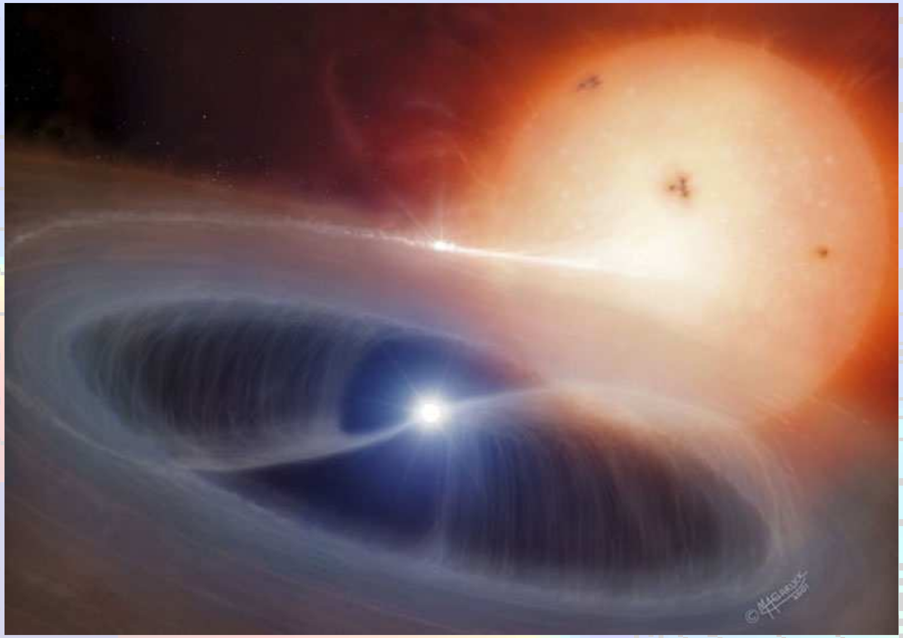


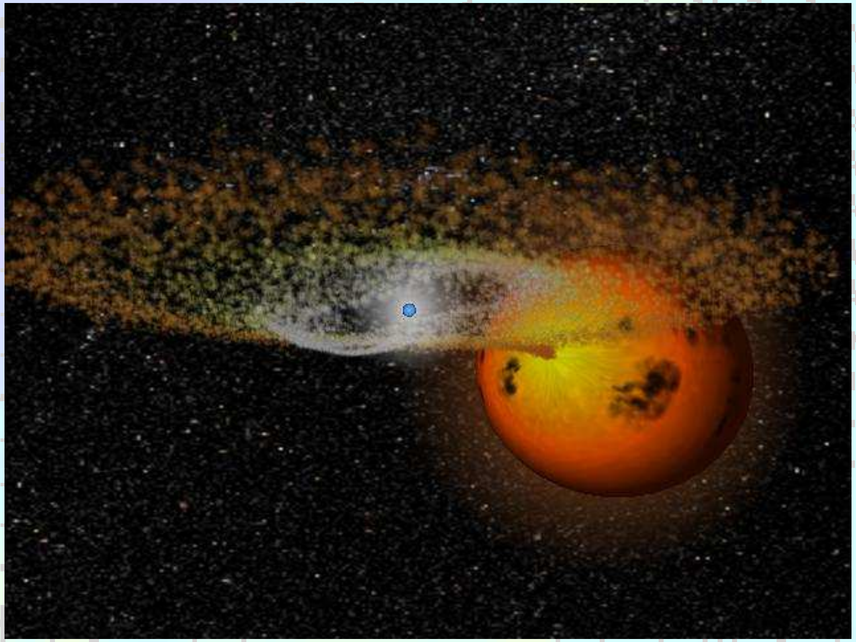
1 – donor-star, 2 – accretor, 3 – stream from L_1, 4 – accretion column, 5 – accretion disk, 6 – hot line.

Depending on the strength of magnetic field, binary systems, where the 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 strong ($B \sim 10^7 - 10^8$ G) that matter from the donor star falls directly onto the primary star along accretion columns. In intermediate polars the magnetic field is not very strong ($B \sim 10^4 - 10^6$ G) and the accretion disc forms.

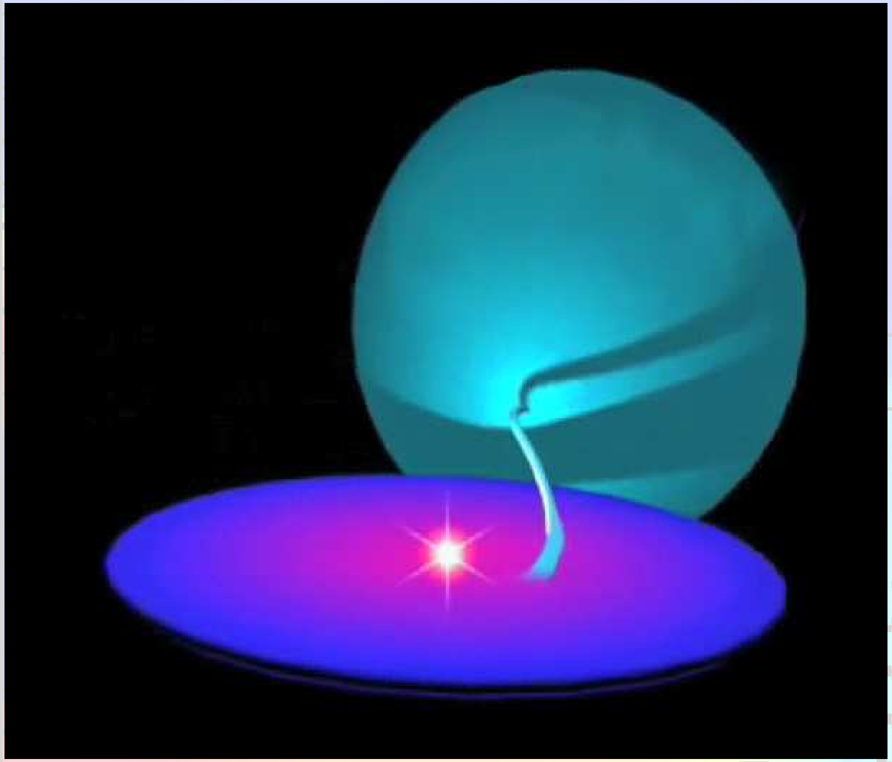
In some cases observations show that the disk in the system is tilted.

Tilted disks: observations and possible mechanisms





Tilted disks in IPs have long been suspected in many observed systems, including the IP TVCol , IP candidate RR Cha, nova XX Tau, and the IP XY Ari. Moreover in some systems (FO Aqr, PQ Gem) observations show presence of accretion curtains twisted in the retrograde direction. Recent eclipse-mapping studies of the DQ Her reveal a twisted dipole emitting pattern near the disk center.



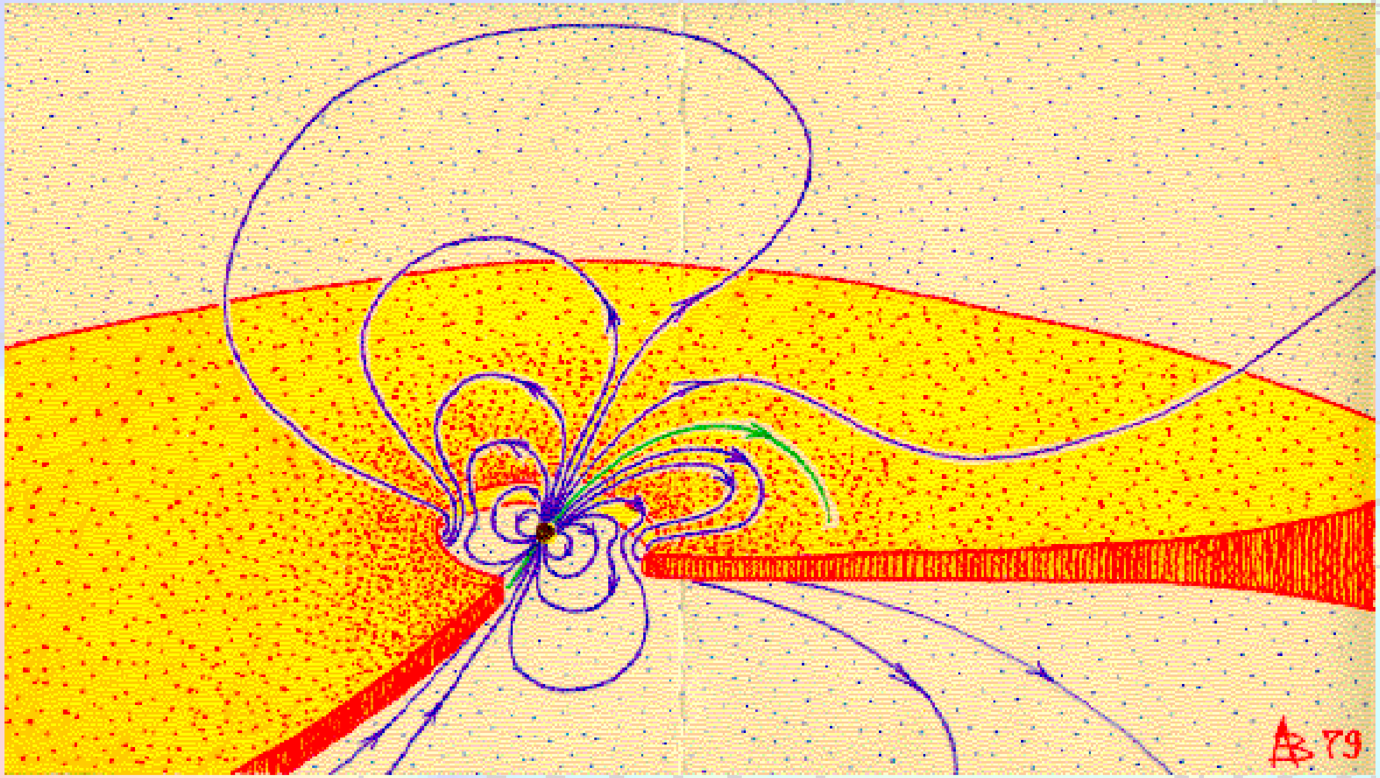
To generate a tilted, warped, or twisted disk, several mechanisms have been proposed.

1. Slave disk model.

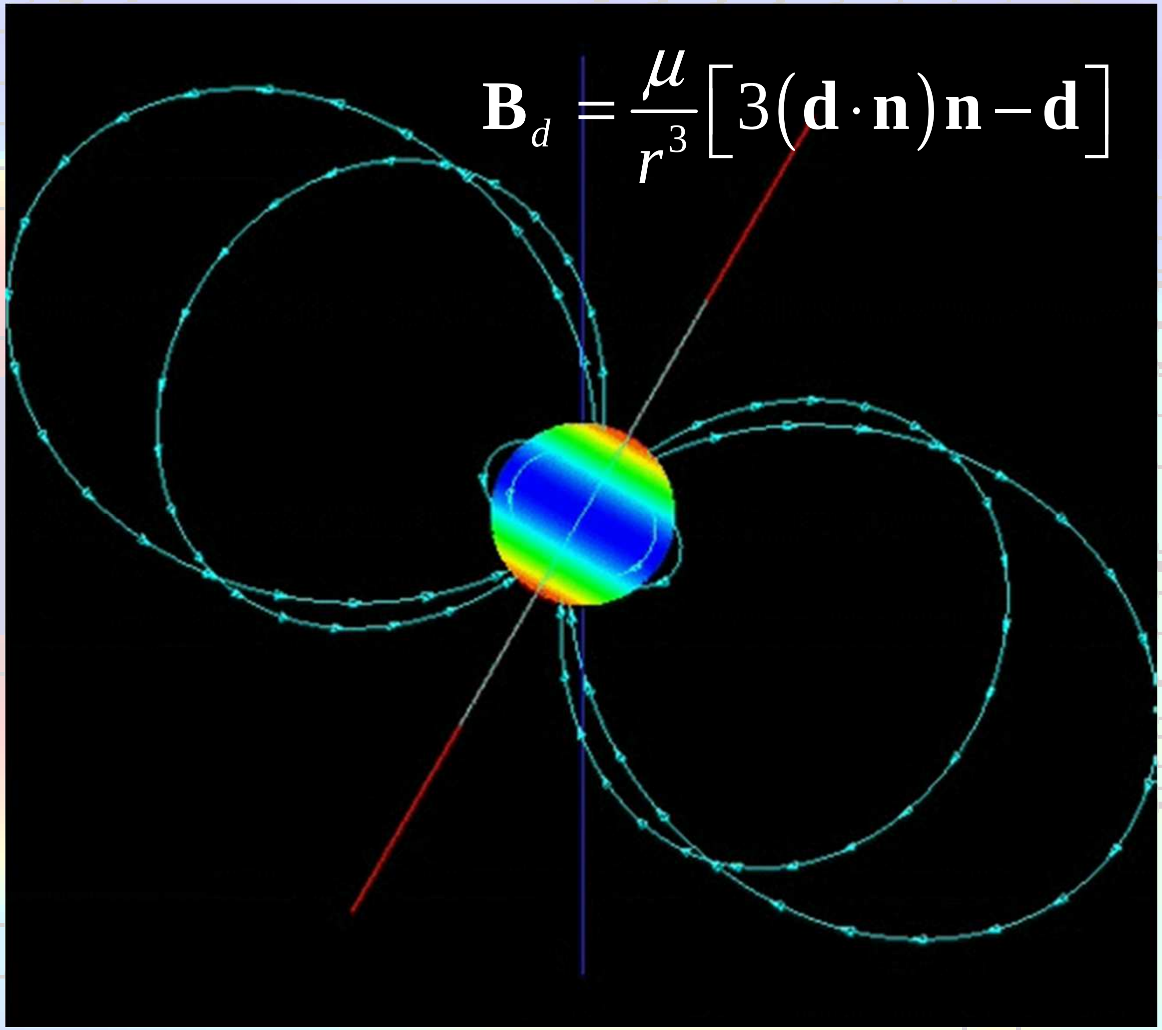
2. The disk tilt can be formed under action of the stream from the L_1 point. The disk tilt can remain constant due to the gas stream fed by the magnetic field of the secondary.

3. A disk tilt instability can result from a coupling of an eccentric instability and Lindblad resonances.

4. The disk tilt may also be induced by the lift force followed by the disk warp and disk precession.

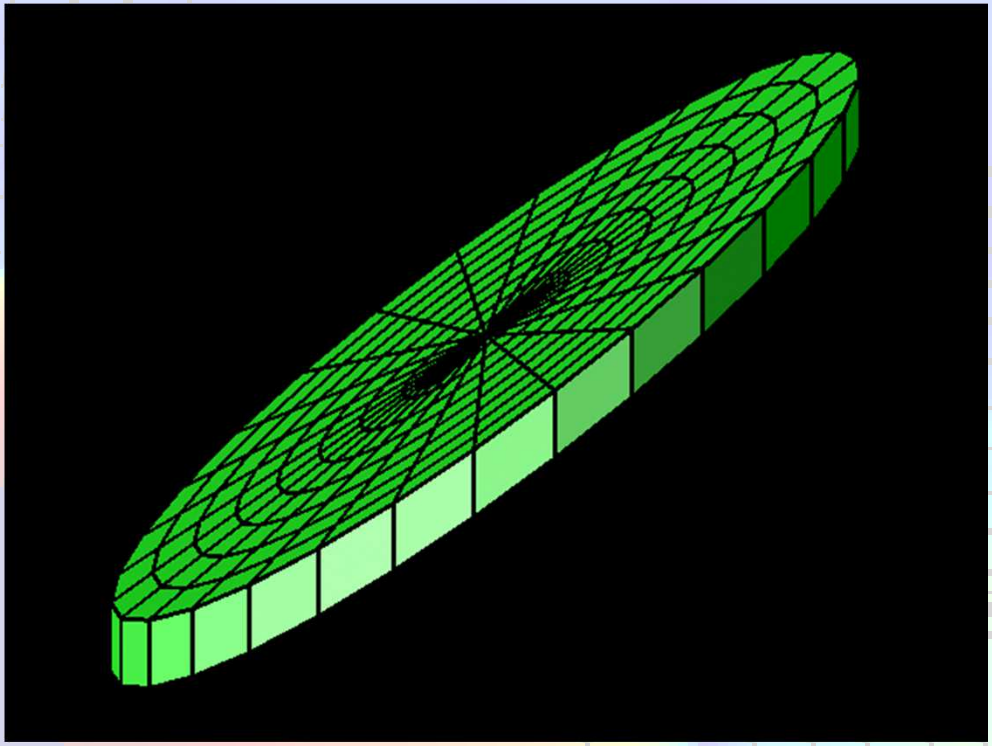


5. A warping instability can be caused by irradiation from the primary.
6. Warping can also be caused by direct tidal action of the secondary on an inclined orbit.
7. The white dwarf 's magnetic field may also distort inner regions of the disk, generating twisted accretion columns.
8. Misalignment of the magnetic field axis with respect to the spin axis of the accretor could also result in the disk tilt.



$$\mathbf{B}_d = \frac{\mu}{r^3}\left[3(\mathbf{d}\cdot\mathbf{n})\mathbf{n} - \mathbf{d}\right]$$

Let us assume that the magnetic field of the accretor is a dipole type field. Here B is magnetic induction on the surface of the primary star, μ is the vector of the magnetic moment. Let us assume that the dipole moment is inclined to the rotation axis.



If the field is a pure dipole and the disk is infinitely thin and perfectly conducting, the electromagnetic force tends to put the disk in a state where the energy of the disk/field interaction is minimal. In this state, the tilt of the disk is equal to the inclination of the magnetic field axis. The total moment of magnetic forces is

$$\mathbf{K} = \frac{8\mu^2}{3\pi R_d^3}\left(\mathbf{n}_\mu \cdot \mathbf{n}_d\right)\left(\mathbf{n}_\mu \times \mathbf{n}_d\right).$$

Note that in the frame of MHD, the dipole magnetic field is force-free and cannot directly influence the dynamics of plasma in the disk. The interaction in this case is possible due to the generation of a proper magnetic field in the plasma of the disk.

Tilted disks:
results of MHD simulations

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

$$\frac{\partial\vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v} = -\frac{\nabla P}{\rho} - \frac{1}{4\pi\rho}[\vec{b}\times(\nabla\times\vec{b})] + 2(\vec{v}\times\vec{\Omega}) - \nabla\Phi - \frac{\vec{v}_\perp}{\tau}$$

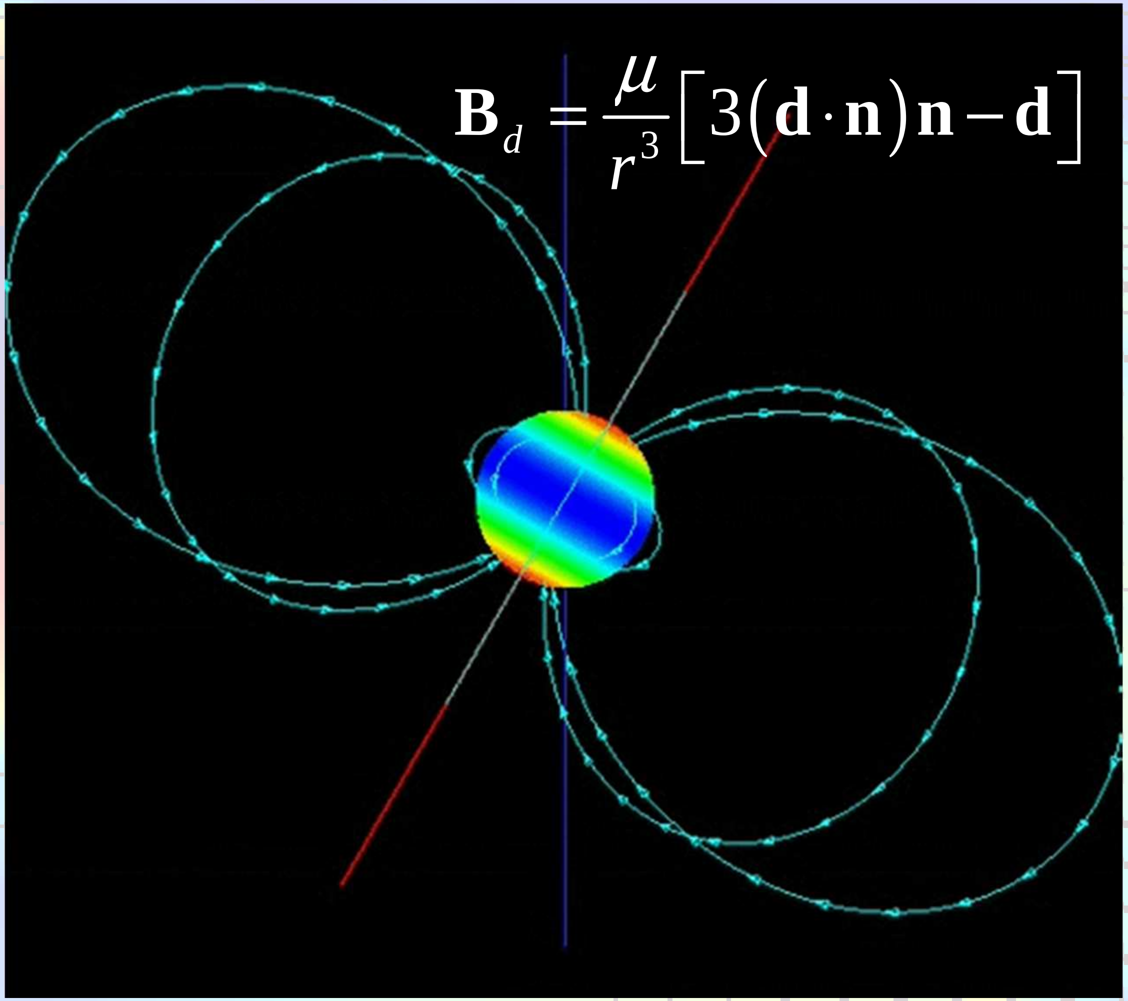
$$\frac{\partial\vec{b}}{\partial t} = \nabla\times[v\times\vec{b} + v\times\vec{B}_* - \eta(\nabla\times\vec{b})]$$

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

$$s = c_V \ln(\frac{P}{\rho^\gamma})$$

In this model, the external magnetic field acts like a fluid that interacts efficiently with the plasma. The last term in (2) can be described as friction between the plasma and magnetic field (Zhilkin and Bisikalo, 2011).

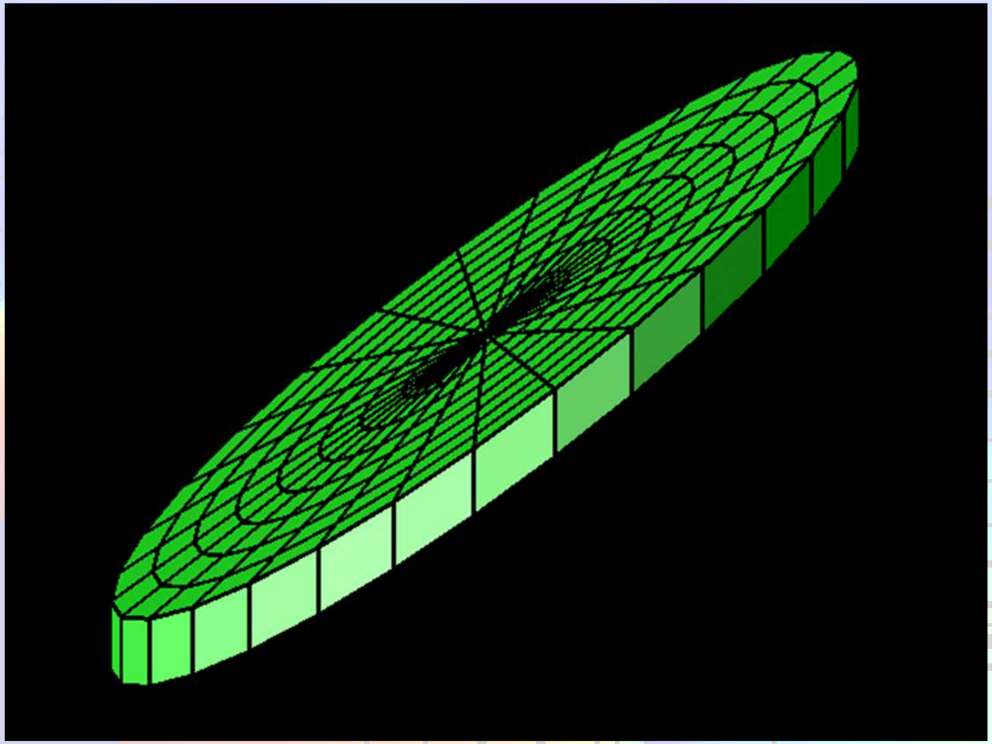
SS Cyg: M_{wd}=0.97 M_{sun}, M_{sec}=0.56 M_{sun}, P=6.6h, A=2.05 R_{sun}, c_s=7.4 km/s, $M_{ar}=10^{-9}$ M_{sun}/yr



The magnetic field of the accretor is considered to be a dipole type field.

We take the value

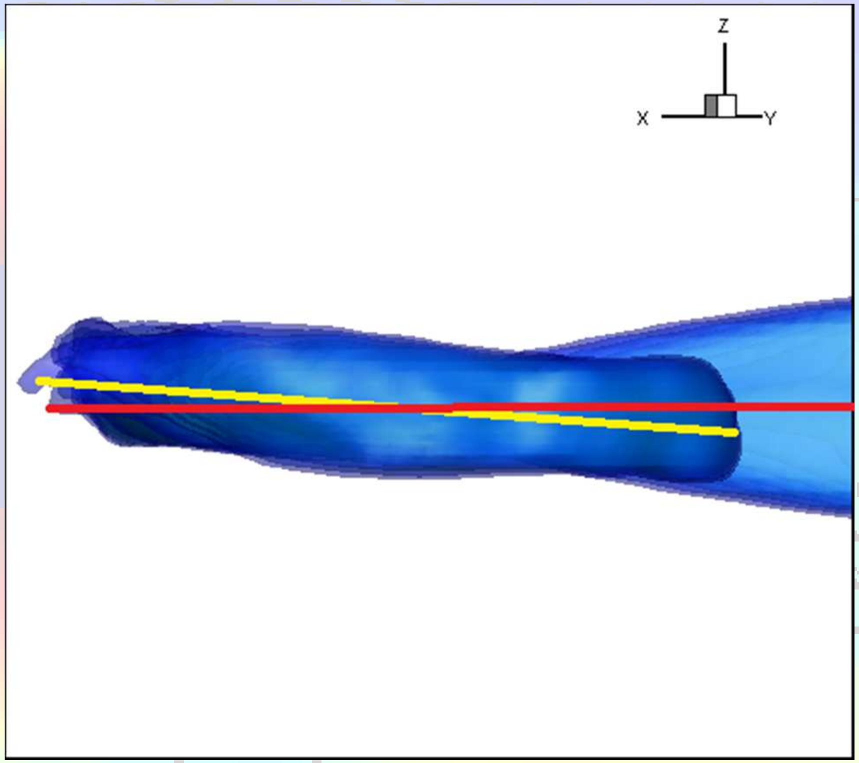
B_d = 10^5 G for magnetic induction on the surface of the compact primary star. We assume that the dipole moment is inclined to the rotation axis at some angle.



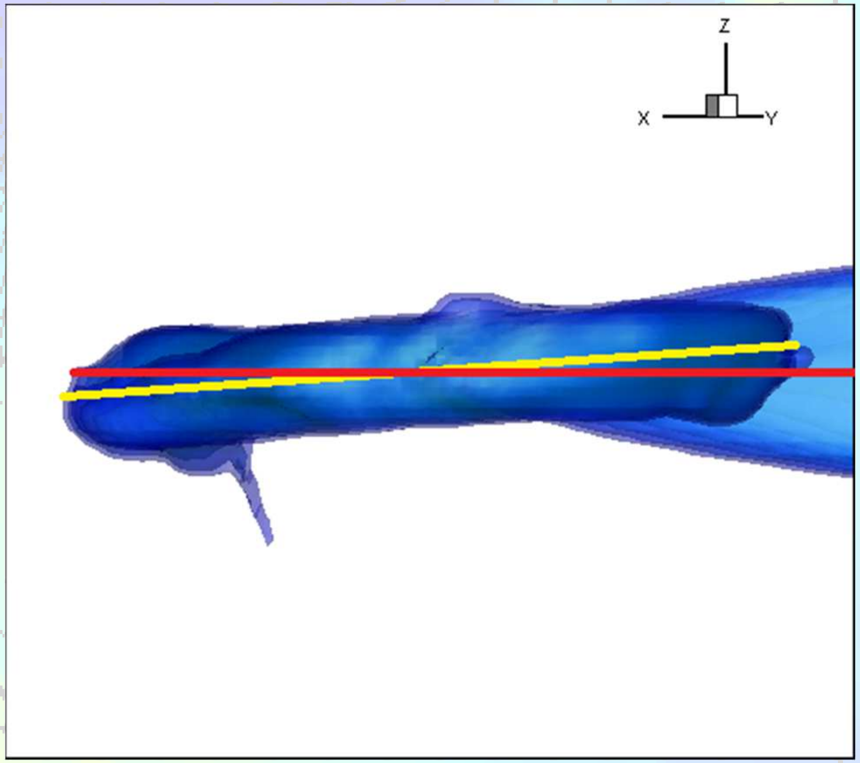
As it follows from analytical consideration, at the initial stages of disk formation, the disk's behavior is completely governed by magnetic field. The disk rests in the chosen rotating coordinate system, and rotates along with the magnetic axis in the laboratory frame.

As the mass of the disk and, hence, gas pressure, grow and magnetic field is generated in plasma, the disk becomes less controlled by the field of the accretor. As it follows from the simulations, starting at $\sim t = 2\ P_{orb}$, the disk no longer follows the accretor's magnetic field. Since the forces keeping the orientation of the disk constant disappear, the disk axis no longer moves in the laboratory frame, and the disk becomes decoupled from the field of the accretor.

$T = 4.95\ P_{orb}$

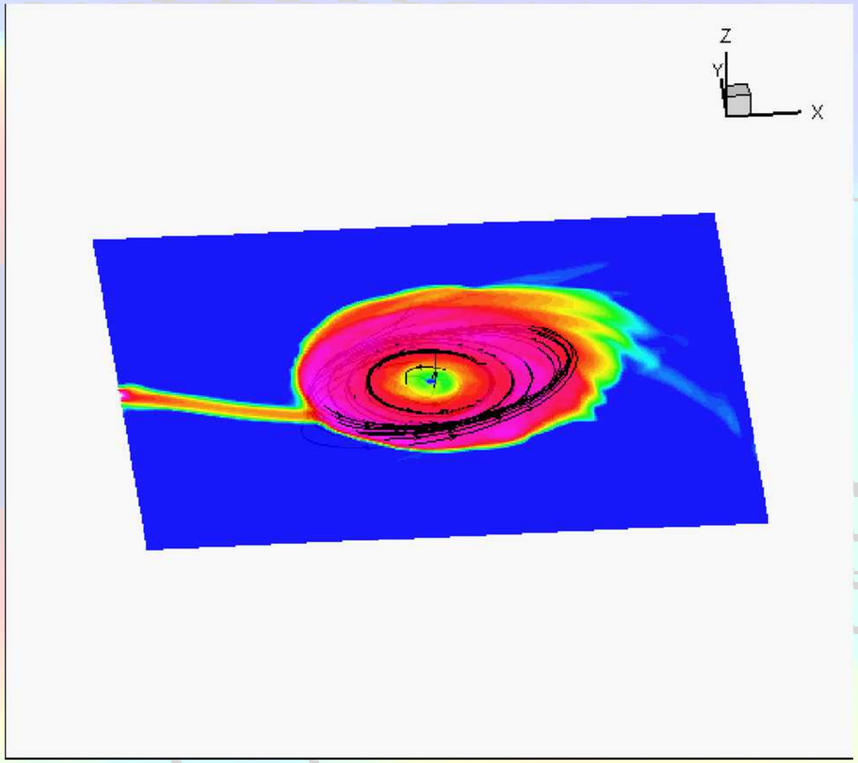


$T = 5.5\ P_{orb}$

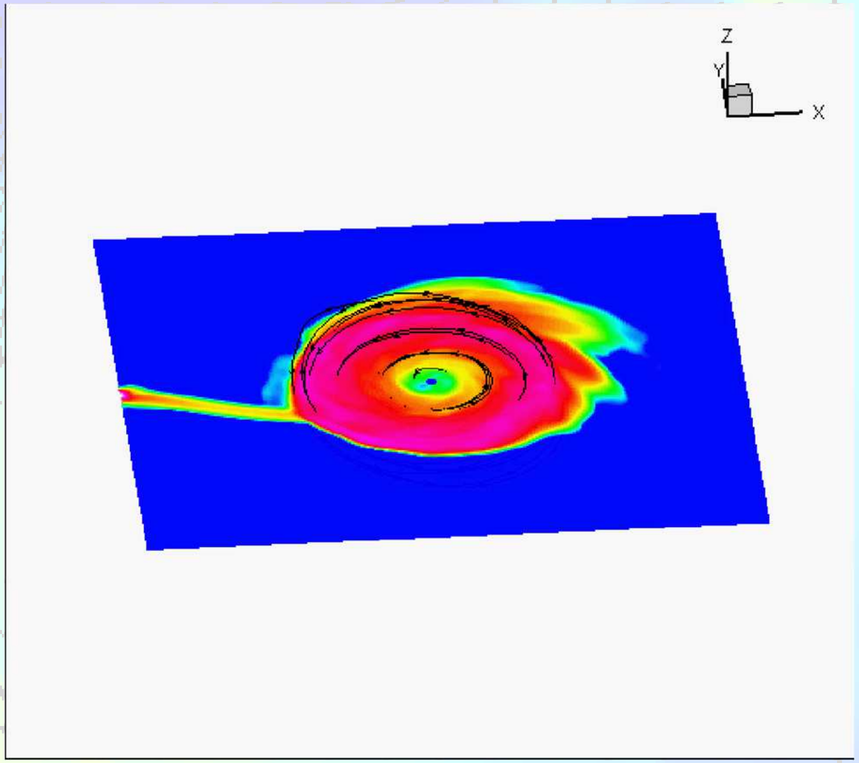


3D density isosurface of the accretion disk at a level of lg ρ = -4 for the model with $B_a = 10^5$ G. For the sake of clarity the isosurfaces are stretched by 5 times in the vertical direction.

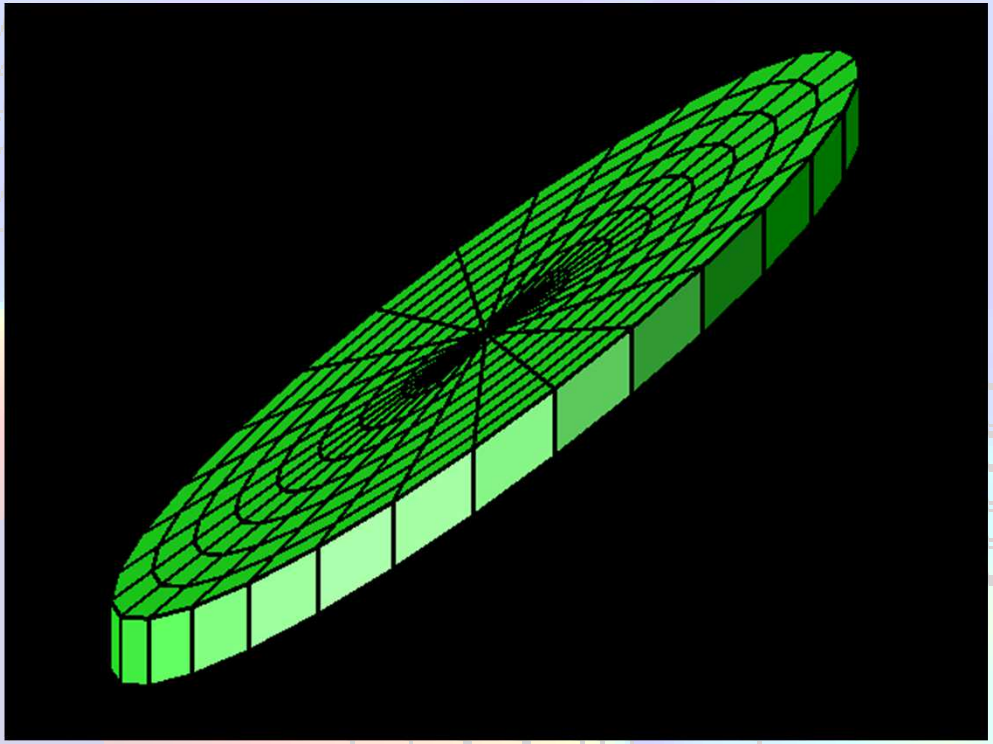
T = 4.95 P_{orb}



T = 5.5 P_{orb}



Density distribution in the equatorial plane of the binary system and streamlines in the accretion disk for the model with $B_a = 10^5$ G.



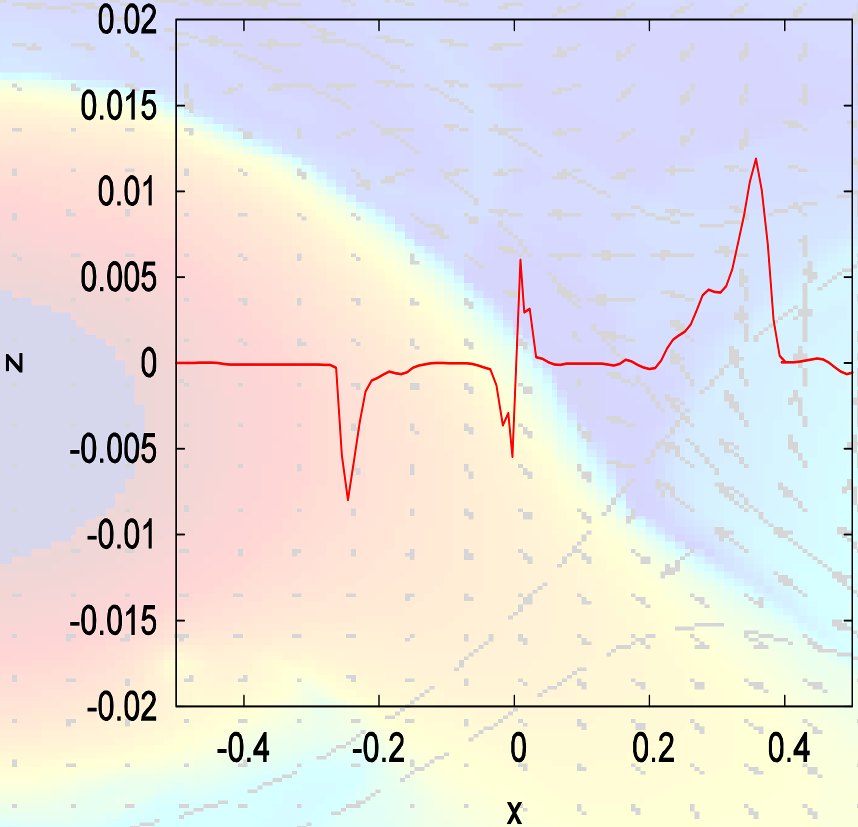
Tidal torques by the secondary, acting on a tilted, rotating accretion disk, should result in the retrograde precession of the disk. In addition to tidal torques, the torque due to the forces exerted by the accretor's magnetic field can also contribute to precession of the disk.

We can approximate the evolution of precession by treating the disk like a rigid body having moment of inertia $I = 2\pi r^3\,\Sigma\Delta r$ and angular velocity $\omega = \omega_K \mathbf{n}_d$:

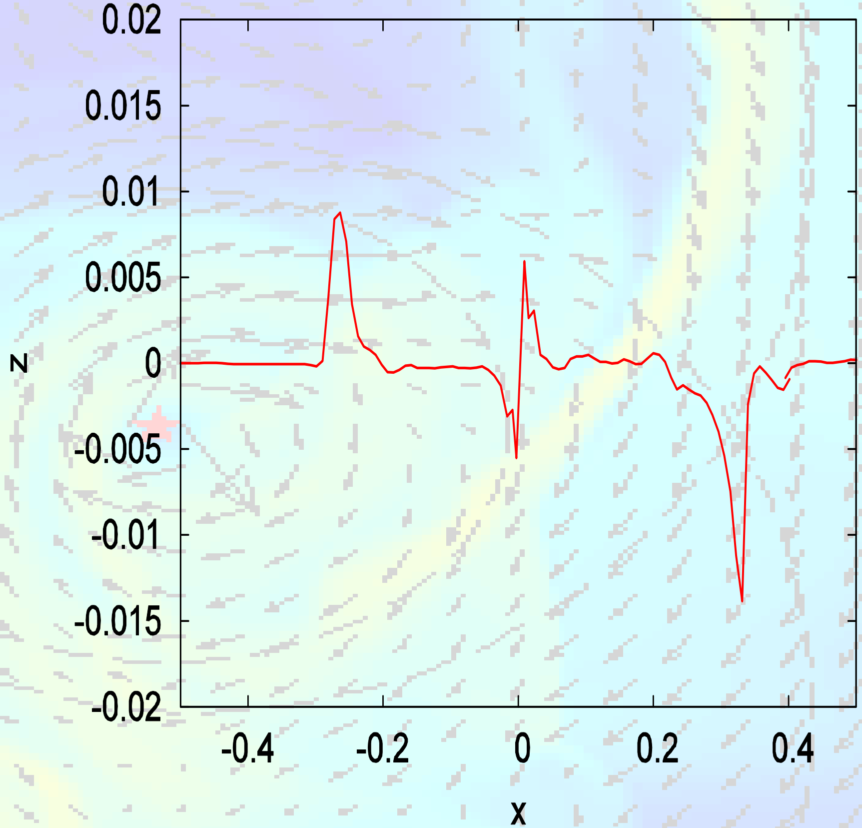
$$\frac{d\mathbf{n}_d}{dt} = \mathbf{\Omega}_{\rm pr} \times \mathbf{n}_d, \text{ where } \quad \mathbf{\Omega}_{\rm pr} = \frac{2\mu^2}{\pi^2 r^7 \Sigma \sqrt{r^2/R_d^2 - 1}} \left(\mathbf{n}_\mu \cdot \mathbf{n}_d\right)\mathbf{n}_\mu .$$

A specific ring in the disk should precess about the magnetic axis with the angular velocity Ω_{pr}, and the disk becomes twisted.

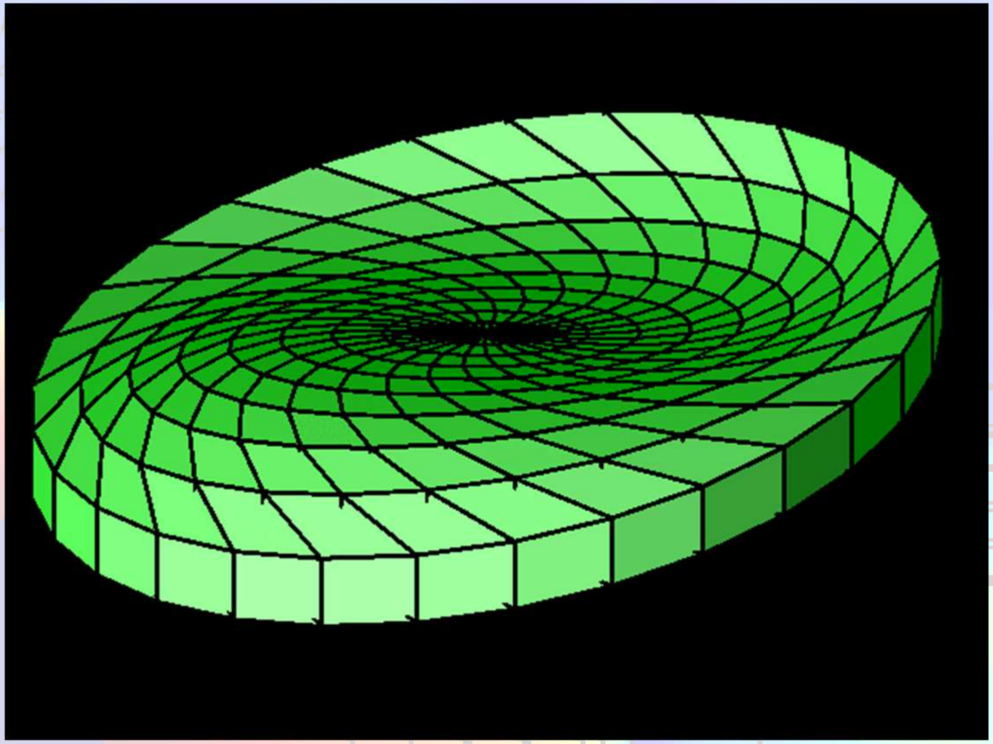
T = 4.95 P_{orb}



T = 5.5 P_{orb}



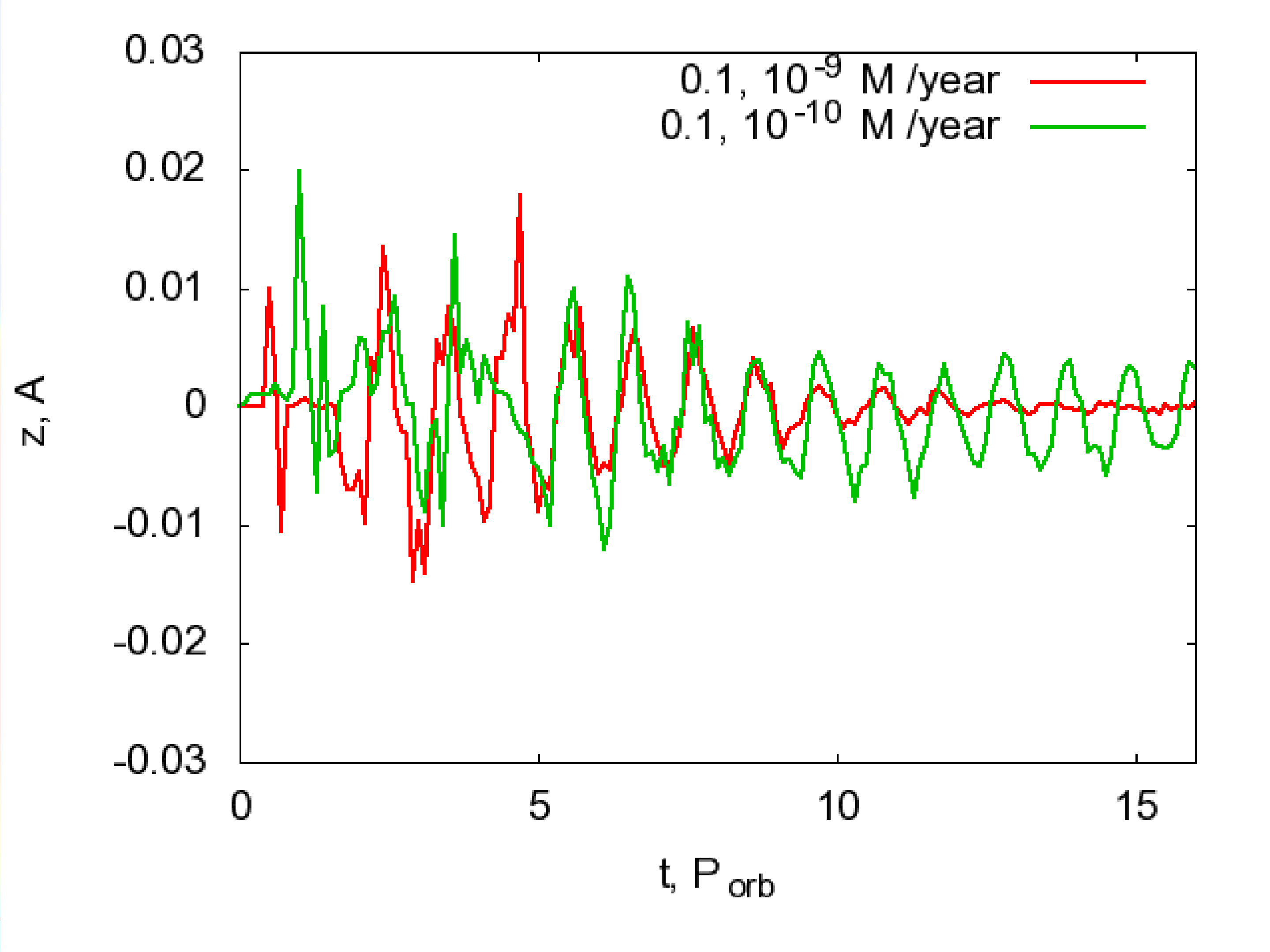
Distribution of the heights of the centers of mass of disk rings along the L_1 - L_3 line . The accretor is located at a point with the coordinates (0,0); the inner Lagrange point is on the left.



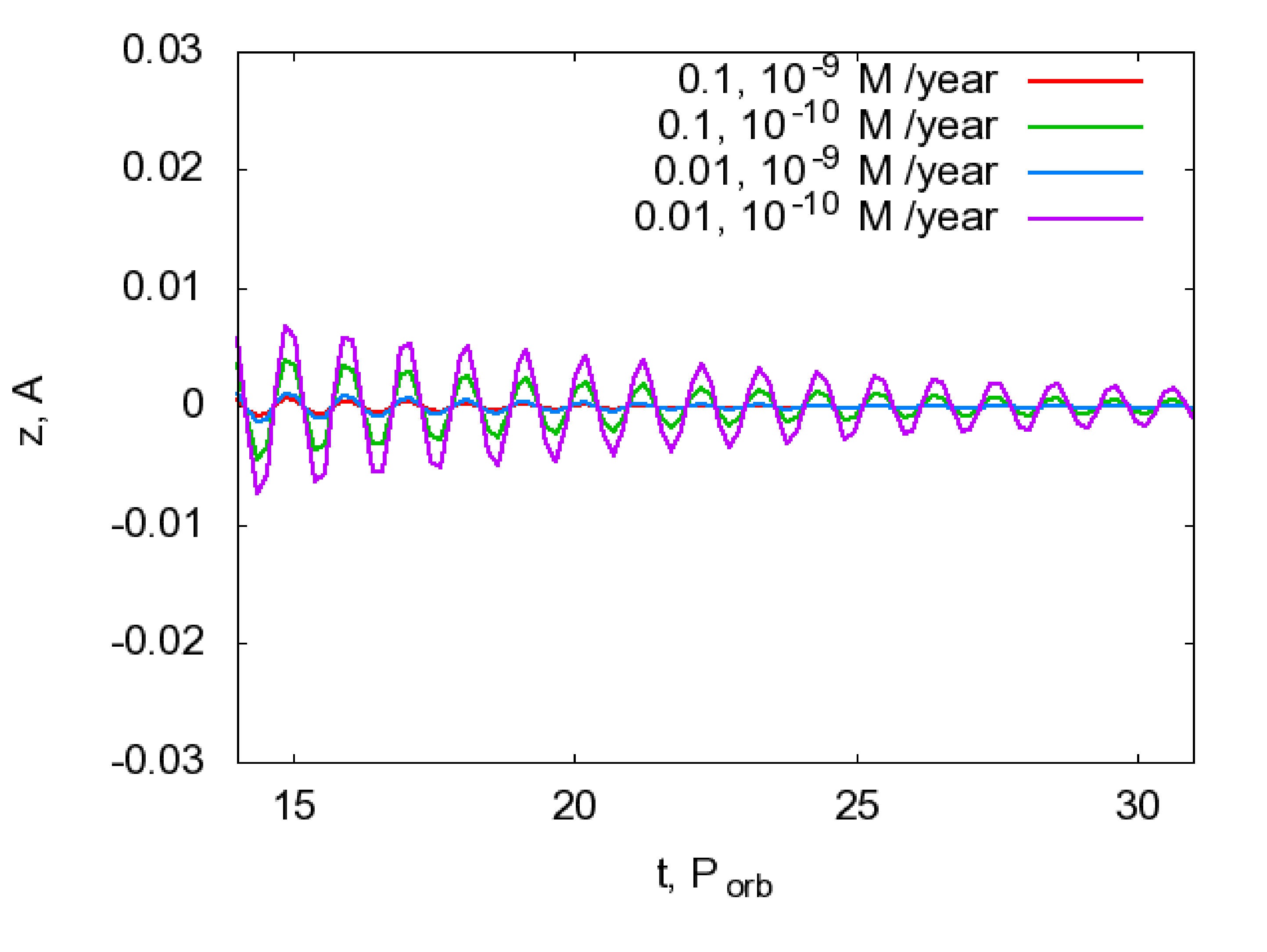
Once the disk is de-coupled from the accretor's magnetic field, its evolution is governed by three forces: viscosity, gravitational perturbations and the gas stream. The initially tilted disk becomes twisted, then warped, and finally the disk returns to the orbital plane.

Since the inner regions of the disk are constantly fed with matter, the inner disk radius grows, and the width of the tilted, twisted, warped outer ring decreases. Over time, the co-planarity of the disk propagates from the inner to outer regions. When the radius of the inner disk reaches the last stable orbit, the accretion disk completely loses its tilt and twist.

What is thy lifetime of the disk tilt?



Time dependence of the height of the center of mass of the disk region with coordinates (0.3A, 0, 0).



Time dependence of the height of the center of mass of the disk region with coordinates (0.3A, 0, 0) for different values of viscosity.

Conclusions

- *Using 3D gas dynamics, we numerically simulate accretion disk formation in typical IPs with dipolar magnetic fields ($B_a \sim 10^5$ G) and misaligned white dwarf magnetic and rotation axes.*

- *Our simulations confirm that a significant misalignment of the axes results in a significant misalignment of the disk with respect to the orbital plane.*

- *However, over time, this disk tilt disappears: early in the simulations, the initial particle positions in the rarefied tilted disk are governed solely by the magnetic field of the white dwarf. Due to the increasing disk mass and, hence, increasing disk gas pressure, the tilted disk eventually becomes decoupled from the magnetic field.*

Conclusions

- *The tidal action of the donor leads to a retrograde (i.e., nodal) precession of the tilted disk's streamlines, and the disk becomes twisted.*

- *When the disk tilt is greater than 4°, the incoming gas stream no longer strikes the disk rim. Matter is now transported over and under the disk rim to the inner regions of the disk. Over time, the increased mass of inner parts of the disk due to the action of the colinear gas stream returns the inner-disk regions to a colinear configuration. Meanwhile, the outer regions of the tilted, twisted disk become warped.*

- *Our simulations suggest that the lifetime of an intermediate polar's tilted disk could be several tens to thousands of orbital periods*.