Wind-magnetosphere interaction in binary pulsar J0737-3039B

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Outline:

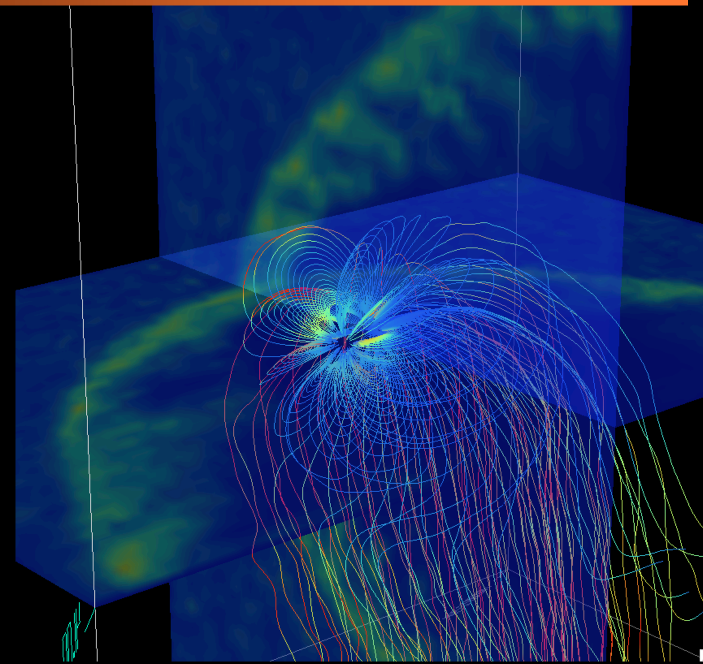
1. Observational review of J0737-3039: outstanding questions

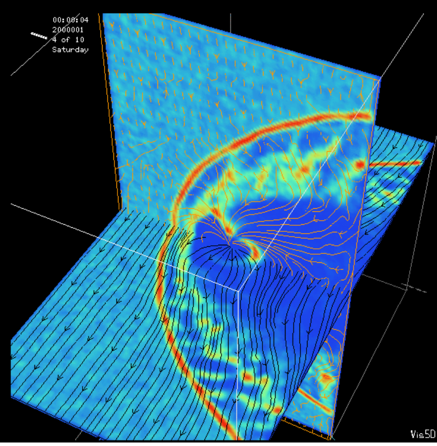
2. Wind-magnetosphere interaction model

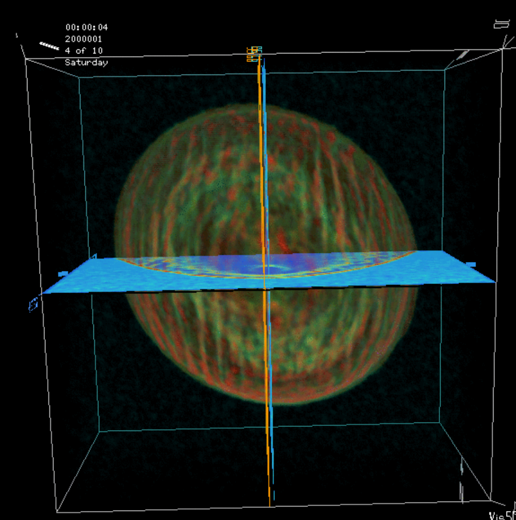
3. Applications to observations

   a) Nature and shape of eclipses
   b) Torques on PSR B
   c) Emission of PSR B

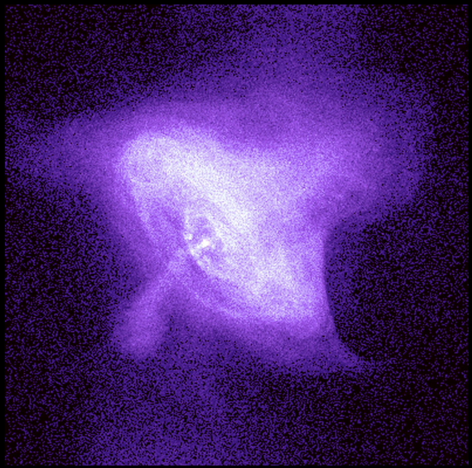
4. Successes and difficulties of the model

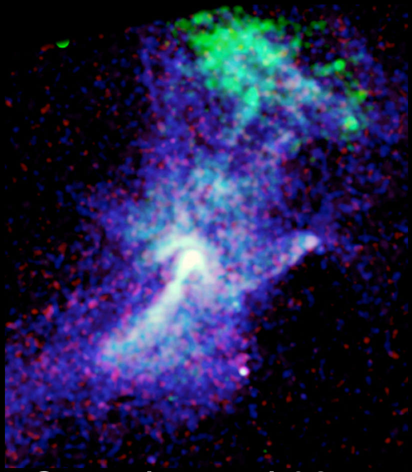


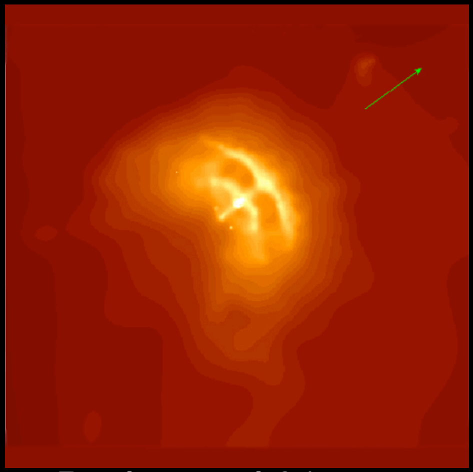




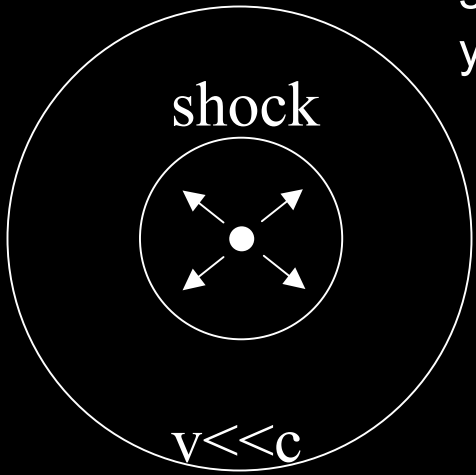
Pulsar winds


Weisskopf et al 00


Gaensler et al 02


Pavlov et al 01

Most of the pulsar energy is lost in the invisible wind. Our main source of information about the wind is Pulsar Wind Nebulae in young supernova remnants.

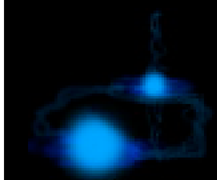


Properties of pulsar winds:

- Highly relativistic ($\gamma \sim 10^6$)
- Kinetic energy dominated at the nebula ($\sigma \sim 10^{-3}$)
- Pole-equator asymmetry and collimation

What are pulsar wind properties at the source?

PSR J0737 A&B - A Laboratory for Late Stellar Evolution, General Relativity and Relativistic Winds and Magnetospheres



Pulsar A

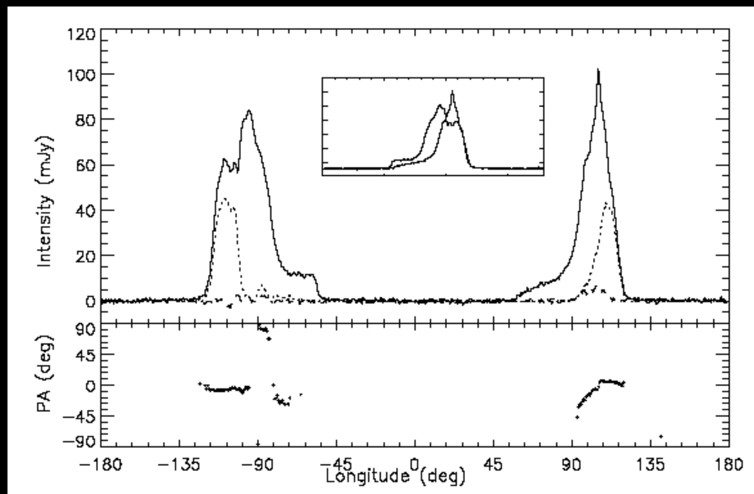


FIG. 1.— Polarization characteristics of J0737–3039A at 0.82 GHz. The inset gives the two portions of the profile 'mirror-folded' to show similarity of outer edges. See text for details.

$$P_A = 22.7\ \mathrm{msec},\ \dot{E}_A = 6 \times 10^{33}\ \mathrm{ergs/s}$$

$$P_B = 2.77\ \mathrm{sec},\ \dot{E}_B = 2 \times 10^{30}\ \mathrm{ergs/s}$$

$$R_{LA} = 1098\ \mathrm{km},\ R_{LB} = 132{,}400\ \mathrm{km}$$

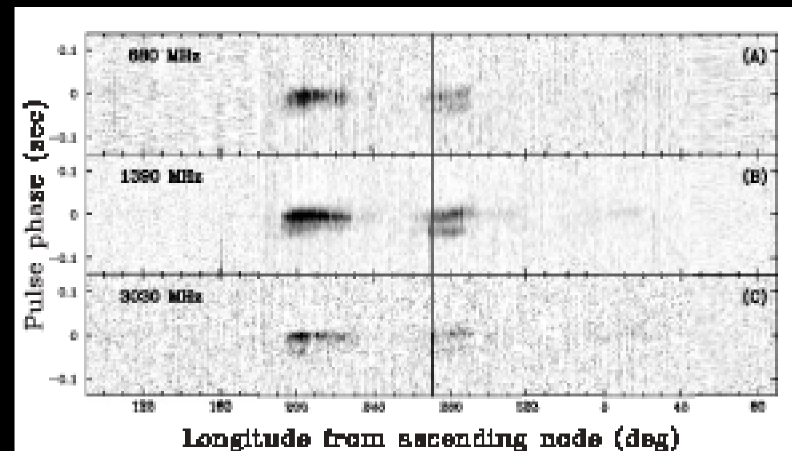
$$B_A = 6.3 \times 10^9 G,\ B_B = 1.6 \times 10^{12} G$$

$$2a = 850{,}000\ \mathrm{km}$$

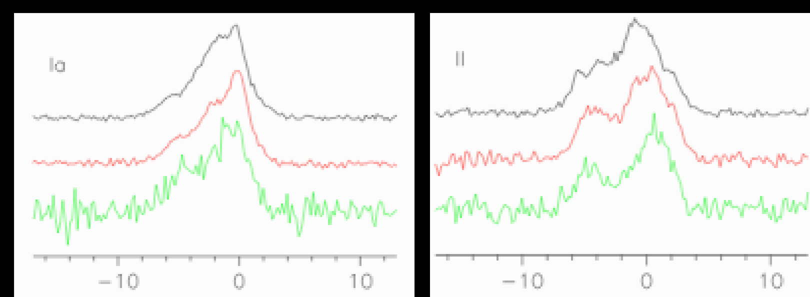
Lyne et al (2004)

Mass is known for both NSs! M_A=1.34 $M_\odot$, M_B=1.25 $M_\odot$
Heaven for GR and evolutionary studies!

Pulsar B



Pulsar B brightness as a function of rotation phase (vertical axis) and orbital phase (horizontal axis) - - Lyne et al (2004 - discovery paper)

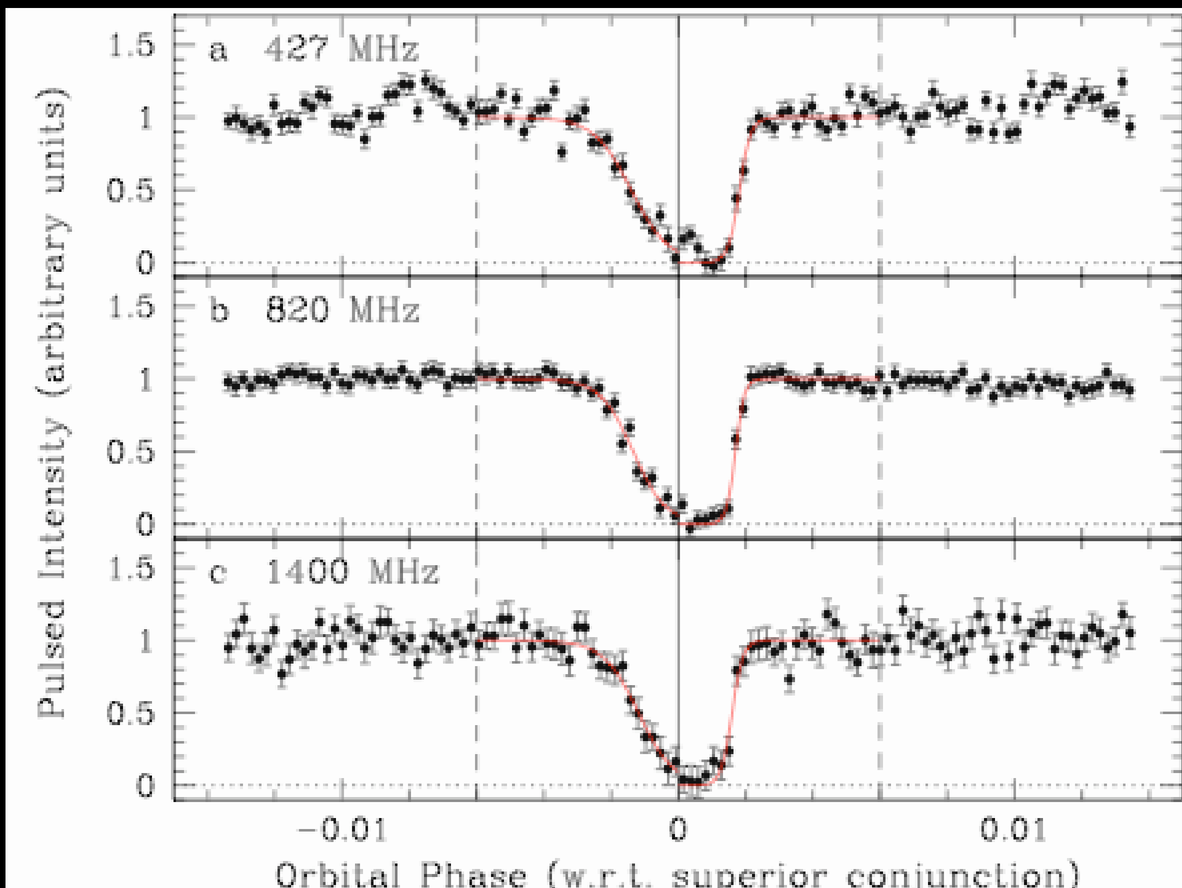


Ramachandran et al 2004

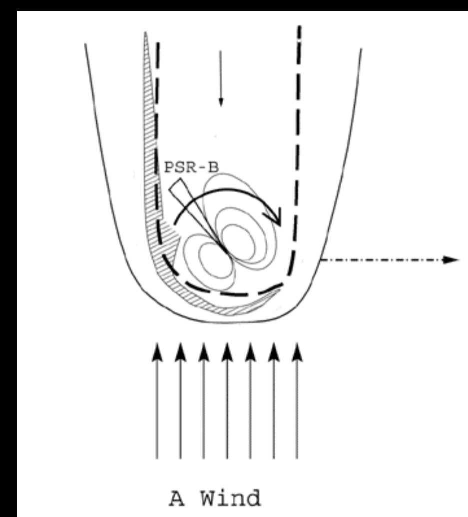
Doppler shifts of pulse period allow measurement of orbital parameters

Eclipses of Pulsar A

Lyne et al 04, Kaspi et al 04 see brief eclipse of A when pulsar B moves in front of A



Pulsed flux of pulsar A for 4 minutes centered on superior conjunction (A behind B). Each data point is a 2 s integration. The eclipse lasts ~30 s, corresponding to a 18,600 km physical dimension of the obscuring material along the direction of orbital motion.

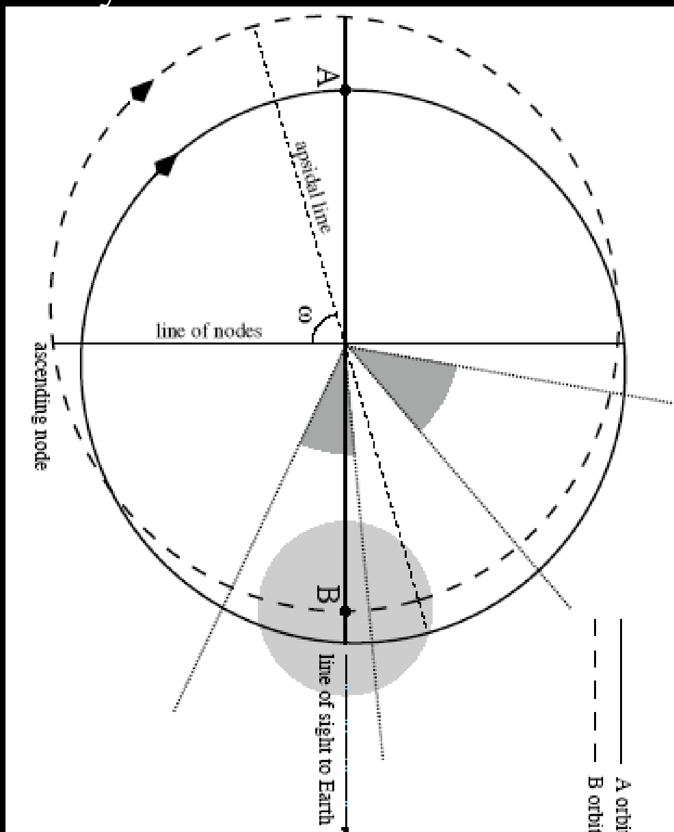


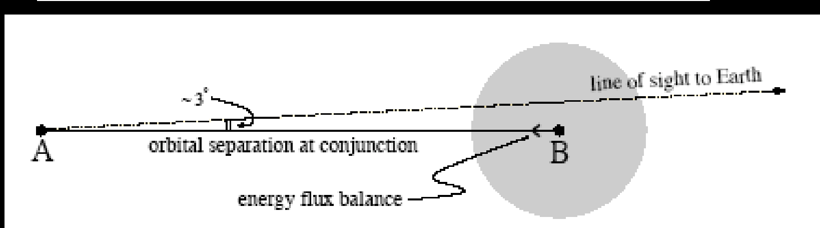
Eclipse is asymmetric and shortens at higher frequencies (Kaspi et al 04)

Cartoon of eclipse model - magnetosheath absorption by PSR B

PSR J0737 A&B -- laboratory for relativistic winds

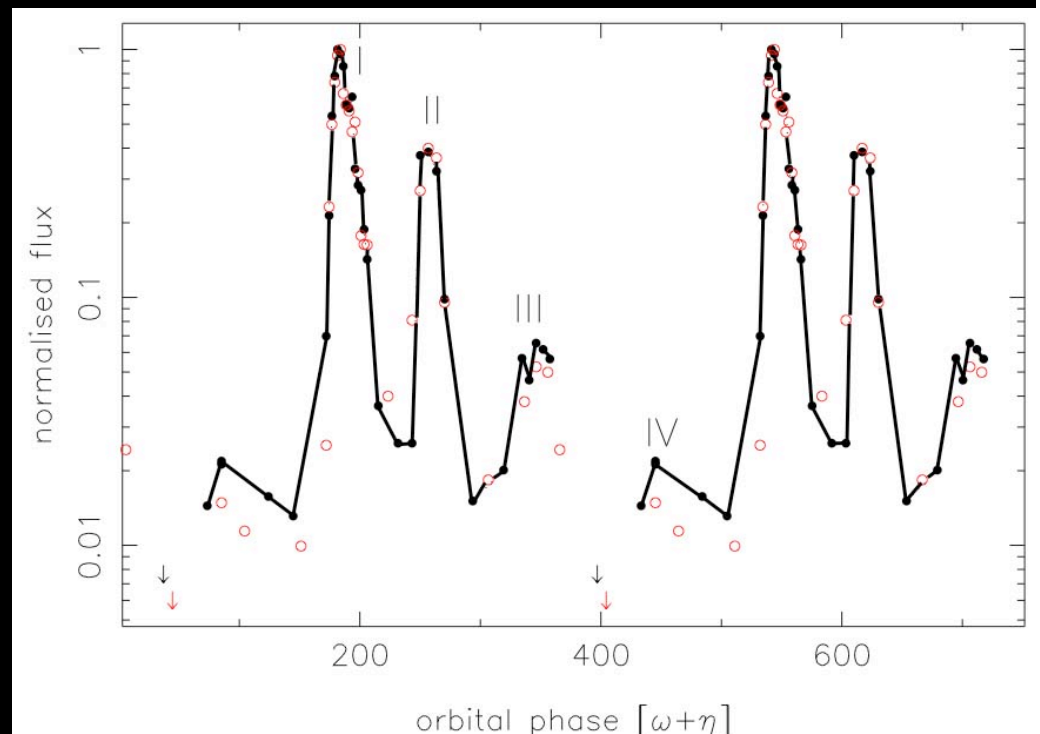
Binary orbit:





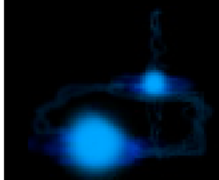
Lyne et al (2004)

Eccentricity: 0.0878
Characteristic age: 270 Myr(A), 50My(B)
Mass ($M_\odot$): 1.33 1.25
Orbital inclination: 88.7°±0.9° (Ransom 04)



Ramachandran et al (2004)

Binary pulsar: outstanding questions



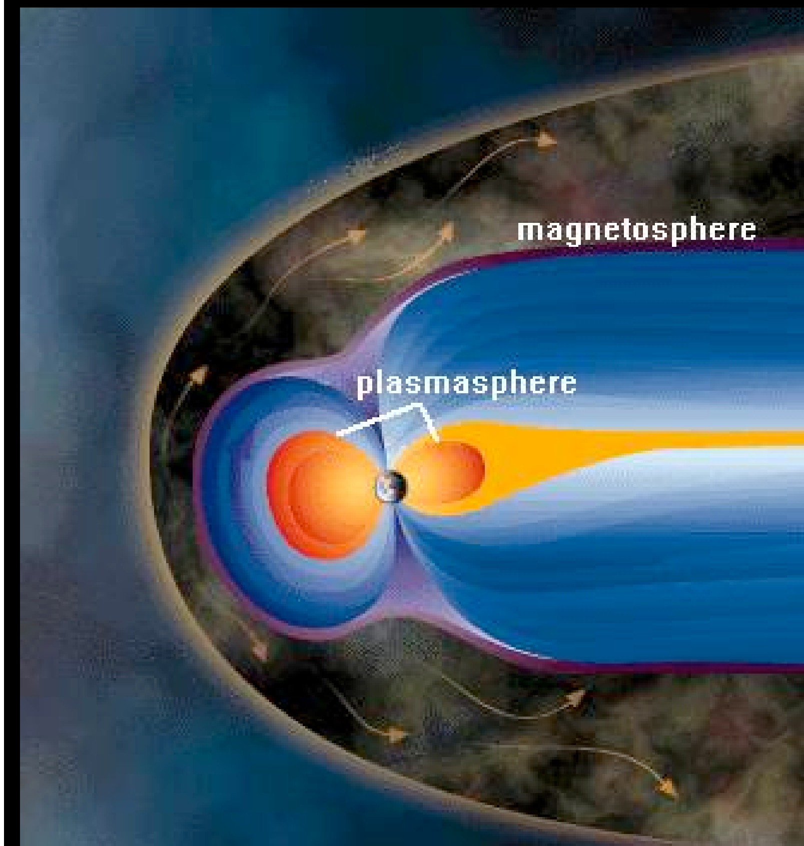
- *What is causing the eclipse of pulsar A?*
- *Why is eclipse asymmetric?*
- *Why does pulsar B change its pulse shape and brightness?*
- *What are the properties of pulsar wind in this system?*
  (closest probe to the source!)

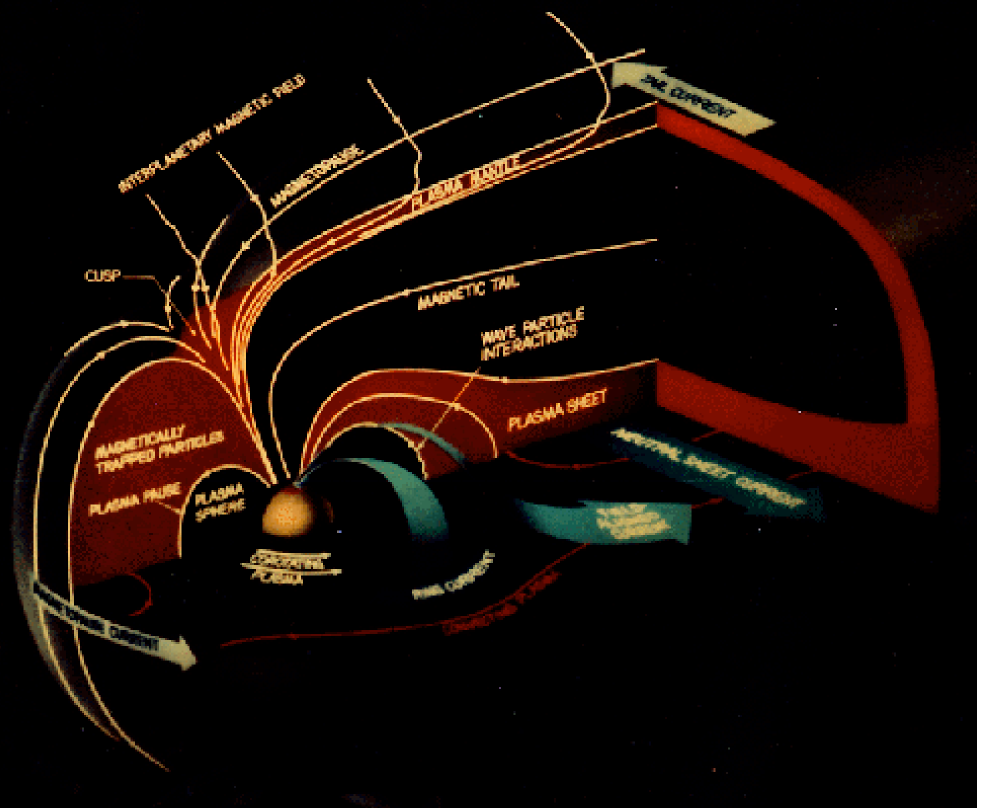
This system is unique in that mutual orientation of two pulsars changes on human timescale (~10yrs) due to GR. Predictions can be verified.

Strategy: investigate which effects can be attributed to the interaction between relativistic wind of A and magnetosphere of B using simulations.

Binary pulsar: wind-magnetosphere interaction

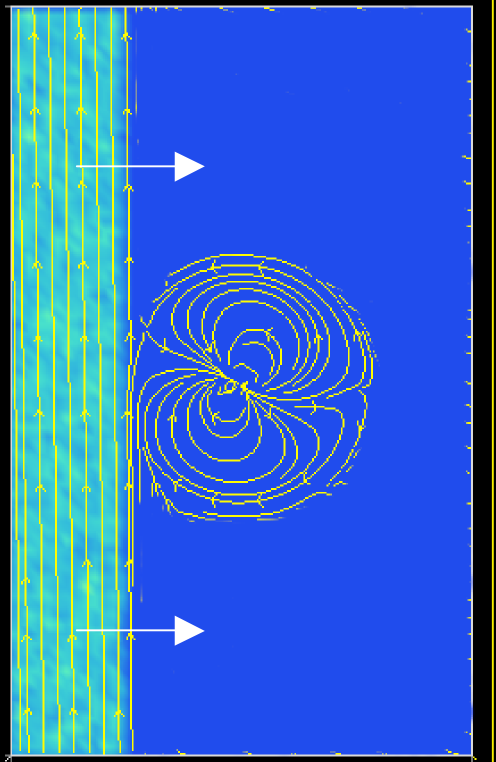
Analogy to Earth magnetosphere:





Difference: pulsar B is strongly inclined, need full 3D to simulate, wind is relativistic.

Numerical simulation of wind-magnetosphere interaction



Equatorial plane

Simulation setup:

Relativistic $e^{\pm}$ wind (γ =10-50) with toroidal B field (σ = 0.1-3)
Inflate bubble of rotating inclined dipole magnetic field
No plasma initially in the magnetosphere, no surface emission

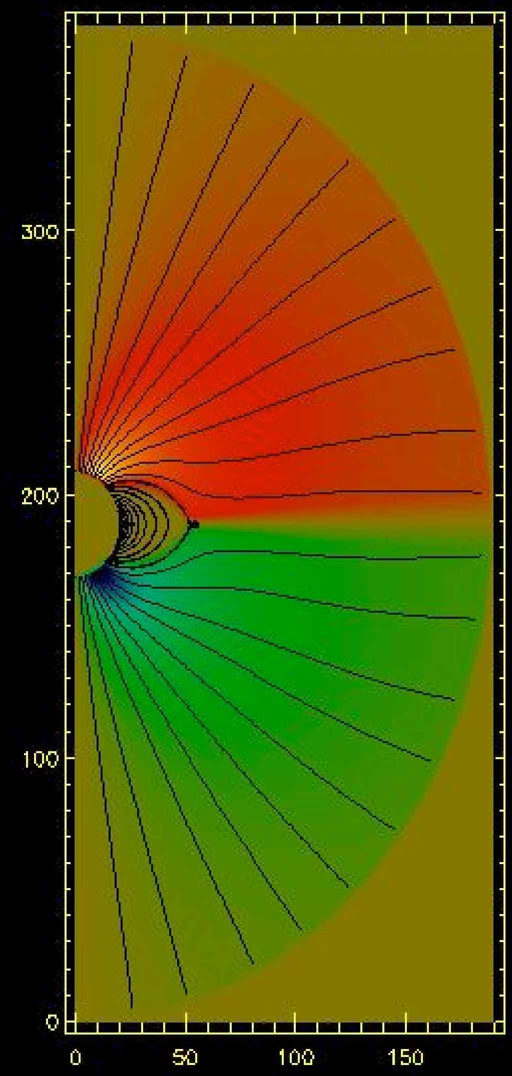
We use particle-based simulation (PIC)

Advantages: fully kinetic, self-consistent collisionless shocks, reconnection physics included automatically
Disadvantages: plasma scales have to be resolved; magnetosphere ~ 50 skin depths; huge simulations
This is doable for pair plasma (no ion scales)
General RMHD behavior is reproduced.

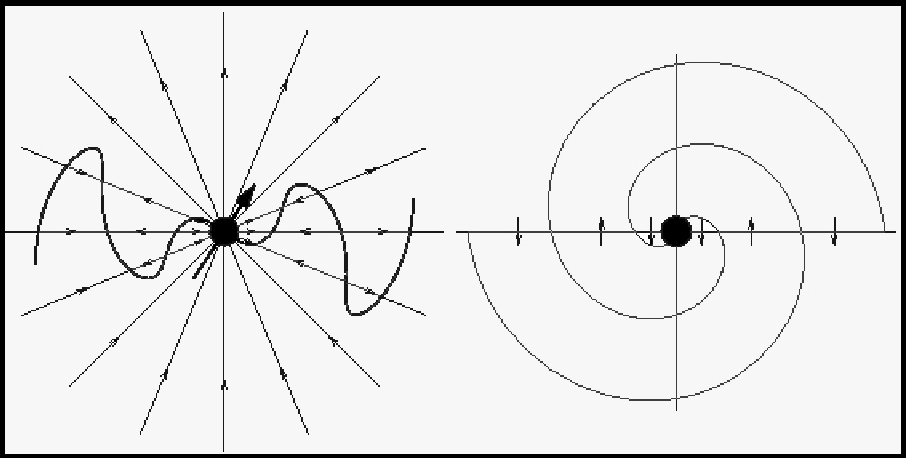
Code "TRISTAN":

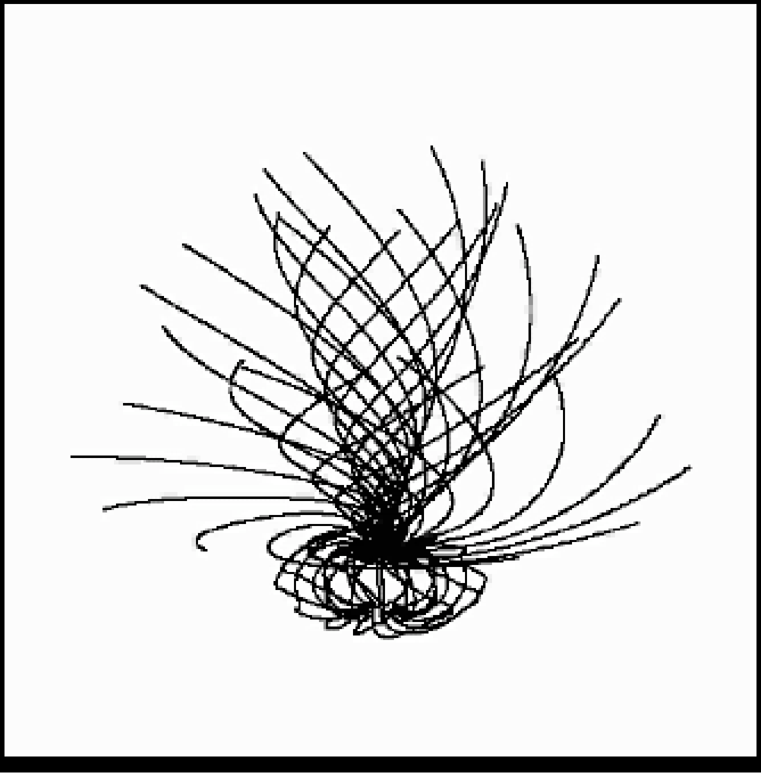
- *3D cartesian electromagnetic particle-in-cell code*
- *Algorithms for rotating magnet*
- *Handles magnetized flows*
- *Fully parallelized (128proc+)*
- *Resolution requirements: typical run 512^3 grid, $6x10^8$ particles, 50+ Gb.*

Magnetic field in the wind of PSR A

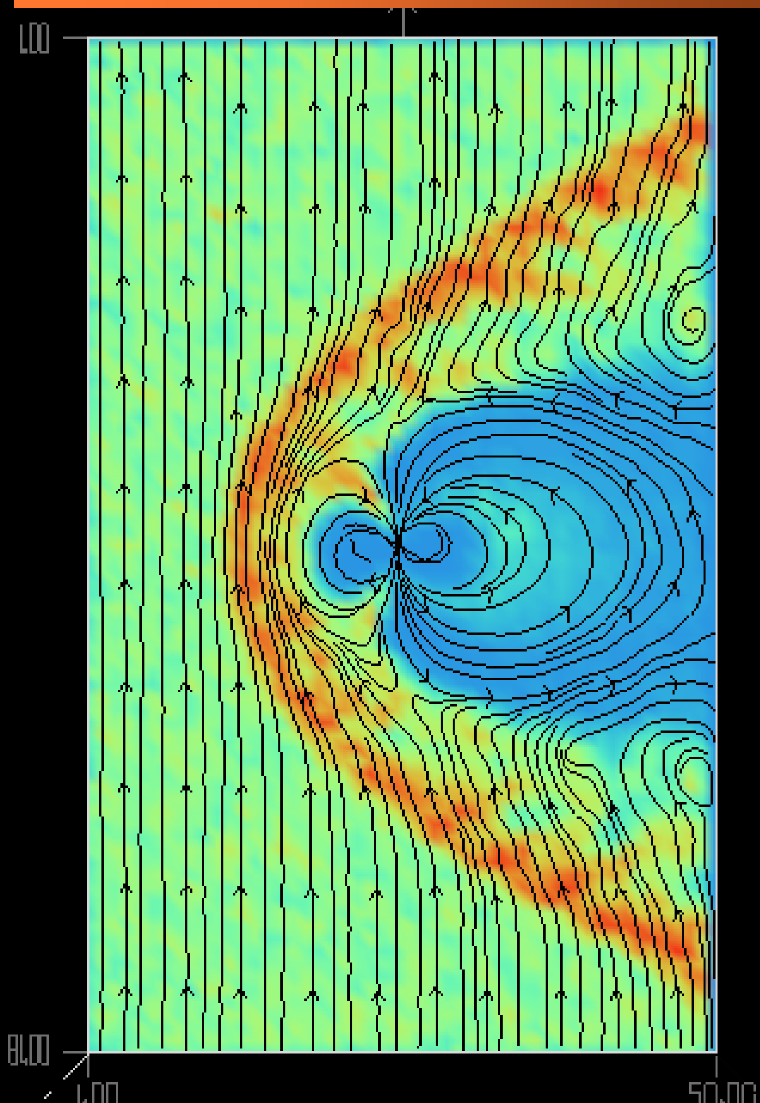


For most of the orbit wind has nonalternating magnetic field

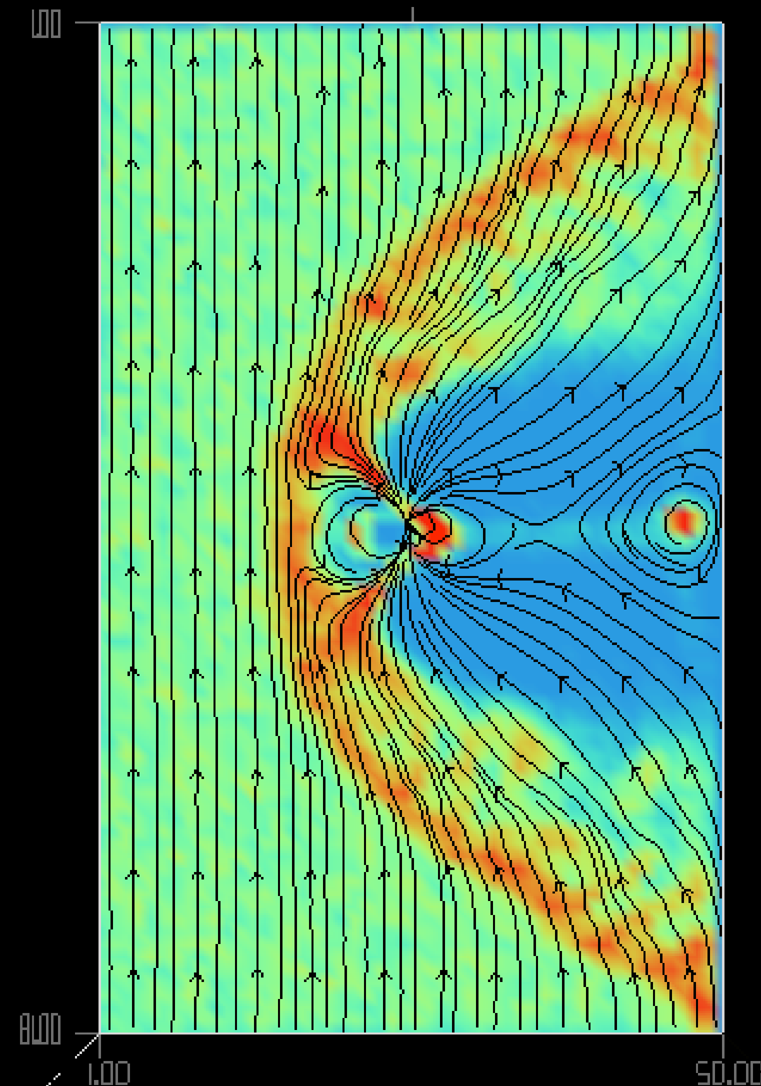




Shock and magnetosheath of pulsar B



No "dayside" reconnection

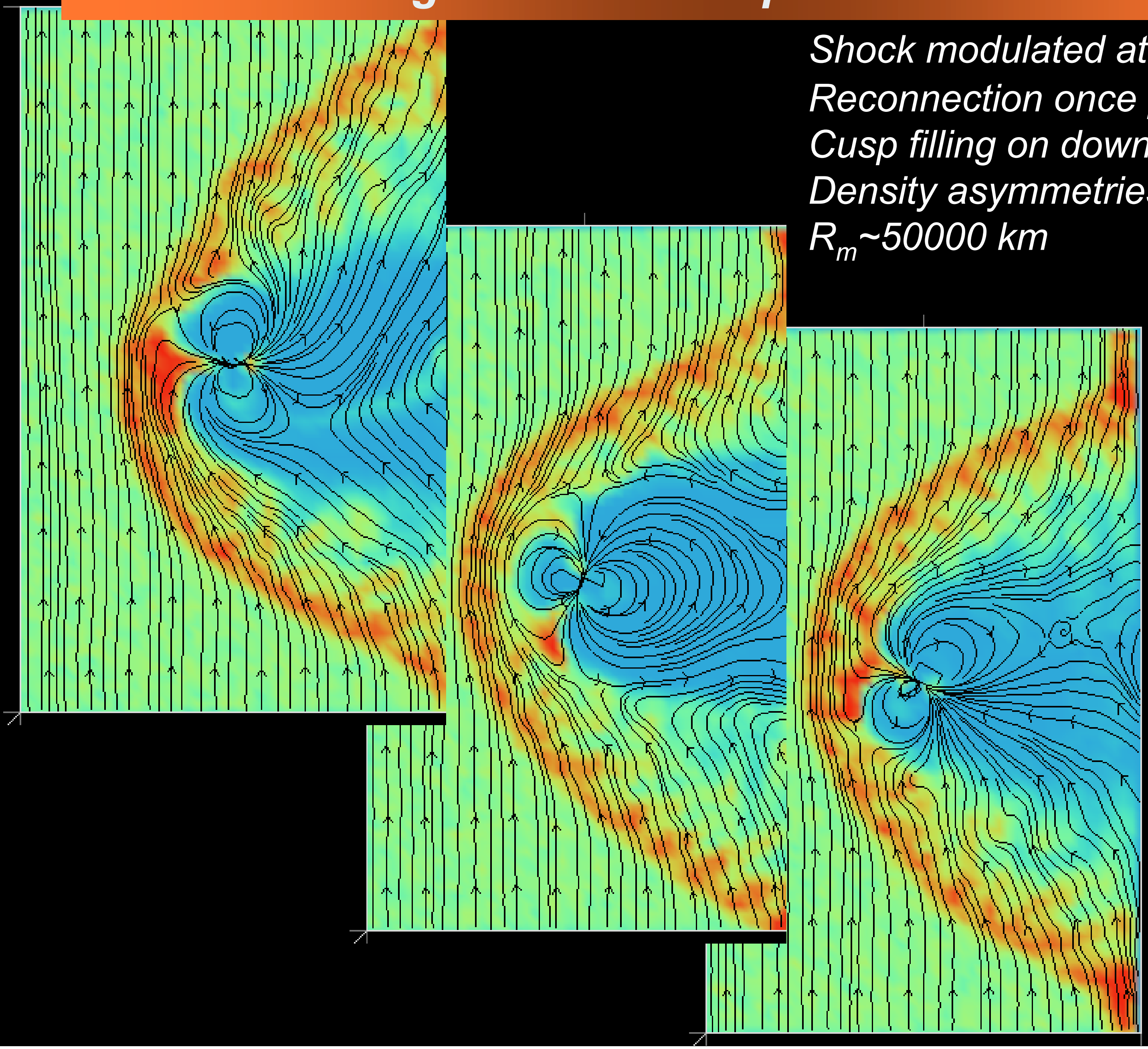


With "dayside" reconnection

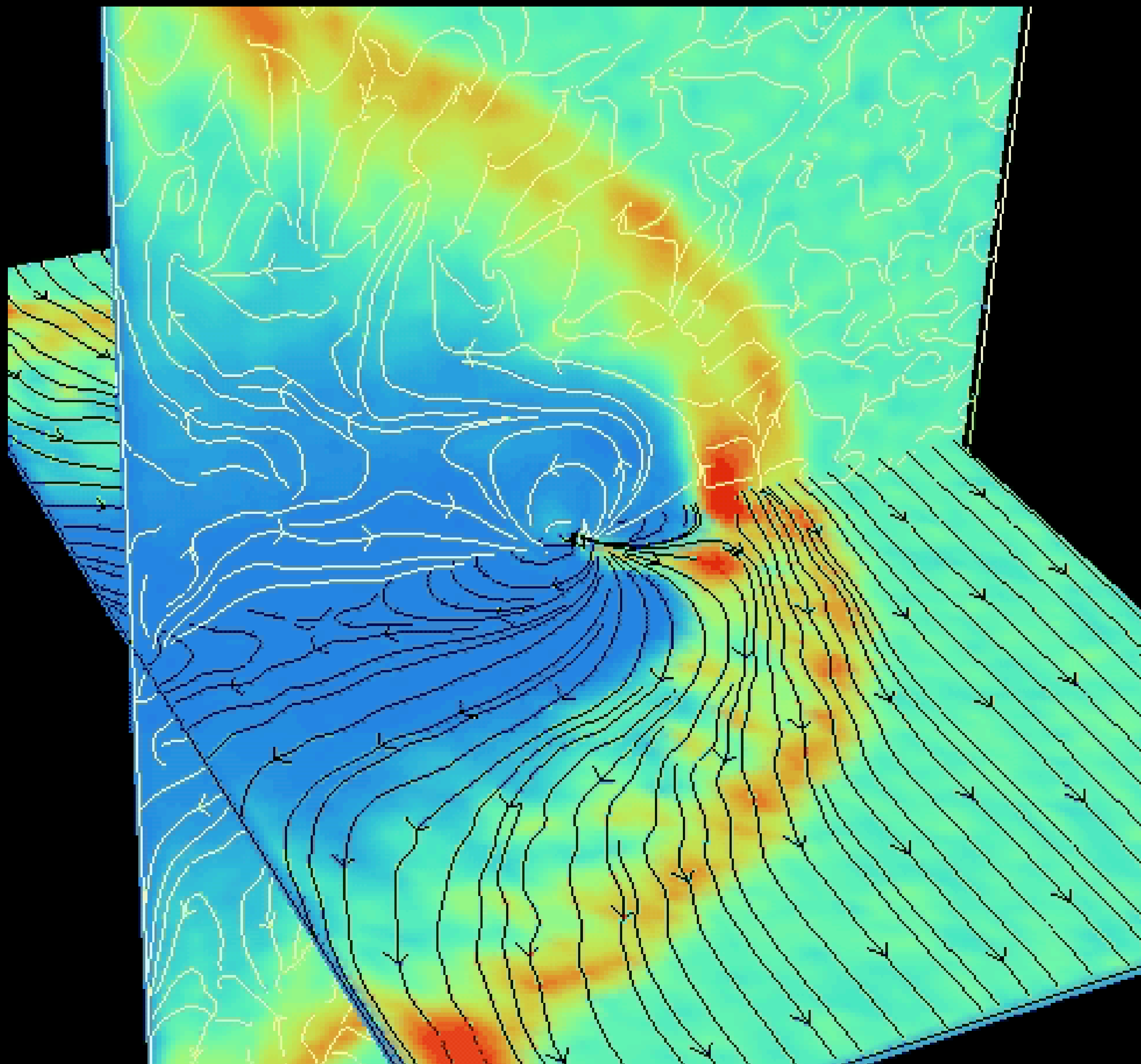
Similar to the interaction between Earth magnetosphere and solar wind.

Shock and magnetosheath of pulsar B: effects of rotation

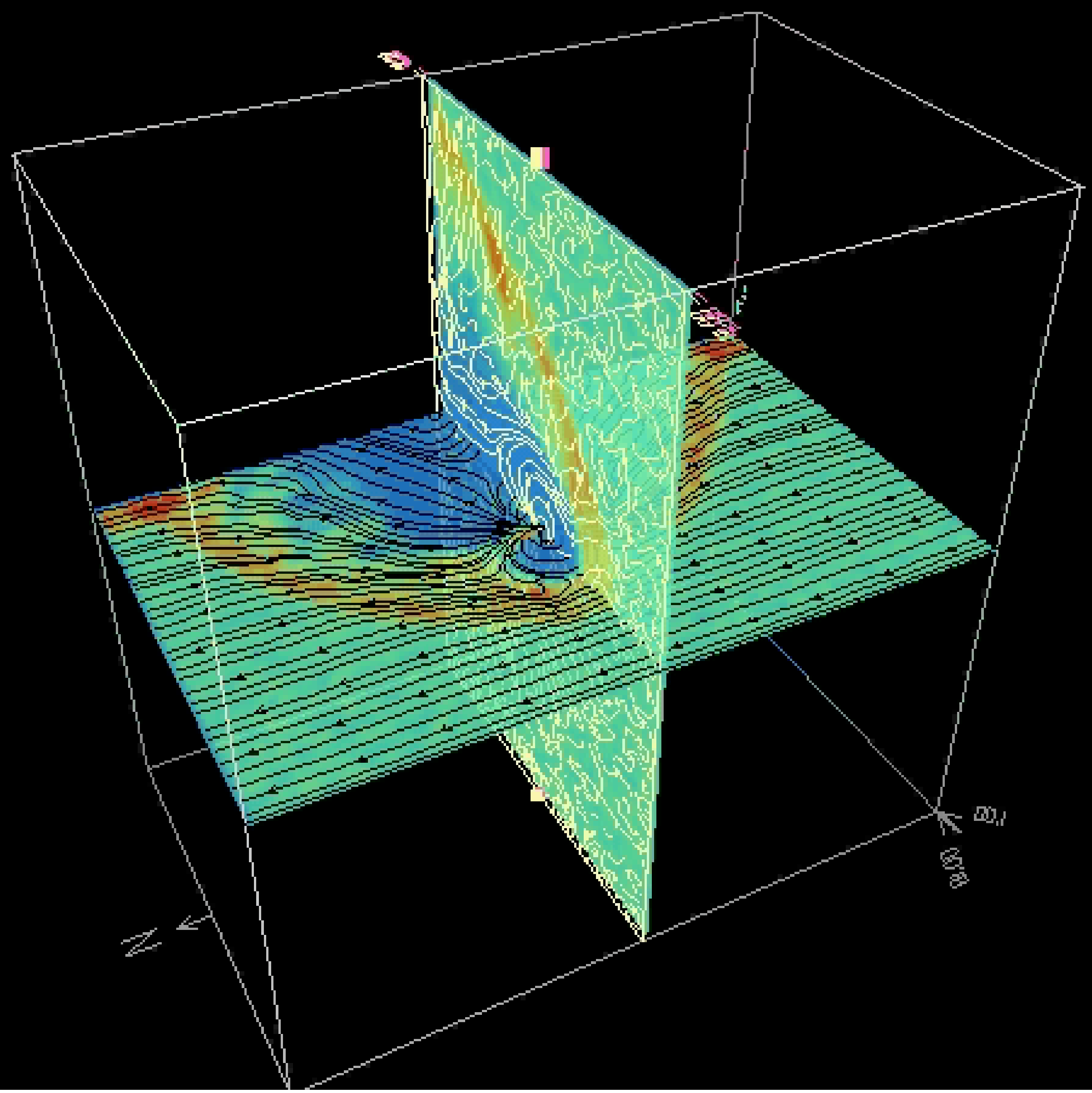
Shock modulated at 2Ω
Reconnection once per period
Cusp filling on downwind side
Density asymmetries
R_m~50000 km



3D magnetosphere



3D magnetosphere



Eclipse and synchrotron absorption

To explain weak frequency dependence of eclipse, need to have high optical depth. Propose synchrotron absorption in the hot postshock plasma as the eclipse mechanism:

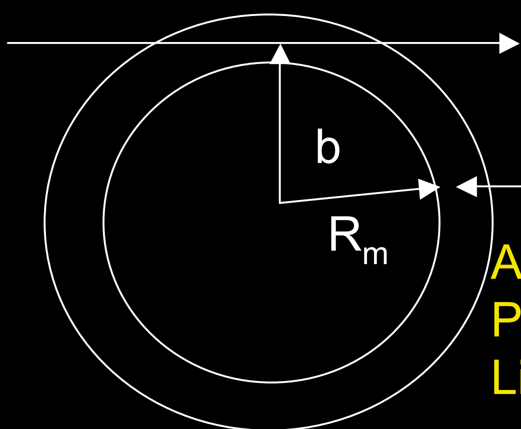
$$\tau_\nu = \frac{\sqrt{3} c r_e n_{1\pm} R_m}{\nu_{g1} T_2 \beta_2} \left(\frac{\nu_{g1}}{\nu}\right)^2 I(z) = \frac{2}{\nu_{1400}^2} \left(\frac{\kappa}{10^6}\right)^2 f(\sigma)$$

To explain eclipse require:

$$\kappa \sim 3 \times 10^6,\ \gamma \sim 10,\ \sigma \sim .1$$

The wind is too dense and too slow according to conventional wisdom! (Also cf Lyutikov 04)

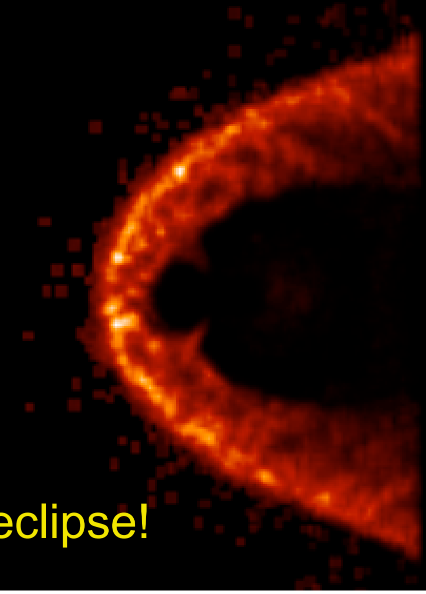
Eclipse duration:



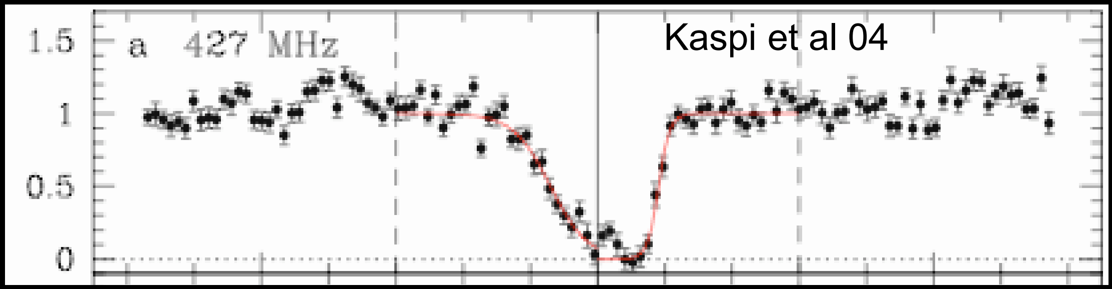
LOS passage through magnetosheath

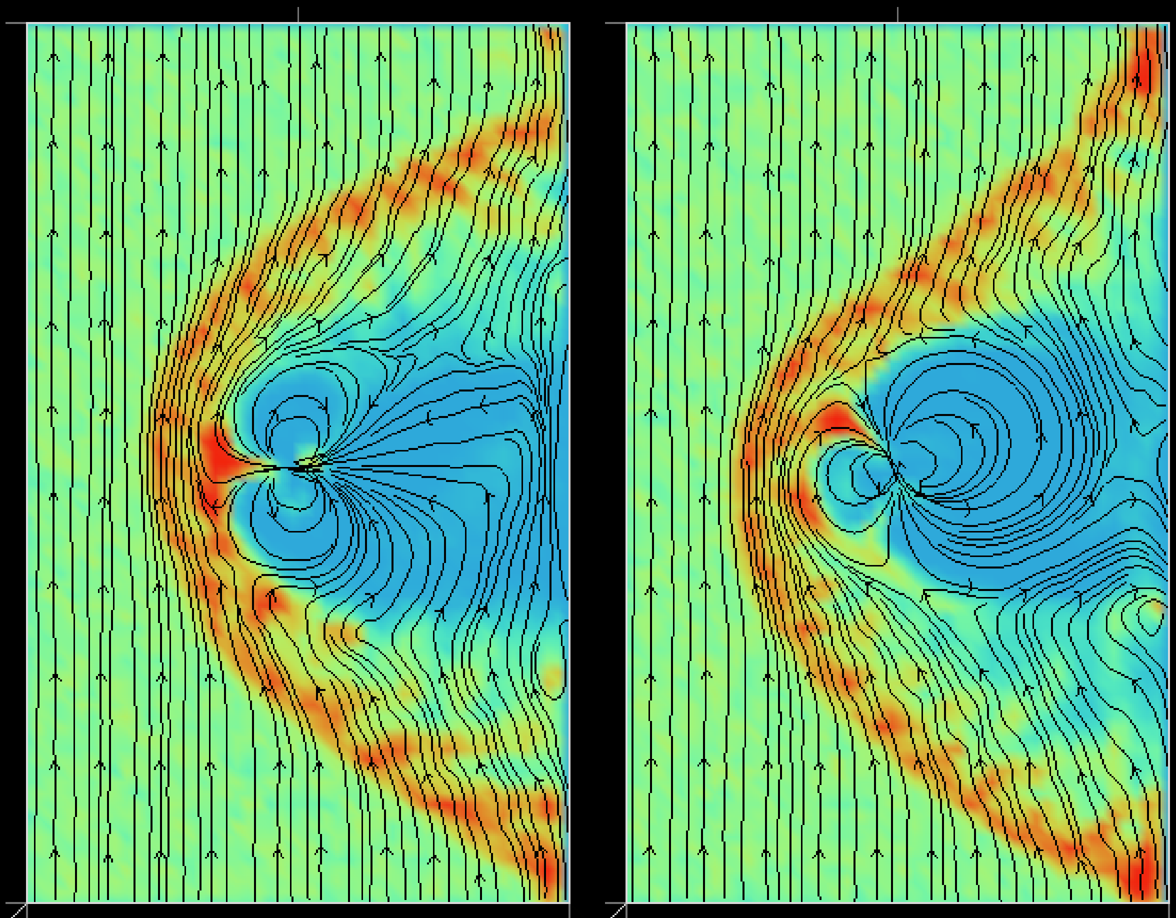
Magnetosheath

At R_m~50000km eclipse is 2.5x longer.
Predict clearing at higher frequencies.
Limb darkening -- clearing in the middle of eclipse!



Eclipse: asymmetries

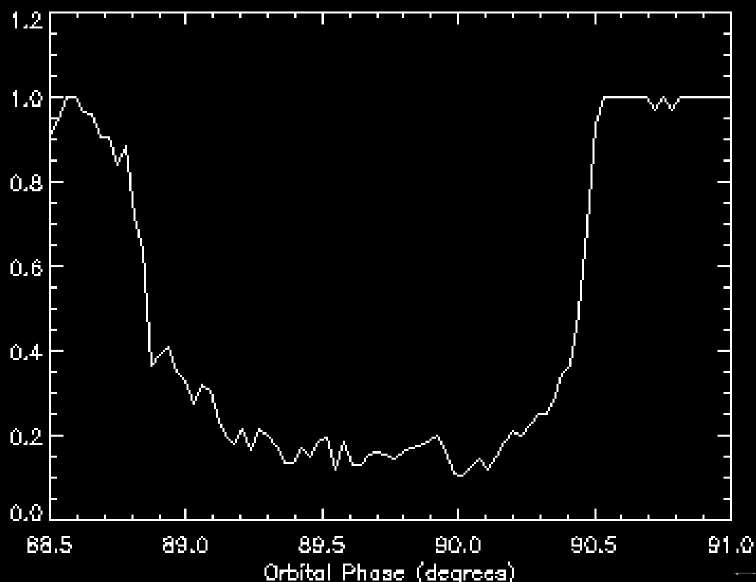


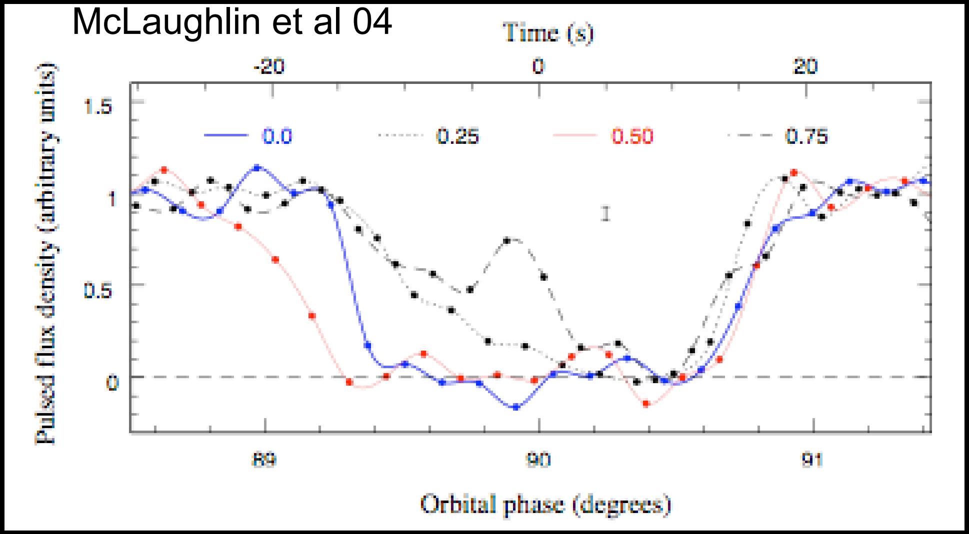


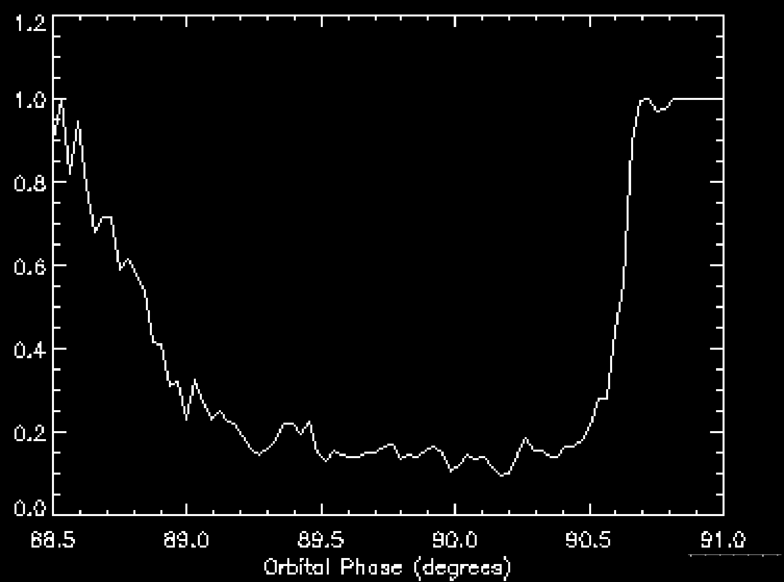
Asymmetry of the eclipse can be due to asymmetries of the absorbing magnetosheath. One candidate is rotationally induced density asymmetry.

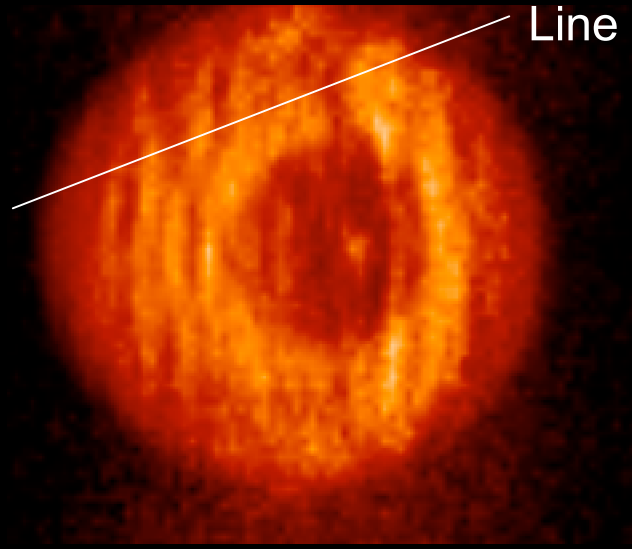
Expect fluctuations in eclipse lightcurve on the timescale of rotation of B (recently confirmed by observations).

Eclipse: asymmetries and phase-resolved lightcurve









Eclipse modeling constrains angular momentum vector of B

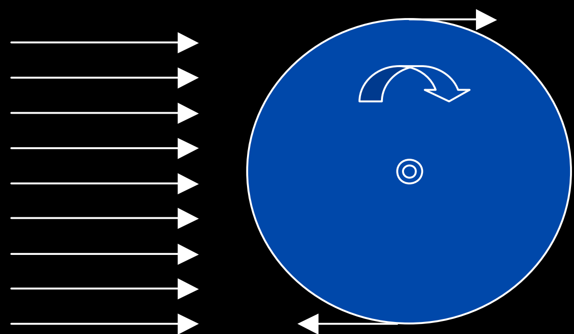
Spindown of pulsar B -- wind torques

How does PSR-B spin down?

1) "Regular" spindown through the tail of the magnetosheath.

$$(\dot{J}_B)_{spindown} = \frac{\dot{\varepsilon}}{\Omega} = \frac{\mu^2\Omega^3}{c^3}\left(\frac{R_m}{R_{LB}}\right)^2 \sim 10^{29} ergs$$

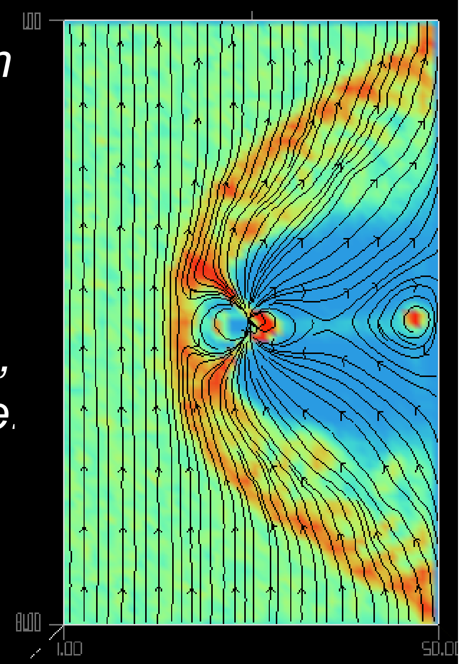
2) "Propellor" torque.



$$(\dot{J}_B)_{propellor} \propto \rho v \Omega R^4$$

In case of PSR-B coupling to the flow is provided through reconnected field.

Acceleration on the dusk side, deceleration on the dawn side. Net torque:



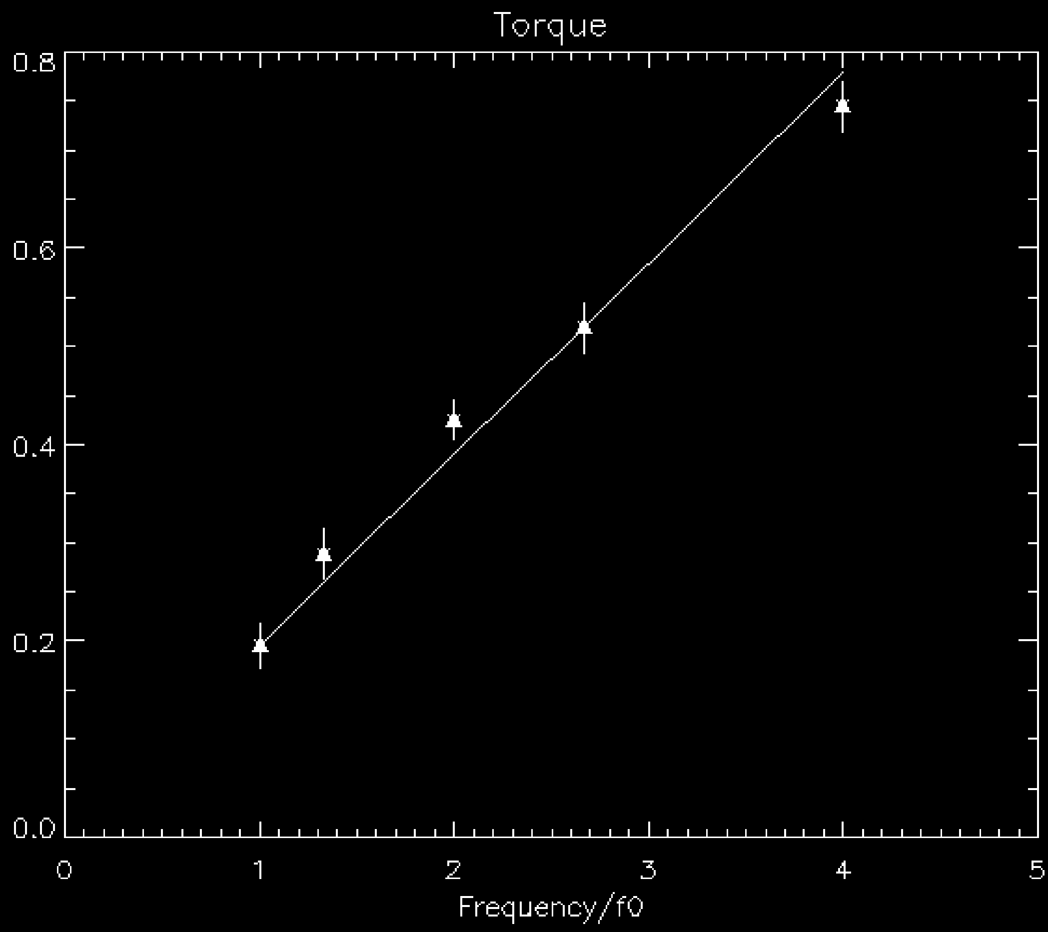
$$(\dot{J}_B)_{rec} = \int dV(\vec{r} \times \frac{1}{c}\vec{j} \times \vec{B}) \cdot \hat{\Omega}_B \sim \left(\frac{\dot{E}_A}{a^2 c}\right)^{1/3} \mu^{4/3} \frac{\Omega_B}{2c\beta_{\parallel}} = 2 \times 10^{30} ergs$$

The wind torque is larger than the regular spindown torque!

This leads to more accurate B field: 4×10^{11}G. R_m=50000km=38%R_{LB}

Spindown of pulsar B -- wind torques

Investigate how torque varies with frequency of the star:



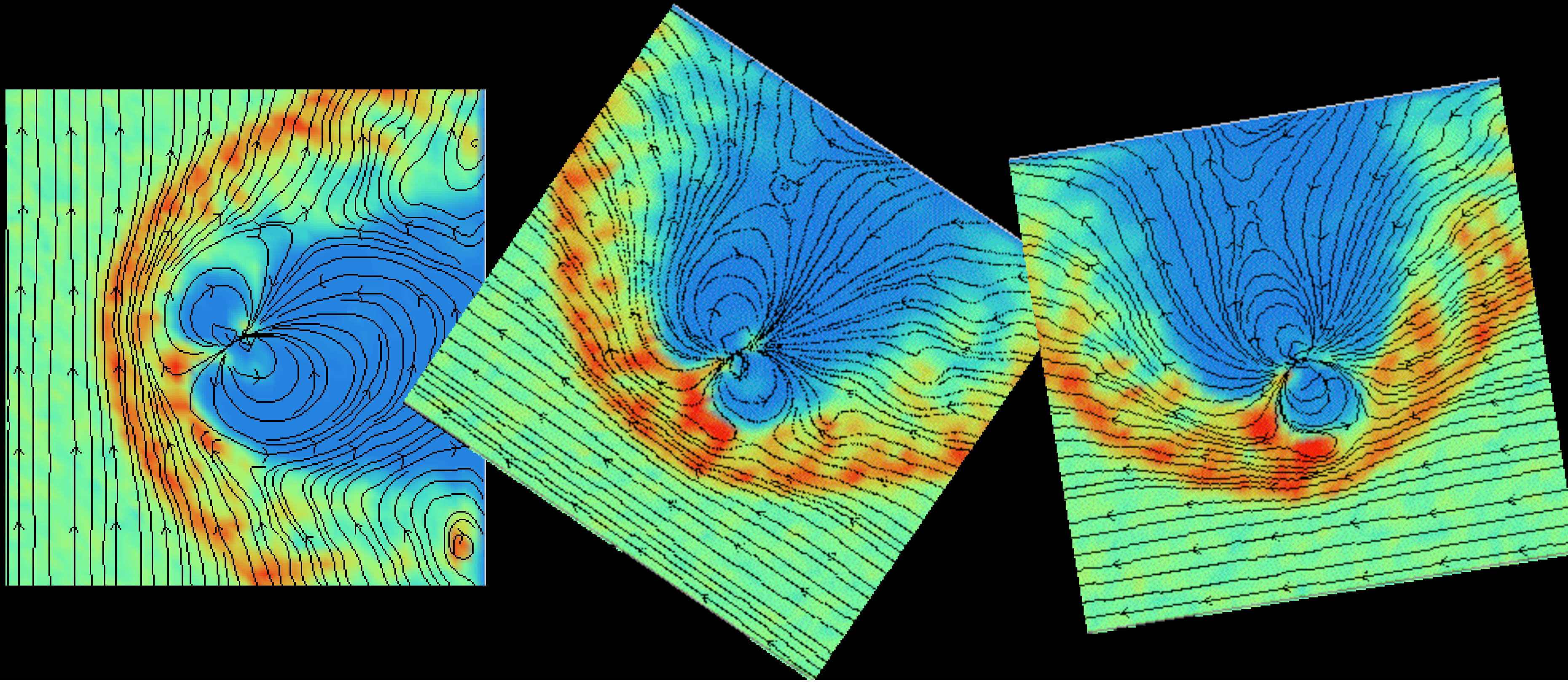
Torque scales linearly with frequency as expected from propellor torque.

Emission morphology of pulsar B

Emission of B depends on orbital phase, both in amplitude and in pulse profile.

Key points:
Wind-magnetosphere interaction as seen from Earth is orbital phase-dependent.

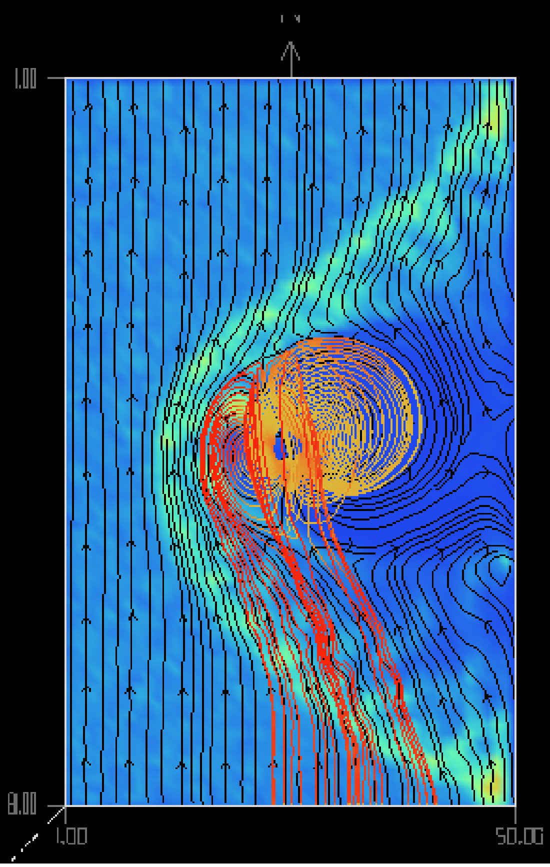
Same rotational phase of B represents varying phases with respect to magnetosheath (A-B line) as a function of orbital phase.

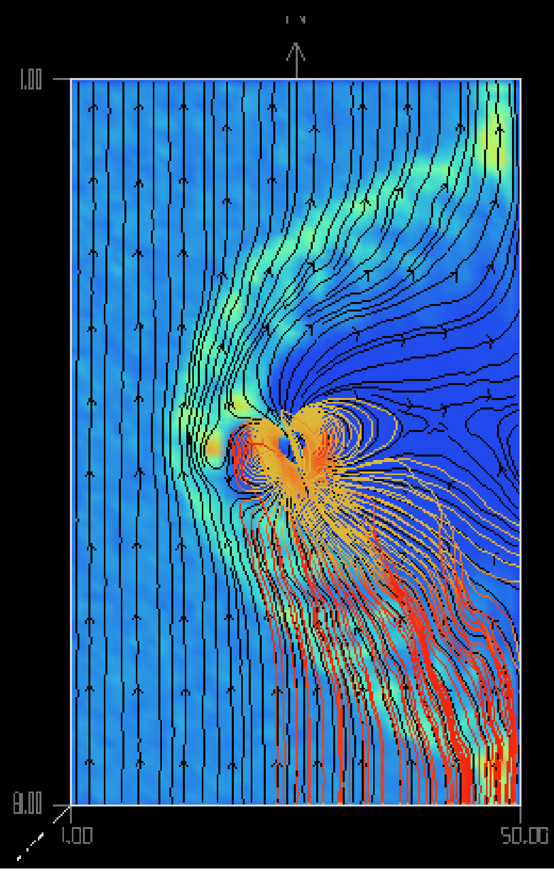


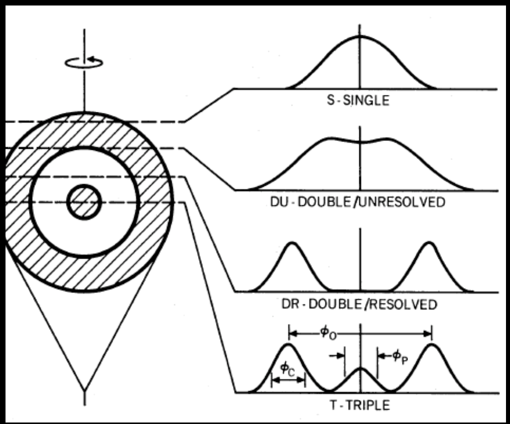
Emission morphology of pulsar B

Orbital phase-dependent effects:

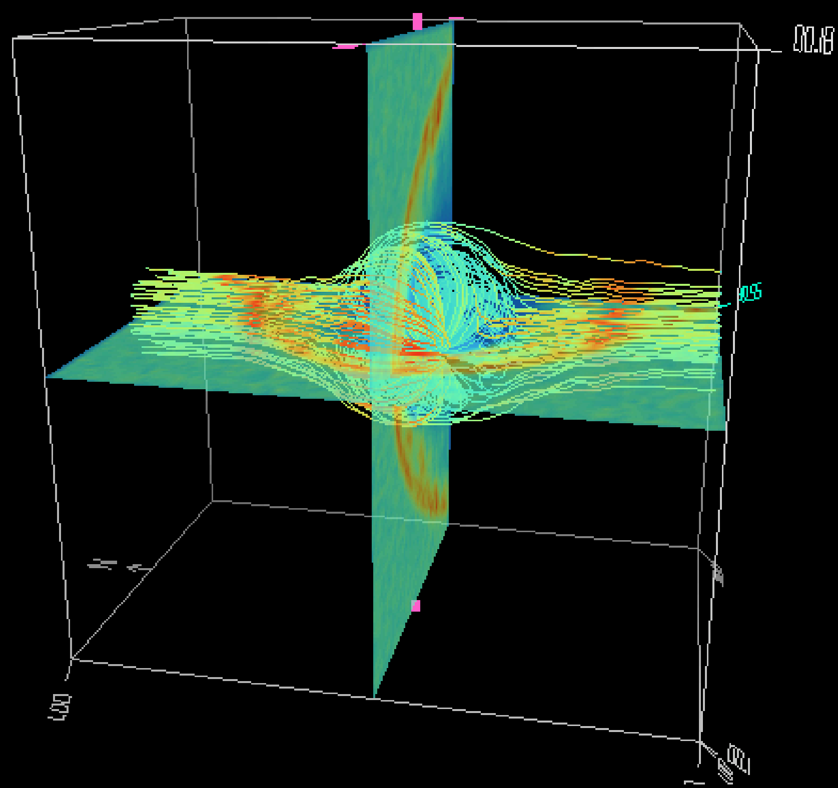
1) *Absorption of B radiation in the magnetosheath*
2) *Plasma penetration into the cusp. Hypothesis: downstreaming plasma affects currents and interrupts radio emission. (cf Zhang and Loeb 04)*
3) *Modulation of the polar cap size. Due to reconnection in some phases number of open fieldlines varies!*

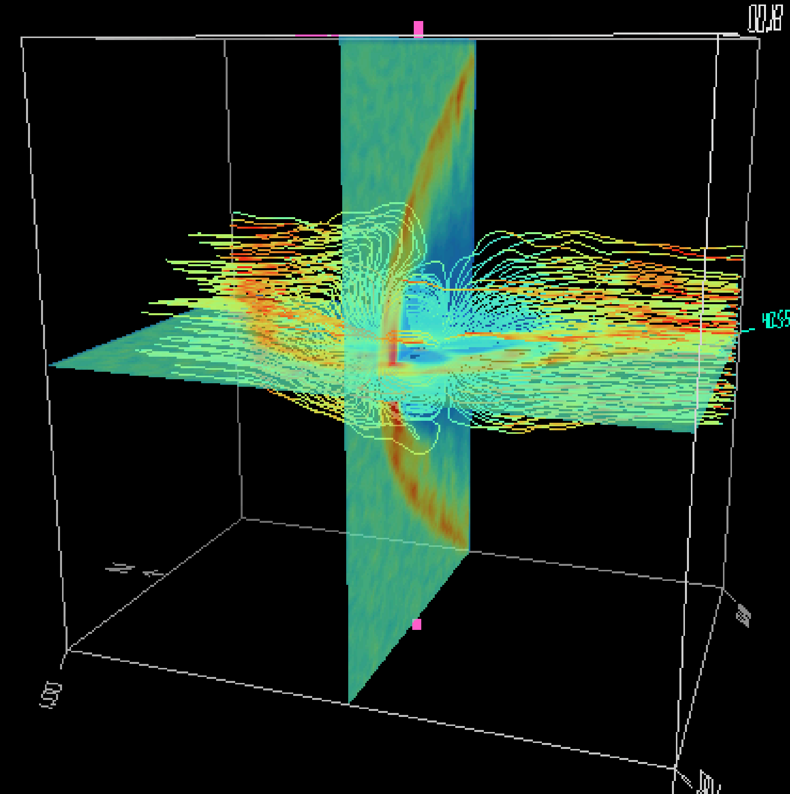






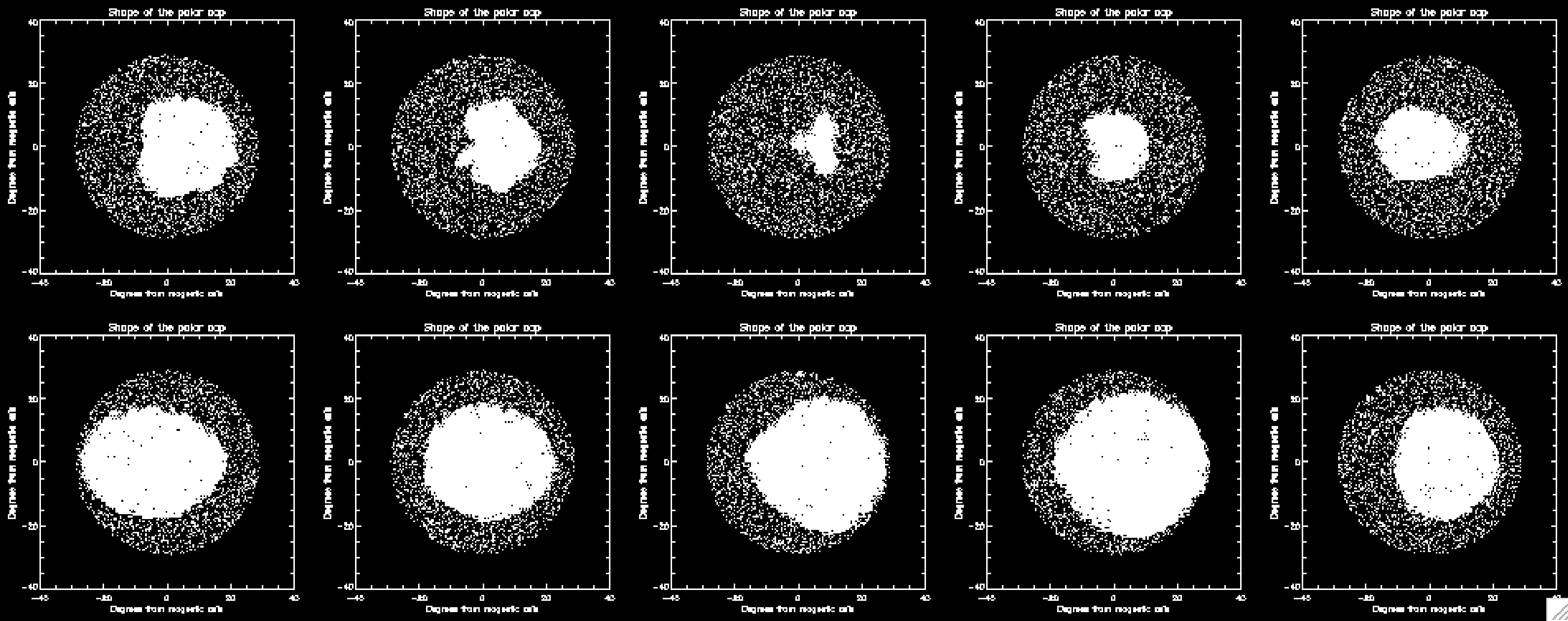
3D magnetosphere: fieldlines

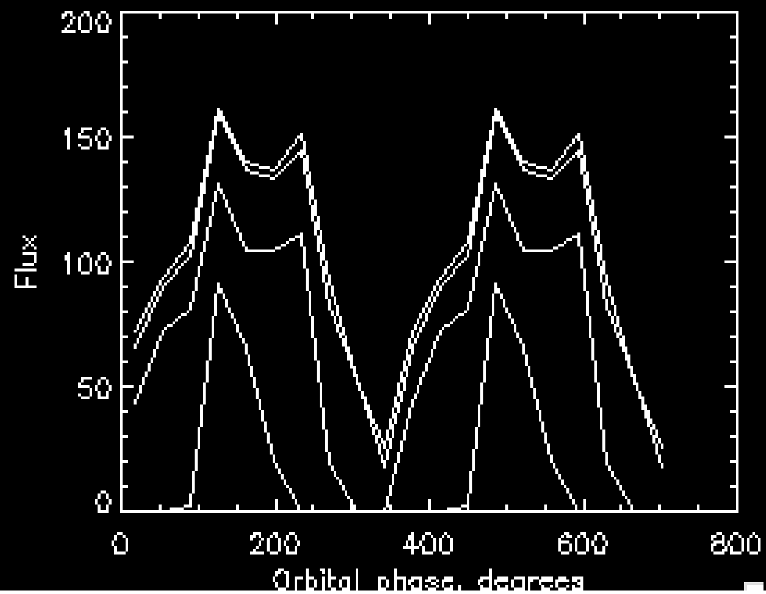


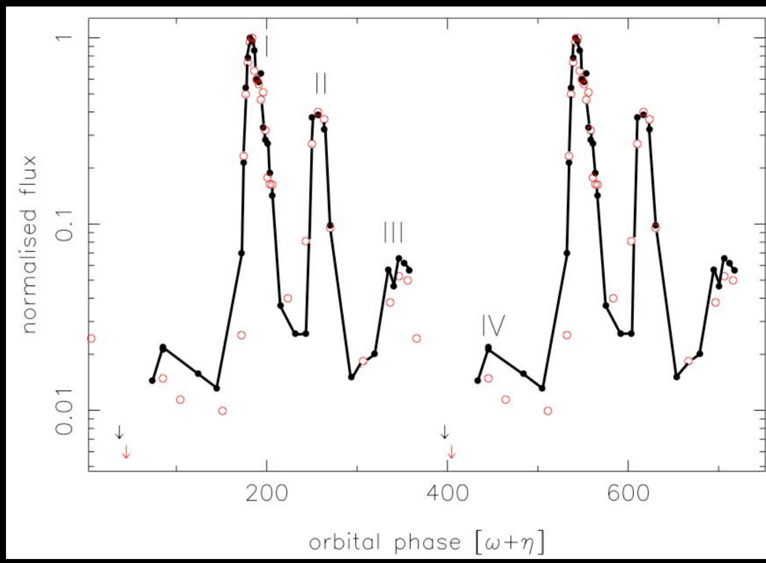


Emission morphology of pulsar B

Polar cap size for different phases of the orbit (lines connected to the wind):







Emission morphology of pulsar B

Orbital phase-dependent effects:

1) *Absorption of B radiation in the magnetosheath*

2) *Plasma penetration into the cusp. Hypothesis: downstreaming plasma affects currents and interrupts radio emission. (cf Zhang and Loeb 04)*

3) *Modulation of the polar cap size due to magnetosheath. Due to reconnection number of open fieldlines varies with rotation phase!*

4) *A realistic wind model of A should have a current sheet in the magnetic equator, which pulsar B will cross twice per orbit. This will result in reversal of toroidal field twice per orbit. This potentially explains emission windows III and IV, sharp changes in B emission, and oscillatory signal from A imprinted in B's signal (McLaughlin et al 04). Sensitive to geometry of the system.*

5) *Wind pressure of the A wind may vary with A's rotational latitude, and hence orbital phase. This will affect the confinement of the magnetosphere of B, and polar cap shape.*

Conclusions

- *We obtain a 3D time-dependent shape of magnetosphere for oblique magnetized rotator interacting with relativistic wind*
- *Synchrotron absorption in the shocked wind is a likely origin of the eclipse phenomena in the system (A&B). Predict clearing > 5GHz.*
- *Wind exerts "propellor" torque -- opportunity to study spindown of a pulsar under stress.*
- *Inferred wind properties are unusual (high particle flux, low magnetization). Further work on coherent effects is being done.*
- *Episodes of B emission likely due to viewing geometry and variation in polar cap size with orbit.*
- *Signature of B rotation expected and observed in the resolved eclipse data.*

Conclusions

To be done:

- *Large parameter space of other magnetic inclinations and wind geometries still unexplored.*
- *A true RMHD simulation would be interesting to compare with our results. Addition of plasma in the magnetosphere also clearly needs to be done.*
- *We look forward to further observational checks of the model*

This system finally allows us to directly probe pulsar physics.