Simulations of pulsar winds: the story of binary system J0737

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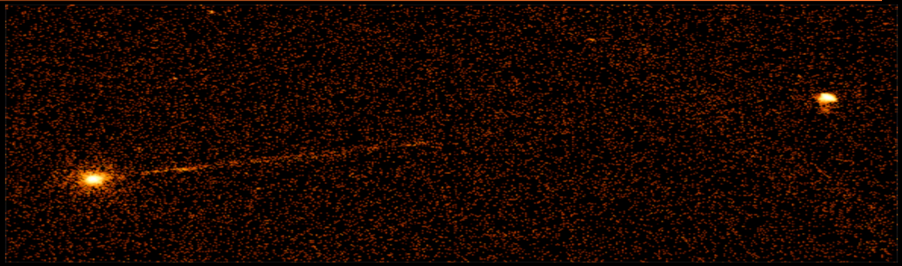
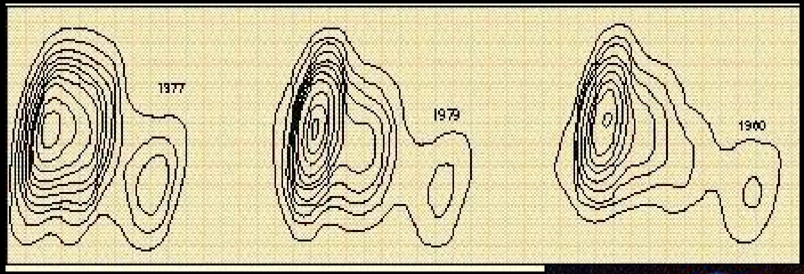
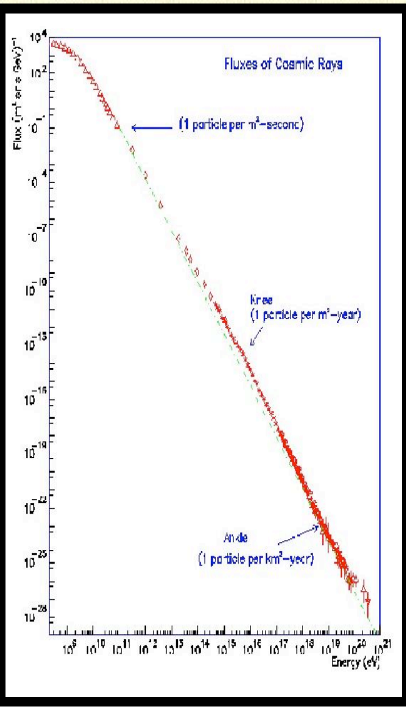
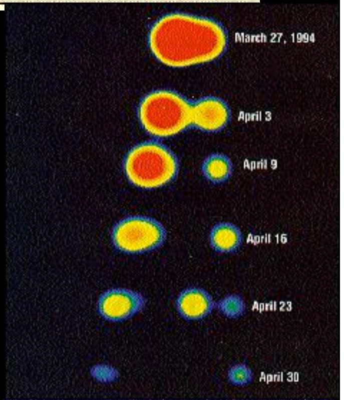
Relativistic (extreme) astrophysics

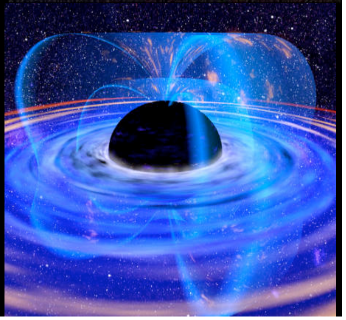


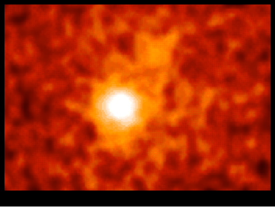
- *Pulsars + winds*
- *Plerions*
- *Extragalactic radio sources*
- *Superluminal expansion*
- *Black hole energy extraction*
- *Gamma ray bursts*
- *Magnetars / AXPs*
- *Galactic superluminal sources*
- *UHE CR*

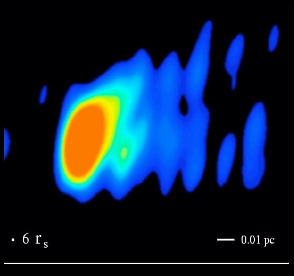


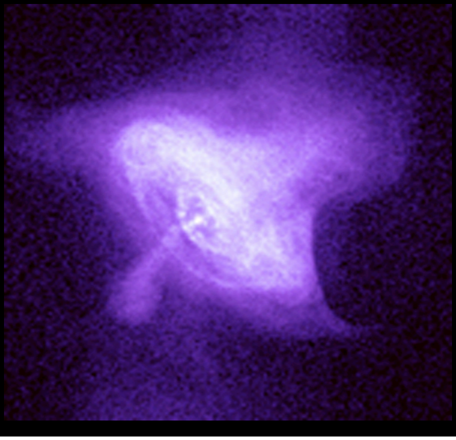










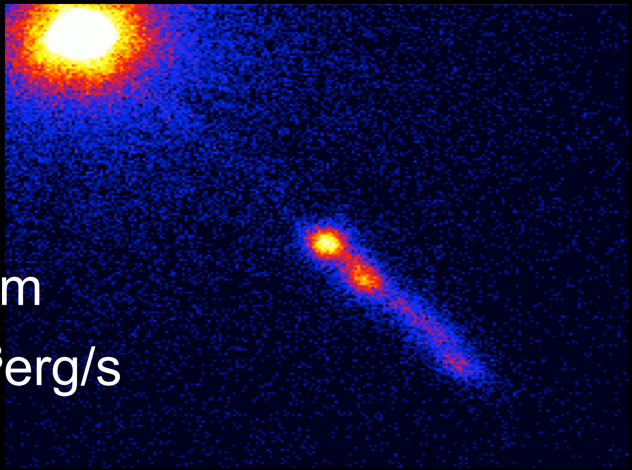


Magnetized rotators

Magnetized rotators are ubiquitous: pulsars, AGN, GRBs (?)

Rotation very efficient at long-term energy storage

Extraction of rotational energy is associated with relativistic outflows: pulsar winds, AGN jets, GRB jet flows.



Unipolar induction: $V \sim \Omega\ \Phi$; $P \sim V^2 / Z_0$

Crab Pulsar

$B \sim 10^{12}$ G, $W \sim 200$ rad s^{-1}, $R \sim 10$ km

$V \sim 3 \times 10^{16}$ V; $I \sim 3 \times 10^{14}$ A; $P \sim 10^{38}$ erg/s

Magnetar

$B \sim 10^{14}$ G; $P \sim 10^{44}$ erg/s

Massive Black Hole in AGN

$B \sim 10^{4}$ G; $P \sim 10^{46}$ erg/s

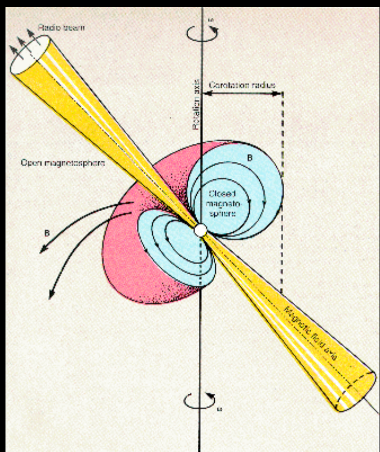
GRB

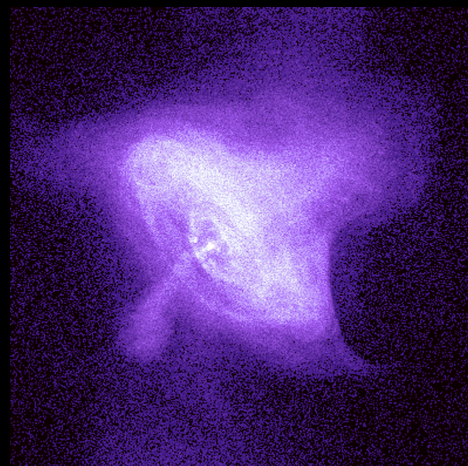
$B \sim 10^{16}$ G; $P \sim 10^{49}$ erg/s

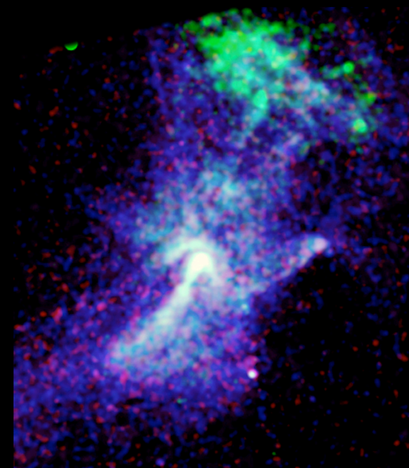
How is energy extracted, transported, collimated?

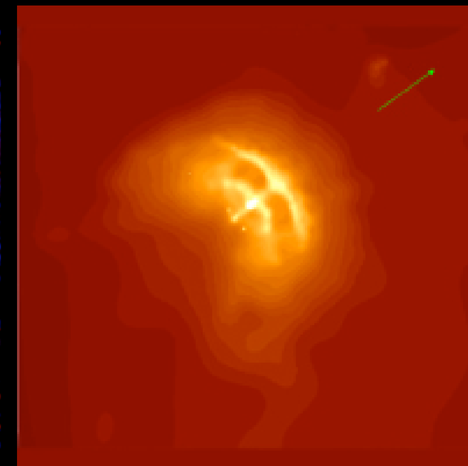
Best example -- pulsar winds

Pulsars and their winds

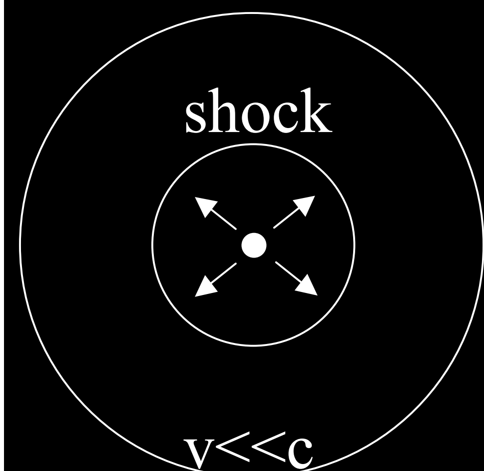








Best studied examples are pulsar winds in young supernova remnants. The wind shines in synchrotron light when collides with the nebula.

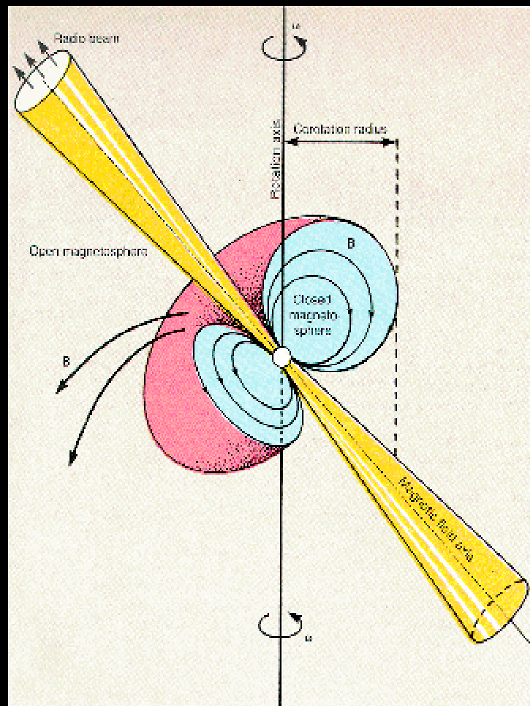


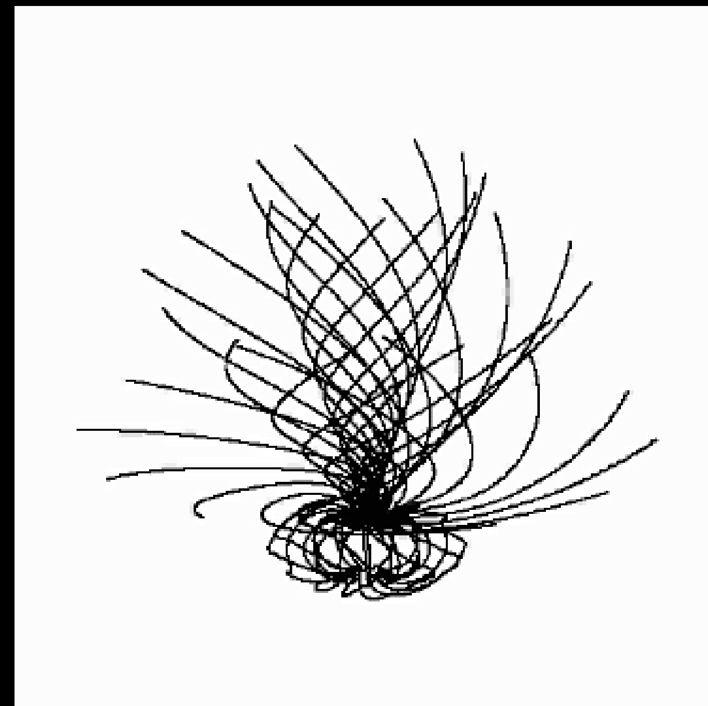
Properties of pulsar winds:

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

How do they do this?

Pulsar spindown: wind energy loss





Corotation radius = "Light Cylinder" (v_{rot}=c) R_L = cP/2π

Energy loss in the form of Poynting flux and particle flux:

$$\dot{E} = -I\Omega\dot{\Omega} = \int dA\left[\frac{c}{4\pi}(\mathbf{E}\times\mathbf{B})_{\mathbf{r}} + \rho(\gamma-1)c^2 v_r\right] = cr^2\frac{B_\phi^2}{4\pi}\left(1+\frac{1}{\sigma}\right)$$

$$= cR_L^2 B_p(R_L)B_\phi(R_L) = c\frac{\mu^2}{R_L^4} = \frac{\mu^2\Omega^4}{c^3}$$

Energy is in particle form at the nebula, but in Poynting flux at the source. How can we probe where the conversion happens?

PSR J7037 A&B - A Laboratory for Late Stellar Evolution, General Relativity and Relativistic Winds and Magnetospheres

Pulsar A

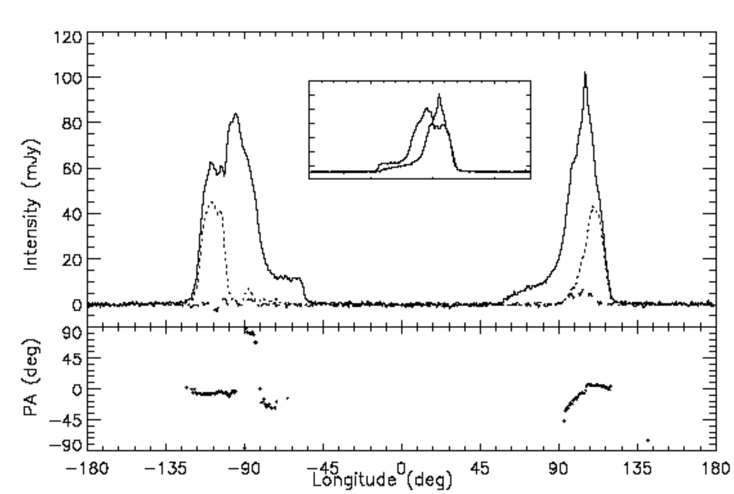
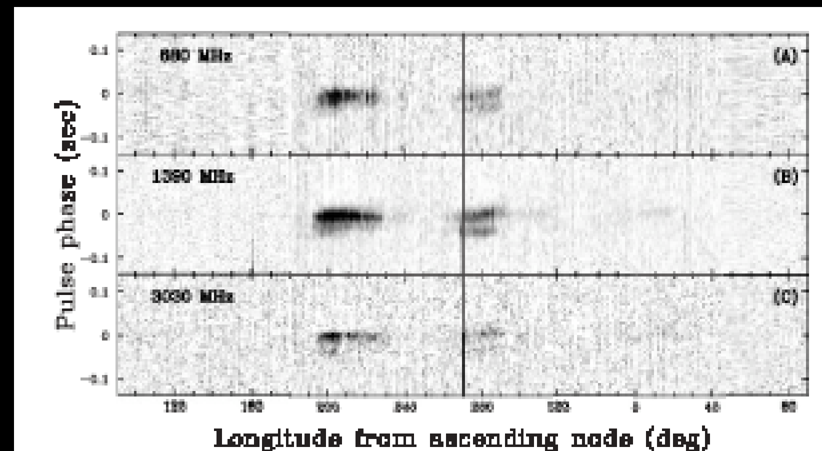
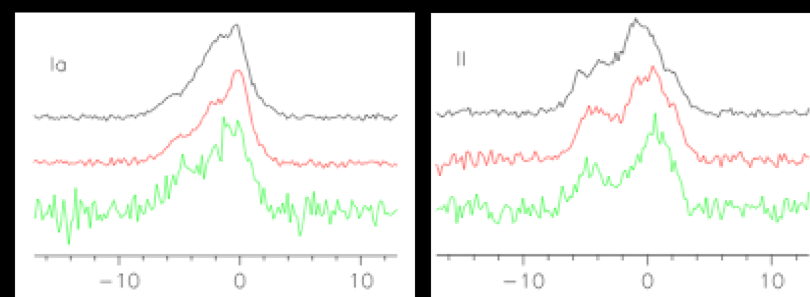


FIG. 1.— Polarization characteristics of J0737–3039A at 0.82 GHz. The inset gives the two portions of the profile 'mirror-folded' to show similarity of outer edges. See text for details. **(Demorest et al 2004)**

Pulsar B



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



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

$$P_B = 2773 \text{ msec}, \dot{E}_B = 2 \times 10^{30} \text{ ergs/s}$$

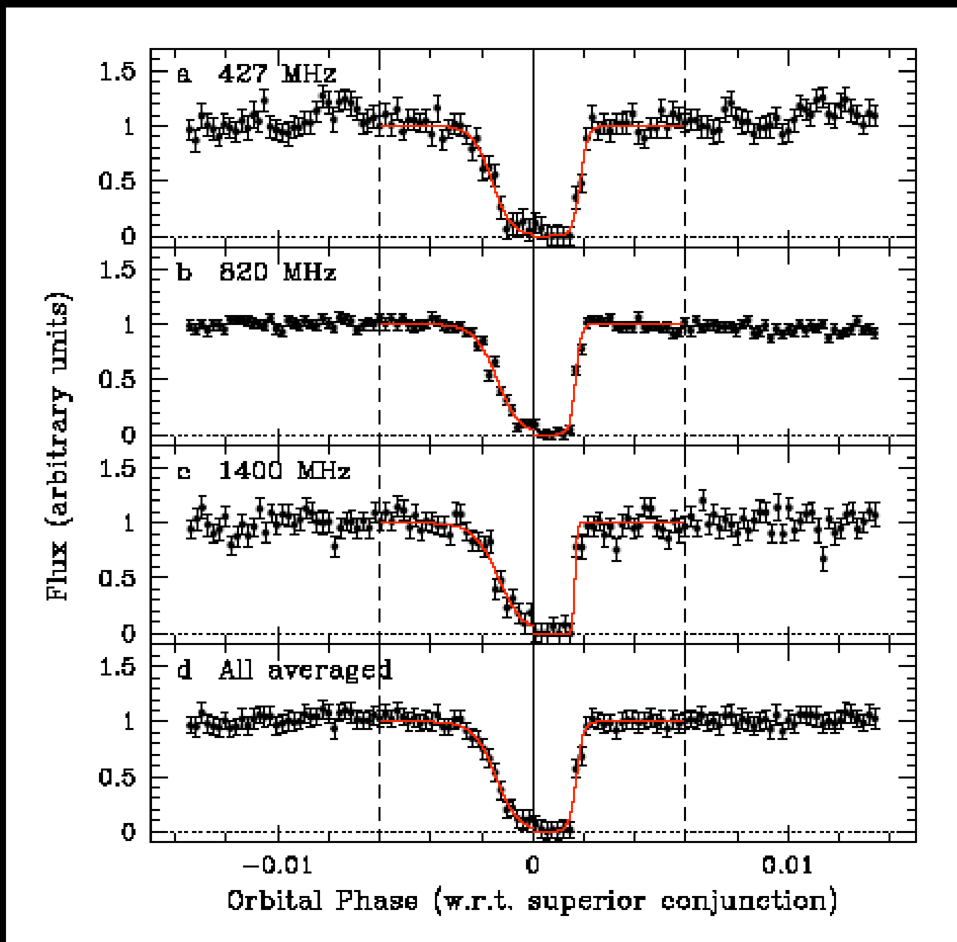
$$R_{LA} = 1098 \text{ km}, R_{LB} = 132{,}400 \text{ km}$$

$$a = 425{,}000 \text{ km}$$

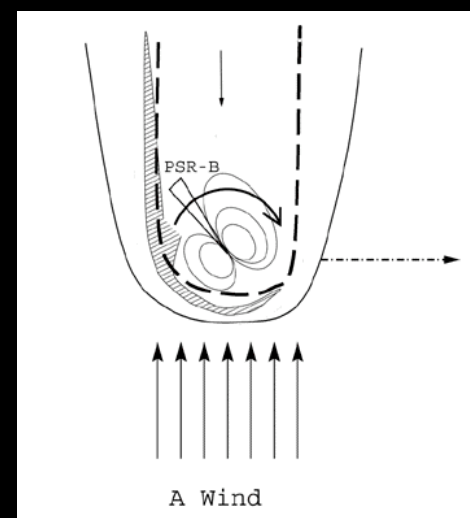
Doppler shifts of pulse period allow
Measurement of orbital parameters

Eclipses of Pulsar A

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



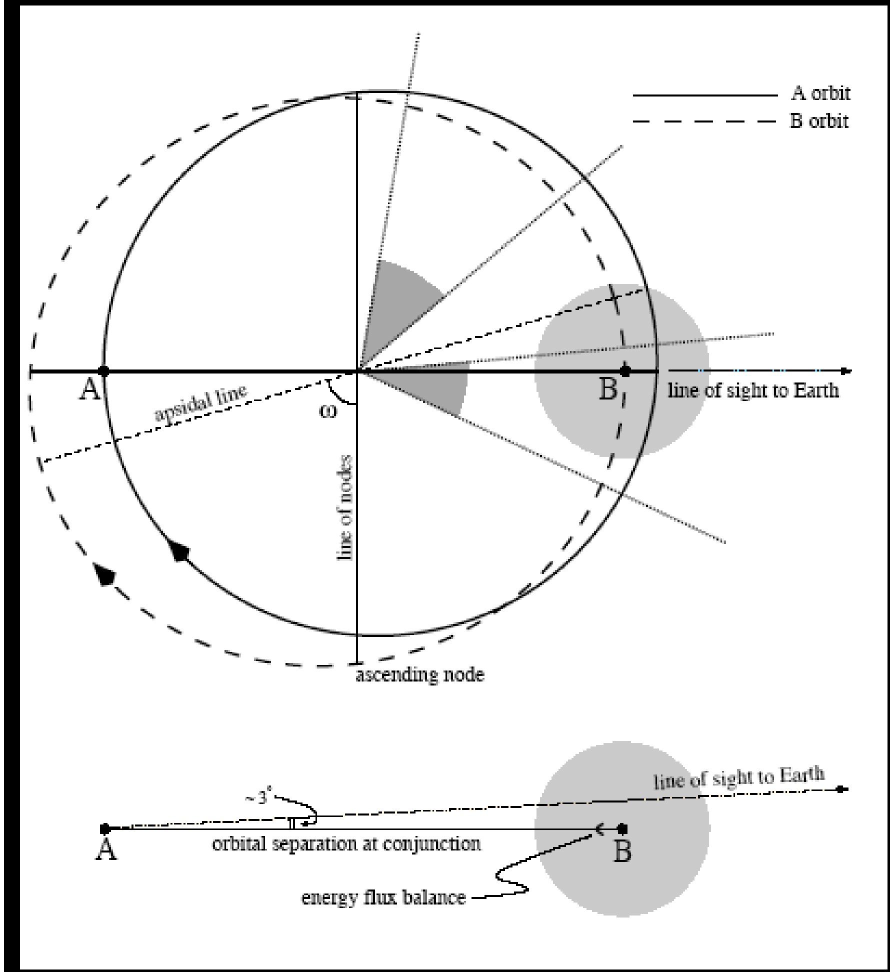
Pulsed flux of pulsar A for 4 minutes centered on superior conjunction (A behind B). Each data point is a 2 s integration. The eclipse lasts ~30 s, corresponding to a 18,600 km physical dimension of the obscuring material along the direction of orbital motion.



Cartoon of eclipse model - magnetosheath absorption by PSR B

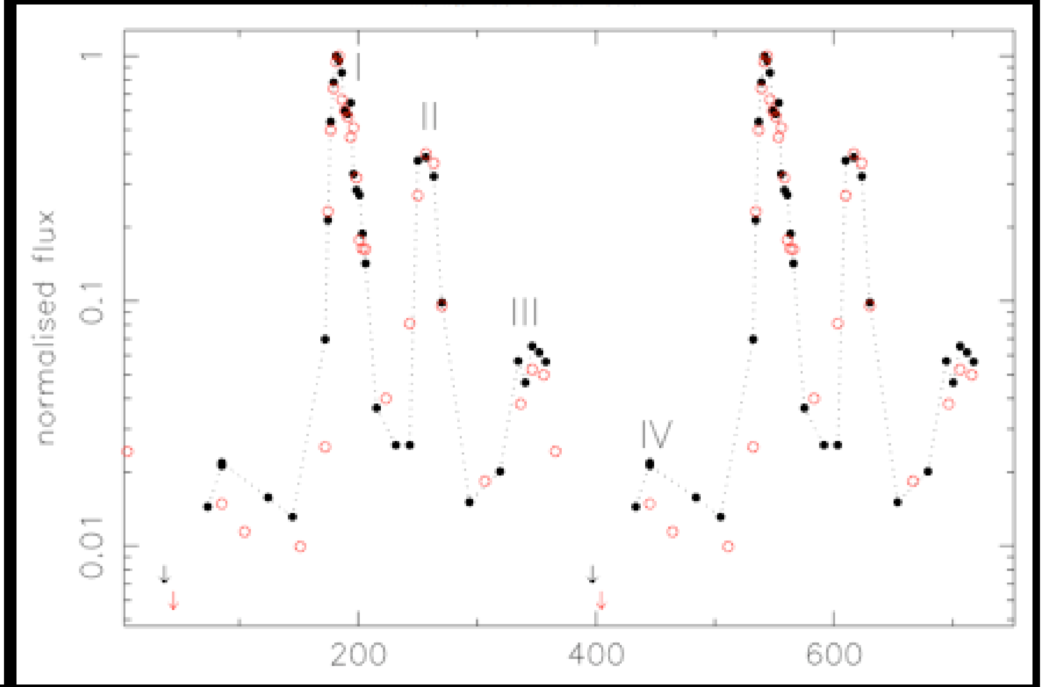
PSR J0737 A&B -- laboratory for relativistic winds

Binary orbit:



Lyne et al (2004)

Eccentricity 0.0878
Characteristic age: 270 Myr(A), 50My(B)
Mass (msun): 1.33 1.25
Orbitall inclination: 87+-3 degrees



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?*

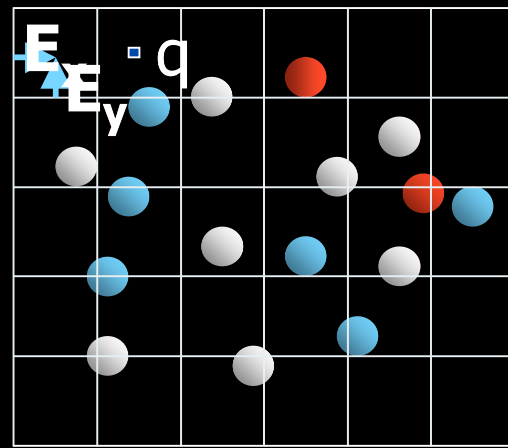
This system is unique in that mutual orientation of two pulsars changes on human timescale (~10yrs) due to GR. Predictions can be verified.

Strategy: investigate wind-magnetosphere interaction using numerical simulations

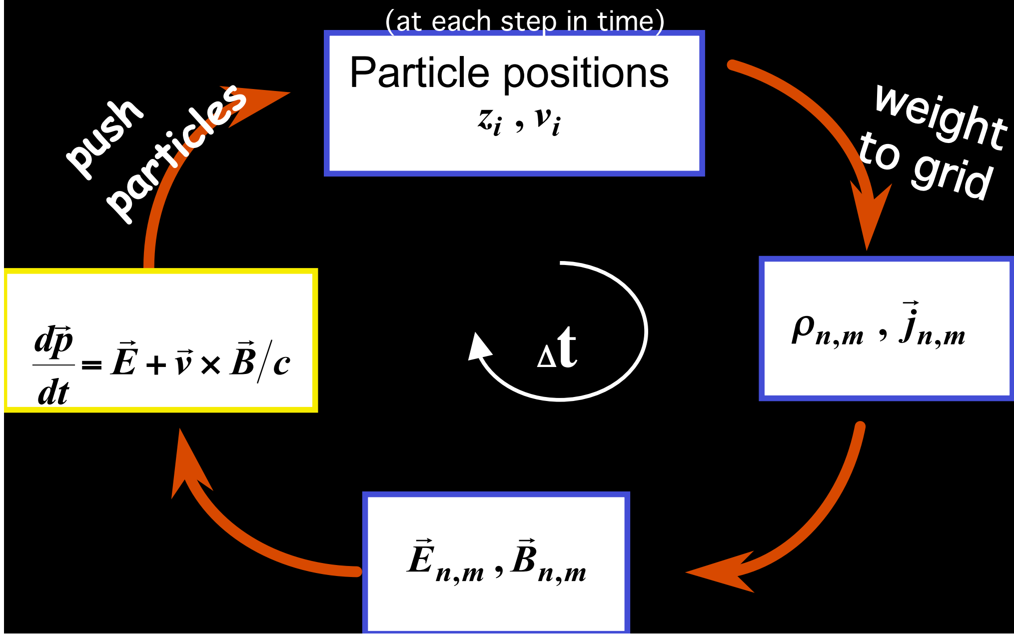
Numerical simulation of wind-magnetosphere interaction

Particle-in-cell method:

- *Collect currents at the cell centers*
- *Find fields on the mesh (Maxwell's eqs)*
- *Interpolate fields to particles positions*
- *Move particles under Lorentz force*



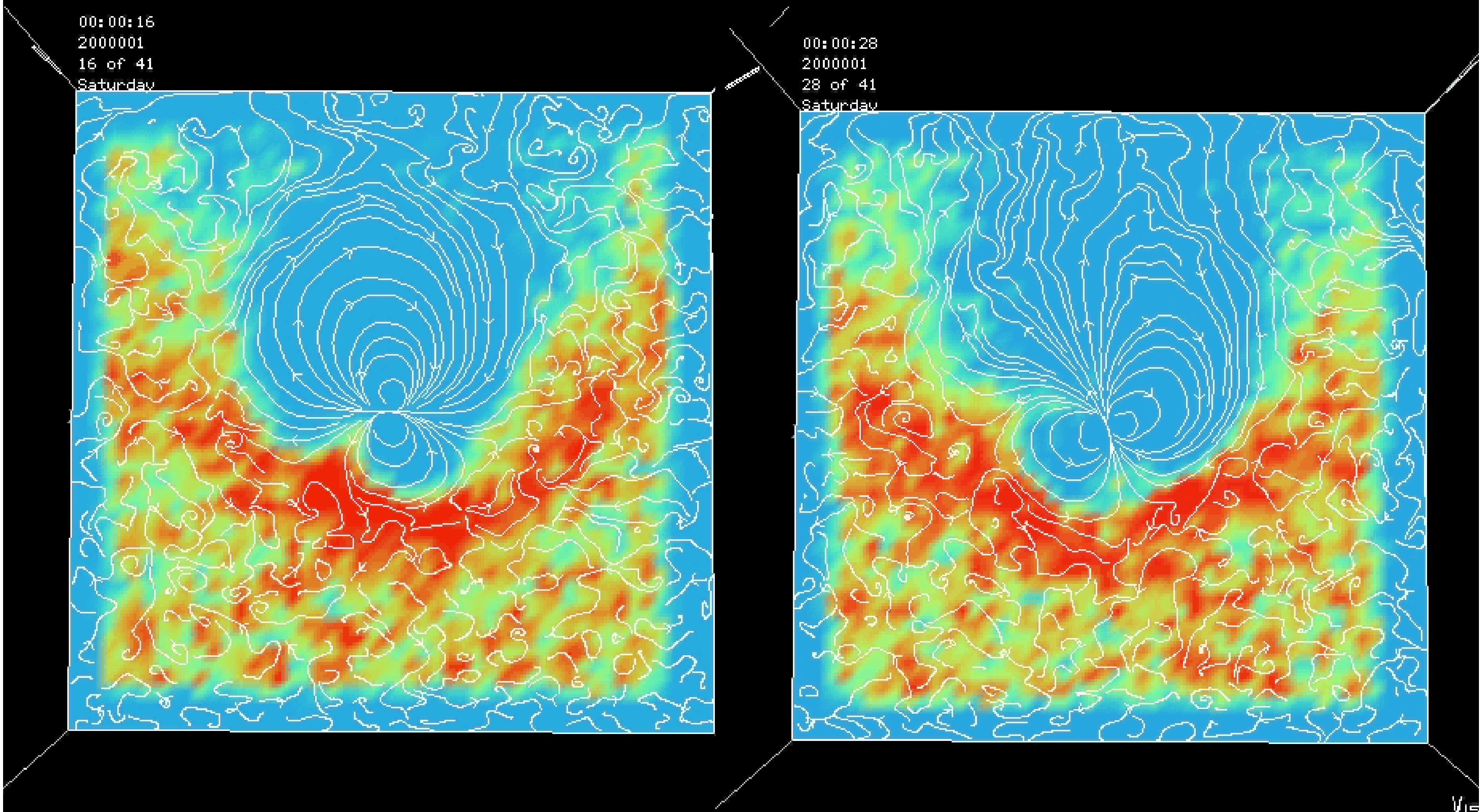
Computational cycle



Code "TRISTAN":

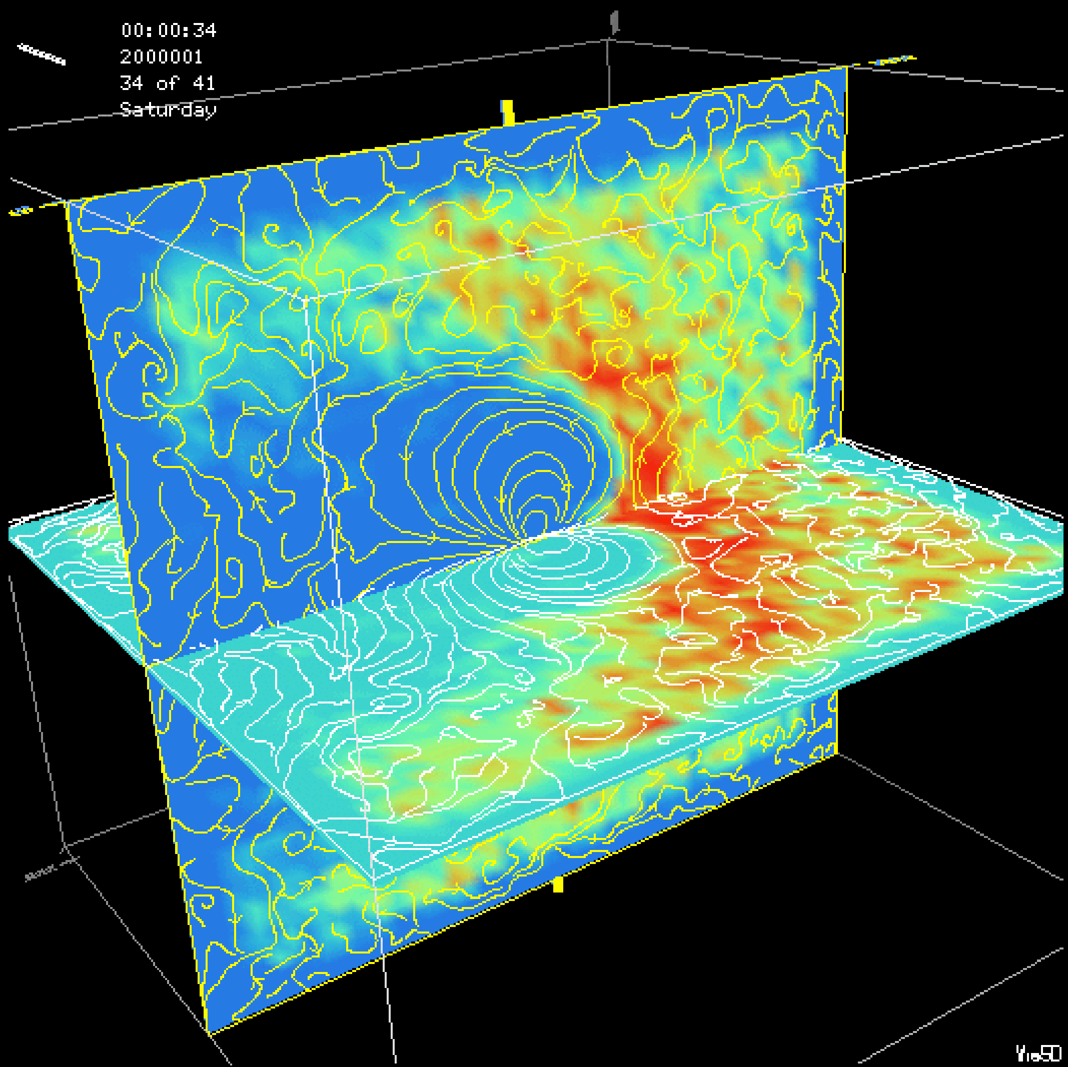
- *2D and 3D cartesian*
- *Algorithms for rotating magnet*
- *Handles magnetized flows*
- *Fully parallelized (128proc+)*
- *Resolution requirements: typical run 512^3 grid, $10^{7\text{-}8}$ particles, 50+ Gb. Run at NERSC.*
- *Diagnostics + visualization*

Movie: magnetosheath of pulsar B

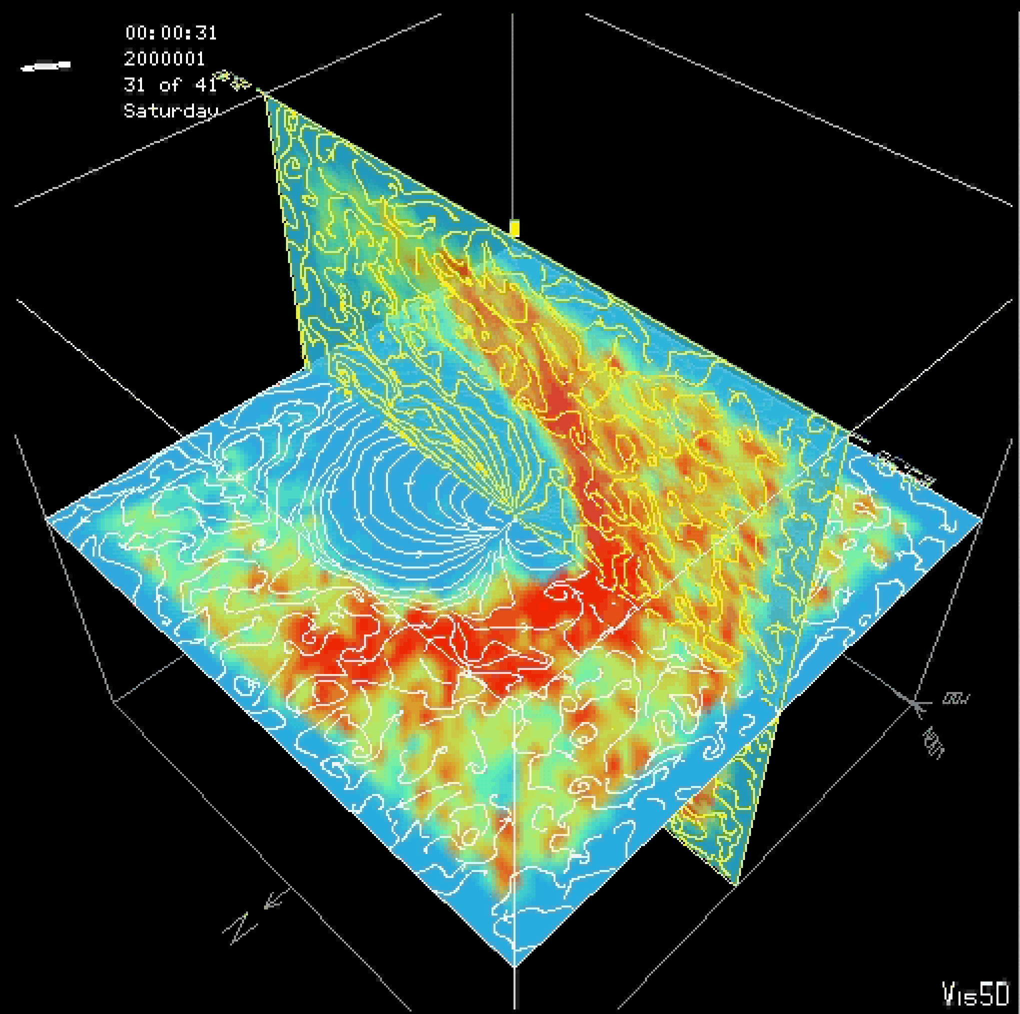


Similar to the interaction between Earth magnetosphere and solar wind.

3D magnetosphere: movies



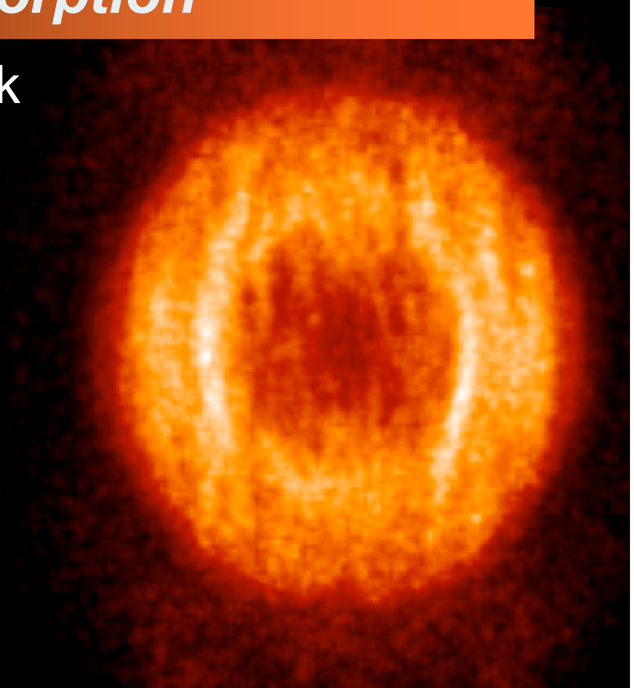
3D magnetosphere: movies



Eclipse and synchrotron absorption

Propose synchrotron absorption in the hot postshock plasma as the eclipse mechanism:

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

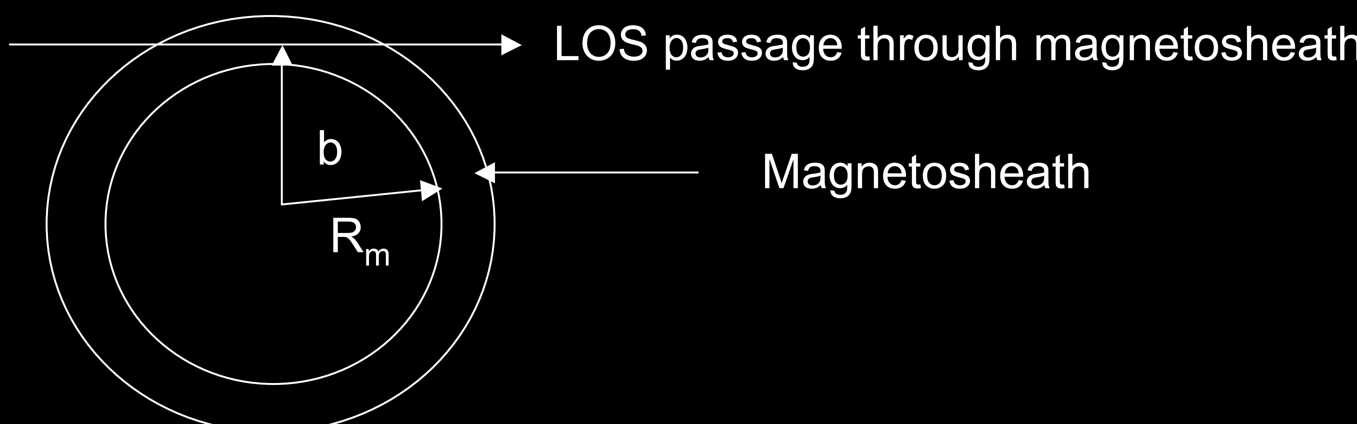


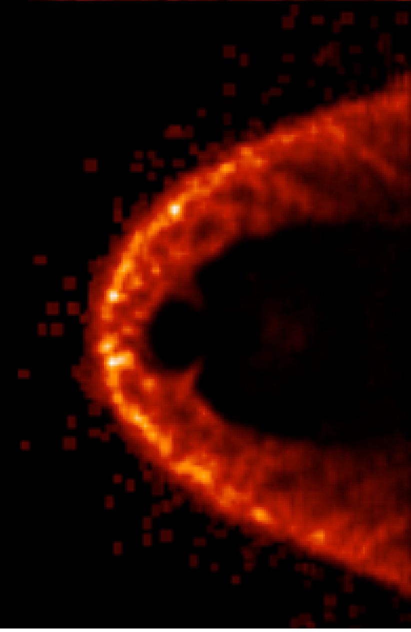
To explain observed eclipse require:

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

The wind is too dense and too slow according to conventional wisdom!

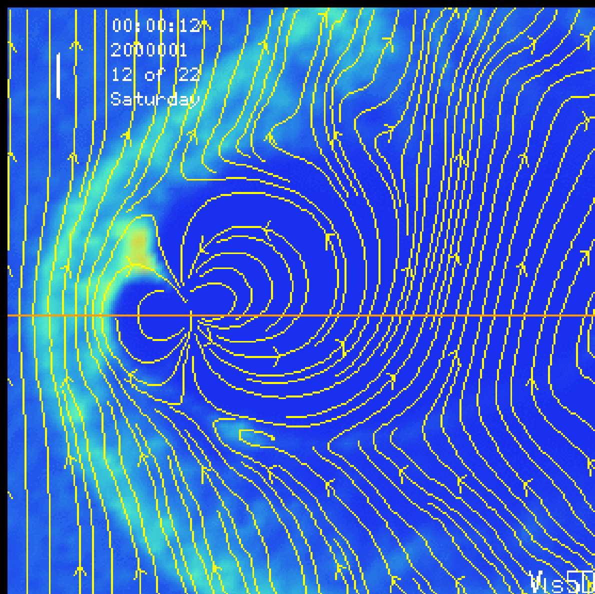
Eclipse duration:

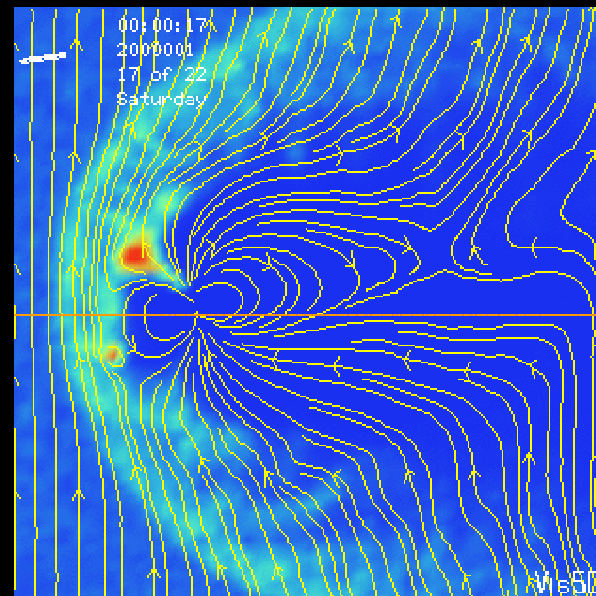




Spindown of pulsar B -- wind torques

Reconnection over half a turn.





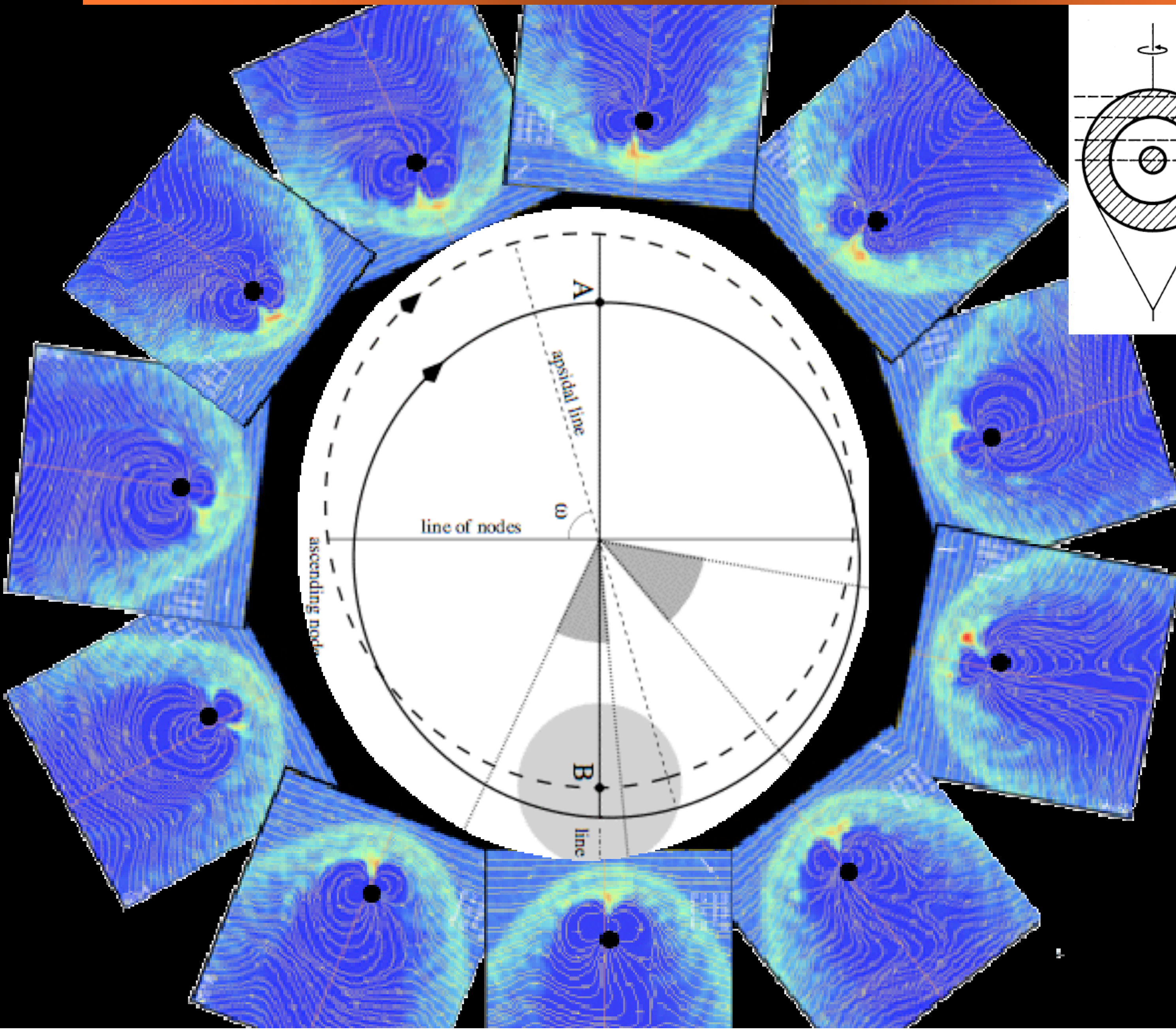
Acceleration on the dusk side, deceleration on the dawn side. Net torque:

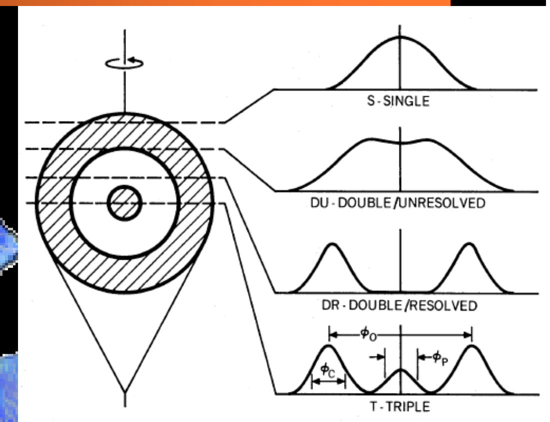
$$(\dot{J}_B)_{rec} = \int dV (\vec{r} \times \frac{1}{c}\vec{j} \times \vec{B}) \cdot \hat{\Omega}_B \sim \left(\frac{\dot{E}_A}{a^2 c}\right)^{1/3} \mu^{4/3} \frac{\Omega_B}{2c\beta_{\|}} = 2 \times 10^{30} ergs$$

The wind torque is comparable to the regular spindown torque:

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

Emission morphology of pulsar B





Conclusions

- First simulation of 3D wind-magnetosphere interaction for oblique magnetized rotators.
- Synchrotron absorption in the shocked wind is a likely origin of the eclipse phenomena in the system
- Wind exerts “propellor” torque -- opportunity to study spindown of a pulsar under stress.
- Inferred wind properties are unusual (high particle flux, low magnetization)
- 3D particle-in-cell simulation allows us to study formation of magnetized collisionless shocks. Kinetic nature of the simulation is essential to understanding collisionless shock acceleration. Magnetized shocks are ubiquitous in astrophysics (pulsars, AGNs, GRBs), yet acceleration is still not understood -- future direction.