Pulsar Winds
Anatoly Spitkovsky (KIPAC, Stanford)

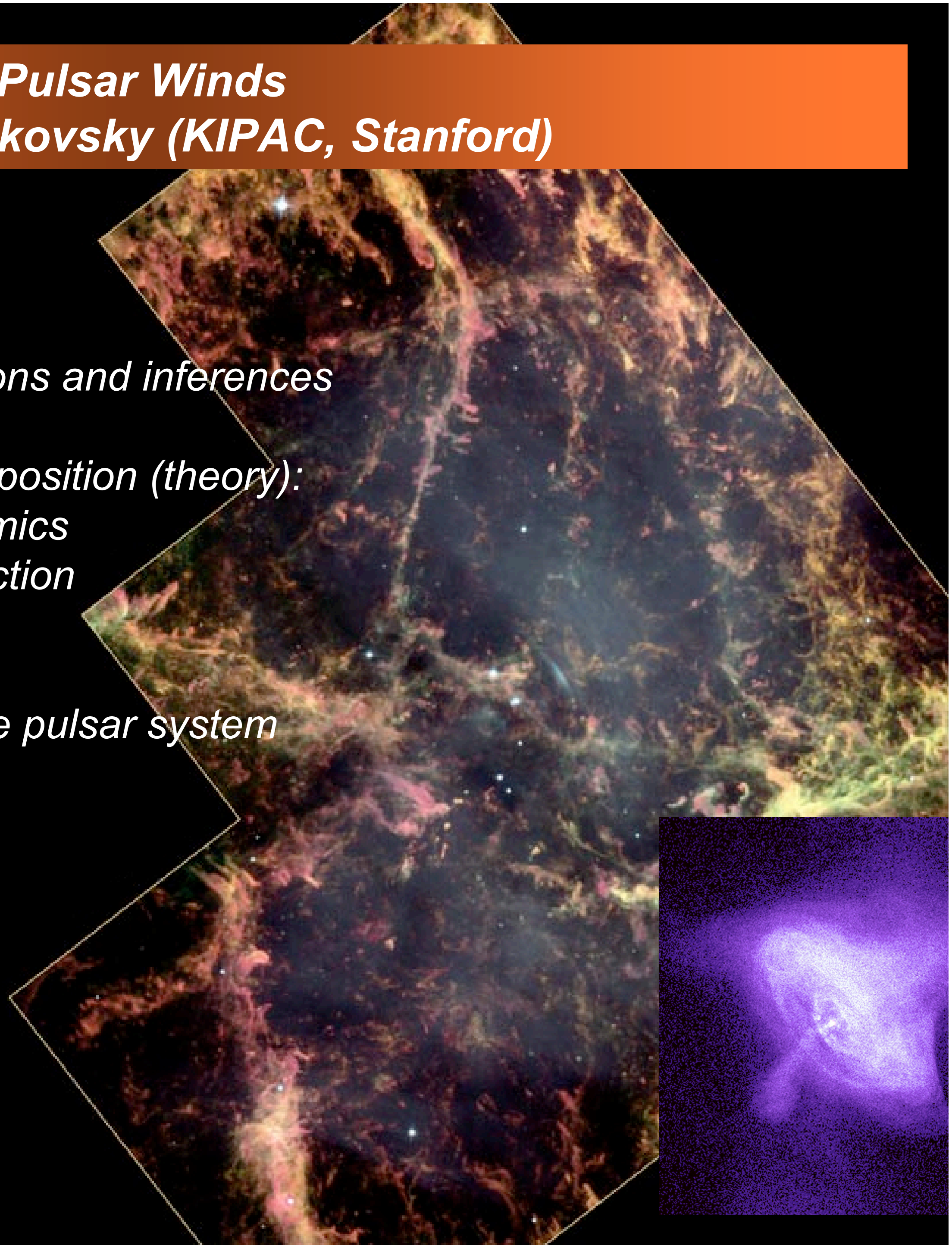
Outline:

1. *Pulsar winds: observations and inferences*

2. *Wind structure and composition (theory):*
   Pulsar electrodynamics
   Wind-nebula interaction
   Shock acceleration

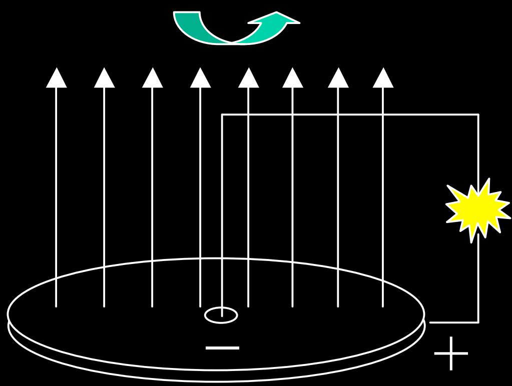
3. *Lessons from the double pulsar system J0737 A & B*

4. *Conclusions and future*

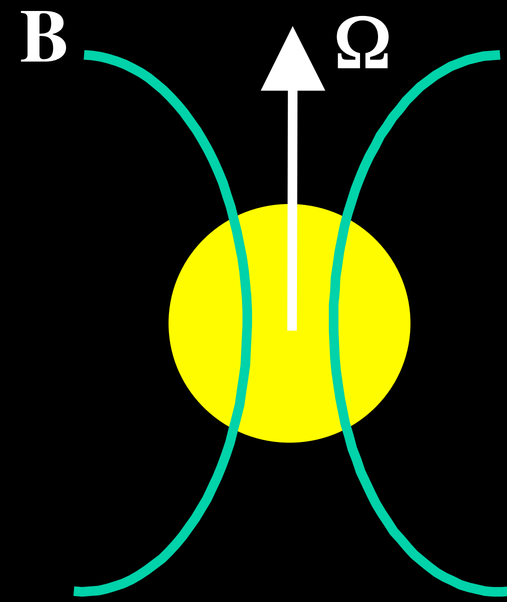


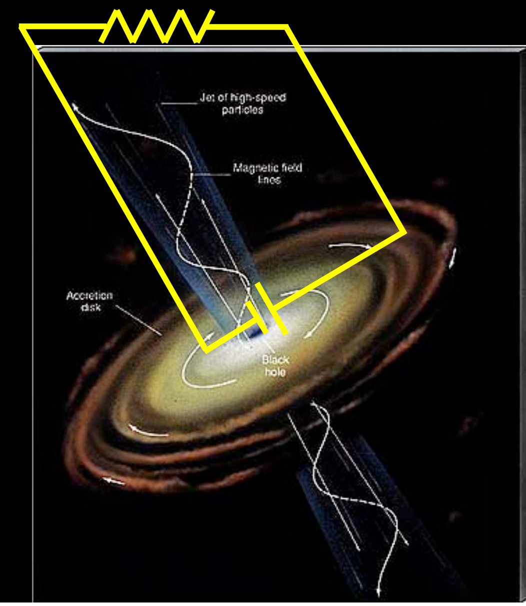
Unipolar Induction: rotating magnetized conductors

- Alfven (1939), aka Faraday wheel
- Rule of thumb: $V \sim \Omega\ \Phi$; $P \sim V^2 / Z_0$
- Crab Pulsar
  - $B \sim 10^{12}$ G, $\Omega \sim 200$ rad s^{-1}, $R \sim 10$ km
  - Voltage ~ 3×10^{16} V; I ~ 3×10^{14} A; P ~ 10^{38}erg/s
- Magnetar
  - $B \sim 10^{14}$ G; P ~ 10^{44}erg/s
- Massive Black Hole in AGN
  - $B \sim 10^{4}$ G; P ~ 10^{46} erg/s
- GRB
  - $B \sim 10^{16}$ G; P ~ 10^{49} erg/s



Faraday disk



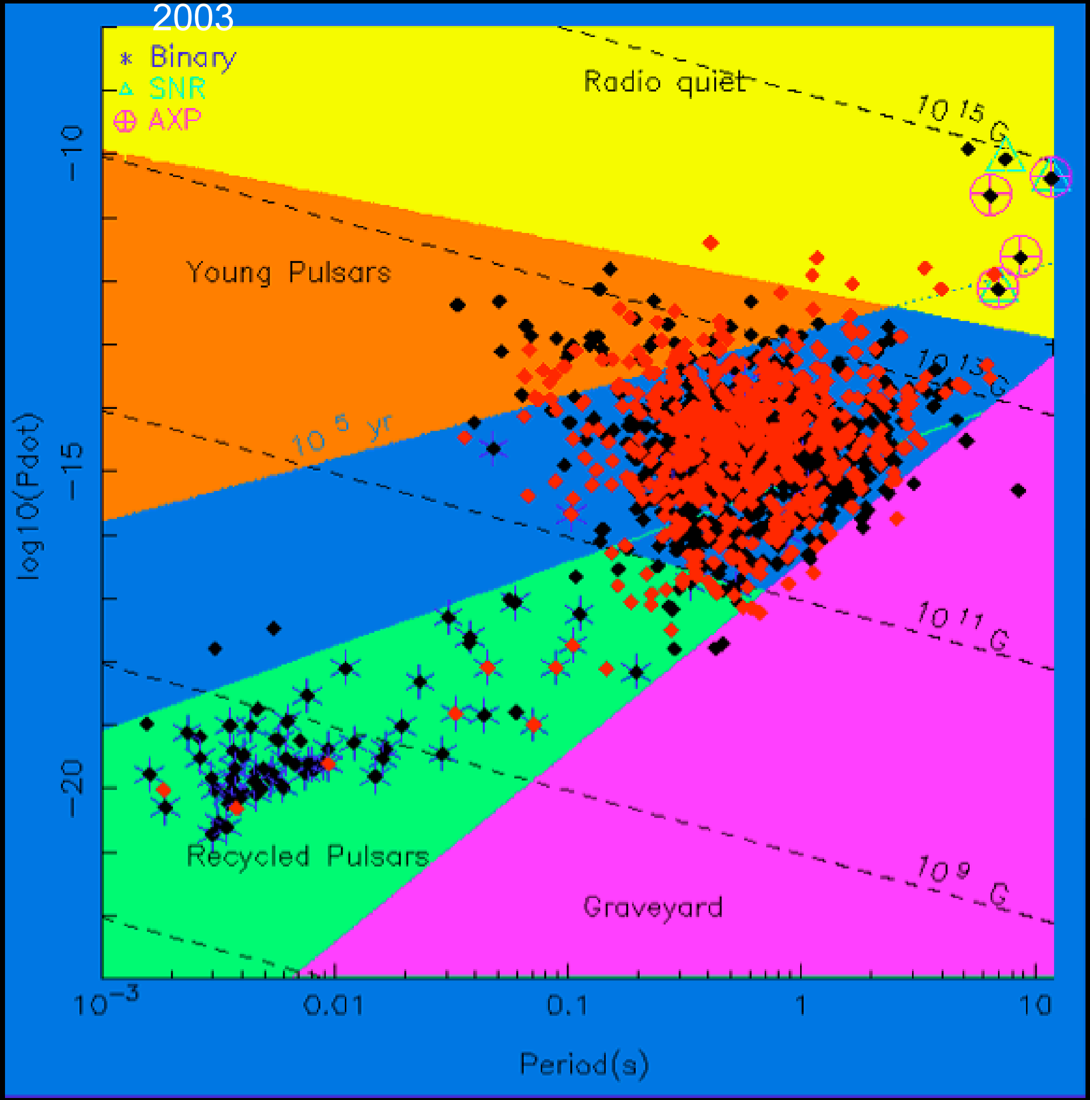


EM energy density >> particle energy density

Energy is extracted electromagnetically: Poynting flux

The life of pulsars

Manchester et al 2001, Morris et al 2002, Kramer et al 2003



All pulsars lose rotational energy and slow down

Spindown age:

$$\tau = \frac{P}{2\dot{P}}$$

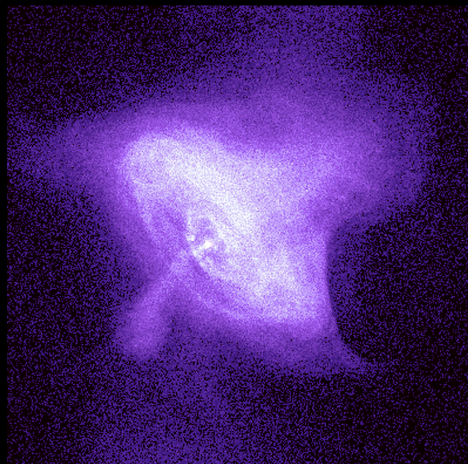
Surface magnetic field

$$B = 3.2 \times 10^{19} \sqrt{P\dot{P}}\ \mathrm{G}$$

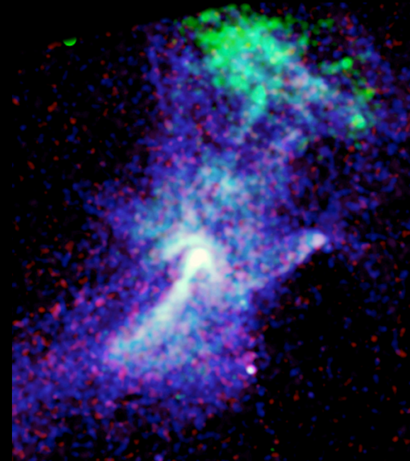
Typical value 10^{12}G

Energy loss in radiation tiny .01-10% of spindown. Most energy is in the wind

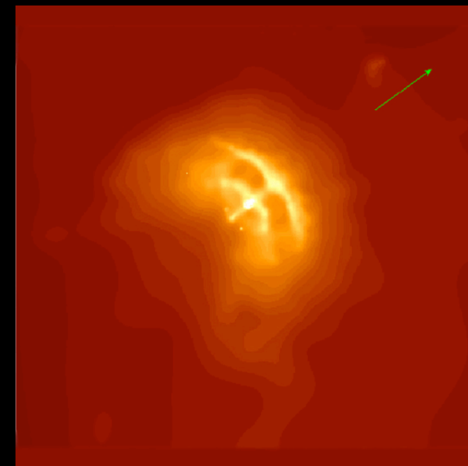
Pulsar wind nebulae



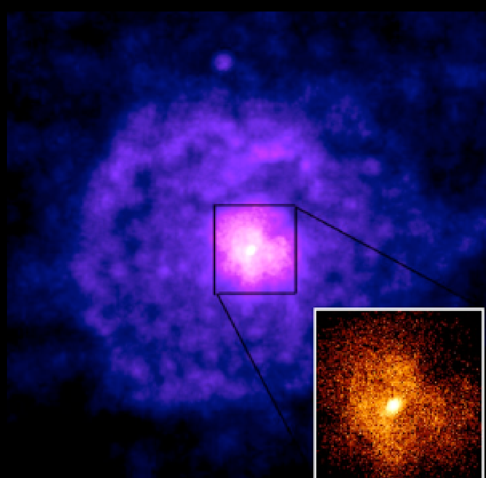
Crab (Weisskopf et al 00)



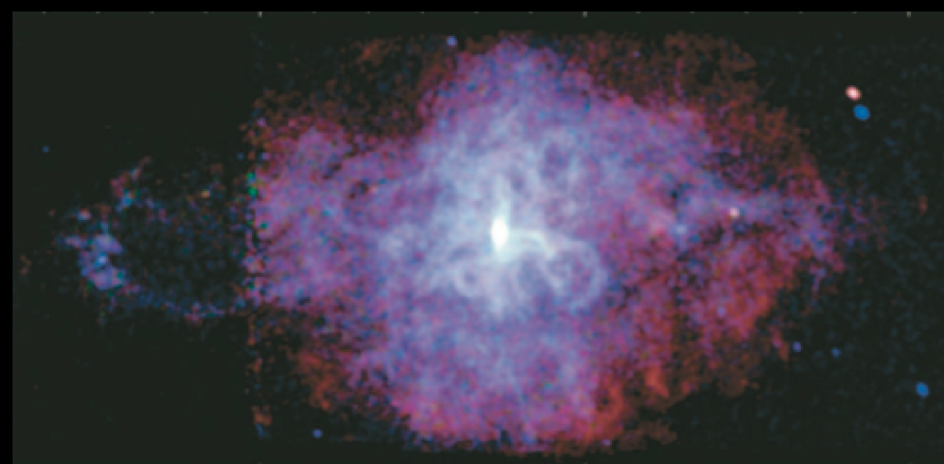
B1509 (Gaensler et al 02)



Vela (Pavlov et al 01)



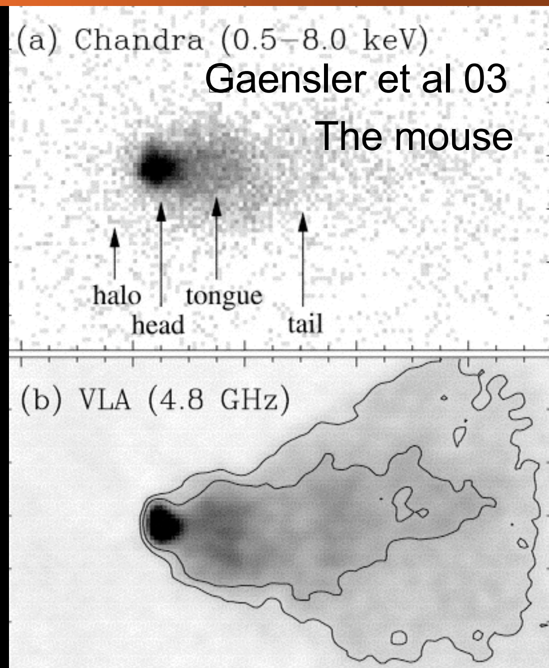
G21.5 (Safi-Harb et al 04)

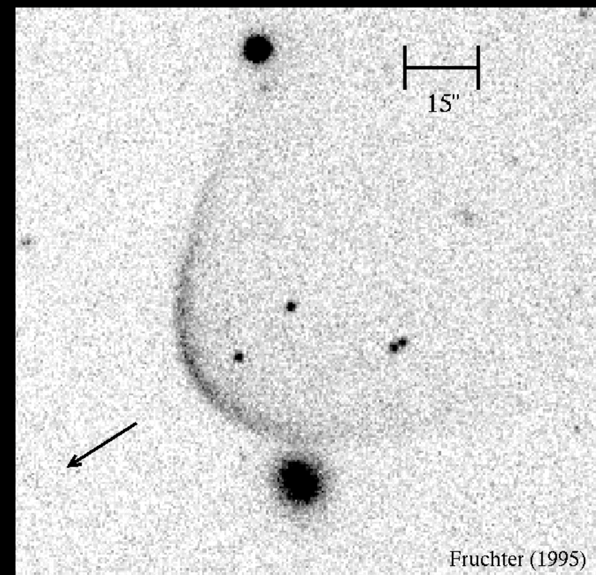


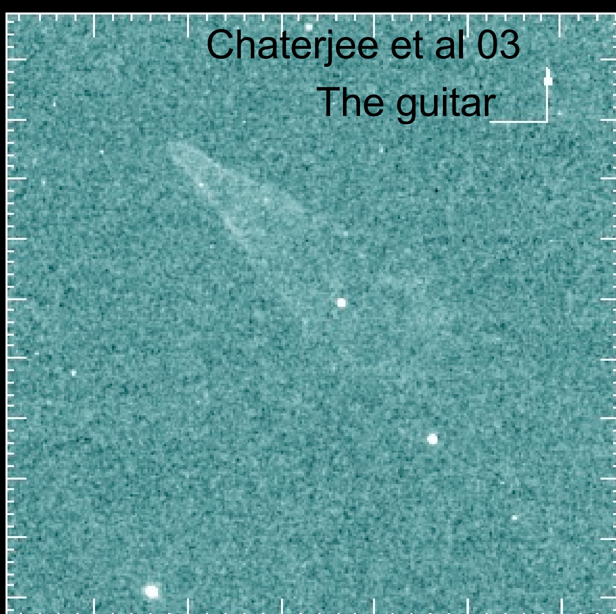
3C58 (Slane et al, 04)

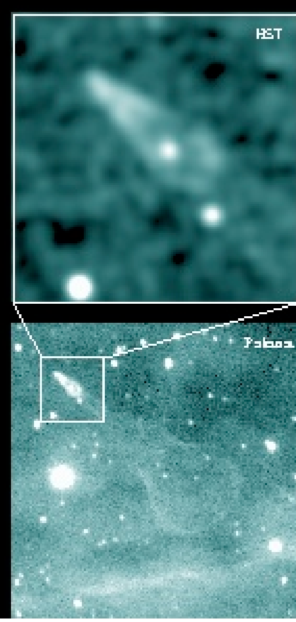
Center-filled morphology, nonthermal spectrum, linear polarization

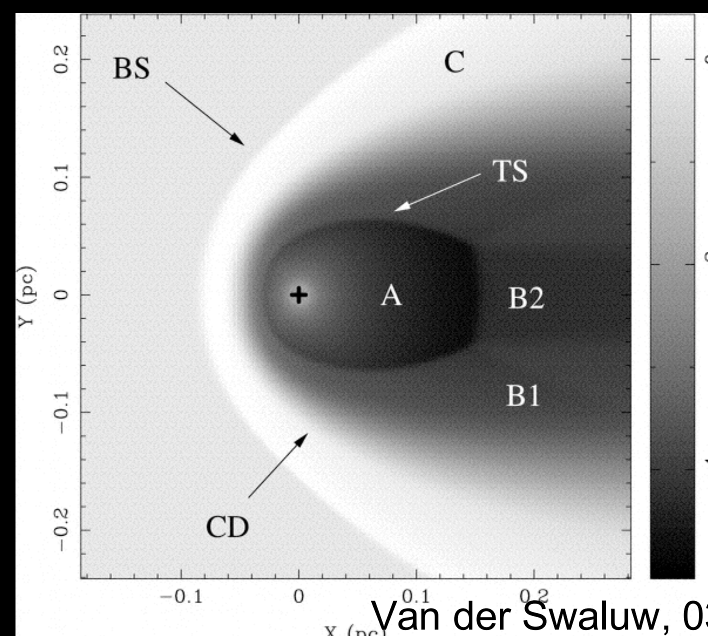
Bow shock nebulae



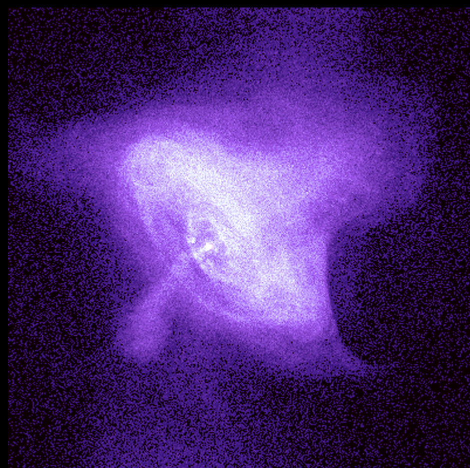








Pulsar wind nebulae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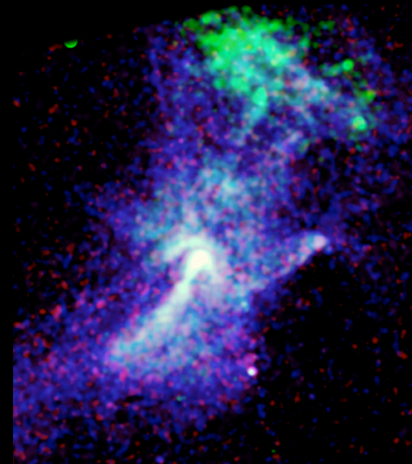
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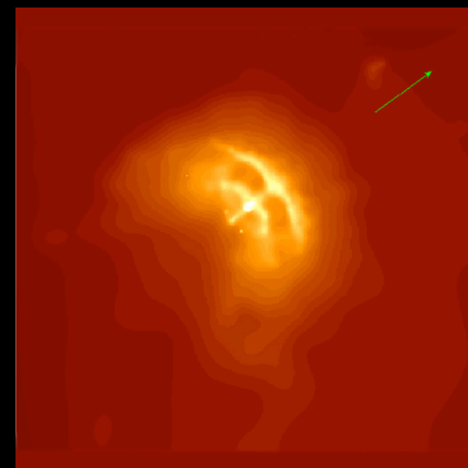
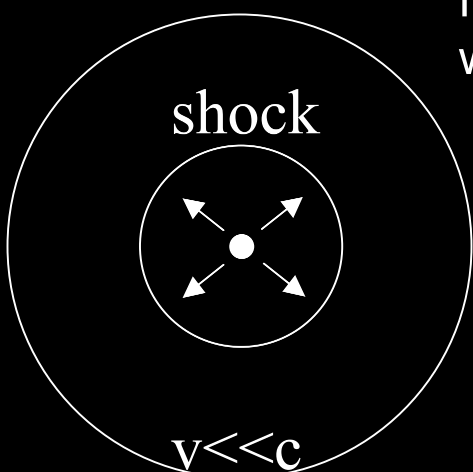

Vela (Pavlov et al 01)

Our main source of information about the wind is Pulsar Wind Nebulae in young supernova remnants. Box calorimeter for the wind. Most of spindown energy ends up in the wind.



Properties and puzzles of pulsar winds:

Highly relativistic ($\gamma \sim 10^6$) upstream, ~c/2 downstream

Kinetic energy dominated at the nebula

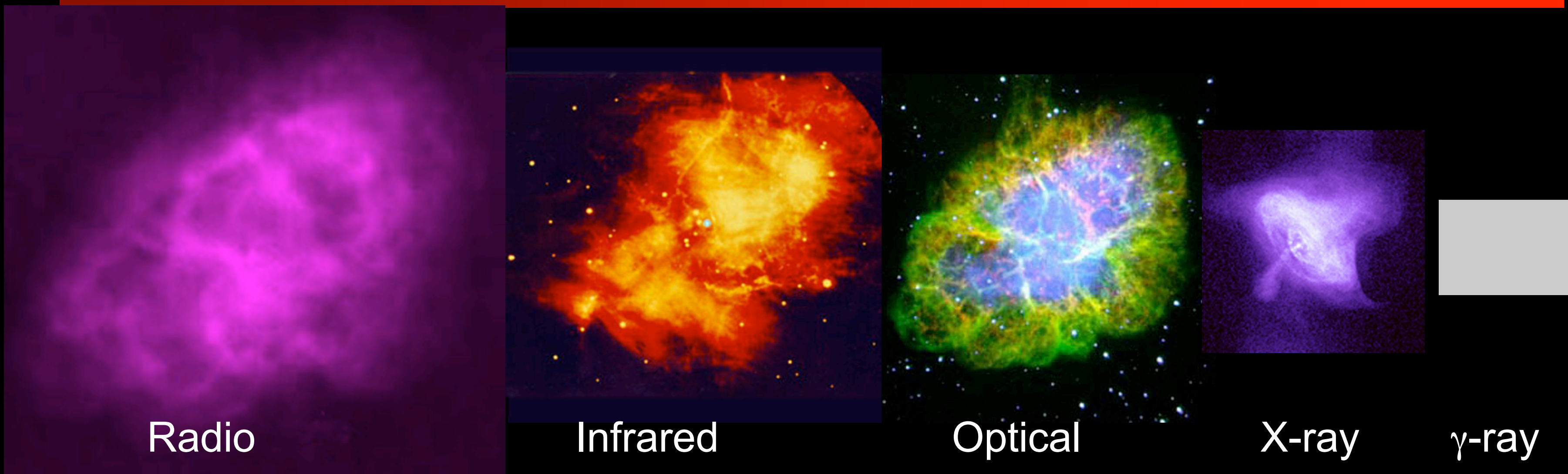
$$\sigma = B^2/(4\pi n \gamma m c^2) \sim 10^{-3}$$

Pole-equator asymmetry and collimation

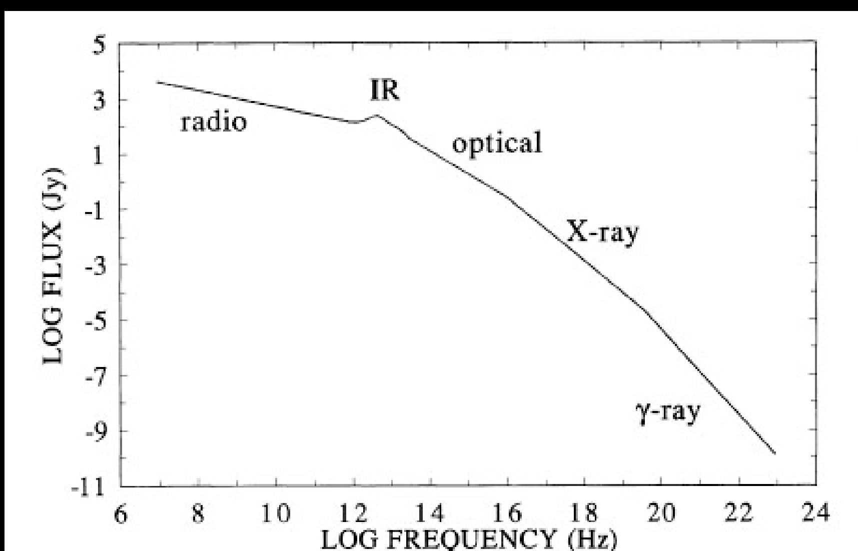
Produce nonthermal particles (how?)

Kennel & Coroniti 84
Rees & Gunn 74

CRAB NEBULA SN1054



$S_\nu \propto \nu^{-0.3}$ (radio); $\nu^{-1.0}$ (X-ray); break



Synchrotron emission:

Lifetime: X-rays -- few years, γ-rays -- months. Need energy input!

Crab pulsar: $E_R = 5 \times 10^{38}$ erg/s, 10-20% efficiency of conversion to radiation.

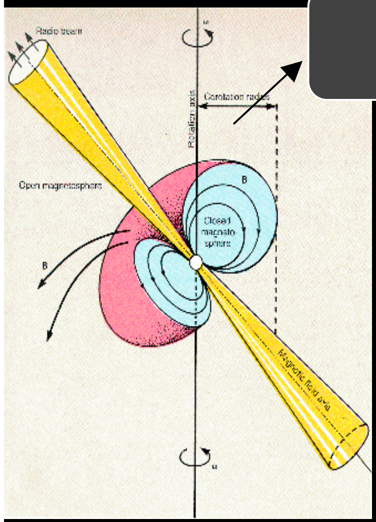
Max particle energy > 3×10^{15} eV, comparable to pulsar voltage.

Nebular shrinkage indicates one accelerating stage:

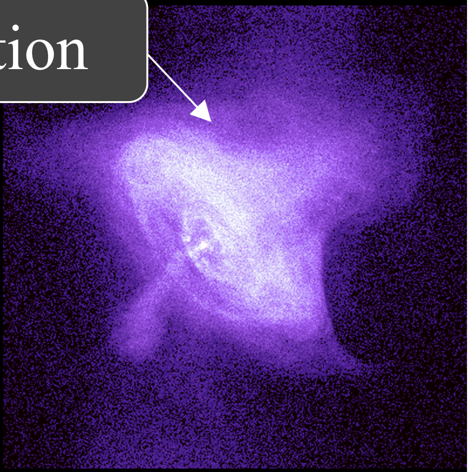
require $10^{38.5} - 10^{39}$ $e^{\pm}$ /s, radio mystery

PSR also injects B field into nebula (~10^{-4} G)

Understanding pulsar winds



Injection → Transport → Deposition

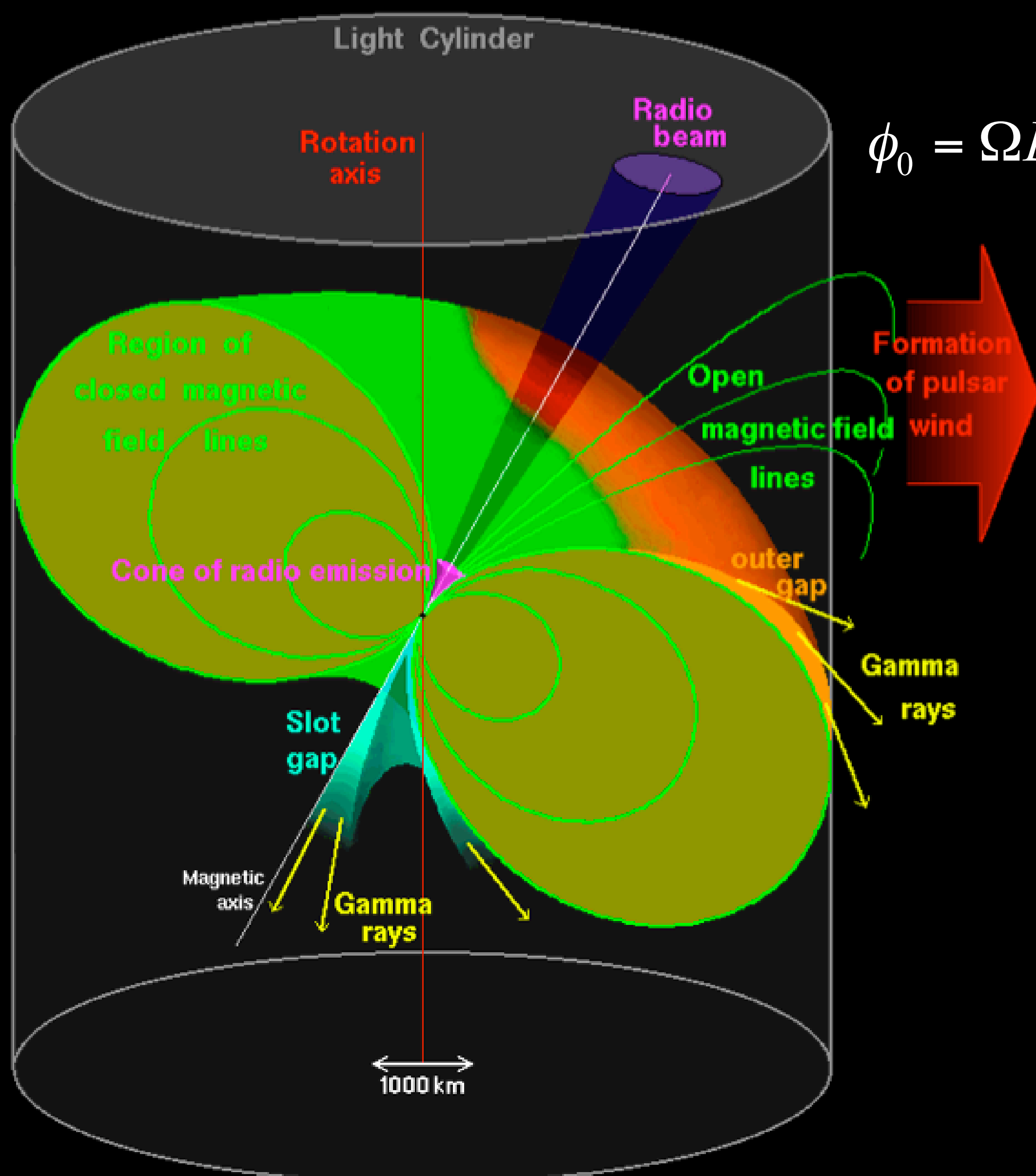


How is the wind produced at the source?
Where does acceleration/collimation happen?
How is flow energy converted into radiation?

Goal:

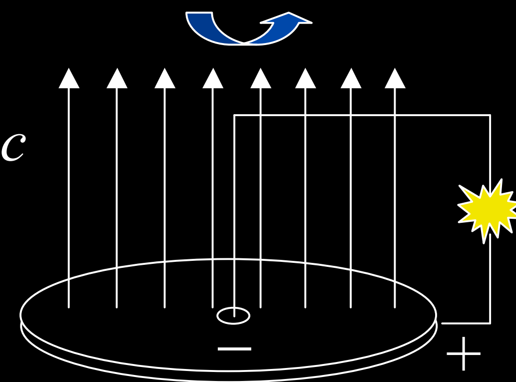
Use modeling of PWN data and ab-initio simulations of magnetospheres to construct a self-consistent picture of wind injection, transport and deposition, and infer wind properties (speed, magnetization, composition). Ultimately, use the wind to get a handle on physics at the source.

Wind injection: what do we expect?



D. Page

$$\phi_0 = \Omega B a^2 / c$$



Faraday disk: unipolar induction

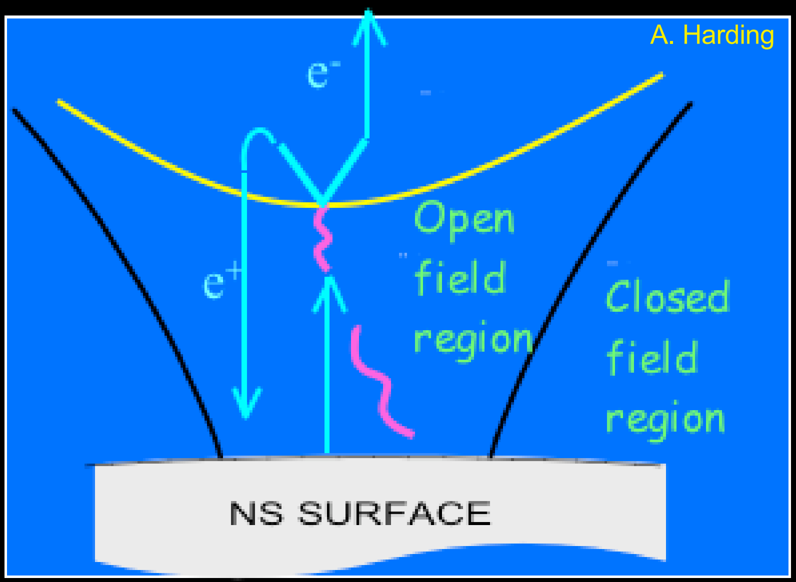
- *Wind not pressure-driven!*
- *Equator-pole potential difference (10^{15}V for Crab)*
- *Charge extraction from the surface (E field >> gravity)*
- *Corotating zone*
- *Expect relativistic motion*
- *Pair formation -- pair-dominated plasma?*
- *Expect strong magnetization*

Plasma supply: pair production

Where does the plasma come from?

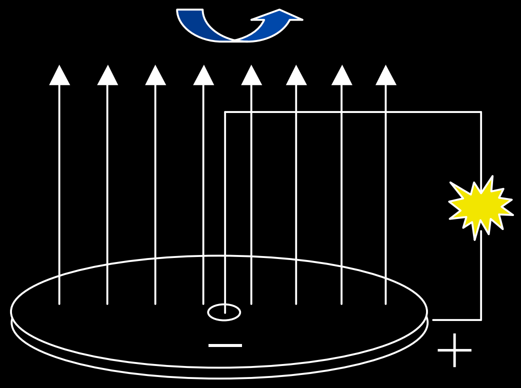
Polar cap is a space-charge limited accelerator. Accelerated primary particles radiate curvature radiation, and pair produce in the strong field. Pair cascade shorts out E*B.

$\gamma_{\text{primary}} \sim 10^7 \quad \gamma_{\text{secondary}} \sim 10^{2-3} \quad \sigma_{\text{LC}} \sim 10^4$



Arons & Scharleman 79, Muslimov & Harding 03

Electrostatic accelerator, non-MHD region



Faraday disk

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Modeling the magnetosphere

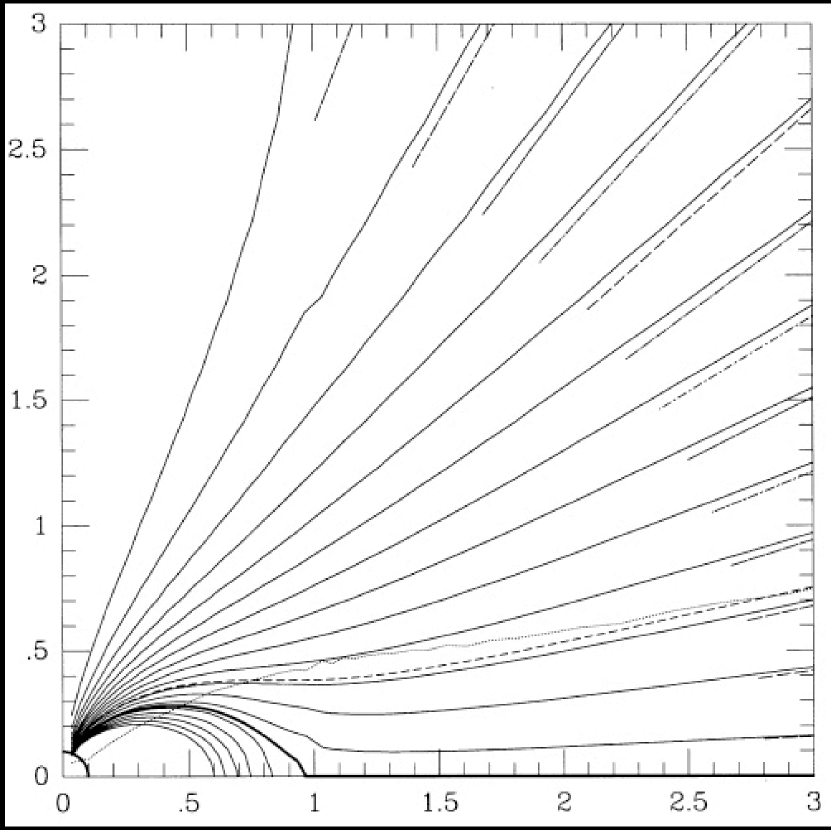
If there is abundant plasma, can use strong-field MHD

Force-free approximation:

$$mn\frac{\partial \gamma \vec{v}}{\partial t} = \rho \vec{E} + \frac{\vec{j}}{c} \times \vec{B} \approx 0$$

Assume enough plasma to provide currents

Two approaches: steady state vs dynamic



Contopoulos et al 99, Gruzinov 05

“Pulsar” equation:

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial z^2} - \frac{1 + x^2}{x(1 - x^2)}\frac{\partial \Psi}{\partial x} = -\frac{I(\Psi)I'(\Psi)}{R_L^2(1 - x^2)} \qquad x = \frac{R}{R_L}$$

Critical points are preset, no guarantee that the physical system actually chooses this solution. No possibility to extend to 3D.

Try the approach from stellar winds -- add time-dependence!

Force-free equations

Full RMHD equations become stiff for high magnetization

$$mn\frac{\partial\gamma\vec{v}}{\partial t} = \rho\vec{E} + \frac{\vec{j}}{c}\times\vec{B} \approx 0$$

Derive dynamical set of equations by ignoring particle inertia but retaining plasma charges and currents.

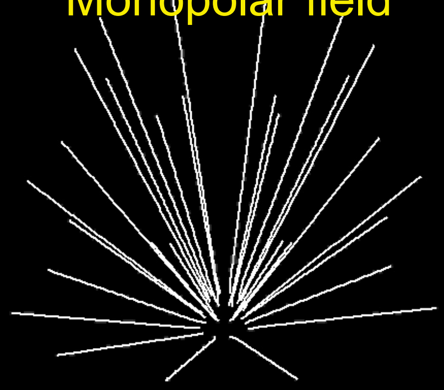
$$\left.\begin{aligned}
\frac{1}{c}\frac{\partial E}{\partial t} &= \nabla\times\vec{B} - \frac{4\pi}{c}\vec{j} \\
\frac{1}{c}\frac{\partial B}{\partial t} &= -\nabla\times\vec{E} \\
\rho\vec{E} + \frac{\vec{j}}{c}\times\vec{B} &= 0 \\
\frac{\partial}{\partial t}\vec{E}\cdot\vec{B} &= 0
\end{aligned}\right\} \quad \vec{j} = \frac{c}{4\pi}(\nabla\cdot\vec{E})\frac{\vec{E}\times\vec{B}}{B^2} + \frac{c\vec{B}(\vec{B}\cdot\nabla\times\vec{B} - \vec{E}\cdot\nabla\times\vec{E})}{4\pi B^2}$$

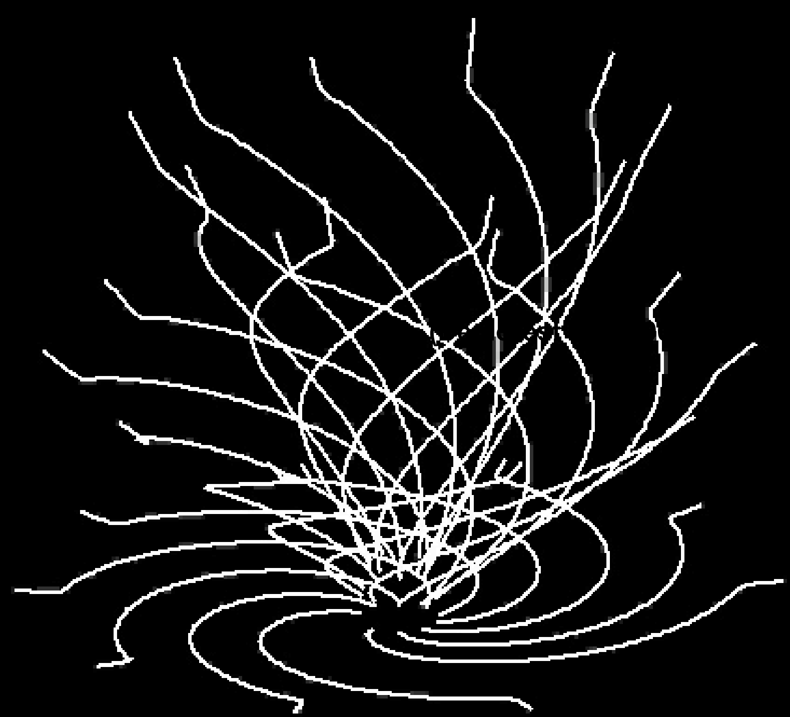
Gruzinov 99, Blandford 01

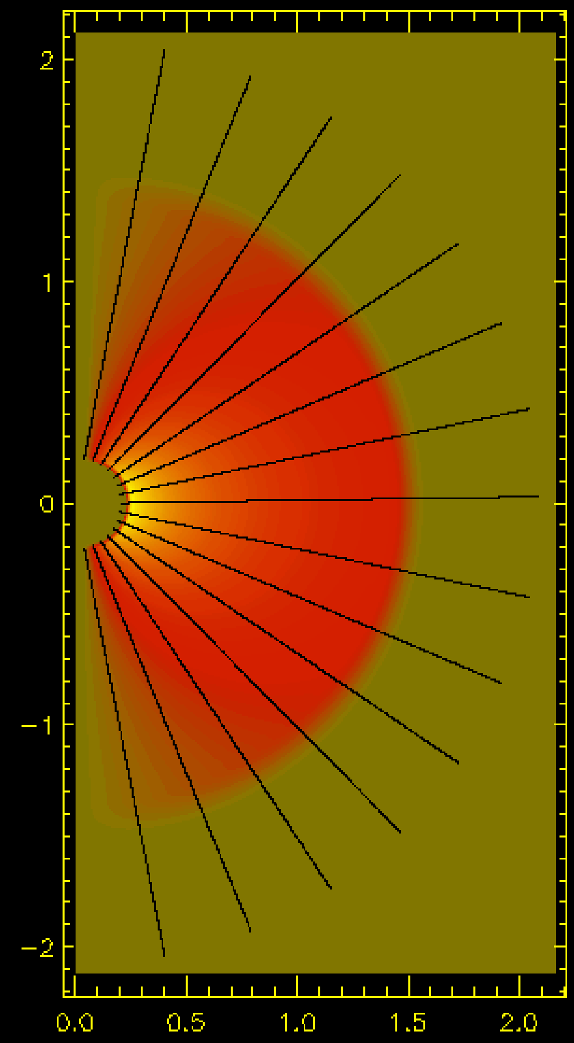
Where is plasma? Assumed to flow with ExB velocity, but velocity along the field is undefined.

Structure of magnetosphere: time-dependent solution

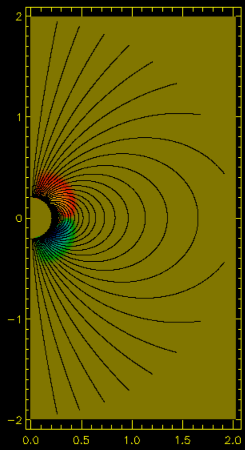
Monopolar field



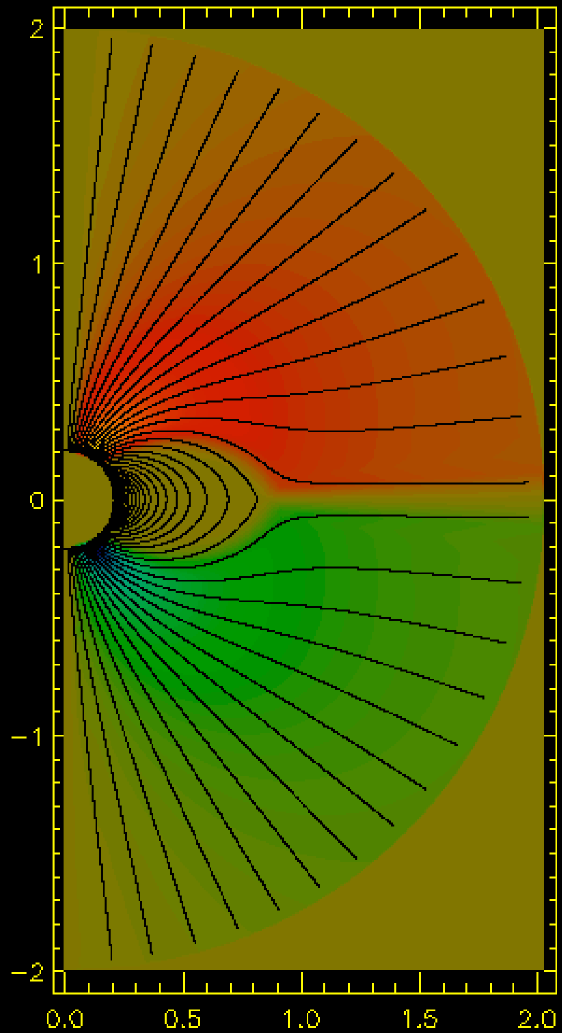




Structure of magnetosphere: time-dependent solution



Toroidal field



Time dependent force-free relativistic MHD approximation.

Properties of the solution:

Spontaneous formation of equatorial current sheet.
Y-point (inside LC)
Field is divergent at Y-point
Field is zero in the equatorial plane
Asymptotically -- monopole
Closed zone expands to LC over 10 period timescale.

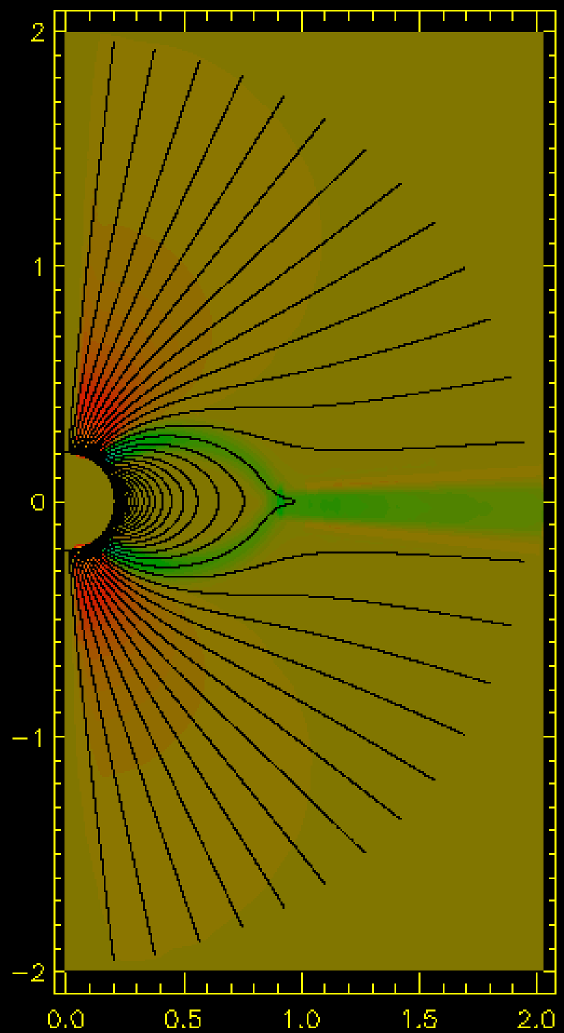
Spindown:

$$\dot{E} = \frac{\mu^2 \Omega^4}{c^3} = c B_{LC}^2 R_{LC}^2$$

A.S. (2005)

Pulsar magnetosphere: time-dependent solution

Current



Spindown:

Energy loss -- Poynting flux,
also =current x voltage.
Current: corotation charge density
(Goldreich & Julian '69) moving at c.

$$\vec{E} = -\frac{\vec{v}}{c}\times\vec{B} = -\frac{\vec{\Omega}}{c}\times\vec{R}\times\vec{B}$$

$$\frac{1}{4\pi}\nabla\cdot\vec{E} = \rho_{GJ} = -\frac{\vec{\Omega}\cdot\vec{B}}{2\pi c}$$

$$\dot{N}_{GJ} = 2\times10^{34}\ \mathrm{s}^{-1}$$

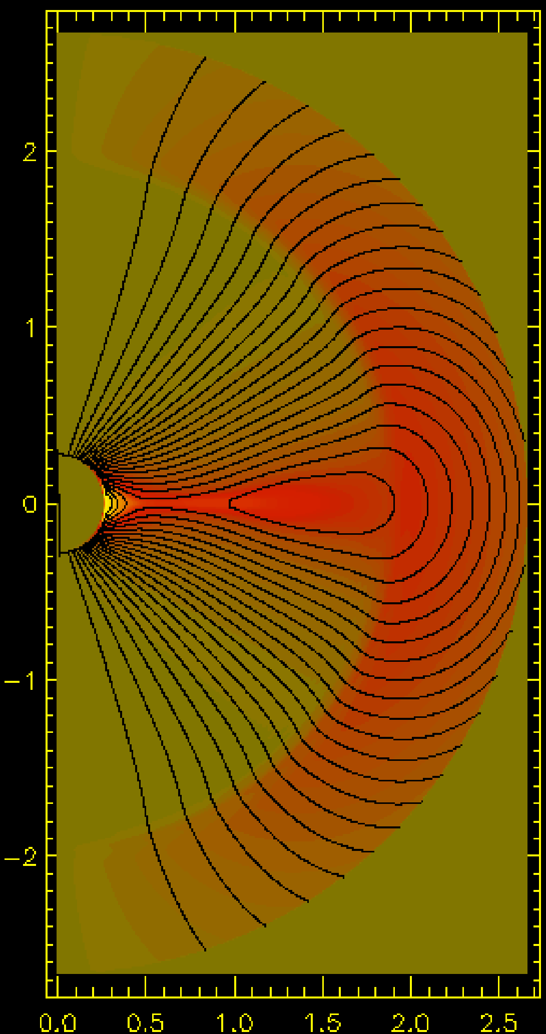
$$\dot{N}_{\pm} = 3\times10^{38}\ \mathrm{s}^{-1}$$

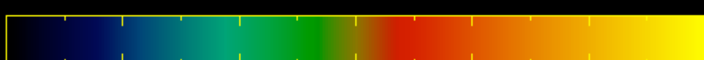
Return current:

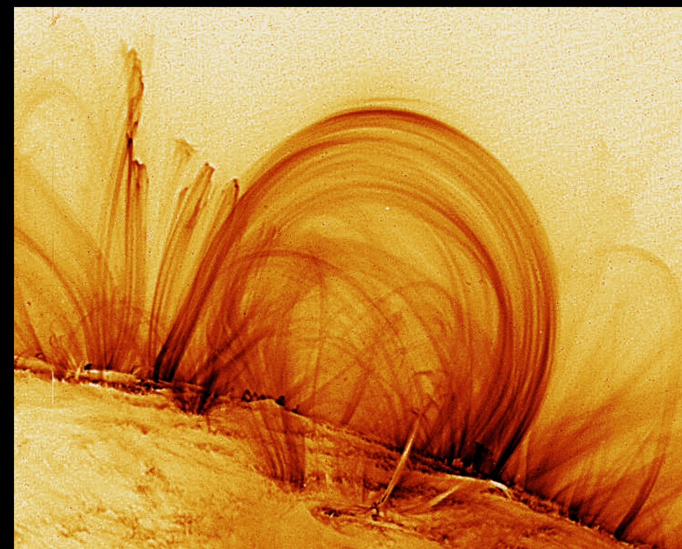
If the main current is carried by electrons, ions could be extracted in the equatorial channel

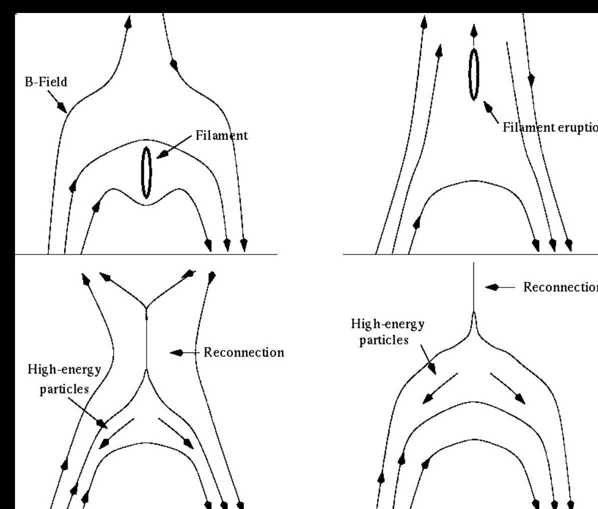
Force-free field configurations

Magnetar starquake



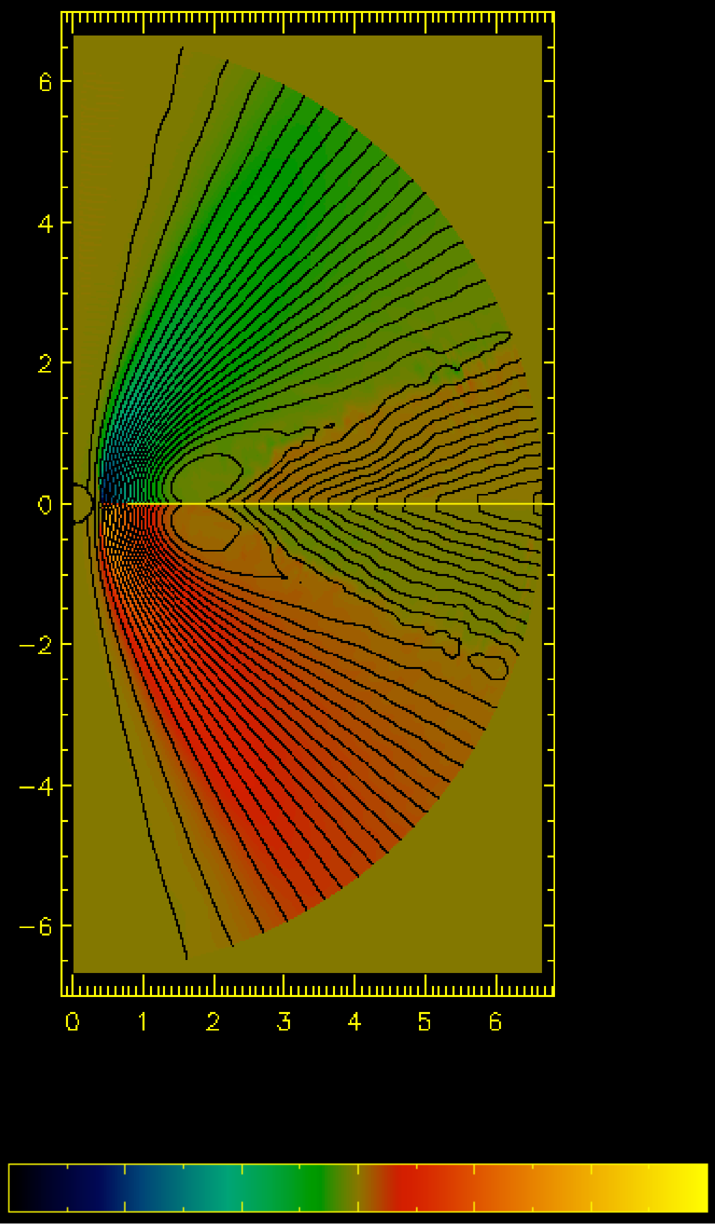


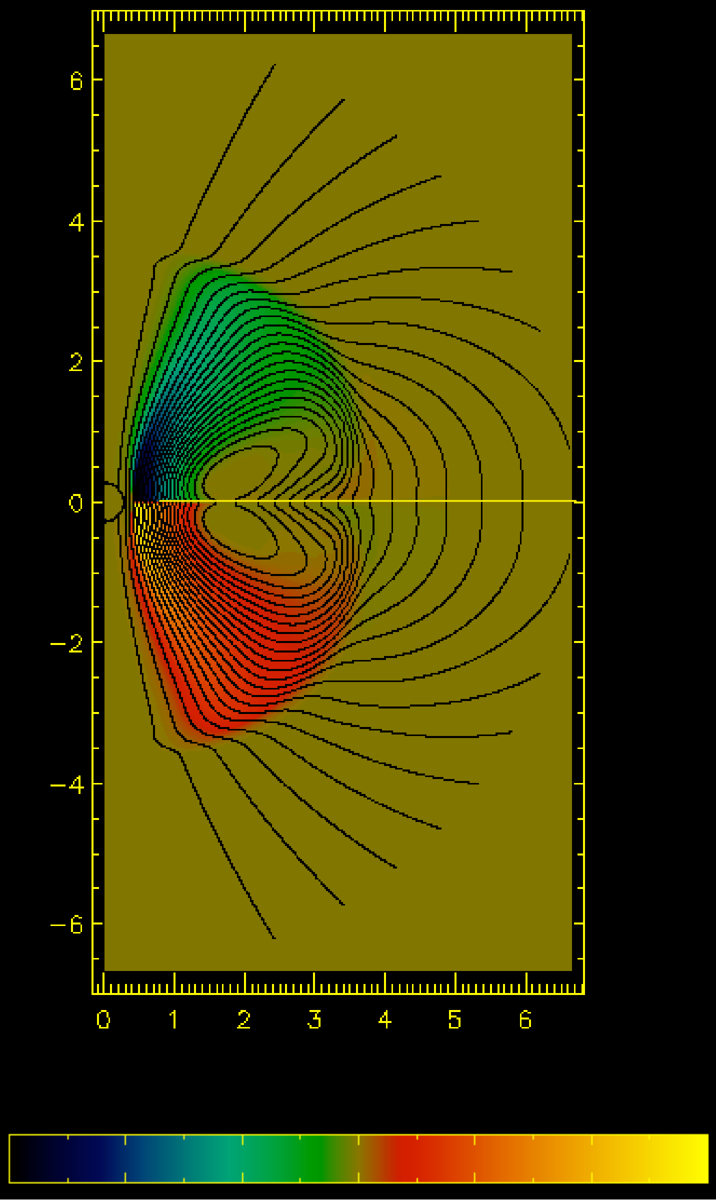




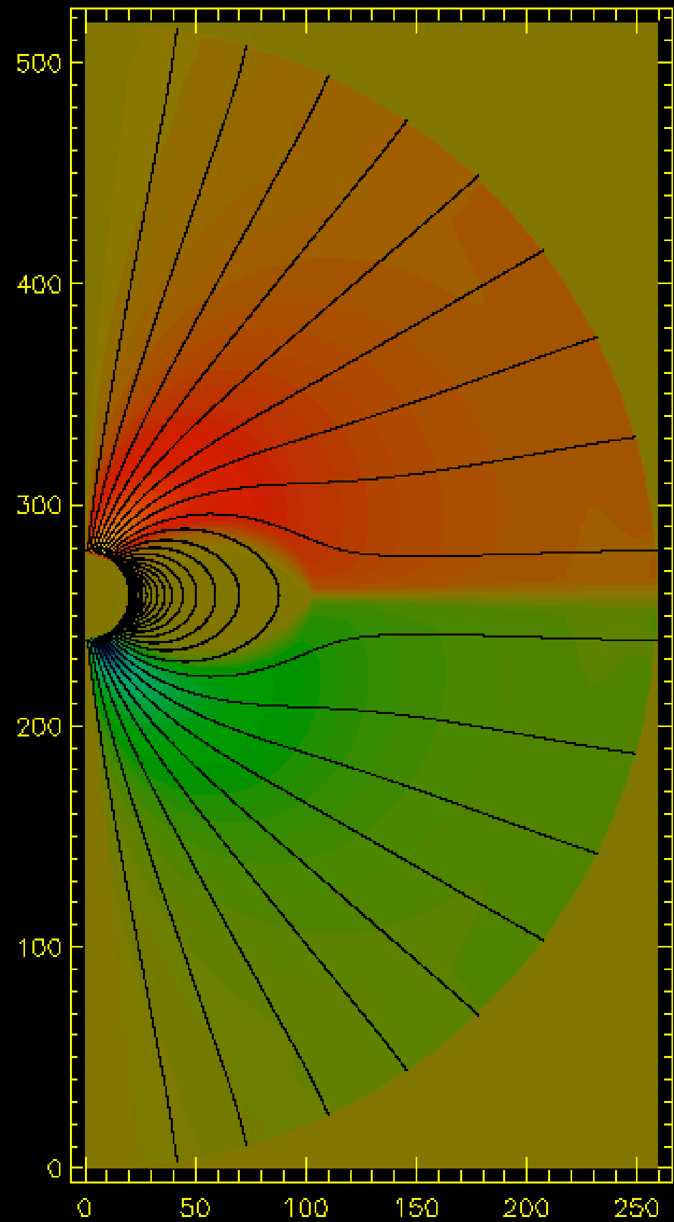
Force-free field configurations

Acretion disk corona





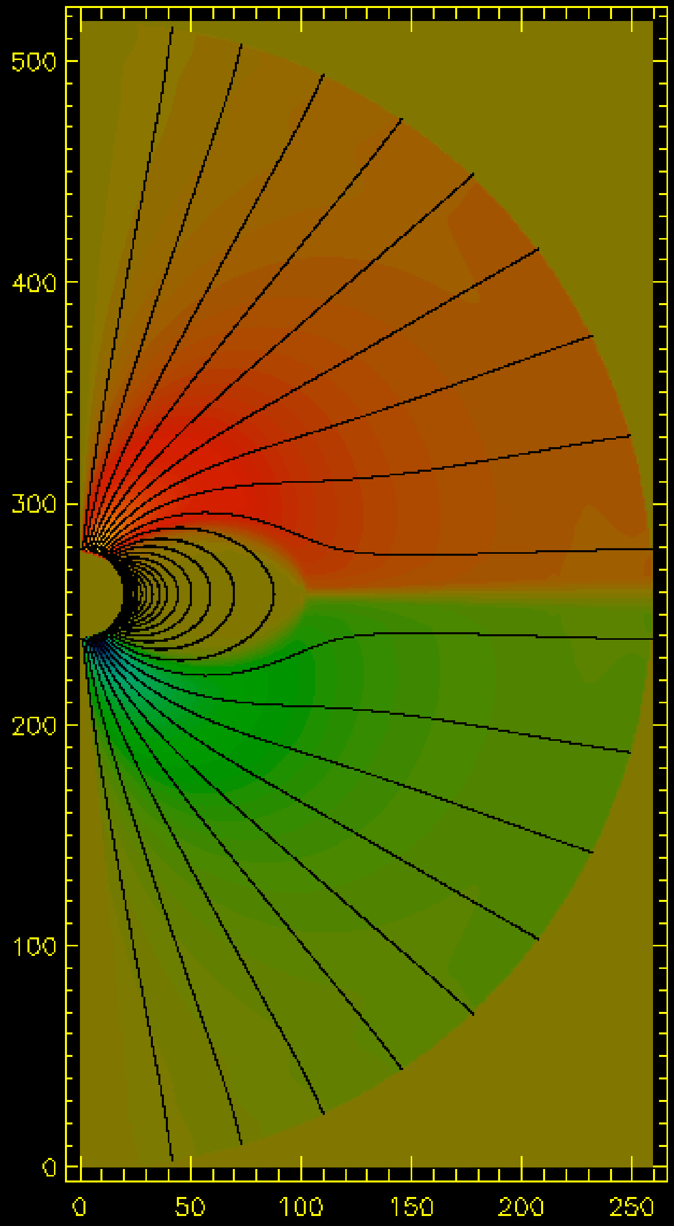
Pulsar theory recap



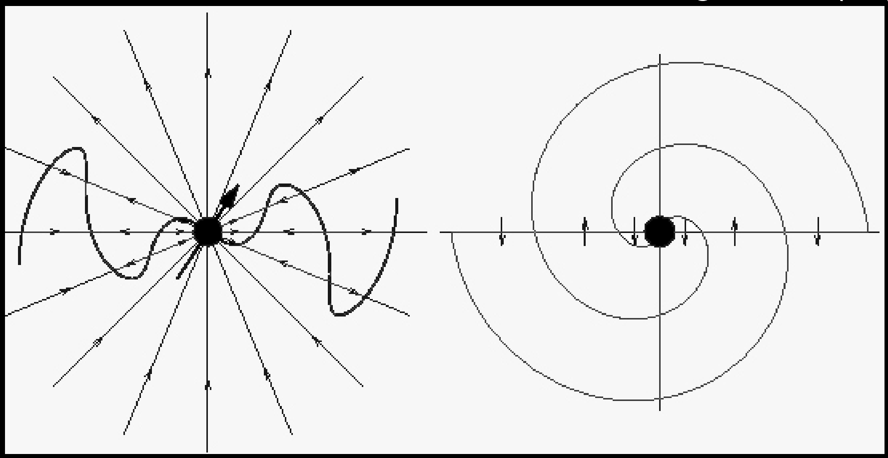
- Field structure -- asymptotic split-monopole, no collimation
- Toroidal field dominates at large distance.
- Open field lines are populated by pairs.
- Return current potentially carried by ions.
- Wind is strongly magnetized at the LC. No mechanism for converting magnetic energy into kinetic by the time wind hits the nebula $\sigma \sim 10^4$ (perhaps current sheet reconnection?)

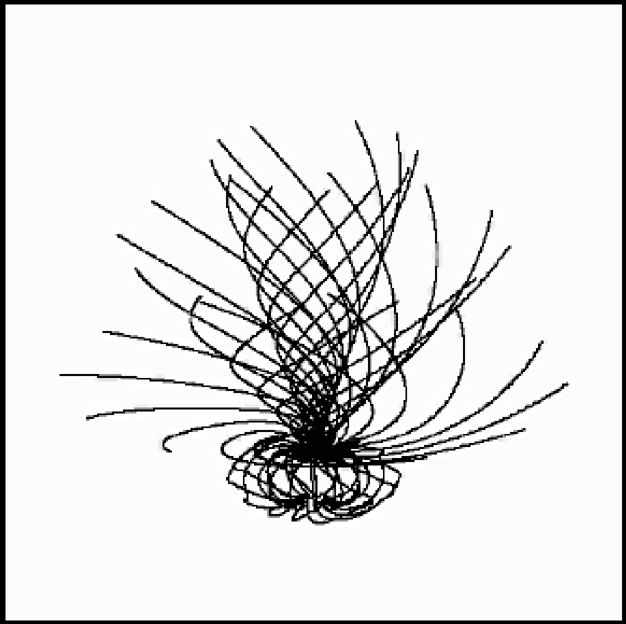
What are observational consequences of such a field structure and the return current pair-ion composition?

Extrapolation to oblique rotator



Bogovalov (99)





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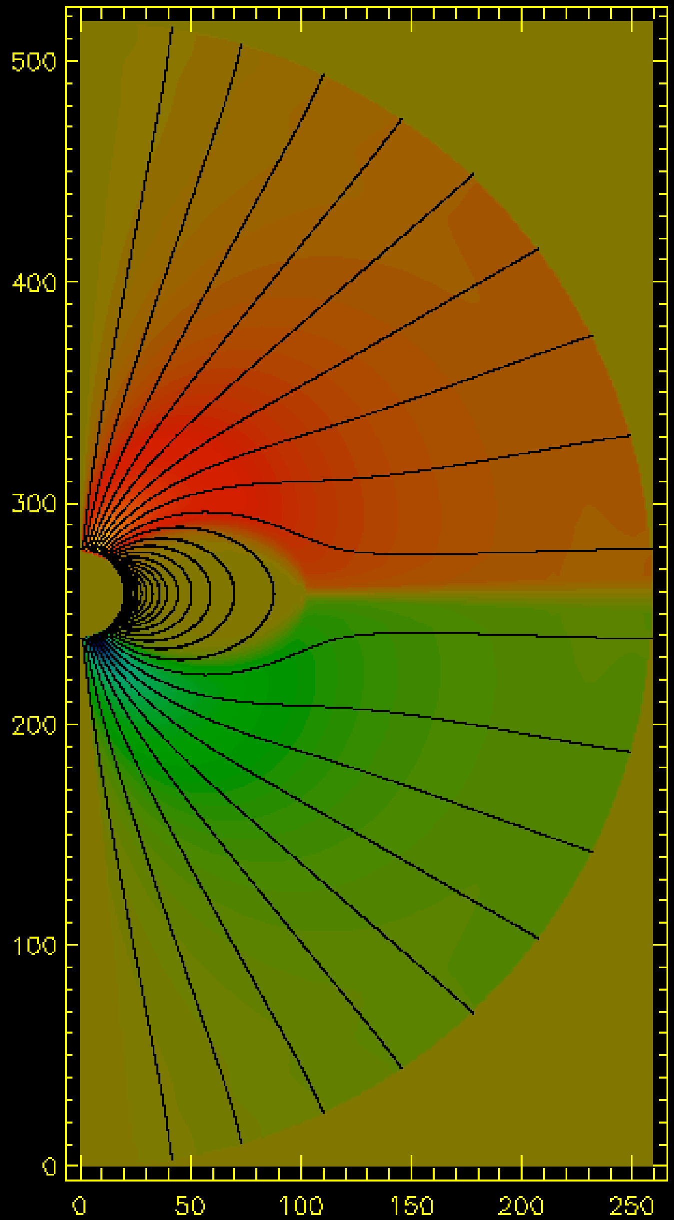

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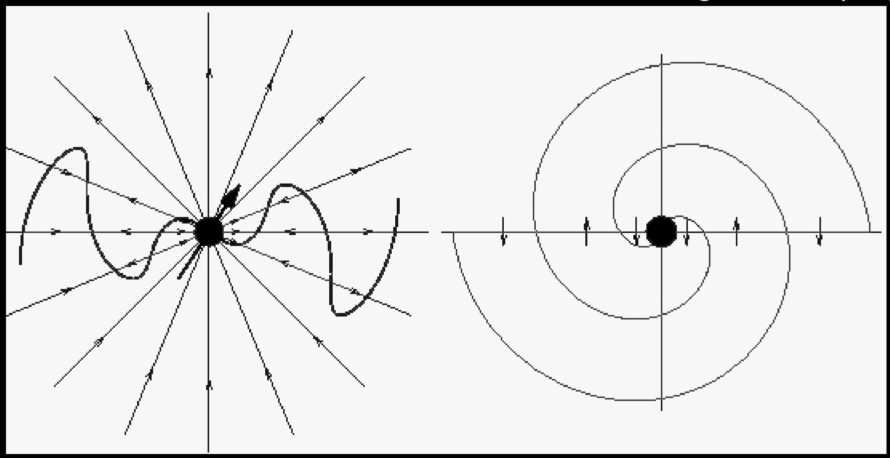


Asymptotically split-monopole

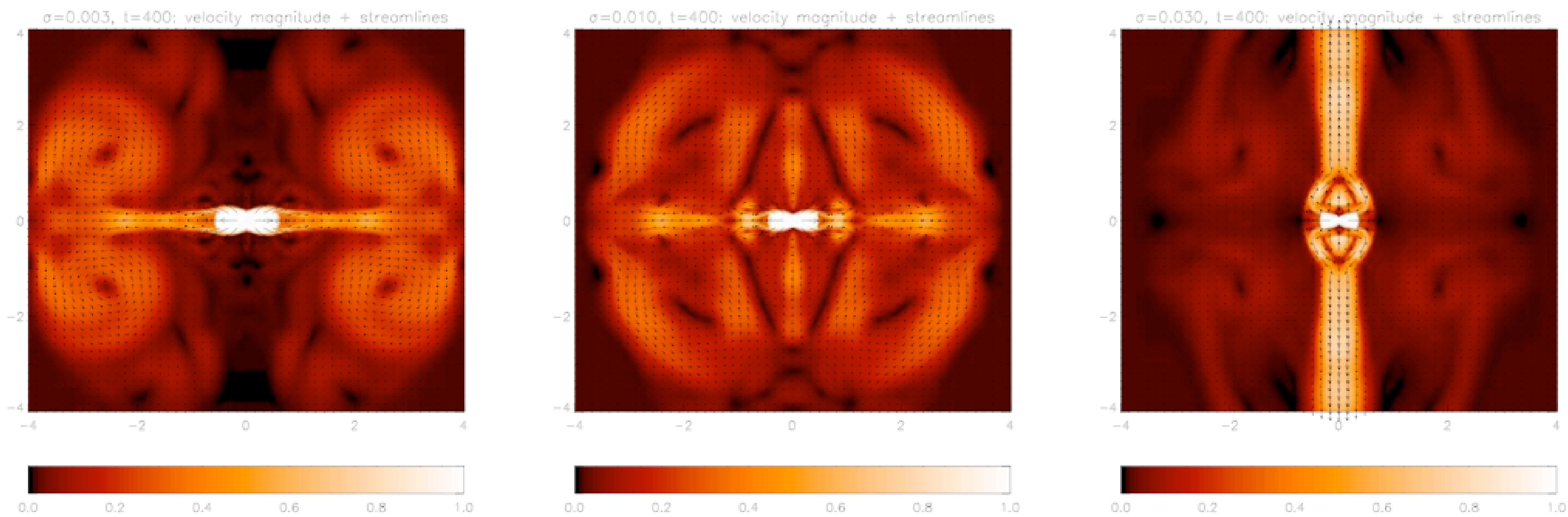
$$B_\varphi \propto \sin\theta \qquad f \propto \sin^2\theta$$

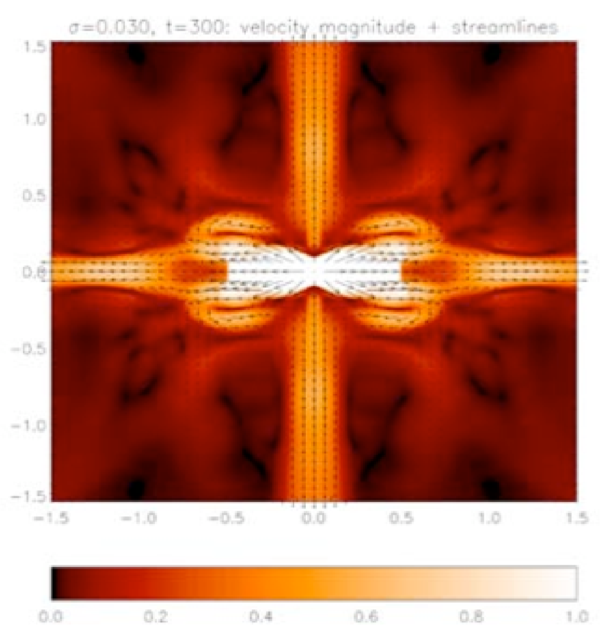
Two models: constant mass flux (del Zanna et al 04), or constant γ (Komissarov & Lyubarsky 03).

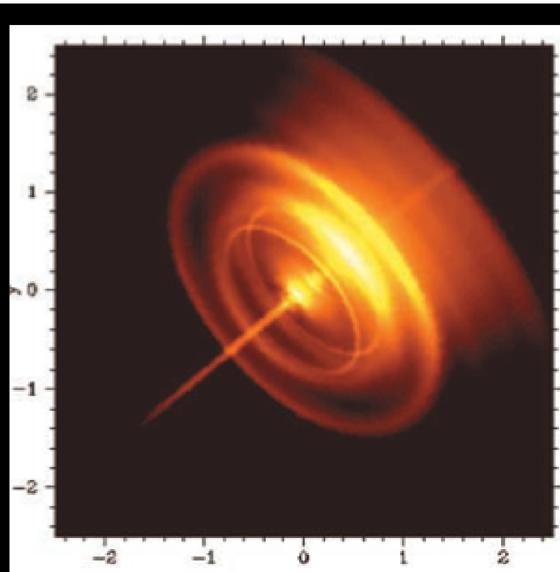
Reconnection in the equator leads to annihilation of B field, e.g.:

$$B_\varphi \propto \sin\theta(1-\frac{2\theta}{\pi})$$

Pulsar wind nebulae in 2D







Energy flux:

$$f \propto \sin^2 \theta$$

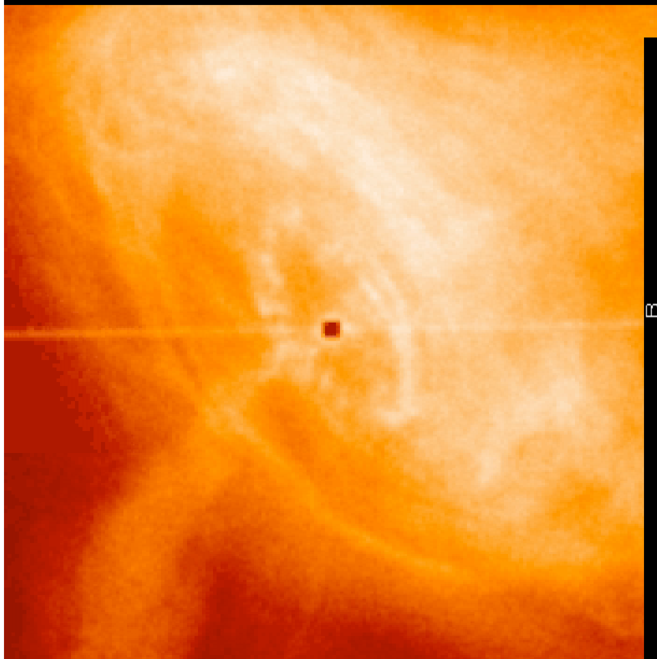
$$B_\varphi \propto \sin\theta(1 - \frac{2\theta}{\pi})$$

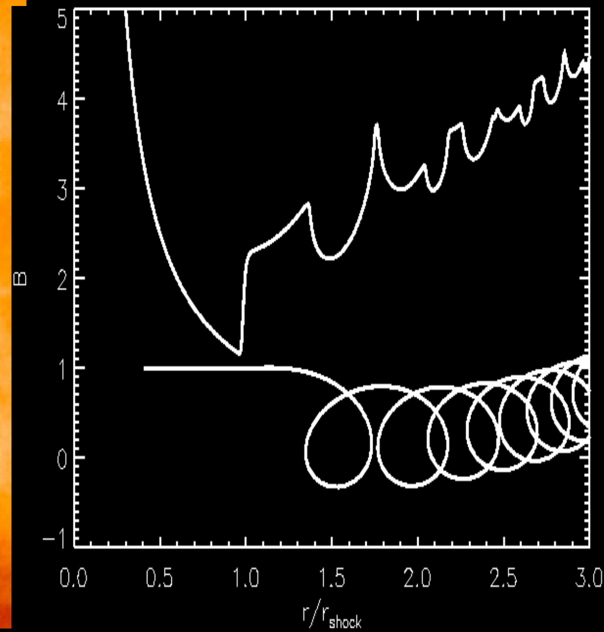
Models with return current work best

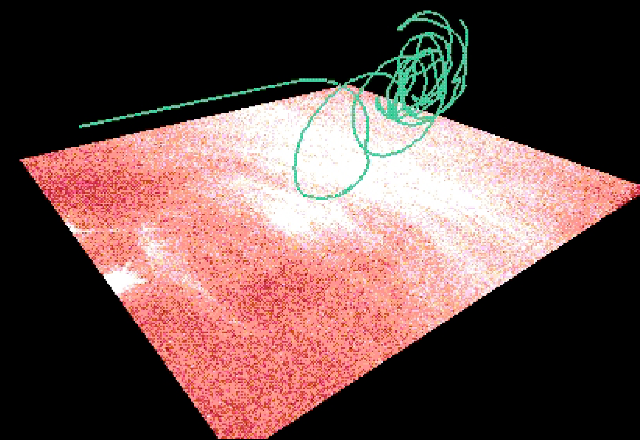
Jets form postshock

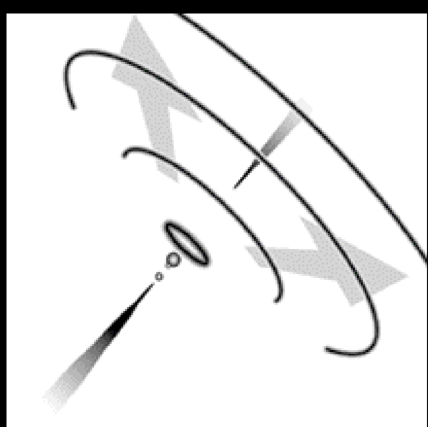
Komissarov & Lyubarsky 03,04, Del Zanna et al 04

Return current in the wind -- reverse shock in the Crab





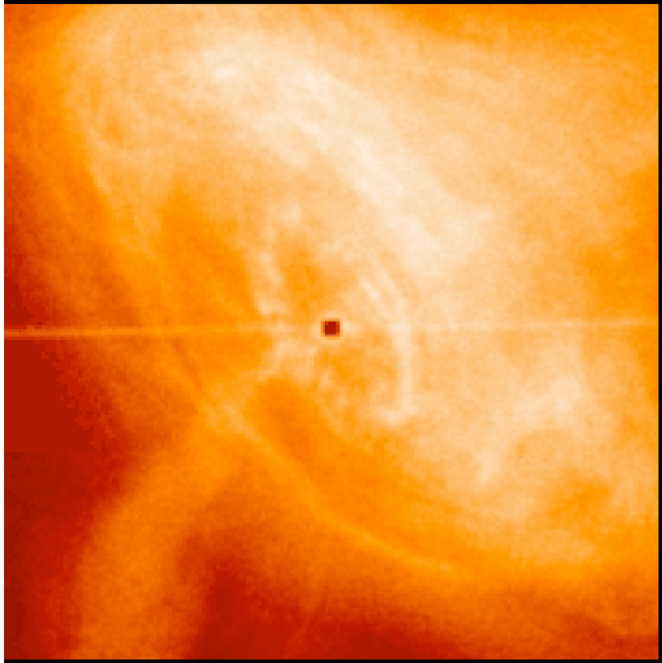


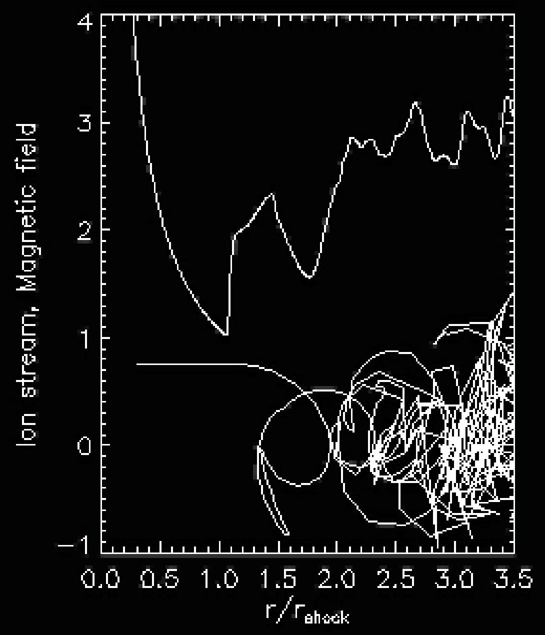


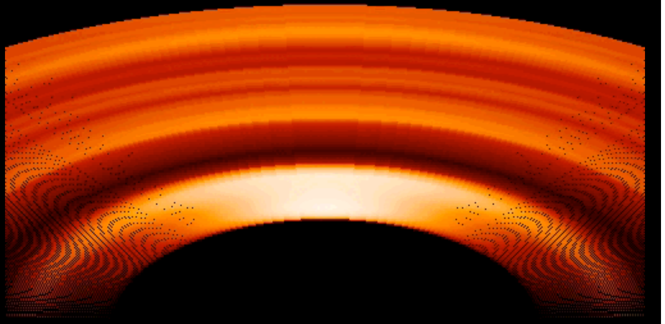
- Ions have macroscopic Larmor radii in the postshock flow.
- Wisp dynamics is driven by ions undergoing cyclotron instability.
- Timescale (~5-6 months) corresponds to ion Larmor time).
- Need to have roughly one GJ current in the ions ($10^{34} s^{-1}$) and 2/3 of the energy of the flow.
- Model does not include reversal of B field.
- Also applied to B1509 (Gaensler et al 02)

A.S. & Arons (2004)

Return current in the wind -- reverse shock in the Crab







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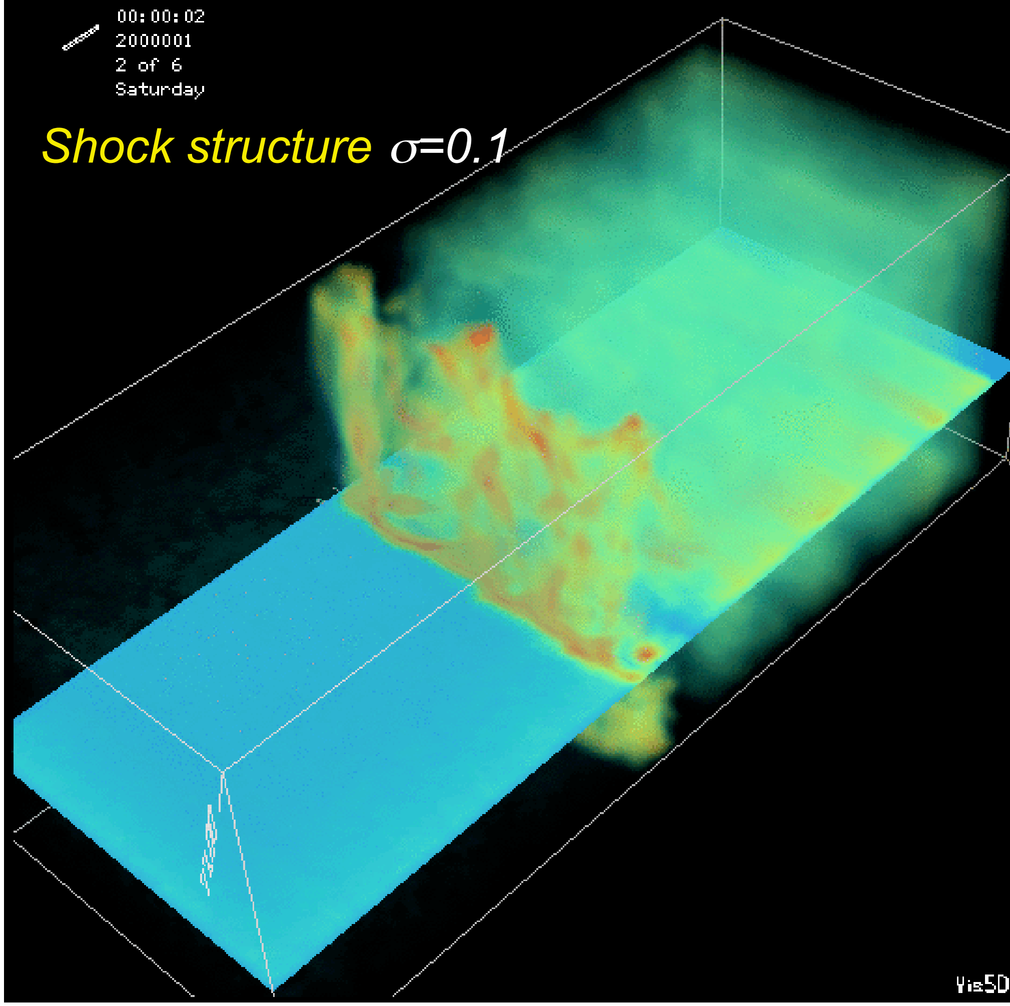
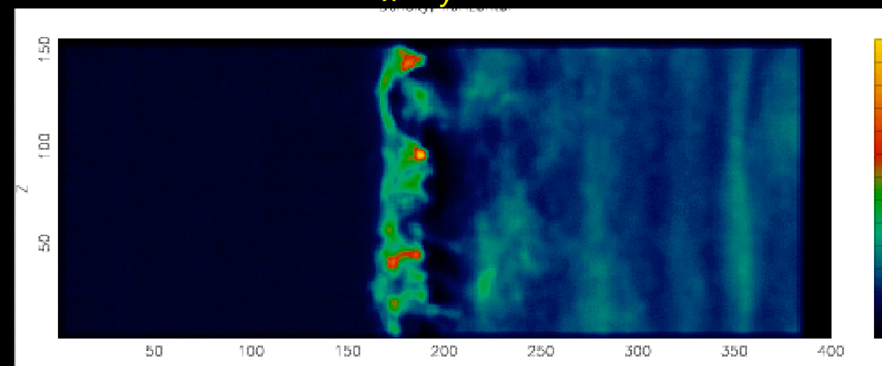
Nonthermal shock acceleration

- It is commonly believed that collisionless shocks efficiently accelerate particles, and diffusive Fermi acceleration operates.
- This belief has been demonstrated wrong for relativistic perpendicular magnetic electron-positron shocks. 1D Hoshino and Arons (1992), 3D A.S. and Arons (05).

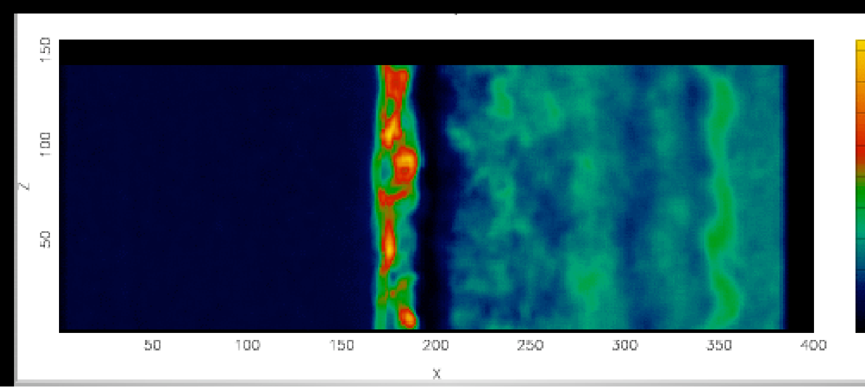


Shock structure σ=0.1

Plane of v_x-B_y

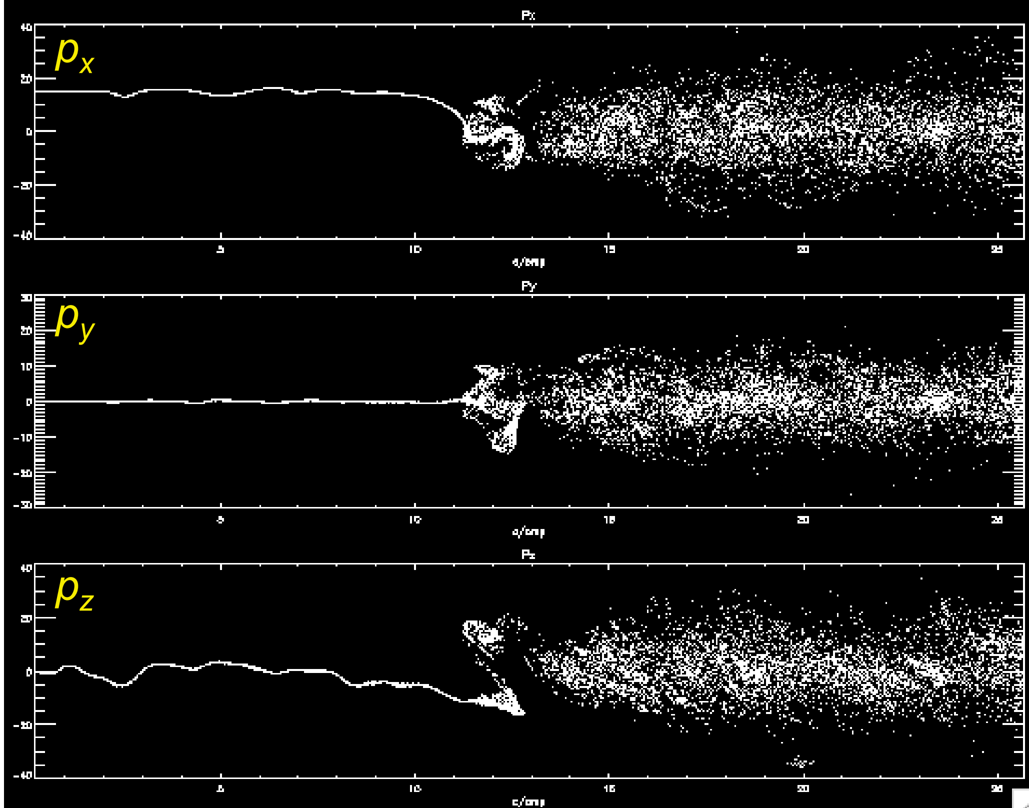


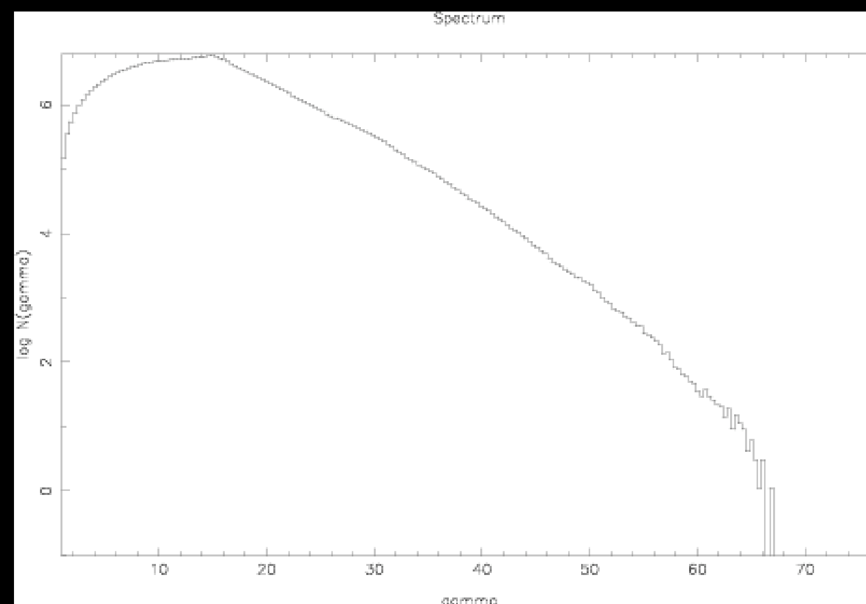
Plane of v_x-E_z



Nonthermal shock acceleration

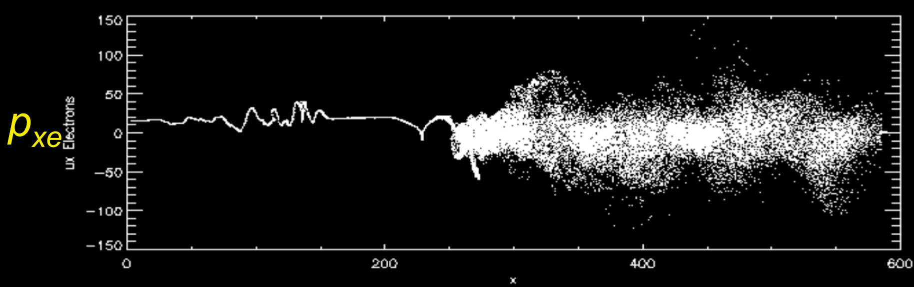
- Shocks are dominated by magnetic reflections -- particles don't cross field lines.
- Particles thermalize by emission and absorption of cyclotron waves.
- No upstream-downstream bouncing as in Fermi acceleration.

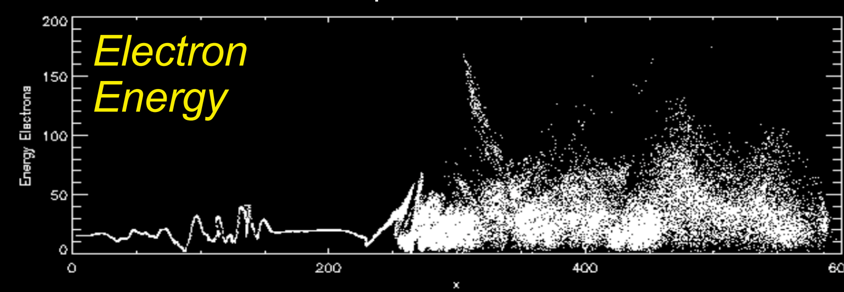


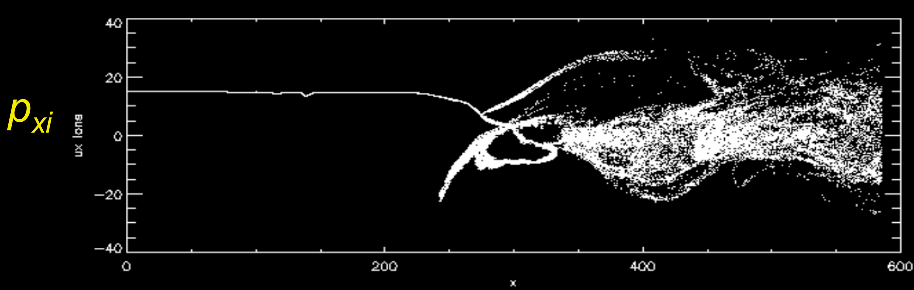


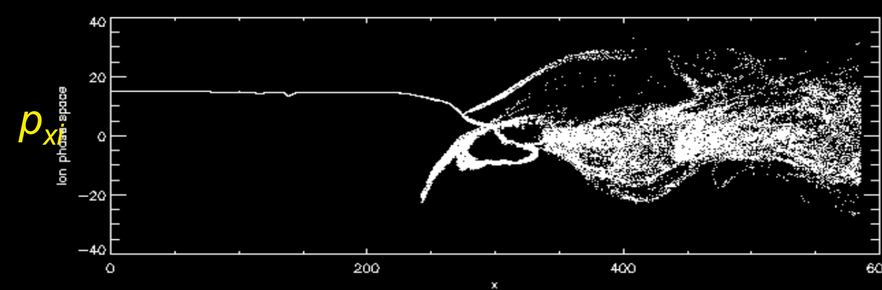
The case for ions -- nonthermal shock acceleration

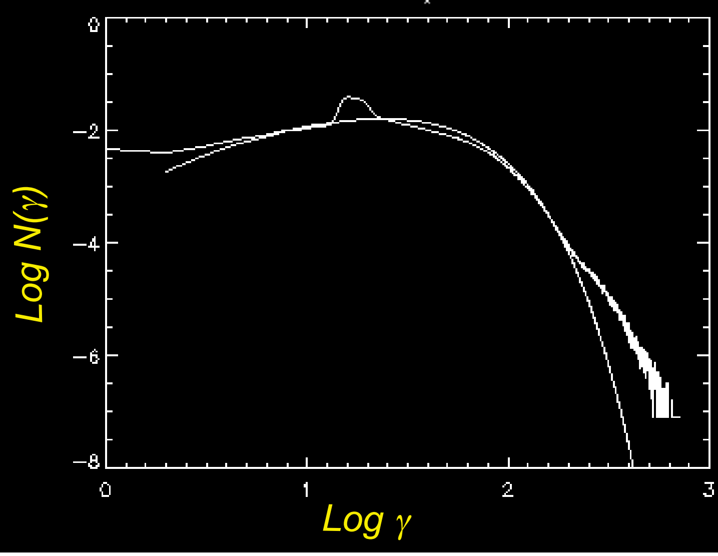
- Ions in the flow provide free energy to accelerate nonthermal electrons; $m_i/m_e=16$ (1D simulations Hoshino & Arons 92, Amato & Arons 2005). Same true in 3D.
- $N(\gamma)=\gamma^{-2,-3}$ (sensitive to ratio of densities). Max. energy $\gamma_e=m_p/m_e\ \gamma_{sh}$







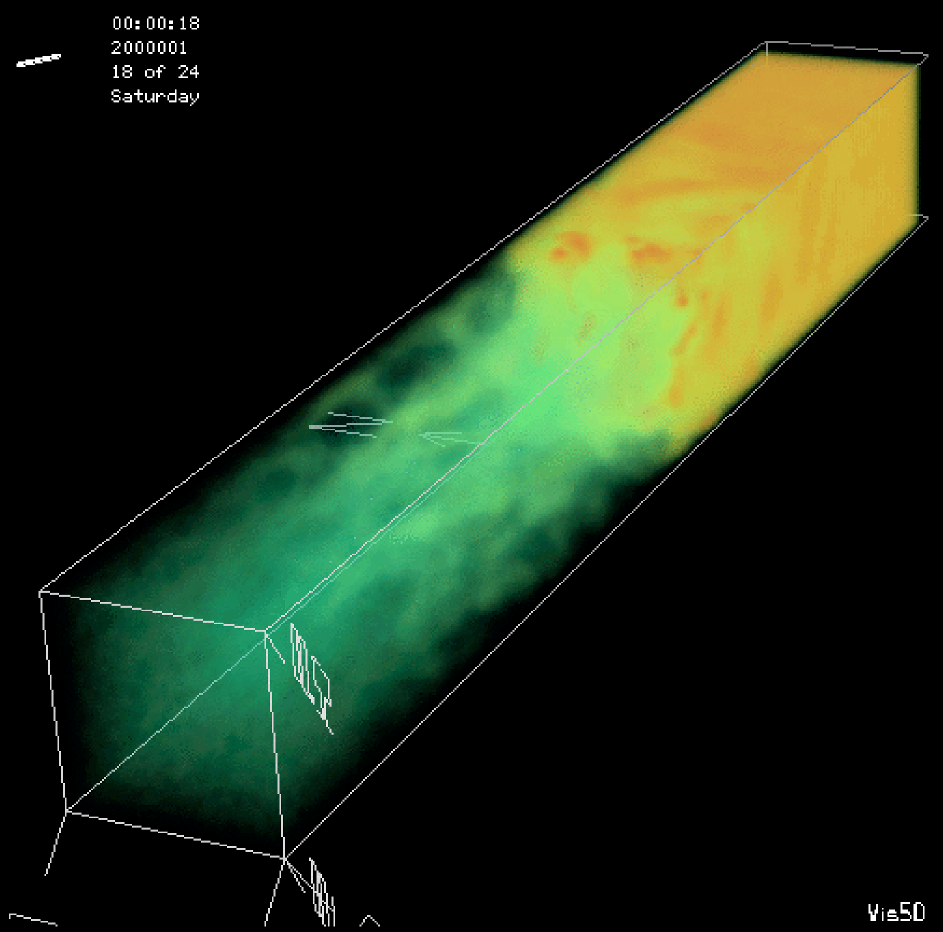


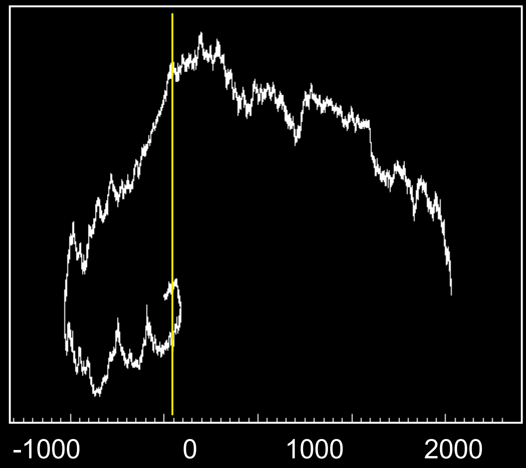


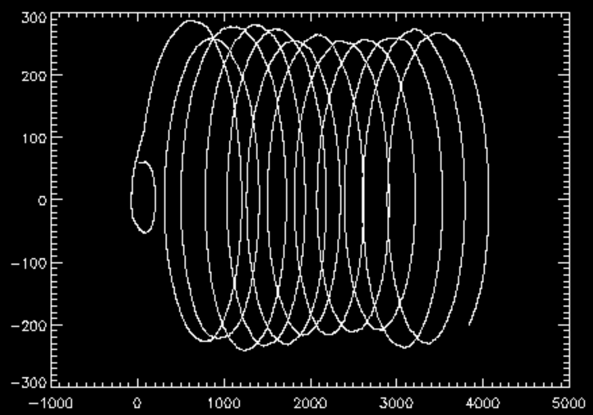
Even with ions acceleration is non-Fermi: combination of cyclotron harmonics absorption and electrostatics at the head of the shock

Alternative -- unmagnetized shocks?

- For low σ, *shocks are mediated not by reflections, but by Weibel instability*
- Turbulent B field is generated in the shock up to 10% equip., decaying to <1%
- Critical magnetization $\sigma<5x10^{-3}$ -- just the range for PWNs near equator.

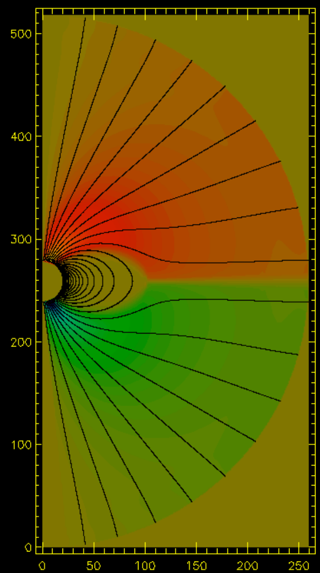






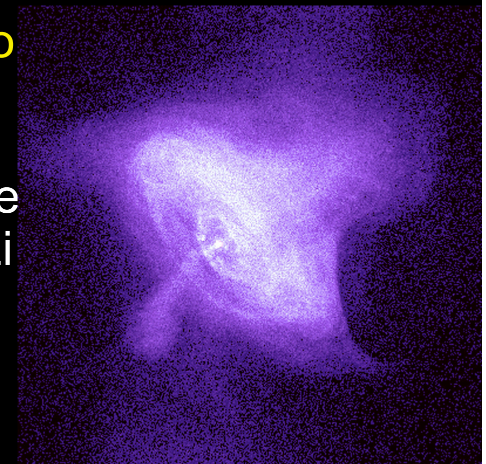
Test particle results promising for DFA, but has not been shown self-consistently in PIC.
Advantage -- universal powerlaw, but will require mixing with magnetized parts to radiate.

Acceleration and collimation: lessons from pulsars



Pulsars: example of "free" relativistic flow. Need to accelerate to decrease magnetization.

- Acceleration and collimation in monopolar-like outflow is logarithmically slow (Begelman & Li 94, Bogovalov 99) for relativistic flow. Hoop stress balanced by electric field. This geometry is picked by PSR simulations.



Ways out:

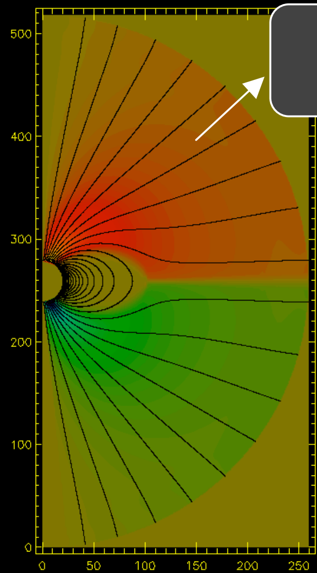
- Ideal MHD: start with anisotropic poloidal flux + self-similarity (e.g. Chiueh et al 98, Konigle & Vlahakis 03). Automatic collimation + acceleration.

- Magnetization is large in the wind and dissipates at the shock (Lyubarsky 03).

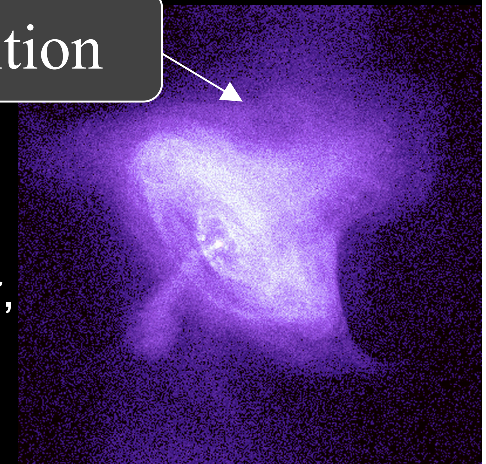
- Magnetization decreases due to dissipation of wrinkled current sheet (Lyubarsky & Kirk 01)

- Does one need pre-shock collimation to explain data in PWN? Not according to MHD simulations!

Pulsar wind properties



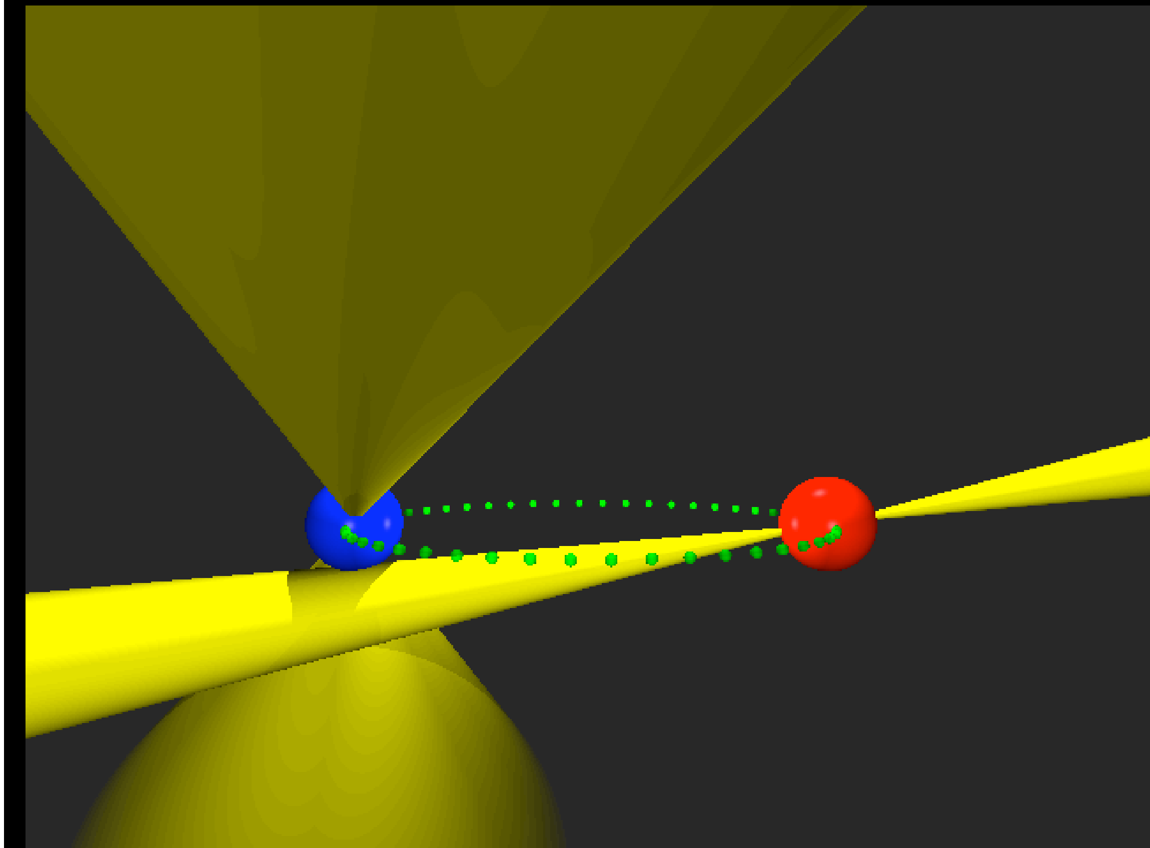
Injection → Transport → Deposition

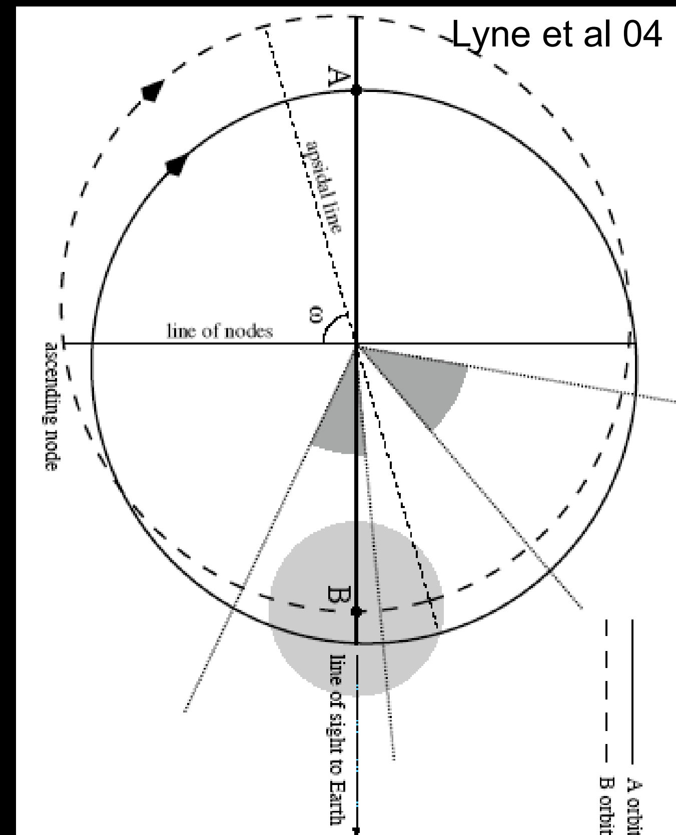


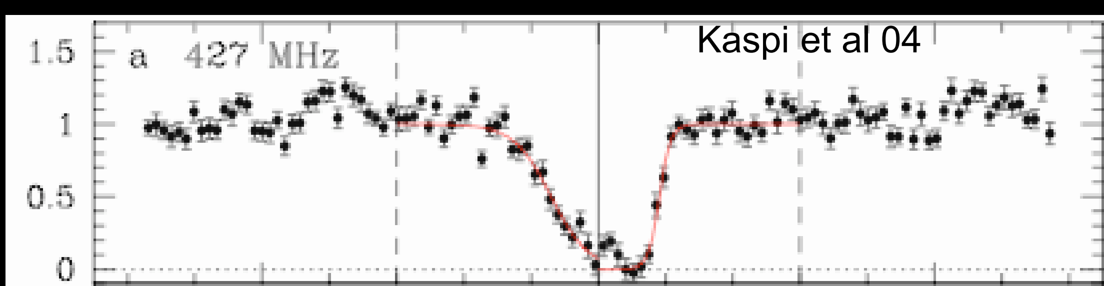
- Pulsar injects a dense relativistic pair wind.
- Wind is magnetically dominated near the star, but converts to kinetic energy @ the nebula
- Wind is an electric circuit.
- Equatorial segment is likely to be a special region for magnetization and composition -- presence of return current.
- Admixture of energetic ions seems to be required on several grounds: electrodynamics (return current), particle acceleration at the nebula, and nebular dynamics.
- All inferences come from very far away from the central injection (~$10^9 R_{LC}$).

A probe of the wind conditions closer to the source would be invaluable…

Double pulsar J0737: laboratory for relativistic winds







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

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

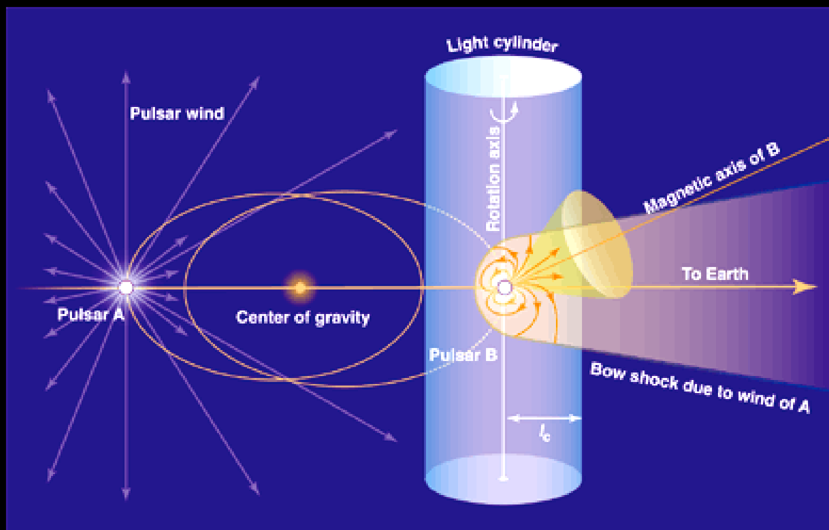
$R_{LA} = 1098$ km, $R_{LB} = 132{,}400$ km

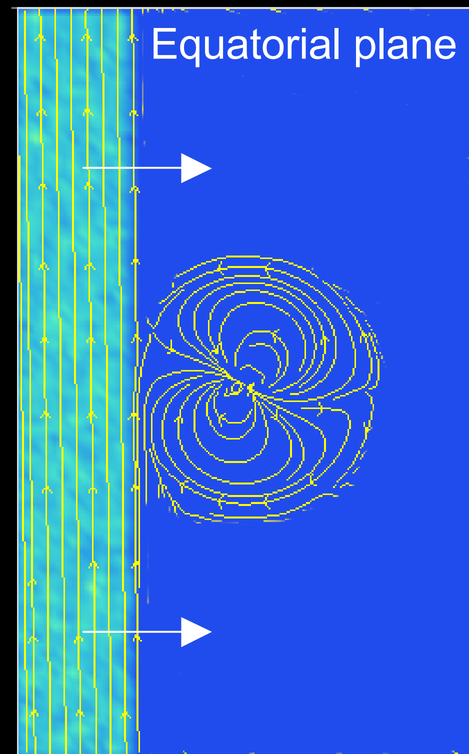
$B_A = 6.3 \times 10^9 G$, $B_B = 1.6 \times 10^{12} G$

$2a = 850{,}000$ km

Double pulsar: wind-magnetosphere interaction

Wind energy density at LC of B:
2.1 erg/cm^3 (A),   0.024 erg/cm^3 (B)





Relativistic solar wind problem with inclined rotator

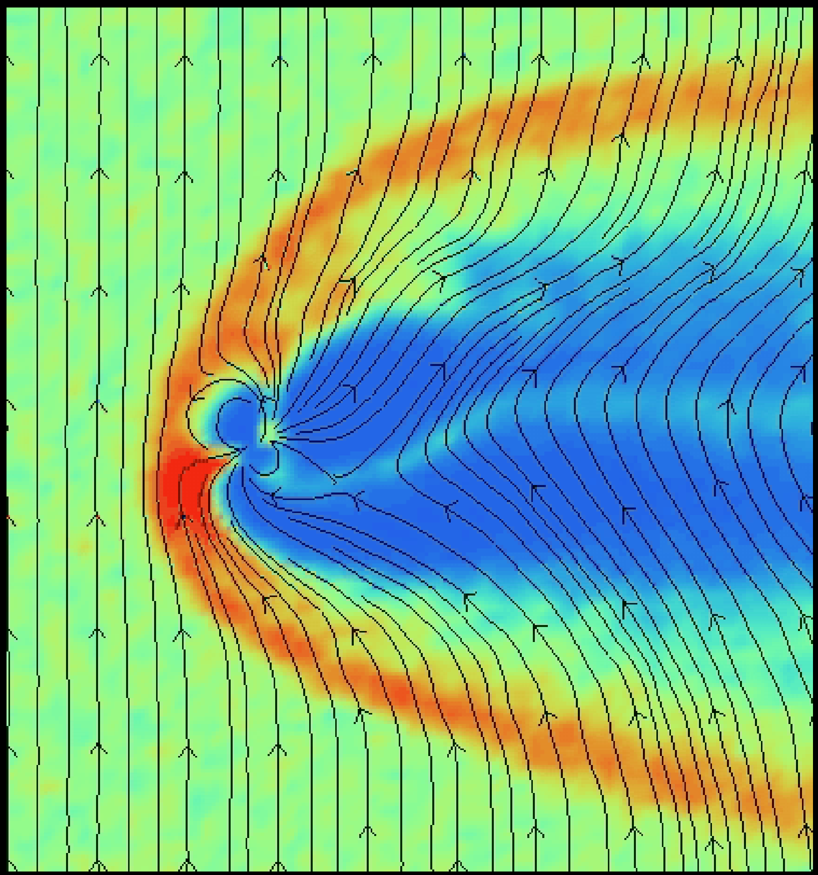
Simulation setup:

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; expensive

Shock and magnetosheath of pulsar B: effects of rotation



Shock modulated at 2Ω

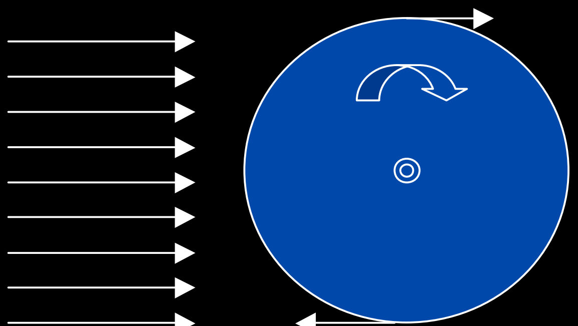
Reconnection once per period

Cusp filling on downwind side

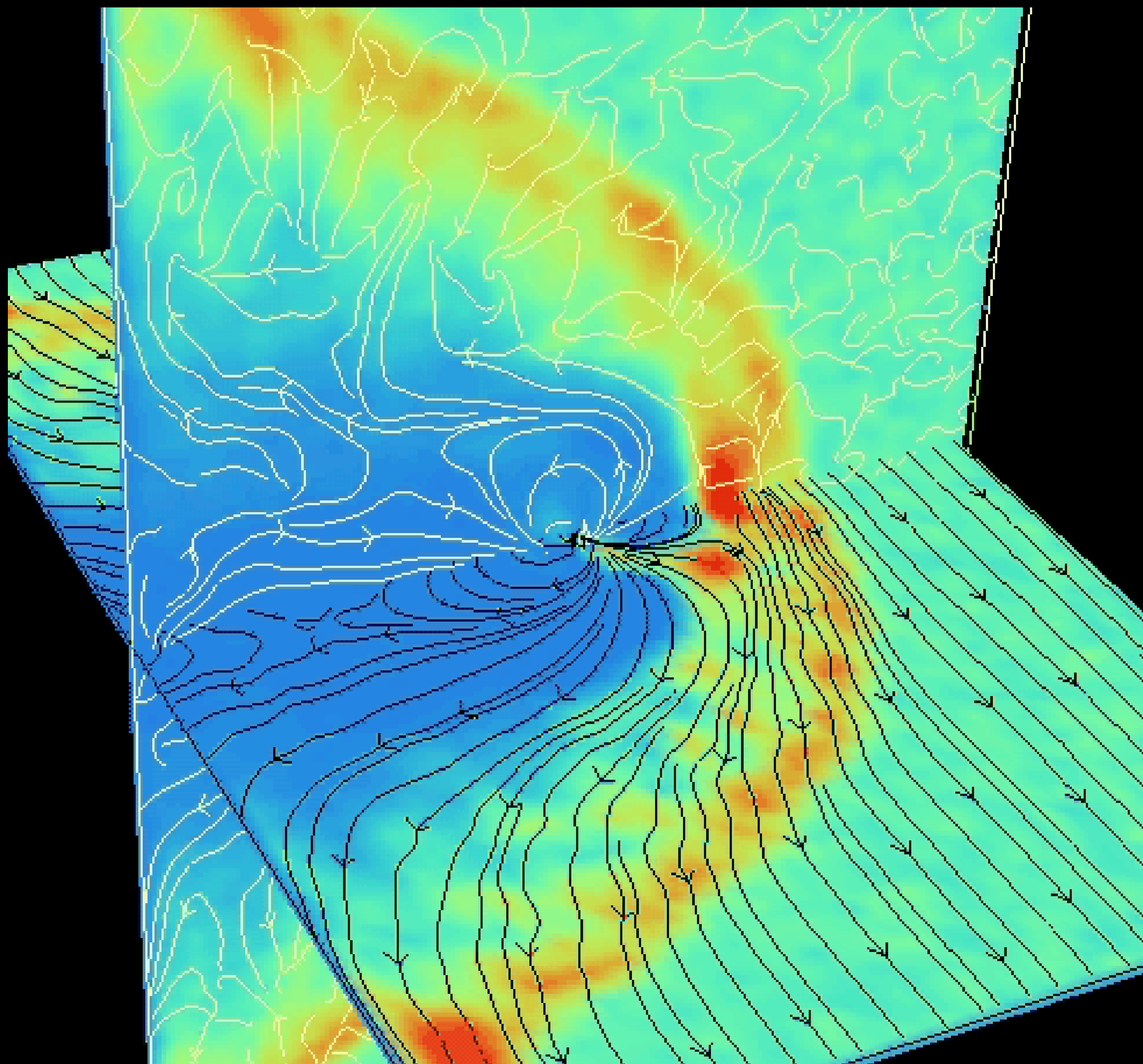
Density asymmetries

R_m~50000 km

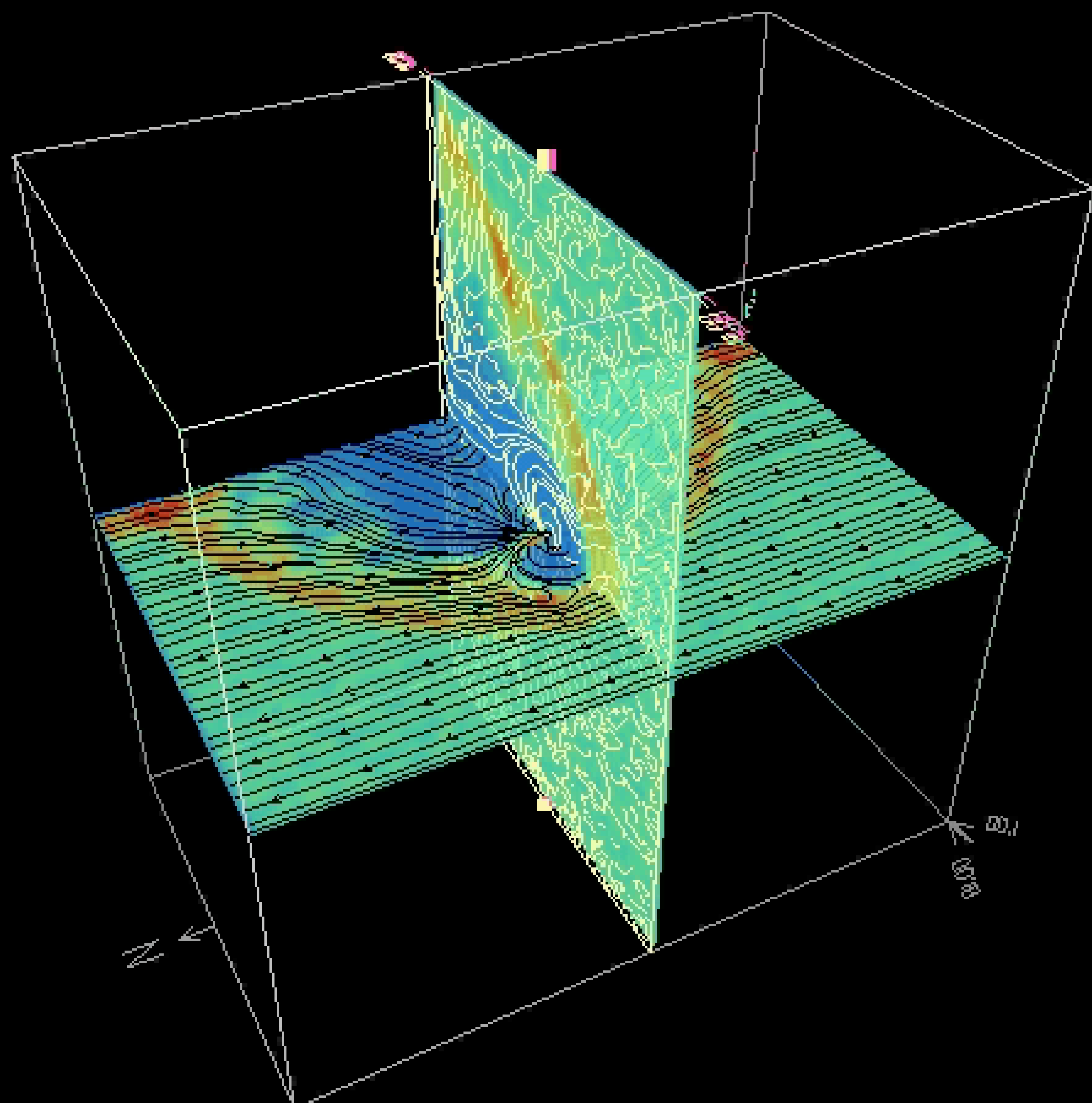
Propeller torque



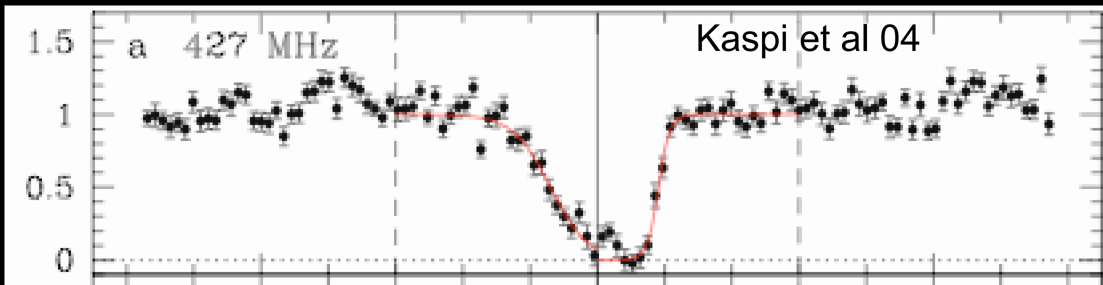
3D magnetosphere



3D magnetosphere

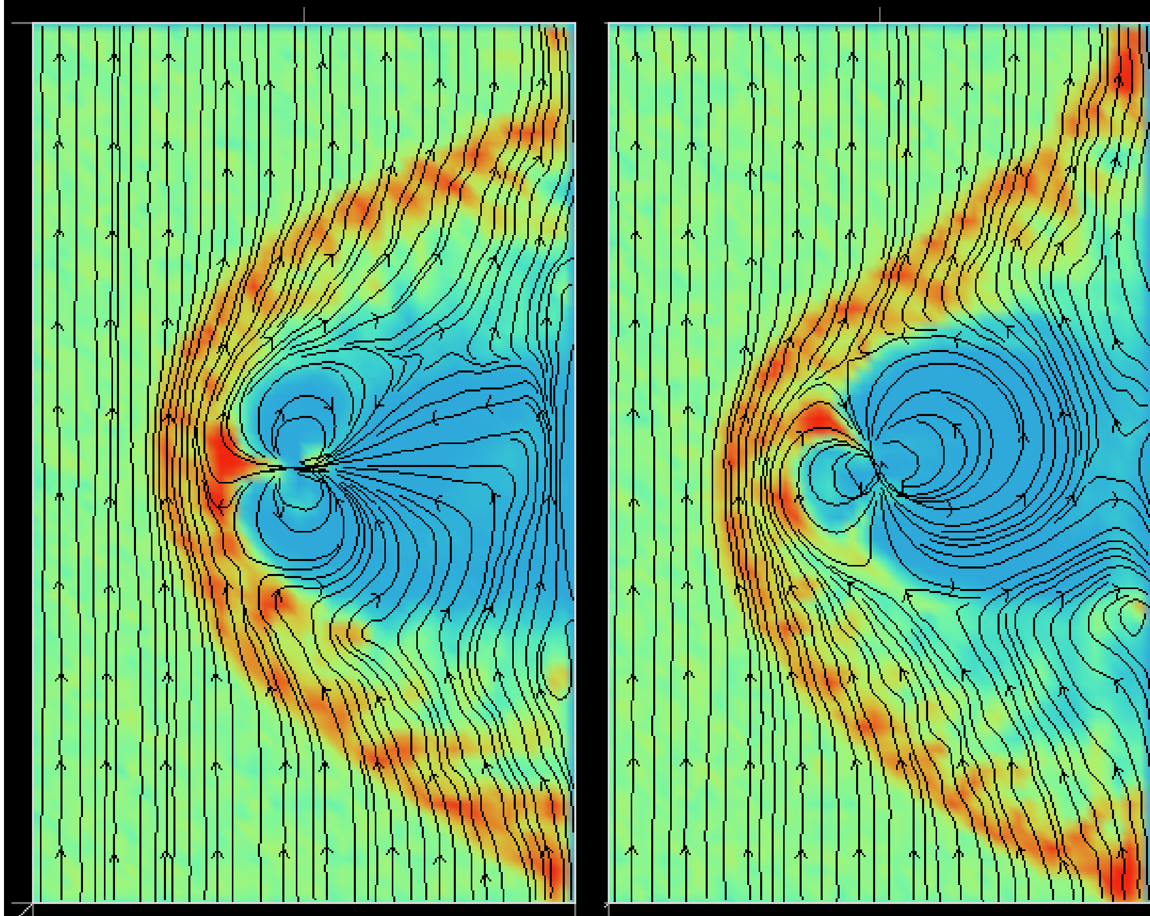


Eclipse and synchrotron absorption

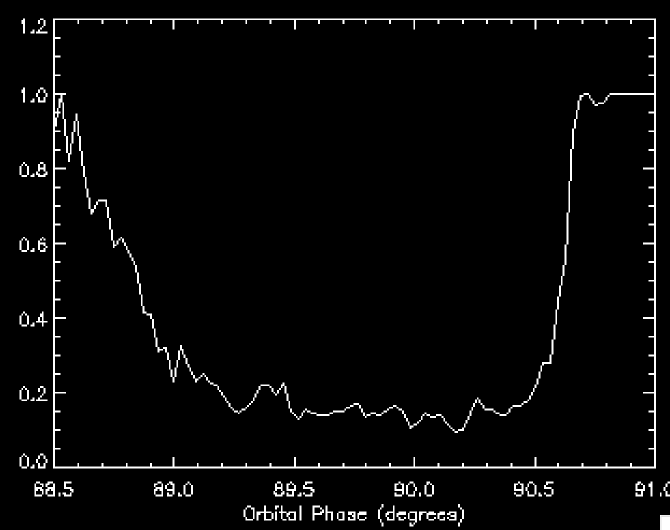


Synchrotron absorption in magnetosheath. To explain eclipse require:

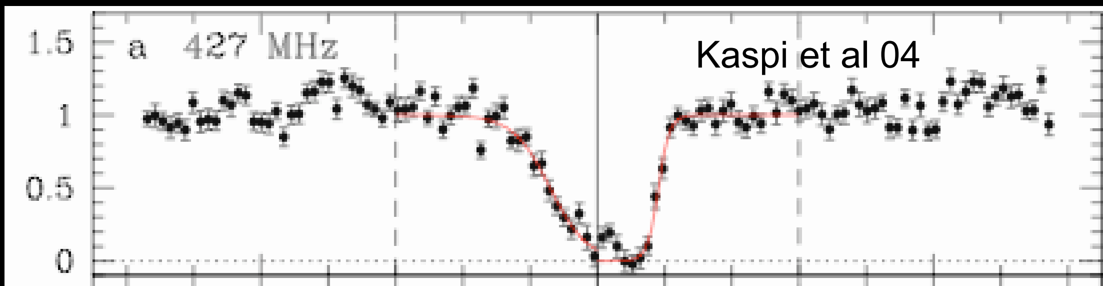
$$\kappa \sim 3 \times 10^6,\ \gamma \sim 10,\ \sigma \sim .1$$



Duration of eclipse a problem
Expect fluctuations in eclipse lightcurve on the timescale of rotation of B.



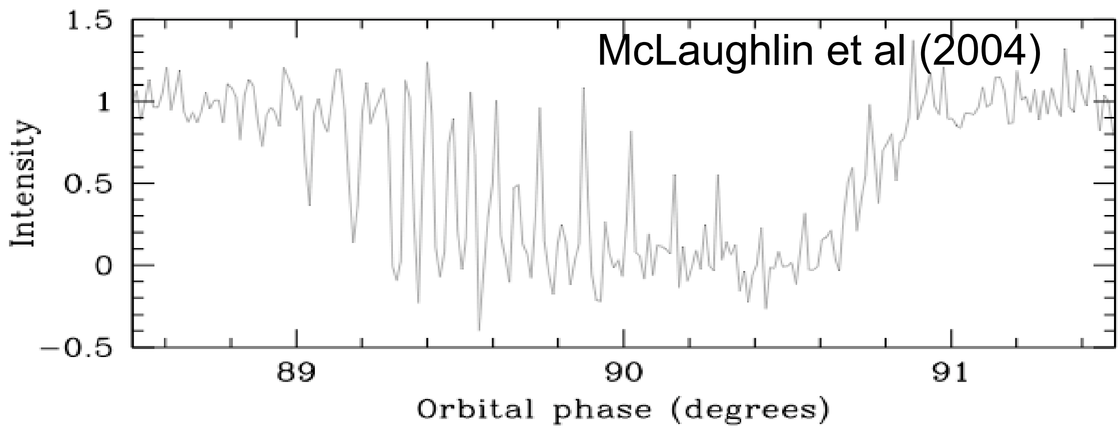
Eclipse inside the magnetosphere

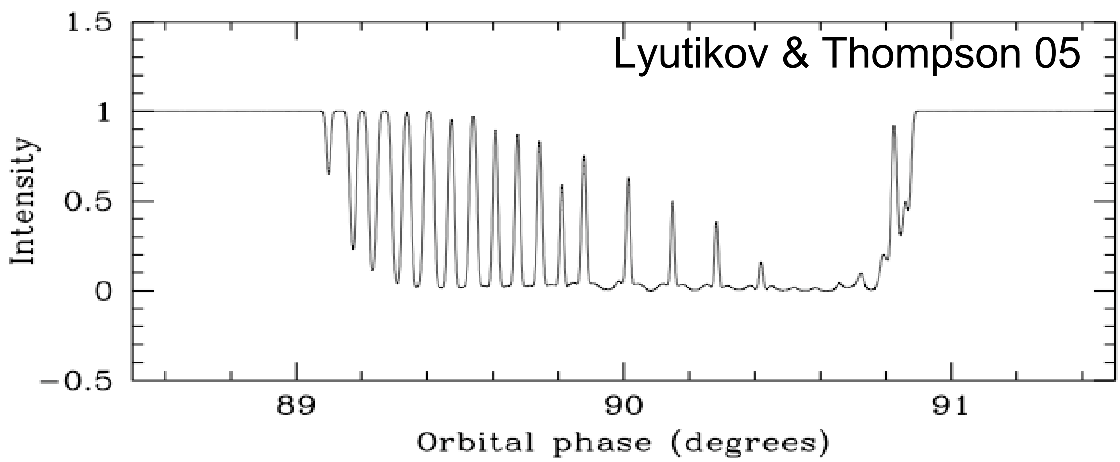


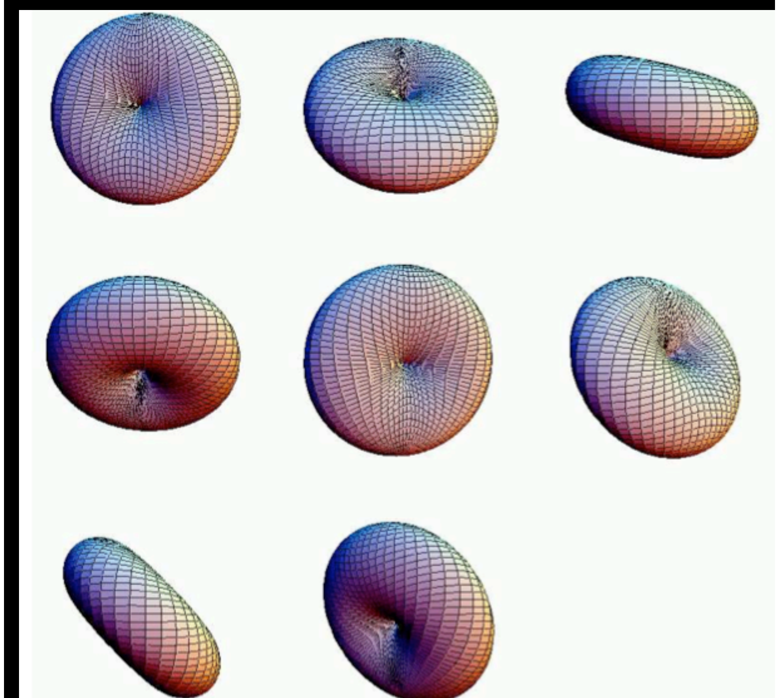
High time-resolution transparent windows are better explained by a model of eclipse inside the magnetosphere -- “Rotating Doughnut Model” (Lyutikov & Thompson 2005)

$$\kappa < 3 \times 10^6, \ \gamma > 10, \ \sigma \geq .1$$

Alas, not a direct probe of wind







Conclusions

- *PWN models with correct electrodynamics (return currents and field structure) work best with observations.*
- *Compositionally, return current can contain ions, with consequences for particle acceleration and nebular dynamics.*
- *If ions are required for generic shock acceleration, this puts constraints on composition of GRB and AGN outflows.*
- *Dynamic pulsar magnetosphere models open a new avenue of research in compact objects, both pulsars and magnetars. Wealth of time-dependent data is not explained.*
- *Current sheet stability and relativistic reconnection physics have to be investigated as a means of radiation and energy conversion*
- *Oblique magnetospheric models are imminent with force-free & MHD technology. Would collimation/acceleration properties be modified?*
- *Double pulsar system is an indirect probe of the wind conditions*