Title: An Auroral Model for Particle Acceleration in Pulsars

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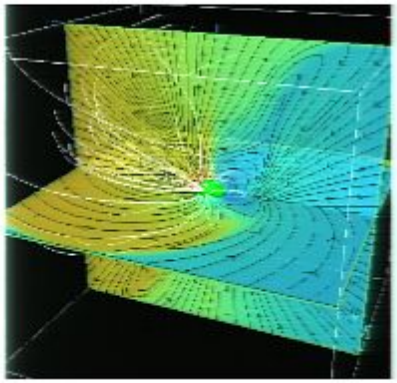
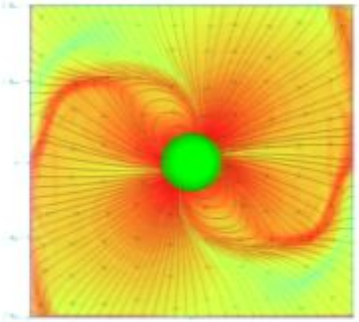
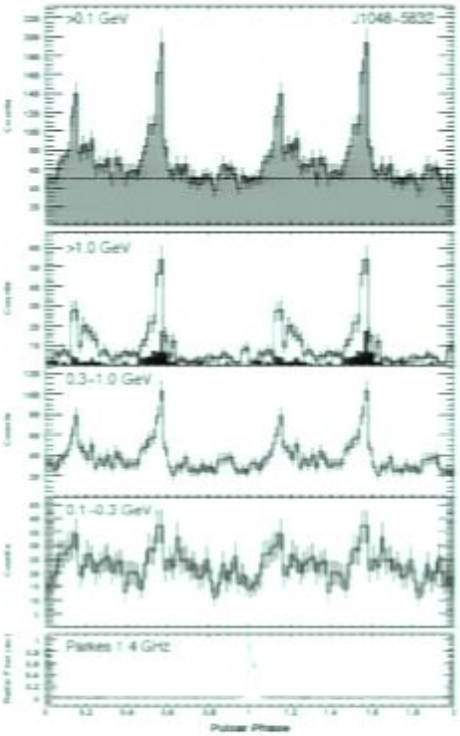
Abstract: I discuss a model for particle acceleration in the current sheet separating the open and closed field line regions, and crossing the neutral line region, of a pulsar's magnetosphere, which has substantial kinship to the phenomena observed in planetary magnetospheres within the solar system. Possible applications to gamma ray emission from pulsars are also described.

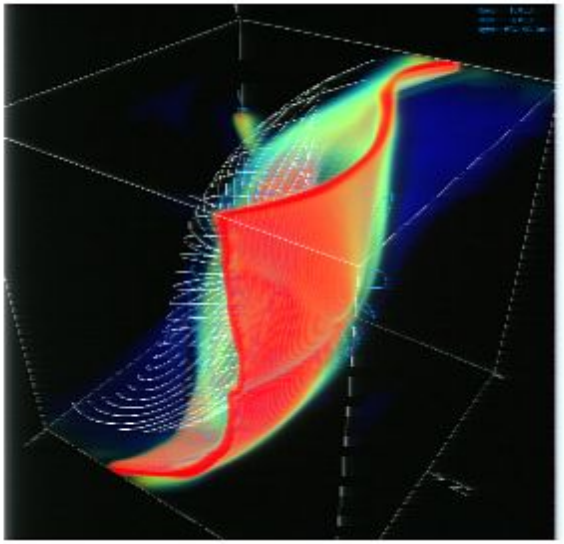
An Auroral Model for Gamma Ray Pulsars
A Work in Progress

Jonathan Arons
University of California, Berkeley



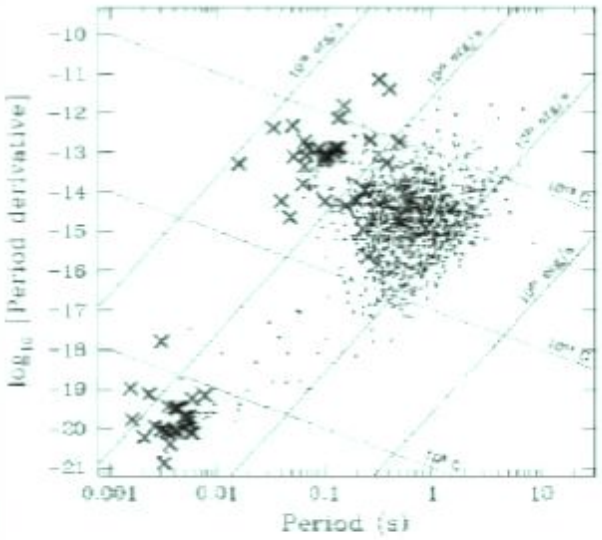






Collaborators: **N. Bucciantini**, **A. Spitkovsky**, A. Timokhin

Follow the Energy: Spindown



Force Free Magnetosphere -
Spin down by EM torques
Magnetic energy dominant, non-vacuum, enough plasma for $E \cdot B = 0$

$$\dot{\Omega} = -K\Omega^n$$

Contopoulos et al, Gruzinov, Timokhin: FF, aligned rotator, steady state: $R_Y \leq R_L$

Komissarov rel mhd, McKinney FF: aligned rotator, evolutionary

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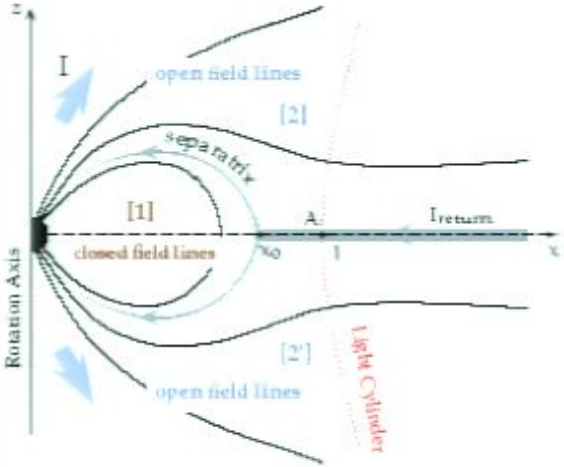

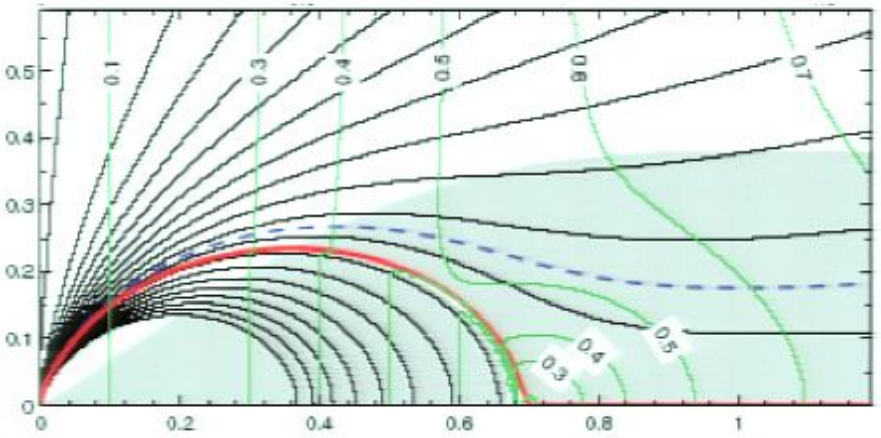

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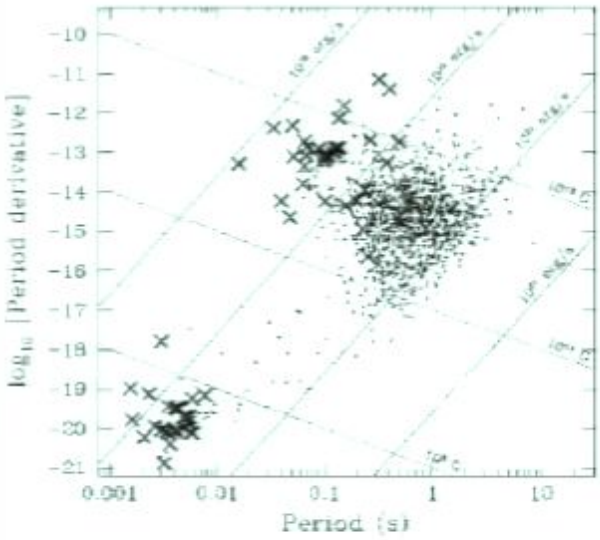

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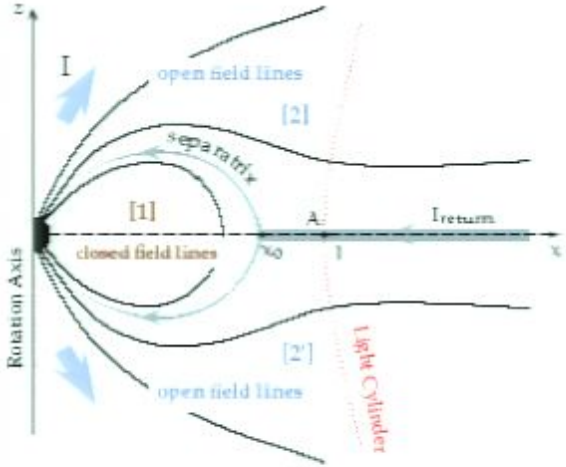
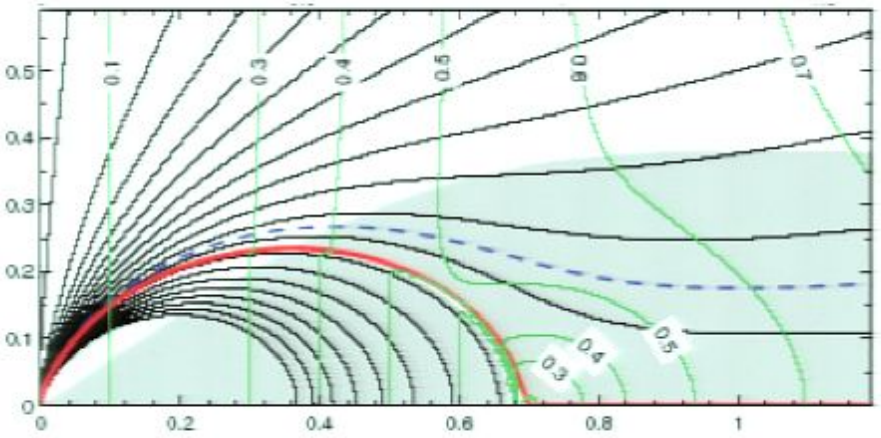




Follow the Mass Loss: From Whence all the Pairs?

Pulsar Wind Nebulae: Nebular Synchrotron requires particle injection $\dot{N}_{\pm}$ >> Goldreich-Julian current $\dot{N}_{GJ} = c\Phi/e$

PAIRS: OUTFLOW DENSE & MAGNETOSPHERE DENSE

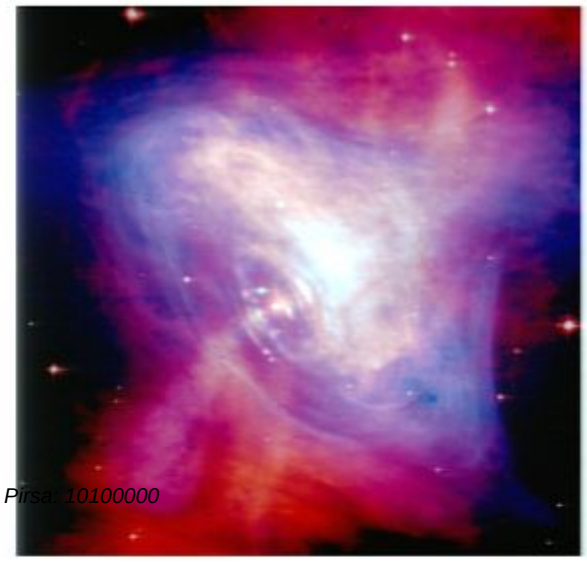
(EVERYWHERE?)

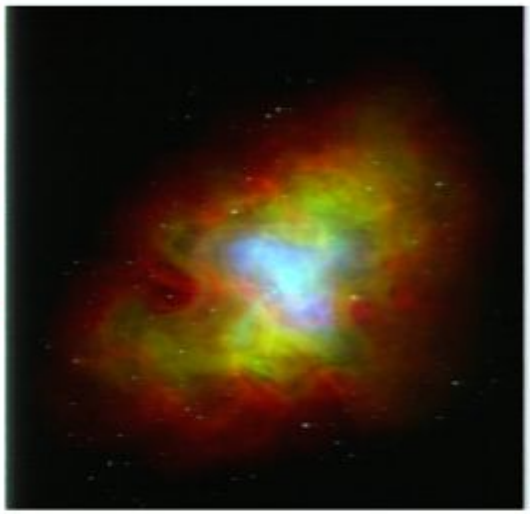
X-Rays: current injection rate (compact, strong B nebulae - Crab, G54,…)

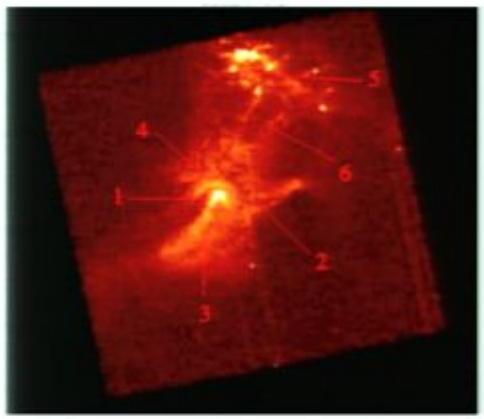
measured rates ~ existing (starvation) gap rates $\kappa_{\pm} = \dot{N}_{\pm}/\dot{N}_{GJ} \leq 10^4$ pairs/GJ

Radio measures injection rate averaged over nebular histories, $\kappa_{\pm} > 10^5$

(NB, JA & EA) >> 10 x all extant pair creation models (discharges? B model?)







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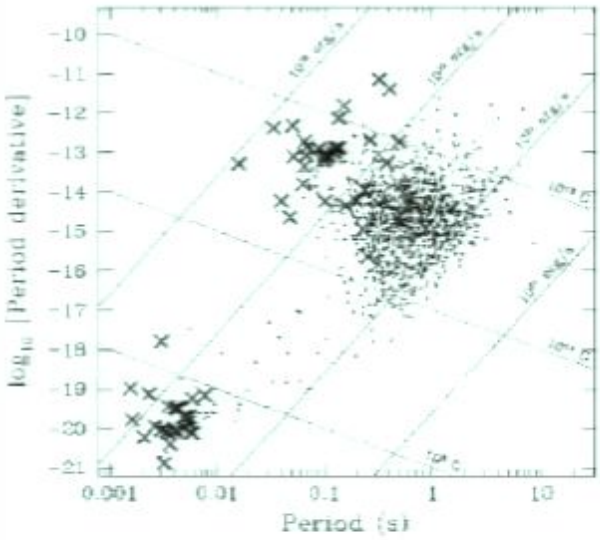

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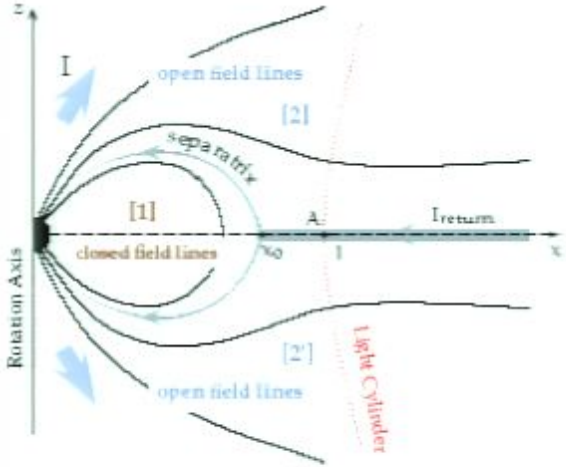

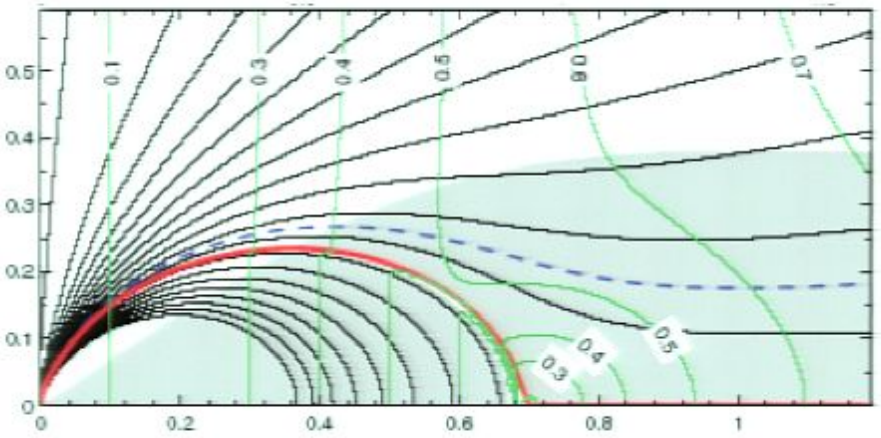

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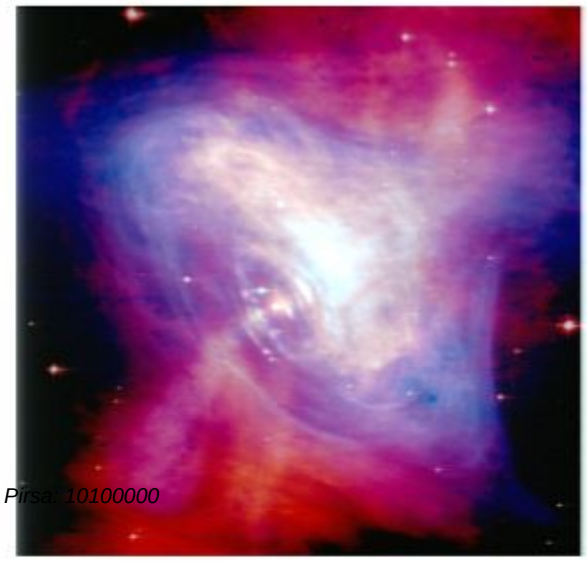

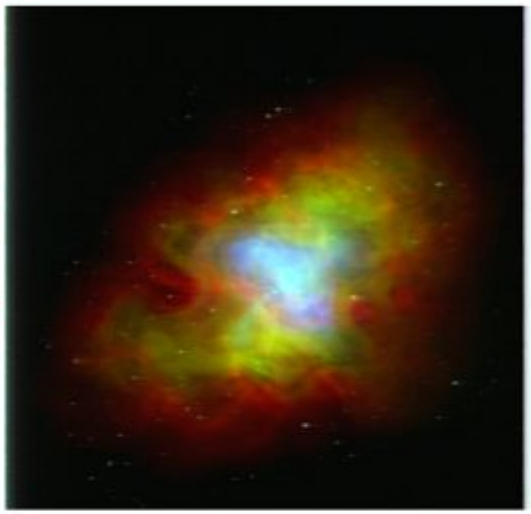

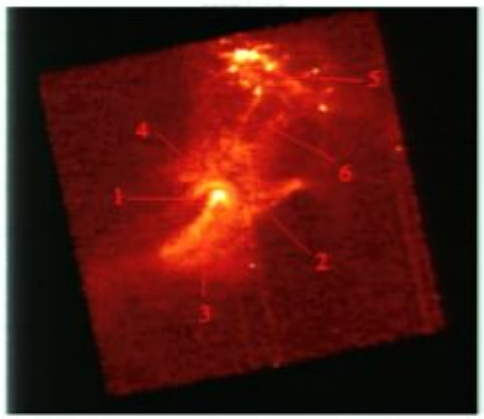

$$R_Y \leq R_L$$

$$n = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2} = 3 + 2\frac{\partial \ln\left(1+\frac{R_L}{R_Y}\right)}{\partial \ln \Omega}$$

$R_Y/R_L < 1$ increases torque because of more open field lines and larger Poynting flux for same R_L:
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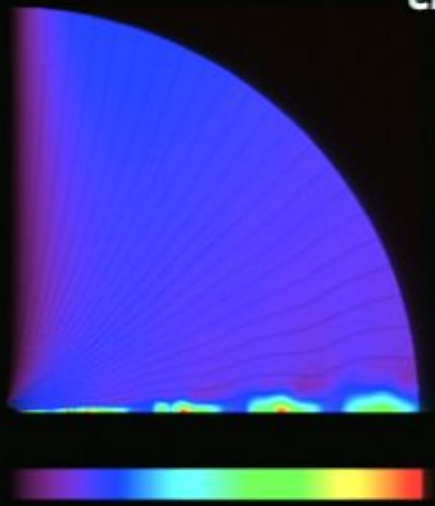
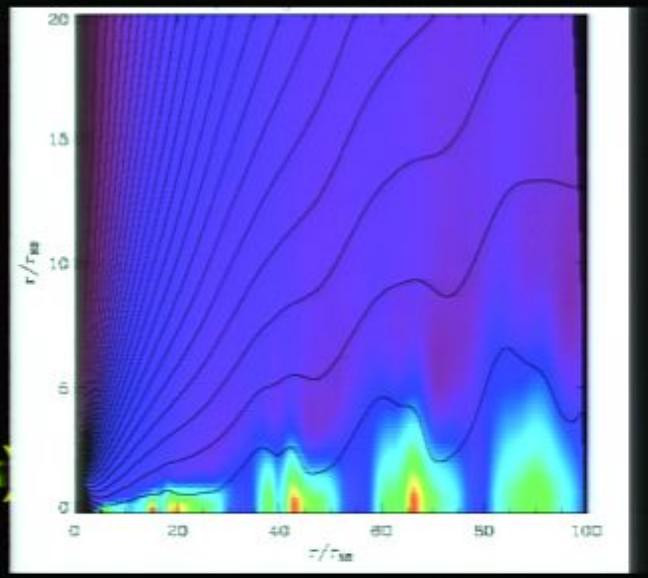
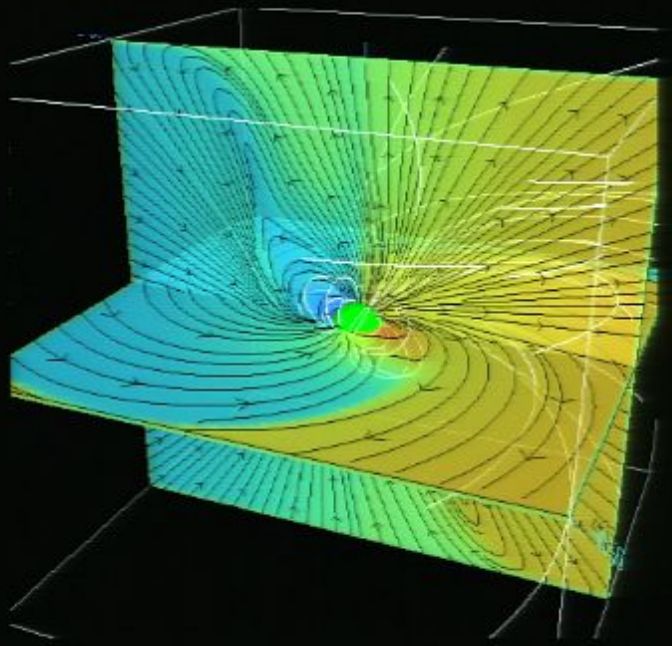
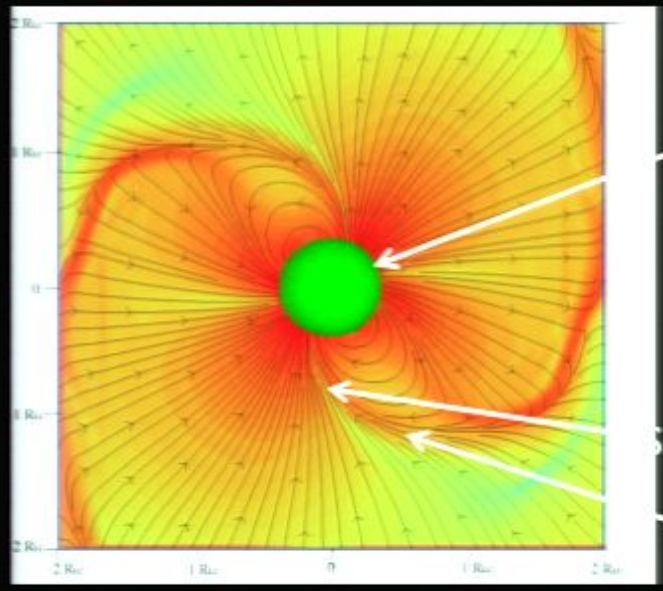


"Average" with respect to plasmoid emission, torque fluctuations
($\delta T/T$ ~ 10-30% ~ obs)



Spitkovsky's (2006) oblique force free rotator





$$\dot{E}_R = -I\Omega\dot{\Omega} = k\frac{\mu^2\Omega^4}{c^3}(1+\sin^2 i),\ k = 1\pm 0.1$$

$$i = \angle(\mu,\Omega)$$

Gaps = local zones of charge density < GJ, Parallel E ≠ 0

Acceleration along B ➔ beamed photons, rotation ➔ lighthouse

Force Free model has no gaps, no parallel accelerator

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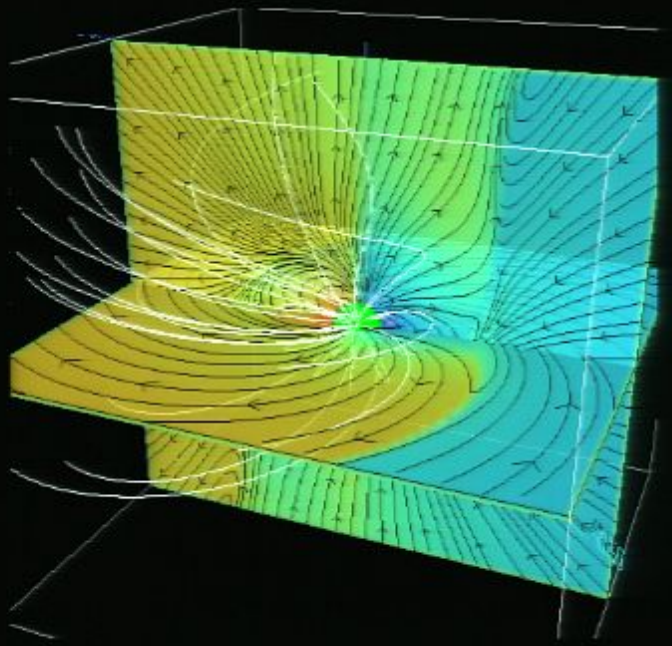

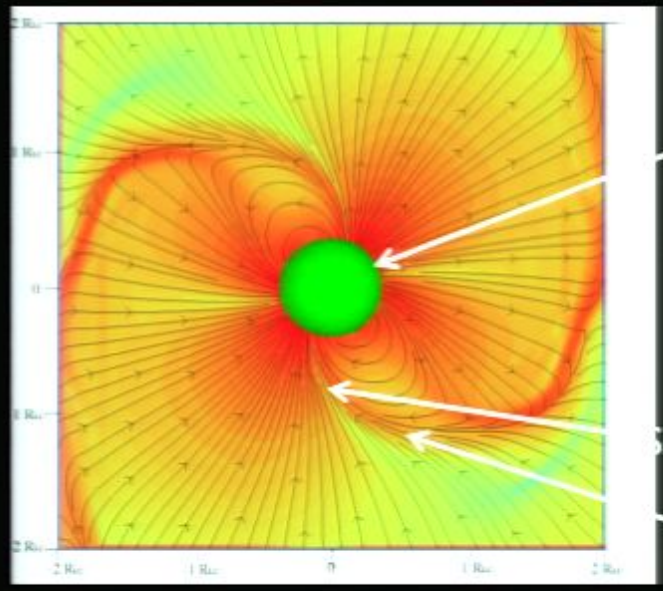

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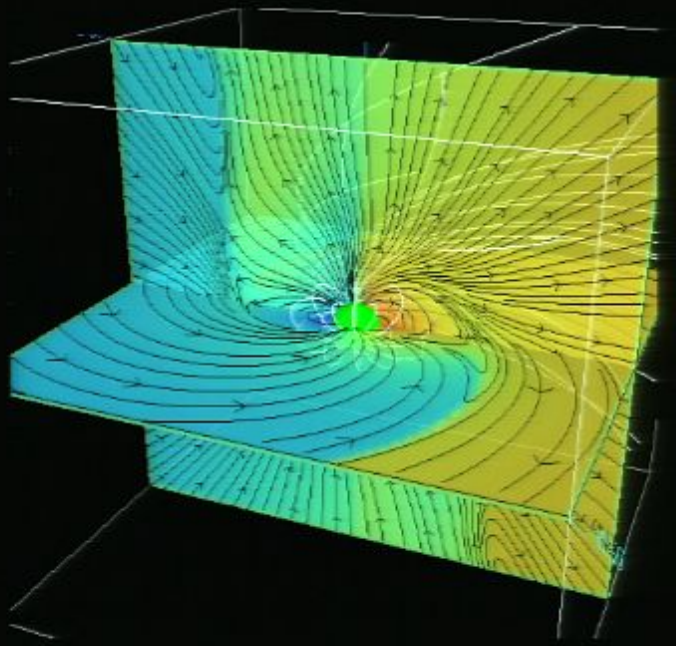

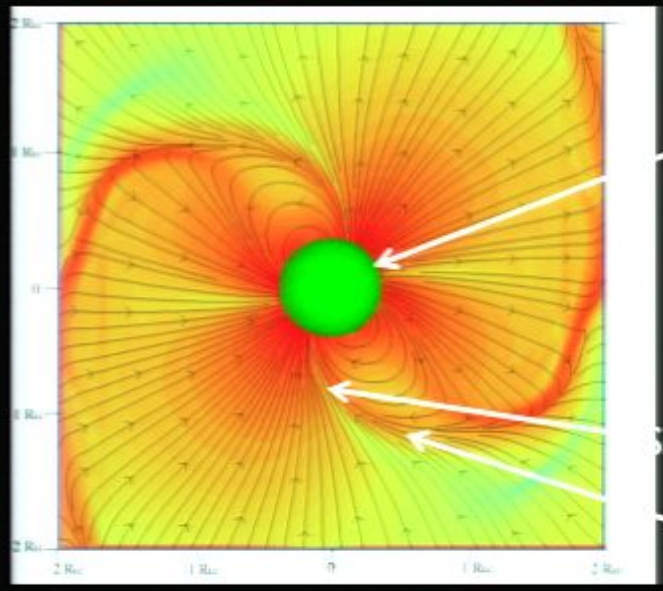

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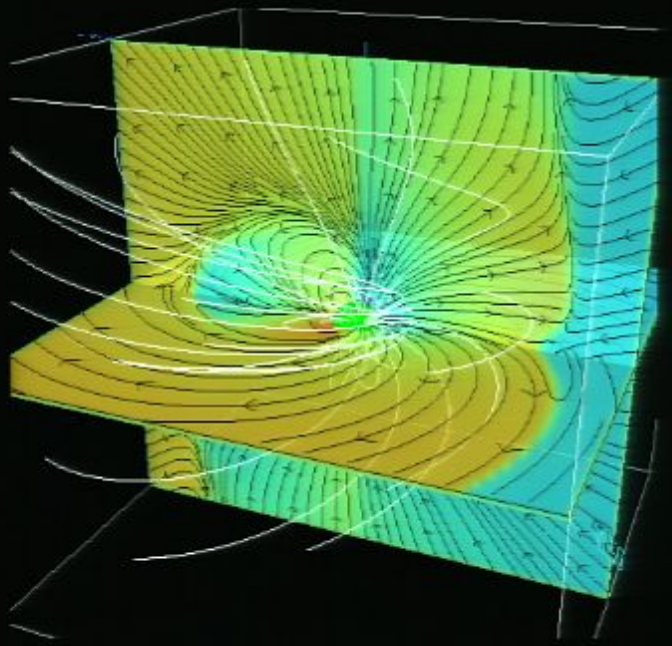

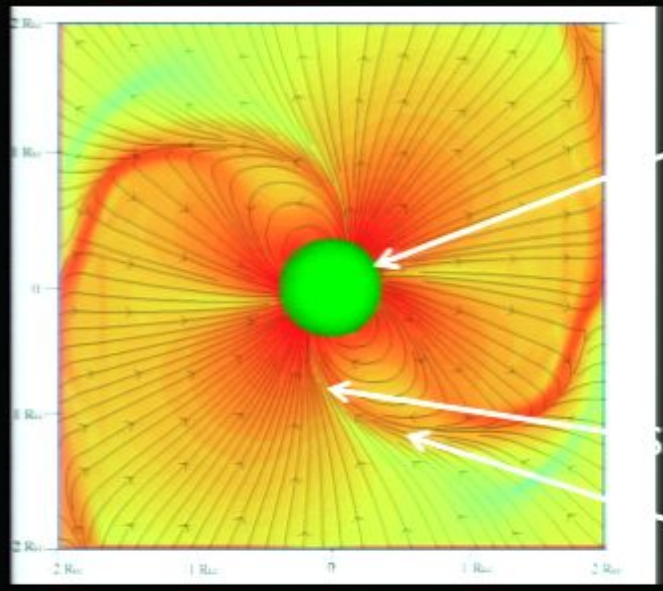

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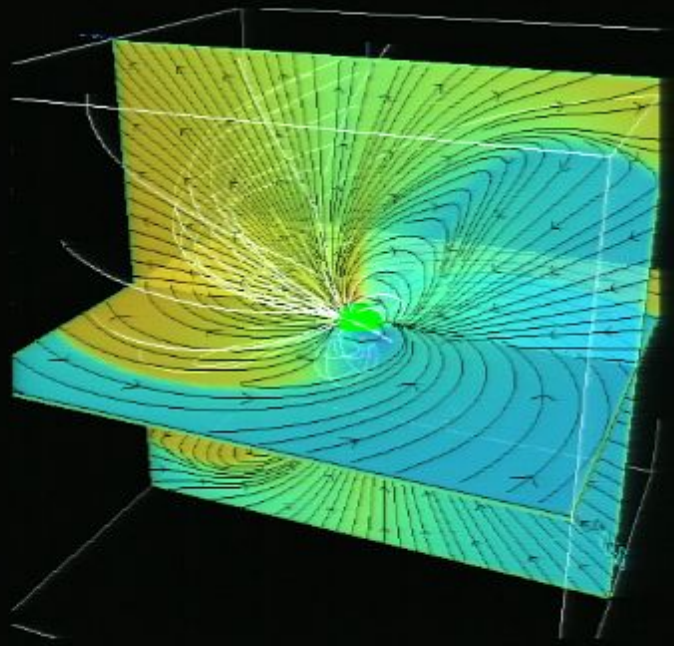

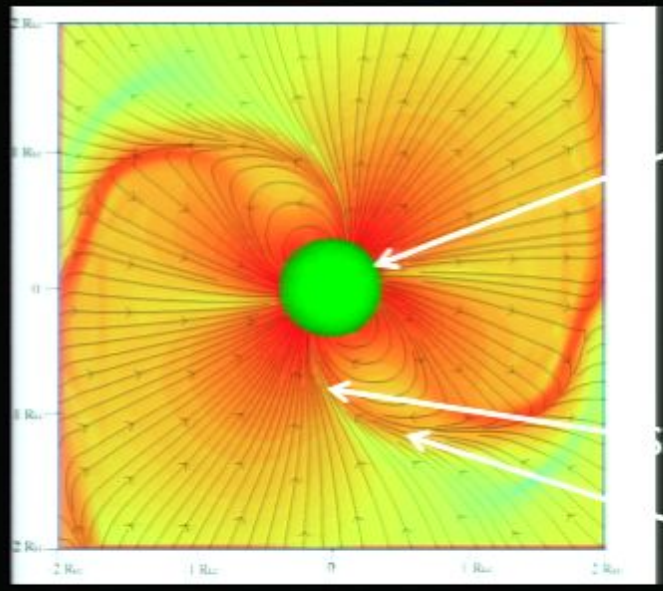

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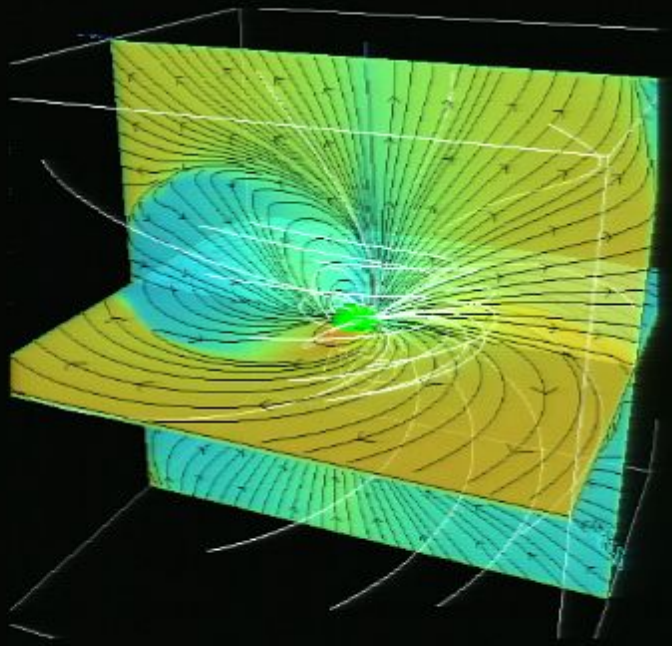

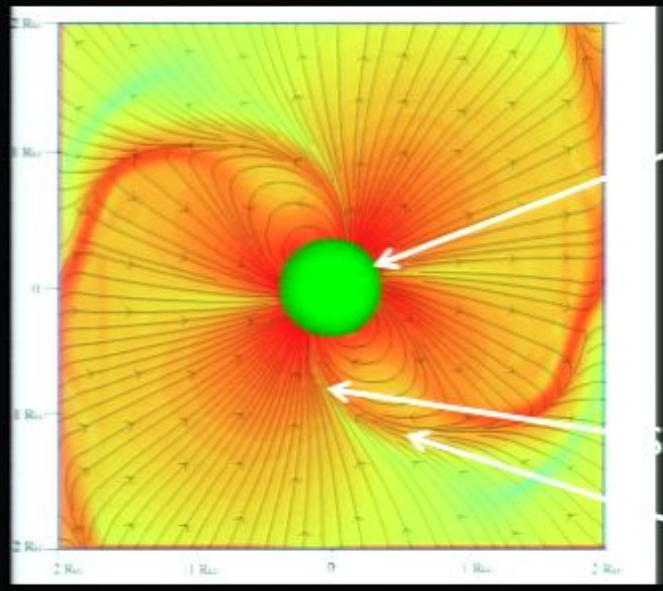

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Implications for Emission:

Polar cap/flux tube size and shape - noncircular shape, center from splaced magnetic axis - polarization - no need to invoke non-dipole B?

Electric current magnitude and sign - return currents both spatially stributed and in thin sheet (proportion depends on obliquity) - if current yers ("gaps") have parallel potential drops small compared to total agnetospheric voltage,

$$\Phi = \sqrt{\frac{\dot{E}_R}{c}} = 4 \times 10^{16}\, Volts \left(\frac{\dot{E}_R}{10^{38.7}\, erg/s} \right)^{1/2} \propto L_{radio},\ L_\gamma (large\ \Phi)$$

ectric current in and outside gaps is known, averaged on magnetosphere ansit time (~P/π), to lowest order in $L_{accel}/L_{spindown}$

ectric currents of current layers (and charge starved, quasi-vacuum "gaps") ust fit into magnetospheric circuit – known from FF model, to lowest rder in $L_{accel}/L_{spindown}$

Location of return current layer determined - realistic site/physics for uter magnetosphere beaming models of high energy emission – Bai & AS

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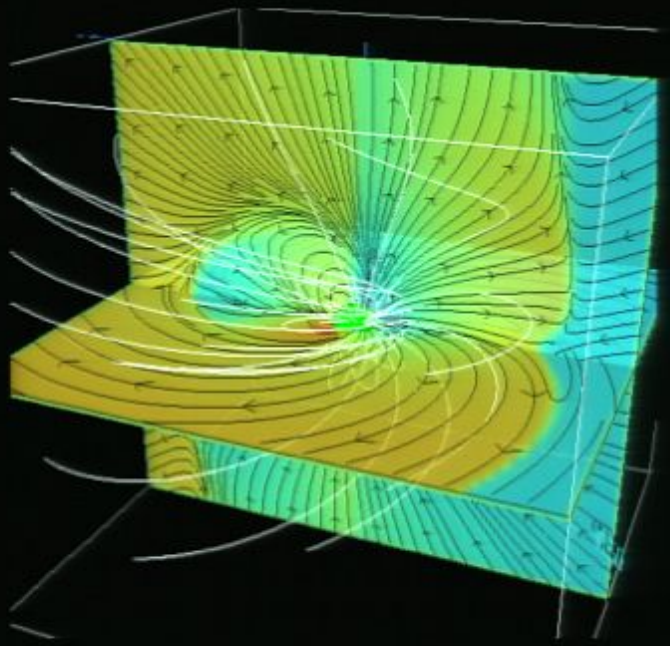

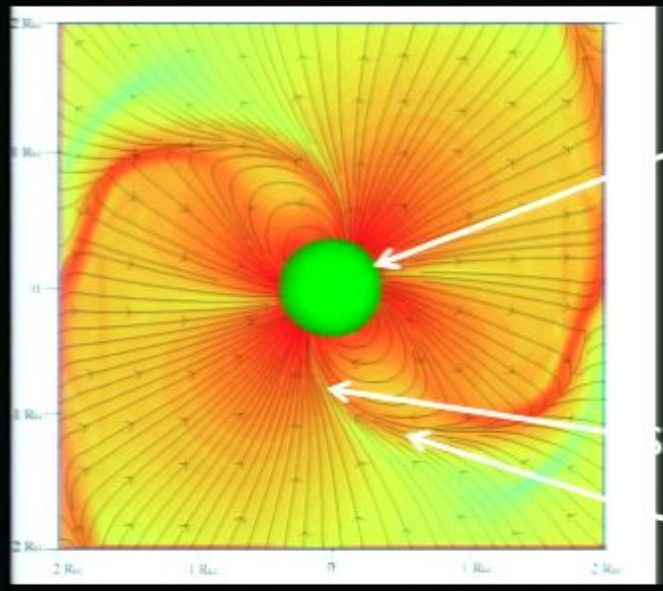

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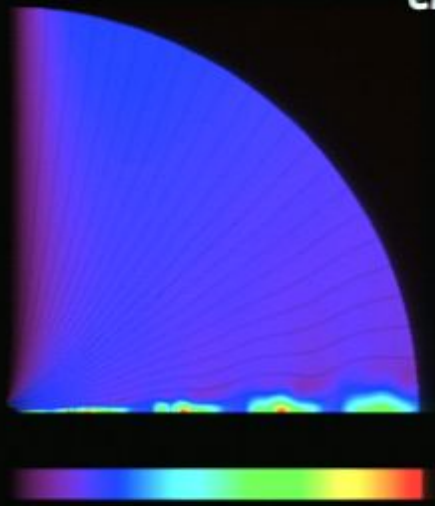

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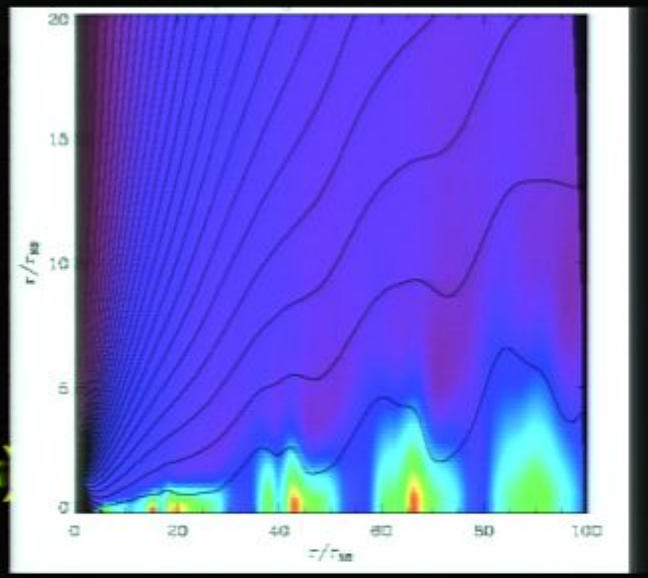

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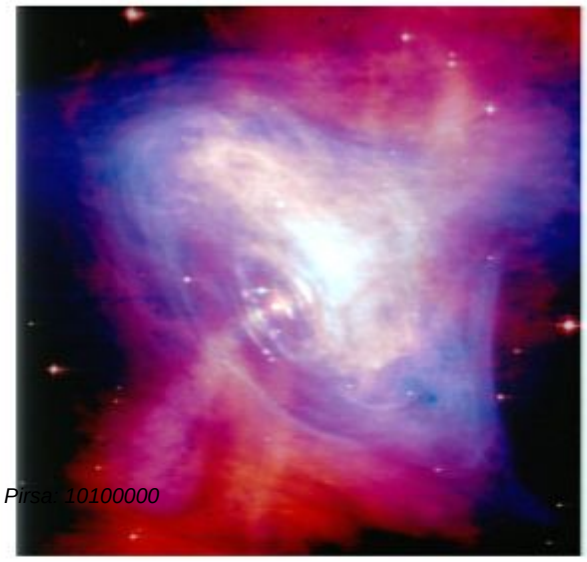

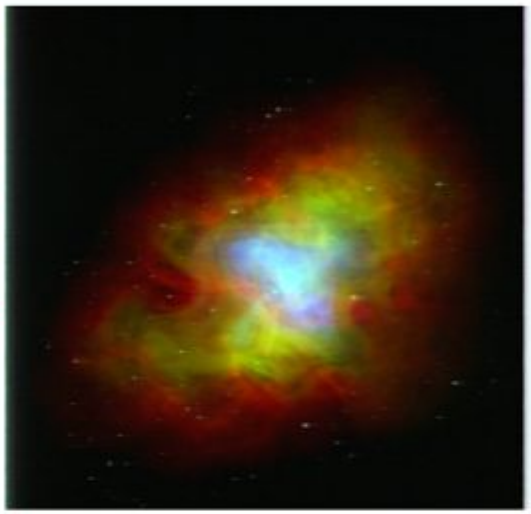

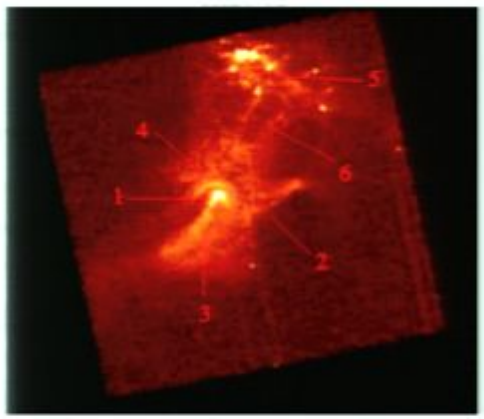

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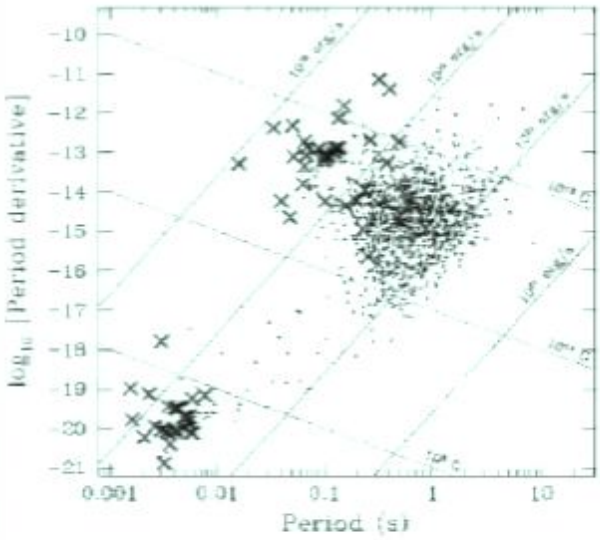


Force Free Magnetosphere -
Spin down by EM torques
Magnetic energy dominant, non-vacuum, enough plasma for $E \cdot B = 0$

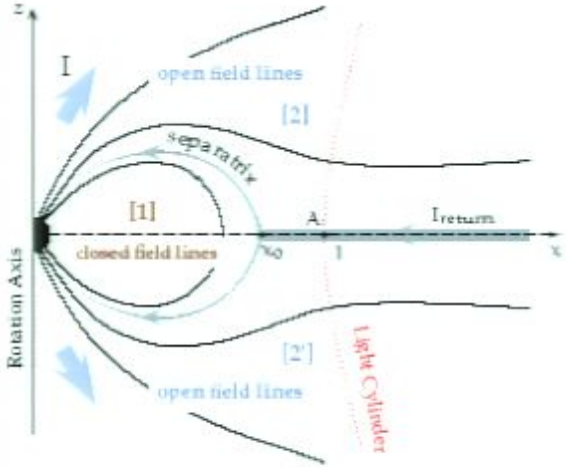
$$\dot{\Omega} = -K\Omega^n$$

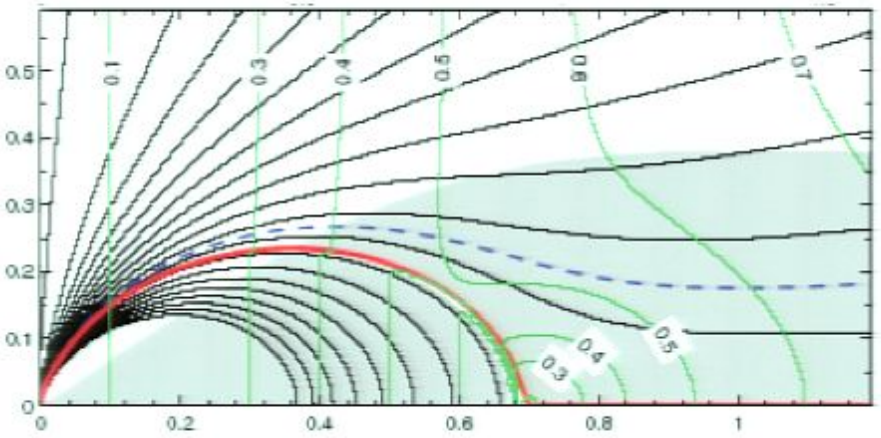
Contopoulos et al, Gruzinov, Timokhin: FF, aligned rotator, steady state: $R_Y \leq R_L$

Komissarov rel mhd, McKinney FF: aligned rotator, evolutionary

Bucciantini et al, rel MHD, pressure driven flow, aligned rotator, evolutionary: $R_Y \rightarrow R_L$

Spitkovsky: FF, evolutionary, aligned & 3D oblique: $R_Y \rightarrow R_L$ (also Kalpotharakos)





Follow the Mass Loss: From Whence all the Pairs?

Pulsar Wind Nebulae: Nebular Synchrotron requires particle injection $\dot{N}_{\pm}$ >> Goldreich-Julian current $\dot{N}_{GJ} = c\Phi/e$

PAIRS: OUTFLOW DENSE & MAGNETOSPHERE DENSE

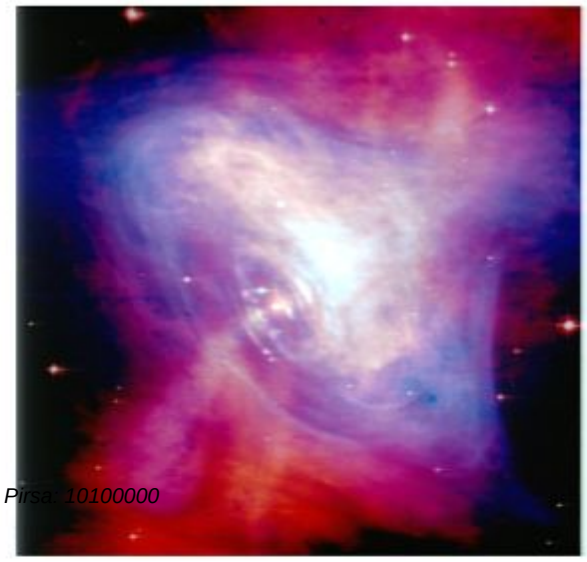
(EVERYWHERE?)

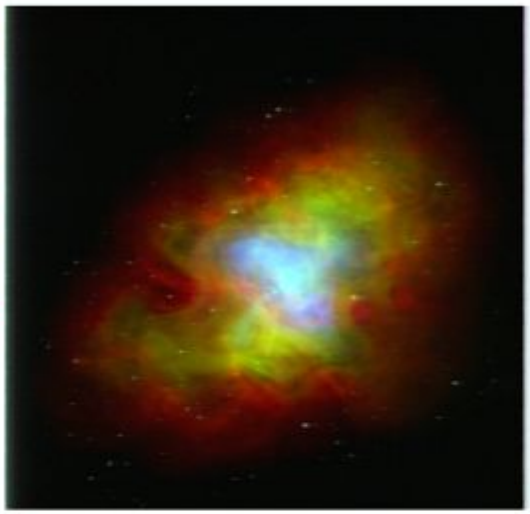
X-Rays: current injection rate (compact, strong B nebulae - Crab, G54,…)

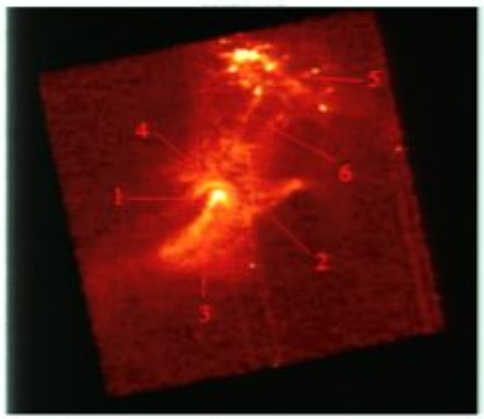
measured rates ~ existing (starvation) gap rates $\kappa_{\pm} = \dot{N}_{\pm}/\dot{N}_{GJ} \leq 10^4$ pairs/GJ

Radio measures injection rate averaged over nebular histories, $\kappa_{\pm} > 10^5$

(NB, JA & EA) >> 10 x all extant pair creation models (discharges? B model?)





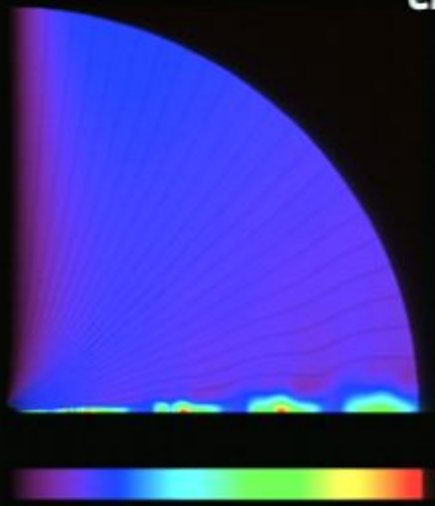


$$R_Y \leq R_L$$

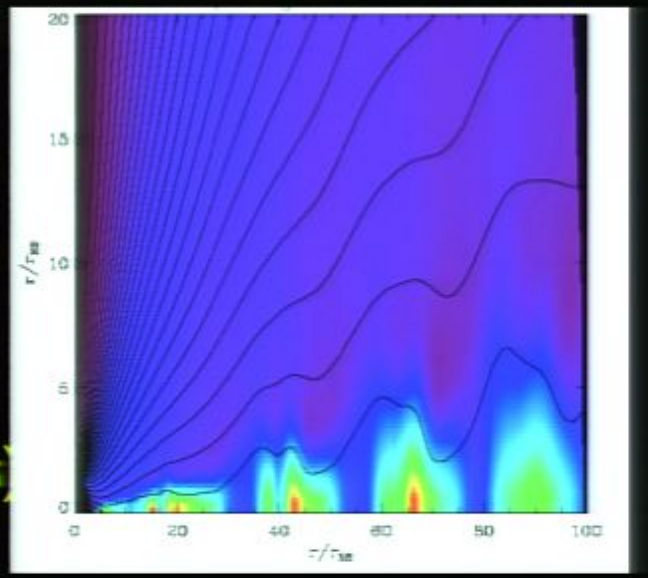
$$n = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2} = 3 + 2\frac{\partial \ln\left(1+\frac{R_L}{R_Y}\right)}{\partial \ln \Omega}$$

$R_Y/R_L < 1$ increases torque because of more open field lines and larger Poynting flux for same R_L:
Reconnection

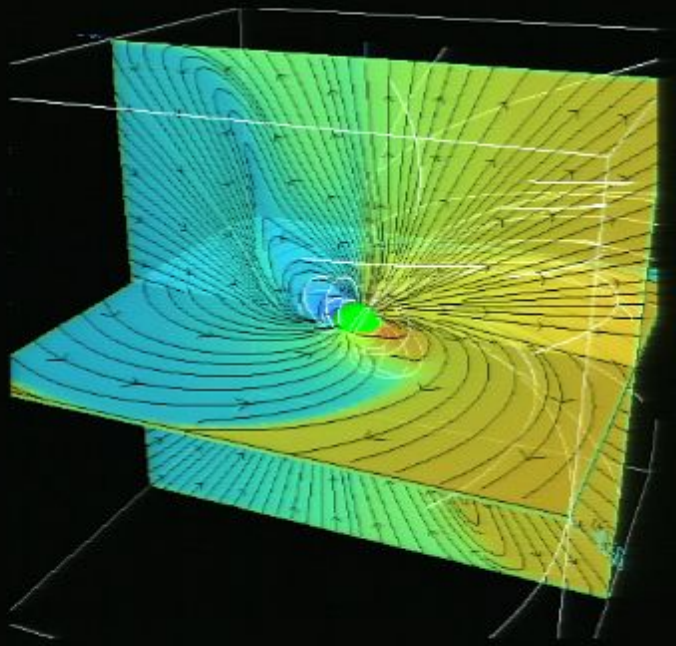
IF R_Y/R_L decreases with decreasing Ω, $n<3$; average R_Y/R_L must decrease on spindown timescale, since $2 < n < 3$

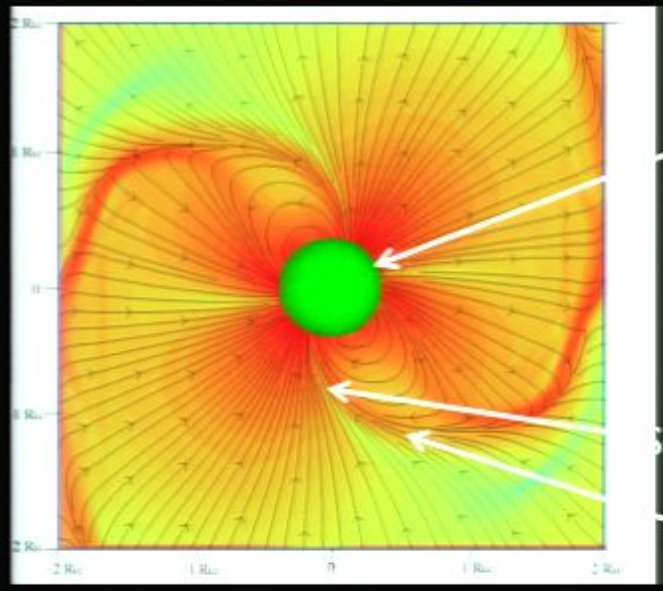


"Average" with respect to plasmoid emission, torque fluctuations ($\delta T/T$ ~ 10-30% ~ obs)



Spitkovsky's (2006) oblique force free rotator





$$\dot{E}_R = -I\Omega\dot{\Omega} = k\frac{\mu^2\Omega^4}{c^3}(1+\sin^2 i),\ k = 1\pm 0.1$$

$$i = \angle(\mu,\Omega)$$

Gaps = local zones of charge density < GJ, Parallel E ≠ 0

Acceleration along B ➔ beamed photons, rotation ➔ lighthouse

Force Free model has no gaps, no parallel accelerator

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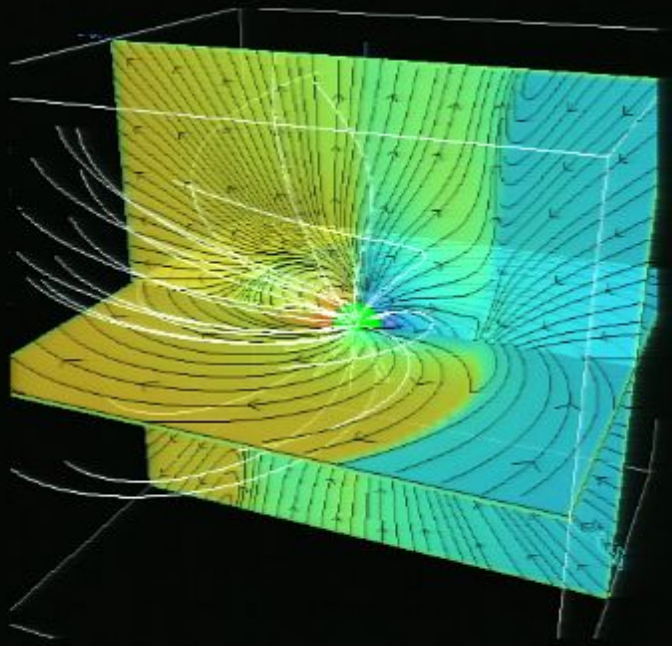

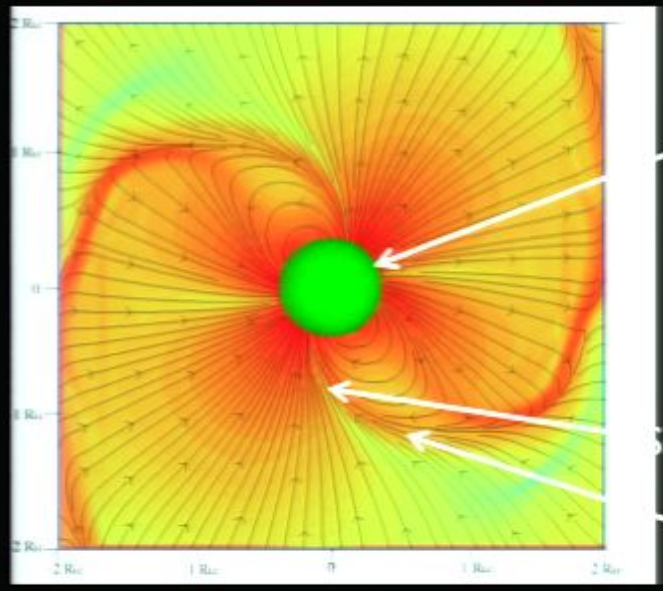

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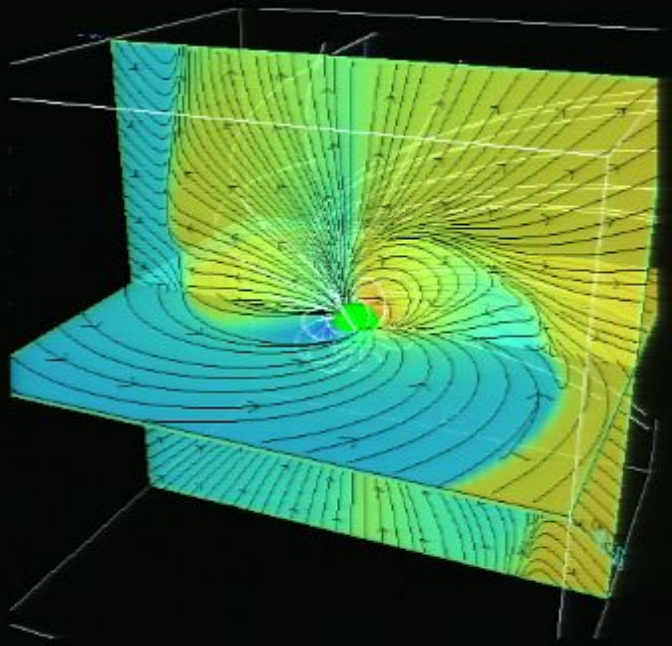

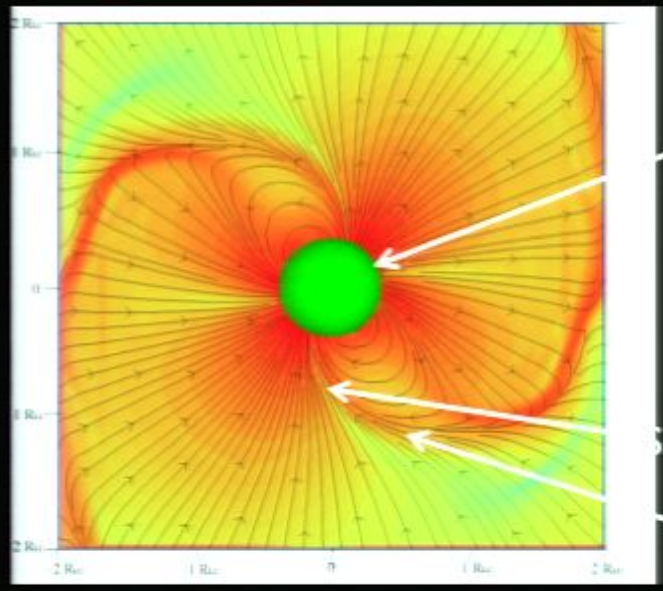

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Force Free model has no gaps, no parallel accelerator

Implications for Emission:

Polar cap/flux tube size and shape - noncircular shape, center from splaced magnetic axis - polarization - no need to invoke non-dipole B?

Electric current magnitude and sign - return currents both spatially stributed and in thin sheet (proportion depends on obliquity) - if current yers ("gaps") have parallel potential drops small compared to total agnetospheric voltage,

$$\Phi = \sqrt{\frac{\dot{E}_R}{c}} = 4 \times 10^{16}\, Volts \left(\frac{\dot{E}_R}{10^{38.7}\, erg/s} \right)^{1/2} \propto L_{radio},\ L_\gamma (large\ \Phi)$$

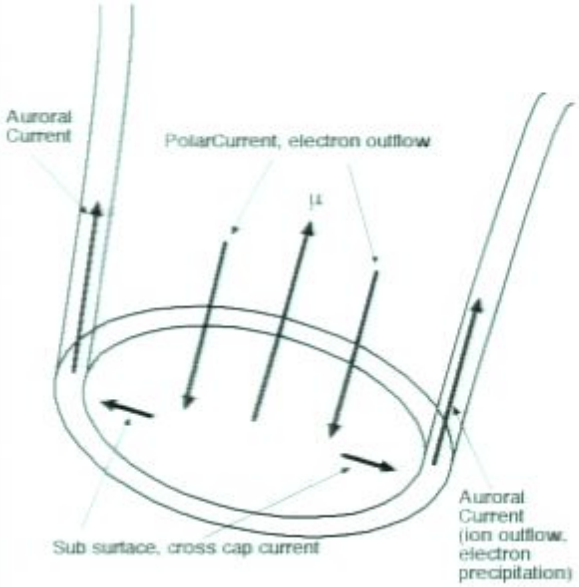
ectric current in and outside gaps is known, averaged on magnetosphere ansit time (~P/π), to lowest order in $L_{accel}/L_{spindown}$

ectric currents of current layers (and charge starved, quasi-vacuum "gaps") ust fit into magnetospheric circuit – known from FF model, to lowest rder in $L_{accel}/L_{spindown}$

Location of return current layer determined - realistic site/physics for uter magnetosphere beaming models of high energy emission – Bai & AS

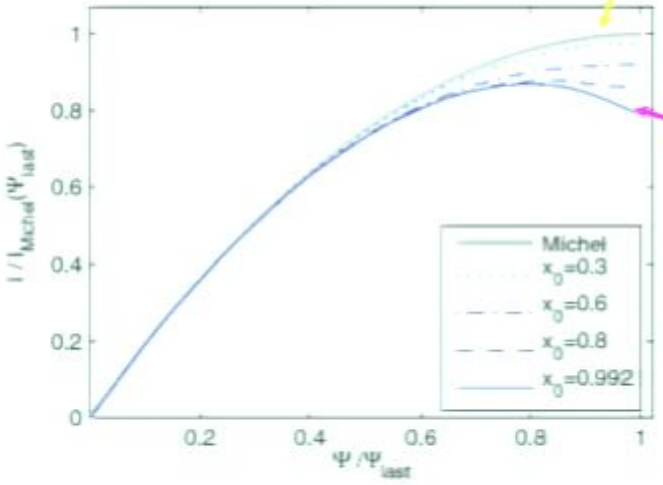
Known Current - Huge Effect on $E_{\parallel}$?

Aligned rotator for clarity



Monopole

Dipole, $R_Y=R_L$



Polar current contained within distance from magnetic axis, $j \neq$ const

$$\varpi = \left(\frac{\Psi}{\pi B_{pole}}\right)^{1/2}, \quad \Psi =$$ Magnetic flux

Cartoon - all models have charge density = GJ, polar current density = constant

"small" $E_{\parallel}$ ($\sim 10^8$ V/m); same true for outer gaps (geometry different, electrodynamics ~ same)

Effect of Current on $E_\parallel$ (continued)

Existing models: starvation $E_\parallel$ extracts a beam -

Beam Charge Density almost equals GJ: current = constant - small $E_\parallel$ - ~10^8 V/m, $\Delta\Phi \sim 10^{12}$ - 10^{13} V

local electrostatic tail wags the magnetospheric dog!

Same issue for outer gaps on open field lines: starvation gap models (steady) produce magnetospheric charge density, not current density, but all energy in current!

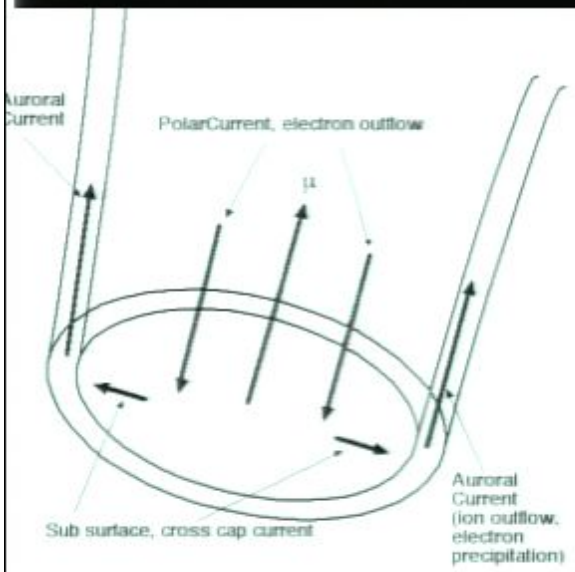
phenomenological models of data all based on such anti-energetics ideas

Follow the Energy (b): Model Gamma Ray Emission

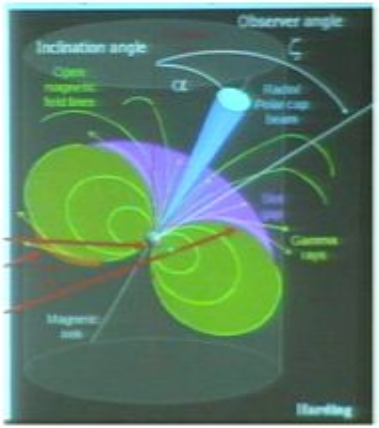
Prospect: Beam Models With Force Free Magnetospheric Structure

Magnetosphere sets time average j_{pc} to be the Force Free current: close to monopole

$$\langle -en_{beam} \rangle - (-en_{GJ}) = \frac{j_{GJ}}{c}\left(1 - \frac{\Psi}{\Psi_{cap}}\right) - \frac{j_{GJ}}{c} = +\frac{|j_{GJ}|}{c}\frac{\varpi^2}{\varpi_{cap}^2} \rightarrow \frac{|j_{GJ}|}{c}, \varpi \rightarrow \varpi_c$$

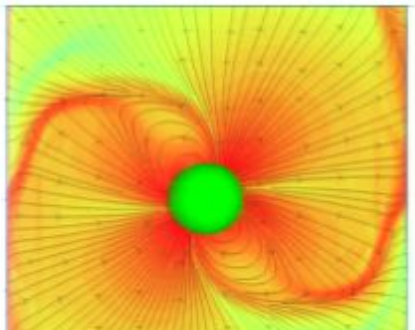


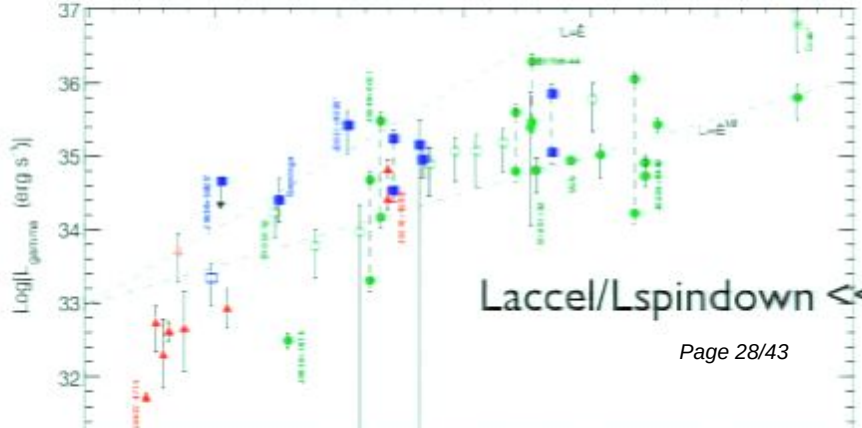
Like a vacuum gap, but $E_{\parallel} = 0$ at crust surface



Probe Structure with Gamma Rays – fold geometry with accelerator, probe parallel electric field

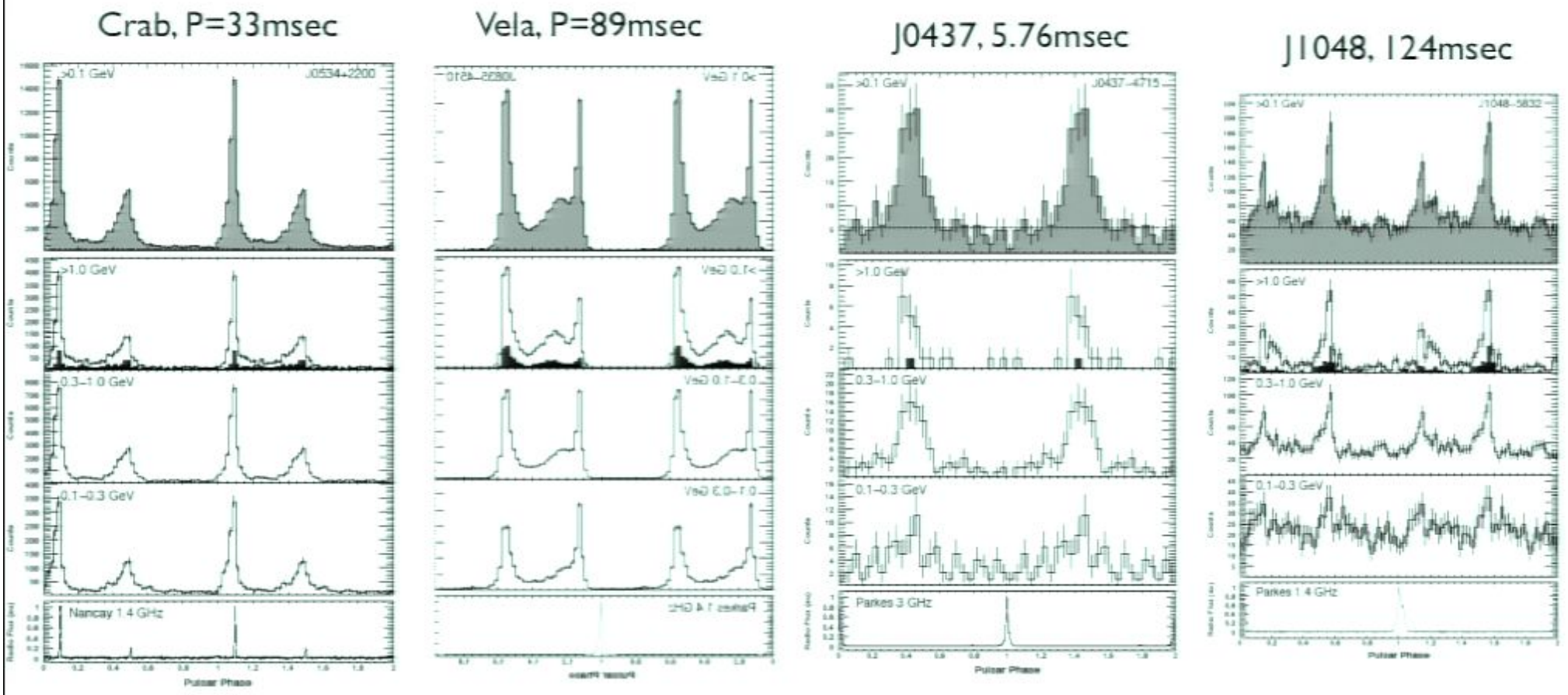
Gamma Ray Efficiency (LAT)





Laccel/Lspindown << 1

- Cartoon for acute rotator: $\angle(\Omega_*, \mu) < \pi / 2$
- Obtuse rotator: positrons precipitate, extract electrons; polar current = ions



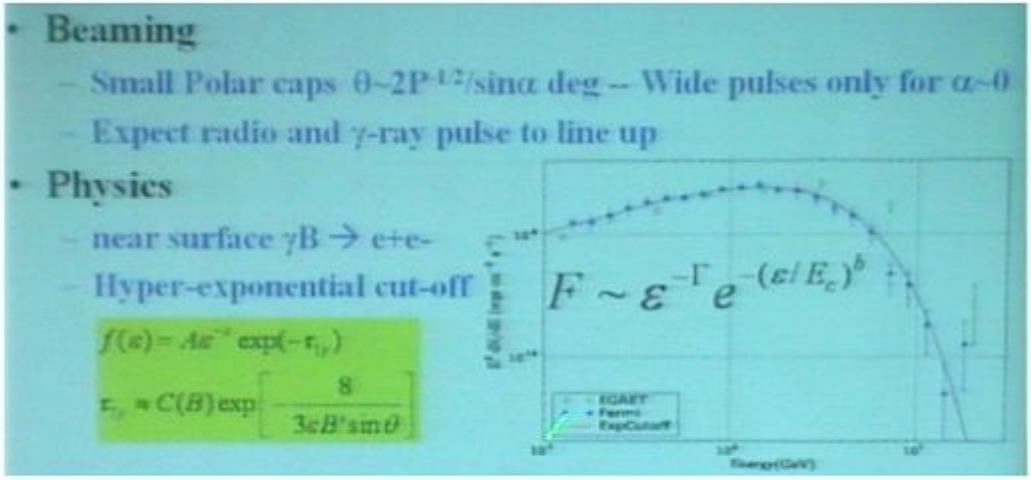
A Few Gamma Pulsars (> 65 seen by FERMI-LAT so far)

Most are double peaked, wide separation in rotation phase,
Radio pulse leads two peaked gamma pulse (B sweepback,…)

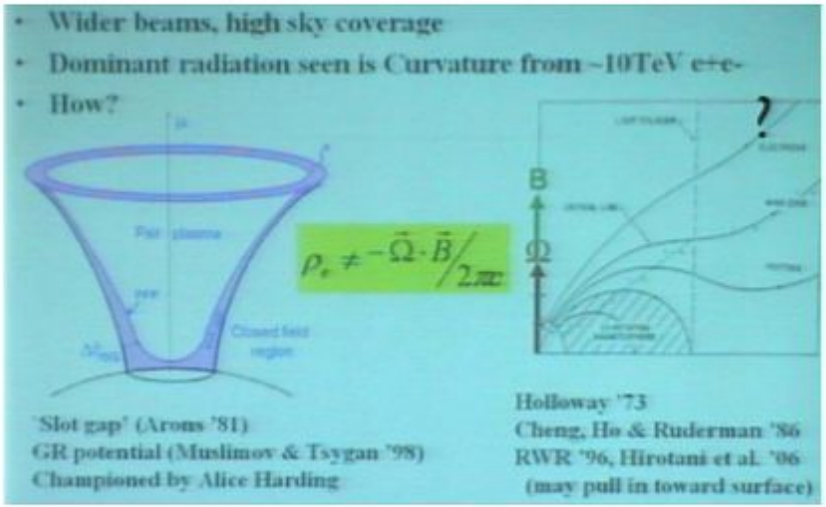
Gamma Ray Tests of Existing Gap Models

Gamma Rays Not from Polar Cap

Super exponential cutoff rejected:
b > 1 rejected at 16 σ



Beamed γ from high altitude more promising – tradition has $E_{\parallel}$ from starvation, quasi-vacuum "gaps"

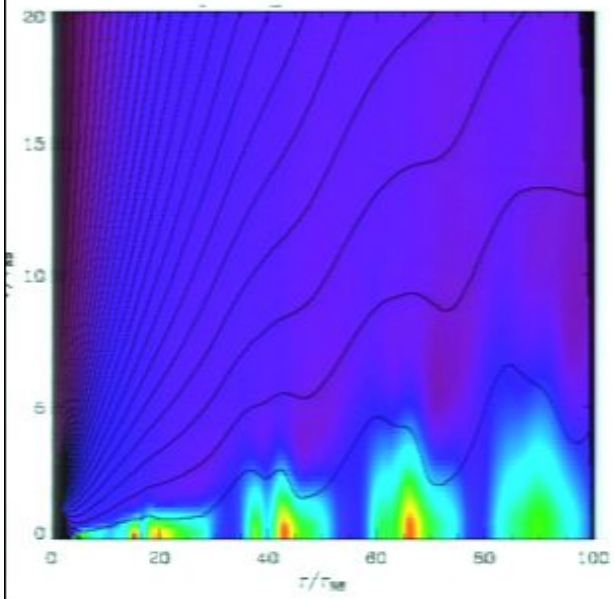


slides from Romani

Slot gap fragile to mild magnetic anomalies, gravitational bending of photon orbits causes pairs to fill slot gap

gap; Outer gap gets filled by reconnection driven flow ("bulk bursty" flow in

Prospect: Time Dependent Reconnection/Return j



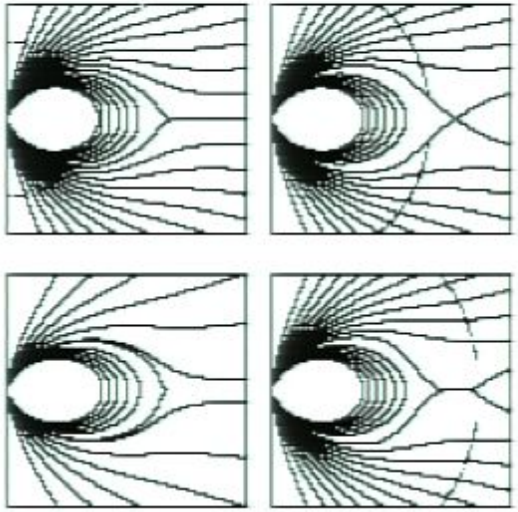
Sporadic X-Point, Plasmoid formation

occurs continuously

Pairs all come from pole.
on open field lines

Sporadic reconnection
moves plasma across
separatrix

non-corotation, time
variable E at all times

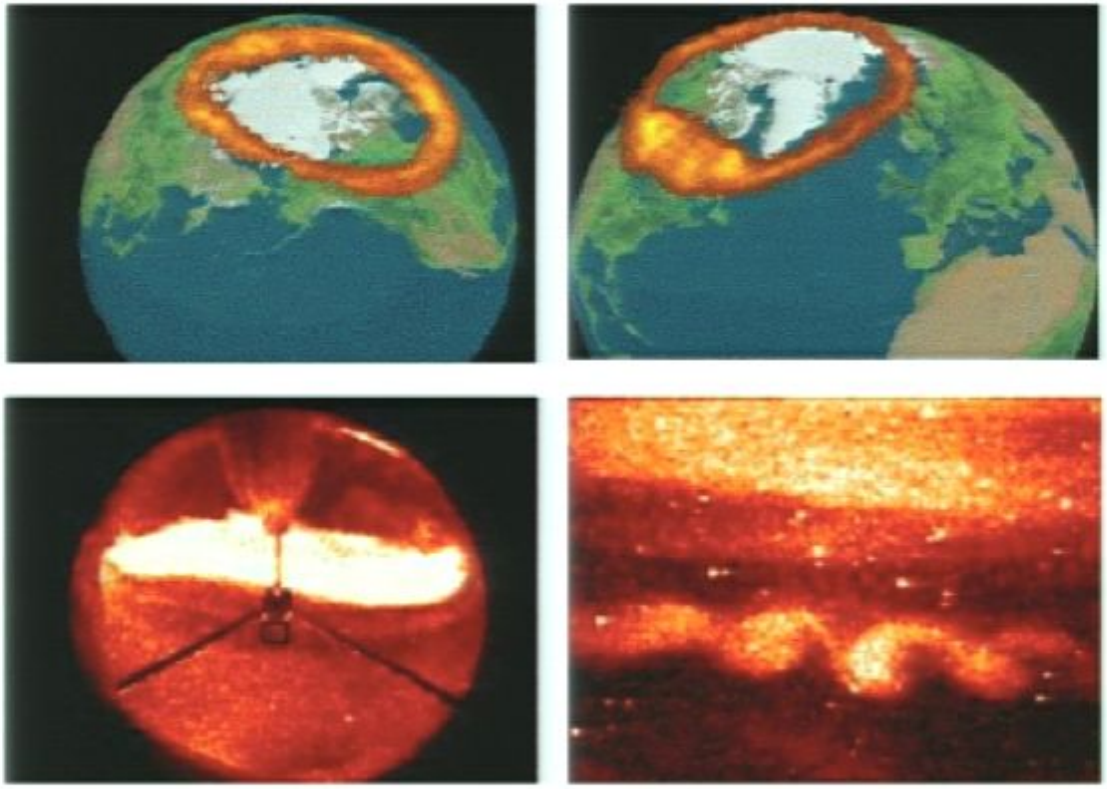


Plasma, j flow to star in thin separatrix layer - dynamics in beams,
Kinetic Alfven waves, boundary layer $E_\parallel$ - replaces outer gap - **AURORA**

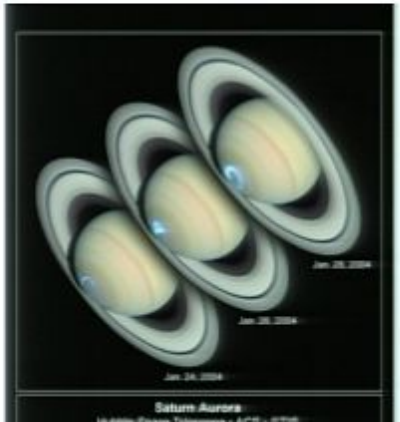
- Space charge in boundary current alters polar acceleration(!)
  enhances pair creation (?)
- Kinetic Alfven wave $E_\parallel$ extracts ion (electron) return current
- Torque fluctuations, limit cycles built in (drifting subpulses)?

Auroral Model-a radiating accelerator in globally FF

Earth Auroral oval from space – current flow along B from magnetotail, subsolar "nose" – dynamo mechanical stress from solar wind inertia, coupled by reconnection
Mechanical stress coupled to magntosphere by reconnection



Emission - lines stimulated by downward accelerated e^- beam $\Delta\Phi \sim \Phi$ (storms), density >>> GJ (non-starvation)

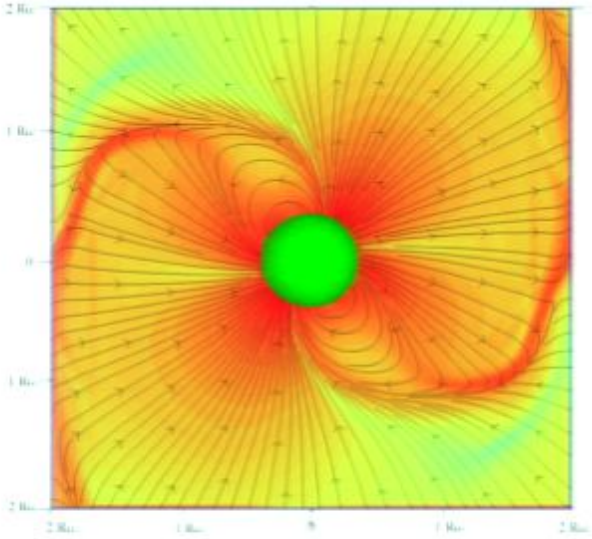


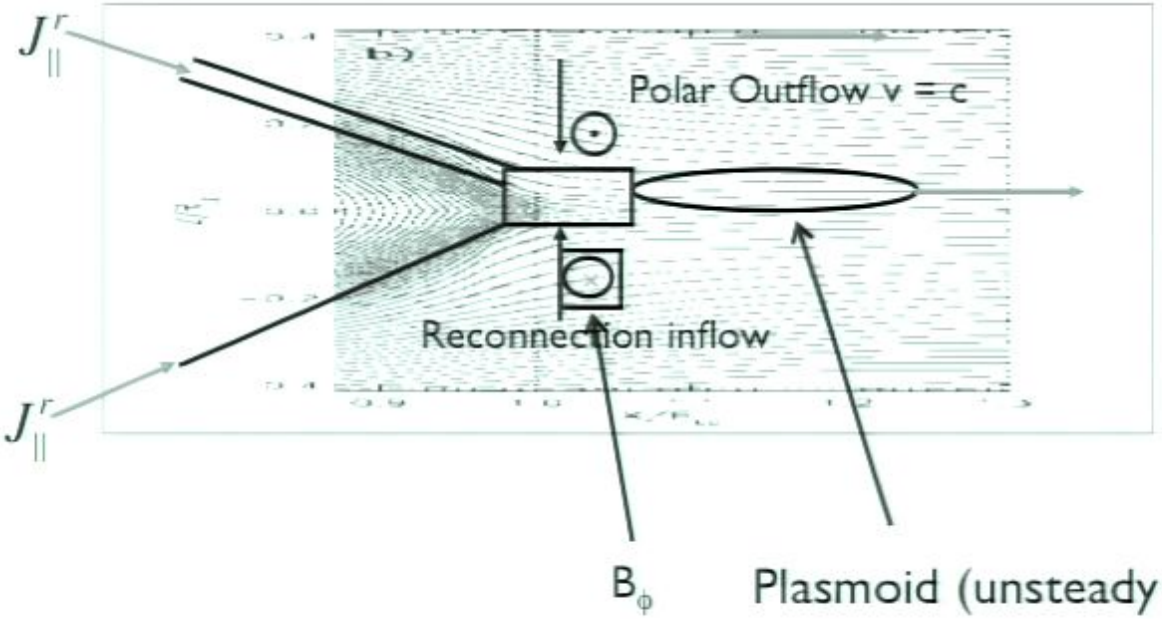
Electronic camera
Pix of auroral arcs

Jupiter, Saturn similar

Hubble

Acceleration in Current Sheets: counterstreaming beams in thin sheet (like Auroral arcs) - in progress, baby steps;





Current Sheet = Beams, KAW, thickness ~ c/ω_p

$E = E_{perp} + v \times B$

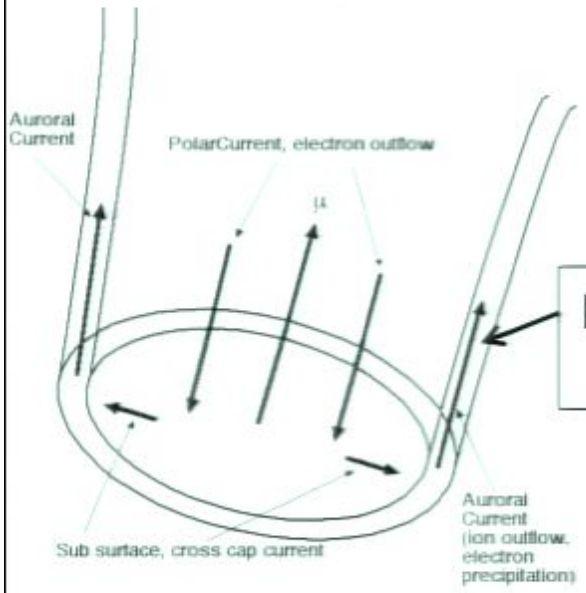
$+ E_{parallel} + \Delta E_{perp}$

Ohm's law:
2 fluid eq of motion

$$E_{||} = \frac{4\pi}{\omega_p^2}\frac{DJ_{||}}{Dt} \propto \frac{m\gamma}{n_{current}}\frac{I}{\Delta_{current}\rho_B}, I \propto \sqrt{\dot{E}_R}$$

Particle inertia provides "resistance" in large inductance circuit, voltage $\Delta\Phi$; but, low density favors larger $E_{parallel}$. Viscous stress establishes reconnection ΔE_{perp}, $E_{parallel}$ in current source box = diffusion region

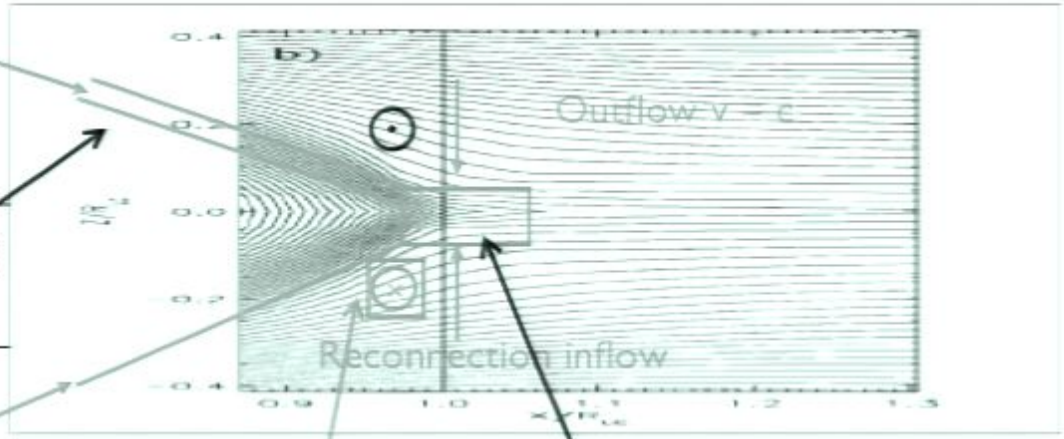
Polar Cap



Return current channel

$J_{\parallel}^{r}$

$J_{\parallel}^{r}$



B_0 Diffusion region, length l_D

$i < 90^o$

Field Aligned current (counterstreaming beams)
possibly also fed by pair creation ($\gamma\gamma$)

Precipitating electrons $\Omega \cdot \mu > 0$
Precipitating positrons $\Omega \cdot \mu < 0$

Current flows in a channel, thickness

$$\Delta_{current} = \Delta_{current,LC} \left(\frac{r}{R_{LC}} \right)^{3/2}$$

Diffusion region height = $2\Delta_{current,LC}$

$$\Delta_{current,LC} \approx \frac{c}{\omega_{p\pm,LC}(\Delta_{current,LC})} \longrightarrow$$

(Channel boundary = conductor – dense, relatively low energy plasma in neighboring outflow, closed zone fed by reconn driven flow)

$$\frac{\Delta\Phi}{\Phi} = \frac{1}{8}\left(\frac{m_{\pm} c^2 \gamma_{\pm,L}}{e\Phi\kappa_{\pm}} \frac{\beta_{wind}}{\beta_{rec}} \right)^{2/3} = \frac{\dot{E}_{accel}}{\dot{E}_R} =$$ radiative efficiency in radiation reaction limit $\propto \dot{E}_R^{-2/3} \Rightarrow L_{\gamma} \propto \dot{E}_R^{1/3}$

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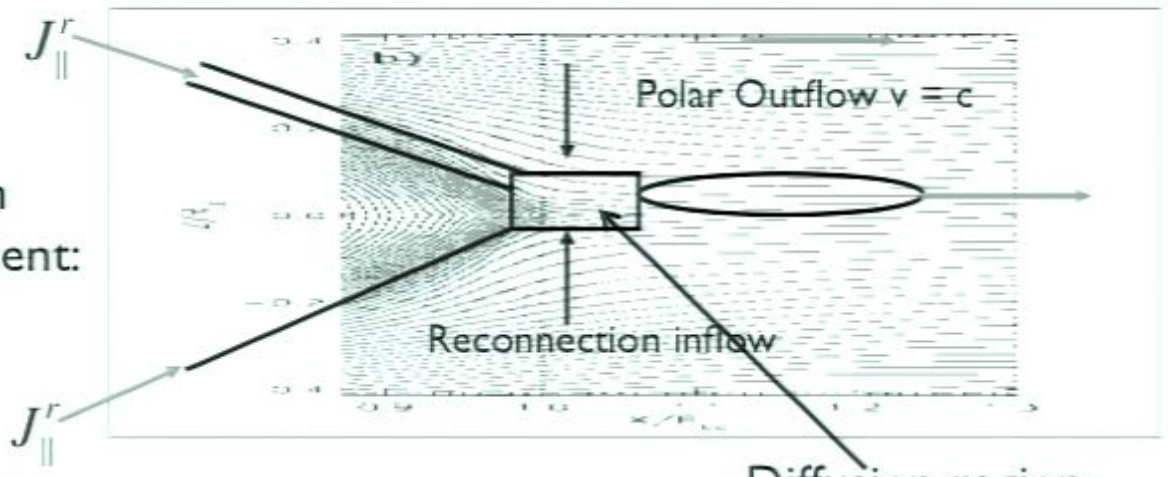


Capture rate into diffusion region from polar outflow with perp gradient:

$$\dot{N}_{\pm}^{in} = \frac{2l_D\Delta_L}{R_L^2}\frac{\beta_{rec}}{\beta_{wind}}\kappa_{\pm}\frac{c\Phi}{e}$$

Captured pairs expelled along B by pressure, B stress inside diffusion region

Electric field in channel stops positrons, accelerates electrons down (electric field in wind current sheet stops electrons/e^+, accelerates positrons/e^- to $r > R_L$)

Downward precipitating electron flux:

ℓ_D = diffusion region length

$$F_v^{(-)} = \frac{\ell_D}{R_L}\frac{\beta_{rec}}{\beta_{wind}}\kappa_{\pm}\frac{c\Phi/e}{2\pi R_L^2}\left(\frac{R_L}{r}\right)^3 = \frac{\ell_D}{R_L}\frac{\beta_{rec}}{\beta_{wind}}\kappa_{\pm}F_{GJ,L}\left(\frac{R_L}{r}\right)^3$$

$\frac{\ell_D}{R_L}$ really is a semi-free parameter, could be as small as $\frac{c}{\omega_{p,L}R_L}$

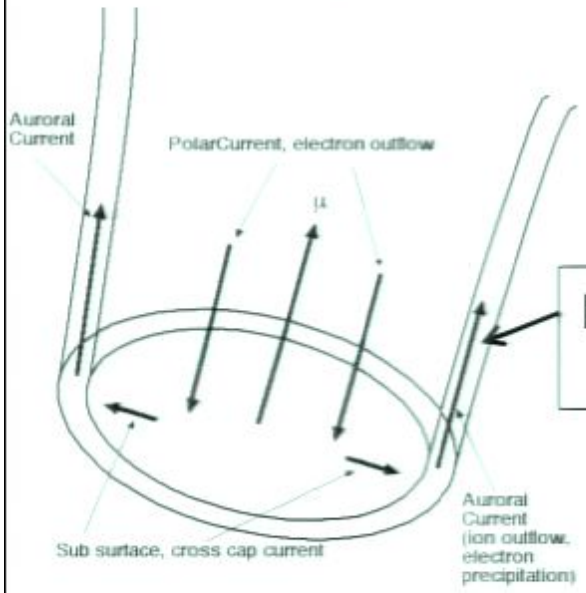
Precipitating electrons are GJ's "hanging charge clouds" needed to form return current extracted from star

$\frac{\ell_D}{R_L} \sim 0.1$ (FF simulations with numerical diffusion, space expt.)

$\beta_{rec} = 0.1$ (2D reconn in pairs current sheet simulation by Hoshino, $v_A = c$)

$$n_v^{(-)} \gg n_{GJ} \text{ if } \frac{\ell_D}{R_L}\frac{\beta_{rec}}{\beta_{wind}}\kappa_{\pm} \gg 1$$

Polar Cap



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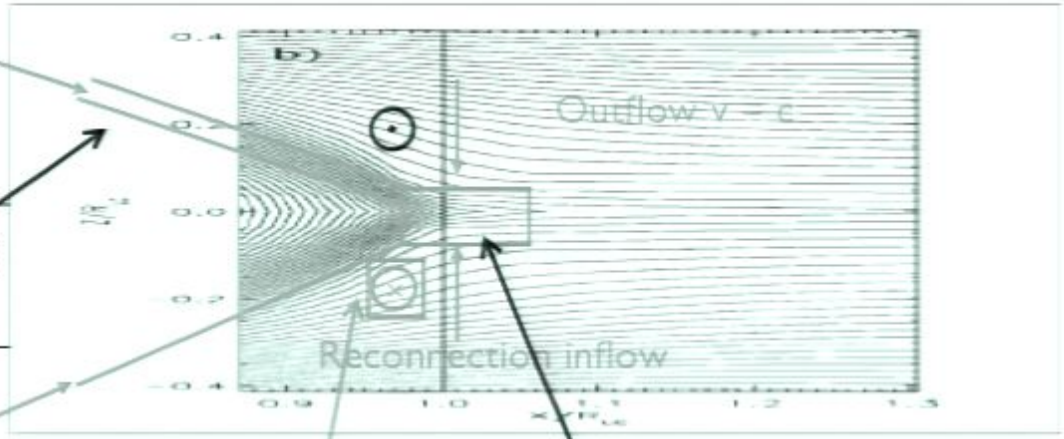

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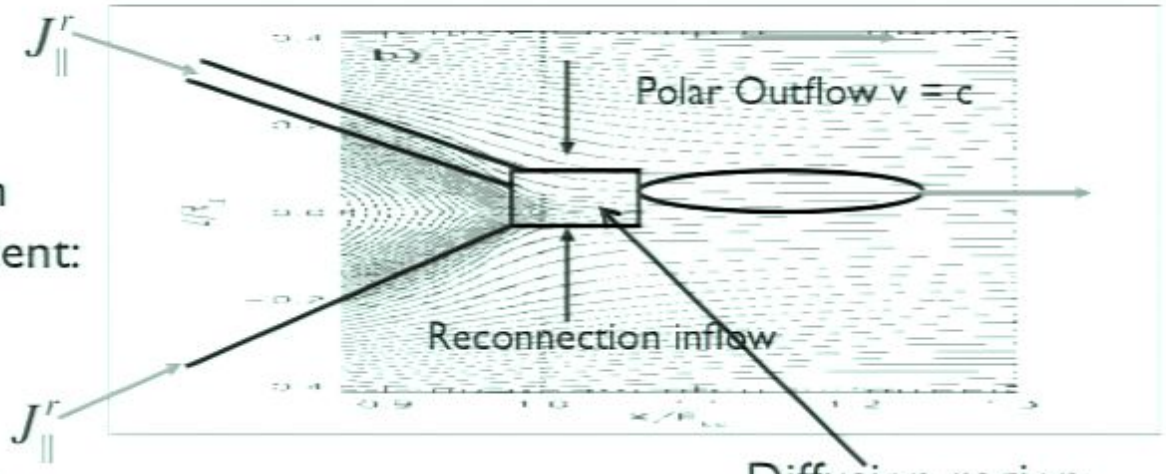

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Downward precipitating electron flux:

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$$F_v^{(-)} = \frac{\ell_D}{R_L}\frac{\beta_{rec}}{\beta_{wind}}\kappa_{\pm}\frac{c\Phi/e}{2\pi R_L^2}\left(\frac{R_L}{r}\right)^3 = \frac{\ell_D}{R_L}\frac{\beta_{rec}}{\beta_{wind}}\kappa_{\pm}F_{GJ,L}\left(\frac{R_L}{r}\right)^3$$

$\frac{\ell_D}{R_L}$ really is a semi-free parameter, could be as small as $\frac{c}{\omega_{p,L}R_L}$

Precipitating electrons are GJ's "hanging charge clouds" needed to form return current extracted from star

$\frac{\ell_D}{R_L} \sim 0.1$ (FF simulations with numerical diffusion, space expt.)

$\beta_{rec} = 0.1$ (2D reconn in pairs current sheet simulation by Hoshino, $v_A = c$)

$$n_v^{(-)} \gg n_{GJ} \text{ if } \frac{\ell_D}{R_L}\frac{\beta_{rec}}{\beta_{wind}}\kappa_{\pm} \gg 1$$

Precipitating electrons cause extraction of ion beam of almost equal charge density from atmosphere – local quasi-neutrality

Total return current in channel = downward relativistic e^- (e^+) + upward ions (electrons) (ios = protons, if atmosphere has floating H)

Quasi-neutrality/space charge limited ion emission yields net charge density in channel = GJ <<

If current channel width = skin depth at LC, mapped down dipole field then

$$\Delta\Phi \approx -\frac{1}{8}\Phi_{mag}\frac{R_*}{R_L}\left(\frac{m_\pm c^2\gamma_\pm}{2e\Phi_{mag}\kappa_\pm}\frac{\beta_{wind}}{\beta_{rec}}\right)^{1/3}\frac{\ell_D}{\Delta_L}\cos i$$

$$= -\frac{1}{8}\Phi_{mag}\frac{R_*}{R_L}\left(\frac{\beta_{wind}}{\beta_{rec}}\right)^{1/3}\frac{\ell_D}{R_L}\cos i$$

For Crab parameters,

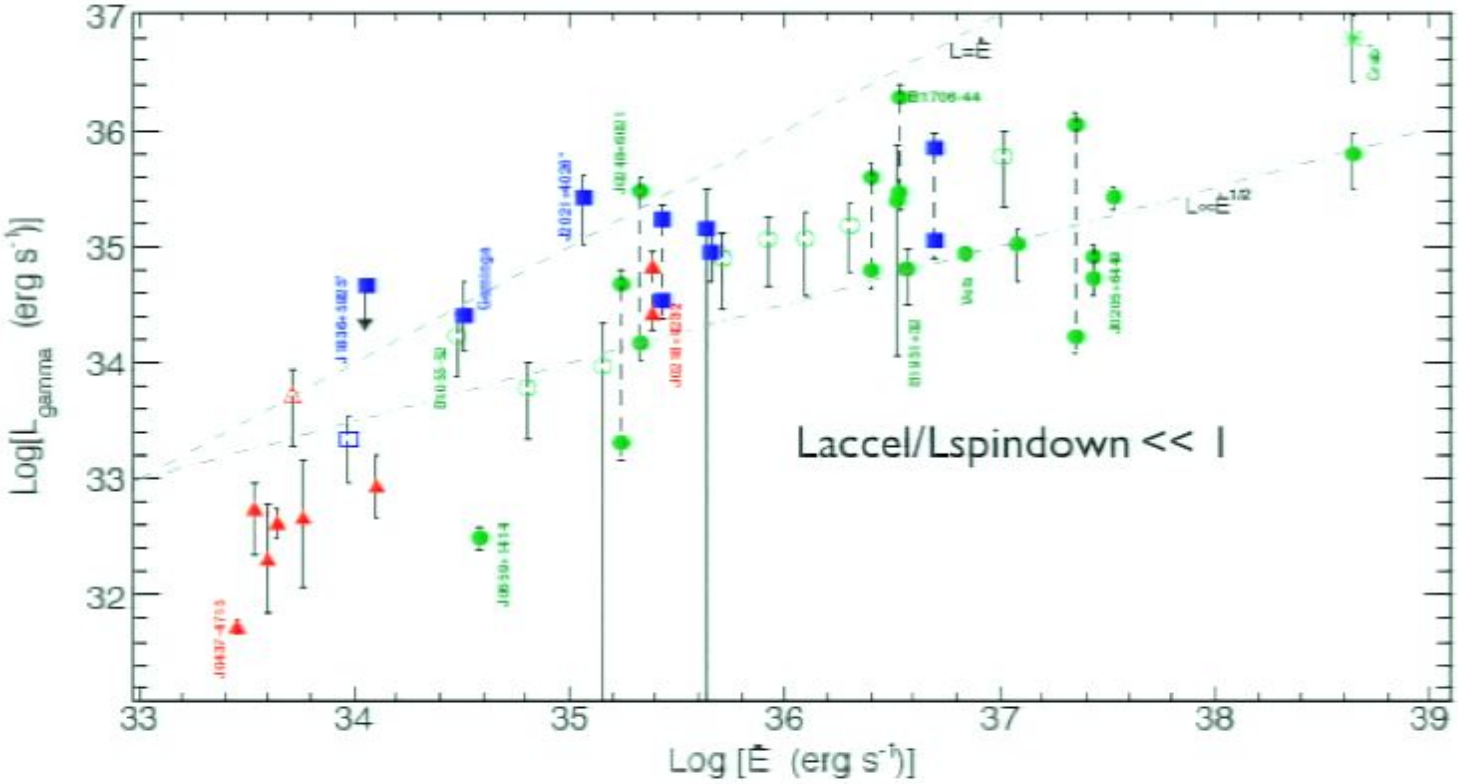
$\frac{\ell_D}{\Delta_L} \sim 1$ yields $\Delta\Phi_{min} \sim$ GV

much larger with macroscopic $\frac{\ell_D}{R_L}$;

Numerical resistivity in FF sims: $\frac{\ell_D}{R_L} \sim 0.1$

$$L_{accel} = I\Delta\Phi = c\Phi_{mag}\Delta\Phi \propto \Phi_{mag}^{5/3}\frac{\ell_D}{\Delta_L} \propto \Phi_{mag}^{1/2} \text{ if } \frac{\ell_D}{\Delta_L} \propto \Phi_{mag}^{-7/6}$$

$$L_{accel} = I\Delta\Phi \propto c\Phi_{mag}\Phi_{mag}^{2/3}\frac{\ell_D}{R_L} \propto \Phi_{mag}^{5/3} \propto \dot{E}_R^{5/6}\frac{\ell_D}{R_L} \propto \Phi_{mag} \propto \dot{E}_R^{1/2} \text{ if } \frac{\ell_D}{R_L} \propto \Phi_{mag}^{-2/3} \propto \dot{E}_R^{-1/3}$$



$L_\gamma \sim \Phi_{mag}$ rough trend

Dispersion

Large:

Distances

Beaming

?

$L_{accel} = I\Delta\Phi = c\Phi_{mag}\Delta\Phi \propto \Phi_{mag} \propto \dot{E}_R^{1/2}$ if $\Delta\Phi \approx$ constant, as in pair creation limited starvation voltage

(JA, Harding) – pair creation depends on gamma emission process

ℓ_D/Δ, requires a reconnection theory for pairs streaming past a cusp – perhaps possible in PIC + relativistic MHD simulations, some steady reconnection semi-analytic modeling also

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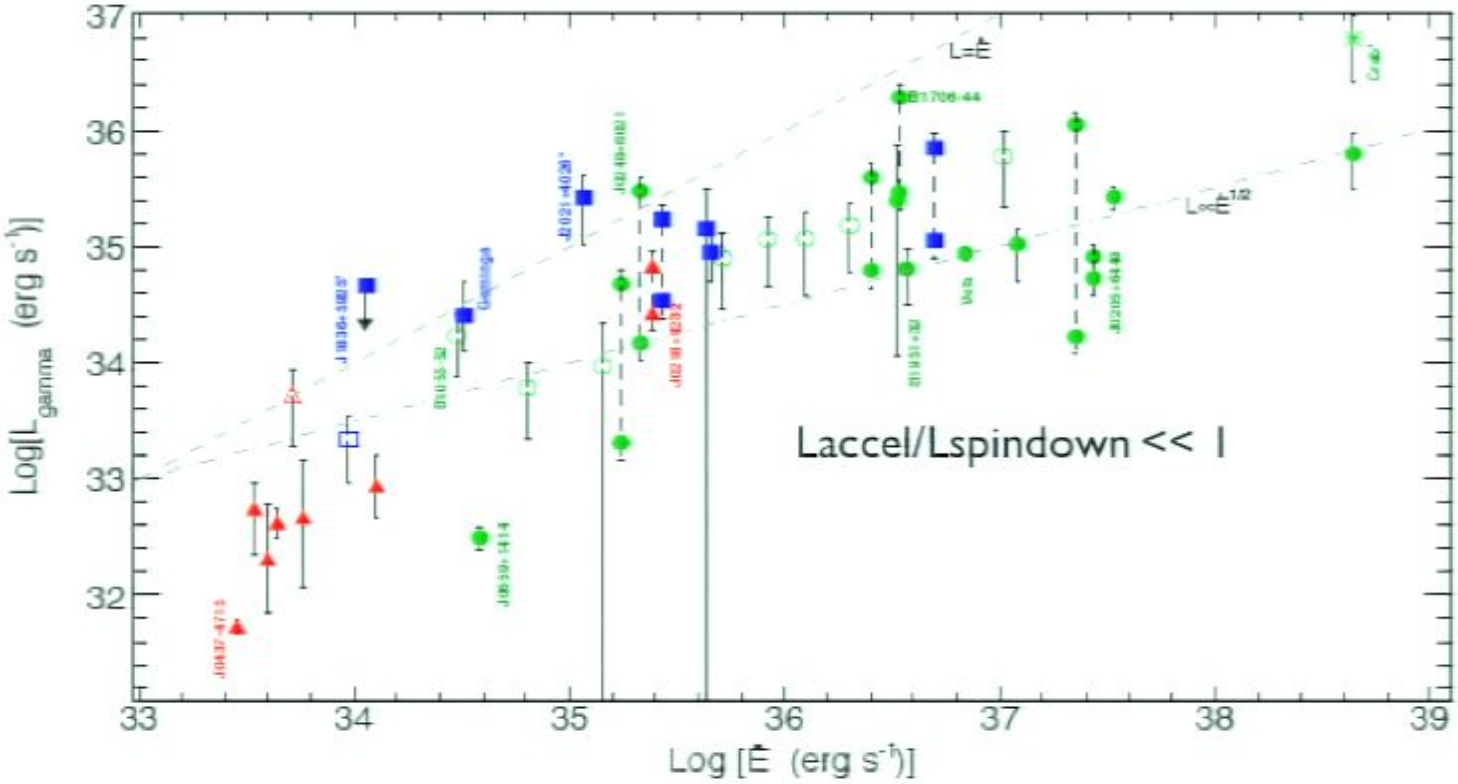

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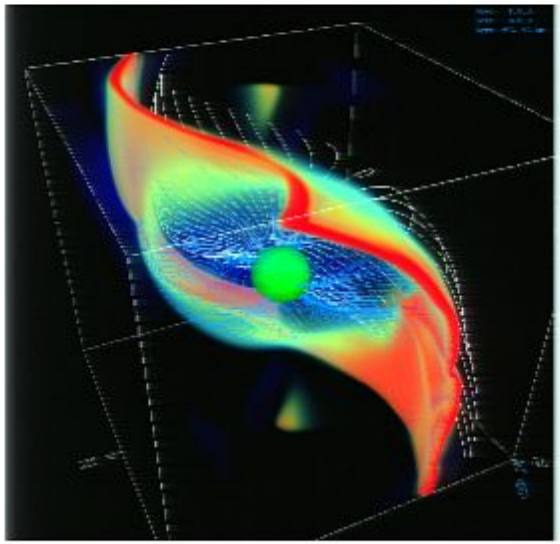

Electron beam goes down, ion beam up ($\Omega \bullet \mu > 0$);
Positron beam goes down, electron beam up ($\Omega \bullet \mu < 0$)

Possible consequences (SPECULATIONS)

Gamma Radiation from beams might be curvature if
ℓ_D is macroscopic

Radiation might be synchrotron:

Counterstreaming beams can be electromagnetically 2 stream unstable
(narrow channel enforces transverse wave structure,
relativistic 2 stream automatically EM)
$\omega_p \sim \omega_{cyclotron}$ in outer magnetosphere, waves can excite Larmor gyration, synchrotron emission
If waves can escape plasma (fast modes), coherent emission:
X-ray – giant pulse correlation, etc., etc.
Synchrotron gamma rays?
Outer magnetosphere pair creation? Inverse Compton emission?

Conversion of interesting plasma model to testable astrophysical model in progress (slowly)

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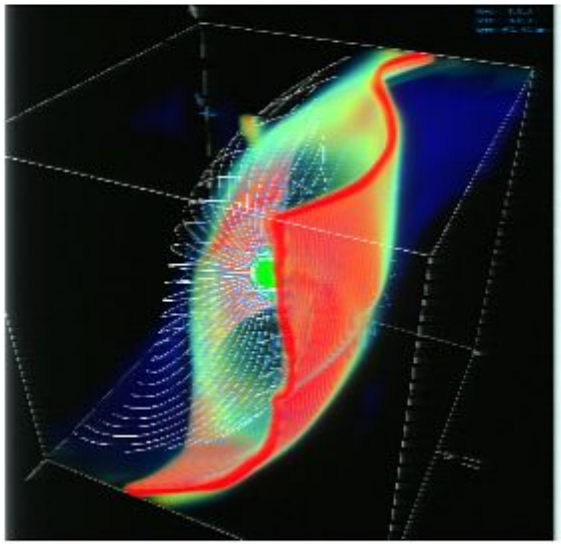

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