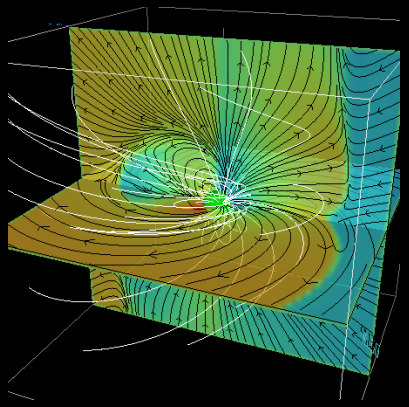
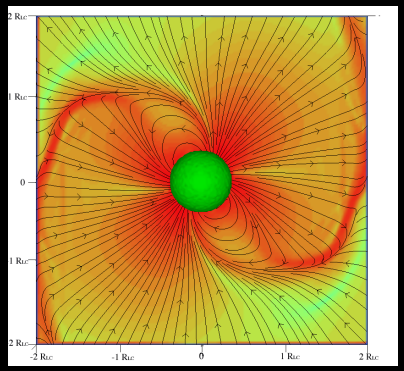
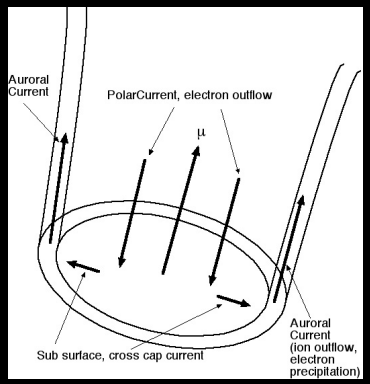
Auroral Acceleration in Pulsars And Gamma Rays

Jonathan Arons
University of California, Berkeley and Santa Cruz



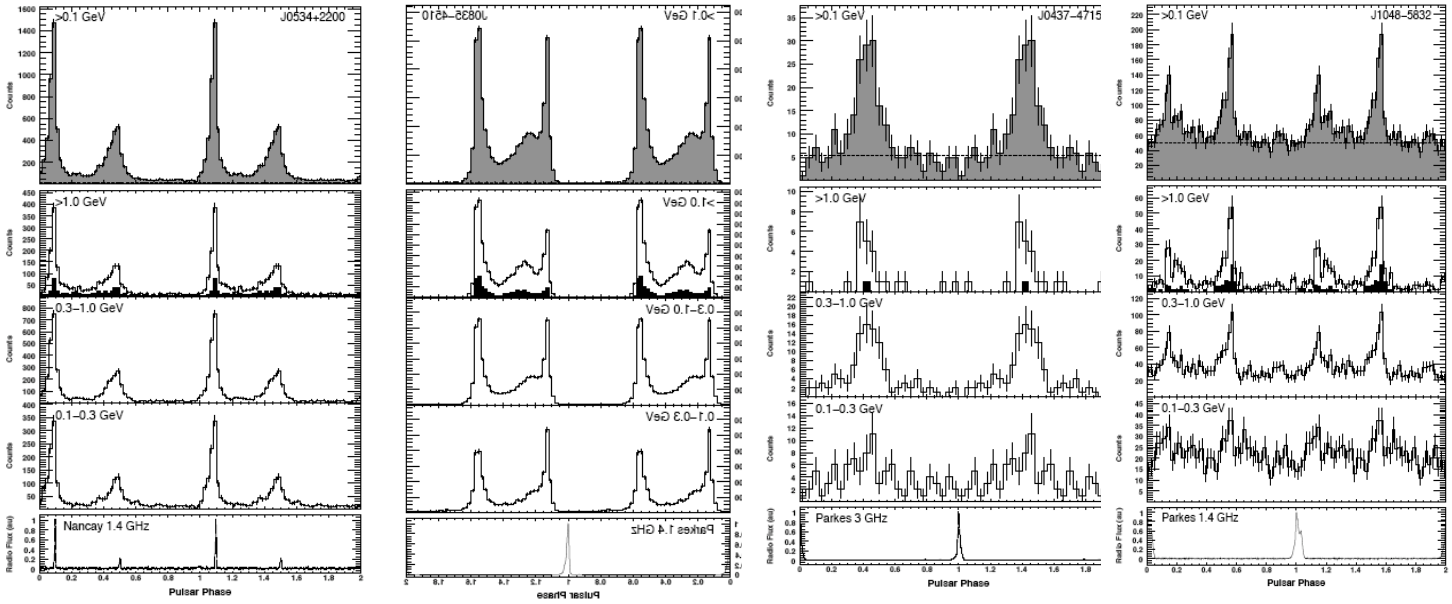




Collaborators: A. Spitkovsky, A. Timokhin

Interlude: Pulsed Gamma Rays⇒Tevatrons

Crab P=33msec | Vela, P=89msec | J0437, 5.76msec | J1048, 124msec

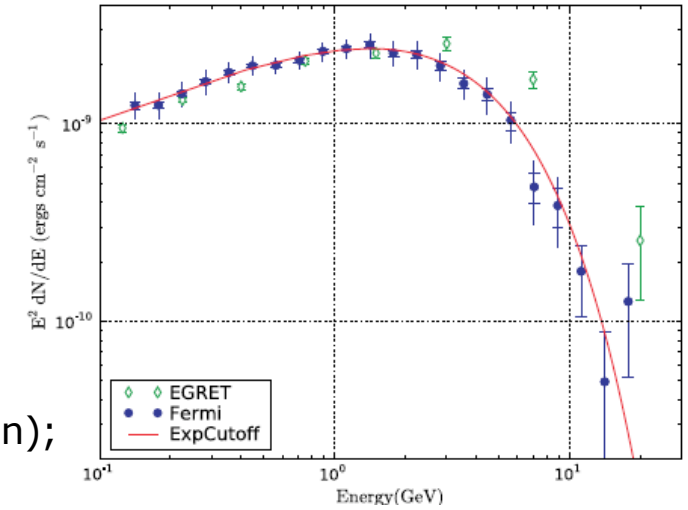


A Few of the Gamma Pulsars (120 in current FERMI-LAT list)

Most are double peaked, wide separation in pulse phase,
Radio pulse leads two peaked gamma pulse
(B sweepback,…); bridge spectrum softer

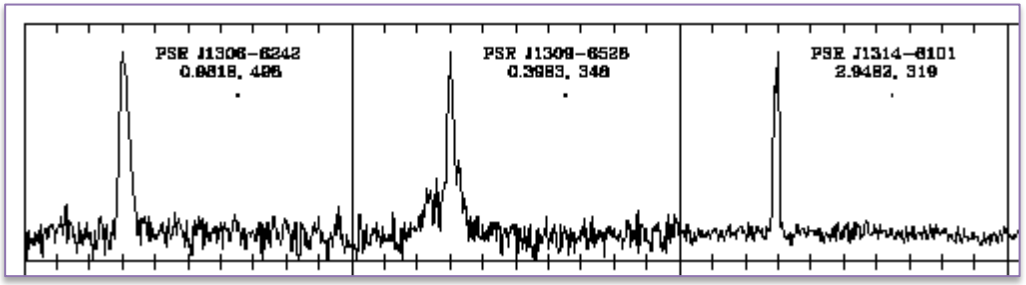
Particle energy E > photon energy $\mathcal{E}$: Gevatron

Radiation mechanism(s): E ≥ 10-10^4ε (curvature, synchrotron);
E ≥ ε (inverse Compton)



Pulse Phase Averaged Vela Spectrum

Pulsed Emission – Pulsar Gevatrons ⟶Tevatrons

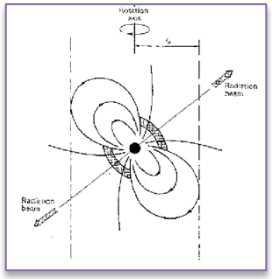


Galactic sources:
D ~ kilo-parsec

Pulsars = "Pulsating Radio Sources"

0.0017 s < P < 8.5 s
Keep accurate time (15 sf)
dP/dt > 0 - clock slows down

Lighthouse Model: Plasma and Radio Radiation beam Along polar B



Radio Beam Pol, Morphology:
emission from Low alt ~ dipole

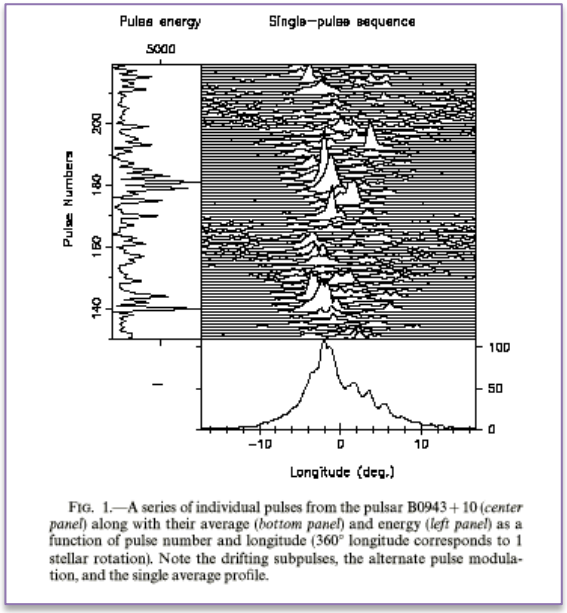


FIG. 1.—A series of individual pulses from the pulsar B0943+10 (*center panel*) along with their average (*bottom panel*) and energy (*left panel*) as a function of pulse number and longitude (360° longitude corresponds to 1 stellar rotation). Note the drifting subpulses, the alternate pulse modulation, and the single average profile.

Energetics: $L_{radio} > 10^{28}$ erg/s~stellar coronae: stellar objects;
msec period -> neutron stars; stable periods (15 sig figs -> stellar rotation)
Energies, densities of emitting particles: ???

Pulsars have Dense Magnetopsheres: Pair Creation

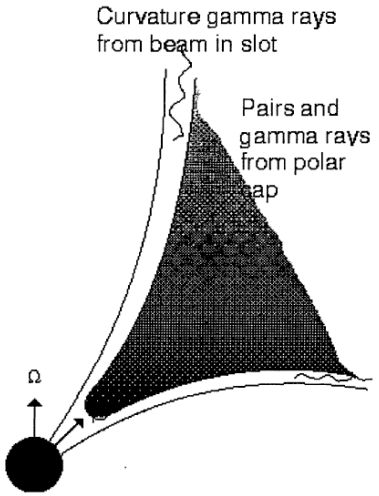
Pulsar Wind Nebulae: Nebular Synchrotron requires particle injection $\dot{N}$ >> Goldreich-Julian current $\dot{N}_{GJ}=c\Phi/e$

Solution: Pair Creation ($e^{\pm}$) inside magnetosphere creates dense, relativistic MHD wind, feeds nebulae

High Voltage Φ: TV up to 10^4 TV >> mc^2/e: relativistic particle acceleration along polar field lines? But Φ=voltage drop ACROSS B (MHD)

relativistic motion along B is accelerated as particle follows curved B, radiates incoherently ("curvature radiation")

$$P = \frac{e^2 c}{\rho_R^2}, \hbar\omega \approx \frac{\hbar c}{\rho_B}\gamma^4 = m_e c^2 \frac{\lambda\!\!\!^{-}_{Compton}}{\rho_B}\left(\frac{E}{mc^2}\right)^4 \sim GeV, E \sim TeV$$



Pulsed gamma rays observed, ~120 gamma PSR to date in FERMI observations – for low altitude?

Pair creation physics: $\gamma_{curvature}$ (B) $\longrightarrow e^{\pm}$

Optical Depth > 1 for one photon Pair Creation in B requires

$\Delta\Phi_{\parallel} \geq 10^{12}$ Volts $\leftrightarrow$ radio death valley -

radio emission requires pairs?

Gamma emission models also need pairs (?)

Formation of Electric Currents need pairs

Model invokes large $E_{\parallel}$ at low altitude – modern model (AT & JA) has strongly time dependent discharges on return current field

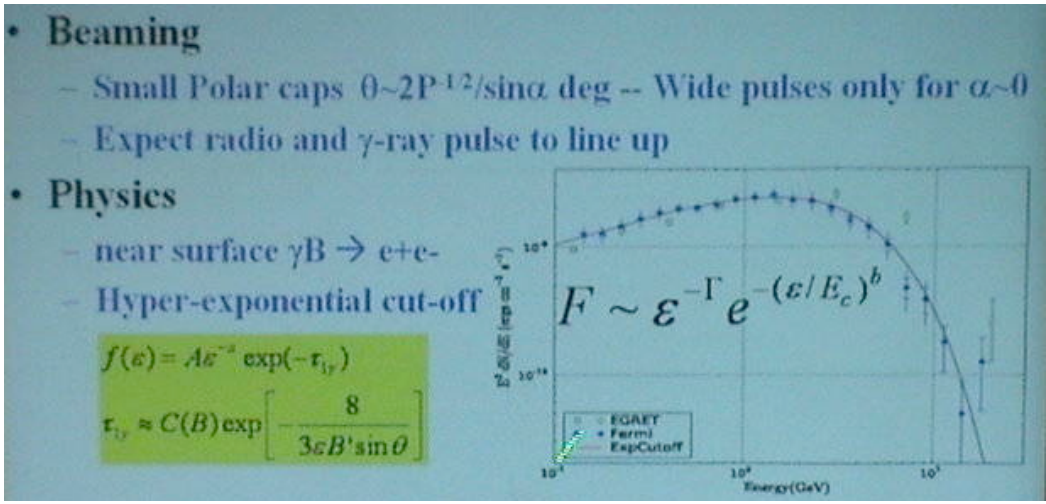
Lighthouse Models: Gamma Rays Beamed from Polar Flux Bundle

Pulsed Gamma Rays not from pair low altitude pair creation

Gamma Rays Not from Polar Cap:
higher energy photons absorbed with super-exponential cutoff:

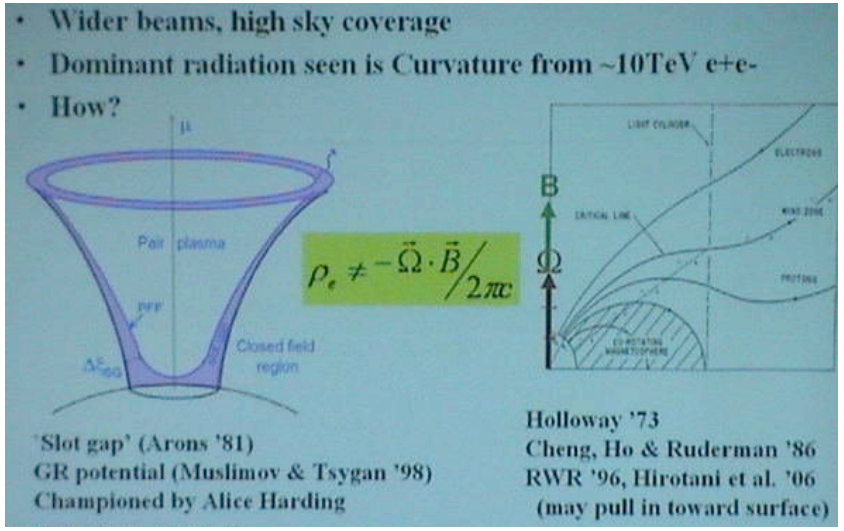
$\gamma + B \longrightarrow e^+ + e^-$ optical depth

$$\tau \propto \exp\left(-\frac{m_{\pm} c^2}{\varepsilon}\frac{m_{\pm}^2 c^3}{\hbar e B}\frac{1}{\angle(B,k)}\right)$$



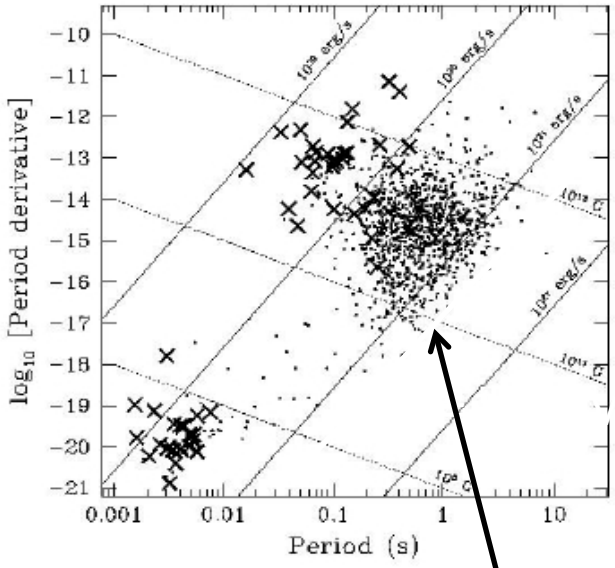
Super exponential cutoff rejected:
b > 1 rejected at 16 sigma

Beamed from high altitude more promising – tradition has γ from electrons/positrons accelerated in quasi-vacuum "gaps" inserted into magnetic field model by hand/flow leaves spaces where quasi-vacuum $E_{\parallel}$ can exist



Follow the Energy: Spindown

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



$\Phi = 10^{12}$ V: "death valley"

Measure Ω to ~15 significant figures

Rotating NS **Model**: angular velocity $\Omega = 2\pi / P$, moment of inertia $I \approx 10^{45}$ cgs

$$\Omega = 2\pi / P$$

$$E_R = \frac{1}{2} I\Omega^2 = 10^{44.5} - 10^{51}\text{erg (up to } 10^{52.7} \text{ ergs possible, } P_{min} \approx 1\text{msec)}$$

$$\dot{E}_R = -\frac{1}{2} I\Omega\dot{\Omega} = \frac{4\pi^2 I\dot{P}}{P^3} = 10^{31} - 10^{38.7} \text{ erg / s } (10^{50} \text{ possible}) : \textbf{spindown}$$

Vacuum Dipole model : Bar Magnet Rotating in Vacuum

Emits magnetic dipole adiation at frequency $\Omega / 2\pi$

$$\text{Energy Loss : } \dot{E}_R = \frac{2}{3}\frac{\mu^2\Omega^4}{c^3}\sin^2 i,\ i = \angle(\boldsymbol{\mu}, \boldsymbol{\Omega})$$

All relativistic spindown models ($B^2 / 4\pi \gg$ all other energies, inclu rest)

$$\dot{E}_R = \frac{\mu^2\Omega^4}{c^3} f(i) \Rightarrow \dot{\Omega} = -\frac{\mu^2\Omega^3}{Ic^3} f(i) = -K\,\Omega^n$$

vacuum : n = 3 if I, μ, i = constant

n observable (6 pulsars) : $1.4 \le n \le 2.8$

$I \neq$ constant?; $\mu \neq$ constant?; $i \neq$ constant;

magnetosphere has plasma with dissipation ("reconnection")?

Co - Rotating Magnetosphere : $\mathbf{E} = -\frac{1}{c}(\boldsymbol{\Omega} \times \mathbf{r}) \times \mathbf{B} \Rightarrow$

$$\text{Voltage : } \Phi = \sqrt{\frac{\dot{E}_R}{c}} = \frac{\mu\Omega^2}{c^2} = \frac{\mu}{R_L^2} \sim 10^{12} - 10^{16.4} \text{ Volts}$$

μ = dipole moment, $10^{26} - 10^{33}$ cgs,

$$B^{pole}_{dipole} = 10^8 - 10^{15} \text{ Gauss}$$

$$R_L = R_{Alfven} = \frac{c}{\Omega} = 48{,}000P \text{ km}$$

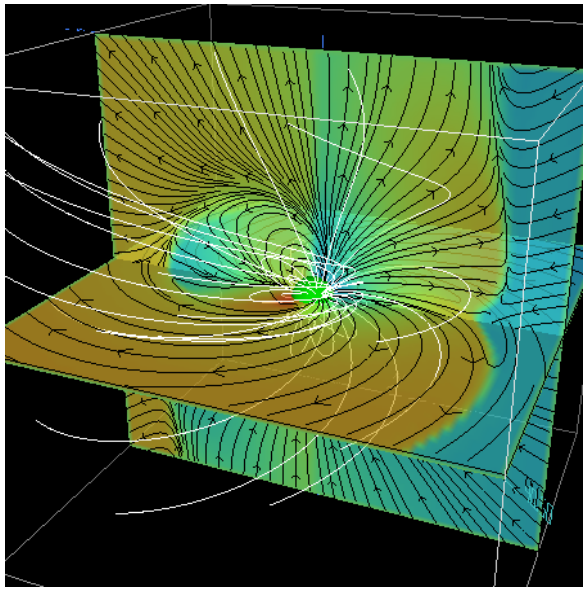
$$\dot{E}_R = c\Phi^2 = I_R\Phi$$

$$I_R = c\Phi$$

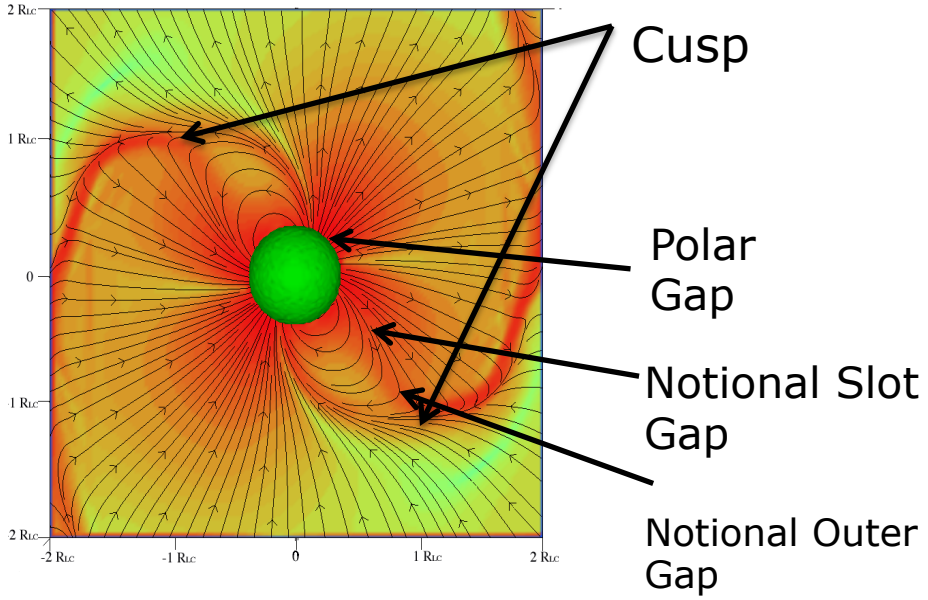
$$\frac{I_R}{e} = 10^{30} - 10^{34.3}\ s^{-1} = \dot{N}_R$$

Aligned/Oblique Rotators structurally similar, J_{cond} + J_{disp} (=0 in aligned)

Spitkovsky's (2006) oblique force free rotator (+ Kalapotharakos 09)



Field Lines (with real open flux)



Total Current

Gaps = local quasi- vacuum $E_{||}$ zones inserted by hand to model gamma ray emission and pair creation

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

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

Acceleration along B ➔ beamed photons, rotation ➔ lighthouse

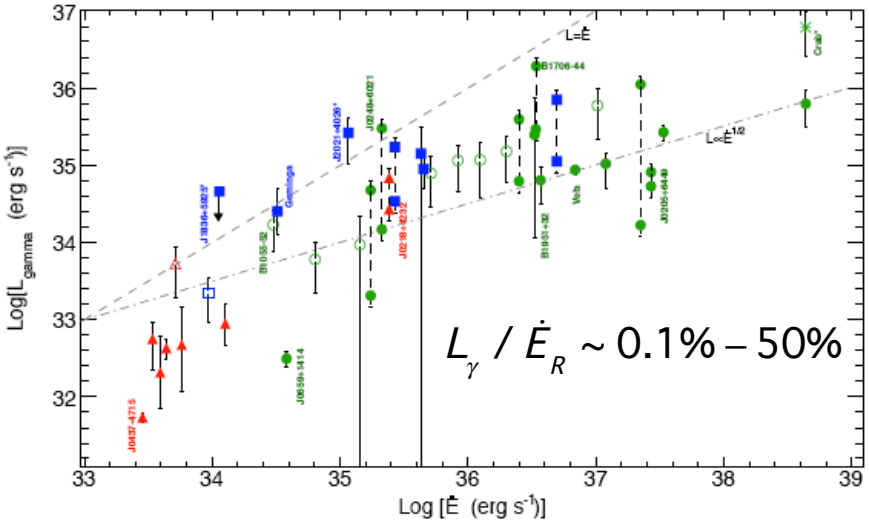
Force Free model has no gaps, no parallel accelerator

Gap Models with vacuum $E_{||}$ have adjustable knobs (particle dist)

Accelerated Beam Models With Force Free Magnetospheric Structure (No Gaps)

Magnetosphere sets time average (over 1 rotation) $J_{\|}$ to be the Force Free Current: Dissipation/HF radiation energy loss small compared to rotational energy loss almost all PSR, gamma & otherwise:

Gamma Ray Efficiency (LAT)



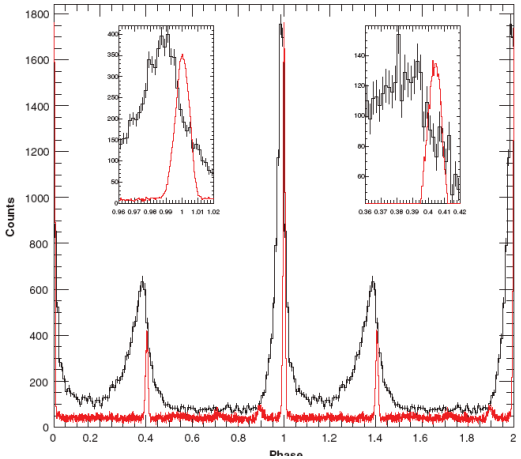
Assume gamma rays come from particles in parallel current accelerated in parallel electric field; acceleration radiation reaction limited

$$L_\gamma = I_R \Delta\Phi_{\|} = c\Phi\Delta\Phi_{\|} \propto \sqrt{\dot{E}_R}$$

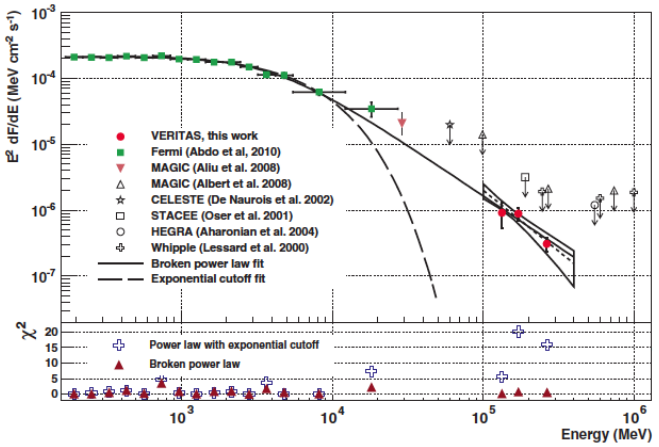
if $\Delta\Phi_{\|}$ ~ constant over range of
- a natural consequence of pair creation in the current flow, pairs poison $E_{\|}$ (JA 1996,Harding)

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

Crab PSR pulsed Gamma Rays: new challenge



Fermi LAT ε > 100 MeV pulse shape



Fermi LAT: fit with exponential cutoff
ε_c ~ 2-3 GeV-curvature rad in gaps could work
particle source models (pairs) fail – high ε excess?

VERITAS: pulsed emission
up to 300 GeV, fit by broken power law
(two peaks? Inverse Compton? Curvature hard if E<B

Curvature Emission: Synchrotron
of pairs sliding along B,
Orbit Radius of Curvature =
Magnetic Field's $\rho_B = fR_L$
particles accel along B in $E_{\|}$
standard radiation physics
in gap models since mid 90s

300 GeV photons have optical depth to ∞ less than unity for emission at $r > 0.2R_L$ ($32R_*$)!!

$$r_1 = R_L\left(\frac{243}{4096}\frac{B(R_L)}{4.4\times10^{13}\mathrm{G}}\ln\Lambda\right)^{2/5}\left(\frac{\varepsilon}{m_e c^2}\right)^{2/5} = 0.22R_L\left(\frac{\ln\Lambda}{30}\right)^{2/5}\left(\frac{\varepsilon}{300\ \mathrm{GeV}}\right)^{2/5}$$

$$\Lambda = 0.00987\alpha_F\frac{R_L}{\lambda_C}\frac{B(R_L)}{4.4\times10^{13}\mathrm{G}}\left(\frac{R_L}{r_1}\right)^4,\ \lambda_C = \text{Compton Wavelength}$$

Crab: $B(R_L)$ = (dipole) = 0.9 MGauss, $R_L = 1590$ km

Radiation Reaction limited Acceleration with Curvature Emission

$ecB\frac{E_{\parallel}}{B} = \frac{2}{3}\frac{e^2}{c}\gamma^4\left(\frac{c}{fR_L}\right)^2$; spectrum exponentially cut off $\varepsilon > \varepsilon_c = \frac{3}{2}\frac{\hbar c}{fR_L}\gamma^3$

$\Rightarrow \varepsilon_c = 22\left(\frac{E_{\parallel}}{B}\right)^{3/4}\sqrt{f}$ GeV, $E = \gamma m_{\pm}c^2 = 48\left(\frac{E_{\parallel}}{B}\right)^{1/4}\sqrt{f}$ TeV

Veritas not exponentially cut off $\Rightarrow$ $(E_{\parallel}/B)^{3/4}\sqrt{f} > 6$

$f > 1, E_{\parallel}/B > 1$: possible in reconnection region at cusp,

inner wind current sheet

Or, radiation mechanism not curvature: Inverse Compton from

Lyutikov & Otte will emerge soon (has been on arXiv for a year)

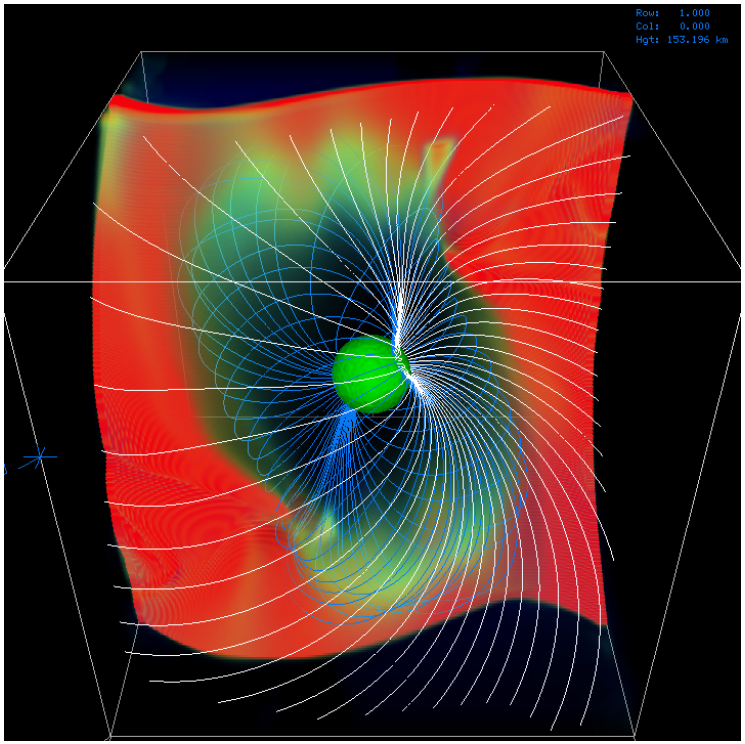
Or synchrotron? - below

Pulsed Gamma Rays Probe transition from dipole magnetosphere to the wind, diagnoses spindown physics = basic machine

Pulsed Gamma Ray Emission from Current Sheets?

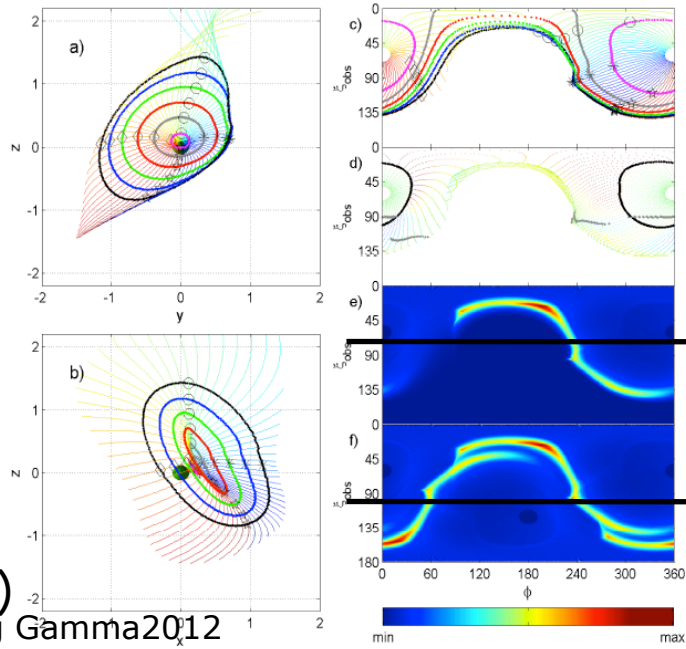
Electrodynamics: Boundary layer between open and closed field lines carries an intense, thin sheet of current – current sheet into wind

Particle inertia, radiation reaction drag supports $E_{\parallel}$ parallel to B (?)



Acceleration in current sheet rotates wide open cone of emission across sky:

geometry from force-free model ($E_{\parallel} = 0$) by Bai & Spitkovsky (2010)

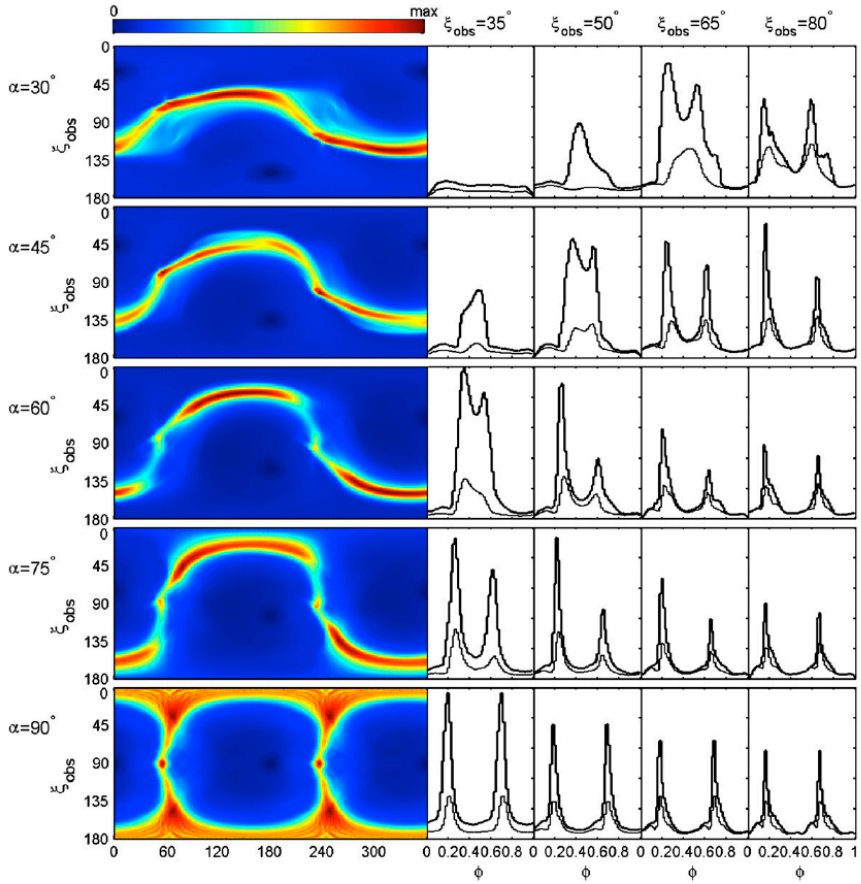


Sky maps

Return current flows in separatrix current sheet & neighboring layer ("Separatrix Layer" = emission zone?)

Light Curves from Separatrix Layer Emission (Bai & Spitkovsky 2010)

Phenomenological emission model – paint separatrix layer with assigned emissivity (e.g. constant along B), beamed along particle trajectories in force free fields (particles have E x B drift + parallel slide along B, v < c)



Peaks are caustics – photons beamed along orbits from separate sites but times of flight and beaming directions conspire to have many arrive together – strong through LC, field lines become straight

Simple beaming model = good account of light curves

Physical emission needs accelerator like Aurora?

$\alpha = \angle(\Omega, \mu)$; ϕ = rotation phase; ζ_{obs} = sky latitude, $\xi_{obs} = \angle(\Omega,$ observer LOS)

Implications of Force Free Rotator Model for Emission:

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

- Electric current magnitude and sign - return currents both spatially distributed and in thin sheet - if dissipation regions ("gaps") have parallel potential drops small compared to total magnetospheric voltage,

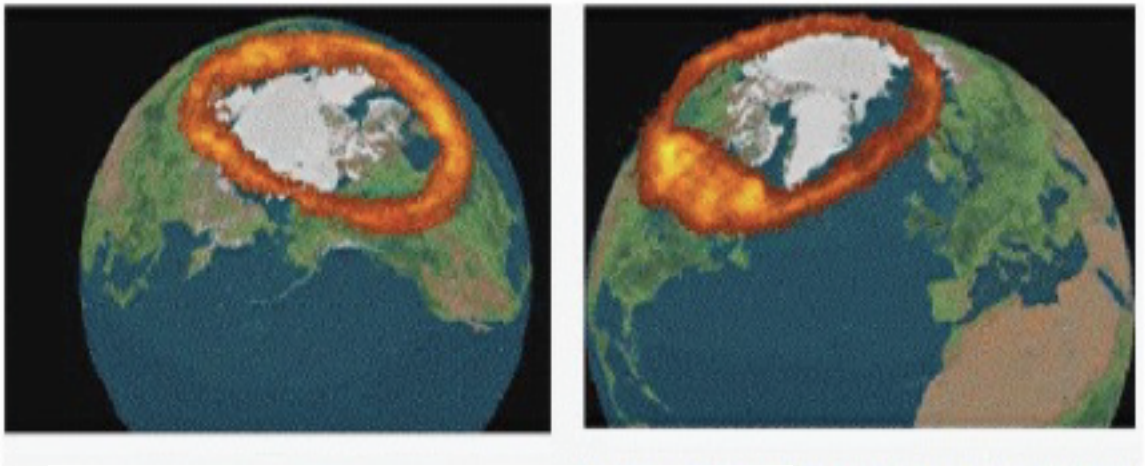
$$\Phi = \sqrt{\frac{\dot{E}_R}{c}} = 4\times 10^{16}\ \text{Volts}\left(\frac{\dot{E}_R}{10^{38.7}\ \text{erg/s}}\right)^{1/2} \propto L_{radio}, L_{\gamma}(\text{large } \Phi)$$

electric current in and outside gaps is known, averaged on magnetosphere transit time (~P/π) - electric currents of gaps/emission sites must fit into magnetospheric circuit

Location of return current layer determined - realistic site/physics for outer magnetosphere beaming models of high energy emission – Bai & AS – heating/non-bulk flow particle accel/radiation requires non-EM load

- **Replace gaps by nonideal physics of parallel E (some akin to well tested in solar system for non-relativistic magnetospheres), generalized to relativistic conditions, with pair creation as needed**

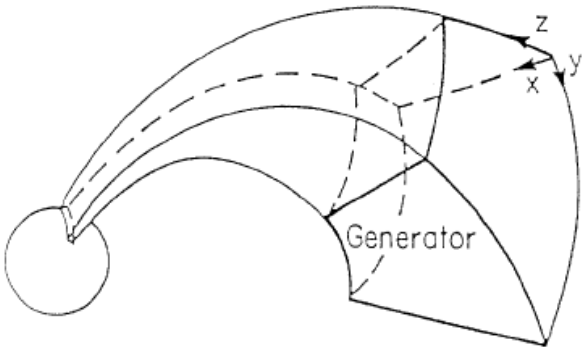
Auroral Model-a radiating sheet accelerator in globally FF



Earth Auroral oval from space – current flow along B driven by solar wind Mechanical stress coupled t magnetosphere by reconnection

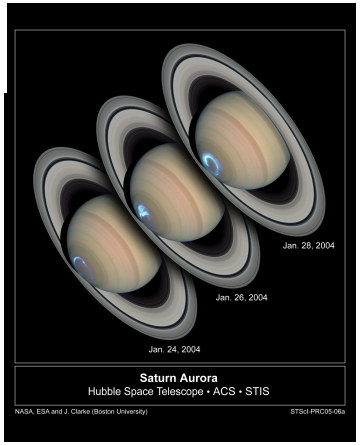
Atmospheric molecular lines stimulated by accelerated, precipitating e^- beam (thin arcs) often have

$$\Delta\Phi_{\parallel} \leq \Phi_{magnetosphere}(\text{solar wind})$$

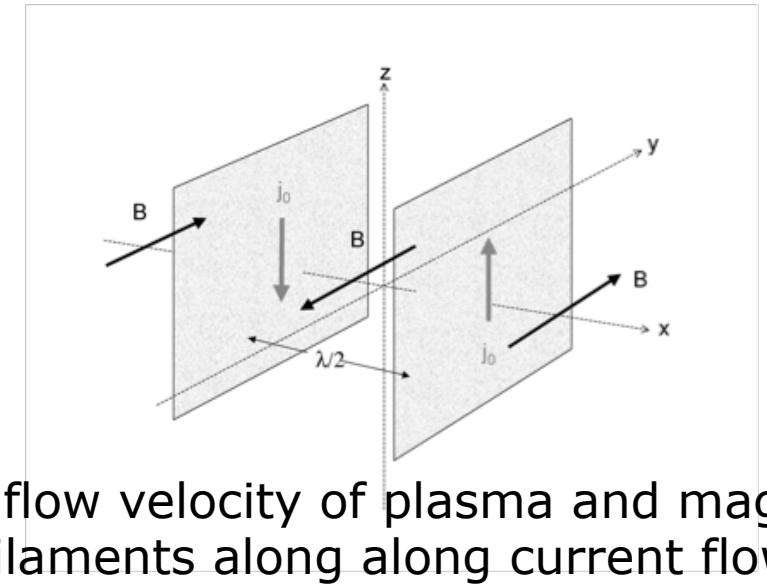


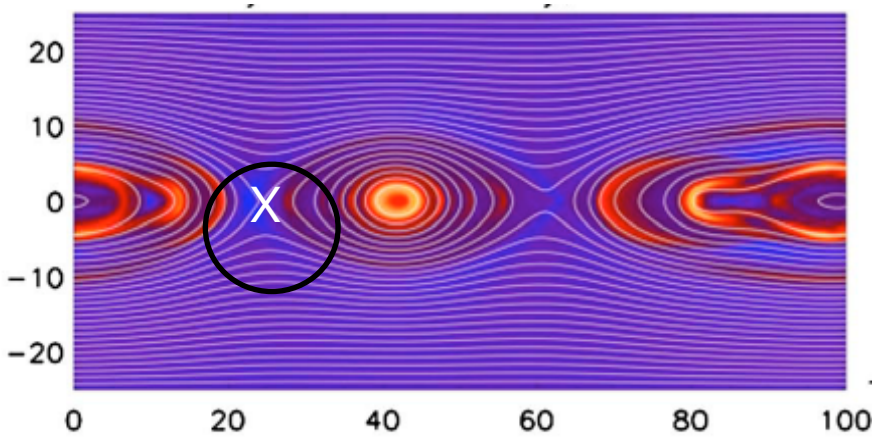
Density >>> GJ:
No vacuum gaps needed to have strong $E_{\parallel}$

Jupiter, Saturn similar



Spontaneous Tearing/Reconnection at Cusp: Current Sheet Tearing





Inflow velocity of plasma and magnetic flux into X-line & O regions (filaments along along current flow lines) is rapid

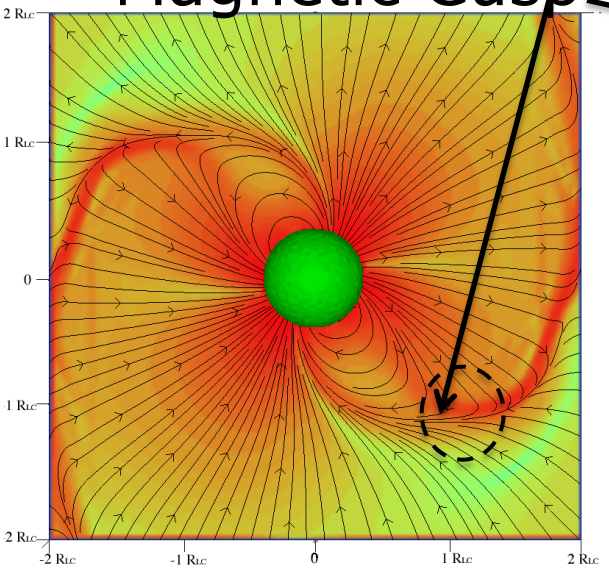
$$\mathbf{v}_{\text{recon}} = \alpha_r \mathbf{v}_A \sim 0.1 c \beta_A$$

Model (JA,relativistic pairs – reconn E_z from Ohm's law with viscosity replacing resistivity):

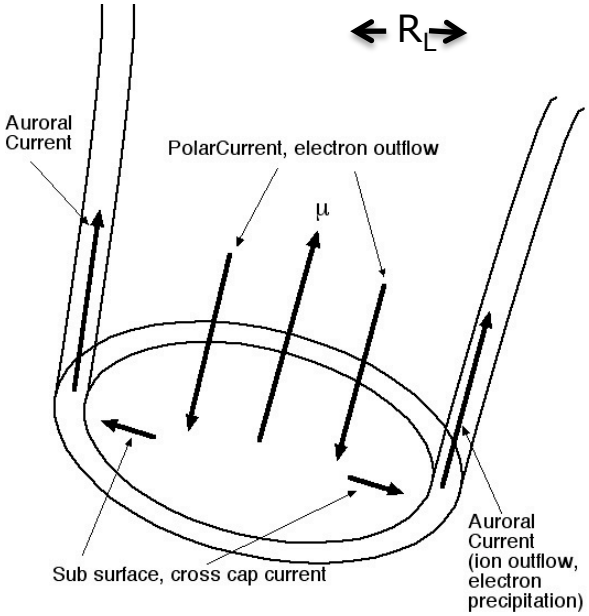
$E_{rec} = \frac{1}{en}\frac{\partial}{\partial z}\left(-\frac{nT}{2\omega_c}\frac{\partial u_x}{\partial x}\right)$, particle bounce frequency (bounce inside diffusion region around x line, trapped by stripe B outside current sheet, $\omega_c = eB/mc\gamma, u_x = p_x/mc$ - from Vlasov hierarchy, truncated with no heat flux), + mass & momntum conservation.

$v_{rec}=cE_{rec}/B_{stripe}$ similar to Hoshino results (not yet compared to Cerruti et al)

Magnetic Cusp

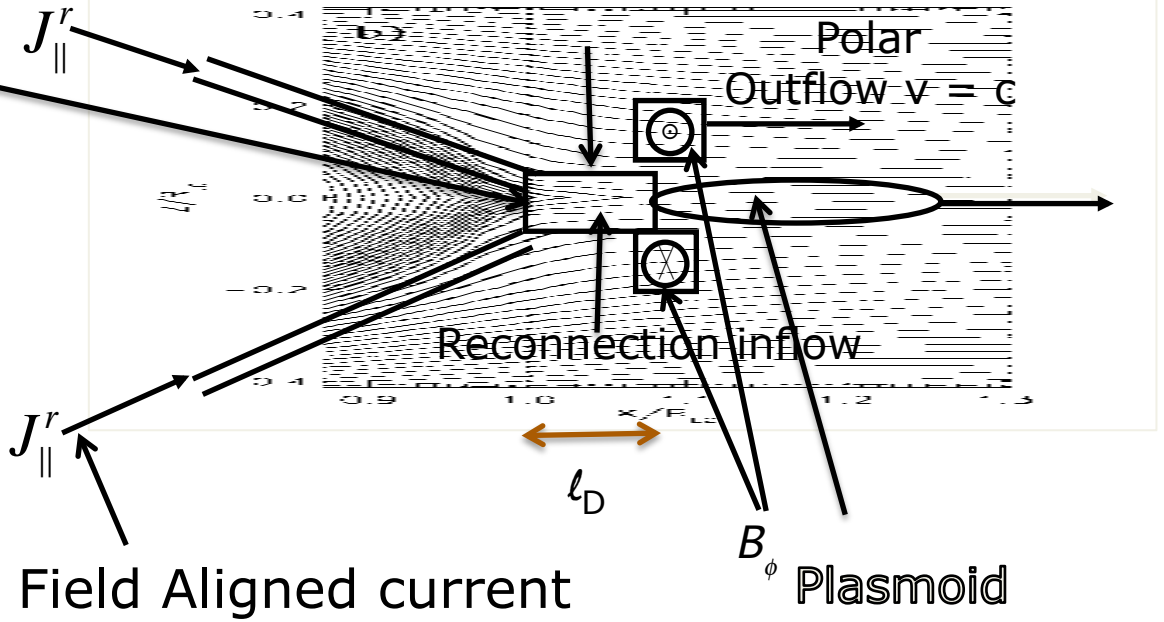


$\leftarrow R_L \rightarrow$



Polar Cap

Acute rotator $\Omega \cdot \mu > 0$



Field Aligned current precipitating electrons + ions from surface

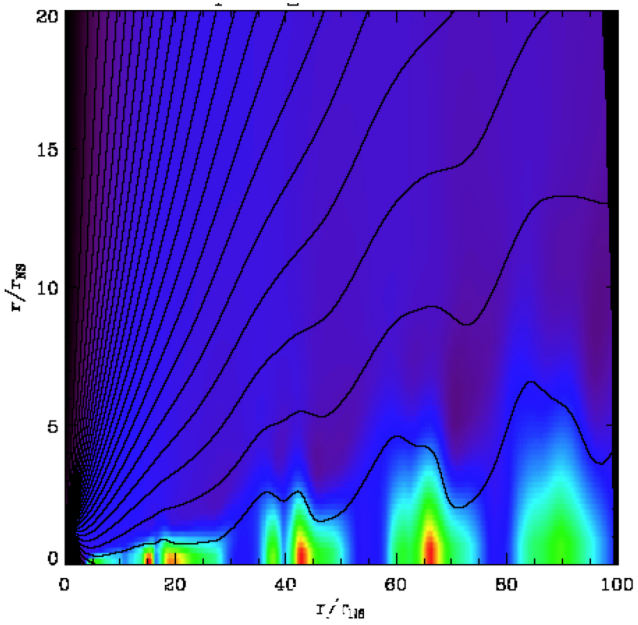
Reconnection E (radial in geometry shown) sustained by off diagonal pressure tensor ("collisionless viscosity" – relativistic reconnection simulations)

$$E + \frac{v}{c} \times B = \frac{e}{mw} \nabla \cdot \vec{P} + \frac{4\pi e}{mwc} J \times B + \frac{1}{\omega_p^2} \left\{ \frac{\partial}{\partial t} \left(\gamma J \right) + \nabla \cdot \left[c\gamma^2 \left(\beta J + J \beta \right) \right] \right\} \quad (Ohm)$$

w=relativistic enthalpy; anomalous resistivity neglected

Obtuse geometry $(\Omega \cdot \mu < 0)$ has precipitating positrons , electron outflow

Prospect: Reconnection/Return j



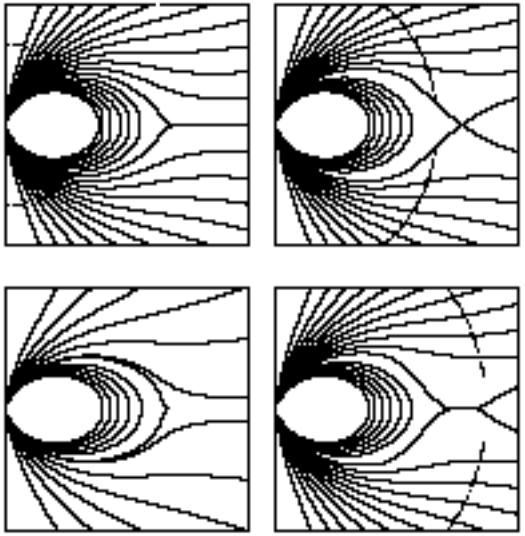
Bucciantini et al 2006
relativistic MHD

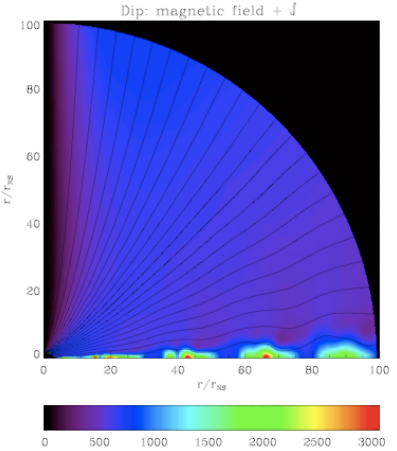
Sporadic X-Point, Plasmoid formation *occurs continuously*

Pairs all come from pole, on open field lines

Sporadic reconnection moves plasma across separatrix

non-corotation, time variable E at all times

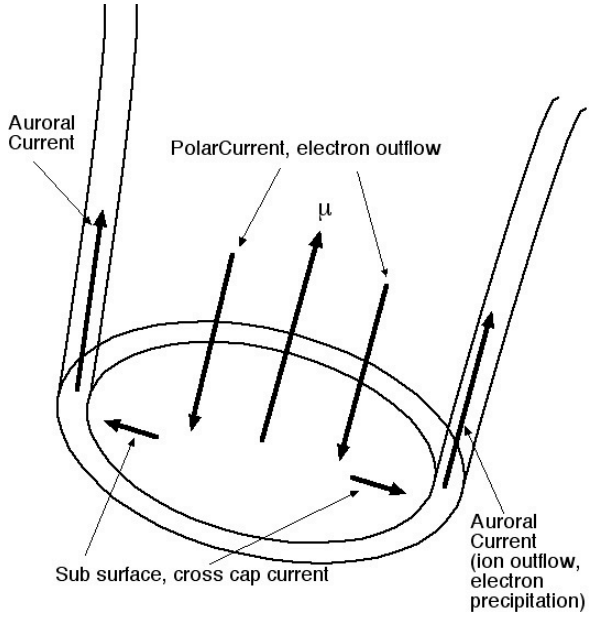


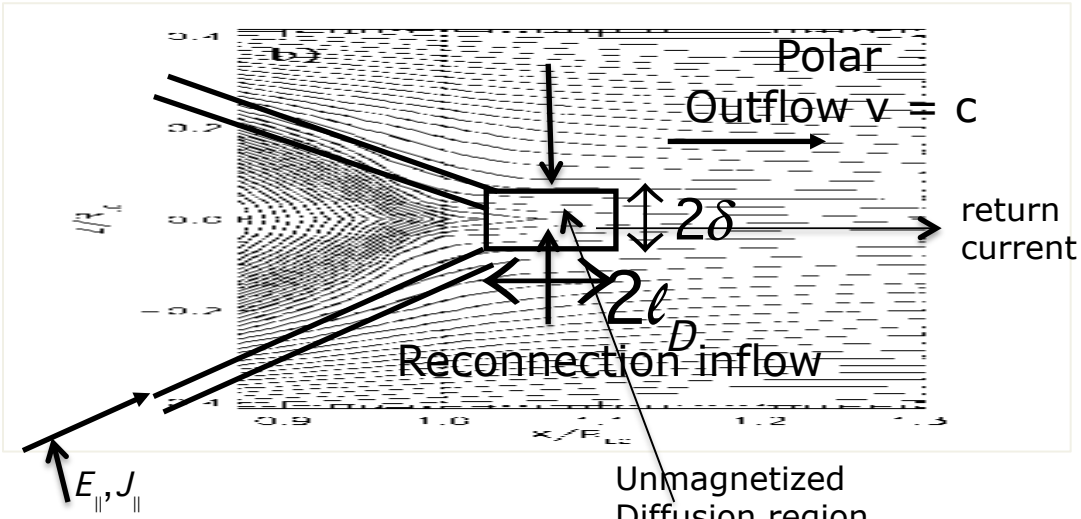


- Plasma, j flow to star in thin separatrix layer dynamics in $E_{\parallel}$ standing Kinetic Alfven wave boundary layer

AURORAL ACCELERATION

- Kinetic Alfven wave $E_{\parallel}$ extracts ion return current
- Torque fluctuations, limit cycles built in (drifting subpulses)?

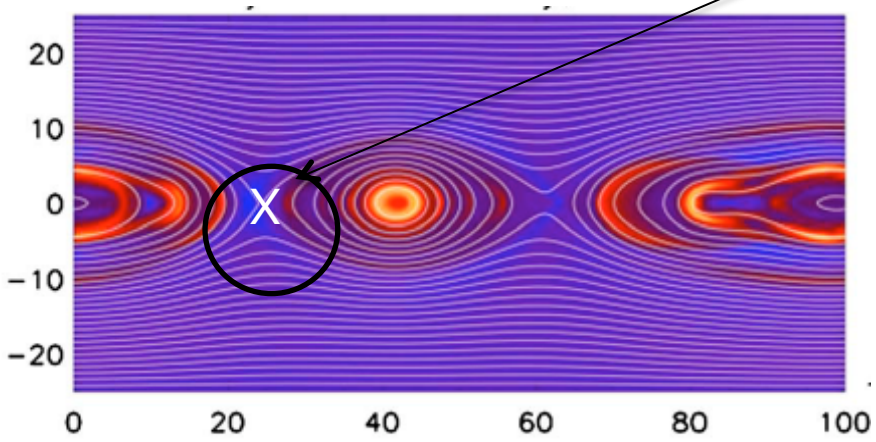




Electric return **channel current**

$\Omega \cdot \mu > 0$ Downward electron beam, upward ion beam

$\Omega \cdot \mu < 0$ Downward positron beam, upward electron beam



PIC reconnection simulation in pairs
Zenitani & Hesse (2½ D)

Acceleration in the Return Current Channel (including current sheet beyond the light cylinder)

Total value of current fixed by the force free magnetosphere

Precipitating Current = outflow from diffusion region

Current from surface set by charge neutrality at atmosphere

Channel current modeled as steady counterstreaming beams

Density of precipitating beam in the return current channel at r = R_L = density in diffusion region, set by reconnection inflow

$$n_{diff} = n_{wind}\frac{\delta}{L_\perp}, L_\perp = \text{density, B gradient scale} \approx R_L : B = B_{wind}\frac{z}{L_\perp} = \frac{\Phi}{R_L}\frac{z}{L_\perp}$$

Diffusion region unmagnetized, particles bounce freely inside: $r_{Larmor}(\delta) = \delta$

$$\Rightarrow \delta = \left(L_\perp \frac{mc^2\gamma_{bounce}}{eB_{wind}}\right)^{1/2}. \text{ Pressure balance: } n_{diff}mc^2\gamma_{bounce} = \frac{B^2}{8\pi} \Rightarrow$$

$$mc^2\gamma_{bounce} = T_{diff} = \frac{e\Phi}{\left(4\kappa_\pm\right)^{2/3}} \sim 340 \text{ GeV} \gg (mc^2\gamma_{thermal})_{wind}, \ \kappa_\pm = \text{pair multiplicity} \sim 10^7 \text{ (Crab)}$$

Viscosity in diffusion region (bounce motion exchanges momentum across flow) heats diffusion region plasma; JxB force ejects plasma Into current channel; radiation losses

Inertia of beams in the channel supports parallel E (standing kinetic Alfven wave) – "resistivity" = particle inertia – a load on the circuit

lower limit to accelerating voltage:

$$\Delta\Phi_{min} \approx -\frac{1}{8}\Phi\frac{R_*}{R_L}\left(\frac{c}{v_{reconnection}}\right)^{1/3}\frac{\delta}{R_L}\frac{\ell_D}{\delta}\cos[\angle(\Omega,\mu)] = -\frac{1}{8}\frac{\Phi}{(4\kappa_\pm)^{1/3}}\frac{R_*}{R_L}\left(\frac{c}{v_{reconnection}}\right)^{1/3}\frac{\ell_D}{\delta}\cos[\angle(\Omega,\mu)] \sim TV(Crab),$$

$\ell_D / \delta \sim$ a few (2D simulation, steady recon. model), δ~1-100 meters

V_{recon}/c ~0.1 (pair reconnection PIC simulations, model)

voltage drop ~ 1-10 TV, enough for GeV gamma ray emission by curvature radiation

possible pair creation through inverse Compton gamma emission from beams – counterstreaming beams might excite synchrotron gamma rays (EM 2-stream instability excites Larmor gyration)

Either inverse Compton or synchrotron might yield Veritas >100 GeV emission.

Conclusion: Force-Free Magnetosphere without gaps can accelerate

also, Alfven would be happy –Auroral beams were his favorites

(also thought neutron stars don't exist)