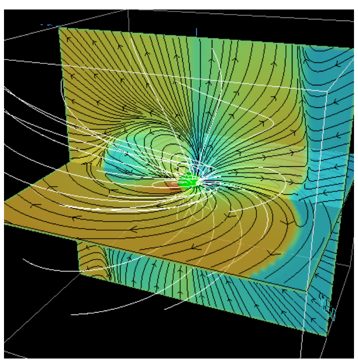
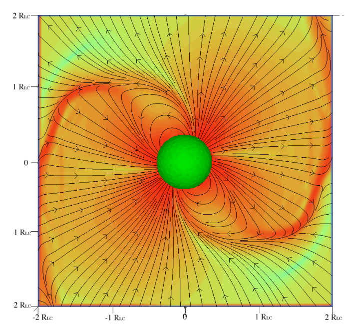
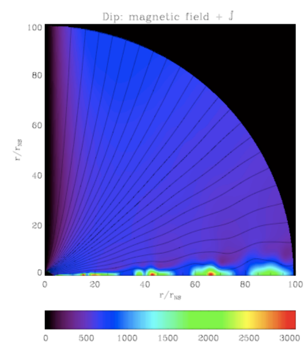
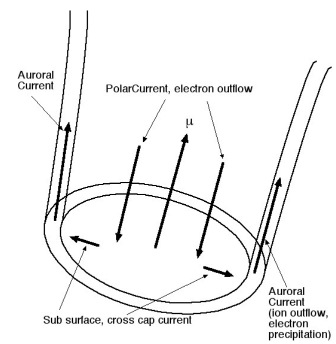
A Tale of Two Current Sheets*

Jonathan Arons
University of California, Berkeley





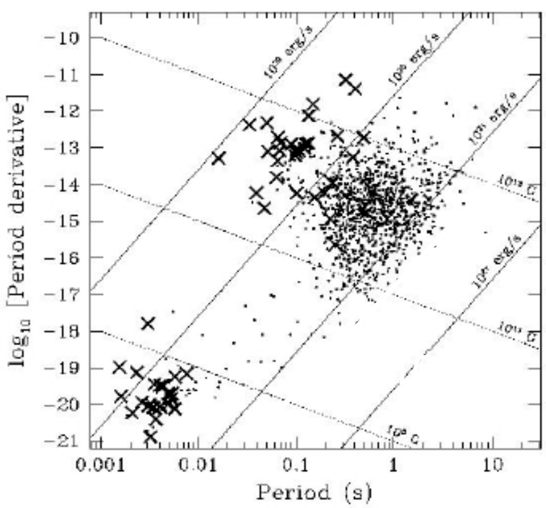




Collaborators: D. Alsop, E. Amato, D. Backer, P. Chang, **N. Bucciantini**, B. Gaensler, Y. Gallant, V. Kaspi, A.B. Langdon, C. Max, E. Quataert, **A. Spitkovsky**, M. Tavani, A. Timokhin

*With apologies to Charles Dickens

Follow the Energy: Spindown



Force Free Magnetosphere -

Spin down by EM torques

Magnetic energy dominant, non-vacuum, enough plasma for $E \cdot B = 0$

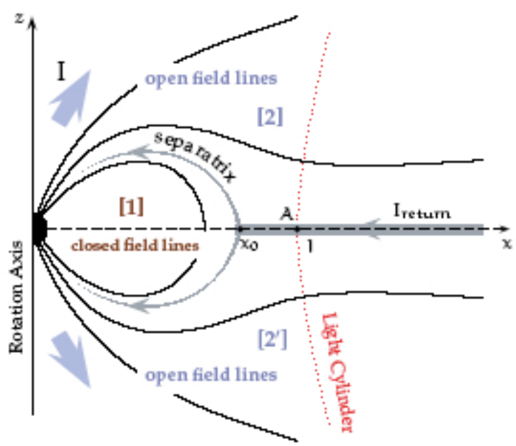
$$\dot{\Omega} = -K\Omega^n$$

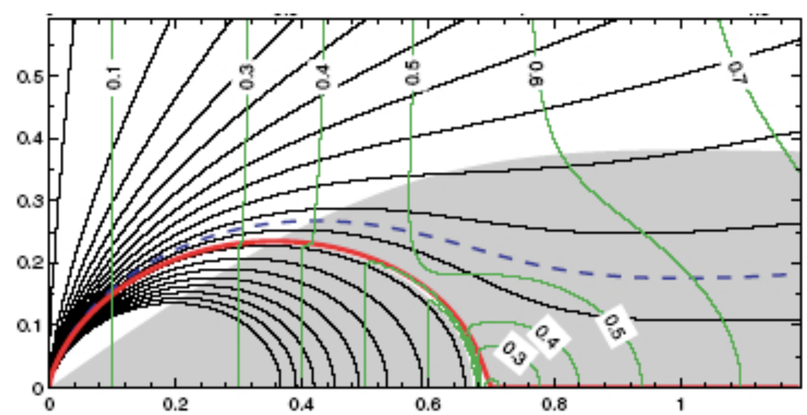
Contopoulos et al, Gruzinov, Timokhin: FF, aligned rotator, steady state: $R_Y \leq R_L$

Komissarov rel mhd, McKinney FF: aligned rotator, evolutionary

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)





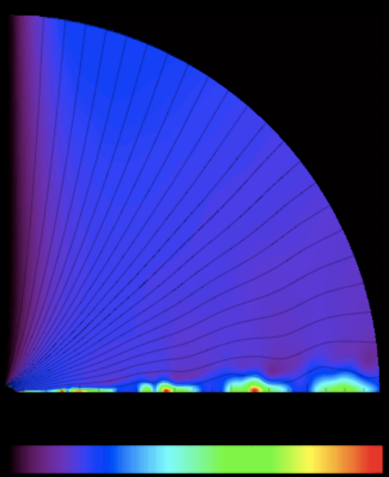
$$R_Y \leq R_L$$

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

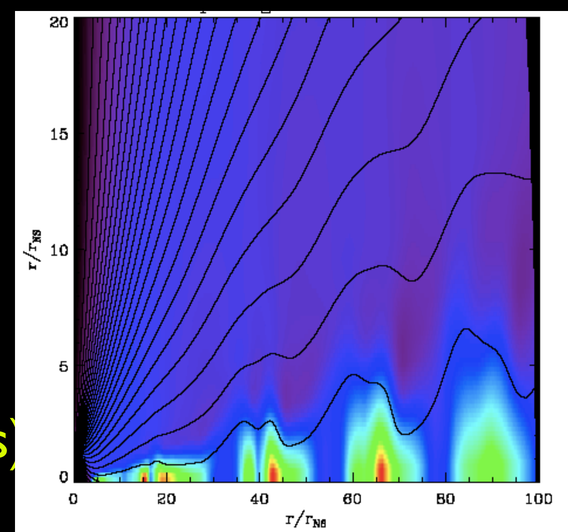
$R_Y/R_L < 1$ increases torque because of more open field lines and larger Poynting flux for same R_L:

Reconnection

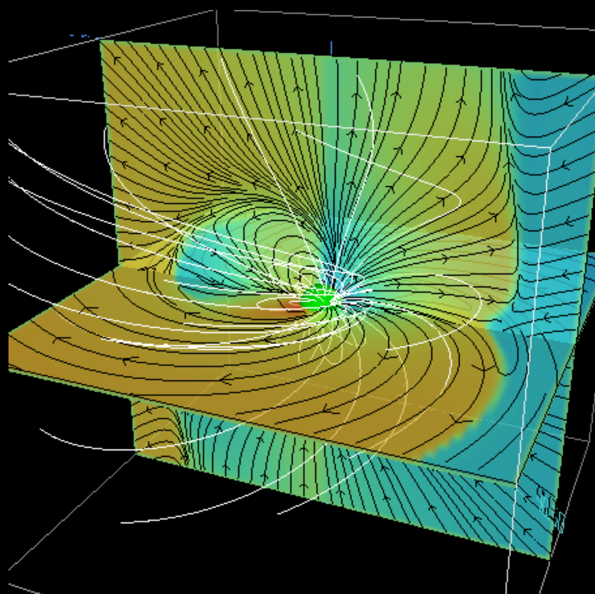
IF R_Y/R_L decreases with decreasing Ω, n<3; average R_Y/R_L must decrease on spindown timescale, since 2 < n < 3

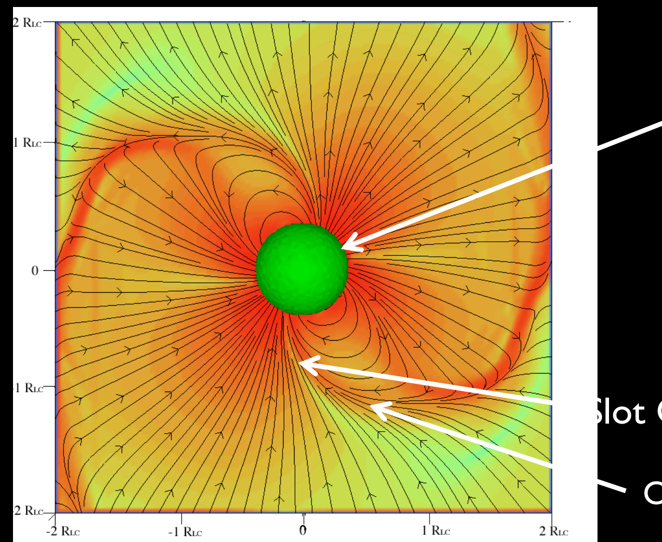


"Average" with respect to plasmoid emission, torque fluctuations ($\delta T/T$ ~ 10-30% ~ obs)



Spitkovsky's (2006) oblique force free rotator





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

Acceleration along B
➔ beamed photons,
rotation ➔ lighthouse

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

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

Force Free model has no gaps, no parallel accelerator

Implications 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 (proportion depends on obliquity) - if current layers ("gaps") have parallel potential drops small compared to total magnetospheric voltage,

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

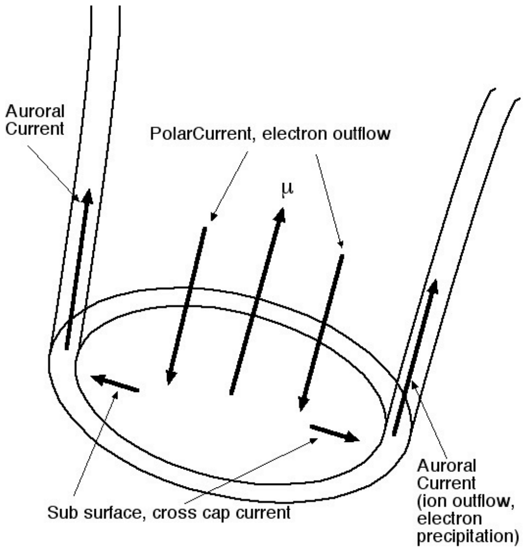
electric current in and outside gaps is known, averaged on magnetosphere transit time (~P/π), to lowest order in $L_{accel}/L_{spindown}$

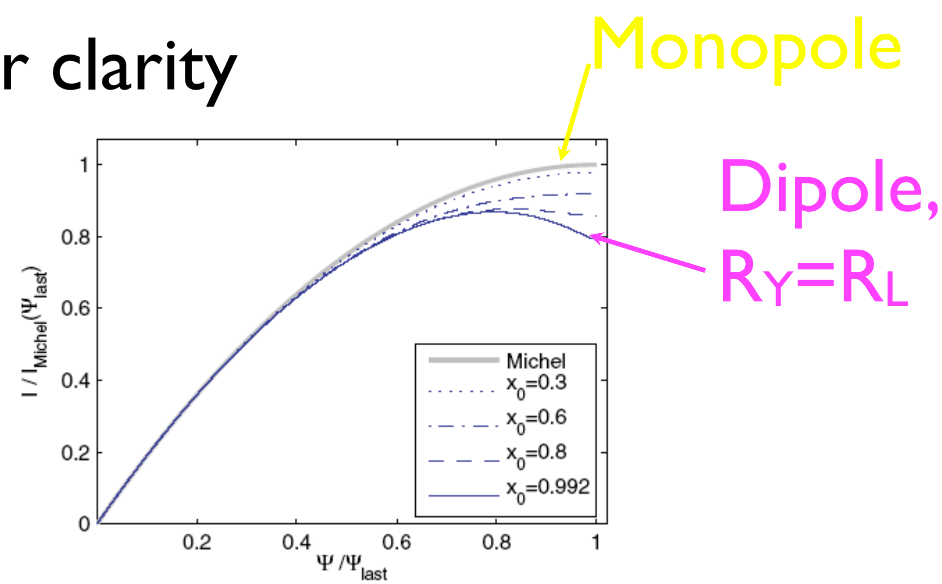
electric currents of current layers (and charge starved, quasi-vacuum "gaps") must fit into magnetospheric circuit – known from FF model, to lowest order in $L_{accel}/L_{spindown}$

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

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

Aligned rotator for clarity





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

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

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

"small" $E_{\parallel}$ (~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!

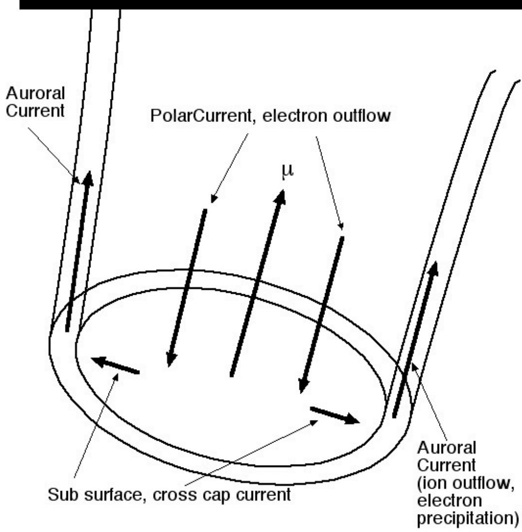
Same issue for outer gaps on open field lines: starvation gap models (steady) produce magnetospheric charge density, not current density, but all energy in current!

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

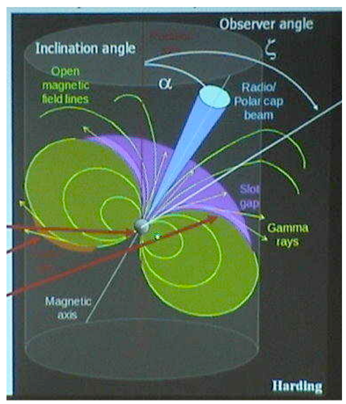
Prospect: Beam Models With Force Free Magnetospheric Structure

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

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

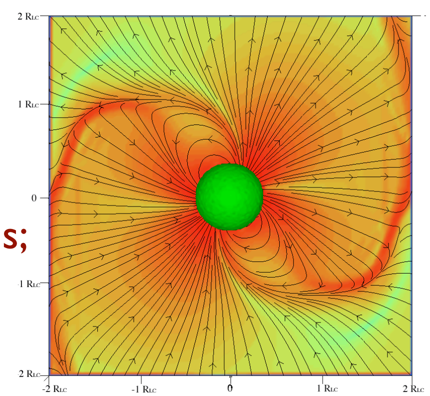


Like a vacuum gap, but $E_{\parallel} = 0$ at crust surface



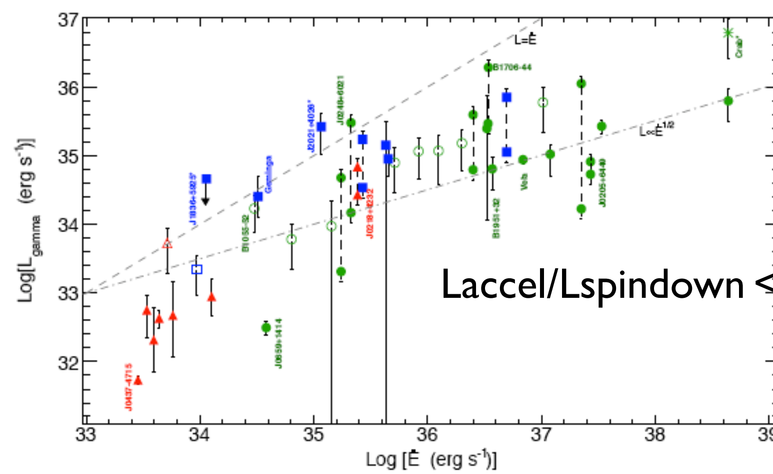
- Cartoon for acute rotator: $\angle(\Omega_*, \mu) < \pi/2$

Obtuse rotator: positrons precipitate, extract electrons; polar current = ions



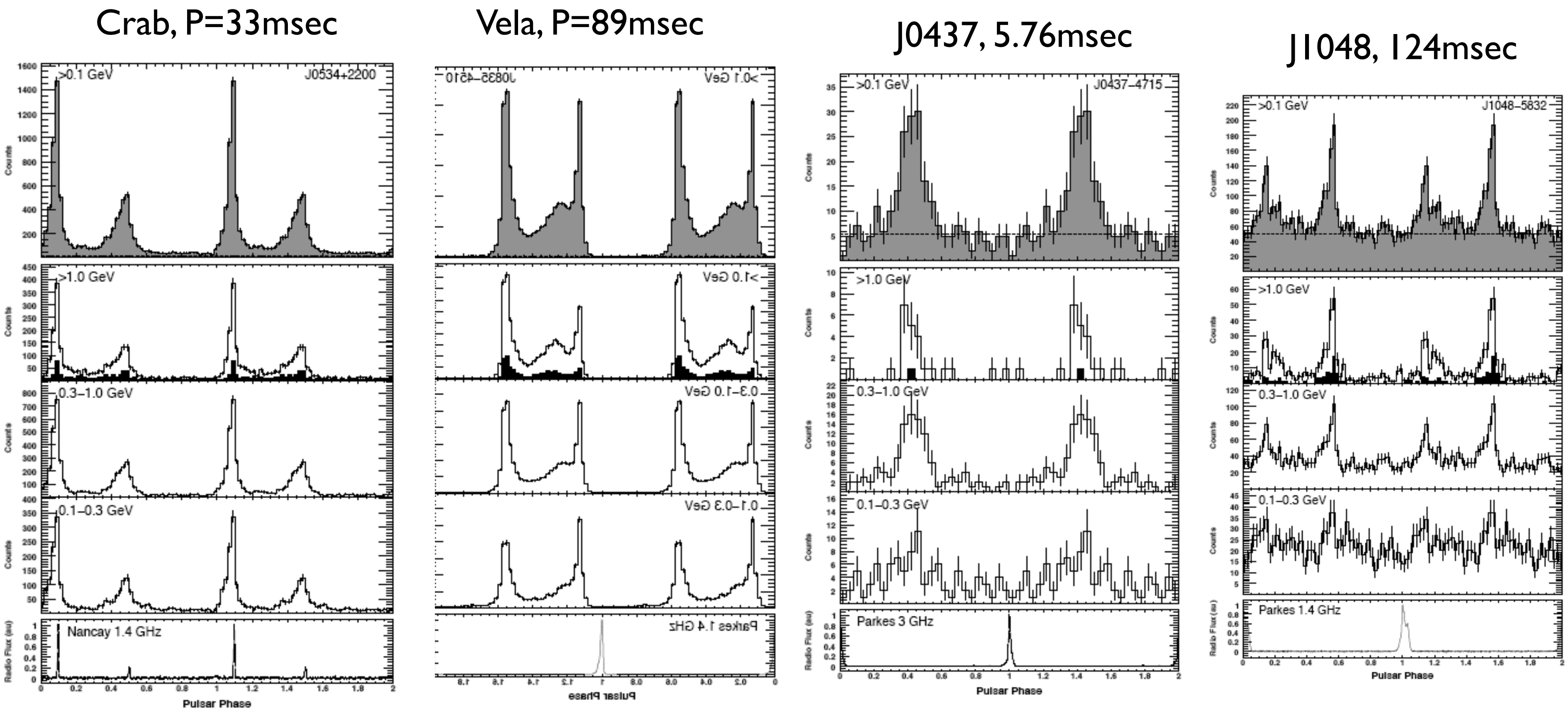
Probe Structure with Gamma Rays – fold geometry with accelerator, probe parallel electric field

Gamma Ray Efficiency (LAT)



Laccel/Lspindown << 1

J.Arons: Aspen Gamma Sources 2010



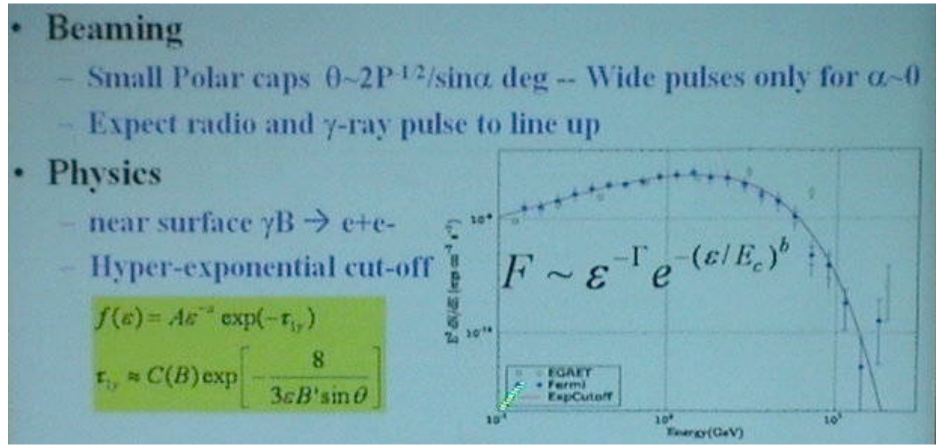
A Few Gamma Pulsars (55 seen by FERMI-LAT in year 1)

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

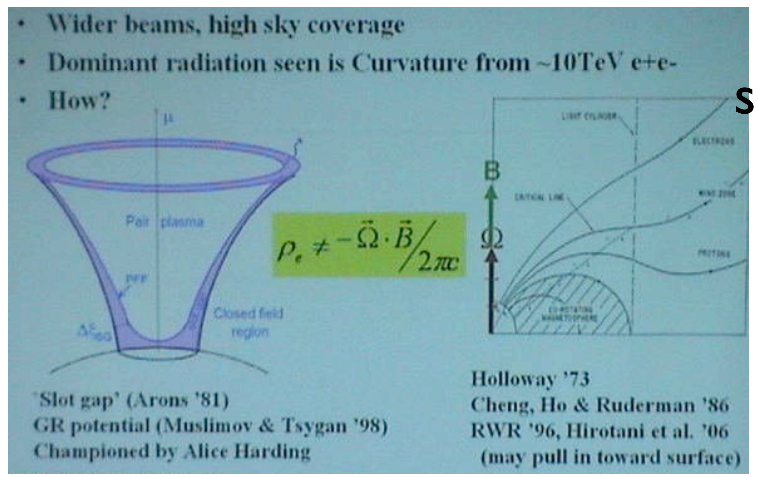
Gamma Ray Tests of Existing Gap Models

Gamma Rays Not from Polar Cap

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



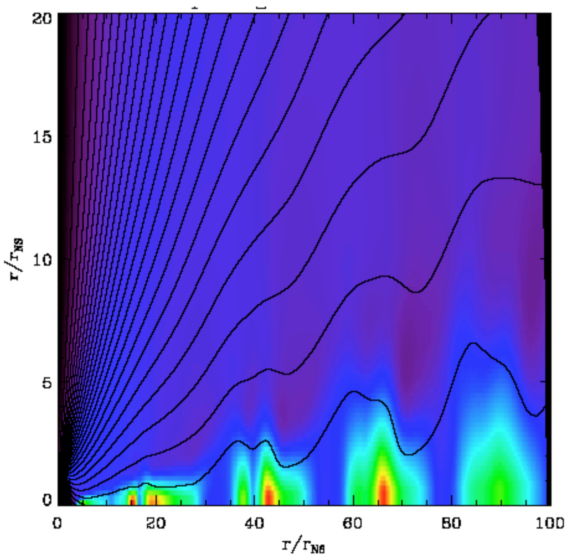
Beamed γ from high altitude more promising – tradition has $E_{\parallel}$ from starvation, quasi-vacuum "gaps"



slides from Romani

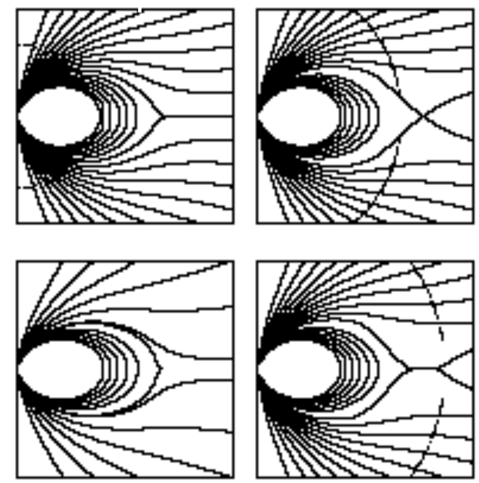
Slot gap fragile to mild magnetic anomalies, gravitational bending of photon orbits causes pairs to fill slot gap gap; Outer gap gets filled by reconnection driven flow ("bulk bursty" flow in Earth magnetosphere)

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

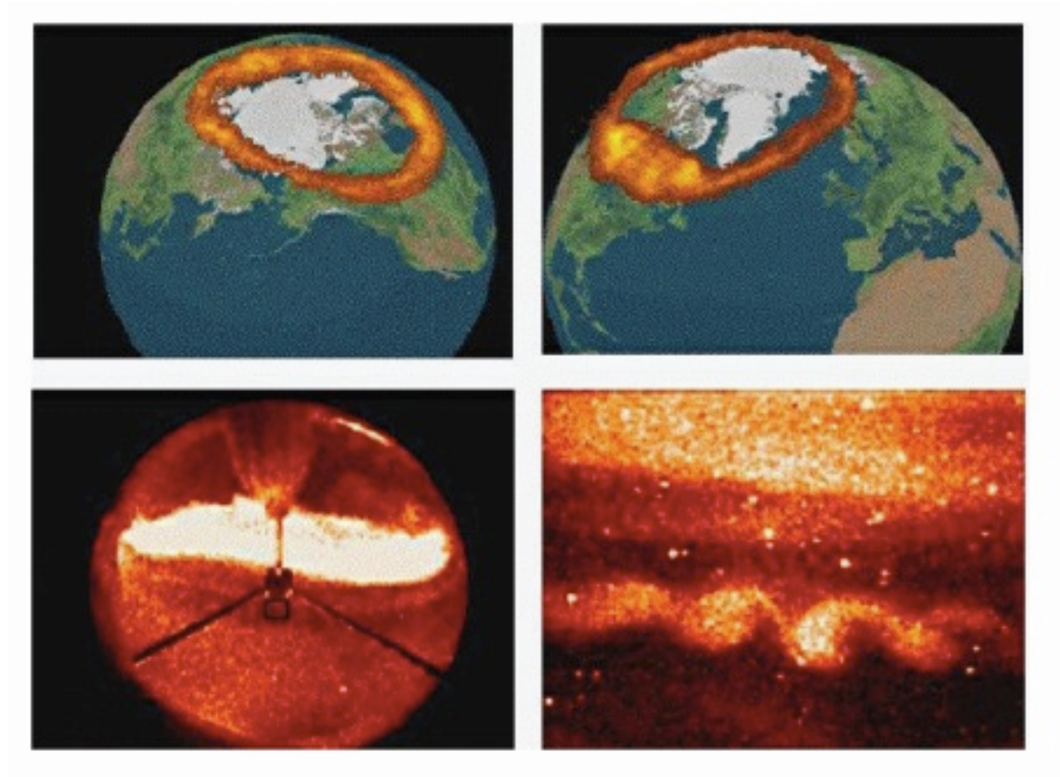


Plasma, j flow to star in thin separatrix layer - dynamics in beams, Kinetic Alfven waves, boundary layer $E_\parallel$ - replaces outer gap - **AURORA**

- 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)?

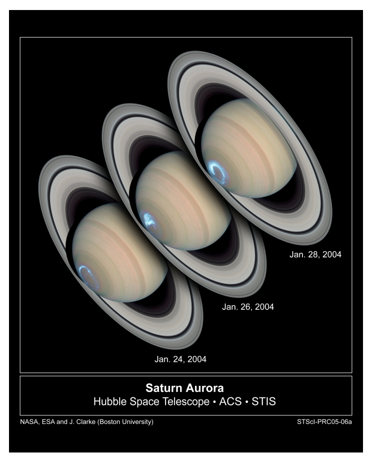
Auroral Model-a radiating accelerator in globally FF

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



Electronic camera
Pix of auroral arcs

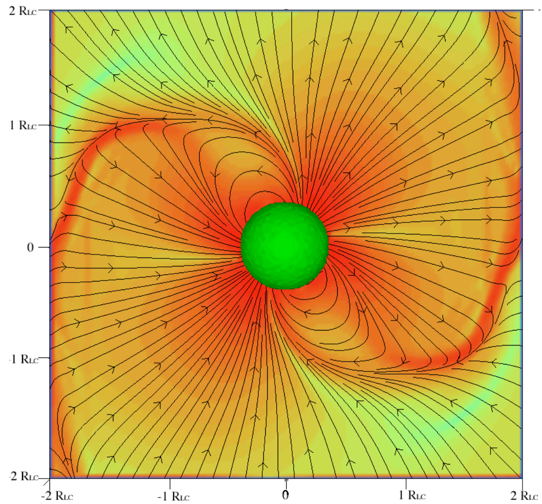
Emission - lines stimulated by downward accelerated e^- beam $\Delta\Phi \sim \Phi$ (storms), density >>> GJ (non-starvation)

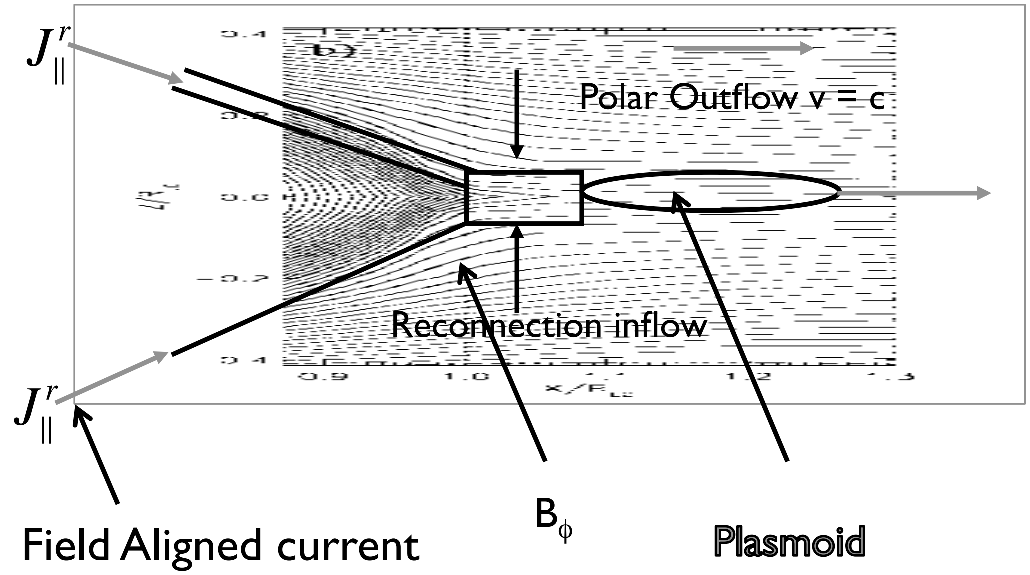


Hubble

Jupiter, Saturn similar

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





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

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

Ohm's law:
2 fluid eq of motion

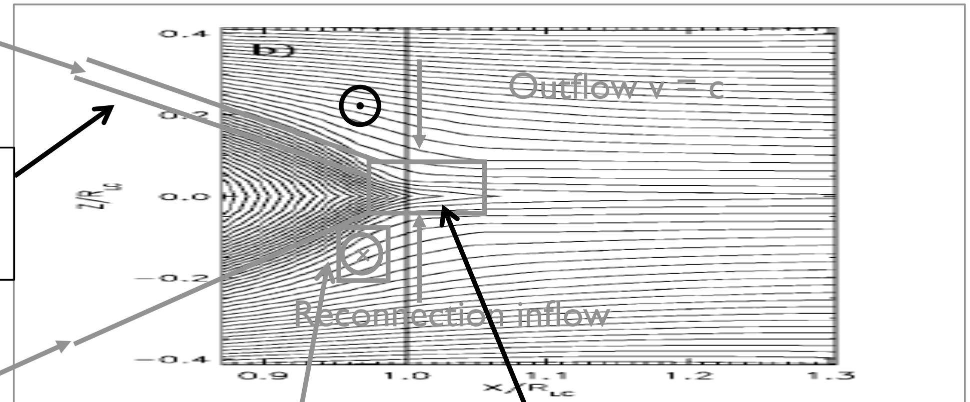
$$E_{\parallel} = \frac{4\pi}{\omega_p^2}\frac{DJ_{\parallel}}{Dt} \propto \frac{m\gamma}{n_{current}}\frac{I}{\Delta_{current}\rho_B}, \; I \propto \sqrt{\dot{E}_R}$$

Particle inertia provides "resistance" in large inductance circuit, voltage $\Delta\Phi$ Φ; but, low density favors $E_{parallel}$. Parallel pressure gradients important in current source box = diffusion region

Precipitating electrons ($\Omega \bullet B > 0$)
positrons ($\Omega \bullet B < 0$)

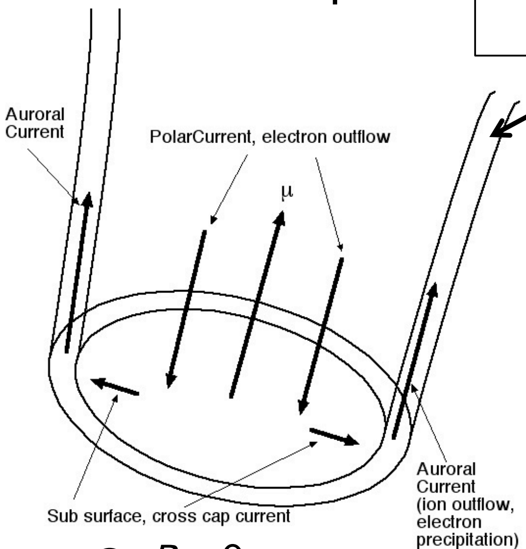
$J^r_\parallel$

Return current channel



$J^r_\parallel$

Polar Cap



$\Omega \bullet B > 0$

B_ϕ Diffusion region, length l_D (~ 0.1 R_L)

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

Current flows in a channel, thickness $\Delta_{current} = \Delta_{current,LC}\left(\frac{r}{R_{LC}}\right)^{3/2}$

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

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

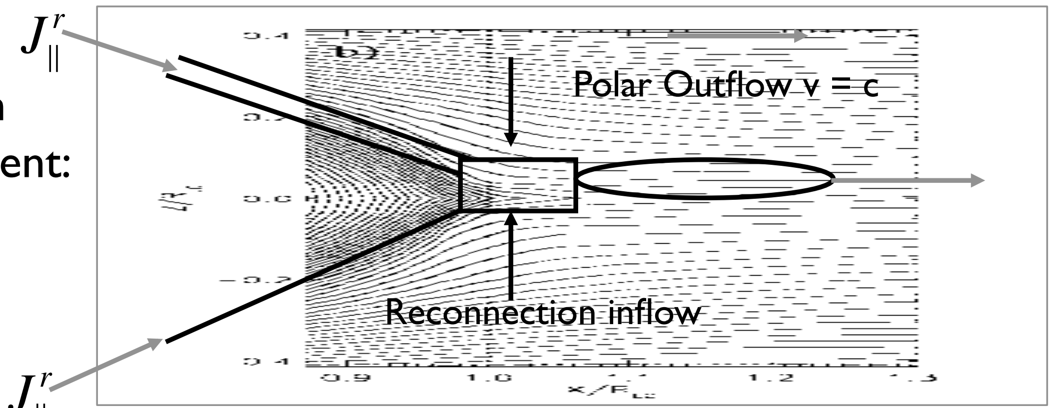
(Channel boundary = conductor – dense, relatively low energy plasma in neighboring outflow, closed zone fed by reconn driven flow)

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

Precipitating electrons ($\Omega \bullet B > 0$)

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

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



Captured pairs expelled along B by pressure inside diffusion region

Electric field in channel stops positrons, accelerates electrons down (electric field in wind current sheet stops electrons, accelerates positrons to r > R_L)

Downward precipitating electron flux:

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

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

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

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

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

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

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^- + upward ions (protons, if atmosphere has residual H floating at top)

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

and

If ℓ_D = skin depth at LC (the smallest possible, << $0.1R_L$), then

$$\Delta\Phi_{max} \approx -\frac{1}{8}\Phi\frac{R_*}{R_L}\left(\frac{m_\pm c^2\gamma_{\pm,L}}{2e\Phi\kappa_\pm}\frac{\beta_{wind}}{\beta_{rec}}\right)^{1/3} \propto \Phi^{2/3} \propto \dot{E}_R^{1/3}$$

$$\Rightarrow$$

$$L_{accel} = I\Delta\Phi \propto \Phi^{5/3} \propto \dot{E}_R^{5/6}, \eta_{accel} = \frac{L_{accel}}{\dot{E}_R} \propto \dot{E}_R^{-1/6}$$

For Crab parameters, $\Delta\Phi \sim$ GV

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

Story is *in medias res* – actually in opening paragraph!

Electron beam goes down ($\Omega \bullet B > 0$); goes up if $\Omega \bullet B < 0$

Possible consequences (SPECULATIONS)

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?

At present stage, hard to know specific observational consequences – but will come, if slowly

Follow the Mass Loss: From Whence all the Pairs?

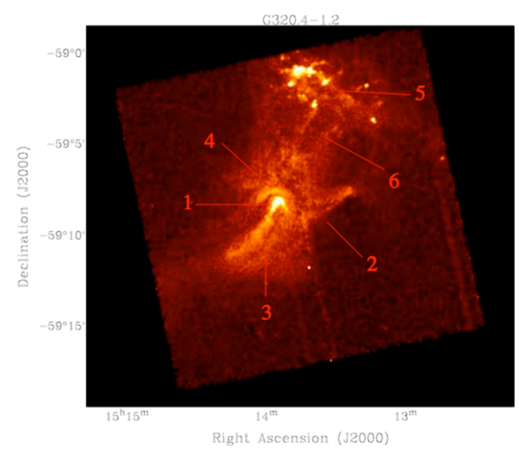
Pulsar Wind Nebulae: Nebular Synchrotron requires particle injection $\dot{N}_{\pm} \gg$ Goldreich-Julian current $\dot{N}_{GJ} = c\Phi/e$

PAIR PROBLEM

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

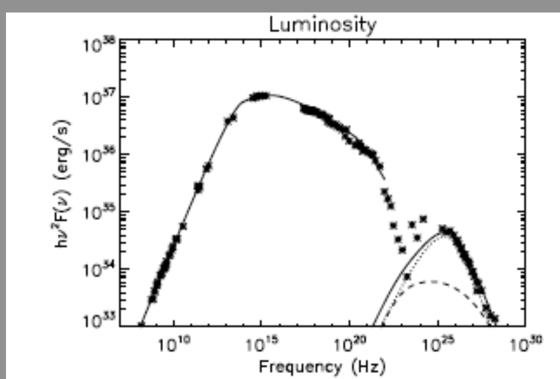
Radio measures injection rate averaged over nebular histories, $\kappa_{\pm} > 10^5$



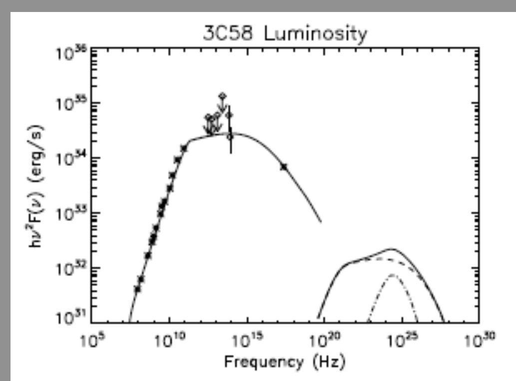
Low $\sigma = B^2/8pm_\pm c^2 n_\pm \Gamma_w$ at termination $\rightarrow$ $\Gamma_w = e\Phi/2m_\pm c^2 \kappa_\pm$

PWN Name	$\kappa_\pm$	Γ_w	Φ_{init}(PV)	Age (yr)
Crab	$> 10^6$	5×10^4	100	955
3C58	$> 10^{5.7}$	3×10^4	15	2100
B1509	$> 10^{5.3}$	1×10^4	121	1570
Kes 75	$> 10^5$	7×10^4	22	650

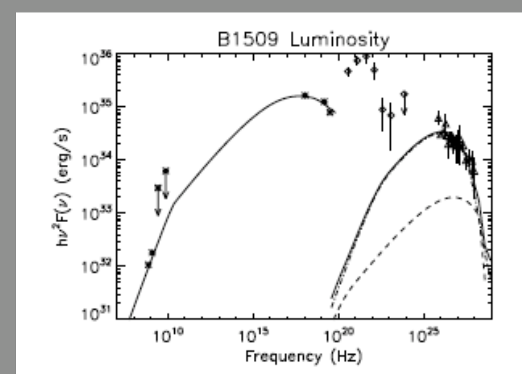
From one zone evolutionary model of observed spectrum including radio (with Bucciantini, Amato: xxx1005.1831) – injection spectrum convex, $\gamma^{-1.5} \rightarrow \gamma^{-2.3}$



Crab



3C58

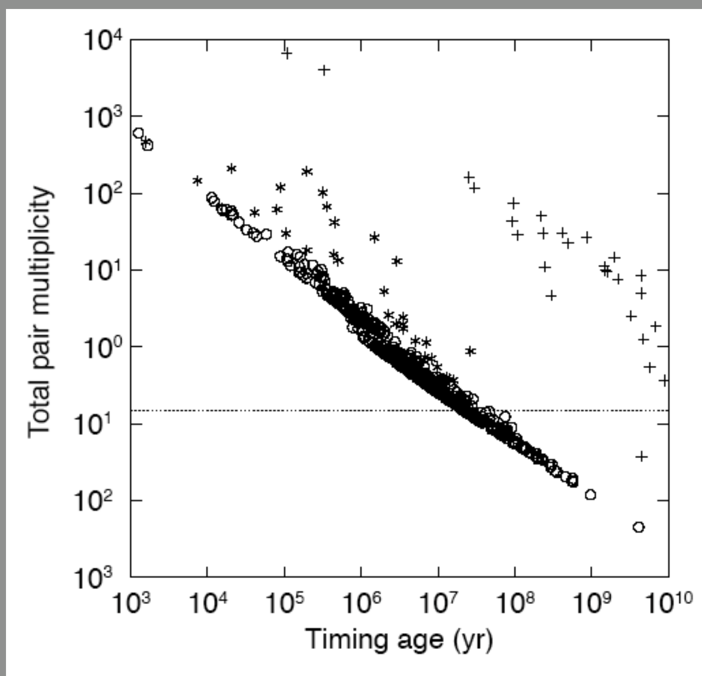


PSR B1509/MSH 15-52

Why so many Pairs (continued)

Pulsar death line ($\Phi = \sqrt{\dot{E}_R / c} \approx 10^{12}$ V) models need dense ($E_{\|} = 0$) pairs over all $P, \dot{P}$ space

Starvation electric field polar caps (charge density controls current) do make a few pairs at low voltage (plenty at high Φ), but not dense - shorting out electric field not clear - more pairs needed (or FF-MHD not applicable) - same lesson as from PWNe



Hibschman & JA 01

Many (not all) radio emission ideas need dense (large multiplicity) pairs

All transfer effects need dense pairs - something is missing

"multipole" fields = tipped offset dipole? gravity bending of photon orbits, 1 pole big B pair yield – magnetic anomaly must be mild, radio pol says B_* close to dipole $r \sim R_*$ - core

Possible flaw: All models assume density >> GJ in current carrying plasma have zero parallel E - NOT TRUE – aurora

Shorting out $E_{parallel}$ at surface of first pair creation assumed by everyone, good idea (?) in steady flow, Perhaps not so in unsteady flow?

• Current + pairs becomes time dependent (? GJ, Alber et al, Levinson, others), averages to FF J? electric field averages to small starvation value? – PC heating? Large $E_{parallel}$ over greater length: more pairs (?)

So far, not so: Timokhin PIC + Monte Carlo hybrid)

Low σ ($\Gamma_w \to \sigma_0$) in unconfined wind requires magnetic dissipation somewhere

Ideal MHD, poloidal field lines almost radial:

acceleration parallel to velocity, inertial force for change of speed proportional to longitudinal mass $m\gamma^3$:

$$\rho c\beta \frac{\partial}{\partial r}(\gamma c\beta) = \rho c^2\left(\beta\frac{\partial\gamma}{\partial r} + \gamma\frac{\partial\beta}{\partial r}\right) = \rho c^2\gamma^3\frac{\partial\beta}{\partial r} \sim -\frac{\partial}{\partial r}\frac{B^2}{8\pi} = \frac{B^2}{4\pi r}$$

Magnetic Spring > Inertia: $1 > \frac{\rho c^2\gamma^3(\partial\beta/\partial r)}{B^2/4\pi r} = \gamma^2\frac{4\pi\rho c^2\gamma}{B^2} r\frac{\partial\beta}{\partial r} \approx M_F^2 \Rightarrow$

Unconfined Relativistic MHD winds accelerate to

$$M_F \approx 1\left(\text{not } \sigma = \frac{\sigma_0}{\gamma} = 1\right), \Rightarrow \gamma_\infty \approx \sigma_0^{1/3}$$

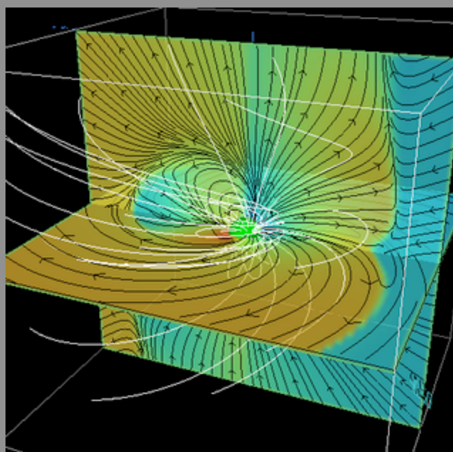
$$(\text{not } \gamma_\infty \approx \sigma_0)$$

Observations (models) require stronger, non-radiative (equatorial) acceleration for r >> $R_F \sim 10^2\ R_L$

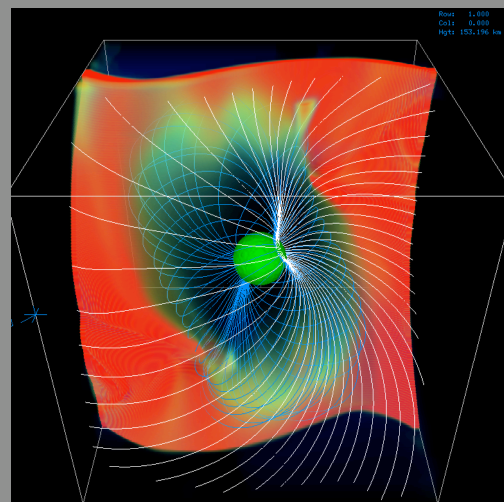
Observed PSR = oblique rotators

Equatorial Current Sheet $\longrightarrow$ Frozen-in Transmission Line

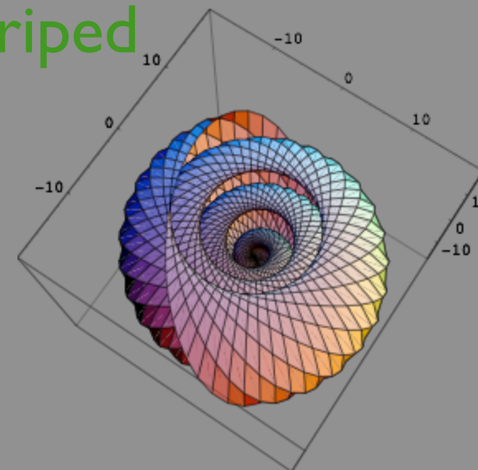
Inner Wind: Magnetically Striped



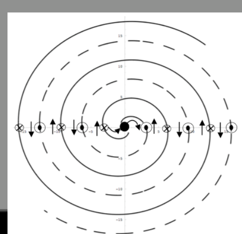
Force Free Simulation of
i=60° Rotator (Spitkovsky)



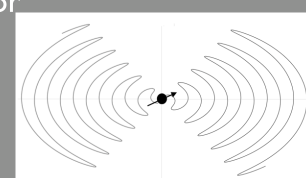
i=60° - topology = aligned rotator
(Bai and Spitkovsky)



Current Sheet Separating Stripes
(from Bogovalov's analytic model)



Equatorial
cross-section



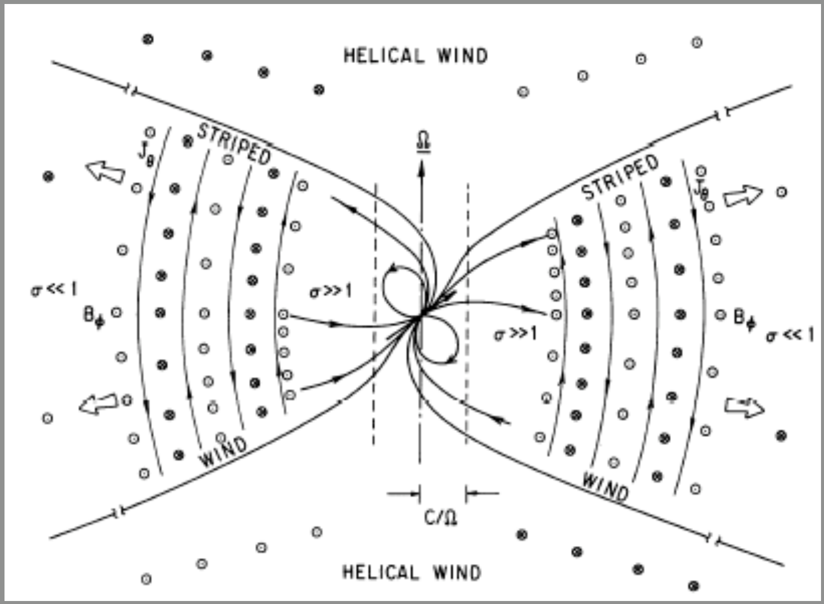
Meridional
cross-section

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

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

Stripe Dissipation Kills $B_{\phi,}$ restores aligned rotator with thick CS

If wrinkled current dissipates, striped field dissipates,
magnetic energy coverts to flow kinetic energy,
"heat" & radiation, perhaps strong waves - partition?



From Coroniti 1990

Sheet spacing: R_L– cold between sheets

Sheet separation = R_L, proper wavelength = $2\Gamma_\omega R_L$
TS at many R_L (10^9 R_L for Crab)
Ideal MHD: Intersheet σ >> 1 conserved
Current sheets' dissipation:
1) Anomalous resistivity forms, plasma in sheets heats, current channels widen, merge at r << R_{TS}
2) Reconnection (also needs resistivity/ inertia) collapses field onto sheets, energy goes to hot islands, sheets spread and merge, devour field upstream of TS
3) Mode conversion - sheet converts to relativistically strong EM waves in flow frame

Plasma pressure in sheets causes wind acceleration as B_ϕ drops

Maximum dissipation

Heating: sheet expansion in wave frame = wind rest frame sheets spread at speed $v_s < c$; sheets expand, merge, $\sigma \longrightarrow$ "0"

sheet separation in wave frame: $\lambda/2 = \pi\Gamma_{wind}R_L$,

Merger time in PWN frame:

$$T_m = \Gamma_{wind}\left(\frac{\lambda/2}{v_s}\right) = \pi\Gamma_{wind}^2\frac{R_L}{v_s}$$

Flow time from star to TS in nebula frame at $r = R_{TS}$: $T_{TS} = R_{TS}/c$

Sheet merger occurs before wind terminates only if $T_m < T_{TS}$:

$$\Gamma_{wind} < \left(\frac{R_{TS}}{\pi R_L}\frac{v_s}{c}\right)^{1/2} = (Crab)\, 3.2\times 10^4\left(\frac{v_s}{c}\right)^{1/2}$$

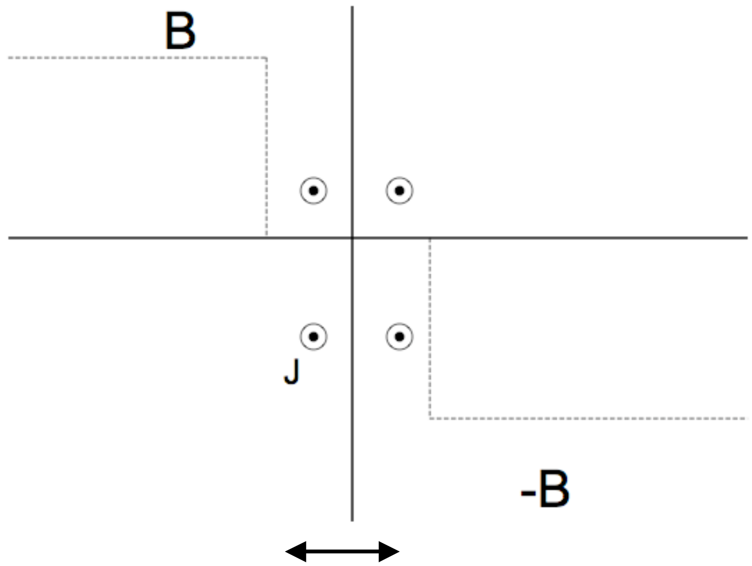
Low σ wind at TS $\Rightarrow \dot{E}_R = \dot{N}_\pm m_\pm c^2(\Gamma_{wind}-1) \Rightarrow \Gamma_{wind}^{(max)} = \dfrac{\dot{E}_R}{2\dot{N}_\pm m_\pm c^2} = 3\times 10^3\,\dfrac{10^{41}\,s^{-1}}{\dot{N}_\pm}\,(Crab\ radio)$

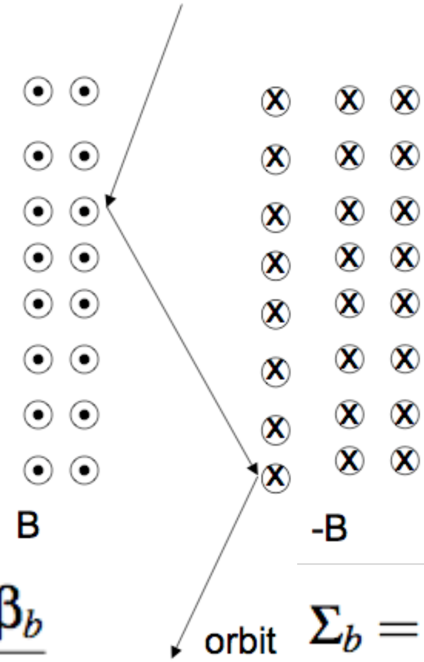
Sheet dissipation upstream of TS may work if

$$v_s/c > 0.01\left(\frac{10^{41}s^{-1}}{\dot{N}_\pm}\right)^2;\ v_s/c < 1 \Leftrightarrow \dot{N}_\pm > 10^{40}\,s^{-1}$$

"fast" sheet dissipation if "slow", dense wind: $\Gamma_{wind} << 10^6, \dot{N}_\pm >> 10^{38}\ s^{-1}$

Simplified Sheet Structure





$$H \approx r_{Lb} = \frac{mc^2\gamma_b\beta_b}{qB}$$

$$\Sigma_b = \frac{j}{cq\beta_b} = \frac{cB}{2\pi q\beta_b}$$

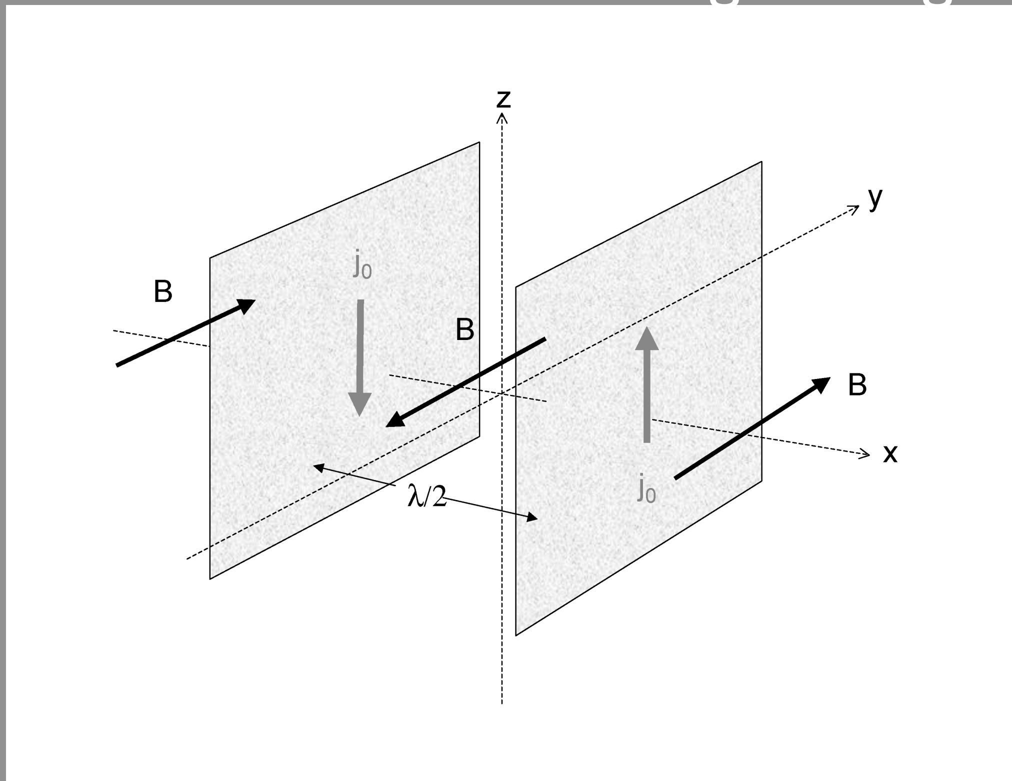
$$P_b = \frac{\Sigma_b}{2H}\gamma_b\beta_b^2 m_b c^2 \left\langle \sin^2\psi \right\rangle \equiv \frac{\Sigma_b}{2H} T_{b\perp} = \frac{B^2}{8\pi} \Rightarrow \frac{H}{R_L} \approx \frac{2T_{b\perp L}}{q_b\Phi}\left(\frac{r}{R_L}\right)^{1/3}$$ *(adiabatic 2D EOS)*

Sheets swallow stripes: $r > R_m = R_L\left(\frac{q_b\Phi}{2\beta_b T_{b\perp L}}\right)^3 = \frac{8\times 10^{21}\dot{P}_{12.4}P_{33}^{-3}}{\left(T_{b\perp L}/m_p c^2\right)^3} R_L$ (Crab) >> R_{shock}

(Crab) $R_m < R_{shock} \approx 10^9 R_L$ only if $\frac{T_{b\perp L}}{m_p c^2} > 2\times 10^4$ - stripes survive?

Rapid Dissipation Mechanism: Anomalous Resistivity

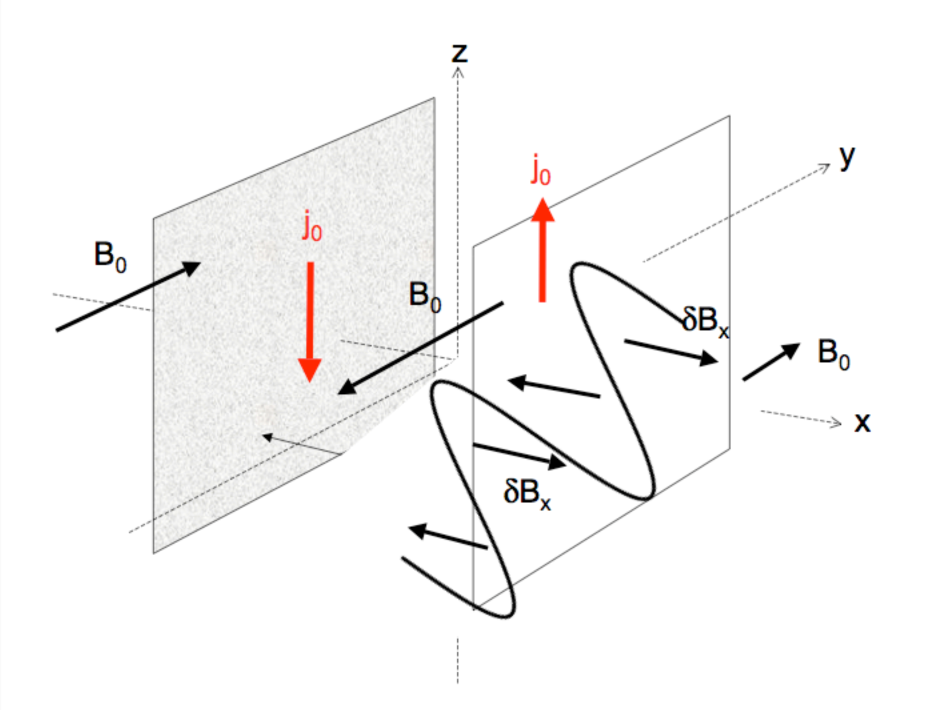
Sheets Interact - Two Neighboring Stream (Weibel-like) instability



$l = 2\pi\Gamma_w R_L << \Gamma_w r$

Dynamics of plasma inside thin sheets as if each sheet is unmagnetized; intersheet medium is high σ MHD $(B^2 \gg 4\pi\rho_0 c^2)$ - sheet current = runaway beam

Two Symmetric Sheet Instability



Growth Rate

2 symmetric sheets = purely growing in proper frame

Wave vector parallel to B $= 2\pi / k_{\|}$

Alfvenic magnetic ripple at each sheet

$$\langle \delta B_x(y) \rangle \propto \exp\left[i\left(k_{\|} y - \omega t \right) \right]$$

Intersheet plasma MHD - sheets couple through Alfven waves modified by inhomogeneity

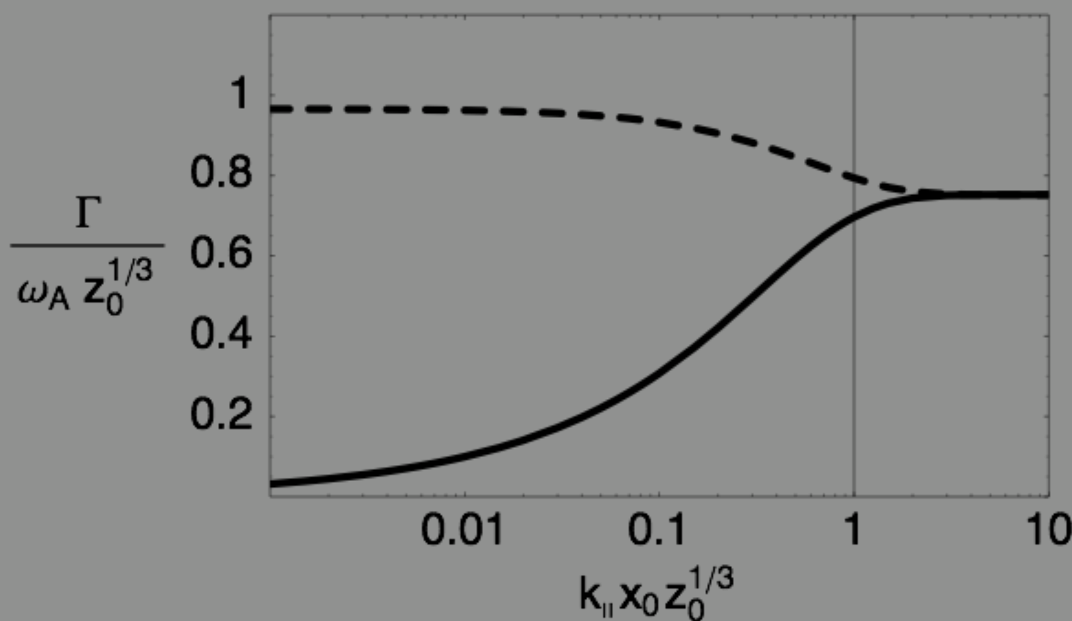
$j_0 \times \delta B_x$ force compresses each sheet's surface density into filaments parallel to j_0

Surface current filaments reinforce δB_x - currents flow in unmagnetized sheets' cores

Weibel instability in flatland

Proper Growth Rate ($v_A = c\beta_A$, $v_{beam} = c\beta_b$)

$$\Gamma_{2sheet} = \frac{2c}{\lambda}\beta_A(\beta_b\beta_A k_\parallel \lambda/2)^{2/3}\left(\frac{\lambda/2}{H}\right)^{1/3}, \text{use } k_\parallel\lambda/2 \sim 1$$



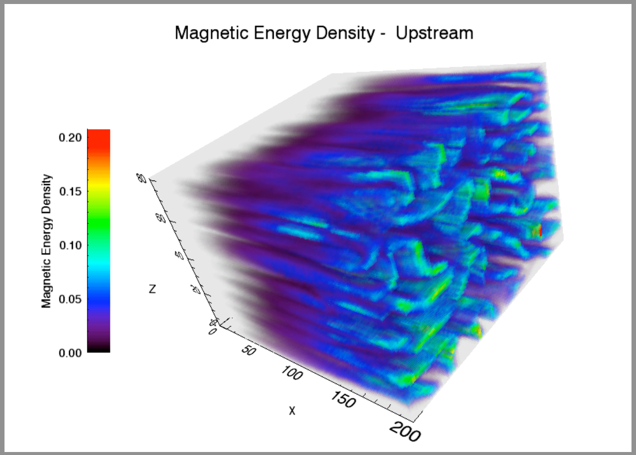
$$\omega_A = k_\parallel c \beta_A$$

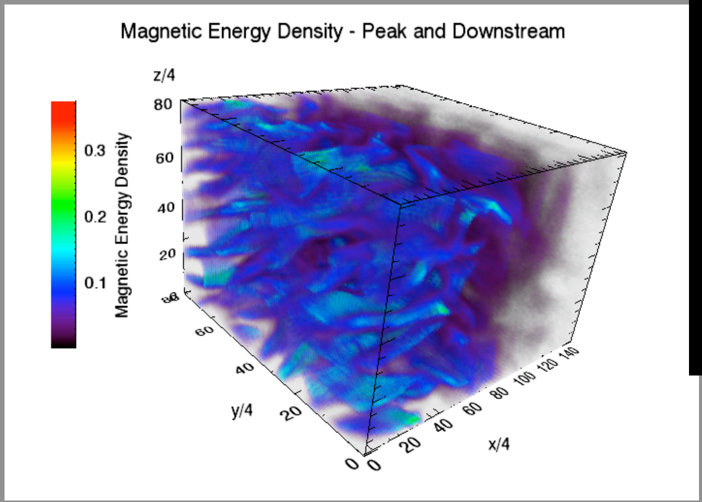
$$z_0 = \frac{\beta_A^2 \beta_b^2}{k_\parallel H}$$

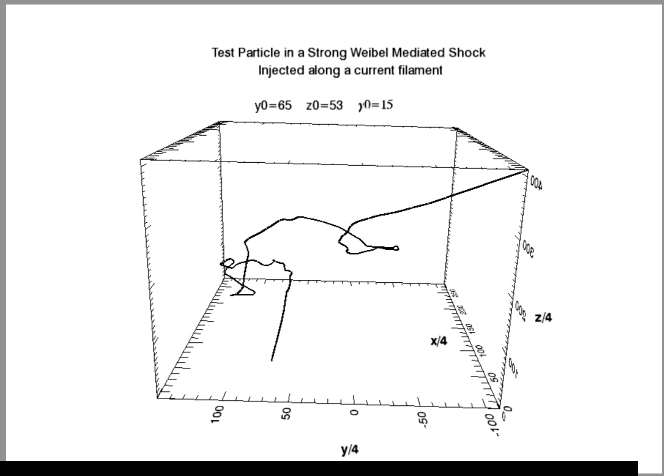
$\Gamma_{2sheet} T_{flow} >> 1$, Sustained Weibel turbulence inside current sheets in wind

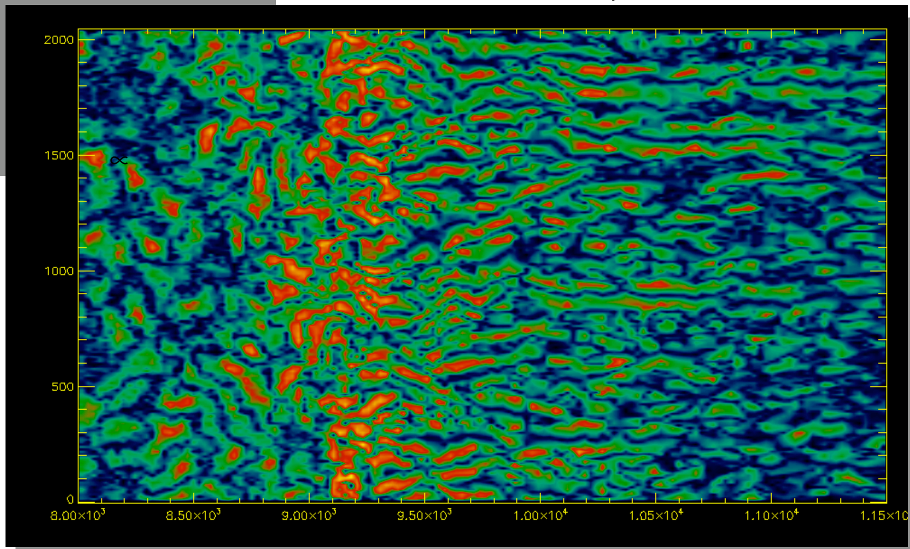
Weibel scatters particles

Weibel in pairs, colliding shells (shock simulations)









Large 2D shock PIC simulation
Labeled plasma particles show scattering

$[x,y,z]=c/\omega_p$

Current carriers scattering nonresonant, $t_{scat} \propto p^2 \Rightarrow$ runaway beams
Γ_{beam} may be as high as $q\Phi$

Alternate model – currents are in main body of sheet plasma, not very relativistic, dissipation = internal Instabilities of Sheets: Collisionless Tearing, Drift Kink (stronger for pairs)

Relativistic Harris-Hoh Equilibrium instead of unidirectional charge neutralized beam

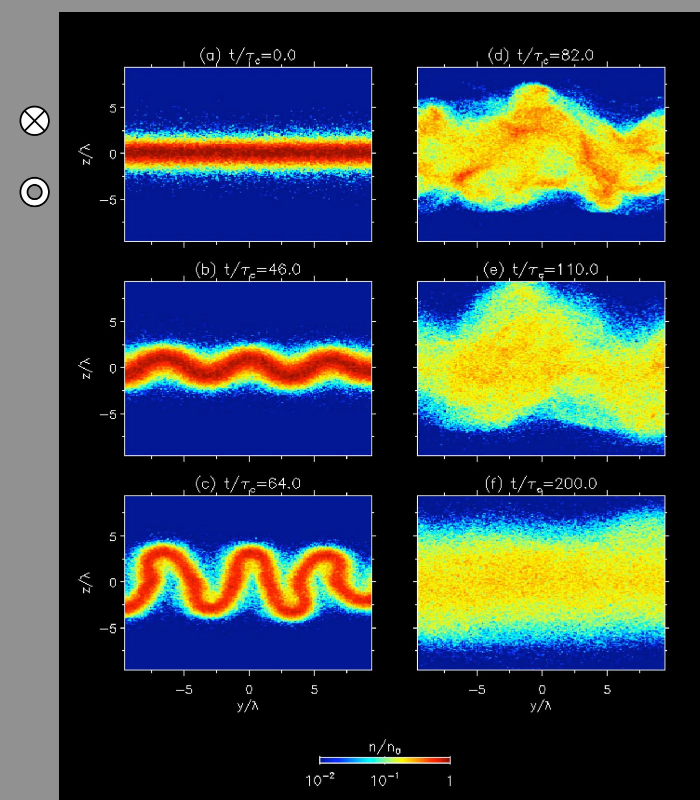
$$\boldsymbol{B} = B_0 \tanh(z/\lambda)\hat{\boldsymbol{x}},$$

$$f_s = \frac{n_0 \cosh^{-2}(z/\lambda)}{4\pi m^2 c T K_2(mc^2/T)} \exp\left[\frac{-\gamma_s(\varepsilon - \beta_s m c u_y)}{T}\right] + \frac{n_{bg}}{4\pi m^2 c T_{bg} K_2(mc^2/T_{bg})} \exp\left(-\frac{\varepsilon}{T_{bg}}\right),$$

Counterstreaming electrons/positrons in channel drives kinking perpendicular to B

$$\tau_c = \frac{\lambda}{c} = \omega_c^{-1} = \frac{m_{\pm} c^2 \Gamma_w}{e\Phi} \frac{r}{2\pi R_L} P$$

fg13_online.h.jpg (JPEG Image, 1945x2366 pixels) - Scaled (41%) http://www.iop.org/EJ/article/0004-637X/670/1/702/fg13_online.h.jp...



Zenitiani & Hoshino initial value PIC
(current stops at late time, not true for PSR sheet)

1 of 1 12/14/09 6:52 PM

Anomalous Resistivity in Sheets & Sheet Merging (beam model)

$\left\langle (\delta B)^2 \right\rangle \neq 0 \Rightarrow$ scattering of beam particles ("collisions")

$$\nu_c = \left\langle \left(\delta\omega_c \right)^2 \right\rangle \tau_{ac} = \Gamma(\Gamma\tau_{ac}) = K_c\Gamma, K_c \geq 1$$

Conductivity inside sheet : $\sigma_{\text{beam}} = \dfrac{\omega_{p,beam}^2}{4\pi\nu_c}$,

Magnetic Diffusivity

$$\nu_m = \frac{c^2}{4\pi\sigma_{\text{beam}}} = \frac{1}{3} cH\alpha_{beam} \left(\frac{H}{\lambda} \right)^{2/3},$$

$\lambda = 2\pi\Gamma_{\text{wind}} R_L =$ stripe wavelength, $D_{\text{Bohm}} = \dfrac{1}{3} cH$ since $H \approx r_{Larmor}$

Sheet Heating: Non-MHD electric field $E_{beam} = J_{beam} / \sigma_{\text{beam}}$ entropy not conserved,

$$\Gamma_{\text{wind}}^2 r \frac{d}{dr} \left(\frac{H}{\Gamma_{\text{wind}}} \right) + \frac{\Gamma_{\text{wind}}}{3} \frac{dH}{dr} = \alpha_{beam} \left(\frac{4H}{\lambda} \right)^{2/3}$$

Heating accelerates the wind

Sheet Heating: Non-MHD electric field $E_{beam} = J_{beam} / \sigma_{\text{beam}}$ entropy not conserved:

$$H = \frac{2T}{eB}, \quad \Gamma^2_{\text{wind}}\, r \frac{d}{dr}\left(\frac{H}{\Gamma_{\text{wind}}}\right) + \frac{\Gamma_{\text{wind}}}{3}\frac{dH}{dr} = \alpha_{beam}\left(\frac{4H}{\lambda}\right)^{2/3}$$

Energy Conservation:

$$\mathrm{R_L}\frac{d\Gamma_{wind}}{dr} = \frac{\alpha_{beam}}{2\pi\Gamma^2_{wind}}\frac{\dot{E}}{\dot{M}c^2}\left(\frac{4H}{\lambda}\right)^{2/3}$$

Similarity Solution:

$$\Gamma_{\text{wind}} = \left(\frac{7}{6\pi}\frac{\dot{E}_R}{\dot{M}c^2}\right)^{1/7}\alpha_{beam}^{2/7}\left(\frac{r}{R_L}\right)^{3/7}, \quad \frac{4H}{2\pi\Gamma_{\text{wind}}R_L} = \left(\frac{36\pi^2}{49}\alpha_{beam}\frac{\dot{M}c^2}{\dot{E}_R}\right)^{3/7}\left(\frac{r}{R_L}\right)^{3/7}$$

Current sheet merger complete, striped B field ~ gone when $4H = 2\pi\Gamma_{\text{wind}}R_L$ at $r = R_{\text{merge}}$.

$$R_{merge} = \frac{49}{36\pi^2\alpha_{beam}}\left(\frac{\dot{E}_R}{\dot{M}c^2}\right)^2 R_L = (Crab)\,\frac{5\times10^8}{\alpha_{beam}}\frac{10^{40}\ s^{-1}}{\dot{N}_\pm}R_L < R_{shock} \approx 10^9 R_L$$

$\alpha_{beam} = 3K_c\beta_A(k_{\|}\lambda\beta_{beam}\beta_A)^{2/3} \sim 1(?)$ = main "wiggle" parameter: $\mathrm{K_c} \sim 1$? PIC sims for process

$\dot{N} > 10^{40}\ s^{-1}$ really needed for feeding radio emission?

Radiation from Wind

Beam model has Relativistically hot current sheets: proper temperature ~ $\gamma_{beam} m_{beam} c^2$ large

$$\frac{T}{m_{beam}c^2} \approx 10^9 \frac{m_\pm}{m_{beam}} \left(\frac{\dot{E}_R}{10^{38.7}\,\mathrm{erg/s}}\right)^{7/13} \left(\frac{\dot{N}_\pm}{10^{41}\mathrm{s}^{-1}}\right)^{6/13} \left(\frac{R_L}{r}\right)^{10/13} \gg 1$$

if $m_{beam} = m_\pm$

Synchrotron emission (observer frame):

$$\frac{L_{wind}^{(synch)}(>r)}{\dot{E}_R} \approx 2\times 10^{-3} \left(\frac{\dot{E}_R}{10^{38.7}\,\mathrm{erg/s}}\right)^{0.45} \left(\frac{\dot{N}_\pm}{10^{41}\mathrm{s}^{-1}}\right)^{1.44} \left(\frac{m_\pm}{m_{beam}}\right)^{2} \left(\frac{R_{\min}}{r}\right)^{-1.92},$$

$$\hbar\omega_{synch} \approx 40 \frac{33\,\mathrm{msec}}{P} \left(\frac{\dot{E}_R}{10^{38.7}\,\mathrm{erg/s}}\right)^{1.04} \left(\frac{\dot{N}_\pm}{10^{41}\mathrm{s}^{-1}}\right)^{0.46} \left(\frac{m_\pm}{m_{beam}}\right)^{3} \left(\frac{R_L}{r}\right)^{1.54} \mathrm{TeV}$$

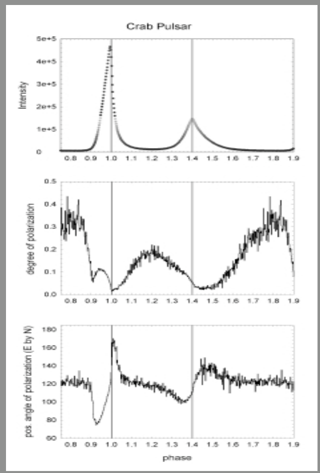
Spectrum calculations: in progress (add shells of relativistic thermal synch)
high energy from inner wind (B_ϕ enclosing sheets large)

Optically thin - yes, except perhaps at highest energy (gg opacity unknown)

Emission from r ~ R_{merge} in optical-UV - unpulsed emission, also faint, B_f small

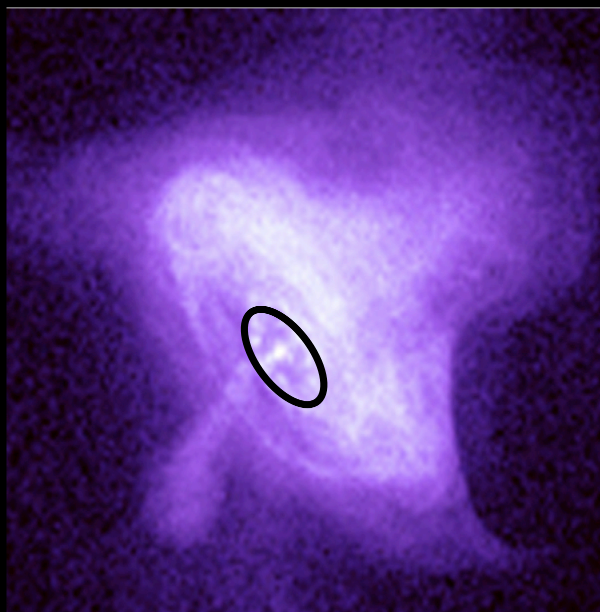
Tev, GeV emission might be pulsed (inner wind), emission regions can be smaller than $r\Gamma_{wind}^2$, therefore radiation in phase with sheet? - alternate to SG, OG magnetospheric beamed emission [old idea (Michel/Arons), recently worked on by Petri and Kirk); there are upper limits on TeV pulsed emission that may challenge model (or allow detection of wind emission - even unpulsed flux might be at energies where nebular flux weakens.)

old ion beam
Idea generalized
to all possibilities
(e^-, e^+, ions – depends
on PSR geometry,
coupling of current flow
to * surface, Y line

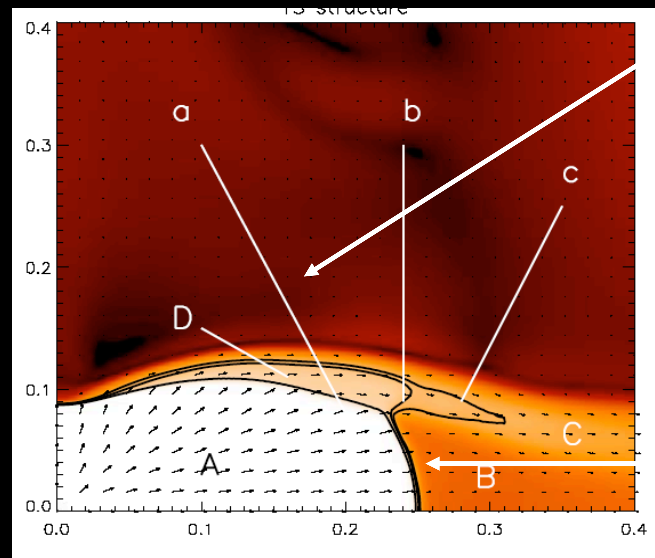


Crab optical pulse, can be modeled by sheet emission (with “knobs”)

Termination Shock = Magnetic Sandwich



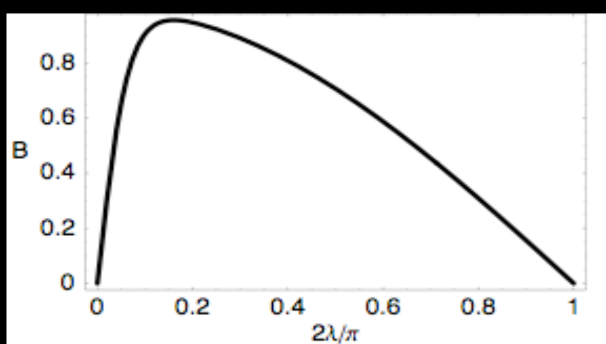
Termination Shock Location



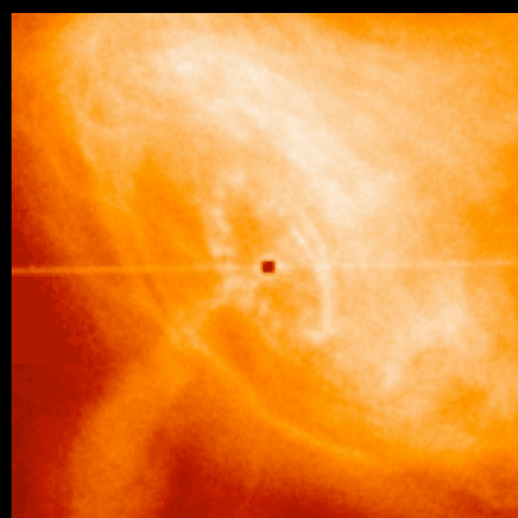
Termination Shock Structure (from del Zanna et al 04)

High density pairs, mildly magnetized shock

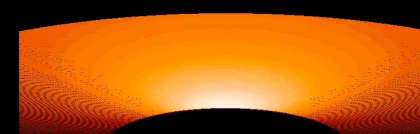
Low density pairs, beam, unmagnetized shock



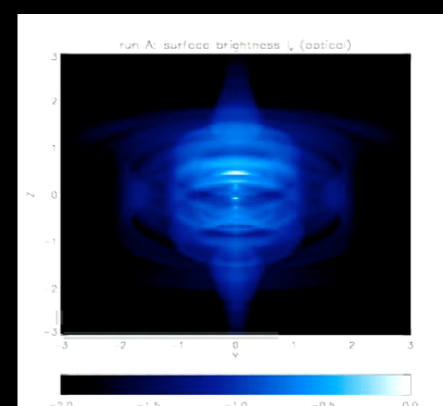
B strength with latitude - Unmagnetized in equator



Chandra Movie



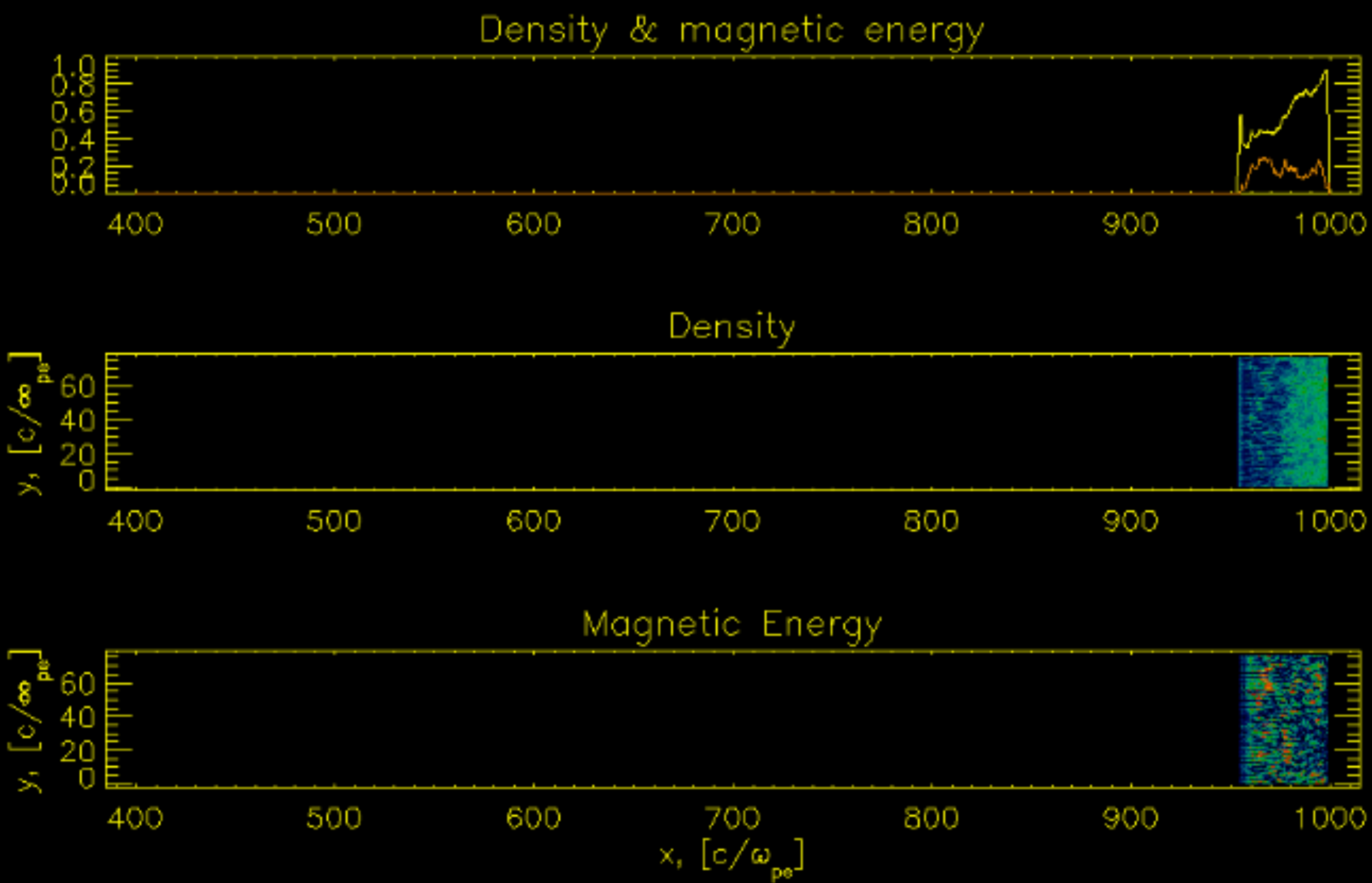
Equatorial beam compressions Movie (AS+)



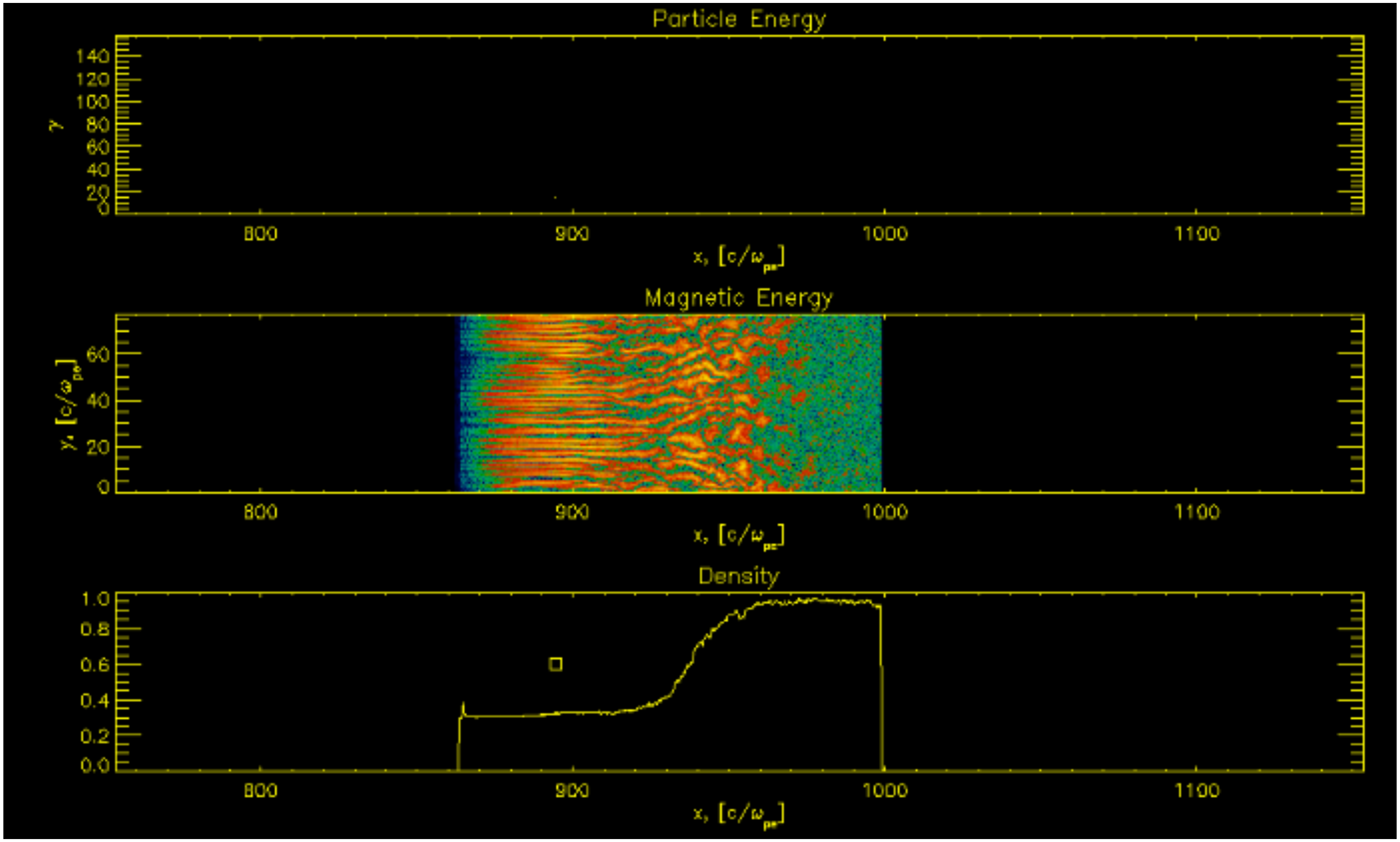
MHD Shear and Vorticity Instability Movie (SK+)

Unmagnetized shock Movie (Spitkovsky 08)
PIC Simulation of Weibel turbulence mediated shock

2.5D relativistic PIC, electrons-positrons, B_0 = 0, Γ=15; 3D (Spitkovsky & JA) similar



Detection of self-consistent Fermi acceleration ($\Gamma_1 = 15$, pairs)



Large simulations (50,000x800 cells, 5000x80c/$\omega_{p\pm}$)- suprathermal particles (Fermi acceleration) well developed

Density, t=8400/ω_p
$B^{1/2}$, t=8400/ω_p

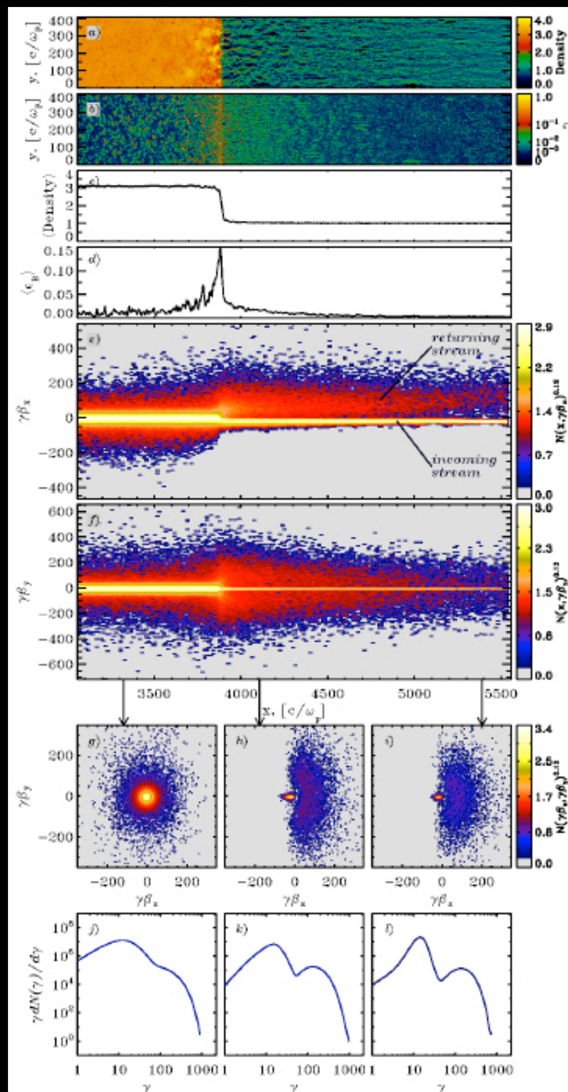
1D density, $B^{1/2}$
t=8400/ω_p

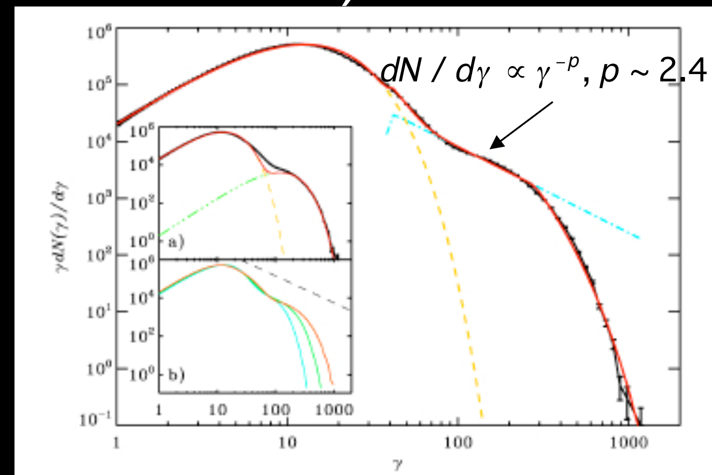
P_{flow}-x

P_{perp}-x

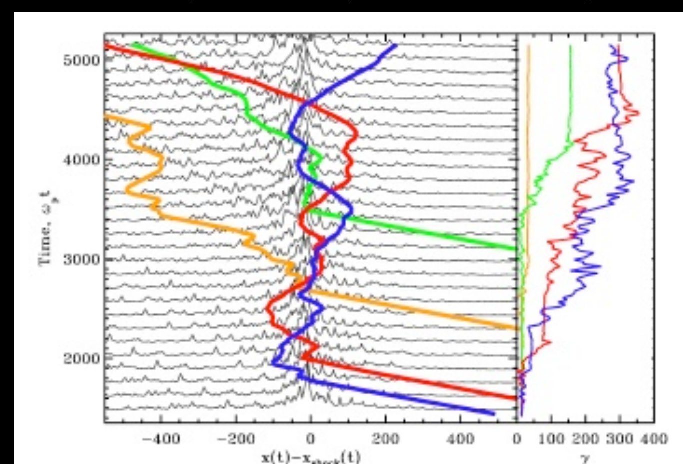
P_{flow}-P_{perp} slices

Particle spectra
in slices





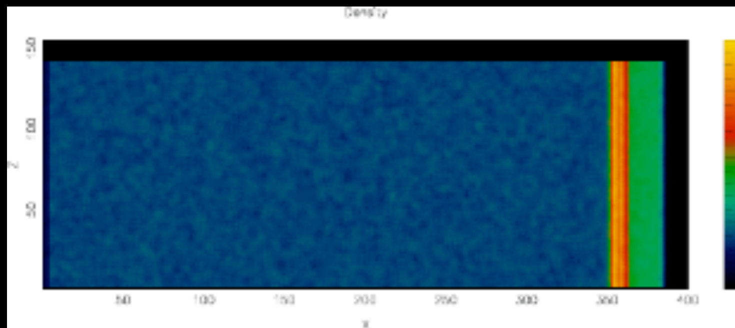
Downstream particle spectra: Maxwellian + exponentially cutoff power law (biMaxwellian, growth of power law component)



Labeled particles gaining energy

Magnetized Transverse Pair Shock (higher latitude):

Pairs, unidirectional B, 3D, colliding shells, $\sigma = 0.1$



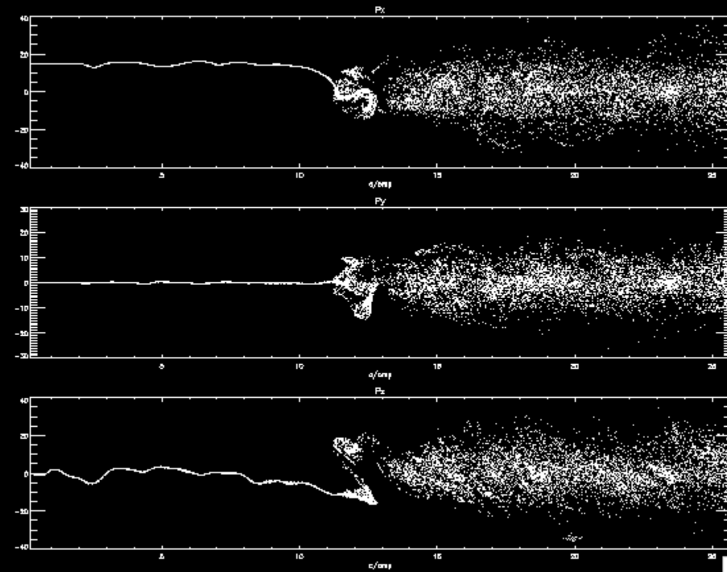
Density in B-v plane Movie

3D Phase space

P_x-x $\langle v_x \rangle$

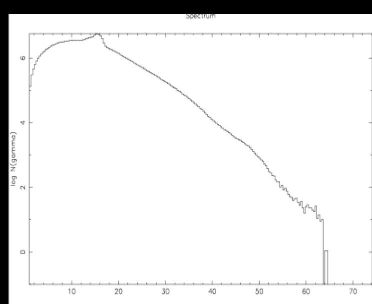
P_y-x B_0

P_z-x E_0

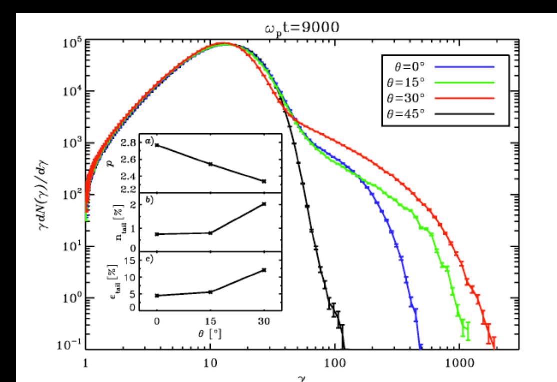


Complete Thermalization – rapid relativistic synchrotron emission and self-absorption (synch thermalization ~ BH disks, but collective) - true for all superluminal Θ_{BN}

Log f(E)



E

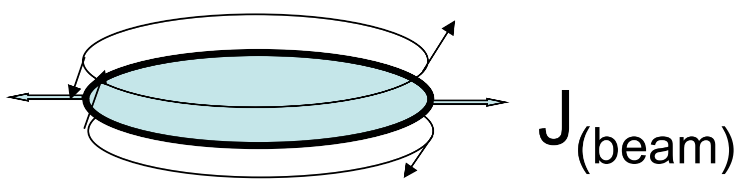


Sironi & Spitkovsky 09

Turbulence too weak, wrong kind (not scattering) to support DSA
in $<\sigma> > 0.01$ flow, = latitude average in MHD nebula models

Pulsar Wind Toroidal Field entirely across flow; composition = pairs.
Does shock acceleration fail for best studied/most easily studied relativistic outflow?

Conclusion applies only if upstream B not structured – high mass loaded, low Γ_w wind has sandwich geometry



Clue: MHD nebular models require unusually weak field in equator, plasma + beam flow in equatorial current sheet allows formation of $\sigma < 10^{-3}$ shock, Fermi acceleration possible in equatorial outflow: feeds torus, if accel to PeV

(needs turbulence not demonstrated in $\sigma < 10^{-3}$ PIC), spectrum OK for optical, X-ray, gamma ray from nebulae

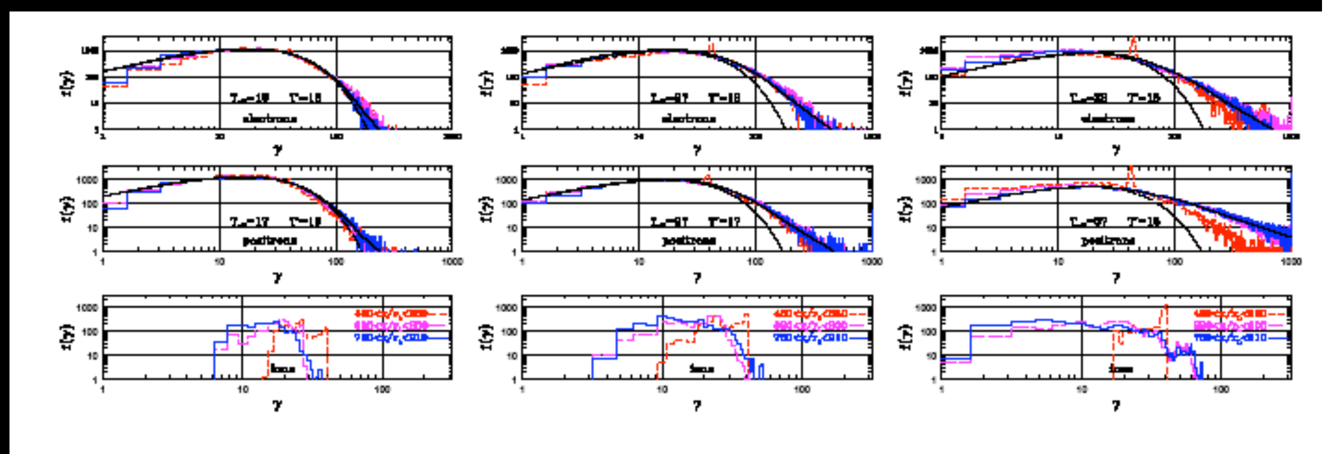
Flat spectrum radio emitters accelerated by cyclotron resonance in higher σ zones at higher latitude?

Amato & JA 1D PIC – hasn't yet been done in 2D and 3D

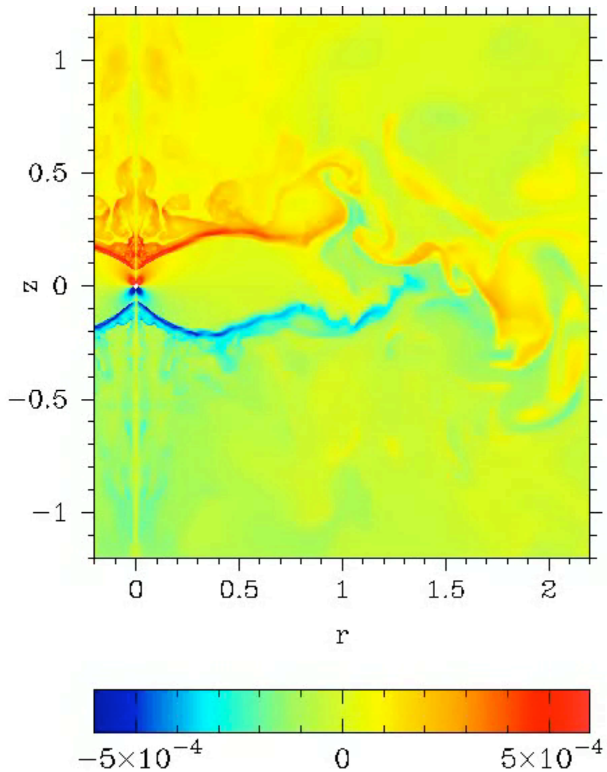
electrons

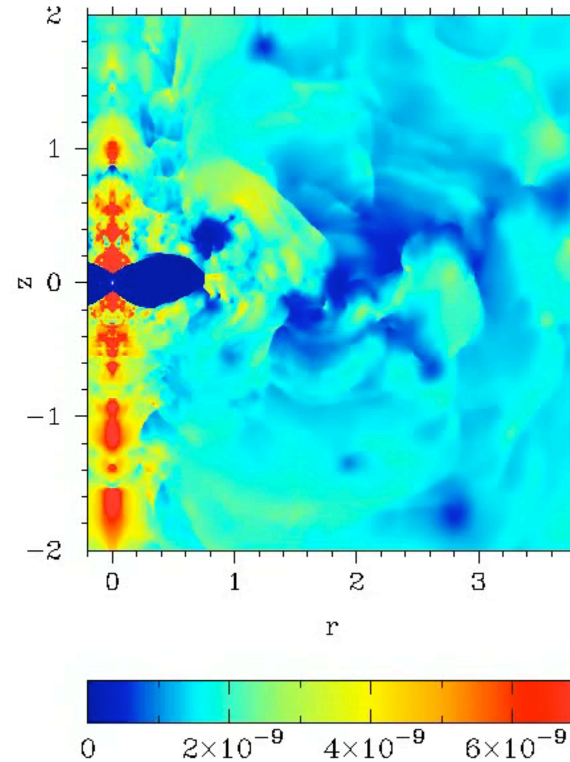
positrons

beam= "protons"



Alternative: Macro-turbulence from unstable flow at shock gives fast 2nd order Fermi ($v_A \sim c/3$)





B from Camus et al 2009 pressure

If turbulence cascades to short wavelength, fast 2nd order Fermi acceleration may accelerate radio emitting spectrum from post shock pairs (??)

Conclusions: Pulsar Problems and Prospects

- Force Free Currents - Charge Neutrality conflicts with j
  New Polar Accelerator Models - short time variability?
- Closed/Open Magnetosphere - Reconnection?
  Cross field transport in closed zone
  Plasma transfer from open to boundary layer, closed field - n < 3?
  Return current formation and plasma $\boldsymbol{E}_{\|}$ - kinetic Alfven waves/beams?
  Torque noise, subpulse phase variations
  Boundary layer acceleration, HE photon emission
  Enhanced Polar Pair Creation (?)
- Wind Current Sheet Dissipation
  High $\sigma \longrightarrow$ low σ? Anomalous resistive decay of stripes in mass loaded, low(er) $\Gamma_w \sim 10^4$; Current in equatorial current sheet = runaway beam? (cyclotron acceleration at TS?)
- PWNe termination shocks – Magnetic Sandwich Geometry
  unmagnetized in equator ("sandwich filling"): Fermi acceleration (O,X,γ)
  cyclotron acceleration at higher latitude: flat radio spectrum?
  turbulence acceleration in equatorial TS: flat radio spectrum?

Variability:

All emission models are steady in co-rotating frame

All radio emission is variable in the corotating frame

Subpulses - T ~ magnetopsheric transit time ~ P/π

unstable magnetospheric reconnection? J mismatch?

Micropulses ~ polar transit time

virtual cathode fluctuations? $T_{pc} \sim \frac{R_*}{c}\left(\frac{R_*}{R_L}\right)^{1/2} \sim 10^{-6}P^{-1/2}$ s

Nanopulses - intrinsic time scale of radio emission turbulence?

Needed - O, X, γ subpulse, micropulse observations!

Needed - plasma dynamical models in Force-Free current flow setting - mostly computational