Relativistic Reconnection in Pairs: Mass Transport (Acceleration?)

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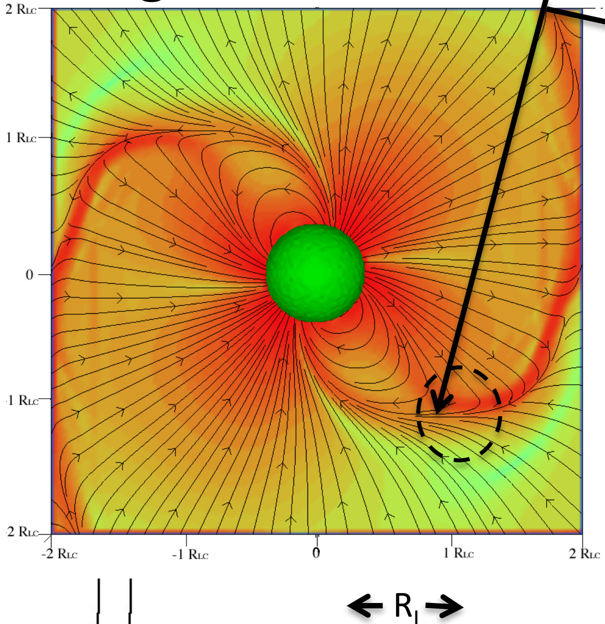
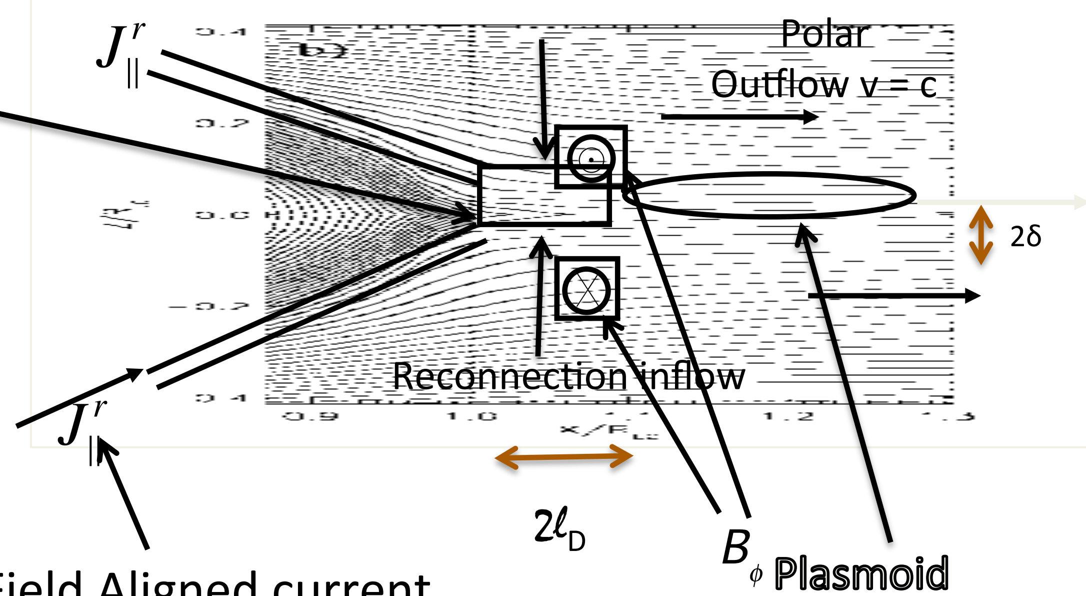
Question: How Does Return Current in PSR Magnetosphere Form?
What is density of current carriers?

Consequences (many): How do beamed gamma rays get emitted?
How do beamed lower energy photons from outer magnetosphere get emitted?
What is the origin of torque fluctuations?

Basic Model: MHD Magnetosphere, fed by $e^{\pm}$ pairs from low altitude polar flux tube (pair creation in high altitude may contribute)

Magnetic Y-line feeds



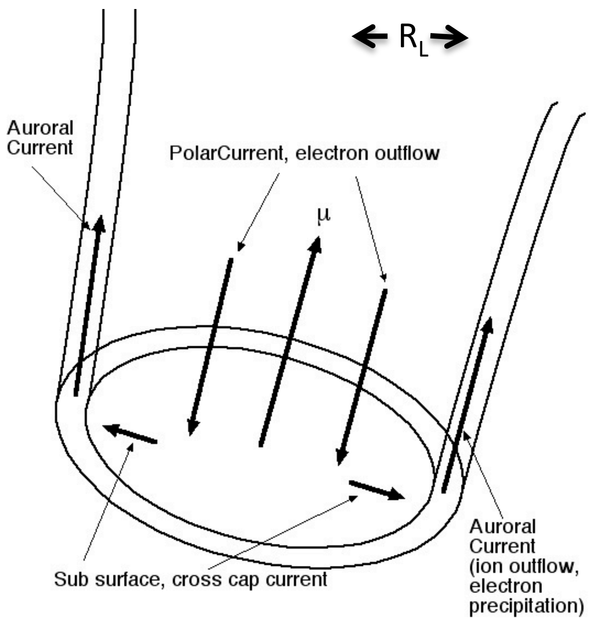


Field Aligned current
precipitating electrons supplied by diffusion box +
upward ions from stellar atmosphere)

Reconnection E (radial in geometry shown) sustained by off diagonal pressure tensor ∝ $\partial p_i/\partial x_j$
(“collisionless viscosity” – seen in all relativistic reconnection in pairs 2D & 3D PIC simulations:
Hoshino & Zenitani; Bessho & Bhattacharjee;
Kagan, Milosavljeic & Spitkovsky,….)

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

w=relativistic enthalpy; anomalous resistivity, rad reaction neglected



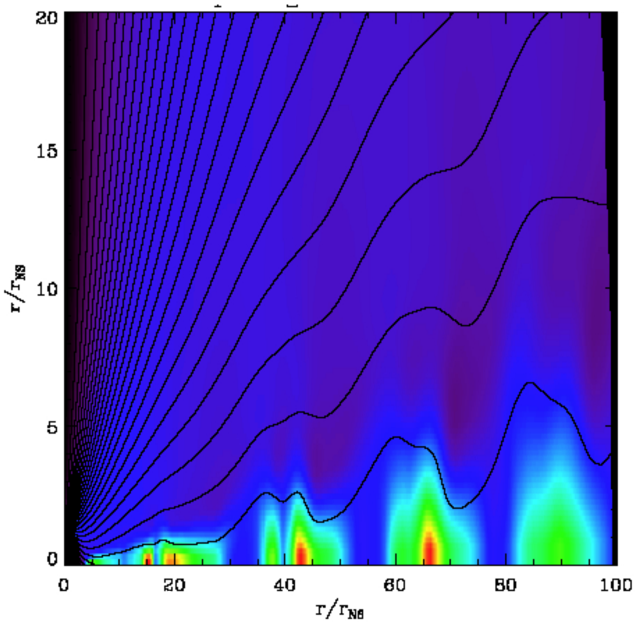
Polar Cap

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

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

Non-MHD inertial E ∝ n^{-1} (T/mc^2): favors low density; hot = high energy

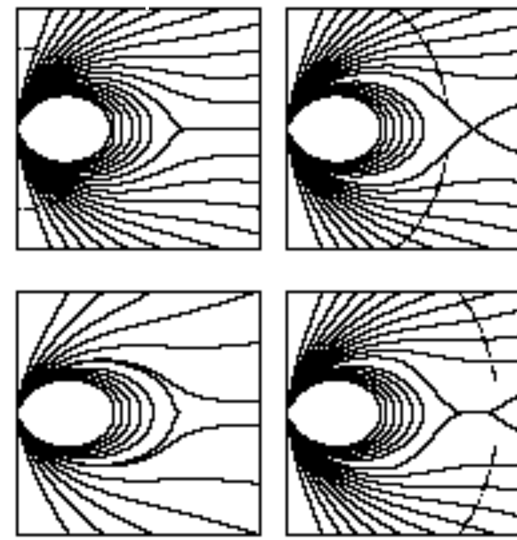
Reconnection/Return j



Sporadic X-Point, Plasmoid formation
occurs continuously

Pairs all come from pole,
on open field lines
Sporadic reconnection
moves plasma across
B – ExB drift in
non-corotation E, time
variable E at all times

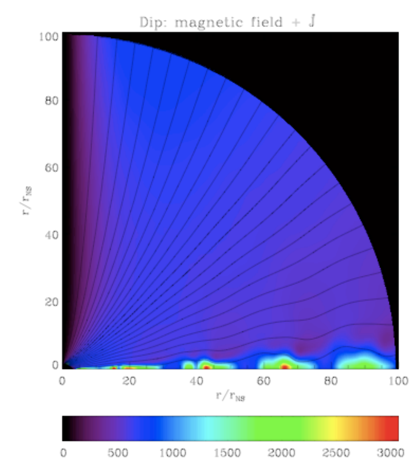
Bucciantini et al 2006
relativistic MHD with numerical dissipation



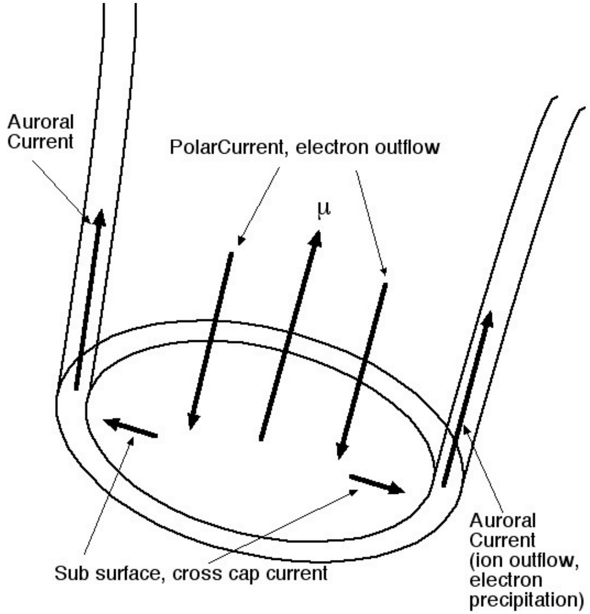
(Contopoulos & Spitkovsky)

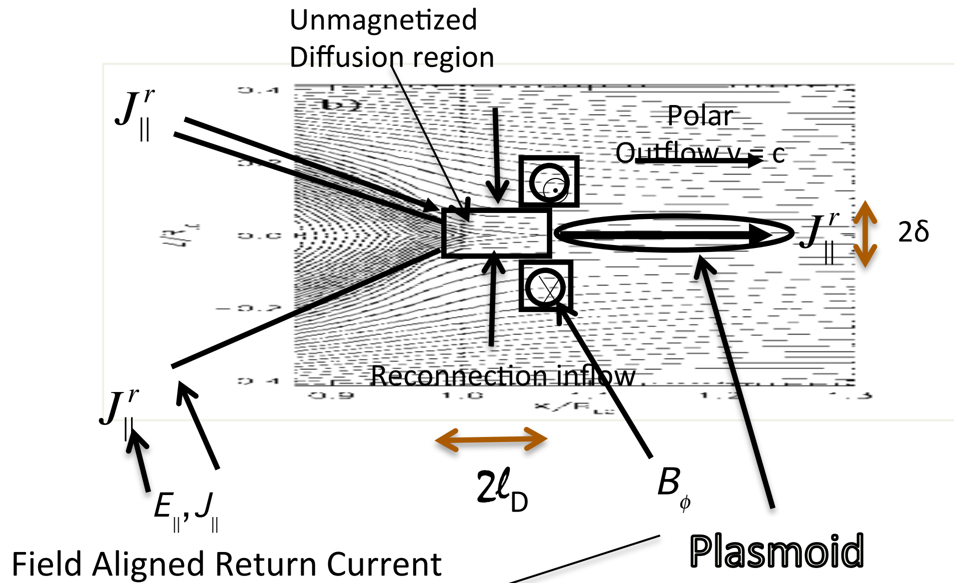
- Plasma, j flow to star in thin separatrix layer dynamics in $E_{||}$ (standing Kinetic Alfven wave boundary layer)

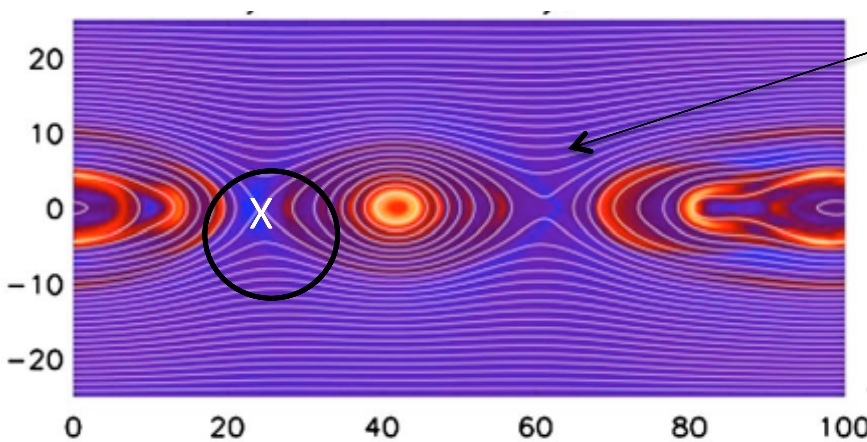
AURORAL ACCELERATION



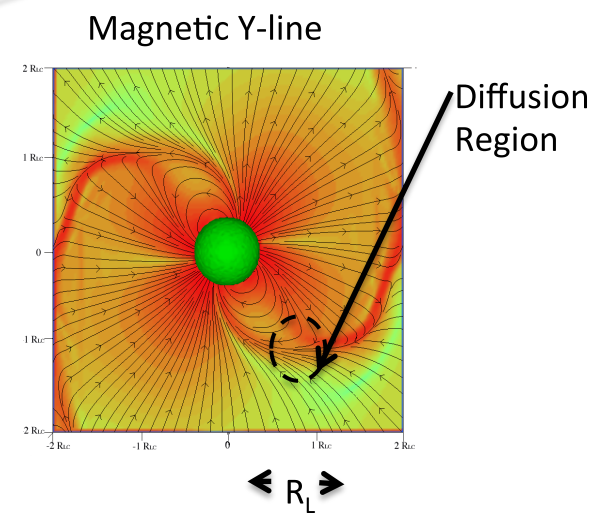
- Kinetic Alfven wave $E_{||}$ extracts return current
- (Torque fluctuations, limit cycles built in (drifting subpulses)?)







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



Electric return **current channel**
$\Omega \cdot \mu > 0$ Downward electron beam, upward ion beam
$\Omega \cdot \mu < 0$ Downward positron beam, upward electron beam

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

Total value of current fixed by the force free magnetosphere;

Reconnection modeled by steady flow, 2 fluid theory of diffusion region – E_{rec} supported by off diagonal pressure tensor - viscosity

Channel current modeled as steady counterstreaming beams

Density of precipitating beam in the return current channel at $r = R_L$ set by density in diffusion region n_{diff}: reconnection inflow=exhaust:

$$n_{diff} = \frac{\beta_{rec}}{\beta_{exhaust}\beta_{wind}} \frac{\ell_D}{\delta} \frac{n_{pair}}{n_{GJ}} \boxed{\frac{e\Phi / m_{\pm}c^2}{2\pi R_L^2 r_e}}$$

(Lyubarsky 96)

= GJ density at LC ≅ $10^{6.2}$ cm^{-3} (Crab), β_{rec}~0.1, ℓ_D

β_{wind}=1, ℓ_D/δ =10-100 (PIC sims, theory)

Multiplicity $\kappa_{\pm} = n_{pair}/n_{GJ} \gg 10^4$ (perhaps 10^7 in the Crab), $B_{LC} = \Phi/R_{LC}$

Diffusion region unmagnetized, particles bounce freely inside:

$$r_{Larmor}(\delta) = \delta = \frac{mc^2\gamma_{bounce}}{eB_{LC}} = \frac{T_d}{e\Phi} R_L$$

Viscosity in diffusion region (bounce motion exchanges momentum across flow) heats diffusion region plasma; synchrotron cooling (curvature radiation with radius of curvature = δ) balances heating:

$$\frac{T_d}{m_{\pm}c^2} = \left(\frac{R_L}{12 r_e} \frac{e\Phi}{m_{\pm}c^2}\right)^{1/5} \left[\frac{v_{wind}}{v_{rec}\kappa_{\pm}} \left(\frac{\ell_D}{\delta}\right)^3\right]^{2/5} = 330 - 20{,}500,\ 10^7 \geq \kappa_{\pm} \geq 10^4\ (170\ \text{MeV} < T_d < 10\ \text{GeV})$$

Reconnection flow supplies particles to Y-line/Current Sheet:

Return Current Formation – space charge limited flow out of hot unmagnetized diffusion region

Direct Accelerator? Geophysics says no, accelerator = field aligned $E_{||}$, reconnection E is perp; could accelerate in B = 0 current channel (Alfven, 1968) – guide field usually exists, suppresses free acceleration

PIC Simulations of Relativistic Reconnection (in Pair Plasma)

Simple Current Sheet Geometry – no Y-line/magnetospheric obstacle

Zenitani and Hoshino 2001-2008

Bessho and Bhattacharjee 2005, 2012

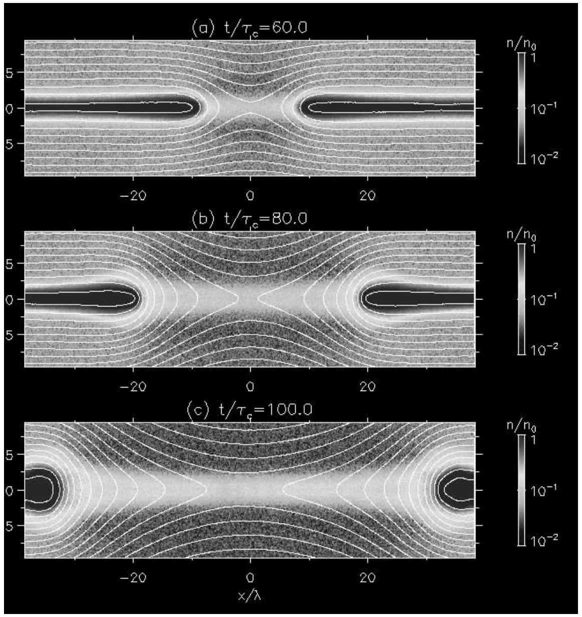
Hesse & Zenitani (NR pairs, 2007)

Sironi & Spitkovsky (2012); Kagan et al (2013)

Cerruti et al (2013 – not analyzed for reconnection physics)

Zenitani & Hoshino snapshots – pairs current sheets tear (fast)

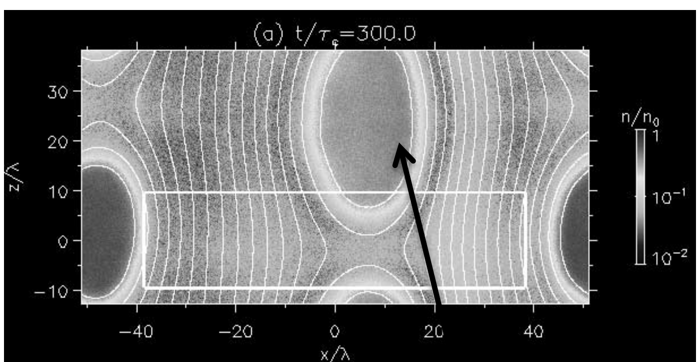
Density & B



t/τ_c=40

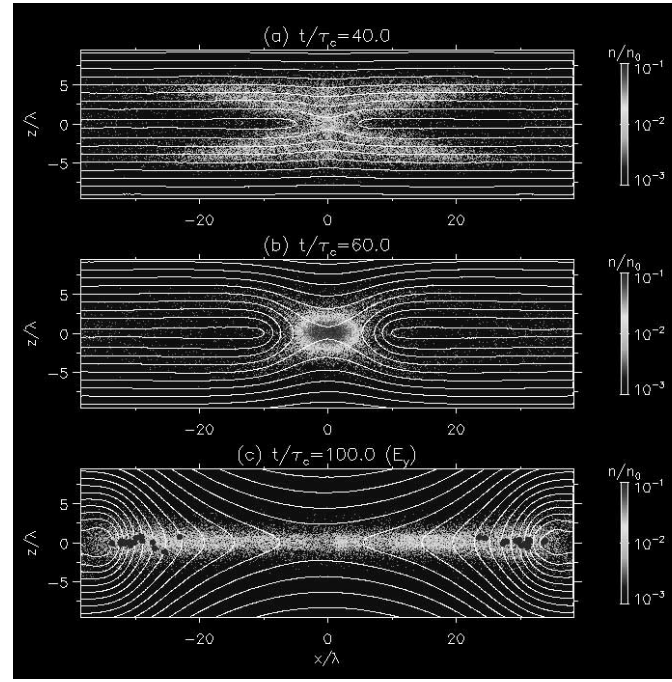
t/τ_c=60

t/τ_c=100



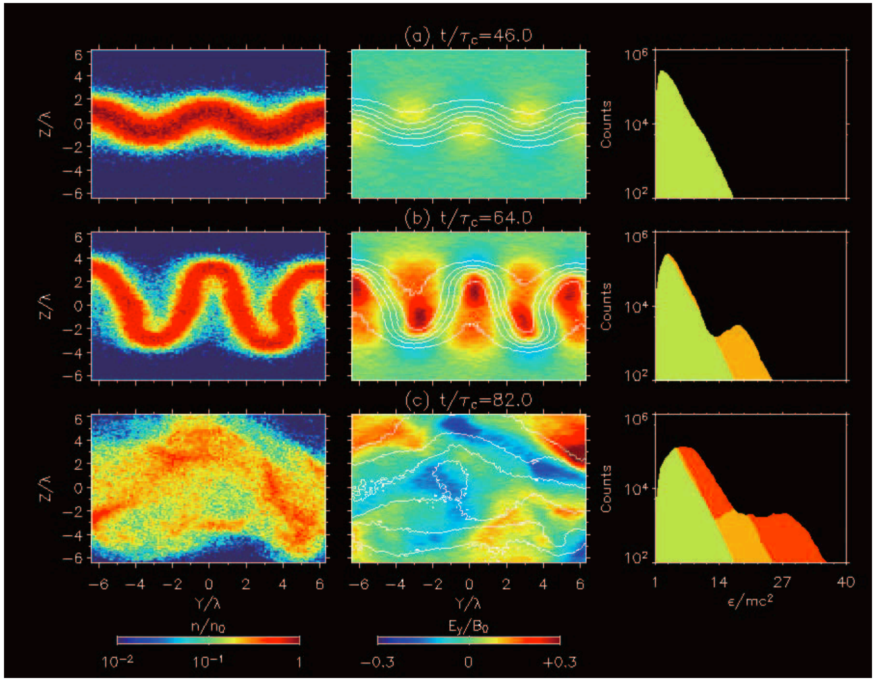
t/τ_c=300

2D Plasmoid

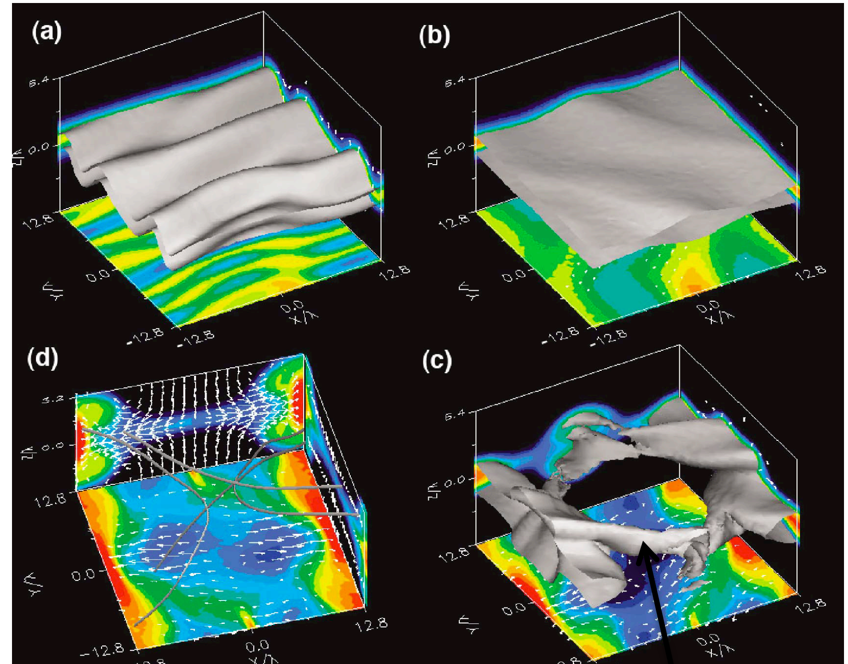


Accelerated Particles spatially,
$\varepsilon > 50\ mc^2$

Sheet Kinks (Drift Kink Instability)



3D – Tearing & Kinks together



Fermi II like acceleration, current sheet broadening

3D plasmoid = flux tube

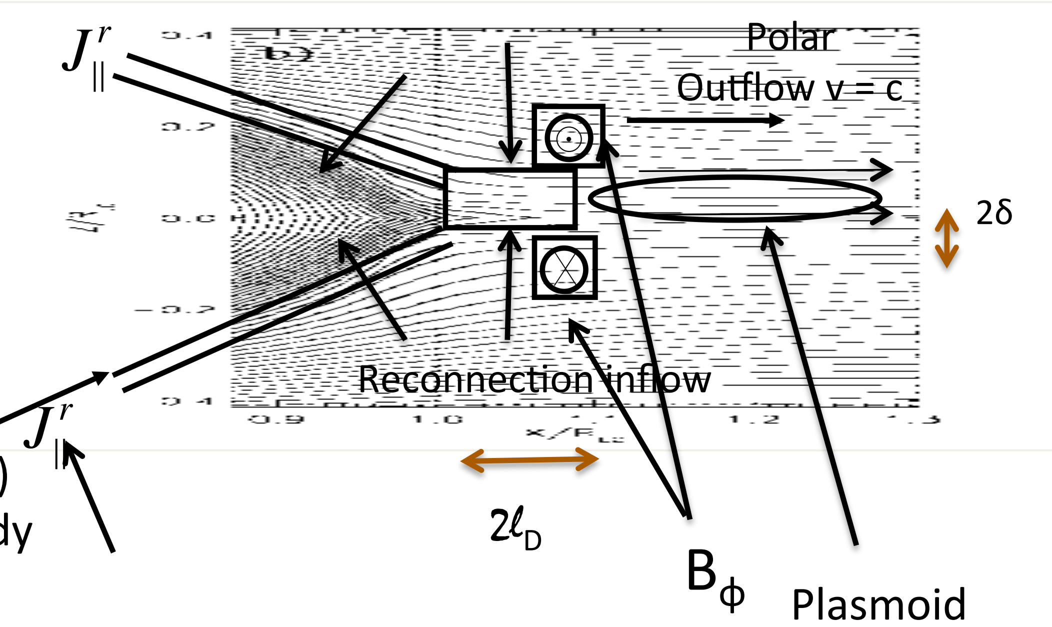
Maximum energies set by residence time – kinks cause drifts out of accelerating E, ‘speiser’ orbits focus particles back into E –

NO UNIQUE ANSWER – set by current sheet length – macroscopic? turbulence coherence lengths? gradient drifts in bent sheets?

Acceleration efficiency – how many particles flow through acceleration (B≈0) region – related to what sets reconnection return current density volume?

Reconnection Flow Model

2 fluid theory of E_{rec}, ℓ_D/δ, etc



Takes pairs from polar outflow/ wind into diffusion region/closed zone/current sheet at speed

$|v_z| = cE_{rec}/B_{ext} = v_{rec}$

Inflow $\text{rate}_{diff} = 2\, n_{wind}\, |v_z|\, 2\pi R_{LC}(2\ell_D)$

Outflow rate = $v_A(\text{out})$: locally steady flow, $\propto \delta$

set inflow = outflow $\Rightarrow n_{diff}$:

$$2\, n_{diff}\, v_A(\text{out}) 2\pi R_{LC}(2\delta) = 2\, n_{\text{polar wind}}\, |v_z|\, 2\pi R_{LC}(2\ell_D)$$

E, B_{out}, ℓ_D, $\delta = T_{diff}/eB_{in}$ Simulations show ℓ_D/δ from a few to ~ 100, $v_A(\text{out}) = c$???

ALL simulators report fast reconnection $v_{rec} = (0.03\text{-}0.3)v_A(\text{upstream})$

All report E_{rec} based on pressure anisotropy: $E_y \propto \partial P_{xy}/\partial x, \partial P_{zy}/\partial z$

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

Diffusion region **unmagnetized**, shear flow:

Useful model: Pressure anisotropy $\longleftrightarrow$ viscous stress:

$$
\begin{aligned}
P_{ij} &= -p_{diff}\delta_{ij} + \nu c\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{1}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right), \\
u_i &= \text{4velocity/c} = \gamma\beta_i, \\
p_{diff} &= 2n_{diff}T_{diff}, \\
\nu &= c\delta = cT_{diff}/eB_{in}
\end{aligned}
$$

Useful model works in non-relativistic current sheet reconnection, gets
E, B_{out}, ℓ_D, $\delta = T_{diff}/eB_{in}$ of simulations ~ OK: viscous heating = adiabatic cooling

Relativistic (young PSR): viscous heating = radiation ("synchrotron" cooling
Relativistic (simulations): viscous heating = adiabatic cooling (Cerruti – radiative)

Solve as in Sweet-Parker model (2D current sheet geometry): $\Longrightarrow$
derivatives: $\partial/\partial z \longrightarrow 1/\delta$, $\partial/\partial x \longrightarrow 1/\ell_D$ - solution still in progress

Use ℓ_D, E from simulations (Kagan et al): , $\ell_D/\delta = 15$, $v_{rec} = 0.05\, v_A(\text{in})$

$$n_{diff} = \frac{\beta_{rec}}{\beta_{exhaust}\beta_{wind}} \frac{\ell_D}{\delta} \frac{n_{pair}}{n_{GJ}} \boxed{\frac{e\Phi / m_\pm c^2}{2\pi R_L^2 r_e}}$$

= GJ density at LC ≅$10^{6.2}$cm^{-3} (Crab), β_{rec}~0.1, β_{wind}=1, ℓ_D/δ =10-100 (PIC sims, model)

$$\frac{n_{diff}}{n_{pair}(\text{wind})} = \frac{\beta_{rec}}{\beta_{exhaust}\beta_{wind}} \frac{\ell_D}{\delta}$$

Multiplicity $\kappa_\pm = n_{pair}/n_{GJ} \gg 10^4$ (perhaps > 10^7 in the Crab)

Diffusion region unmagnetized, particles bounce freely inside:

$$r_{Larmor}(\delta) = \delta = \frac{mc^2\gamma_{bounce}}{eB_{LC}} = \frac{T_d}{e\Phi} R_L$$

Viscous heating in diffusion = synchrotron cooling:

$$\frac{T_d}{m_\pm c^2} = \left(\frac{R_L}{12 r_e} \frac{e\Phi}{m_\pm c^2} \right)^{1/5} \left[\frac{v_{wind}}{v_{rec}\kappa_\pm} \left(\frac{\ell_D}{\delta} \right)^3 \right]^{2/5} = 330 - 20{,}500, 10^7 \geq \kappa_\pm \geq 10^4 \ (170 \text{ MeV} < T_d < 10 \text{ GeV})$$

Density of particles at start of wind current sheet and precipitating onto star = n_{diff}
at start of current channels ~ 10^{13}/cc in Crab

Y-line model same as 2d current sheet?

Current Sheet as Accelerator: Crab flares (Blazars)

a) Where
b) How long? Islands between X-lines merge?
c) E/B_{in}?
d) B_{in}? Is the B field outside the sheet uniform?

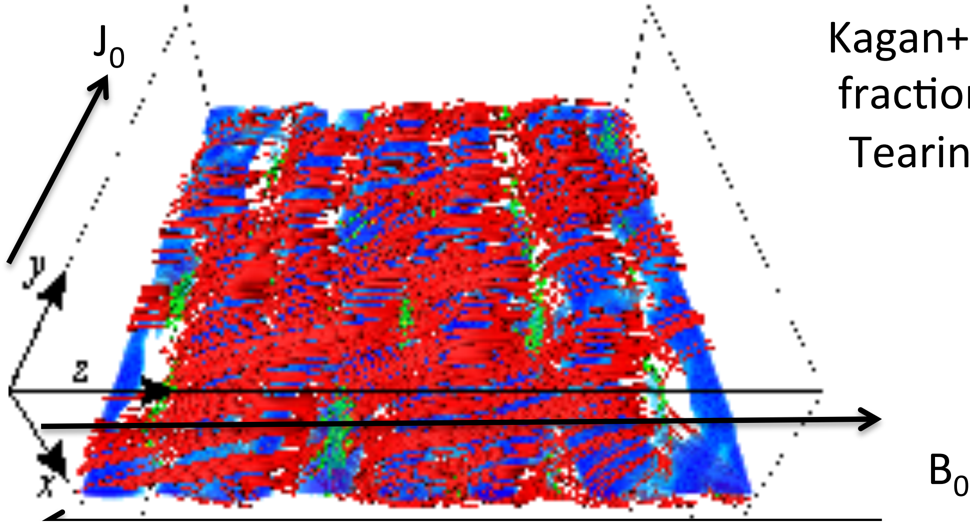
For Crab flares, with no Doppler Boost, L = light days, E/B_{in} < few:
B ~ milligauss

Hard or easy? Hard to have large magnetic overshoots in high σ polar regions, if flux doesn't accumulate, even 1 mG hard to reach

Time interval between flares – flux accumulation time?
Artifact of beaming (Doppler or kinetic)?

Kagan+ - 3D pairs, flux tubes quasi 2D (plasmoids), fraction of volume with E along X-lines small

Tearing dominated (σ not large)



Where is E?