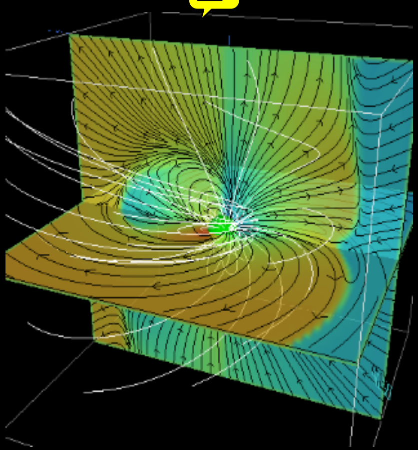
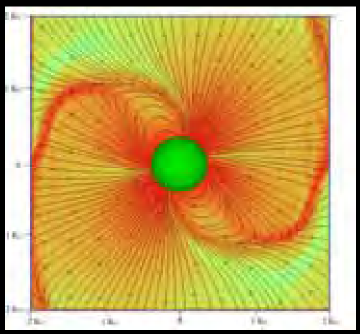
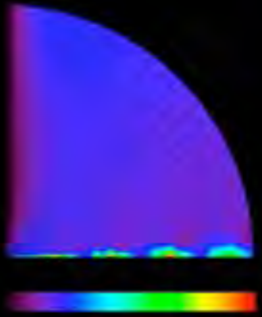
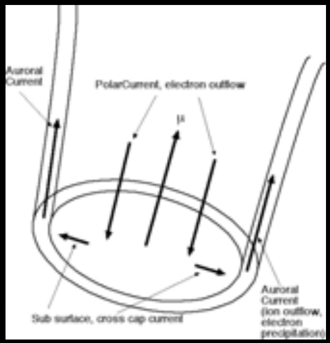
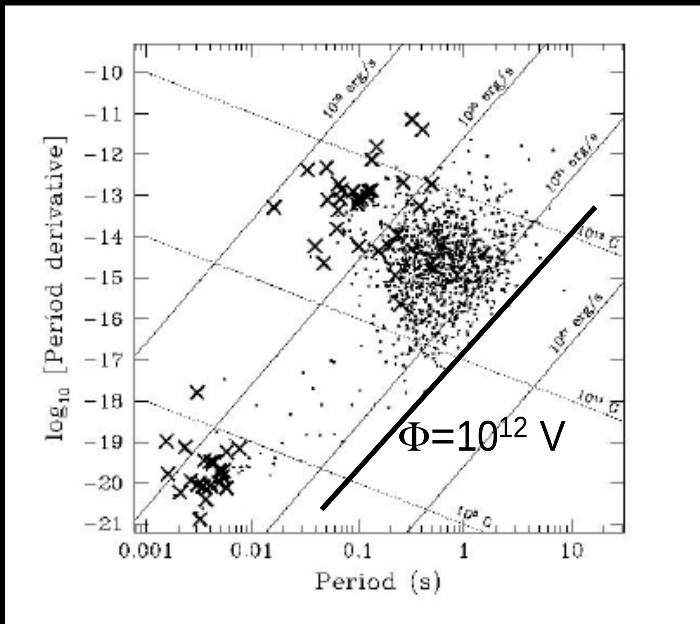
Pulsars: Problems and Prospects

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**, **B. Schmekel**, **A. Spitkovsky**, M. Tavani

Follow the Energy: Spindown



Force Free Magnetosphere -

Spin down by EM torques

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

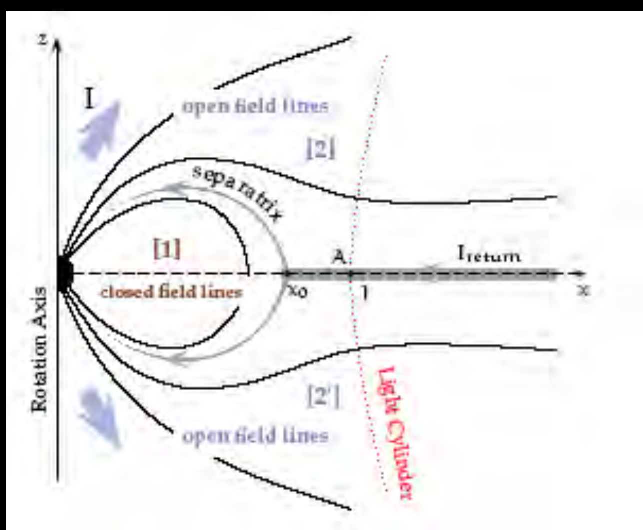
Contopoulos et al (99APJ), Gruzinov (05PRL), Timokhin (06MN, 02-15): FF, aligned rotator, steady state: $R_Y \leq R_L$

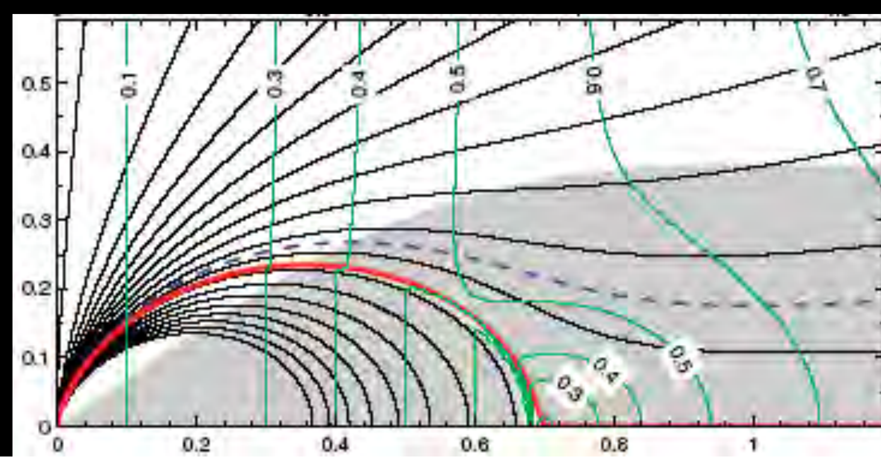
Komissarov 06MN rel MHD, McKinney 06 ApJ

FF: aligned rotator, evolutionary $R_Y \rightarrow R_L$

Bucciantini et al 06MN, rel MHD, pressure driven flow, aligned rotator, evolutionary: $R_Y < R_L$

Spitkovsky 06ApJ: FF, evolutionary, aligned & 3D oblique



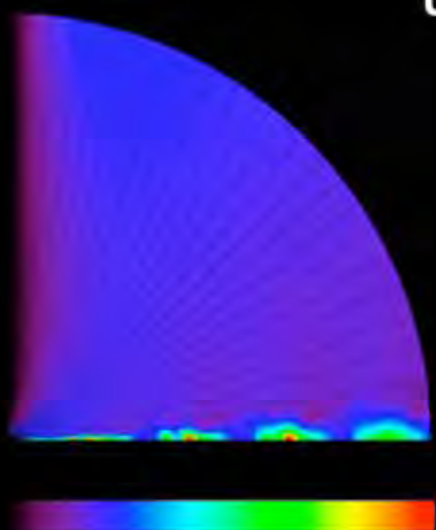


$$R_Y \le R_L$$

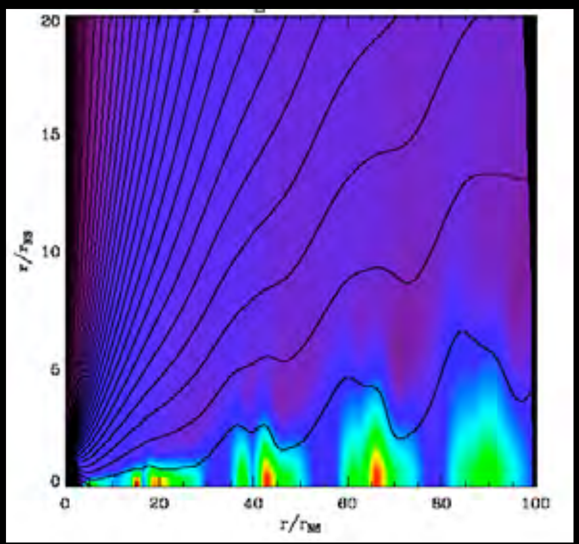
$$n = \frac{\Omega\ddot{\Omega}}{\dot{\Omega}^2} = 3 + 2\frac{\partial \ln\left(1+\frac{R_L}{R_Y}\right)}{\partial \ln \Omega}$$

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

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 ($\delta T/T$ obs) ~ 10-30% ~

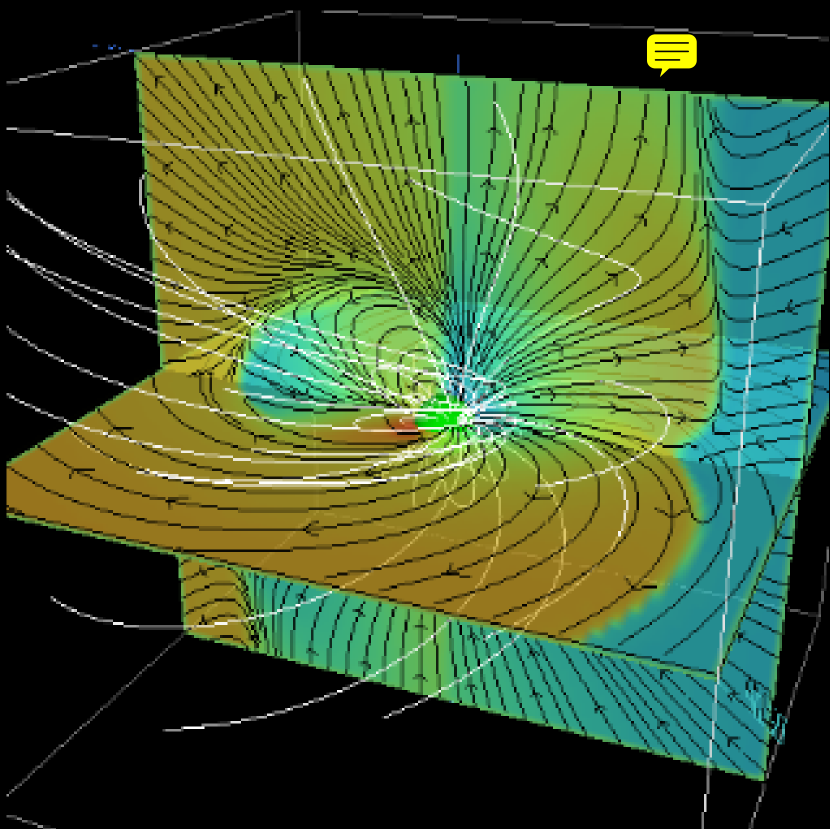


Spindown biases fluctuations toward increasingly open flux??

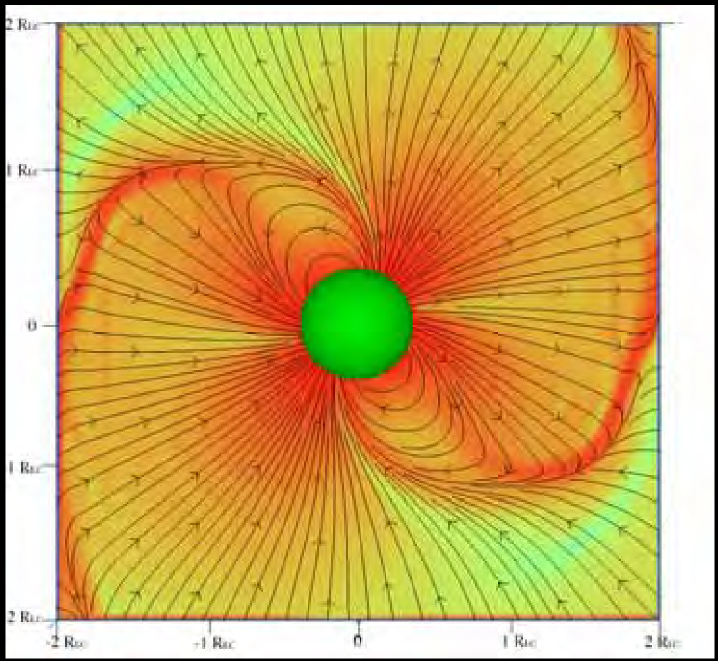
Bucciantini et al 06

Aligned Rotator IS like the oblique object (spindown)

Spitkovsky's (2006) oblique force free rotator (ApJL)



Field Lines (with real open flux)

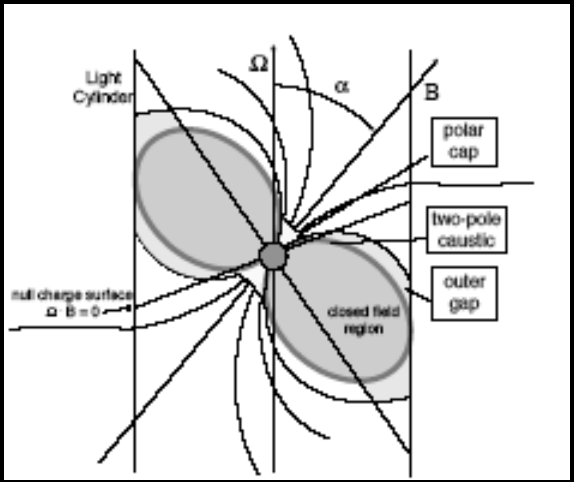


Total Current

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

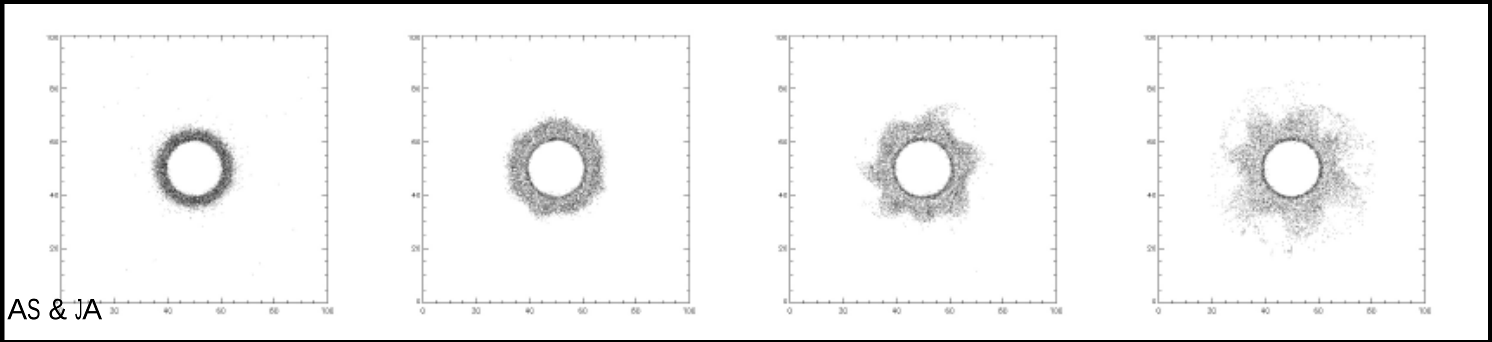
Force Free: Outstanding Issue

Filling the Closed Zone



- Showers of Pairs from Outer Gaps
  doesn't work for larger P
  overheats surface

- Cross B transport - E x B drift (Petri, see 02-24)
  Closed zone not electrically dead, KH unstable, turbulent ExB drift filling, active return current boundary layer (replaces OG as γ emission geometry)



AS & JA

Implications for Emission:

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

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

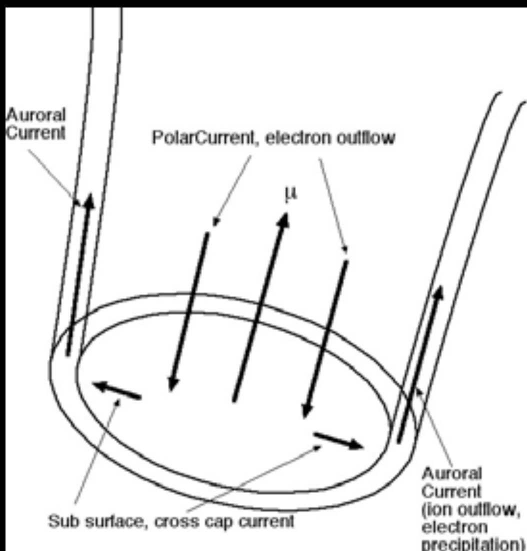
$$\Phi = \sqrt{\frac{\dot{E}_R}{c}} = 4 \times 10^{16}\, Volts \left(\frac{\dot{E}_R}{10^{38.7}\, erg/s}\right)^{1/2} \propto L_{radio},\, L_\gamma(large\, \Phi)$$

electric current in and outside gaps is known, averaged on magnetosphere transit time (~P/π) - electric currents of gaps/emission sites must fit into magnetospheric circuit (when averaged over ***possible*** pair creation/virtual cathode/two stream fluctuations) - or force free magnetospheric model is wrong - but energy all in field, hard to be non-FF

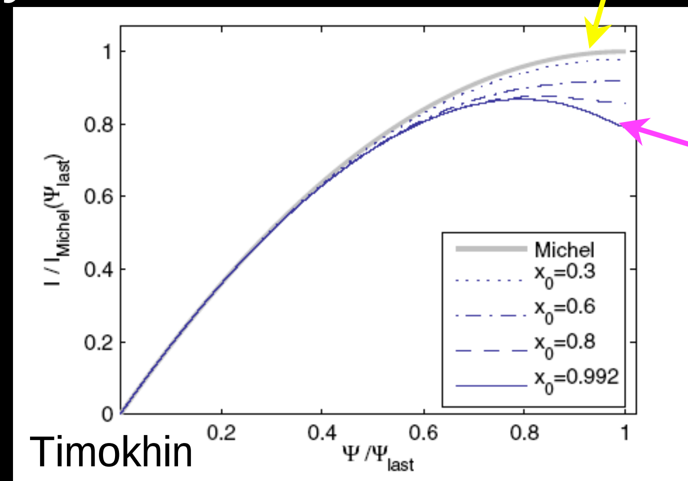
- Location of return current layer determined - realistic site/physics for outer magnetosphere beaming models of high energy emission

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

Aligned rotator for clarity



Monopole



Dipole, $R_Y = R_L$

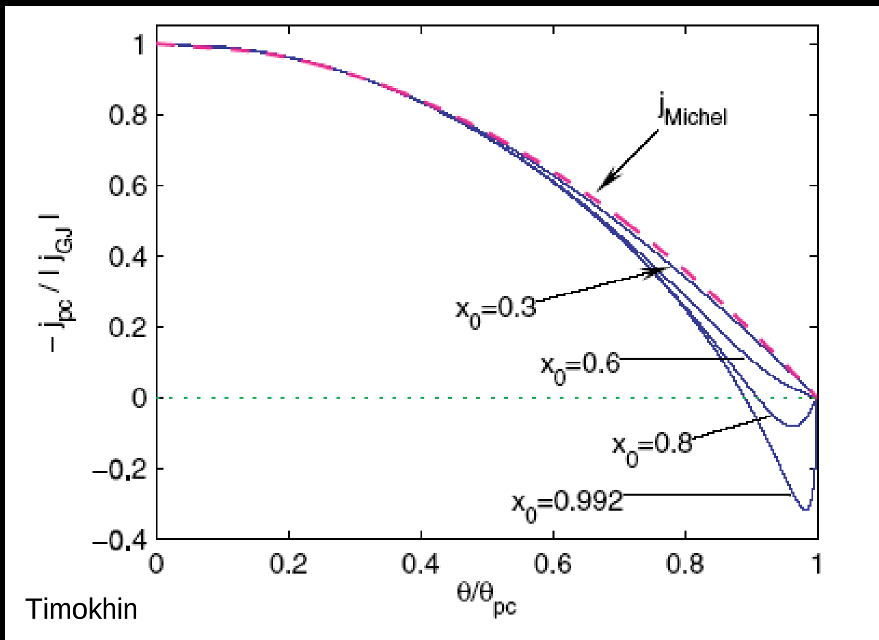
Polar current contained within distance from magnetic axis, j ≠ const

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

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

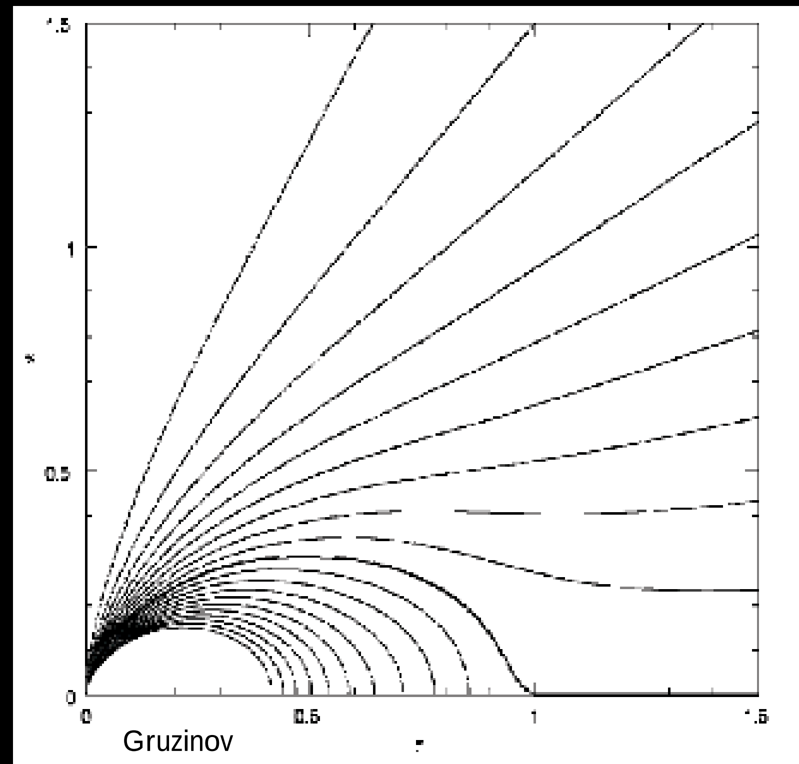
$\Rightarrow$ "small" $E_\parallel$ (~10^8 V/m); same true for outer gaps (geometry different, electrodynamics ~ same)

Effect of Current on $E_{\|}$ (continued)



$$j_{Michel} = \frac{dI}{d\psi} = j_{GJ}\left(1-\frac{\psi}{\psi_{cap}}\right) = J_0\left(1-\frac{\varpi^2}{\varpi_{cap}^2}\right)$$

Monopole field at large r maps monopole current into polar cap



~ monoplar B field, r>>R_L

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

Existing models (RS, FAS, SAF, MT): 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!

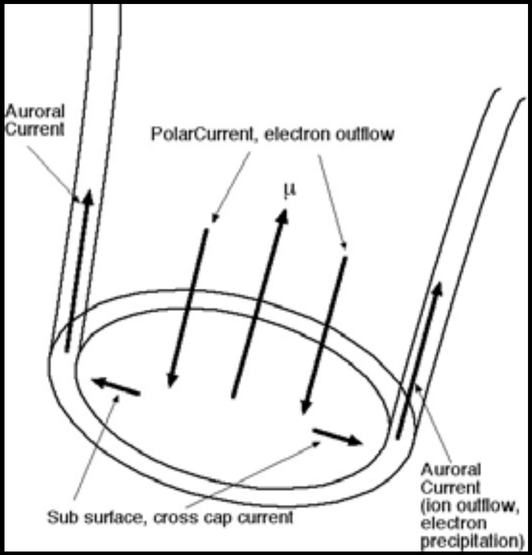
Same issue for outer gaps on open field lines:
starvation gap models (steady or unsteady) produce magnetospheric charge density, not current density,
but all energy in current!

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

Prospect: Beam & Other Models With Magnetospheric Currents:

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 $E_{\|} \rightarrow 0$ at crust surface

- Keep starvation $E_{\|}$ & add electrons shot down from above to reduce j_{pc} with charge density still GJ (Timokhin) - new kind of pair formation front, different gamma rays? PC heating?

- Current + pairs becomes time dependent, averages to FF (GJ, Alber et al, Levinson, others), electric field averages to small starvation (?) value - PC heating?

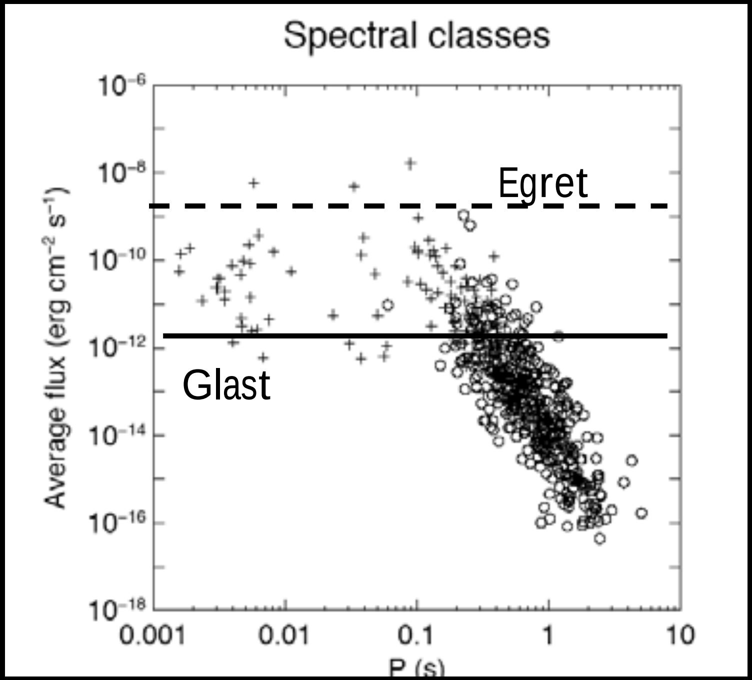
Large $E_{\|}$,~ steady beam: is this really a problem? Large "surface" charges, larger pair creation? (double layers)

Gamma Ray Tests of Existing Gap Models

Outer Gaps: GLAST observations of unidentified EGRET sources, of lower voltage pulsars - predictions?

Polar Caps - so far untested, too faint for EGRET
observe PSR showing core radio emission - straight onto pole ("look down the gun barrel")

SCLF Beam Model, j fixed by charge density



Prediction of Monopolar Current Density Polar Cap Models: ?

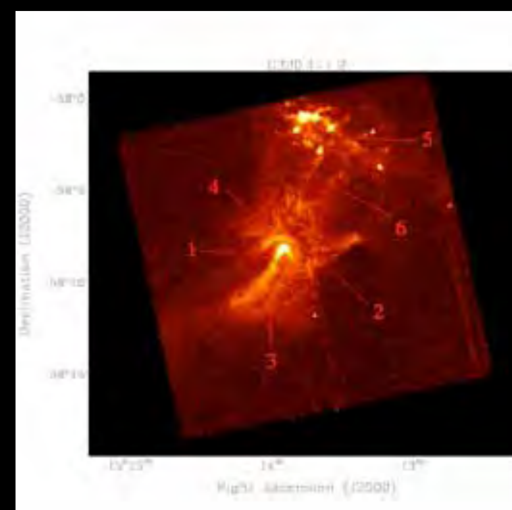
Pulse Shape predictions: ***Use correct Oblique Force Free Model!!!***

Follow the Mass Loss: From Whence all the Pairs?

Pulsar Wind Nebulae: Nebular Synchrotron requires particle injection >> Goldreich-Julian current

PAIR PROBLEM

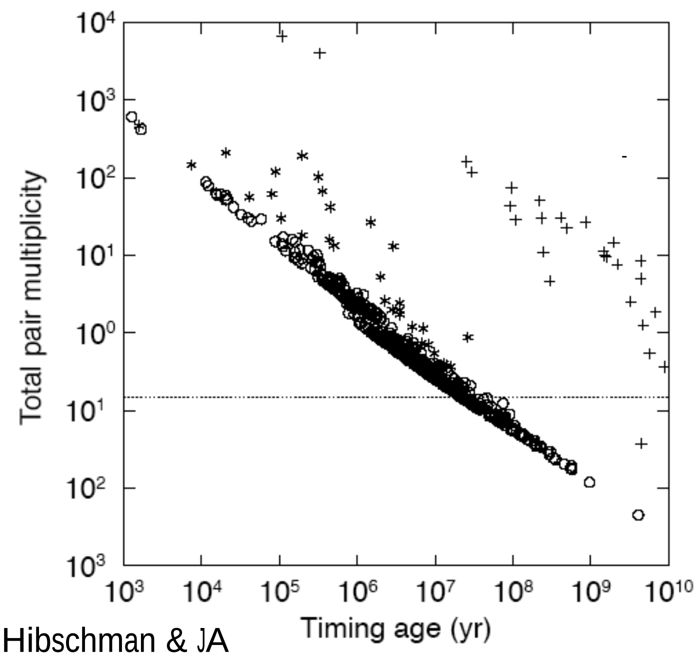
X-Rays:current injection rate (compact, strong B nebulae - Crab, G54,…)
measured rates ~ existing (charge density) gap rates ~10^4 pairs/GJ
Radio measures injection rate averaged over nebular histories,
rate >> all existing gap pair production rates



Where are the Pairs (continued)

Pulsar death line ($\Phi = \sqrt{\dot{E}_R / c} \approx 10^{12}$ V) models need dense ($E_P = 0$)
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



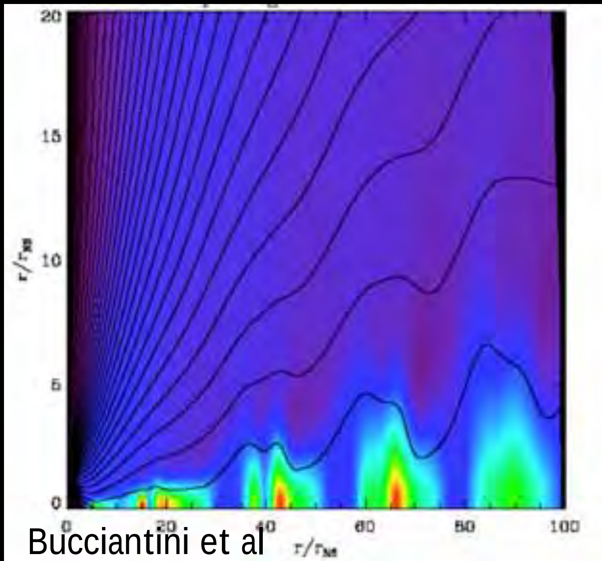
Hibschman & JA

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

All transfer effects need dense pairs - something is missing

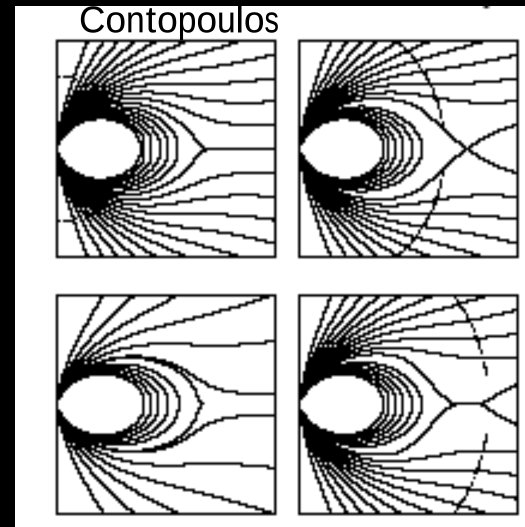
(not non-dipole fields!)

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
  Kinetic Alfven waves, boundary layer $E_{\|}$ - replaces outer gap
- Space charge in boundary current alters polar acceleration(!)
  enhances pair creation (?)
- Kinetic Alfven wave $E_{\|}$ extracts ion return current
- Torque fluctuations, limit cycles built in (drifting, other subpulses)
- Beamed γ-, X-rays from boundary layer? Hollow cone radio?

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

Micropulses ~ polar transit time $T_{pc} \sim \frac{R_*}{c}\left(\frac{R_*}{R_L}\right)^{1/2} \sim 10^{-6} P^{-1/2}$ s

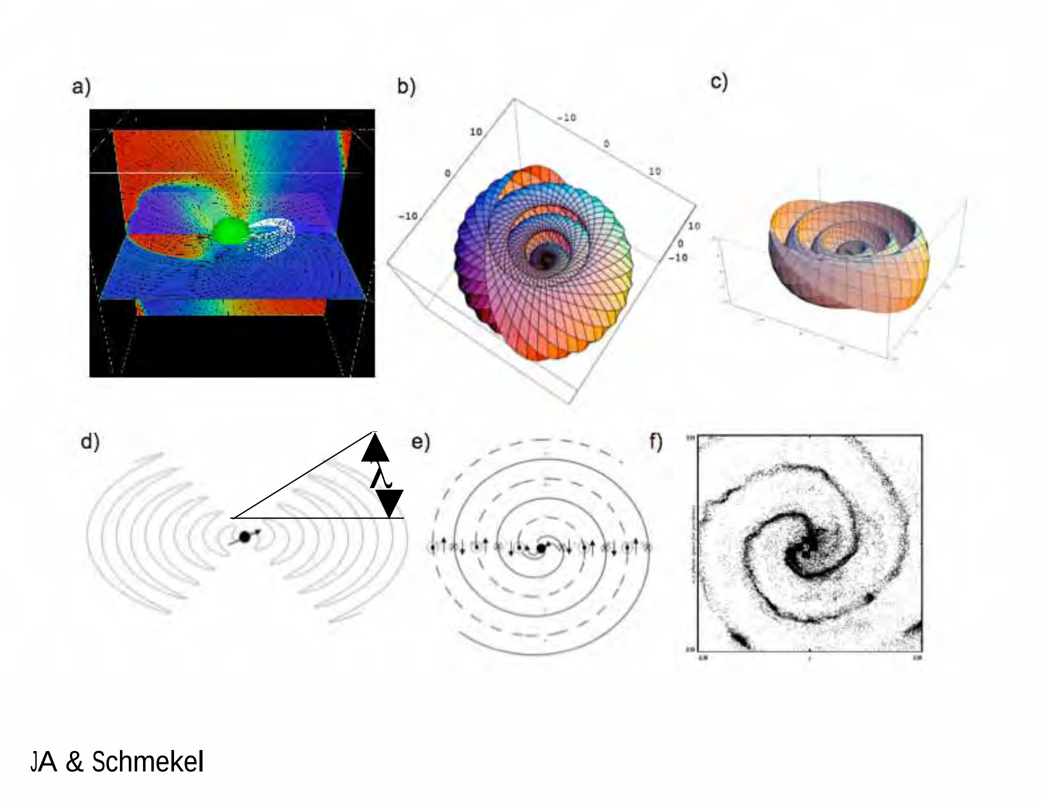
virtual cathode fluctuations?

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

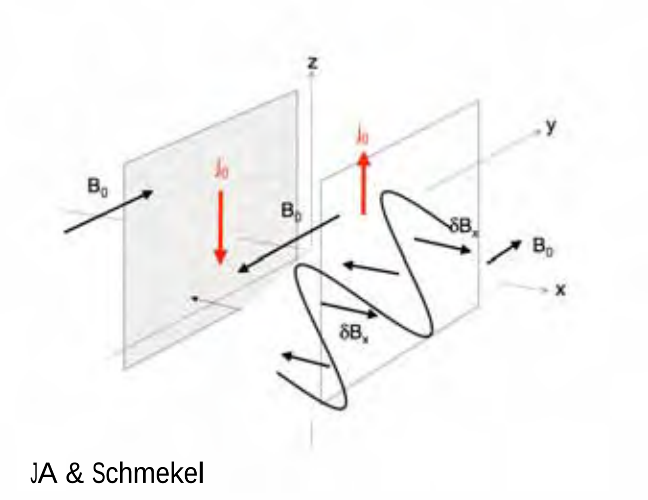
Prospect: Wind Structure, dissipation and (?) emission



Oblique rotator:
striped wind ($-\iota < \lambda < \iota$)

Current sheets blow out at speed c

Sheets dissipate, $R_L << r << R_{shock}$

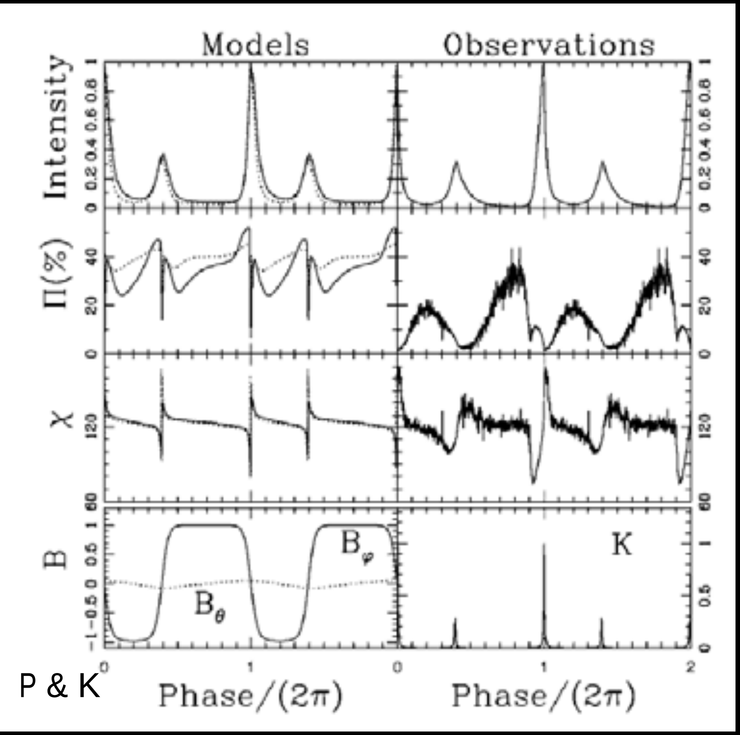


Two Stream (Weibel-like)
Instability of neighboring sheets

Dissipation of Stripes (low σ)?
Radiation from stripes (pulses?)

Asymptotic wind ⟶ aligned rotator?

Sheet Radiation: Pulses? (Kirk et al) - r >> R_L



Dissipating sheets start emitting at $r > r_0 >> R_L$, stop emitting at $r << 2\Gamma^2 r_0$ gives pulsed emission (JA79)
- emissivity profiles assumed

Some similarity to observed gamma-ray pulses can be obtained if Γ not large - certainly << 10^6 - inner wind must be slow, $\Gamma \sim (\sigma_0)^{1/3}$

Polarization (Petri & Kirk 05)

Shows better agreement with Crab optical pol than outer gap models

Oddity - kept B_θ (not in FF theory), dropped B_ϕ (included in FF)

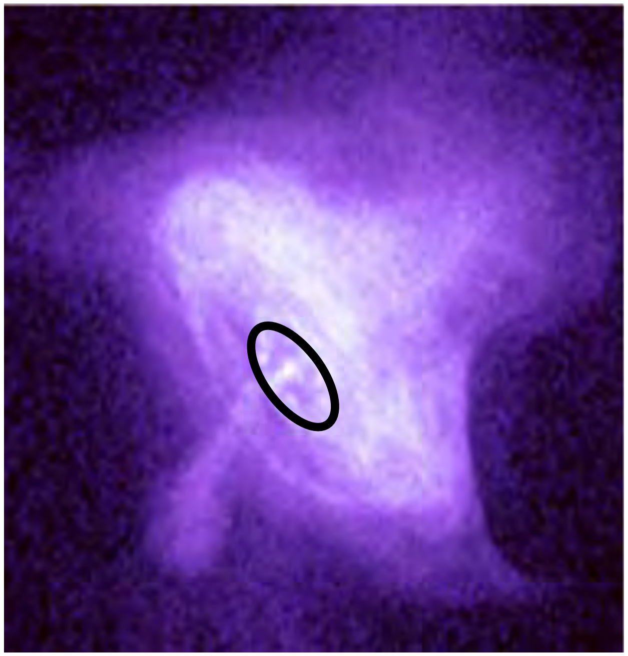
PWN Prospects (compact, confined nebulae):

TeV γ observations consistent with IC upscatter
shock acceleration in rotational equator yields particle spectrum with energies up to $e\Phi$

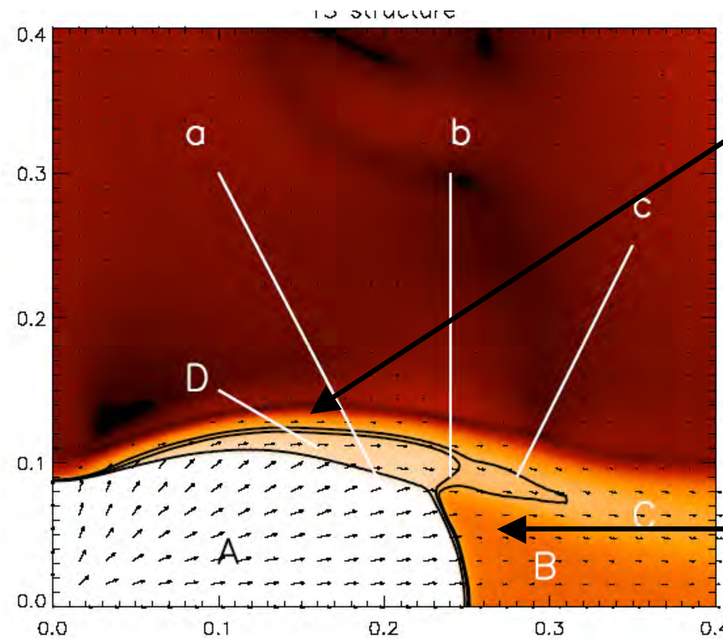
Acceleration zone: return current layer, pair density low, radio emitting particles at higher latitude

Simulations of B ~ 0 shocks may yield observed results "soon"; prediction - acceleration in midplane

Ultra high energy ions in return current layer?
- useful for modeling wisp dynamics
- photopion gamma emission masked by IC
- UHE photopion neutrinos detectable by Ice Cube



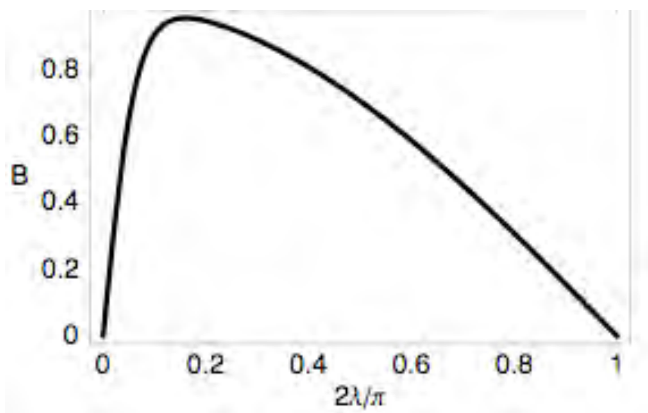
Termination Shock Location



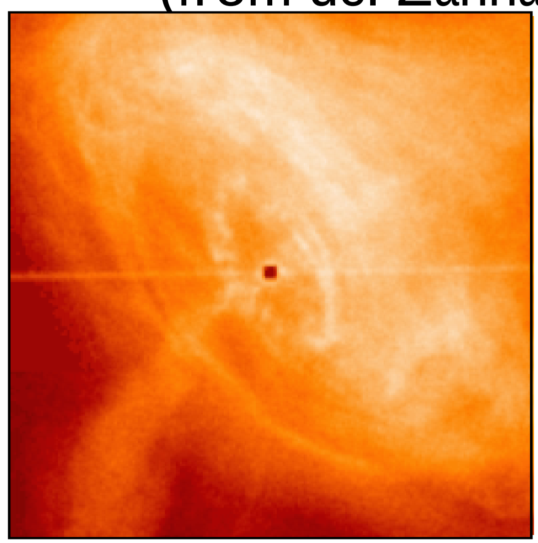
Termination Shock Structure
(from del Zanna et al 04)

High density pairs, mildly magnetized shock

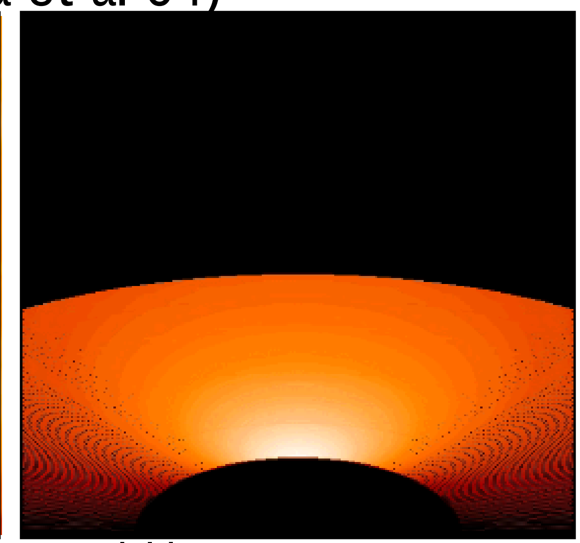
Low density pairs, ions, unmagnetized shock



B strength with latitude -
Unmagnetized in equator



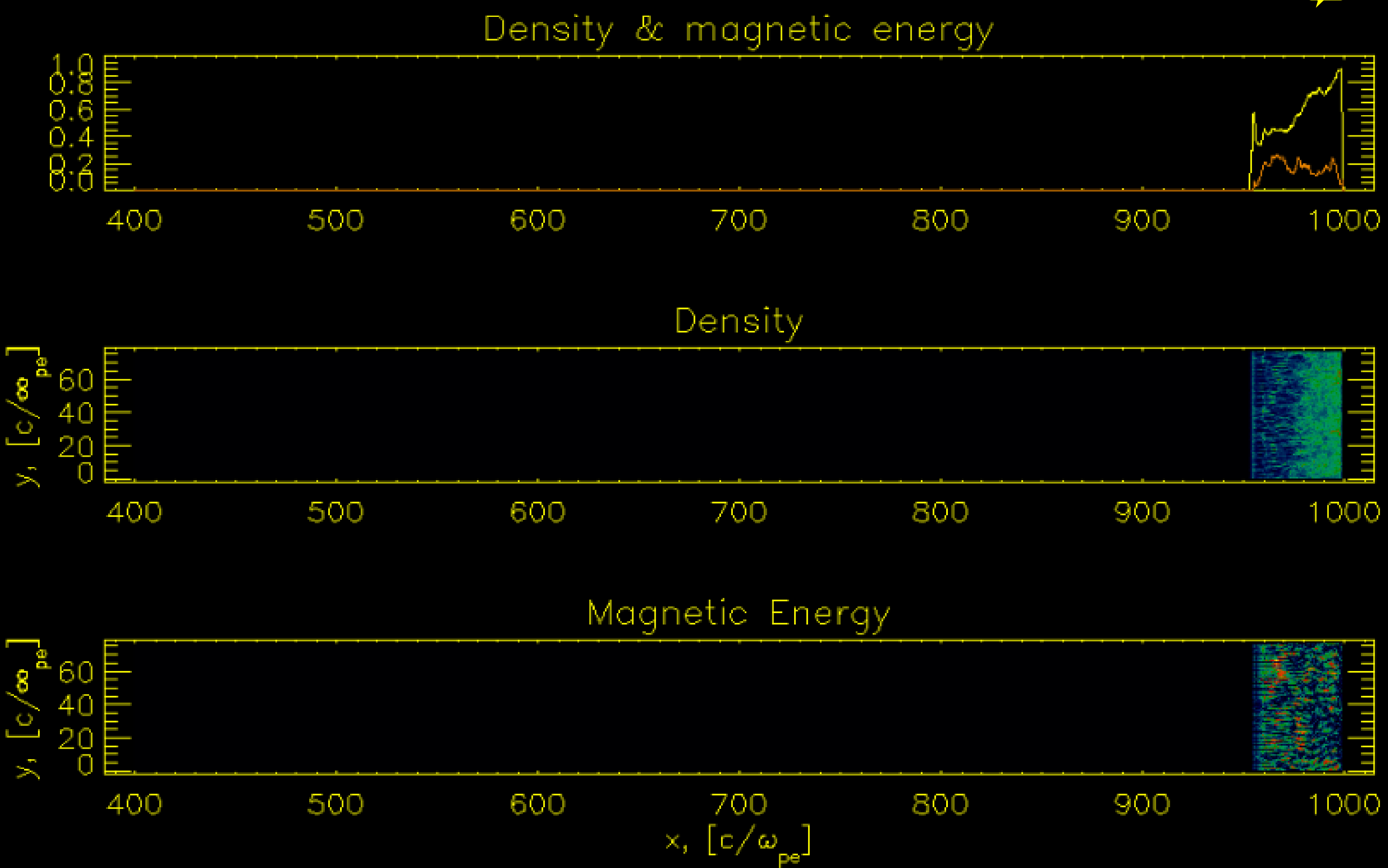
Chandra Movie



Equatorial ion return current compressions (Spitkovsky & JA)

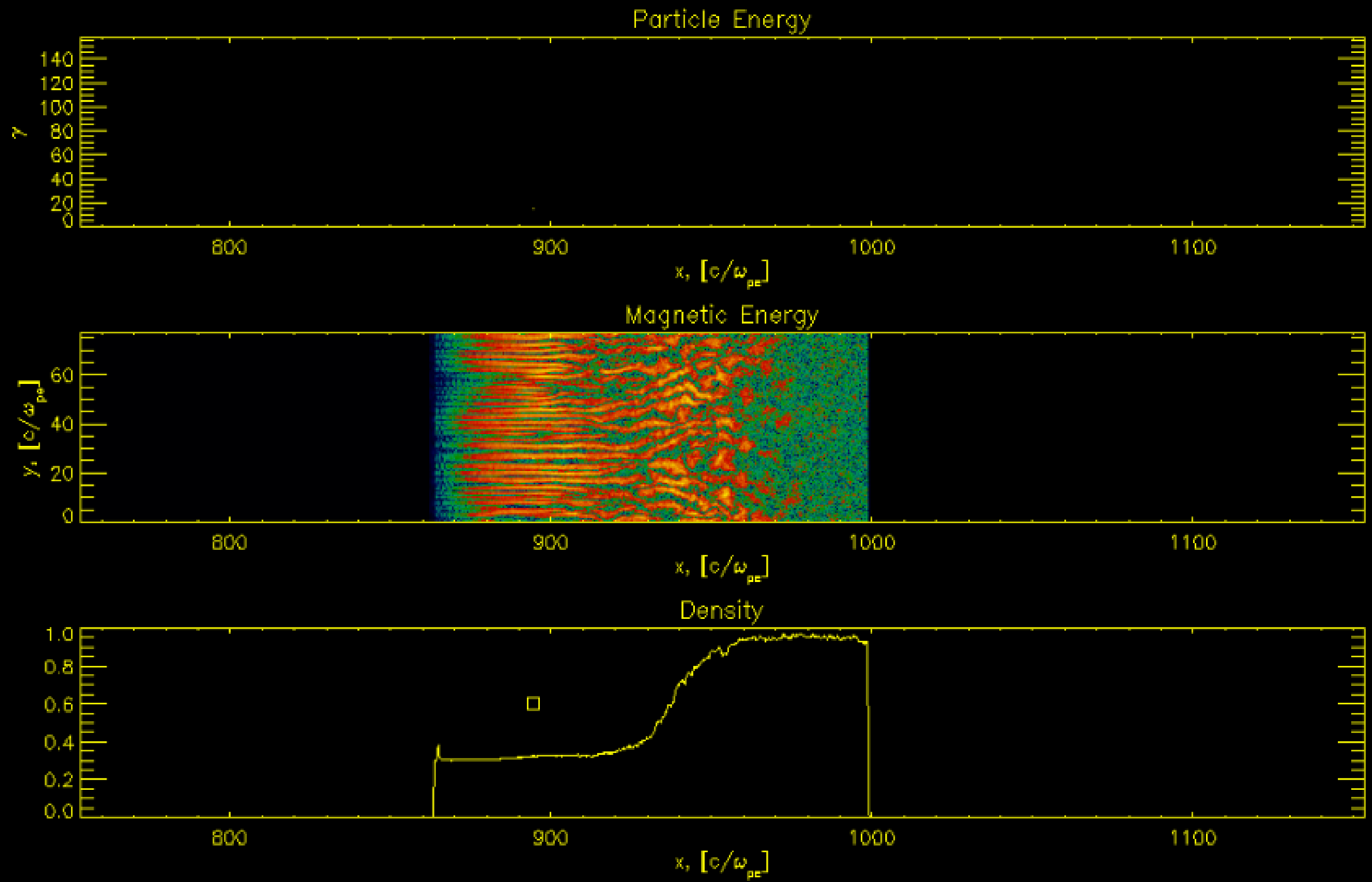
Tentative detection of self-consistent Fermi acceleration: Unmagnetized shock

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



Tentative detection of self-consistent Fermi acceleration

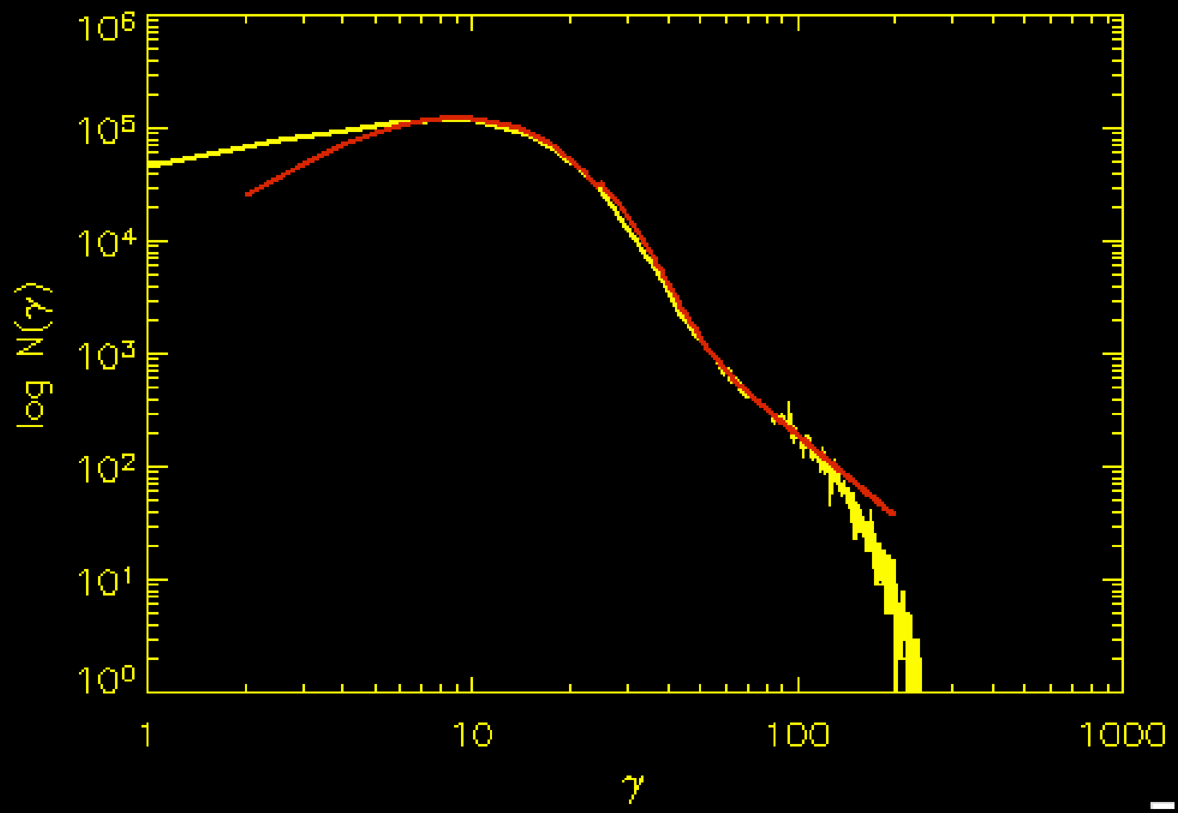
Trace particles that end up in the tail - scattering weakens at large γ, particles lost to tail.



Tentative detection of self-consistent Fermi acceleration

Used 2.5D simulation on large domain (3000x80 c/ω_p). Initial evolution is very similar to 3D. Run long enough to establish steady state. Nonthermal tail develops, $N(E) \sim E^{-2.4}$. Nonthermal contribution is 5% by number, 20% by energy.

Early signature of this process is seen in the 3D also.



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 $E_{\|}$ - kinetic Alfven waves
  - Torque noise, subpulse phase variations
  - Boundary layer acceleration, HE photon emission
  - Enhanced Polar Pair Creation (?)
- Wind Current Sheet Dissipation
  - High $\sigma \rightarrow$ low σ? HE/radio emission from sheets? pulsed? unpulsed? Strong waves?
- PWNe termination shocks
  - unmagnetized in equator, Fermi acceleration(?)
  - larger pair flow at higher latitude from polar cap (?)
  - UHE ν from high energy p-γ – need HE time resolution, polarization.
- Radio Emission and Transfer - ask Usov!
  - Core emission - 2 stream? Conal emission - shear? Transfer!!