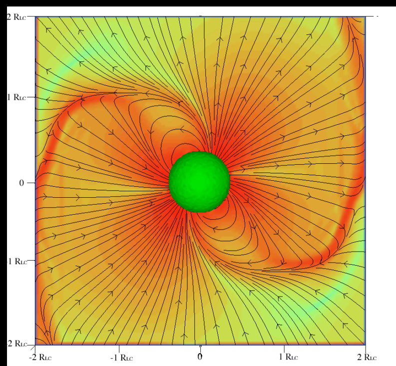
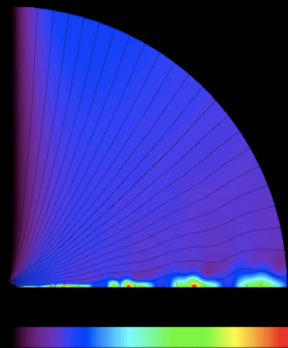
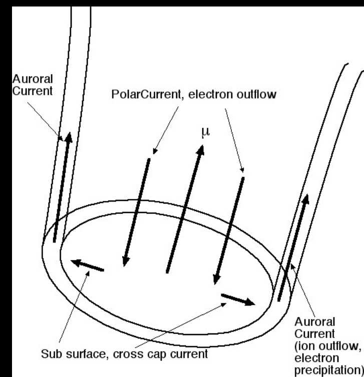
Pulsars as Particle Accelerators: A Current Sheet's Tale*

Jonathan Arons
University of California, Berkeley and Santa Cruz







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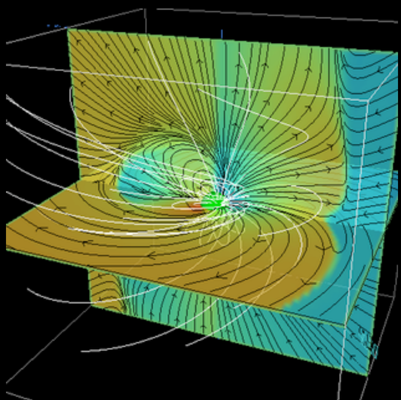

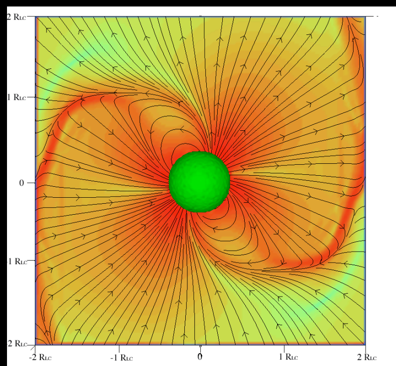

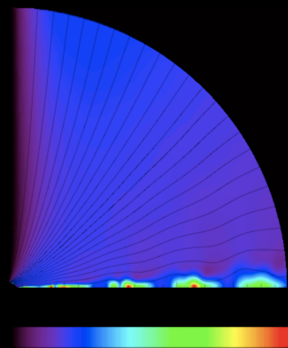

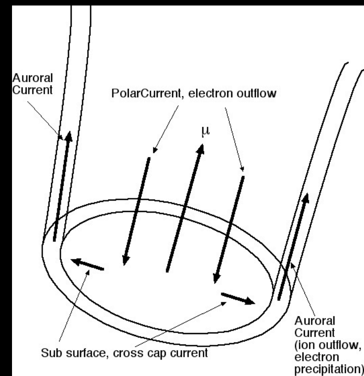

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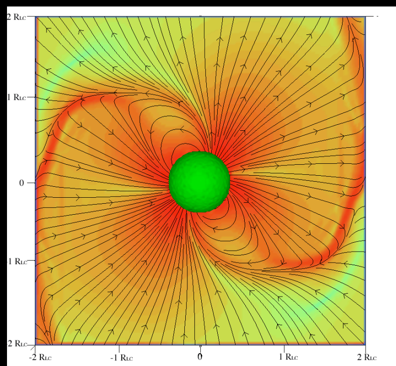

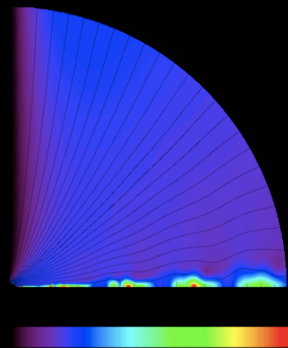

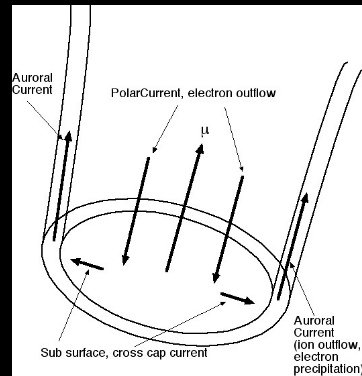

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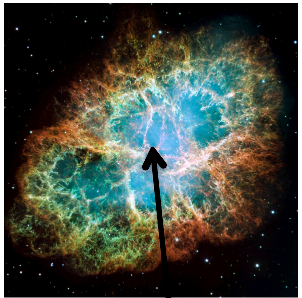
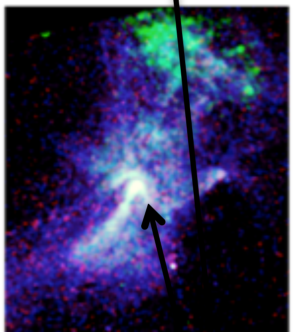
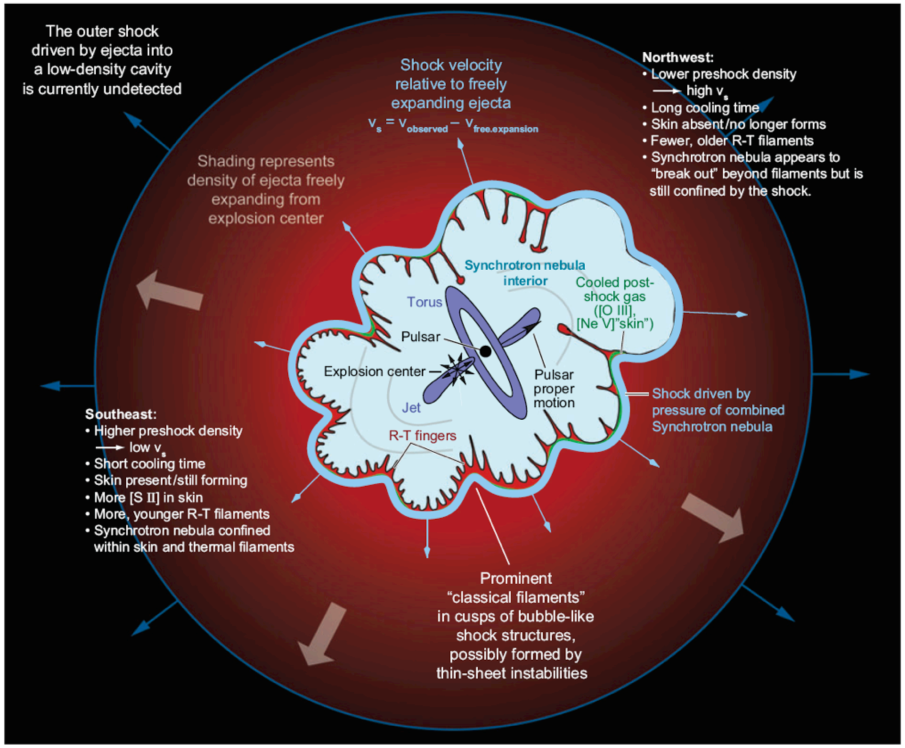
Nebular Gamma Rays (Global Energy Budget): PeVatrons



Crab, D = 2kpc



1509 D = 5 kpc

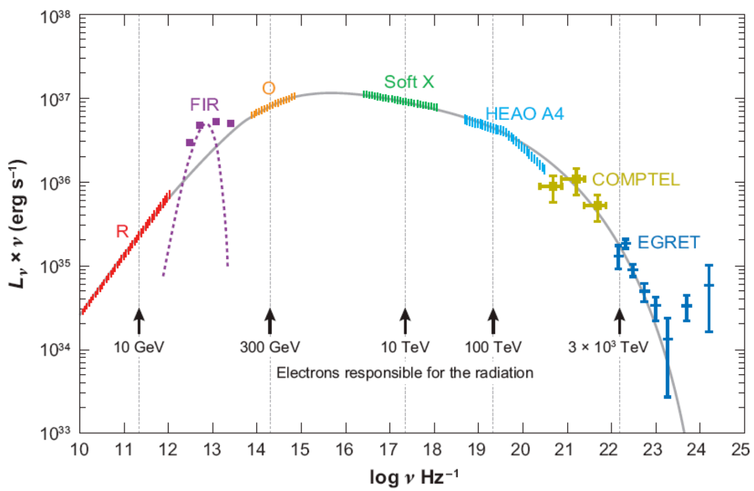


Synchroton Radiation from nonthermal electrons (+ positrons)

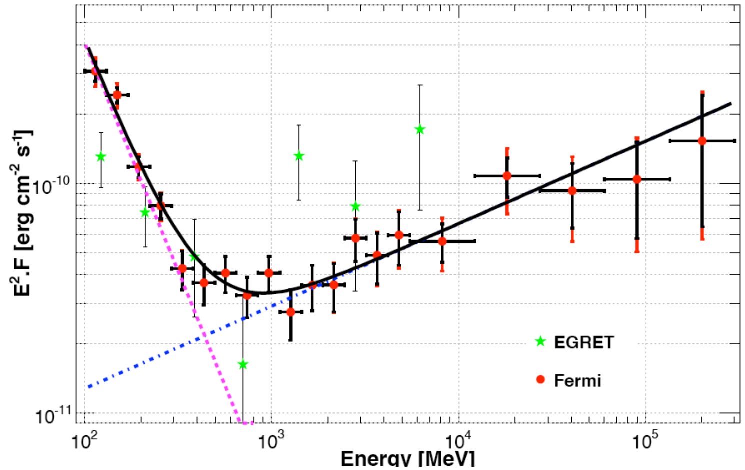
X-ray & optical shown, < 1″ resolution; also radio, IR, gamma ray

Near IR & harder radiation needs continuous power supply – central pulsar

Crab Spectrum, Size vs ε



Synchrotron Spectrum



FERMI LAT AVG

Nebula shrinks with ε increasing up through 10s of keV - nebula is a cooling flow, high energy particles burn off:

VHE (100 MeV – GeV) source, accelerator compact

0.1 - 1 GeV radiation can track days or longer accelerator variability Recent observations (Agile, Fermi) show variability down to hours, big flares $\delta L / L \sim$ months to 1 year separation

$$\varepsilon_{synch} = 1.5\hbar\omega_c\gamma^2 = 100\varepsilon_{100}\,\text{MeV} \Rightarrow$$

$$E = \gamma m_{\pm}c^2 = 2.1\sqrt{\varepsilon_{100}\frac{0.5\,\text{mG}}{B}}\,\text{PeV}$$

$$\text{r}_{\text{Larmor}} = 0.005\sqrt{\varepsilon_{100}\left(\frac{0.5\,\text{mG}}{B}\right)^3}\,\text{pc}$$

$$\text{T}_{\text{synch}} = 2.3\sqrt{\varepsilon_{100}^{-1}\left(\frac{0.5\,\text{mG}}{B}\right)^3}\,\textbf{days}$$

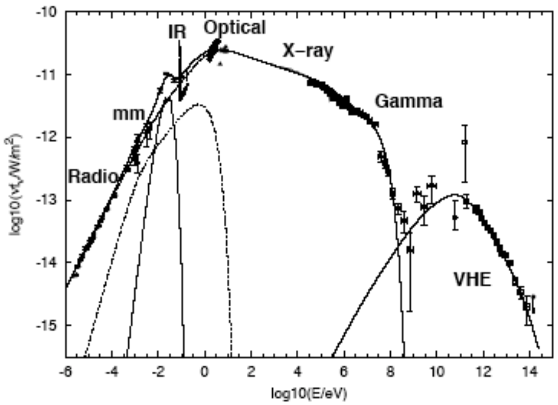
Accelerating E <(?) B: synch spectrum exponentially cutoff $\propto \exp(-\varepsilon/\varepsilon_s)$, $\varepsilon_s = 236(E/B)$ MeV

Cosmic Pevatrons: The Excitation of Pulsar Wind Nebulae

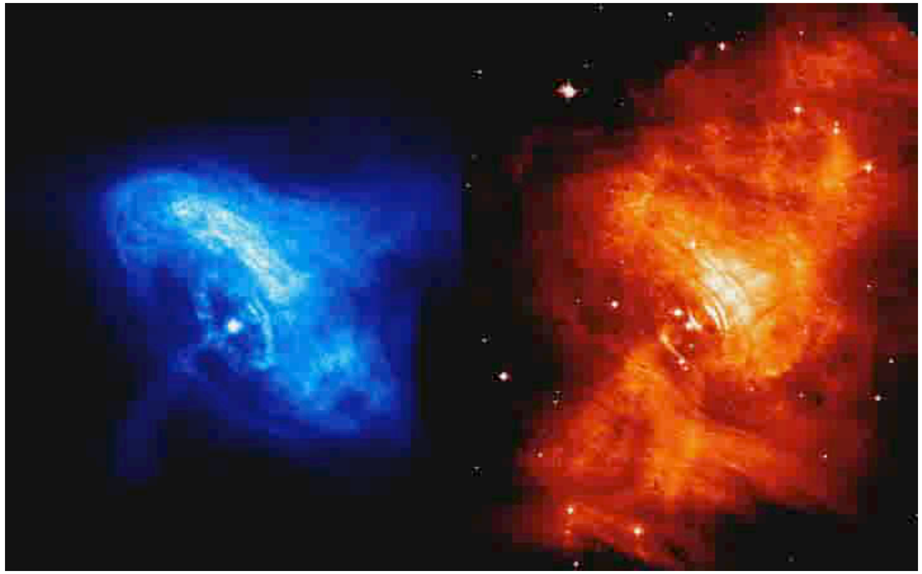
Crab Nebula - 1054 SNR

R, IR, O, X, γ: synchrotron emission
Particle radiative lifetime (γ): days
Continuous power supply: $L_{rad} \sim 10^{38}$ erg/s
Nebula contracts onto central source
with increasing ε(synchrotron emission)
Spectra are NONTHERMAL: acceleration
of $e^-(e^+)$ to PeV energies
Central Pulsar supplies power: Spindown

$$\dot{E}_R = \frac{d}{dt}\frac{1}{2} I\Omega^2 = 5\times 10^{38}\ \text{erg/s},\ \Gamma_{\text{wind}} \approx 10^4$$



Nebula reprocesses 20% of spindown loss
Gamma Ray Flares



Speed of features: ~0.5 c
Inferred upstream 4-speed 10^{3-4}c (was 10^6c)
Chandra ring stationary (no boost) lumpy

Scale: 10^{18} cm

Morphology: sudden deceleration
of magnetized relativistic flow - -
shock converts flow energy to nonthermally
heated electron (+ positron) spectrum –
synchrotron emission in post-shock flow

Basic Questions:
what carries the rotation power? - MHD wind
how is it converted to synchrotron emitting
particle spectra? – **relativistic "shock"**
relativistic reconnection

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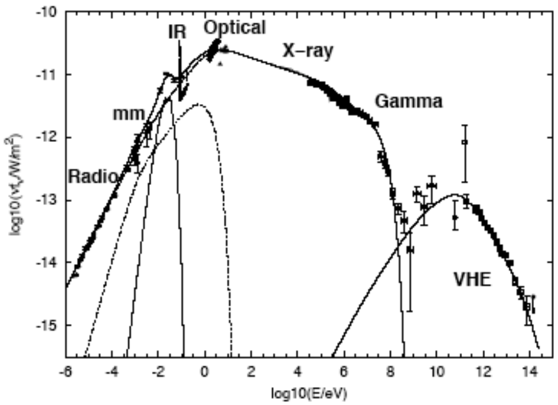

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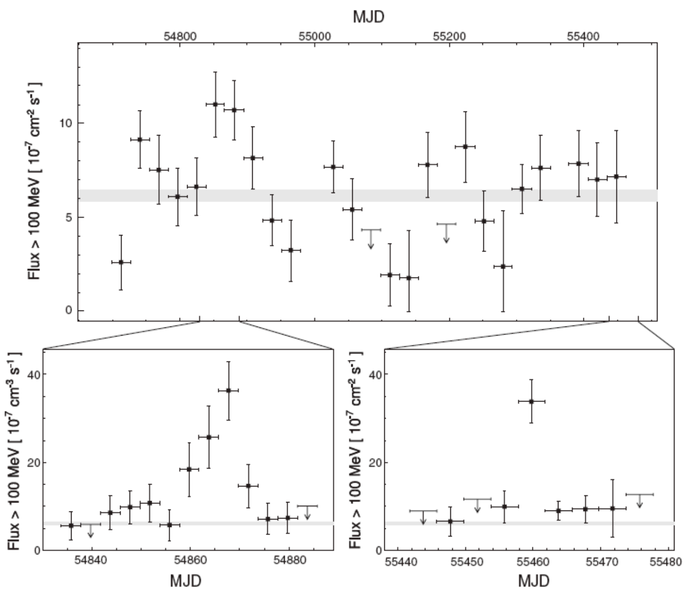
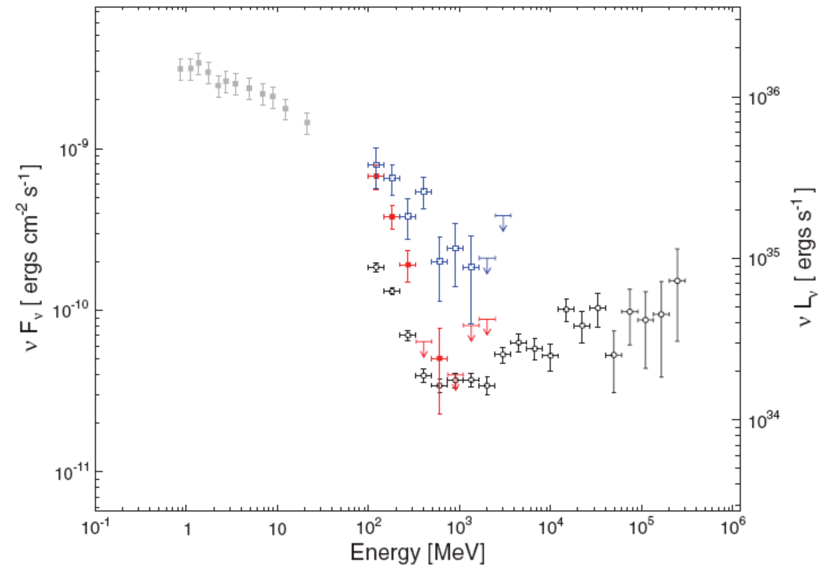
Fast Variability (Gamma Ray)





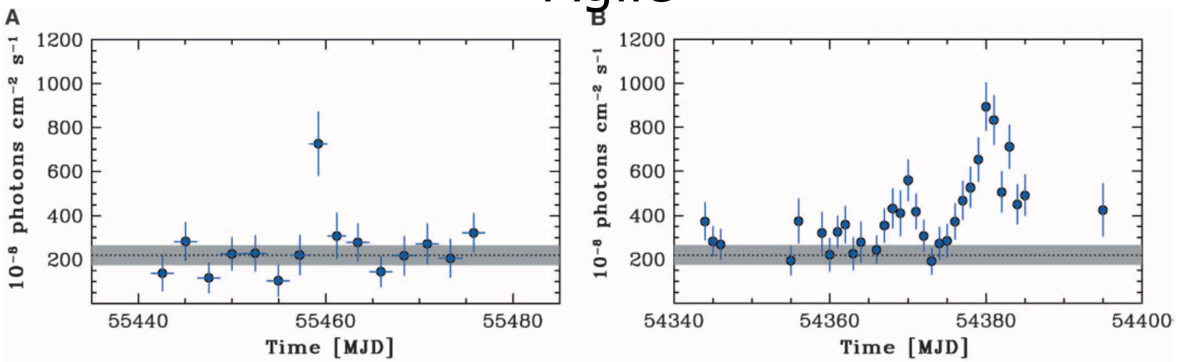
2/2009

9/2010

Average   2/2009   9/2010

Fermi LAT

Agile



9-10/2010

9-10/2007

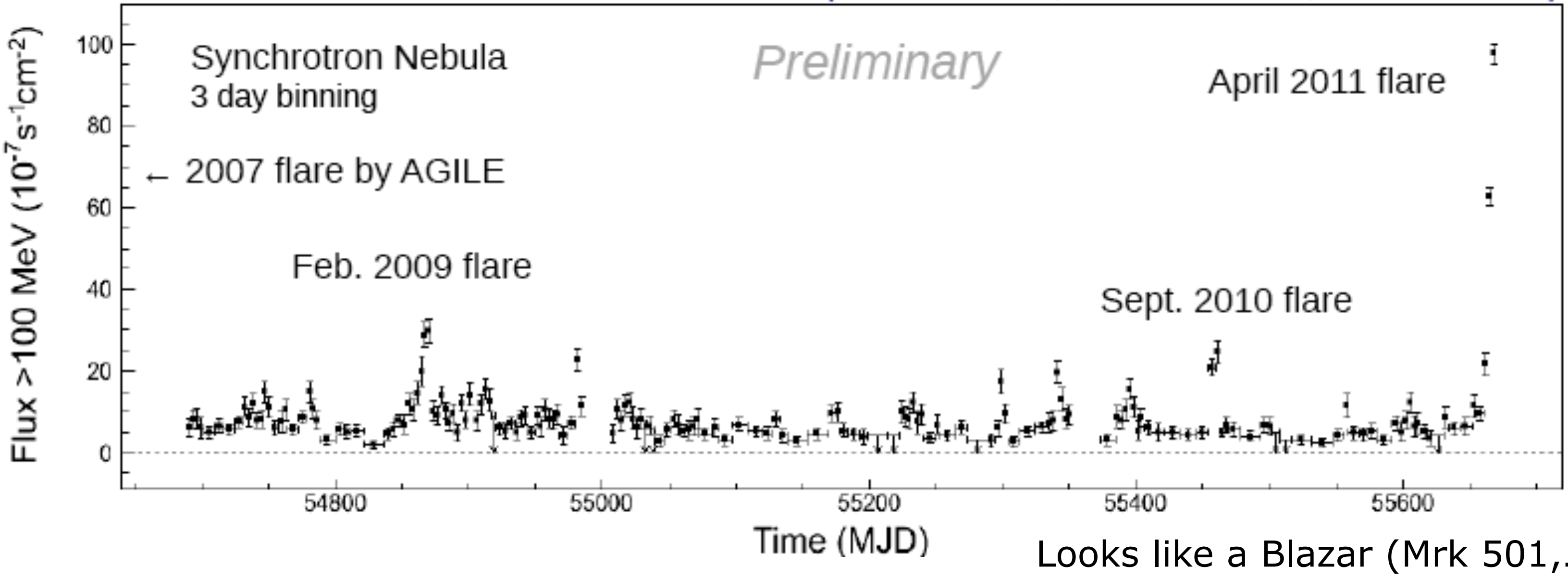
LAT
2011 April 9 to t
>04/15

$$\frac{\delta L}{L} > 5\,(\varepsilon > 100\,MeV)$$

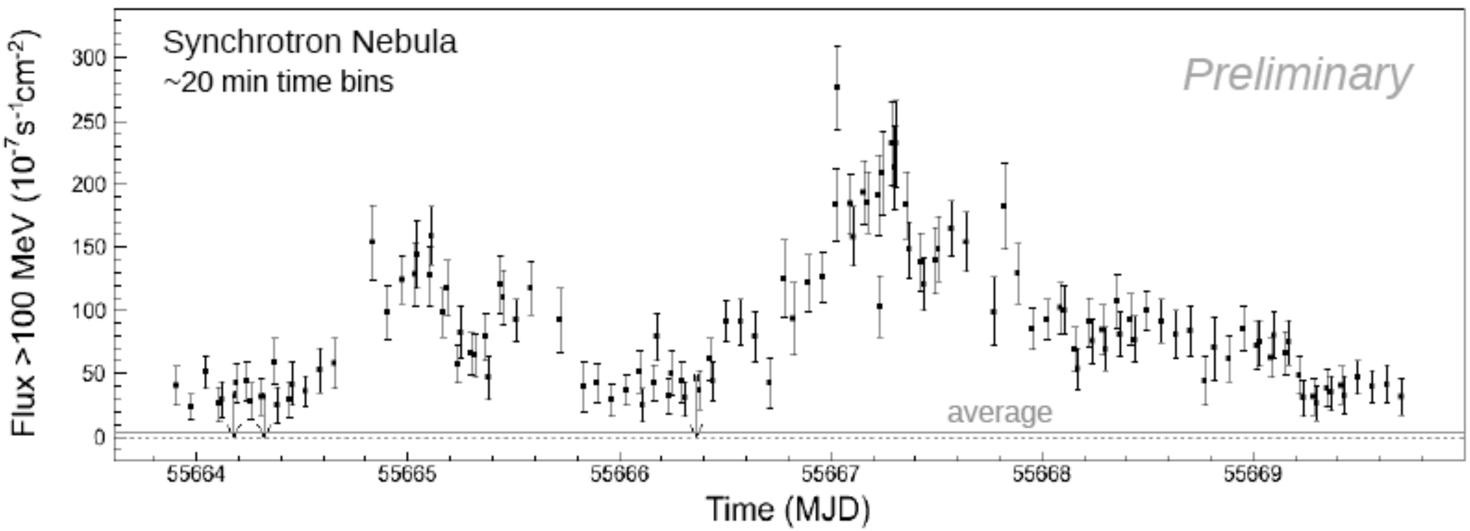
Spectrum peaked around 500 MeV?

Crab Flares – brightest γ source in sky at peak in 04/2011

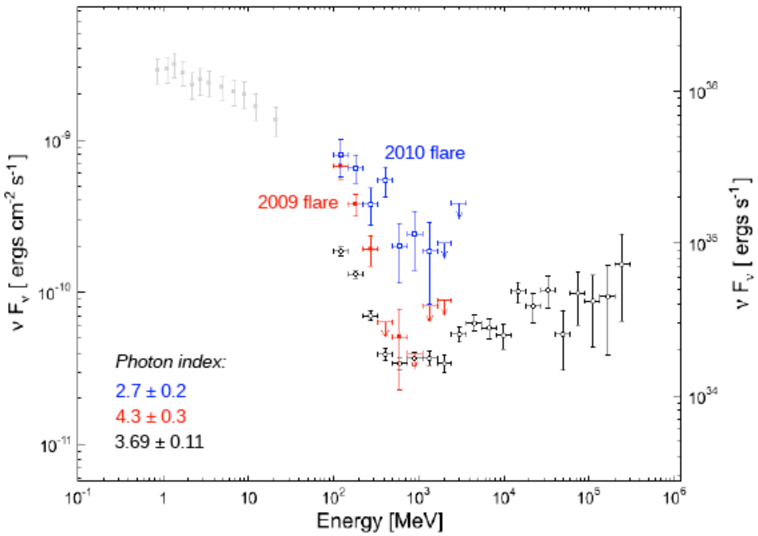
(Abdo et al 2011, Tavani et al 2011, Balbo et al 2011)

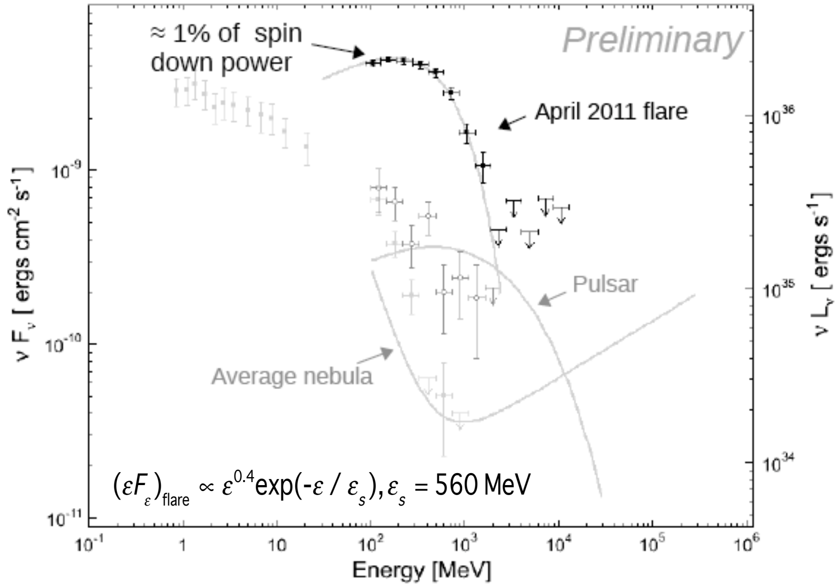


Looks like a Blazar (Mrk 501,…)

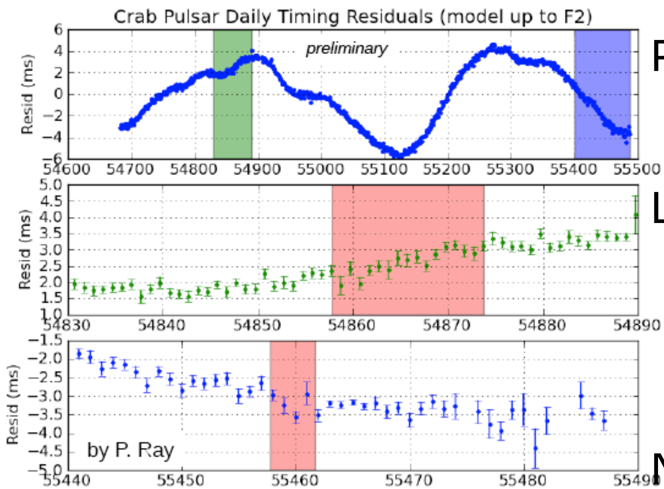


Flare Spectra – Fermi LAT





Total energy budget known - $\dot{E}_R = -I\Omega\dot{\Omega} = 5\times 10^{38}$ erg/s (timing)



Pulsar's spindown & pulsed emission unchanged
– no alteration of magnetosphere

Long delay between observed big flares –
T_{repeat} ~ 6 months – much too early
to draw conclusion, what's big, smaller
variability always present – amplitude spectrum

Nebular Event – particle spectrum ~
beam dump – runaways in E>B zone?

Flare accelerated spectrum – synchrotron cooled electrons + positrons (steady injection)
(inverse Compton? – separate spectral component)

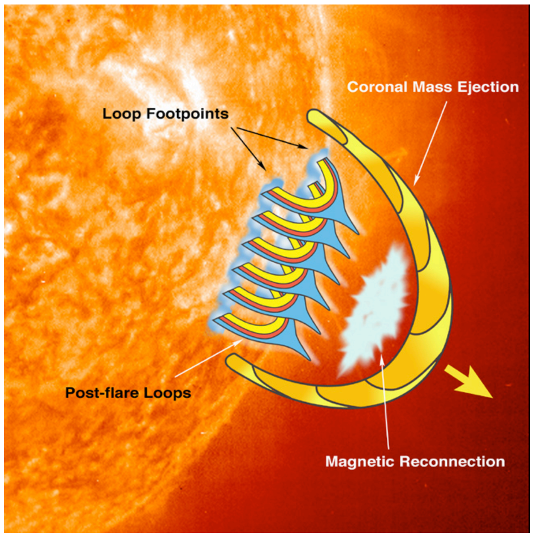
$$\dot{N}_{\text{injected}\pm}(\gamma) \propto \gamma^{-1.2},\ \gamma < \gamma_2 = \frac{3\,\text{PeV}}{m_{\pm}c^2} = 5.8\times 10^9$$

$$e\Phi_{\text{magnetosphere, wind}} = \frac{eI}{c} = e\sqrt{\frac{\dot{E}_R}{c}} = 40\ \text{PeV - 10\% of maximum voltage accessed}$$

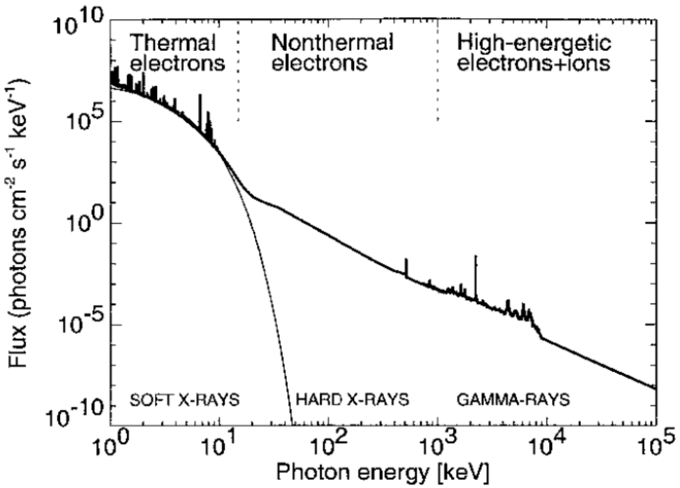
$$\dot{E}_R = I\Phi = \frac{\Omega^4\mu^2}{c^3},\ \mu = \text{magnetic dipole moment}$$

$$L_{flare}^{(peak)} \approx 0.1\dot{E}_R = 0.1I\Phi = 0.1c\Phi^2\left(\Phi = I\mathcal{R},\ \mathcal{R} = \frac{1}{c}\right)$$

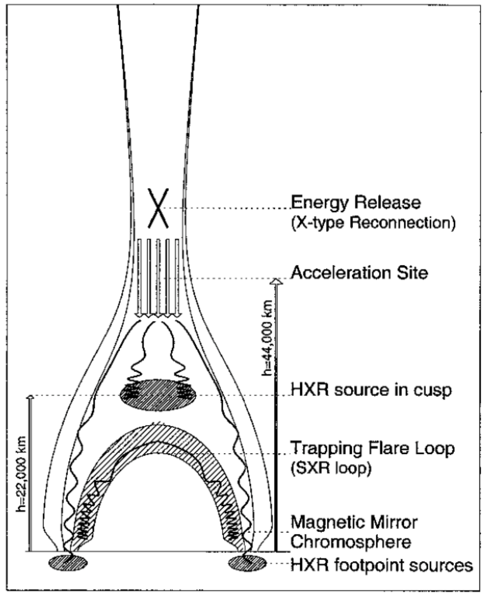
Spectrum, impulsive behavior ~ ultrarelativistic clone of solar flare impulsive X-rays:
bursty reconnection accelerated electron beams – collisionless tearing (?) of large scale current sheet into current filaments, magnetic islands



http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/



Composite large flare photon spectrum



Nebular Energization: Radiatively Inefficient Relativistic MHD Wind

Energy transported to world by MHD wind: outflow is dense
Outflow MHD-like ($E \bullet B = 0$ possible) if

$$\dot{N}_{\pm} \gg \frac{2c\Phi}{e} = 2\dot{N}_{GJ} \approx 2\times 10^{34}\frac{\Phi}{10^{16.6}\,V}\,s^{-1};\ c\Phi = \text{"Goldreich-Julian" electric current}$$

$$\dot{M} = 2m_{\pm}\dot{N}_{\pm} = \textit{mass loss rate}$$

observations (Crab as proxy for all) - nebula as calorimeter
synchrotron cooling time < nebula age = 957 years (O, X, γ)

$\left(\dot{N}_{\pm}\right)_{OX\gamma} \approx 2\times 10^{38}\ \mathrm{s}^{-1}$ required, $e^{\pm}$ pair creation by pulsar only source

~ pair creation rate found in 2nd generation models

- nebula as pair plasma storage device (inertial confinement): R, IR

$(\dot{N}_{\pm})_R > 10^{40}\ s^{-1}$(Crab) >> pair creation models (3rd generation under development, AT & JA)

Multiplicity $\kappa_{\pm} \equiv \frac{2\dot{N}_{\pm}}{\dot{N}_{GJ}}$ **$>10^6$ (Crab), $>10^5$ in 5 other PWNe (Bucciantini + 2010):**

pair creation models challenged

PAIR "OBSERVATIONS"

X-Rays: injection rate measured from X-rays in compact, strong B nebulae –

Crab, G54,...; rapid synchrotron cooling: calorimeters

measured calorimeter injection rates ~ existing gap model rates

$\kappa_\pm = \dot{N}_\pm / \dot{N}_R \lesssim 10^4$ pairs/current carrier

Radio measures injection rate <u>averaged over nebular histories</u>, inferred $\kappa_\pm > 10^{5\text{-}6} >>$ existing pair creation models

From evolutionary modeling of pulsar wind nebulae

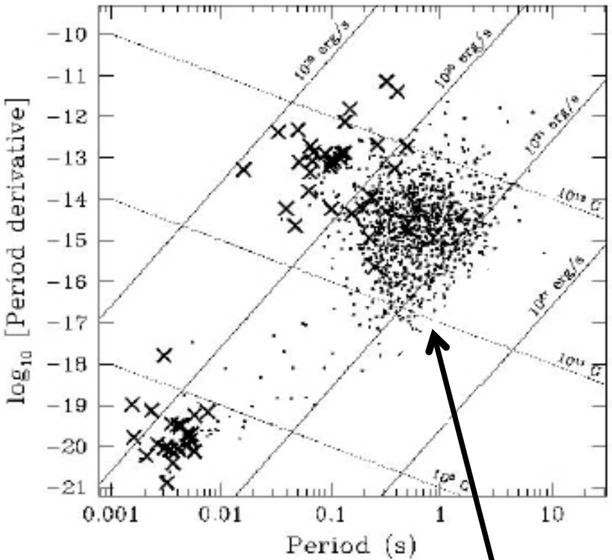
$$\sigma = \frac{B^2}{8\pi m_\pm c^2 n_\pm \Gamma_{wind}} \ll 1 (\sim 0.02 \text{ inferred}) \text{ at wind termination} \Rightarrow \Gamma_{wind} = \frac{e\Phi}{2m_\pm c^2 \kappa_\pm} \sim 10^3 - 10^4$$

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

(Bucciantini, JA, Amato 2010)

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) : $1.4 \le n \le 2.8$

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

magnetosphere has plasma with dissipation ("reconnection")?

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

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

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

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

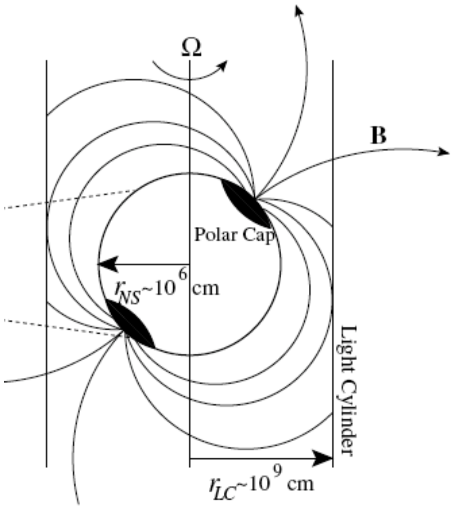
$$R_L = R_{Alfven} = \frac{c}{\Omega} = 48{,}000P \text{ km}$$

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

$$I_R = c\Phi$$

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

Interlude: Pulsar Theory



Rotating magnet - angular velocity Ω (~few - hundreds)

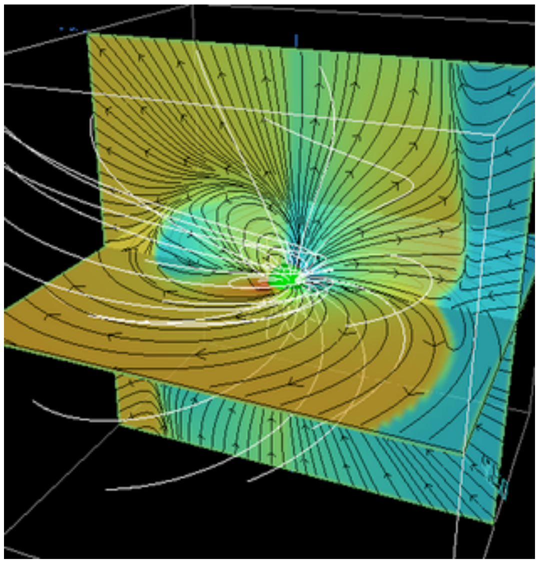
Rotating Magnet has voltage (dynamo):

Magnetic moment μ~10^{26} - 10^{33} cgs, B_* ~ 10^8 - 10^{15} Gauss

$$\Phi = \frac{\Omega^2 \mu}{c^2} = \frac{\mu}{r_{LC}^2} \sim 10^{12} - 10^{17} \text{ Volts } (10^{22} \text{ V possible})$$

Electric field extracts current: $I = c\Phi = 10^{15.5} - 10^{20.5}$ Amp =Goldreich-Julian current electrons from poles, in geometry shown; current connects to "earth" (= nebula), causes torque – carried in Poynting flux

Energy Loss (energy from rotation, flywheel spins down):



$$\dot{E}_R = I\Phi = \frac{\Omega^4 \mu^2}{c^3}$$

$$\text{Vacuum Rotator: } \dot{E}_{Vac} = \frac{2}{3}\frac{\Omega^4 \mu^2}{c^3}\sin^2 \angle(\boldsymbol{\mu},\boldsymbol{\Omega}) \quad \text{(textbooks)}$$

Relativistic Rotator with Plasma (force free MHD):

$$\dot{E}_{FF} = \frac{\Omega^4 \mu^2}{c^3}\left(1+\sin^2 \angle(\boldsymbol{\mu},\boldsymbol{\Omega})\right) \quad \text{(Spitkovsky 2006)}$$

MHD model has both displacement & conduction currents

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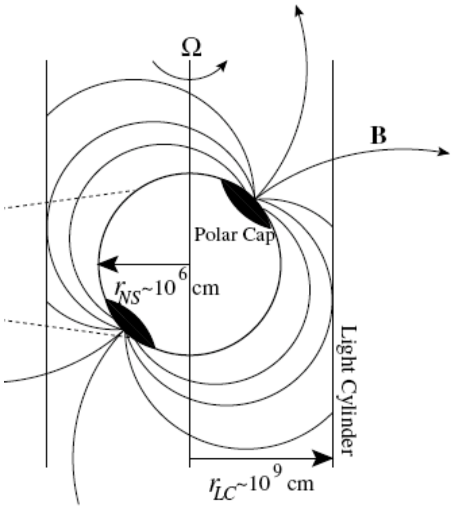

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MHD model has both displacement & conduction currents

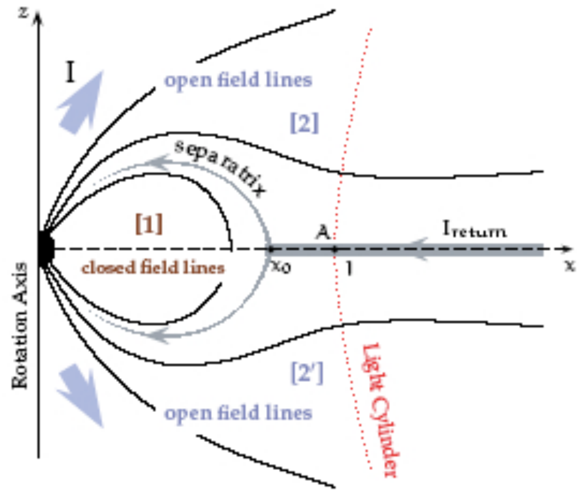
$$\boldsymbol{E} \bullet \boldsymbol{B} = 0$$

Co - Rotation of B

$$\mathrm{E} = -\frac{(\boldsymbol{\Omega} \times \mathbf{r})}{c} \times \mathrm{B} = \mathrm{E}_{co}$$

$$\Rightarrow$$

Charge Density



Timokhin 2006

$$\eta_c = -\frac{\boldsymbol{\Omega} \bullet \boldsymbol{B}}{2\pi c} + \frac{1}{4\pi c}(\boldsymbol{\Omega} \times \boldsymbol{r}) \bullet \nabla \times \boldsymbol{B} \equiv \eta_R = \text{co - rotation charge density}$$

("Goldreich - Julian" density)

Charge density outflow $\Rightarrow$ electric current

$$\mathrm{I} = \mathrm{ce}\dot{\mathrm{N}}_R = c\Phi = c\sqrt{\frac{\dot{E}_R}{c}} = \frac{\Omega^2 \mu}{c}, \mu = \text{ dipole moment}$$

Magnetosphere isolated, gravity strong: no obvious source of charges

Does not <u>require</u> quasi-neutral plasma

But

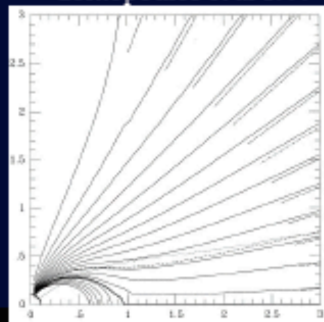
Large mass loss feeding young PWNe ($\dot{\mathrm{N}}_{\pm} \gg \dot{\mathrm{N}}_R$) $\Longrightarrow$ plasma, dense & quasi - neutral

Hypothesis: Basic State is MHD co-rotating magnetopshere (hf Radiative Output << Spindown Power)

- NS is immersed in massless conducting fluid. Includes plasma currents.
- Force-free evolution. B field dominates. Inertia is small:

$$\cancel{mn\frac{\partial \gamma \vec{v}}{\partial t}} = \rho \vec{E} + \frac{\vec{j}}{c} \times \vec{B} \approx 0$$

Contopoulos et al 1999



"Pulsar equation" (Michel '73; Scharleman &Wagoner '73):

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial z^2} - \frac{1+x^2}{x(1-x^2)}\frac{\partial \Psi}{\partial x} = -\frac{I(\Psi)I'(\Psi)}{R_L^2(1-x^2)}$$

$$\left.\begin{aligned} \frac{1}{c}\frac{\partial E}{\partial t} &= \nabla \times \vec{B} - \frac{4\pi}{c}\vec{j} \\ \frac{1}{c}\frac{\partial B}{\partial t} &= -\nabla \times \vec{E} \\ \rho \vec{E} + \frac{\vec{j}}{c} \times \vec{B} &= 0 \\ \frac{\partial}{\partial t}\vec{E}\cdot\vec{B} &= 0 \end{aligned}\right\} \quad \vec{j} = \underbrace{\frac{c}{4\pi}(\nabla \cdot \vec{E})\frac{\vec{E}\times\vec{B}}{B^2}}_{\text{Perpendicular current}} + \underbrace{\frac{c\vec{B}(\vec{B}\cdot\nabla\times\vec{B} - \vec{E}\cdot\nabla\times\vec{E})}{4\pi B^2}}_{\text{Parallel current}}$$

Gruzinov 99, Blandford 01

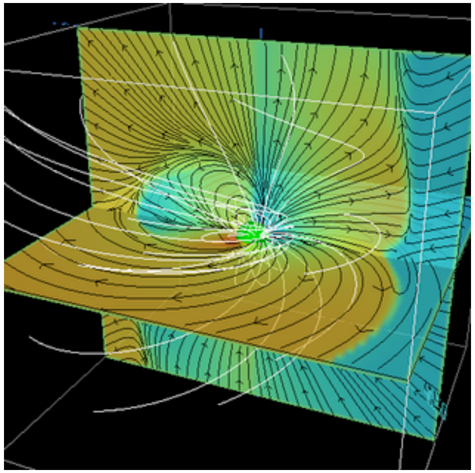
Hyperbolic equations, can be evolved in time

Abundant plasma	
Force-free	
none / re-connection?	
$\frac{\mu^2\Omega^4}{c^3}(1+\sin^2\theta)$	

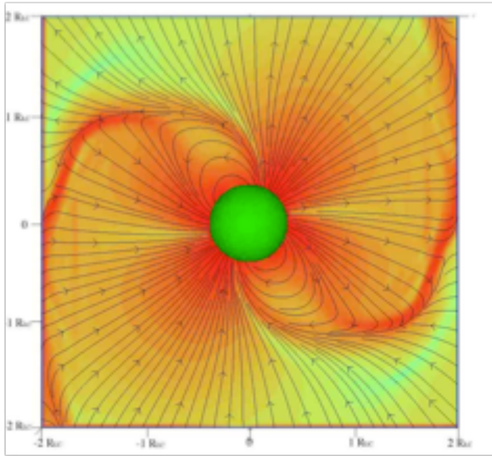
Contopoulos 99; Gruzinov 05; Timokhin 06; AS 06

(from Spitkovsky Aspen 2010)

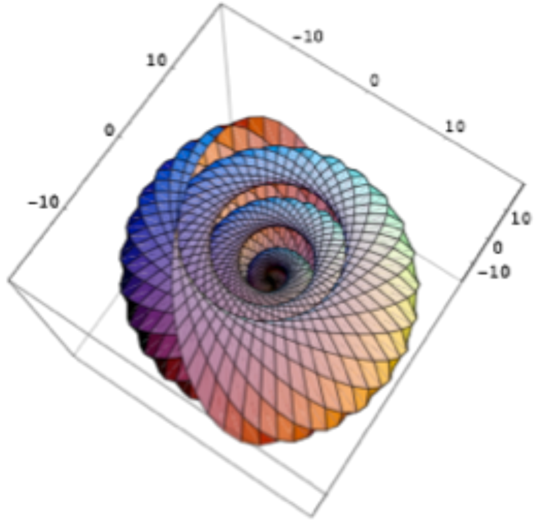
Inner Wind: Magnetically Striped, Magnetically Dominated (Force-Free)



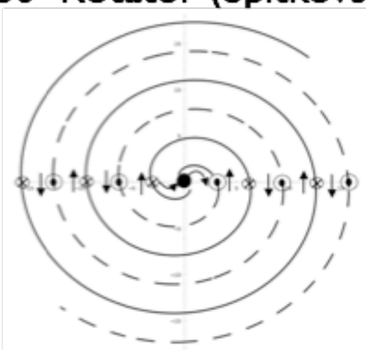
Force Free Simulation of i=60° Rotator (Spitkovsky)



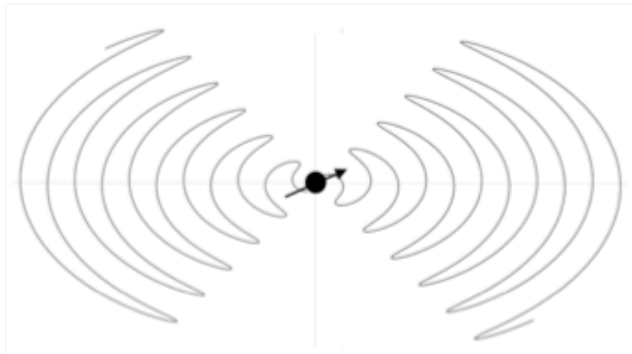
i=60° - topology = aligned rotator



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



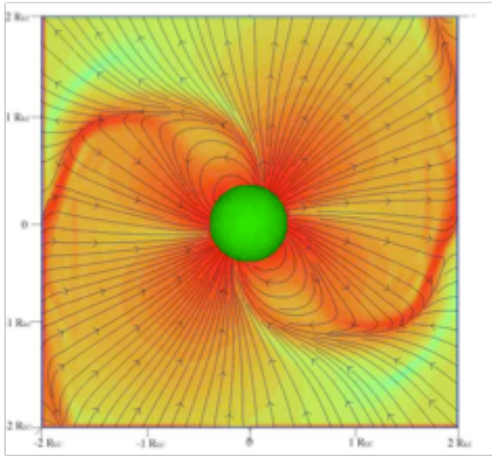
Equatorial cross-section

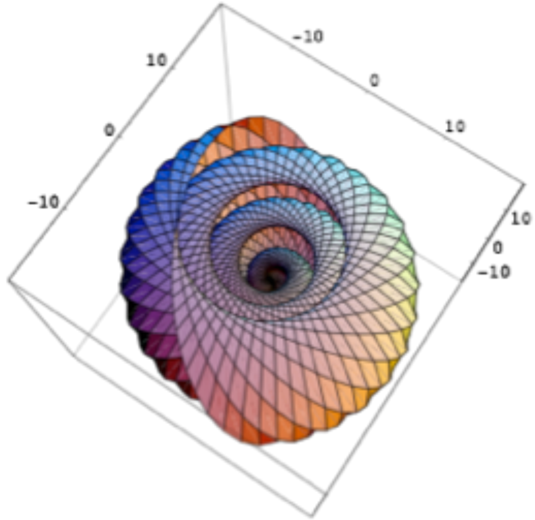


Meridional cross-section

Equatorial Current Sheet = frozen in transmission line, carries whole (return) current, B = 0 in middle of sheet (sheet pinch)

Inner Wind: Magnetically Striped, Magnetically Dominated (Force-Free)





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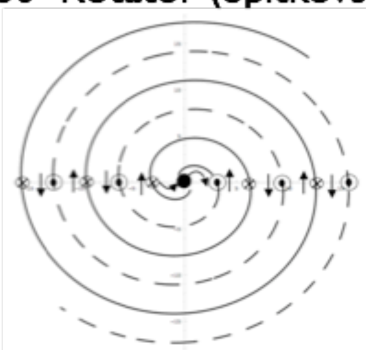

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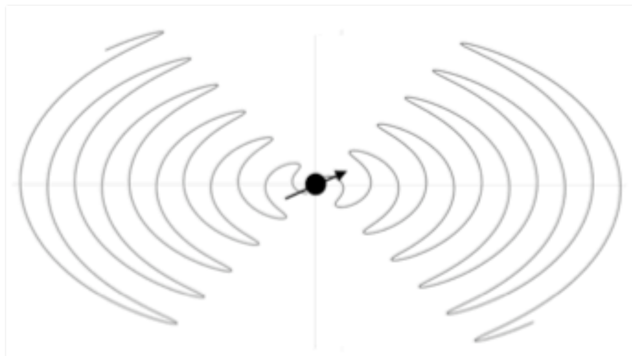


Meridional cross-section

Equatorial Current Sheet = frozen in transmission line, carries whole (return) current, B = 0 in middle of sheet (sheet pinch)

Ideal MHD wind has final 4-velocity << 10^6

$$r > R_L = \frac{c}{\Omega} = 48{,}000P \text{ km}$$

$$B = B_\phi = \frac{\mu}{R_L^2 r} = \frac{\Phi}{r} \quad \text{magnetic "spring"} \left(-\nabla \frac{B^2}{8\pi}\right) \text{accelerates flow}$$

$$\sigma \equiv \frac{B^2}{4\pi m_\pm (2n_\pm) c^2 \Gamma_{wind}} = \frac{(B')^2}{4\pi m_\pm (2n'_\pm) c^2} = \sigma_0 = \frac{\dot{E}_R}{\dot{M}c^2} = \frac{e\Phi}{2\kappa_\pm m_\pm c^2} \gg 1$$

$$\text{accelerates if } v = c\left(1 - \frac{1}{\gamma^2}\right)^{1/2} < v_A = \frac{c}{\sqrt{1 + \frac{4\pi\rho\gamma c^2}{B^2}}} = c\gamma_A \beta_A$$

flow outruns spring, accel stops when $v \to v_A$, $\mathrm{M}_F = 1$,

$$M_F^2 \equiv \frac{(\gamma\beta)^2}{u_A^2} = \frac{\gamma^3}{\sigma_0} < 1,\ u_A^2 \equiv \frac{B^2}{4\pi\rho\gamma c^2} = \text{Alfven 4 speed} = \frac{\sigma_0}{\gamma}, \text{ at}$$

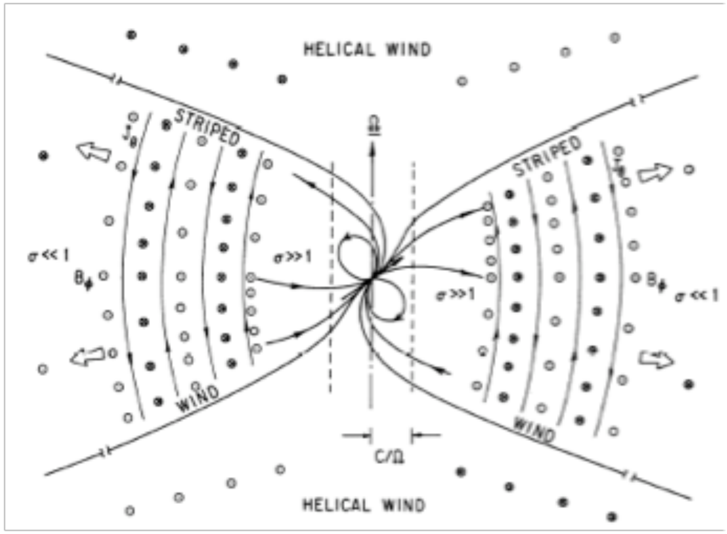
$$r = R_{fast} = R_L \sigma_0^{1/3}.$$

For $r > R_{fast}, \gamma = \Gamma_{wind} = \sigma_0^{1/3} =$ constant, $\sigma = \sigma_0 / \Gamma_{wind} =$ constant $= \sigma_0^{2/3} \gg 1$

$$\sigma_0 = (\Gamma_{wind})_{\max} = 3 \times 10^3 \frac{\dot{P}}{10^{-12.34}} \left(\frac{30 \text{ msec}}{P}\right)^3 \frac{10^{41} \text{ s}^{-1}}{\dot{N}_\pm} \ll 10^6$$

Stripe Decay: Upstream of TS? At/Near TS?

If wrinkled current thickens, striped field dissipates (B field, cold plasma in stripes flows into thickening current sheets), magnetic energy coverts to flow kinetic energy, "heat" (& radiation, but most of outflow volume radiatively inefficient, wind dark - HOW DARK?

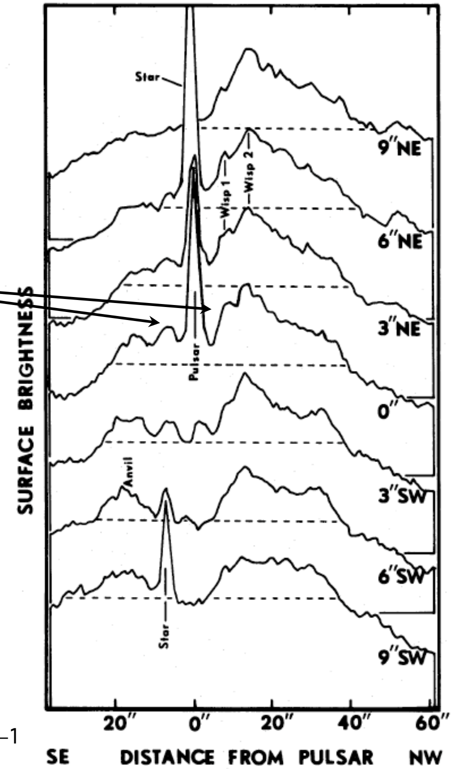


From Coroniti 1990

Striped B decay upstream:

Foreground ......

Underluminous cavity (wind?)

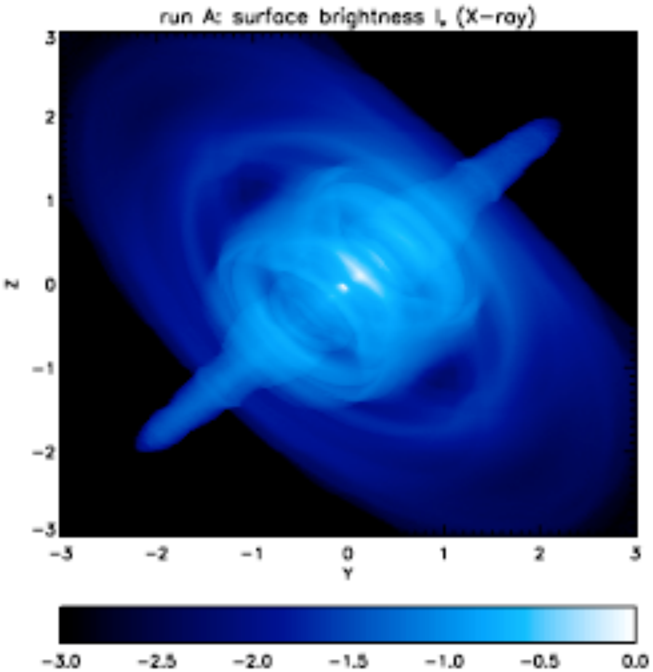


Sheet separation = $R_L = cP/2\pi = 1576(P/33\ \mathrm{msec})$ km, wavelength = $2R_L$. TS lies at many R_L ($10^9\ R_L$ for Crab) - frozen in wave has very short wavelength

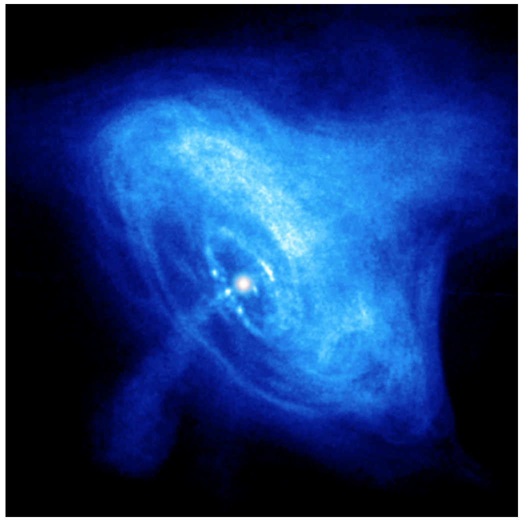
Decay upstream occurs if wind "ultra-dense", $\dot{N}_\pm \gg \dot{N}_{OX\gamma} \approx 10^4 \dot{N}_{GJ} \approx 10^{38}\ \mathrm{s}^{-1}$ ($\Gamma_{wind} < 10^4$) - true if high density flow for radio is in the striped sector and $\eta_{eff} \sim$ Bohm - Decay radius in Crab $\sim 0.1 R_{shock}$ (JA08)

Beaver et al 1979

Infer <σ> ~ 0.02 at wind Termination Surface (TS), R_{TS}=3x10^{17} cm = 0.1 pc, to get jet to torus brightness ratio correct (del Zanna+ 2006).



Synthetic X-ray image



Chandra image

IF TS = simple shock, B just behind shock is

$$(B_2)_{TS} \sim 0.4\left(\frac{\sigma}{0.02}\right)^{1/2} \text{ milliGauss}$$

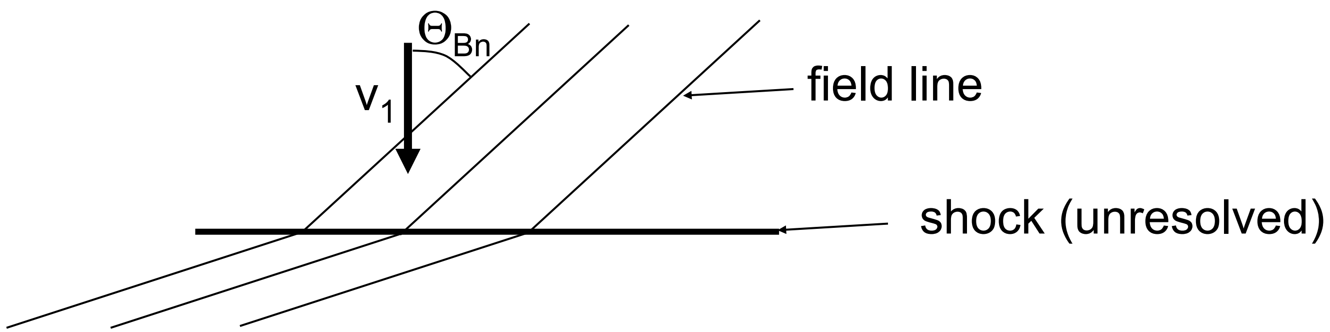
Ideal MHD predicts σ>>1 in wind and in nebula, magnetic dissipation implied - where

Upstream decay model works well as input into detailed simulations of nebular surface brightness

Model magnetic structure has weak B in torus midplane = rotational equator

Standard Accelerator Model

"Shock Acceleration":
Termination Surface (TS) = MHD shock wave(?)
Shock = collisionless magnetosonic shock (in pairs, for PSRs)
unstructured upstream flow, toroidal B perpendicular to v (for PSRs, jets).
acceleration usually assumed to be Diffusive First order Fermi Acceleration (DFA) - particles must access upstream from downstream many times while following B.

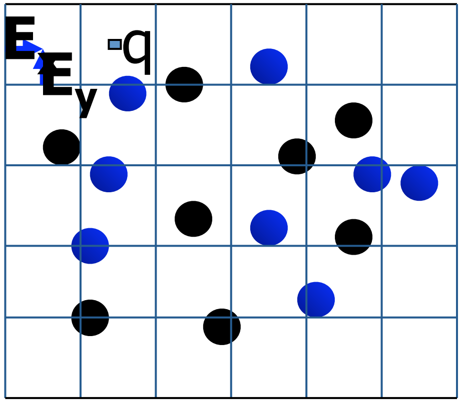


Many crossings - particles like between converging walls, gain energy/bounce
relativistic test particles (isotropic scattering in flow frames-

$$N(E) \propto E^{-2.22}$$

Spectrum ≈ distribution inferred from O-X-γ (ε≪100 MeV) average nebula

<u>caution</u>: wave-particle interaction is not pure scattering
– emission/absorption of fluctuations = waves → thermalization/Maxwellians,
Kinetic physics, study with Monte Carlo (scatt), Particle-in-Cell (PIC)



Amato, Gallant, Hoshino, Langdon, Spitkovsky, JA; Silva et al

Particle-in-cell method:

- *Collect currents at the cell edges*
- *Solve fields on the mesh (Maxwell's eqs)*
- *Interpolate fields to particles positions*
- *Move particles under Lorentz force*

Modified code "TRISTAN" (Buneman, AS) - also OOPIC(Verboncoeur), Starfield (Hoshino), Zohar (Langdon), Vorpal (TechX), Osiris (UCLA/Silva):

- *3D cartesian electromagnetic particle-in-cell code*
- *Radiation BCs; moving window*
- *Charge-conservative current deposition (no Poisson eq)*
- *Filtering of current data*
- *Fully parallelized (up to 1024 proc) domain decomposition*
- *Have used to 10 billion+ particles*
- *Special methods to suppress numerical Cherenkov instability*

Simulation setup:

Relativistic $e^{\pm}$ or e^{-}- ion wind (Γ =15) with B field ($\sigma = \omega_c^2/\omega_p^2 = B^2/(4\pi n_{\pm} mc^2)$ = 0-10)

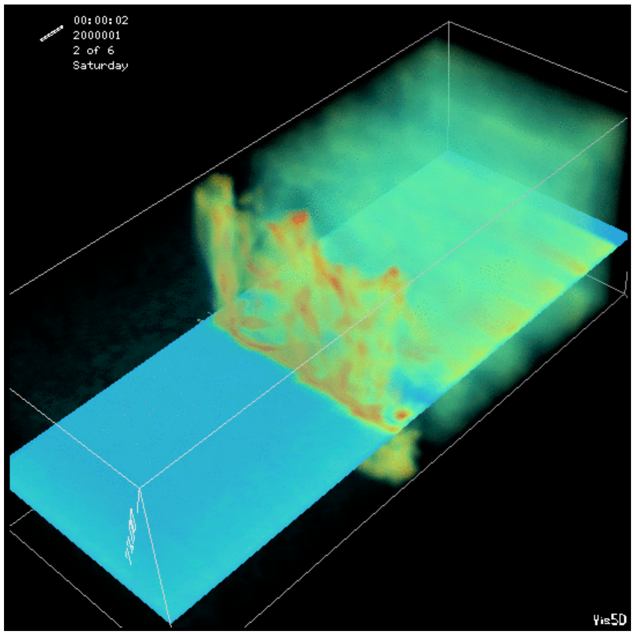
Entry at left wall, speed $c\beta_1 \mathbf{e}_x$, $E_y/B_z=\beta_1$ Reflecting right wall (particles and fields)

Upstream c/ω_p=10 cells, c/ω_c>5 cells; up to 8000x500x500 grid, 800x50x50 c/ω_{pe}

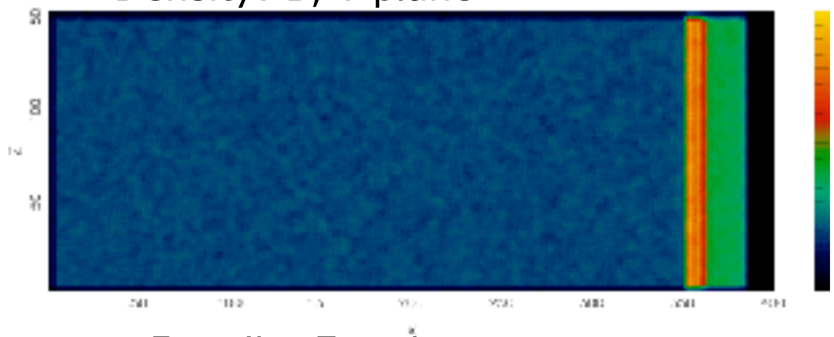
Transverse B suppresses diffusive Fermi acceleration (particles can't bounce between up & downstream, needs $v \parallel B > c$)
cross field diffusion inadequate: self-consistent turbulence (including field line wandering) too weak; too slow
Model problematic, such shocks make relativistic Maxwellians
(PIC simulations: Langdon, JA & Max '88 to Sironi & Spitkovsky 09):
perpendicular shocks with Larmor radii < 20 x c/ω_p ($\sigma_{upstream} > 0.003$
thermalize through cyclotron interactions, absorption > scattering

Magnetized perpendicular pair shock

From JA & AS, survey of perpendicular pair shocks, 3E-5 <σ<0.3

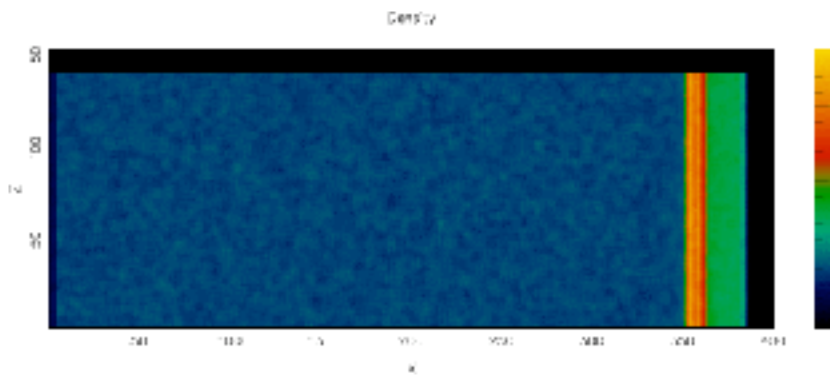


Density: B, v plane



$\sigma=0.1$
$\gamma=15$

Density, E,v plane



Downstream Spectrum: Rel. Maxwellian

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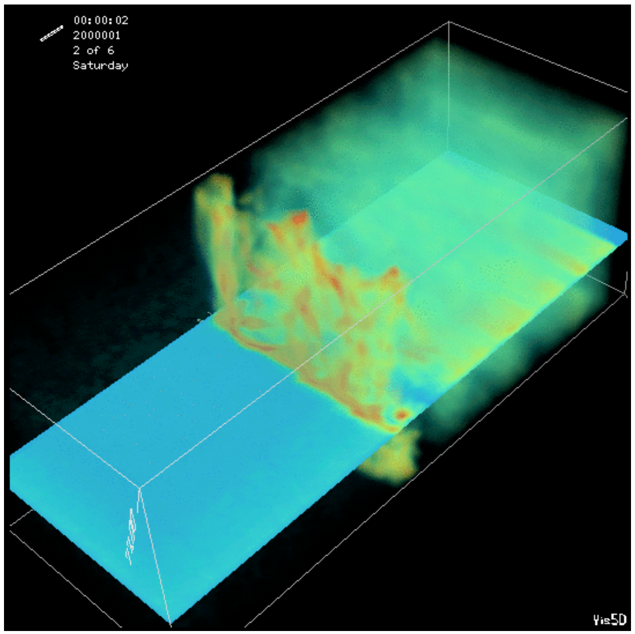

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σ=0.1
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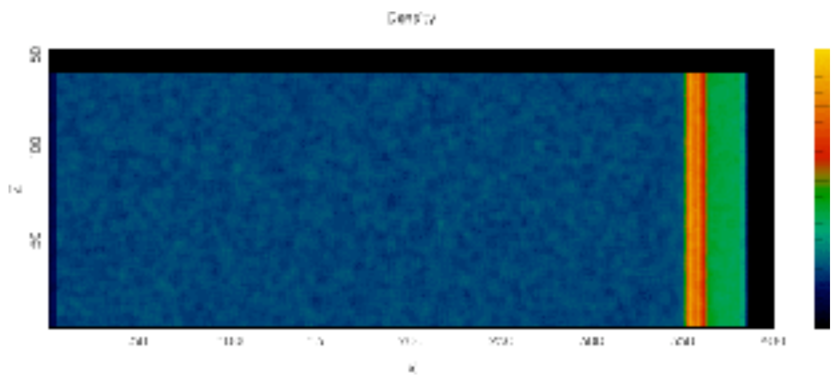
Density, E,v plane



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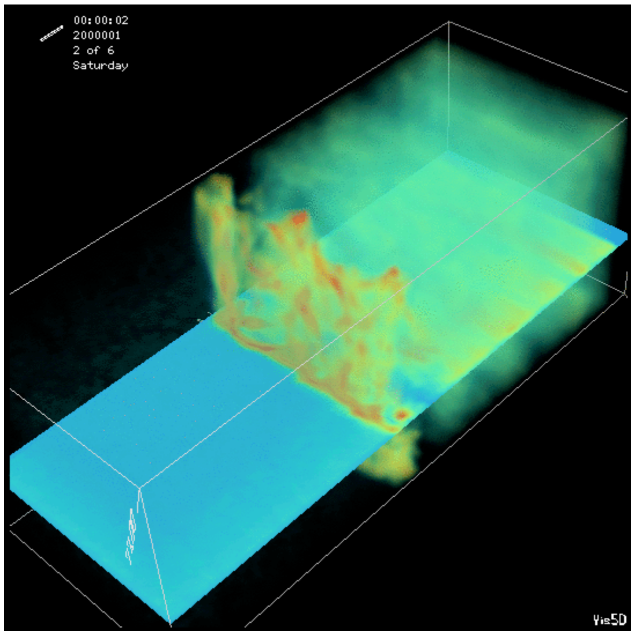
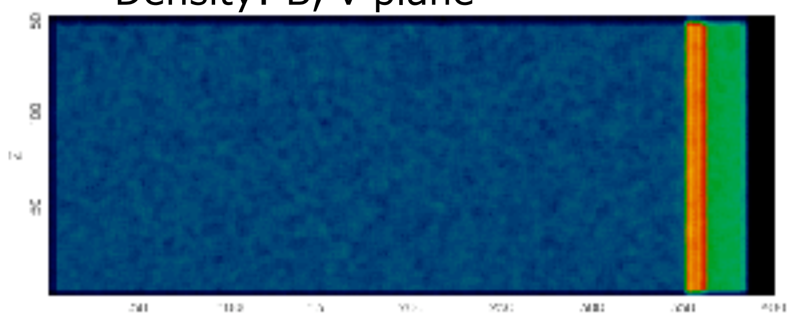




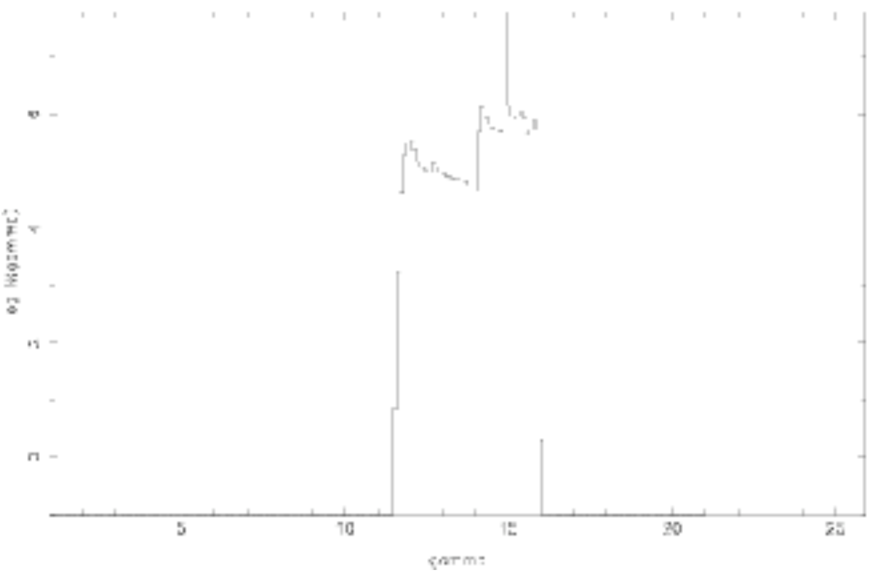
Density, E,v plane

σ=0.1
γ=15

Downstream Spectrum: Rel. Maxwellian

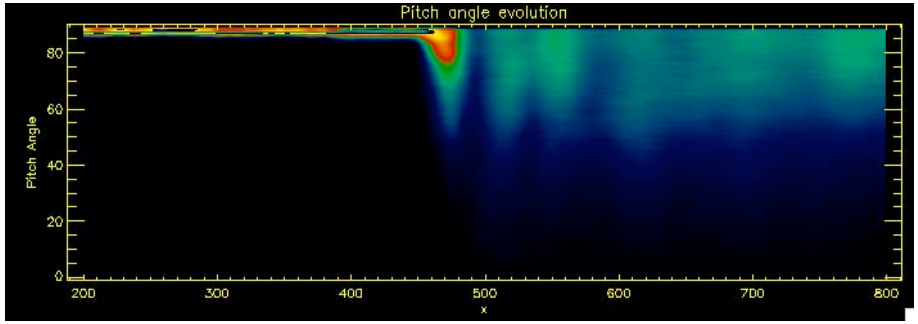
Superluminal perpendicular phase space

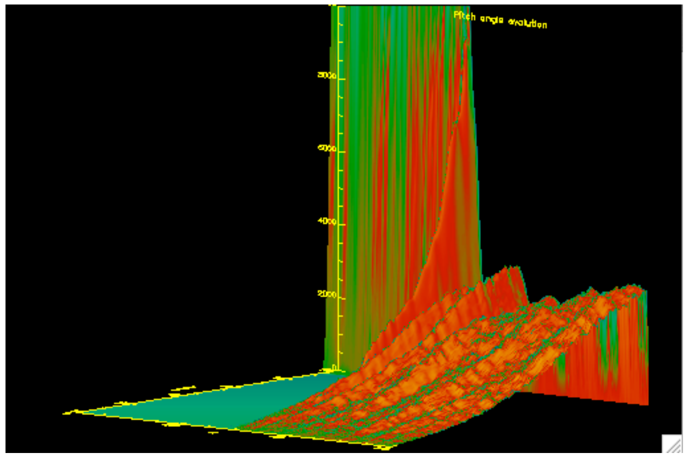
Spectrum (whole box)



Particle Spectrum
Maxwellian (log-linear)

Pitch Angle Distribution



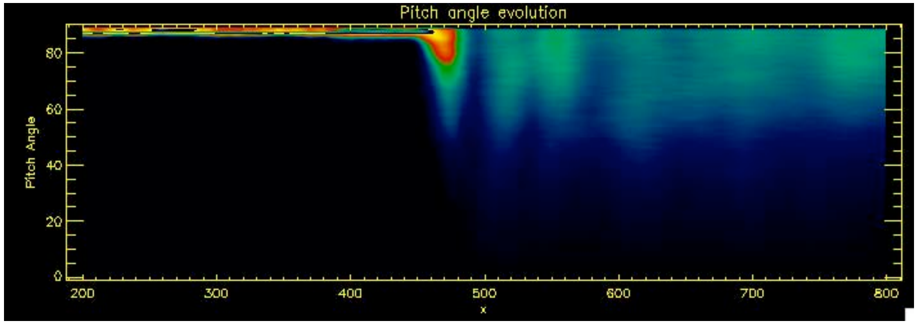


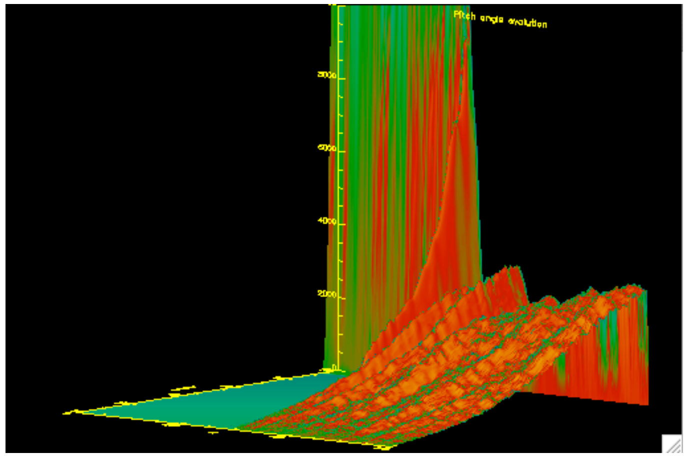
Partially isotropized: perhaps isotropization progressing slowly at end of simulation

Superluminal perpendicular
phase space

Spectrum (whole box)

Pitch Angle Distribution





Particle Spectrum
Maxwellian (log-linear)

Partially isotropized: perhaps isotropization progressing slowly at end of simulation ε > 100 MeV synchrotron radiation makes diffusive Fermi acceleration of PeV $e^{\pm}$ at a shock impossible!

Radiative losses too strong, independent of shock geometry

Particles must diffuse across B up and downstream, takes many cyclotron gyration times

Average B in Nebula ~ 0.2 milliGauss

Stronger in central regions, ~ 0.5-1 milligauss (all models)

Synchrotron photons: $\varepsilon \approx \varepsilon_s = \frac{3}{2}\hbar\Omega_{c\pm}\gamma^2 - \varepsilon \sim 0.1 - 3\,\text{GeV, B} \sim \text{mG} \;\Rightarrow 0.1\,\text{PeV} < E < 0.8\,\text{PeV}$

Relativistic Cyclotron time: $t_{cyc} = \frac{2\pi\gamma}{\Omega_{c\pm}} = 194\frac{E_{PeV}}{B_{milliGauss}}$ hours, $\Omega_{c\pm} = \frac{eB}{m_\pm c}, \gamma = \frac{E}{m_\pm c^2}$

Synchroton Cooling Time: $t_{synch} = \frac{6\pi m_\pm c^2}{c\sigma_{Thomson}B^2\gamma} = \frac{36.6}{B_{mG}^2 E_{PeV}}$ hours

$$\frac{t_{cyc}}{t_{synch}} = \frac{9}{4}\gamma^2\frac{r_e\Omega_{c\pm}}{c}, \quad \gamma^2 = \frac{2}{3}\frac{\varepsilon}{\hbar\Omega_{c\pm}} \text{(synchrotron radiation)}$$

$$\Rightarrow$$

$$\frac{t_{cyc}}{t_{synch}} \approx \frac{9}{4}\frac{2}{3}\frac{\varepsilon}{\hbar\Omega_\pm}\frac{r_e\Omega_{c\pm}}{c} = \frac{3}{2}\frac{\varepsilon}{\hbar c}r_e = \frac{3}{2}\frac{\varepsilon}{m_\pm c^2}\alpha_F = 21.4\varepsilon_{Gev}$$

Independent of B, synchrotron losses require acceleration rate > Larmor gyration rate

PeV Accelerator not in MHD region?

$$\dot{\gamma}_{accel} = \frac{ec\beta E}{mc^2} = \frac{eB}{mc}\frac{E}{B}, \quad T_{accel} = \frac{\gamma}{\dot{\gamma}_{accel}} = 4\frac{B}{E}\frac{\gamma}{6\times 10^9 B_{milliGauss}} \text{ days}$$

$$\dot{\gamma}_{synch} = \frac{1}{6\pi}\frac{c\sigma_T B^2\gamma^2}{mc^2}, \quad T_{synch} = \frac{1.5 \text{ days}}{B^2_{milliGauss}}\frac{6\times 10^9}{\gamma}$$

Accelerate to radiation reaction limit $T_{accel} = T_{synch} \Rightarrow$

$$\gamma^2 = \frac{9}{4}\frac{mc^2}{e^2}\frac{mc^2}{eB}\frac{E}{B} \Rightarrow$$

$$\varepsilon_{synch} = \frac{3}{2}\hbar\frac{eB}{mc}\gamma^2 = \frac{27}{8}\frac{\hbar c}{e^2}mc^2\frac{E}{B} = 236 \text{ MeV}\frac{E}{B}$$

$E \leq B$ marginally OK for average nebular synchrotron gamma ray spectrum

large flare of April 9, 2011 needs $\varepsilon_{synch} = 560$ Mev

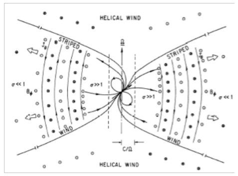
$$\Rightarrow$$

during 2011 flare, $\frac{E}{B} \approx 2.4$

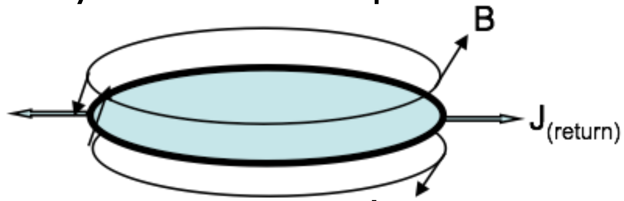
Modify (complicate) the flow model/physics: flow more structured – “Termination Shock” = Working Surface

a) Weak B in midplane allows Fermi acceleration: low latitude where $\sigma_{upstream} < 0.003$ allows up- downstream bouncing in Weibel turbulence at shock (Spitkovsky 2008)
b) Linear Accelerator (Striped Wind Current Sheets)
c) Linear Accelerator (Magnetic Sandwich Current Sheet)
d) [Other Ideas (Magnetic Pumping in Downstream Turbulence, cyclotron resonant acceleration by large r_{Larmor} component of wind –historically ions, could be runaway beam from current sheet,…)]

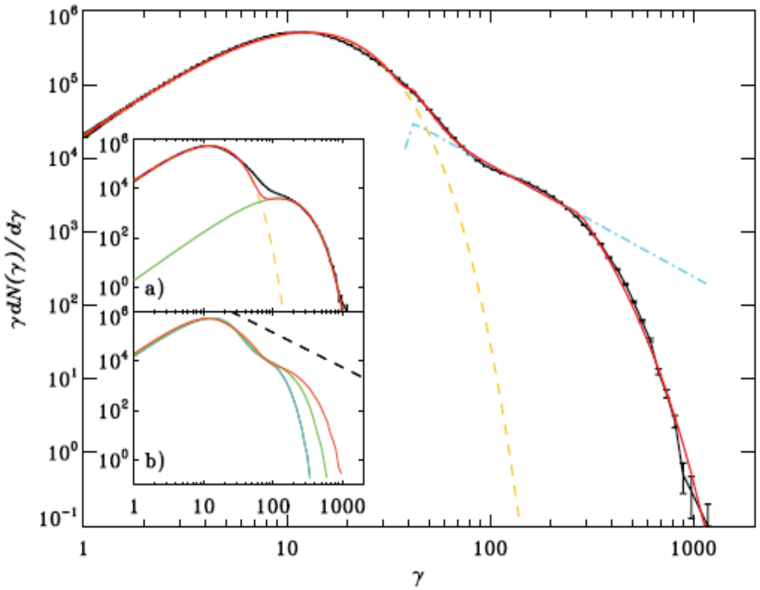
I Magnetic Sandwich (stripes decay): B very weak in midplane

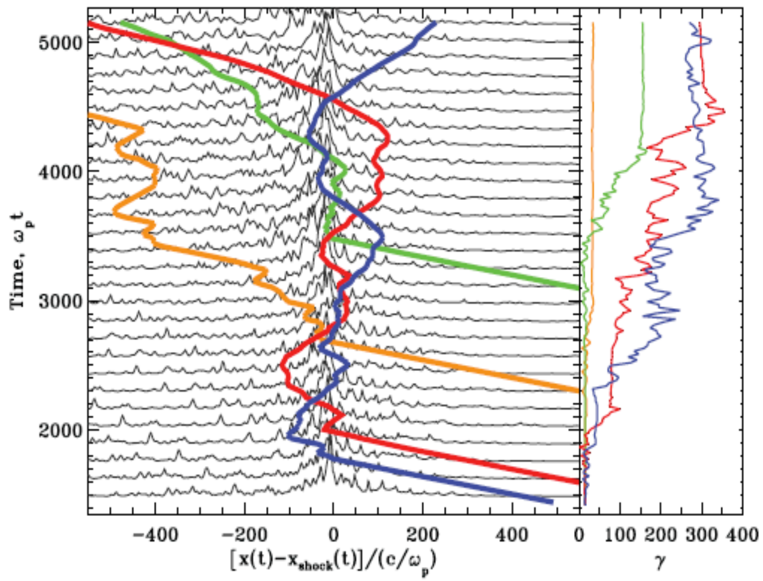


Upstream stripe decay relaxes structure to magnetic sandwich, **thick** equatorial current sheet, B_φ oppositely directed in upper/ lower hemispheres



If $\sigma < 3\times10^{-3}$, magnetized shock looks unmagnetized
Weibel turbulence scatters between up- and down-stream,
Diffusive Fermi in pairs exists (Spitkovsky 08)

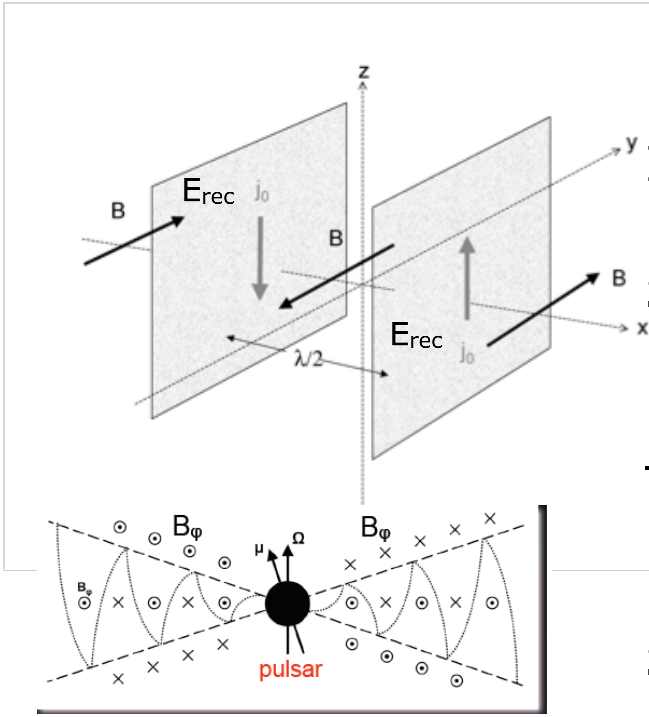




B=0 and quasi-parallel (Θ_{Bn} < 1/Γ1, Kirk & Begelman 1991, Sironi & Spitkovsky 09)
Strong turbulence localized to shock, particles escape easily, hard to get to PeV?; more scattering up & downstream: turbulence created by nebular flow? Can have DSA-like spectra in central sandwich filling – energy flow OK if sheet thick
Spectra always Maxwellian + suprathermal tail. No sign of Maxwellian in observations. Masked by something else?

II. Reconnection in Surviving Stripes' Current Sheets (Lyubarsky, Sironi): Low Mass Loss (e.g. $\dot{N}_{\pm} \sim \dot{N}_{OX\gamma}$): B =0 in sheet center, E > B possible

$$E_{\max} = eE_{rec}L = \alpha_{rec}\beta_A \Phi \frac{L}{R_{TS}}$$

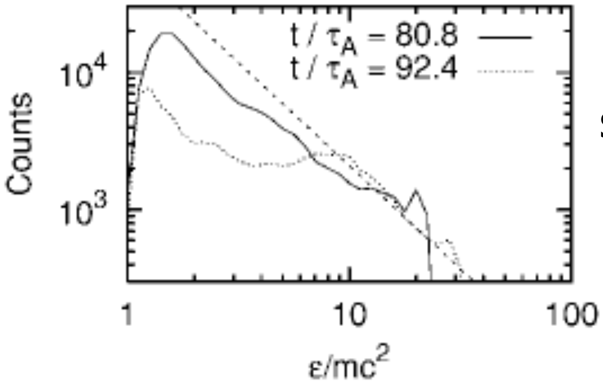


L = circumferential distance, not radial.
If L ~ r, maximum energy ~ $e\alpha_{rec}\beta_A\ \Phi$

Sheets are closely spaced, $\Delta r \approx R_L \approx 10^{-9} R_{TS}$, particles wander easily into neighboring sheets with opposite E_{rec}, no (stochastic) gain
Then L might be as small as $R_L \sim 10^{-9} R_{TS}$, not useful for VHE emitting particles.

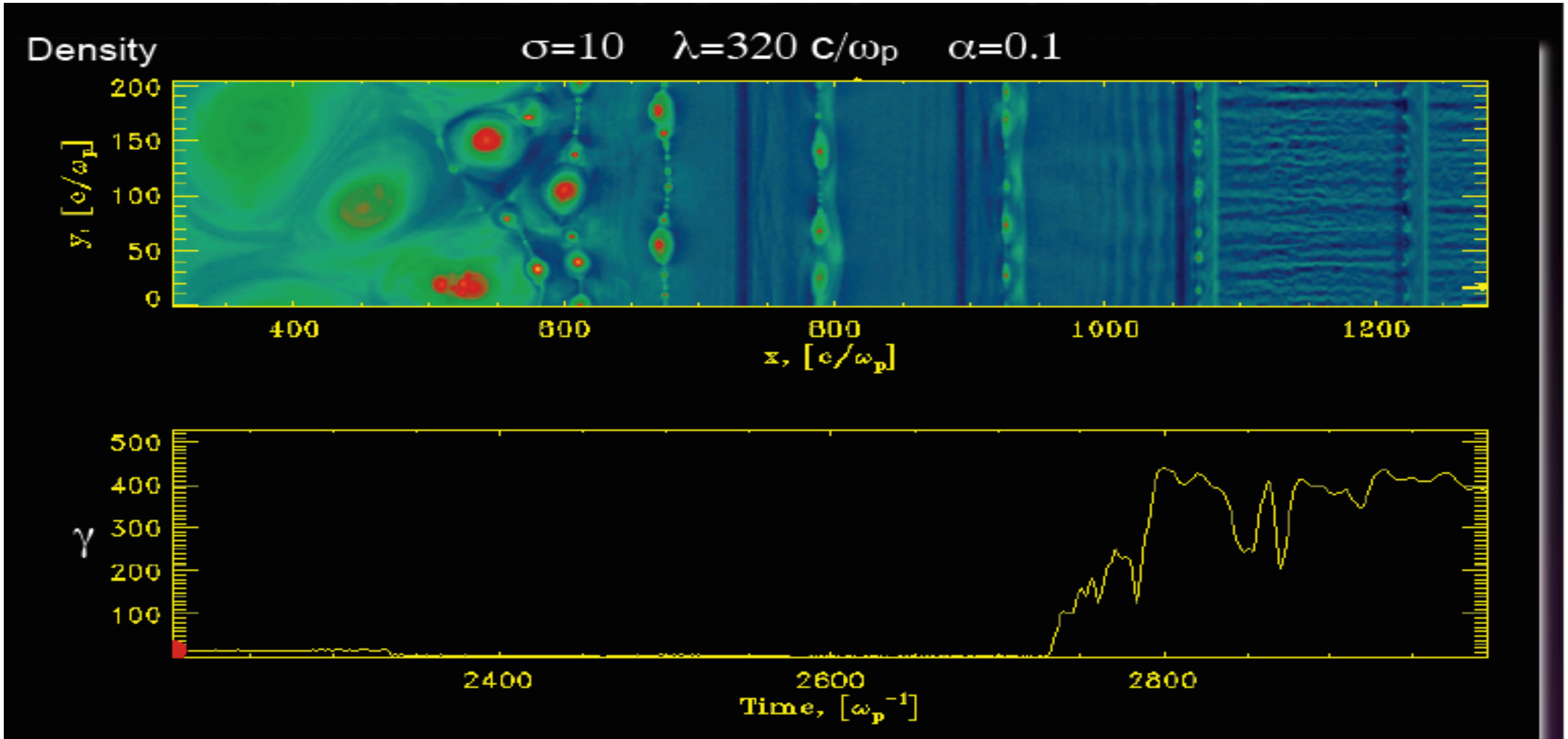
Simulations in pair plasma (Sironi) show reconnection creates magnetic islands, transverse size $\sim R_L$= sheet spacing

Acceleration continues until particles drift into islands, results in $R_L \sim L << R_{TS}$,
$E_{max} << 0.1 e\Phi$



Particle Spectra: flat, E^{-1}; much larger sims needed (Larabee et al 1994)

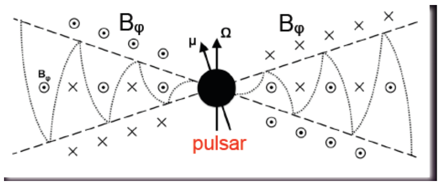
L ~ R_L Reconnection accel useful for acceleration of flat spectrum radio emitting pairs (E ~ GeV)?
Zenitani & Hoshino, Sironi

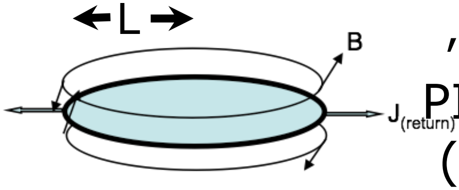


Particles are accelerated by the out-of-plane reconnection electric field at X-points.
Acceleration proceeds till the particle is advected into the nearest island.

Sandwich Reconnection :

Stripes decay upstream (High Mass loss PSR), B reverses across midplane, Axisymmetric current sheet tears into radial current beams, L~R_{TS}



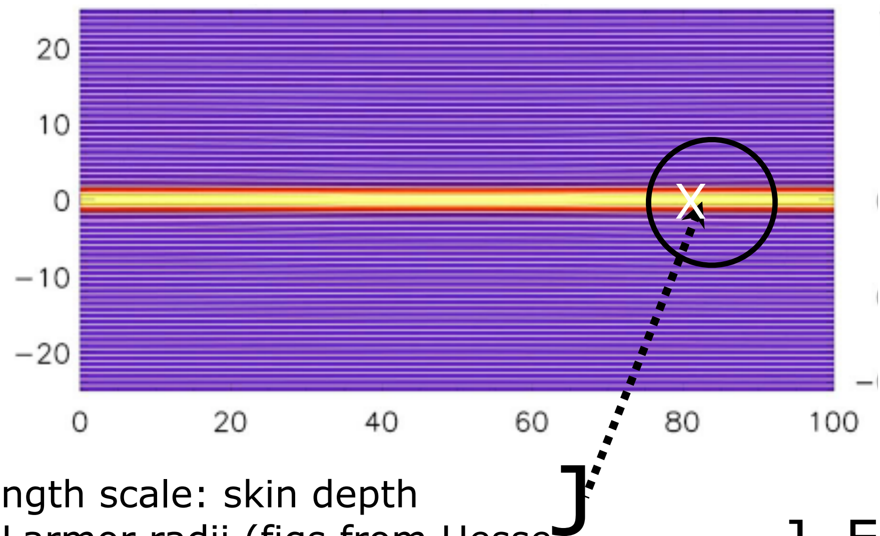


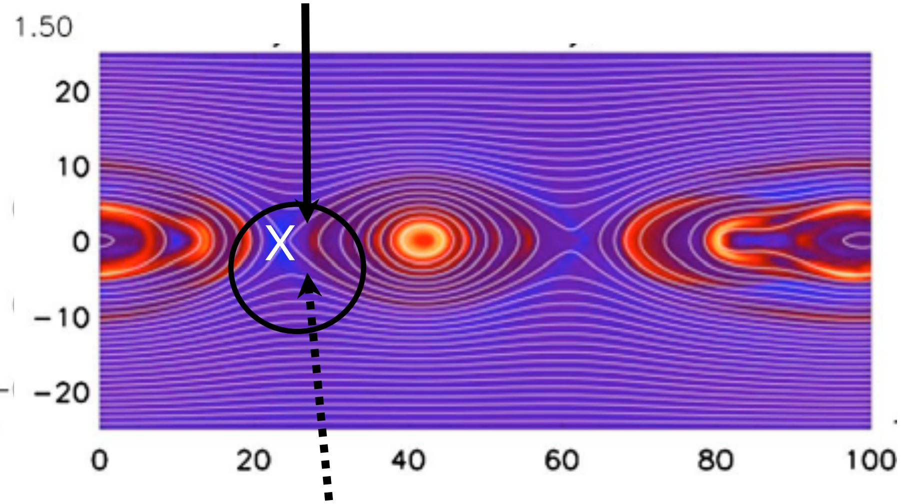
, $\dot{N}_{\pm} \sim \dot{N}_{total}$

PIC in pairs shows fast reconnection (Zenitani, etc.)-anomalous viscosity in diffusion region around X lines allows radial E_{rec}

All possible reversed field decays, Leaves non-zero $B_{\varphi}(z)$ with $B_{\varphi}(0)=0$

$$v_{recon} = \alpha_r v_A \sim 0.1 c\beta_A$$





Length scale: skin depth ~ Larmor radii (figs from Hesse & Zenitani 07)

J, $E_{rec} = (v_{recon}/c)B$: radial E, J filaments

linear accelerator around X line – radial islands

Acceleration: E>B near X lines; Particles that stay in current filaments for distance L ~ R_{TS} gain energy up to PeV “easily”; Full spindown current in filaments ⇒ flare power available; efficiency depends on leakage into islands

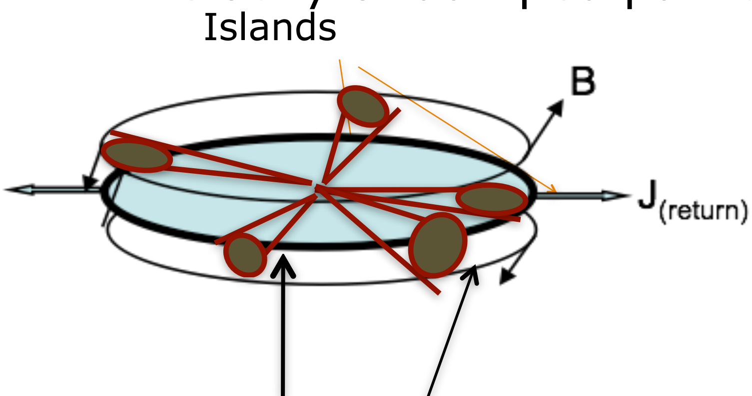
Future promises

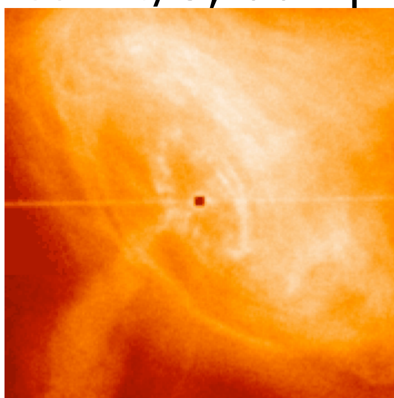
Equatorial magnetic sandwich reconnection? (JA’s favorite)

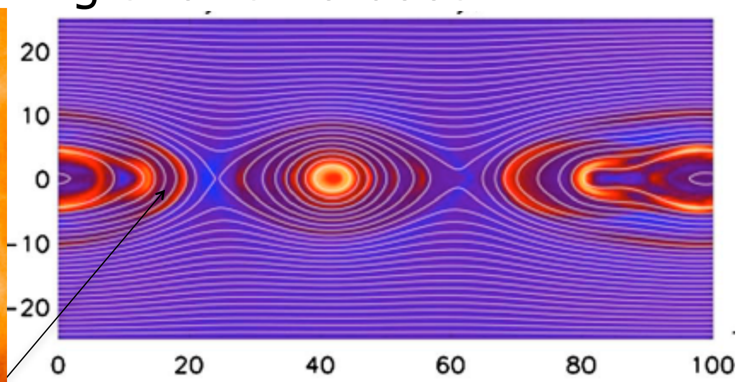
Separate toroidal seqments causally disconnected, short flare duration time?

Big Flare repetitions – current filament kinking, flapping? or, rare events in amplitude spectrum?

Doppler boosts? Small since beam dumps are equatorial, flow velocity of dumped particles ~c/3, dump ring shows no boost







Radial Current beam filaments, X-lines

Scale of filaments, beams set by vertical gradient of B_φ in upstream wind after stripes are dissipated ~ $R_{stripe} \sin\angle(\Omega,\mu) < 0.8\text{-}0.9 R_{TS}$

Acceleration voltage big fraction of Φ

Beam dump = Chandra ring? Ring hotspots = filament terminations?

Reconnection bursty? (always true) = continuous flaring

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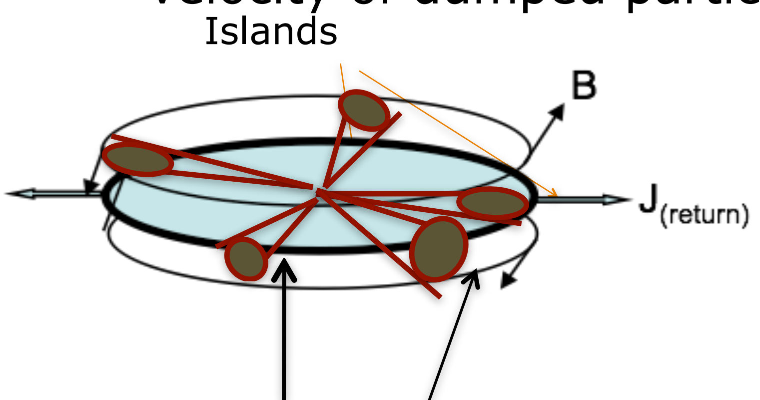

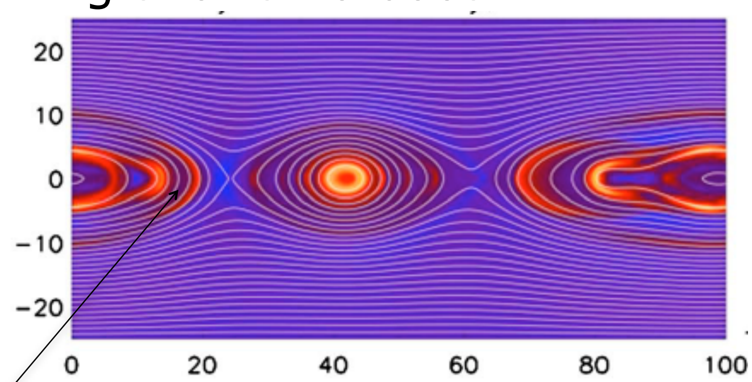

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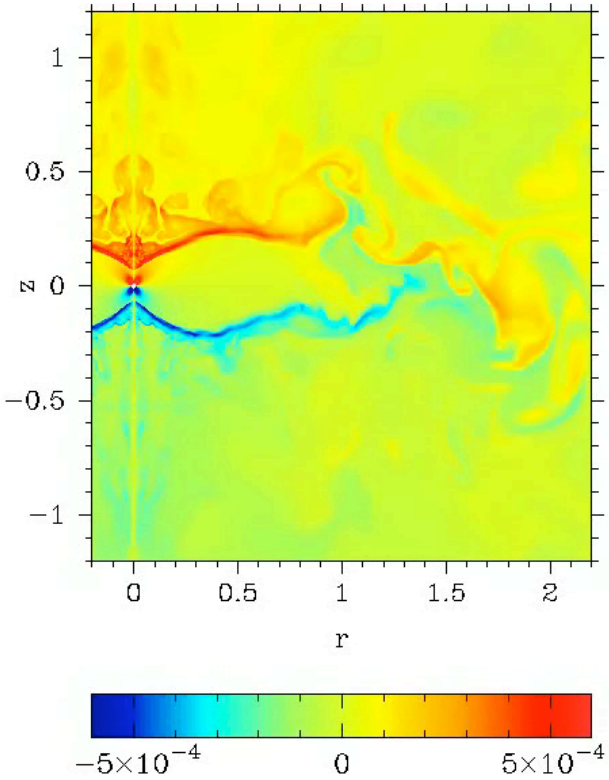
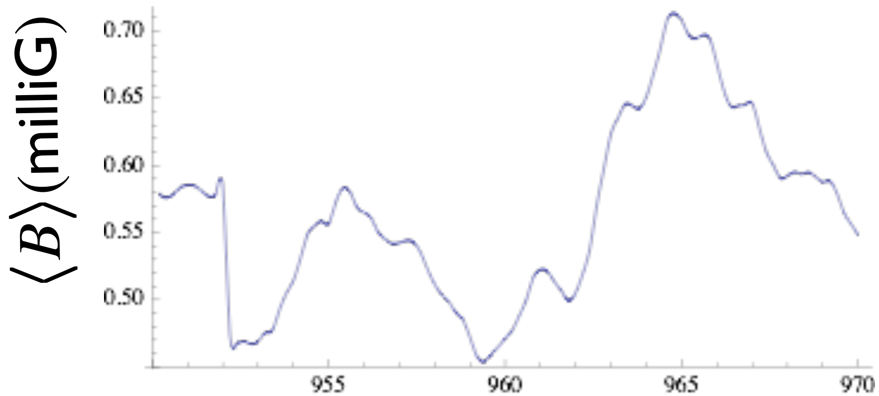
B^2



Magnetic Pumping - Betatron effect with pitch angle diffusion (or transverse spatial diffusion)

Shock, immediate downstream very time variable (Komissarov, Bucciantini)
Axisymmetric, relativistic MHD, B toroidal, inject at shock with low sigma: Flux tubes compress, decompress - average B over (1-2)R_{TS}

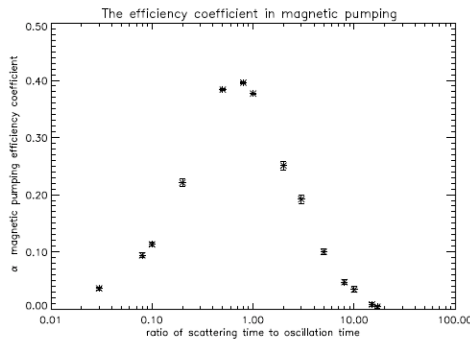


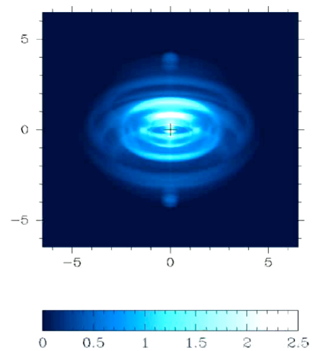
(t-1054)$_{\text{years}}$

High outflow speed toward us, larger Doppler boost (Lyutikov & Komissarov), time contraction (energy flow sufficient?)

ω = compression rate

$$\dot{\gamma}_{bet,av} = \frac{\alpha\omega}{4\pi}\left(\frac{\Delta B}{B}\right)^2 \frac{1}{1+\Delta B/B}\frac{(\gamma^2-1)}{\gamma}$$





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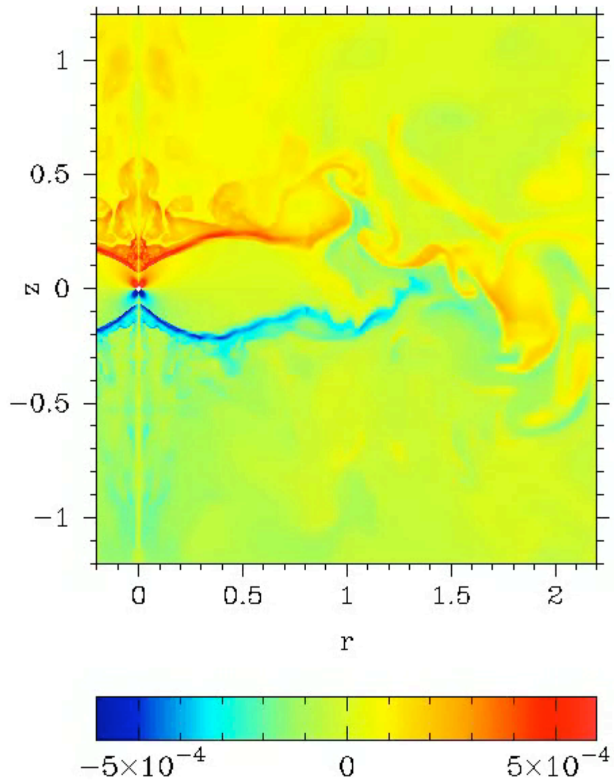

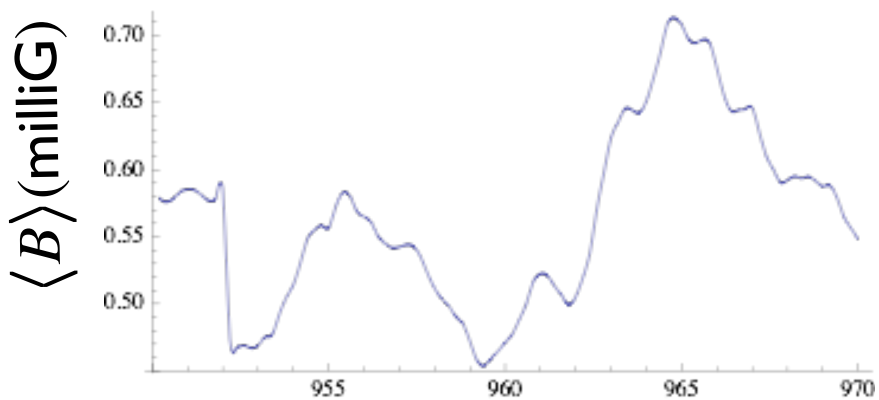

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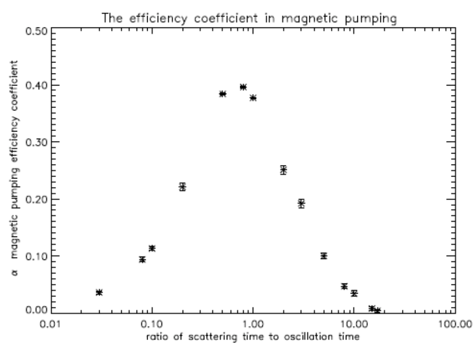

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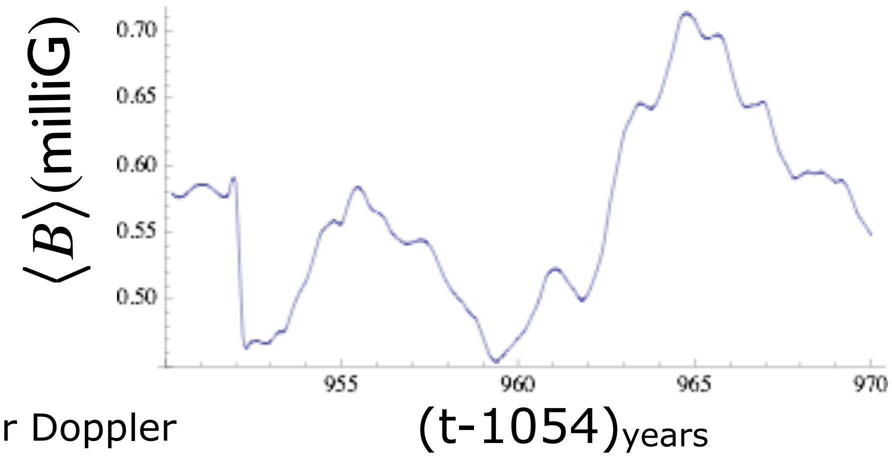

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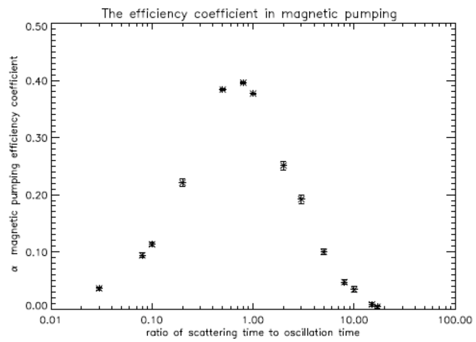
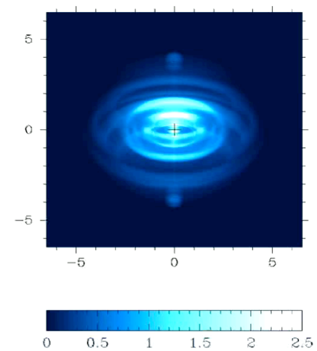




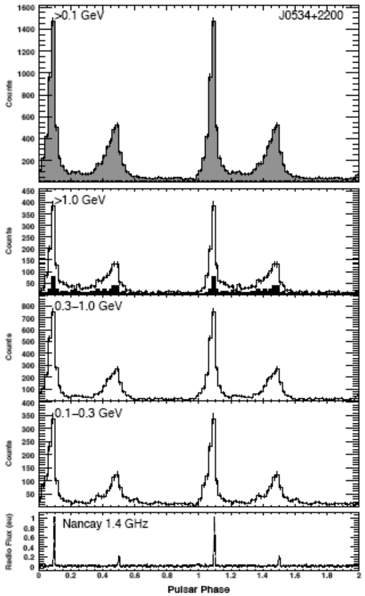
Summary

Large Crab Gamma Ray flares suggest E > B accelerator – current sheet based linear accelerator in an extended layer (radial extent comparable to R_{TS}) of particular interest – can encompass continuously unsteady emission

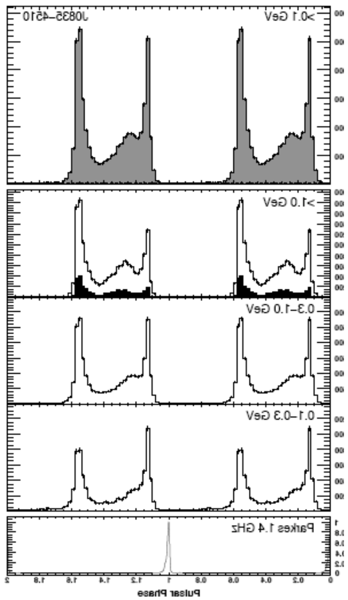
Fermi acceleration in weak B of sandwich filling accelerates particles to ~0.1 PeV energy, good enough for average spectrum - scattering? Either nebular turbulence drives magnetic pumping (Fermi II) or nebular turbulence mediates Fermi I in shock inside the sandwich filling

Pulsed Gamma Rays: Tevatrons

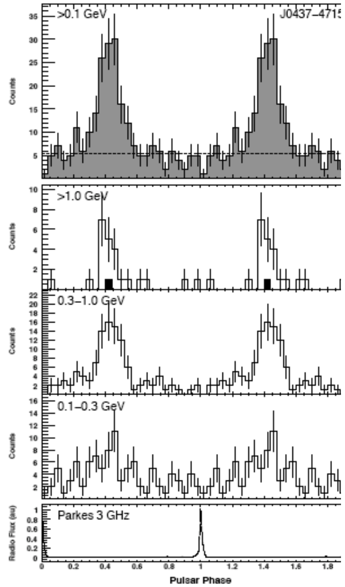
Crab P=33msec



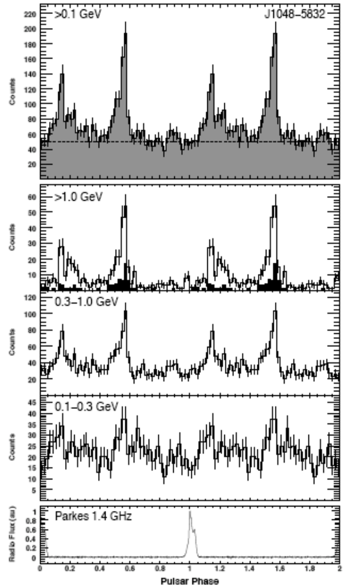
Vela, P=89msec



J0437, 5.76msec



J1048, 124msec

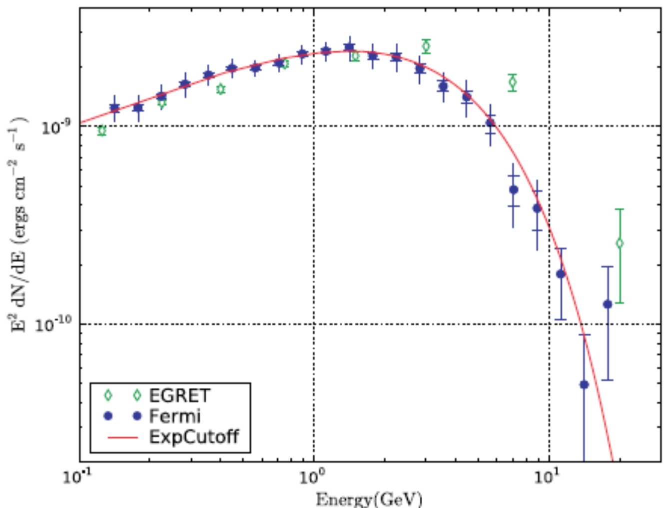


A Few of the Gamma Pulsars (88 in current FERMI-LAT list`

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

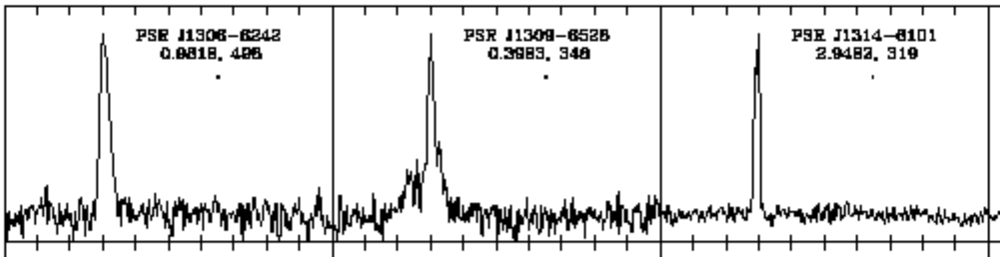
Particle energy E > photon energy $\mathcal{E}$: Gevatron

Radiation mechanism(s): E ≥ 10-10⁴ε
(curvature, synchrotron); E ≥ ε (inverse Compton)



Pulse Phase Averaged Vela Spectrum

Pulsed Emission – Gevatrons ⟶ Tevatrons

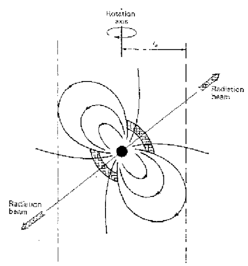


Galactic sources:
D ~ kilo-parsec

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

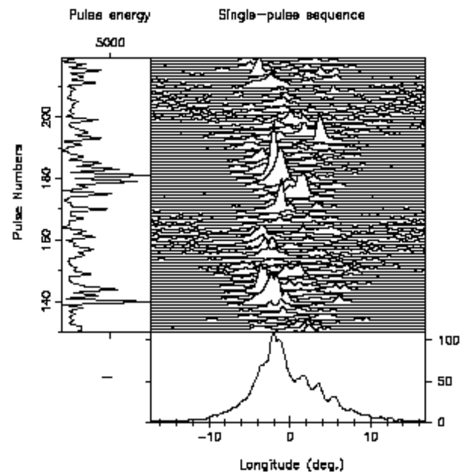
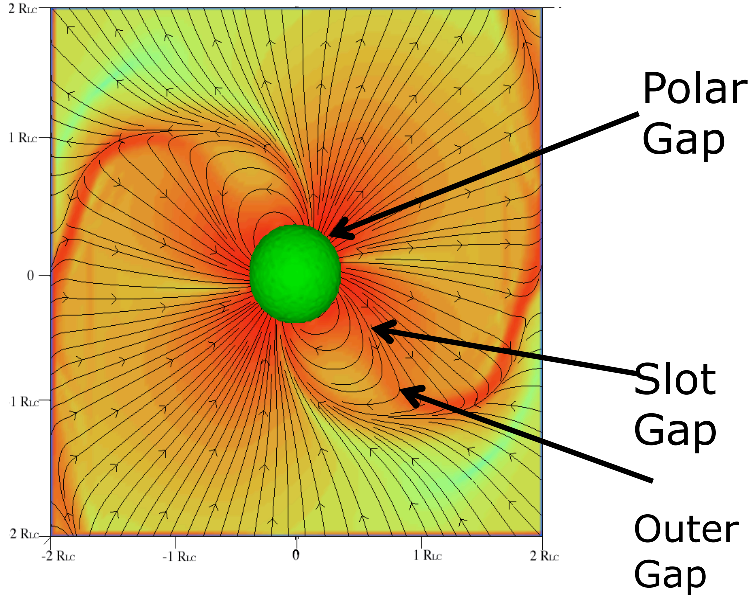


FIG. 1.—A series of individual pulses from the pulsar B0943+10 (*center panel*) along with their average (*bottom panel*) and energy (*left panel*) as a function of pulse number and longitude (360° longitude corresponds to 1 stellar rotation). Note the drifting subpulses, the alternate pulse modulation,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

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

Spitkovsky's (2006) oblique force free rotator



Total Current

Field Lines (with real open flux)

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

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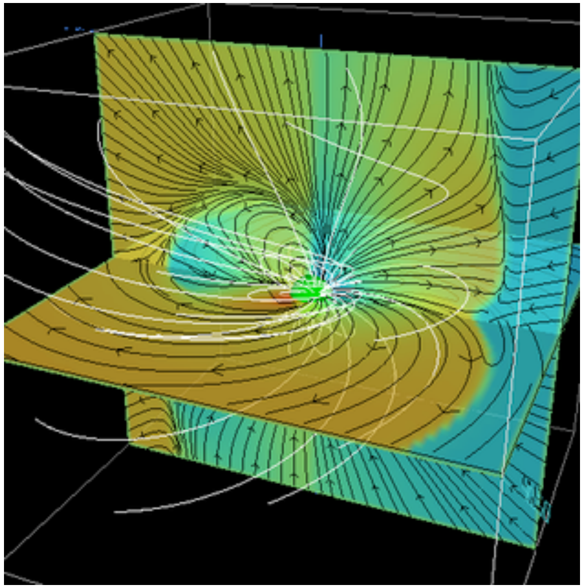

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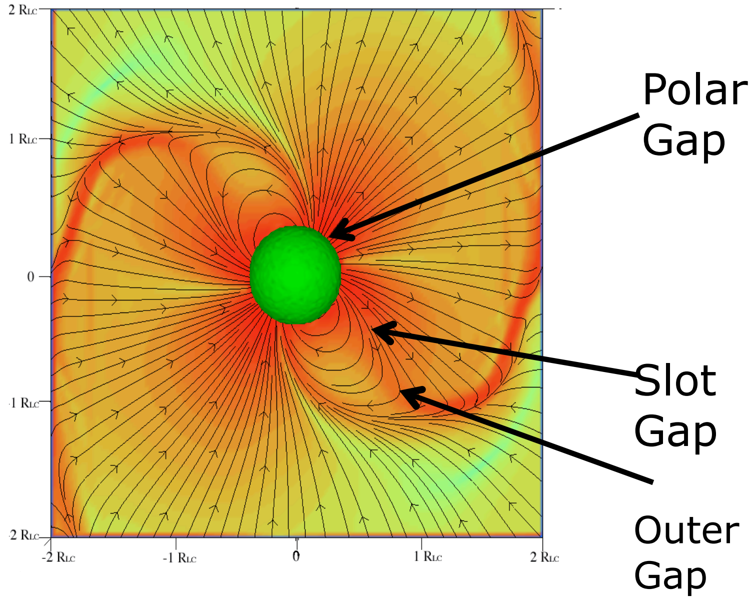

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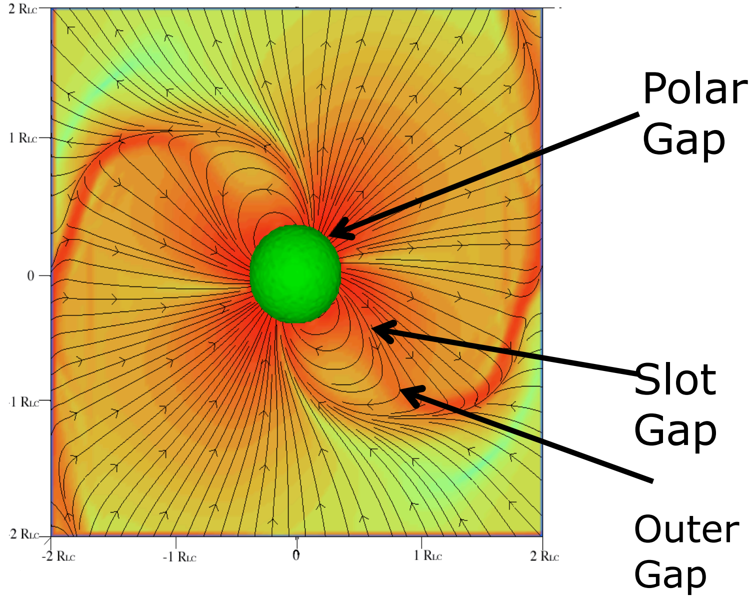

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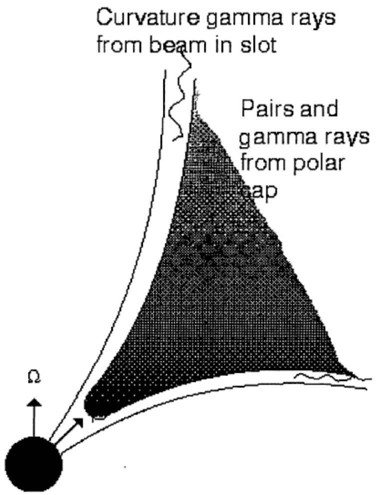
Pulsars have Dense Magnetopsheres: Pair Creation

Pulsar Wind Nebulae: Nebular Synchrotron requires
particle injection $\dot{N} >> $ Goldreich-Julian current $\dot{N}_{GJ} = c\Phi/e$
Solution(?): Pair Creation inside magnetosphere creates $\pm$
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")

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



Pulsed gamma rays observed, > 55 gamma
PSR to date in FERMI observations
Pair creation physics: $\gamma_{curvature}(B) \longrightarrow e^{\pm}$
Optical Depth > 1 for one photon Pair Creation in B requires
$\Delta\Phi_{||} \geq 10^{12}$ Volts $\leftrightarrow$ radio death valley -
radio emission requires pairs?

Gamma emission models also need pairs (?)

Formation of Electric Currents need pairs

Model invokes large $E_{||}$
at low altitude – some variants also make pairs at large r, but only for shorter period, larger Φ pulsars

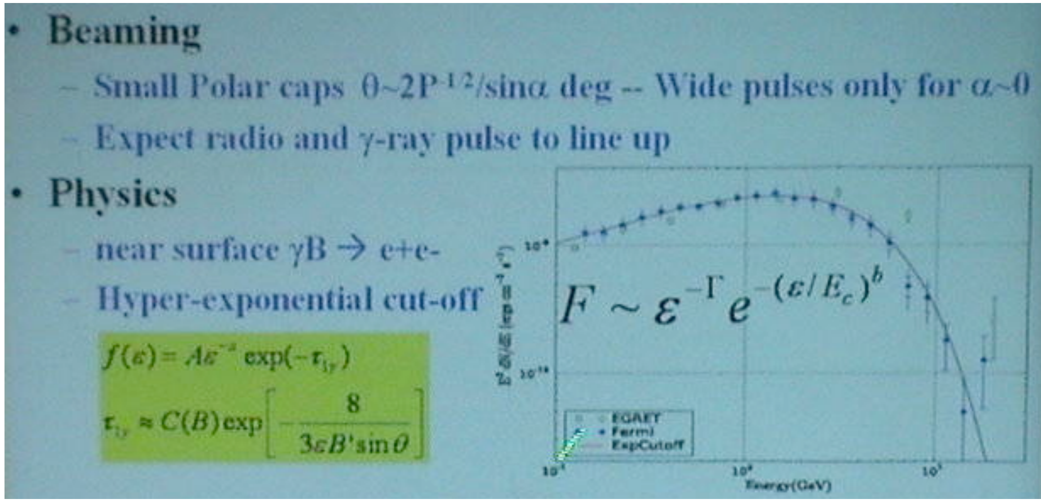
Pulsed Gamma Rays not from pair low altitude pair creation

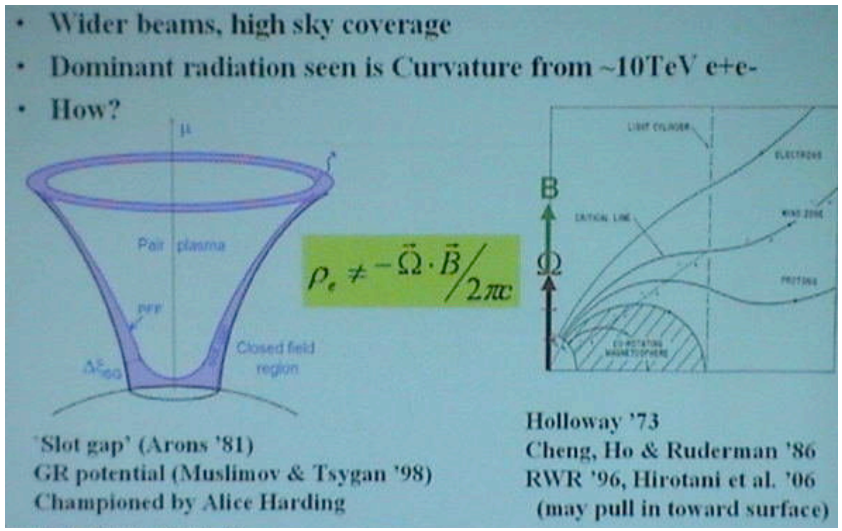
Gamma Rays Not from Polar Cap:
higher energy photons absorbed
with super-exponential cutoff:

γ +B ⟶ 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 quasi-vacuum "gaps"
inserted by hand/flow leaves
spaces where quasi-vacuum
$E_{\parallel}$ can exist



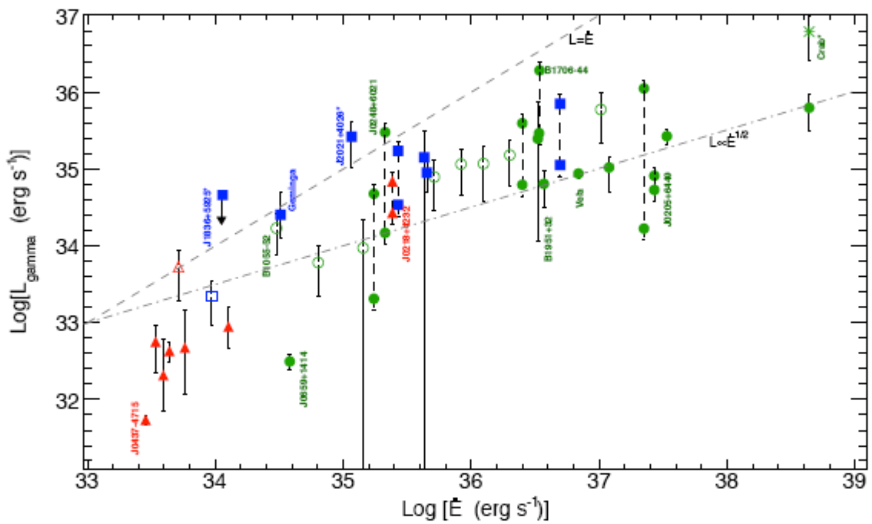


Figures from R. Romani

Prospect: Beam Models With Force Free Magnetospheric Structure

Magnetosphere sets time average (over 1 rotation) $J_{||}$ to be the Force Free Current: Can work if dissipation/radiation energy loss small compared to ideal energy loss:

Gamma Ray Efficiency (LAT)



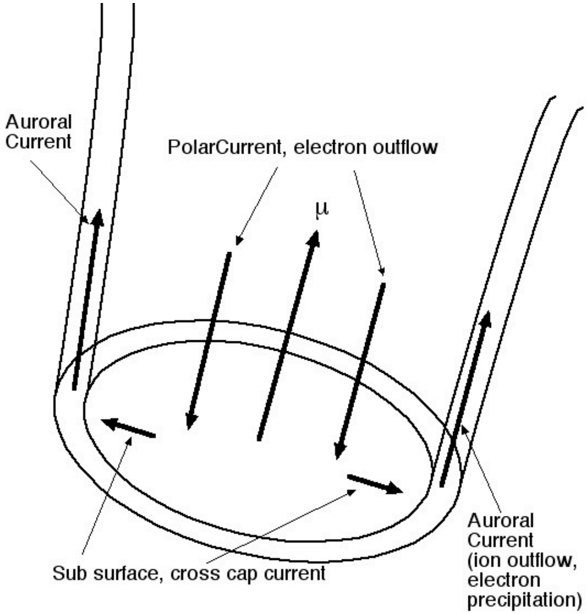
Assume gamma rays come from particles in parallel current accelerated in parallel electric field

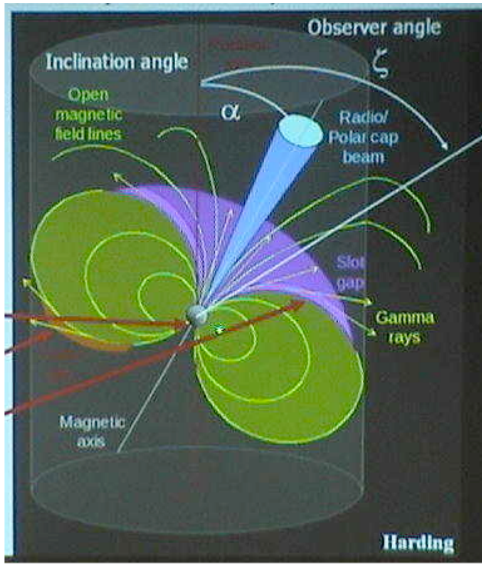
$$L_\gamma = I_R \Delta\Phi_{||} = c\Phi\Delta\Phi_{||} \propto \sqrt{\dot{E}_R}$$

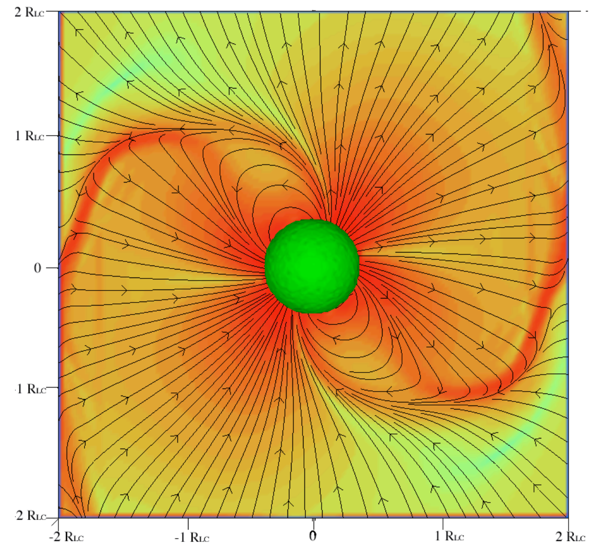
if $\Delta\Phi_{||}$ ~ constant over range of $\dot{E}_R$ - a natural consequence of pair creation in the current flow, pairs poison $E_{||}$ (JA 1996,Harding "confirmed" by 5 EGRET PSR)

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

Structural Components of the Magnetosphere







Possible Acceleration sites: polar caps, outer magnetosphere gaps or current sheets

MHD (Force-Free & Otherwise) + corotation: Charge density is

$$\eta_R = -\frac{\mathbf{\Omega}\bullet \mathrm{B}}{2\pi c}\left[+\frac{1}{4\pi c}(\mathbf{\Omega}\times \mathrm{r})\bullet\nabla\times\mathbf{B}\right]$$

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?

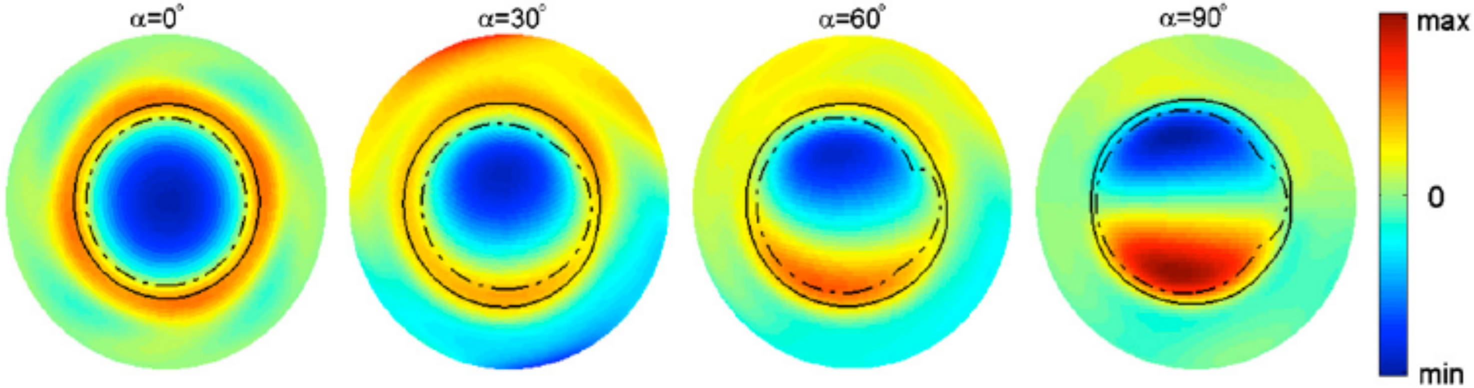
- Electric current magnitude and sign - return currents both spatially distributed and in thin sheet - if dissipation regions ("gaps") have parallel potential drops small compared to total magnetospheric voltage,

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

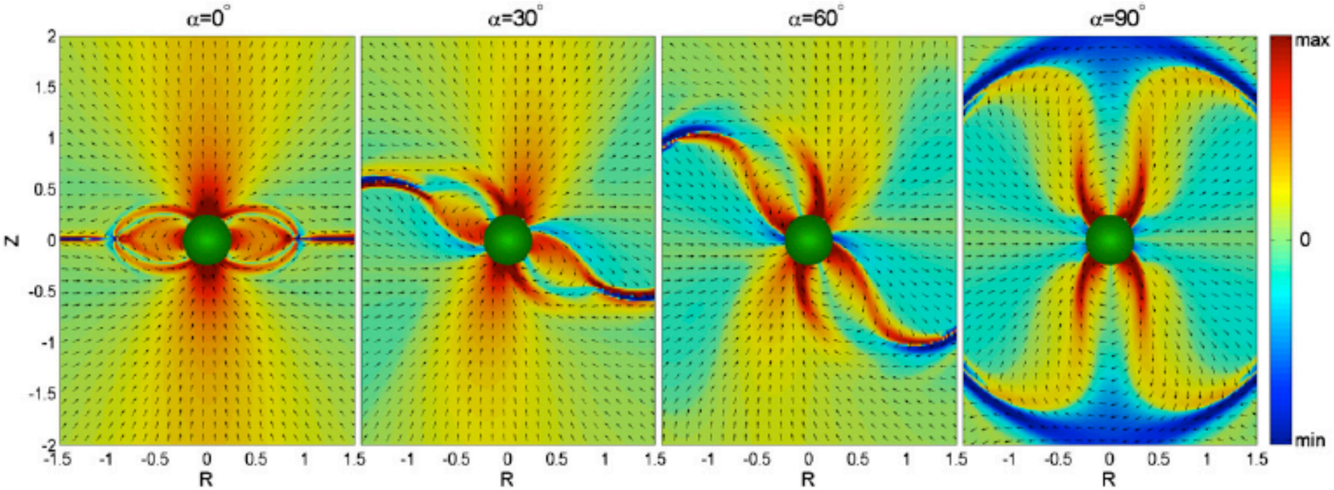
electric current in and outside gaps is known, averaged on magnetosphere transit time ($\sim P/\pi$) - electric currents of gaps/emission sites must fit into magnetospheric circuit - or force free magnetospheric model is wrong - but energy all in field, hard to be non-FF

- Location of return current layer determined - realistic site/physics for outer magnetosphere beaming models of high energy emission – Bai & AS –replace gaps by nonideal MHD physics well tested in solar system, generalized to relativistic conditions, with pair creation

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



Polar Cap Current (Bai & Spitkovsky 2010):
blue = current, red = return current

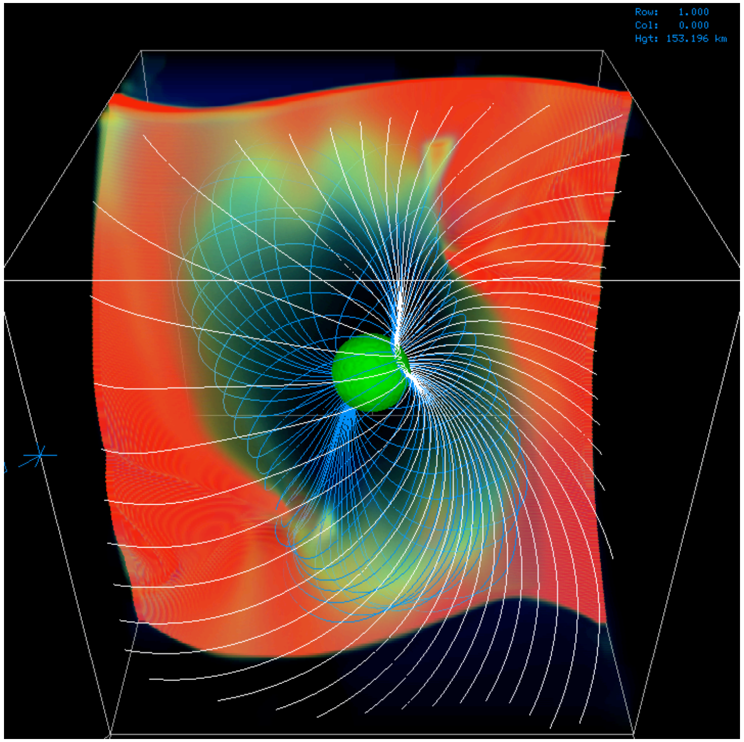


Magnetosphere and inner wind current structure (same ref)
thin sheet current component not shown – part of return current
in aligned, moderately oblique, becomes pole to pole linkage in orthogonal

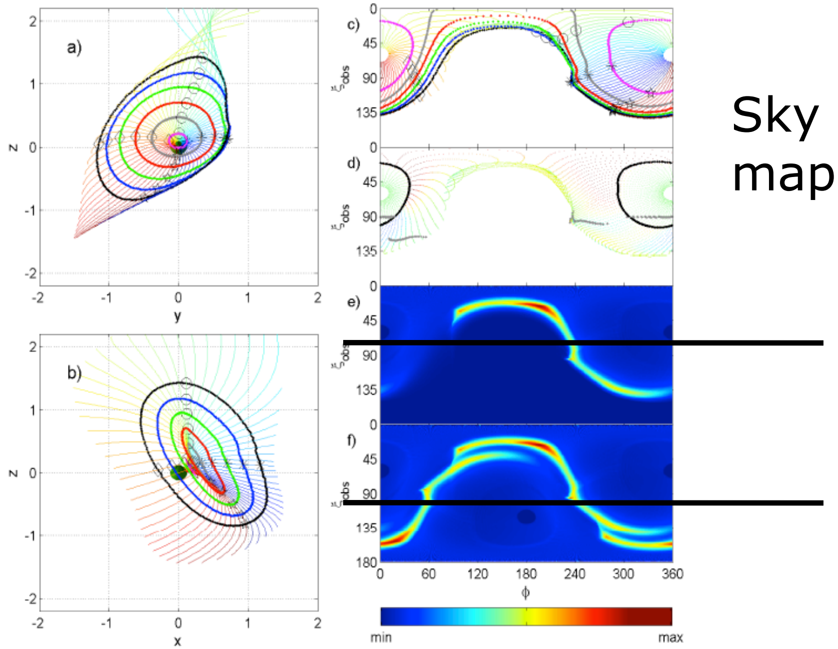
Pulsed Gamma Ray Emission from Current Sheets

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 to B (?)



Acceleration in current sheet rotates wide open cone of emission across sky:
geometry from force-free model ($E_{||}=0$) by Bai & Spitkovsky (2010)



Sky maps

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

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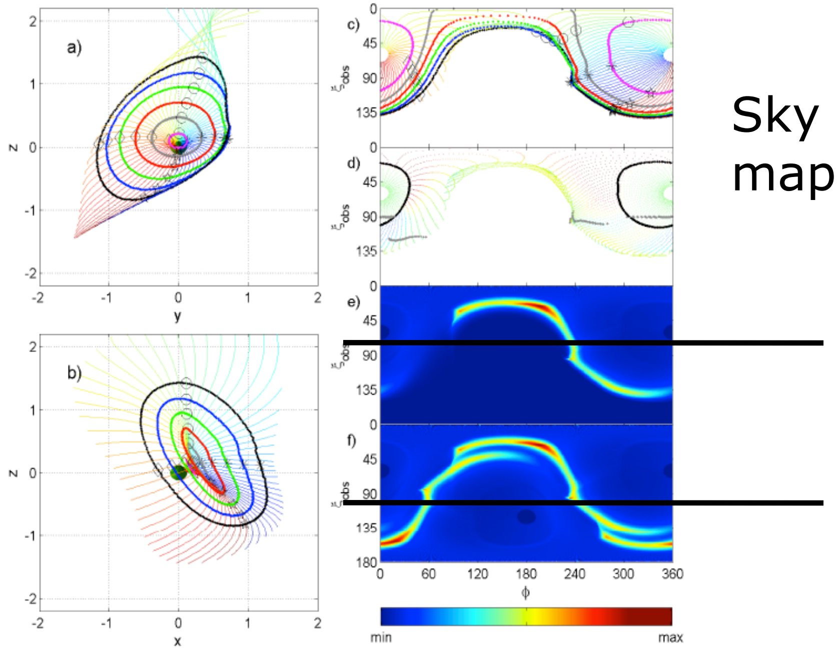

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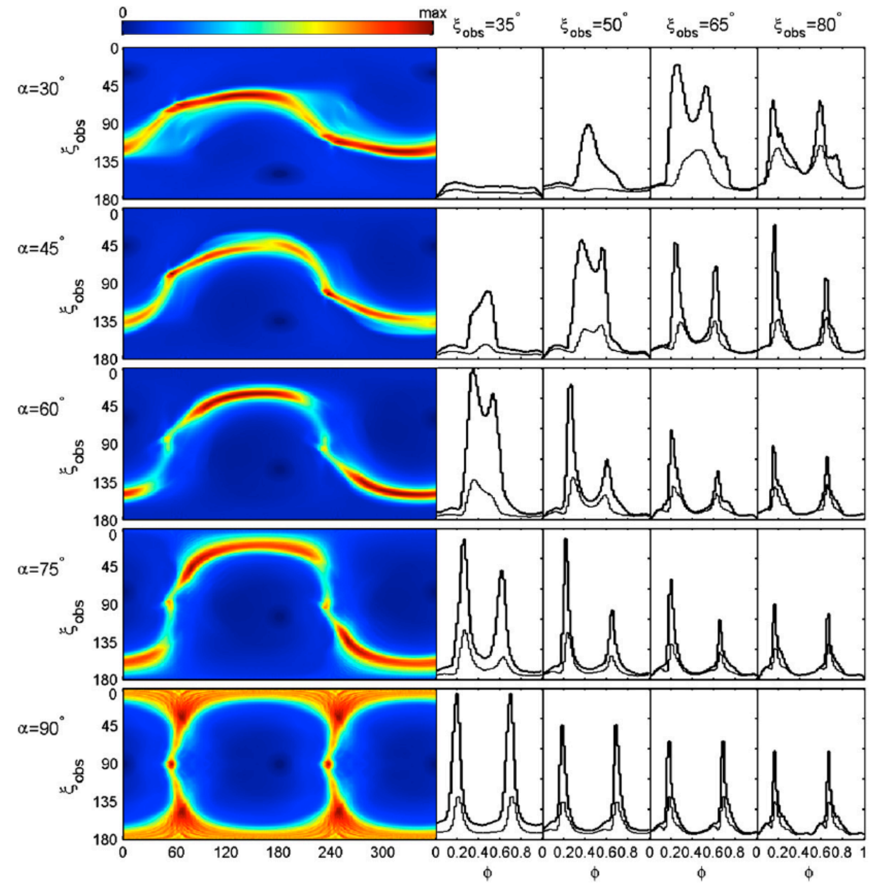
Light Curves from Separatrix Layer Emission (Bai & Spitkovsky 2010)

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 <u>through</u> LC, field lines become straight

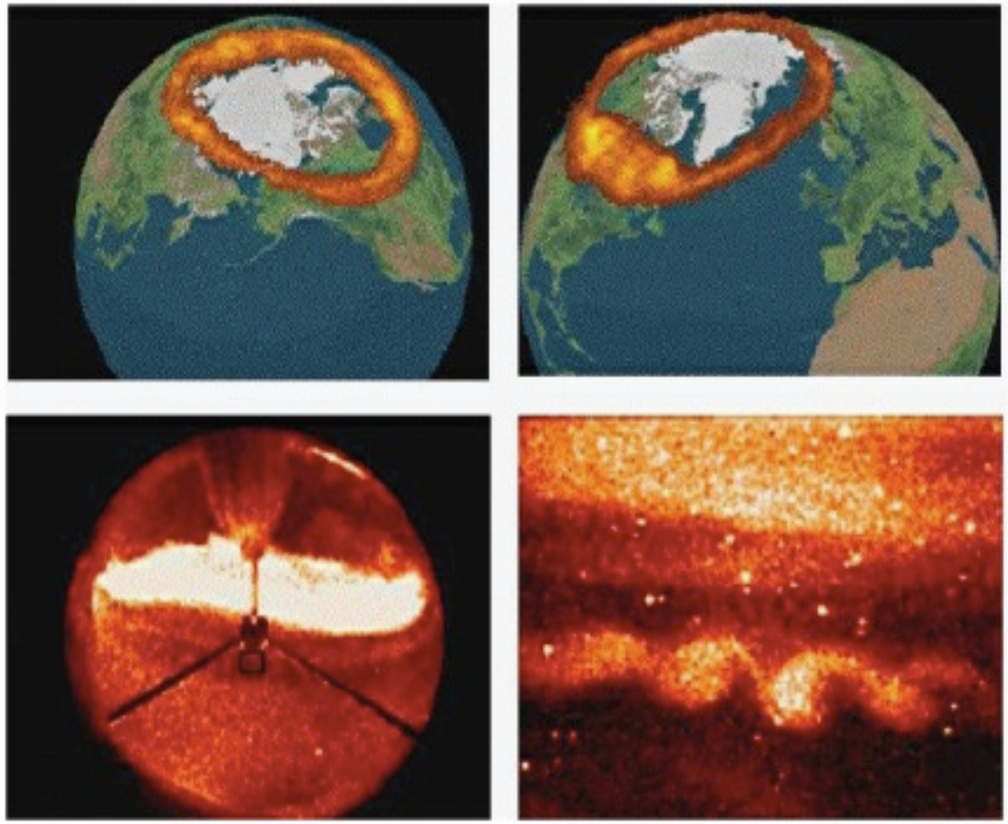
Simple beaming model = good account of light curves

Physical emission needs accelerator like Aurora?

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

Auroral Model-a radiating sheet accelerator in globally FF

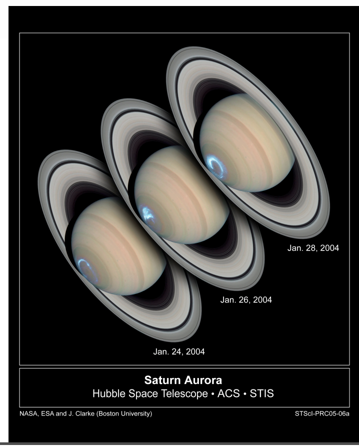
Earth Auroral oval from space – current flow along B driven by solar wind Mechanical stress coupled to magntosphere by reconnection



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

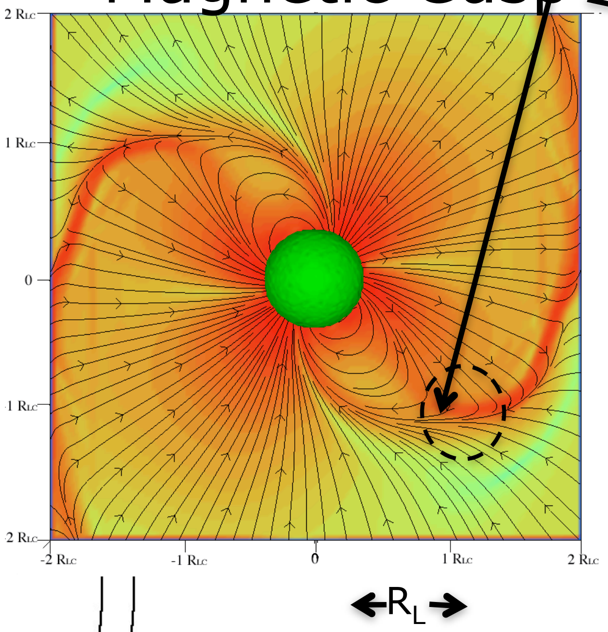
$$\Delta\Phi_{||} \geq \Phi_{magnetosphere}\text{(solar wind)}$$

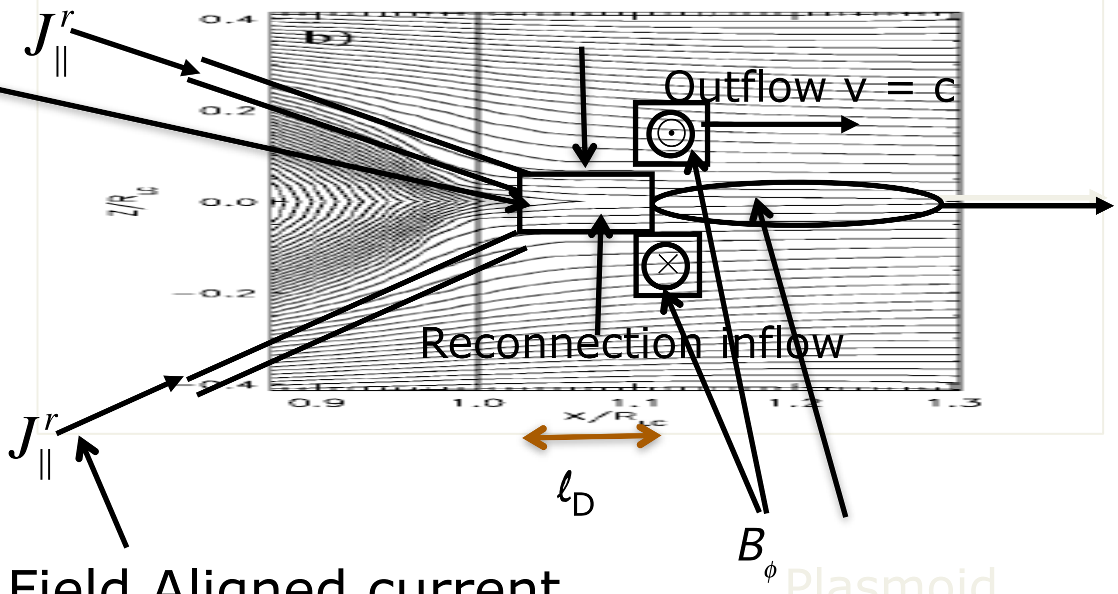
Density >>> GJ:
No vacuum gaps needed to have strong $E_{||}$



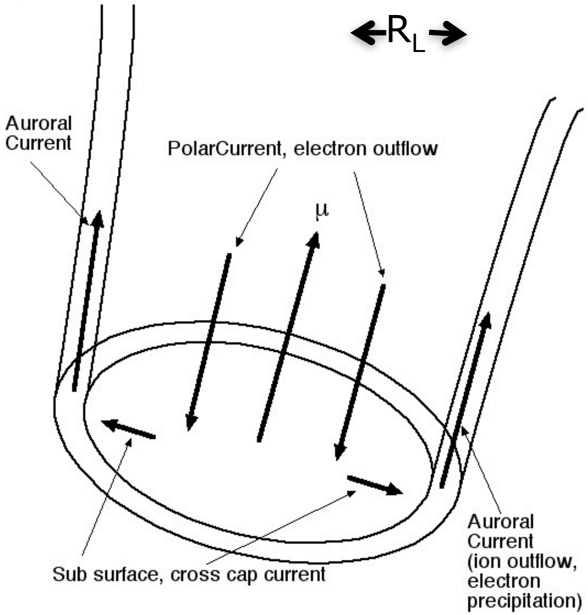
Jupiter, Saturn similar

Magnetic Cusp





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)

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

w=relativistic enthalpy; anomalous resistivity neglected

Polar Cap $\Omega\cdot\mu > 0$

Acute rotator

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

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

Total value of current fixed by the force free magnetosphere
Current density of precipitating and outgoing beams in the return current channel depends on the length of the diffusion region ℓ_D, which could be as small as the width = formal Larmor radius and as much as many % of the macroscopic scale, the light cylinder distance. Can be estimated & simulated, here treat as parameter.

Inertia of beams in the channel supports parallel E (kinetic Alfven wave)

Simple estimates: lower limit to accelerating voltage

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

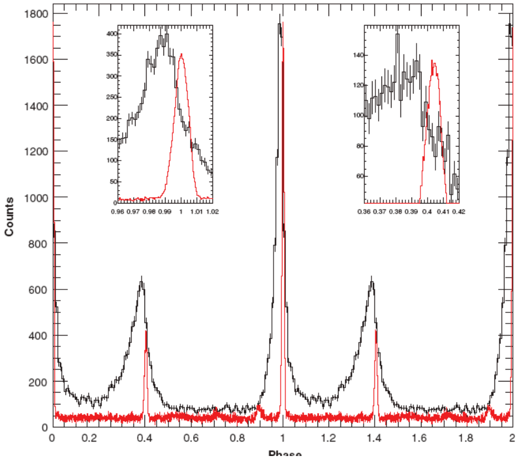
V_{recon}/c ~0.1 (pair reconnection PIC simulations)

ℓ_D/R_l macroscopic: e.g., ~0.1, as in FF simulations due to numerics, parallel voltage drop ~ 1-10 TV, enough for GeV gamma ray emission by curvature radiation, possible pair creation – is curvature radiation the emission mechanism

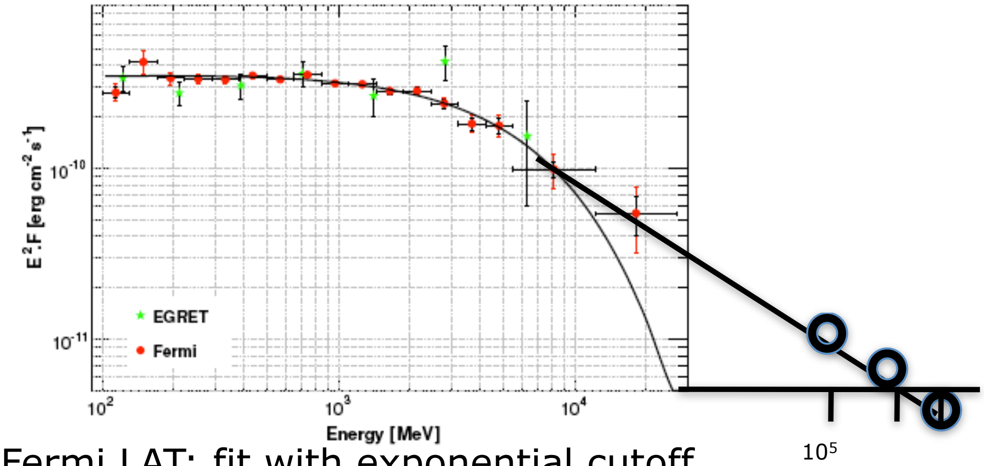
Curvature emission (assumed in gap models) challenged by VERITAS Crab PSR obs.

ℓ_D/R_l microscopic (multiple skin depths): voltage drop 1-10 GV, gammas from synchrotron radiation – colliding beams unstable, excite Larmor gyration

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 – high ε excess?

VERITAS (submitted): pulsed emission up to 300 GeV, fit by broken power law (two peaks? Curvature + Inverse Compton?

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

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

$$r_1 = R_L\left(\frac{243}{4096}\frac{B(R_L)}{4.4\times 10^{13}\,\mathrm{G}}\ln\Lambda\right)^{2/5}\left(\frac{\varepsilon}{m_e c^2}\right)^{2/5} = 0.22R_L\left(\frac{\ln\Lambda}{30}\right)^{2/5}\left(\frac{\varepsilon}{300\ \mathrm{GeV}}\right)^{2/5}$$

$$\Lambda = 0.00987\alpha_F\frac{R_L}{\lambda_C}\frac{B(R_L)}{4.4\times 10^{13}\,\mathrm{G}}\left(\frac{R_L}{r_1}\right)^4,\ \lambda_C = \text{ Compton Wavelength}$$

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

Radiation Reaction limited Acceleration with Curvature Emission

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

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

Veritas not exponentially cut off ($\varepsilon_c > 300$ GeV) $\Rightarrow$ $(E_{\parallel}/B)^{3/4}\sqrt{f}>6$

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

inner wind current sheet

Or, radiation mechanism not curvature: Inverse Compton model from Lyutikov & Otte will emerge soon

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

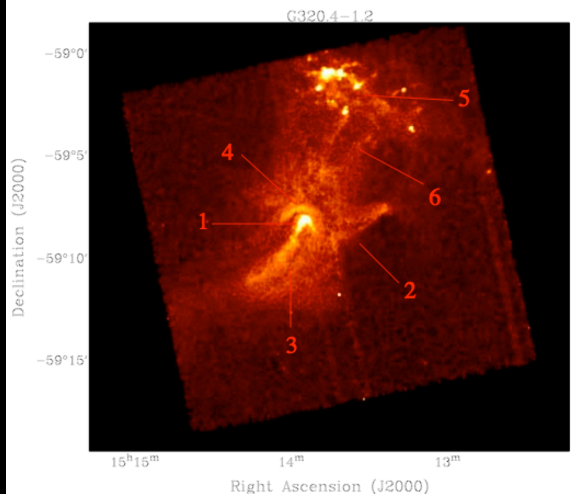
Follow the Mass Loss: From Whence all the Pairs?

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

PAIR PROBLEM

X-Rays: current injection rate (compact, strong B nebulae - Crab, G54,...)
measured rates ~ existing (starvation) gap rates $\kappa_{\pm} = \dot{N}_{\pm} / \dot{N}_{GJ} \lesssim 10^4$ pairs/GJ

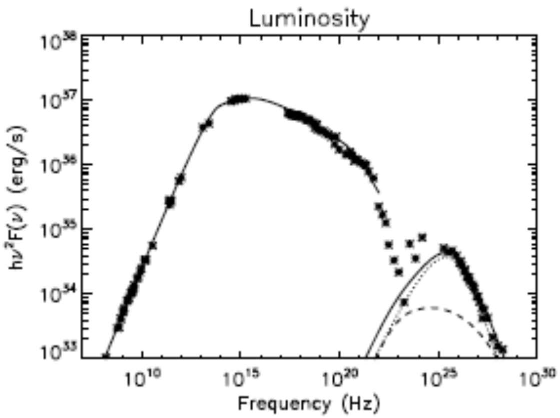
Radio measures injection rate averaged over nebular histories



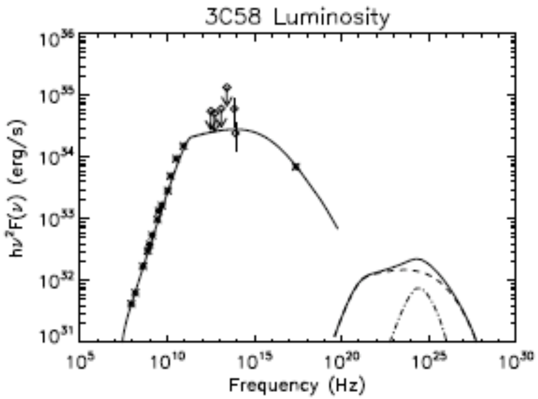
Low $\sigma = B^2/8\pi m_\pm c^2 n_\pm \Gamma_w$ at termination $\quad \Gamma_w = e\Phi/2m_\pm c^2 \kappa_\pm < 10^{4.3}$

PWN Name	±	wind	(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

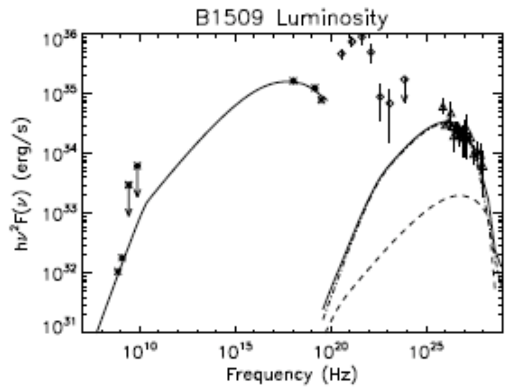
From one zone evolutionary model of observed spectrum <u>including</u> radio (with Bucciantini, Amato) – injection spectrum <u>convex,</u> $\gamma^{-1.3} \longrightarrow \gamma^{-2.3}$



Crab



3C58

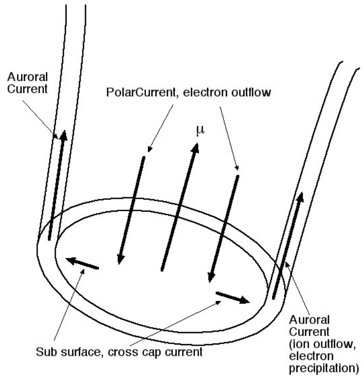


PSR B1509/MSH 15-52

Polar Cap Pairs – Largest Source, All (?) PSR, all radio?
"Starvation" Electric Fields (with A. Timokhin)

Strong $g=10^{14}$ cgs, $T_*\sim10^6$ K: no corona, charge separated magnetosphere

Model: Atmosphere freely releases charge
residuum of vacuum electric field pulls charge out
into a relativistic beam, shorts out most of $E_\parallel$



unshorted $E_\parallel$ would drop all of Φ within
height = polar cap width = $R_*(R_*/R_{LC})^{1/2}$ = 100m – 1 km

Beam electron (positron) moves on curved B, emits γ rays

γ's go one absorption length in superstong B turn into $e^\pm$,
multiply in a cascade

Beam density = electric current density ≃ GJ = eΦ/c*(area),
~ Force free expectation

Newborn pairs poison residual vacuum, shut off $E_\parallel$ at a
fixed voltage drop ≈ 10^{12} V = radio death boundary in $P,\dot{P}$
$\approx L_\gamma \propto \sqrt{\dot{E}_R}$ in gamma ray data

Polar beam model like a diode:
cathode =stellar atmosphere, anode = surface of first pair creation
diode operates with ΔΦ fixed by anode at τ=1 ↔ Φ=10^{12} V

current voltage characteristic: $J_{||}$ =B/P exactly

PIC + Monte Carlo Simulation of Standard Model

1D, applies to young pulsars

Concept: Atmosphere freely emits charge, assume monotonic acceleration to $v_{||}=c$; accel in unshorted vacuum $E_{||}$ (some? all?); (flow is steady in corotating frame on time << P); charge density of beam $\neq \eta_R \equiv -\mathbf{\Omega}\cdot\mathbf{B}/2\pi c$ = charge density $\ni E_{||}=0$ – idea is to accelerate up until charges emit curvature + inverse Compton γs, convert to pairs, pairs short out $E_{||}$ ("pair formation front" = PFF) where $\tau_{\gamma B} = 1$

$\Delta\Phi_{||} \approx 10^{12}$ V almost independent of parameters (if $\tau_{\gamma B} = 1$ possible at all)

Defines a cathode (stellar atmosphere) – anode (PFF) pair with $E_{||}=0$ at both ends – unique beam charge $\eta = J_{||}/c$

If η_R = constant, unique answer is

$$J_{||}/c = \eta_R$$

then $E_{||}=0$, no acceleration!

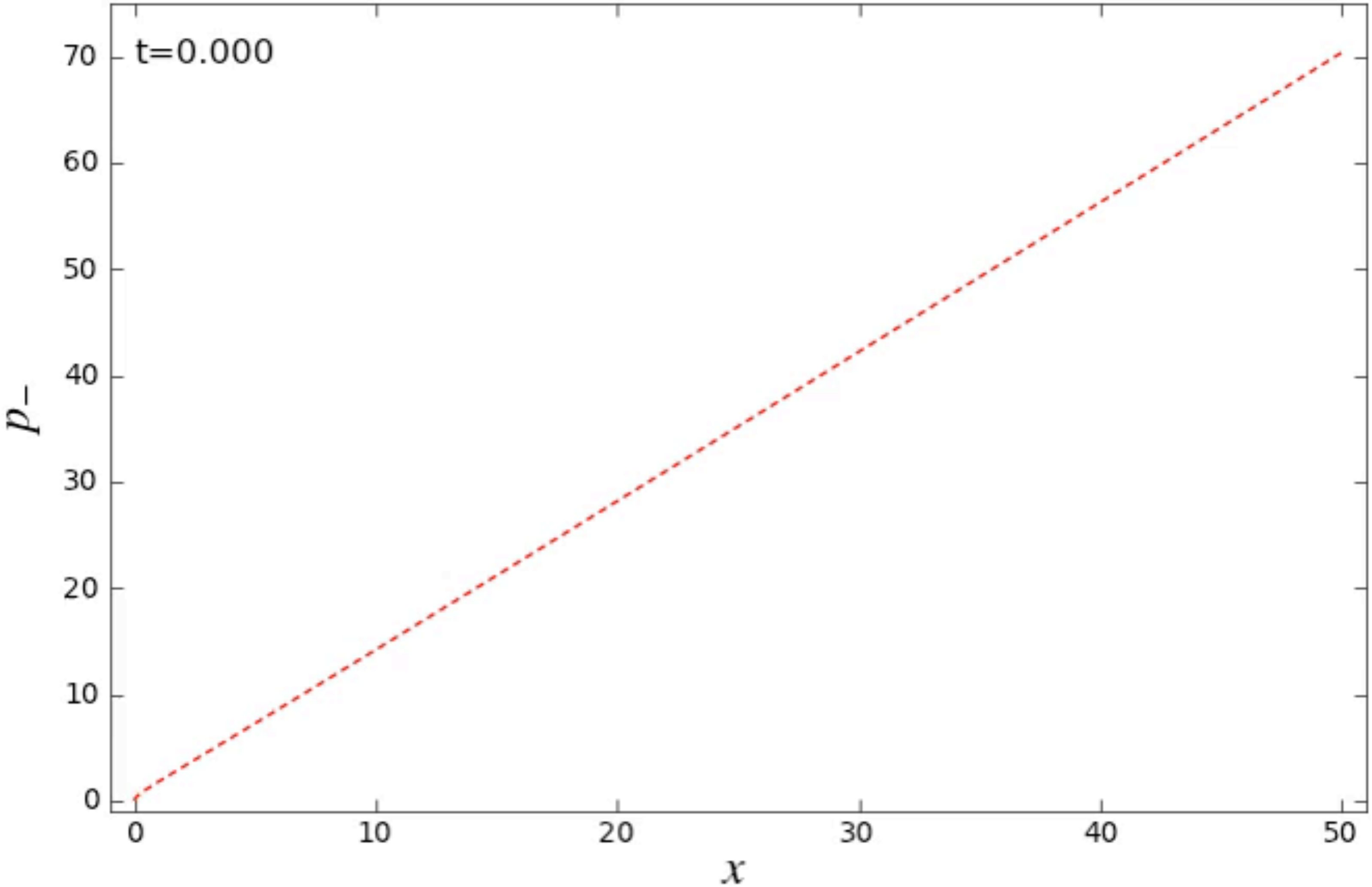
Total Φ huge, small variation of η_R allows $\eta - \eta_R \neq 0$, $\Delta\Phi_{||} \gg 10^{12}$ V if no pairs

$$\Omega \approx \Omega_* \left[1 - 0.4\frac{GM}{R_* c^2}\left(\frac{R_*}{r}\right)^3\right]$$

Biggest effect – dragging of inertial frames,

effective Ω increases with r, vaccum starvation goes up

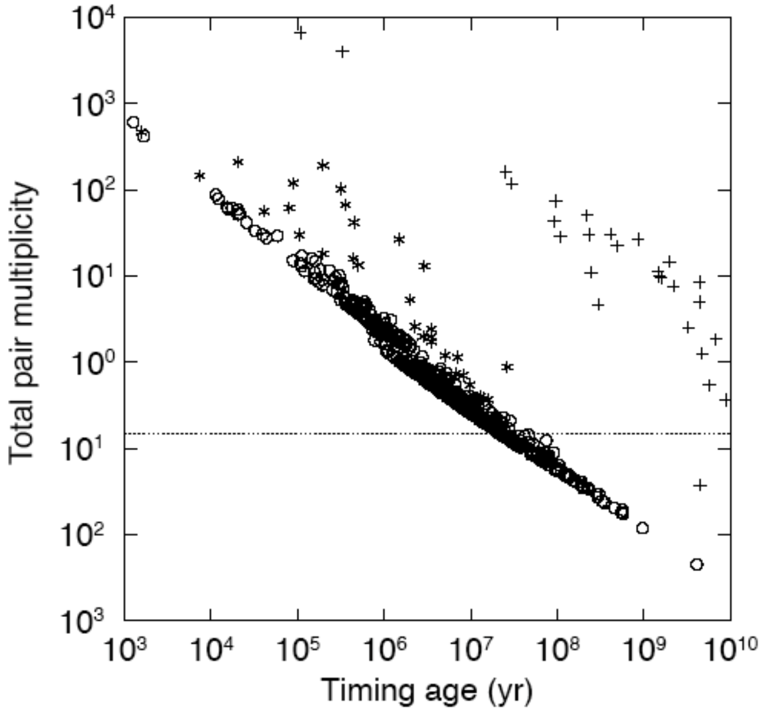
Relativistic Space Charge Limited Flow (A Timokhin)



Relativistic Space Charge Limited Flow (A Timokhin)

Poison Worms in the bottle:

1) Pulsar death line ($\Phi = \sqrt{\dot{E}_R / c} = 10^{12}$ V) models need dense ($E_{||}=0$) pairs over all $P, \dot{P}$ space – works fine at large Φ, young stars, but fails badly at longer period, greater age



Hibschman & JA 01

2) $J_{||} = B/P = \rho_{charge} c$ is what was expected to **order of magnitude** for the force free magnetosphere, but actual force free solutions need something different

1) May be solved by simple modification of exact star centered dipole geometry near surface – offset dipole with dipole axis tipped away from radial direction increases optical depth, more pairs

2) Solutions of force-free structure show $|J_{||}| \lesseqgtr |\eta_c| c$ and $J_{||}$ with sign opposite to $c\eta_c$ over part of open flux tube (distributed return current), behavior not the relativistic acceleration of unidirectional beam – cathode-anode operate with current fixed, "gap" adjusts quickly to slowly changing global B

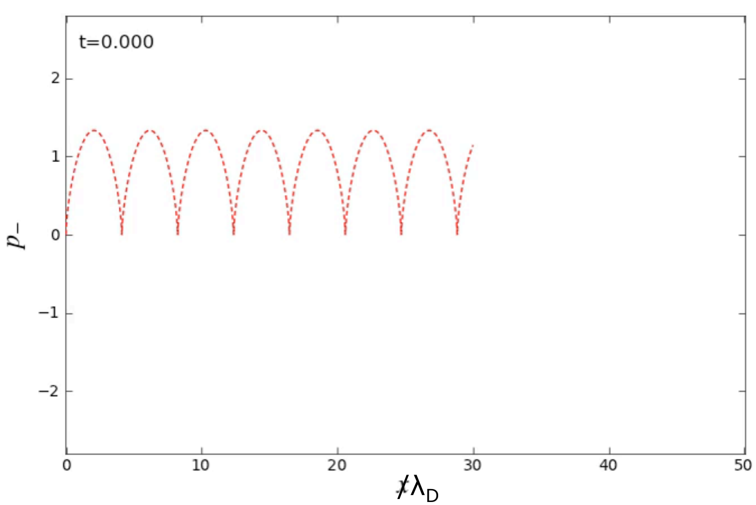
Low Altitude Accelerator with $J_{||}/c\eta_R \neq 1$

what happens if beam extracted from stellar atmosphere has “wrong” charge density ($\eta \neq \eta_R$)? (Timokhin & JA, 1D PIC+MC)

$0 < j \equiv J_{||}/c\eta_R < 1$: Low voltage beam +non-neutral trapped cloud blue on polar cap current plots

Cold beam flow has stationary, $\gamma \sim$few non-monotonic flow. Stationary finite amplitude spatial plasma oscillation with $E_{||}$ cusped at velocity zeros (MW, Beloborodov)

$J_{||}/c\eta_R = +0.5$



Wave breaks immediately, trapped particles provide the rest of the co-rotation charge density

No pair creation, γ too small

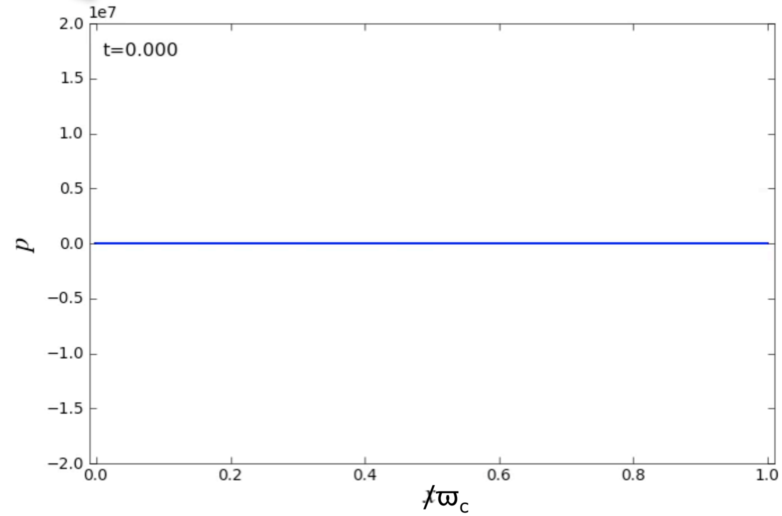
$J_{||}/c\eta_R < 0$ (return current, red)

$J_{||}/c\eta_R > 1$

>TV unsteady discharges with pairs

$p = \gamma\beta$

$J_{||}/c\eta_R = -1.5$



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$/\lambda_D$

Wave breaks immediately, trapped particles
provide the rest of the co-rotation charge
density

No pair creation, γ too small

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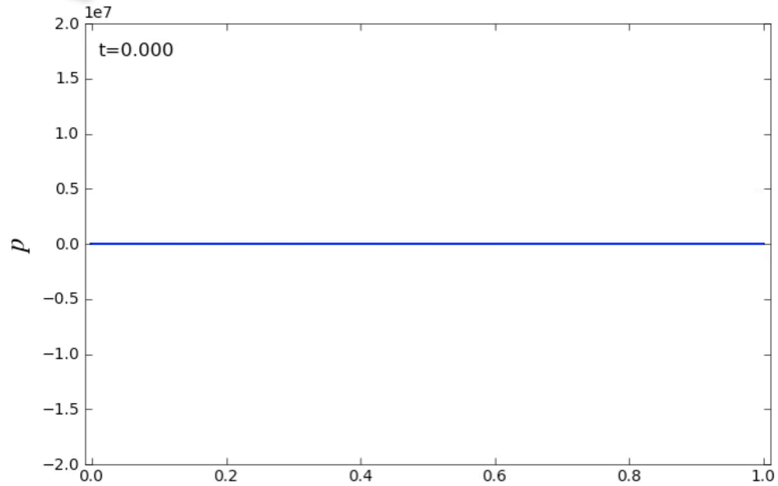

x/ϖ_c

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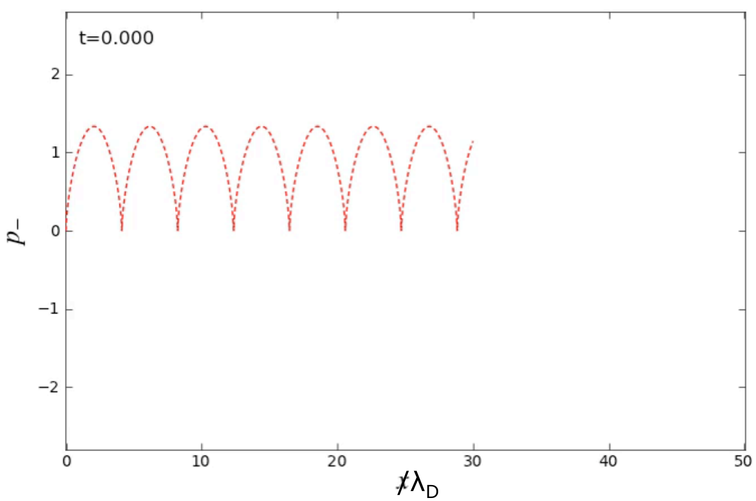

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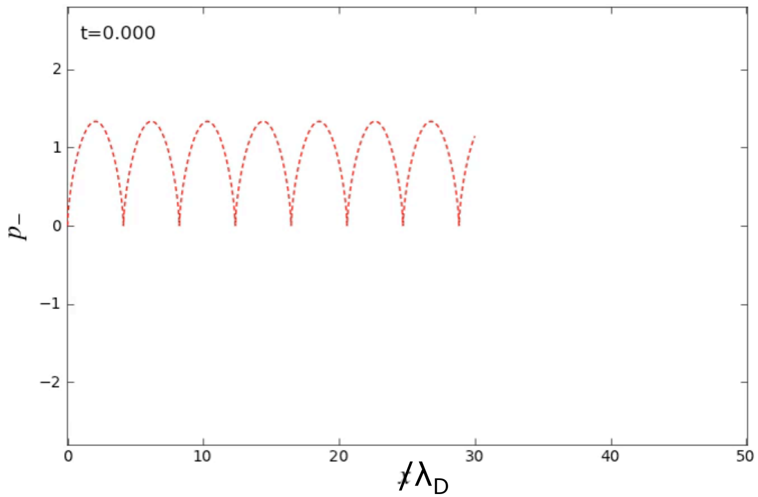
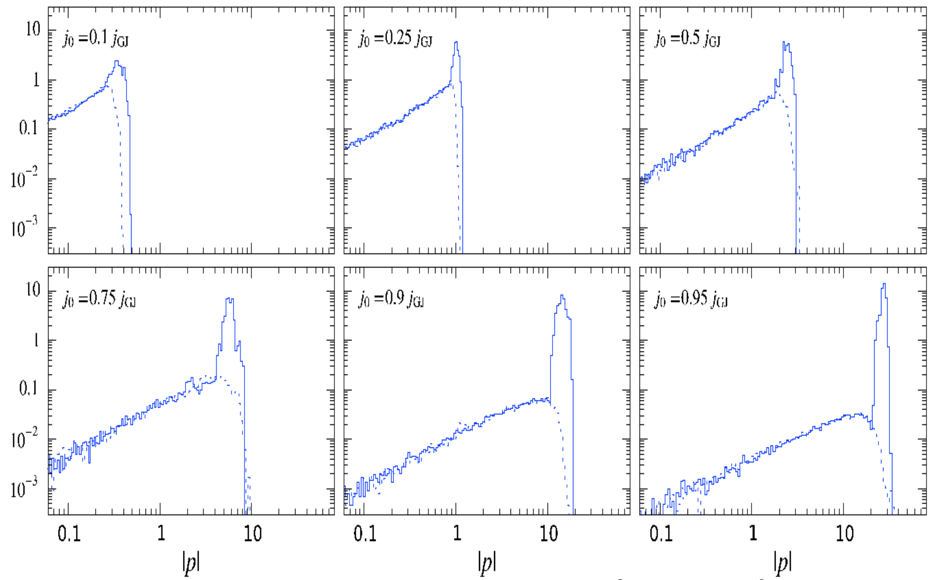
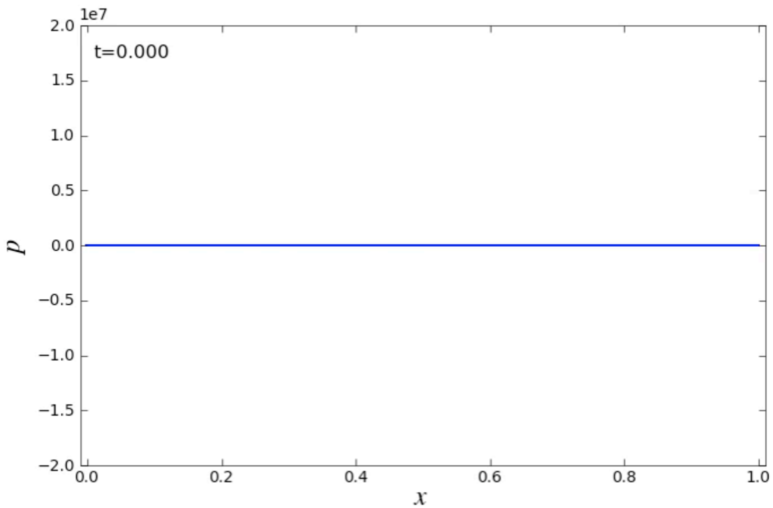




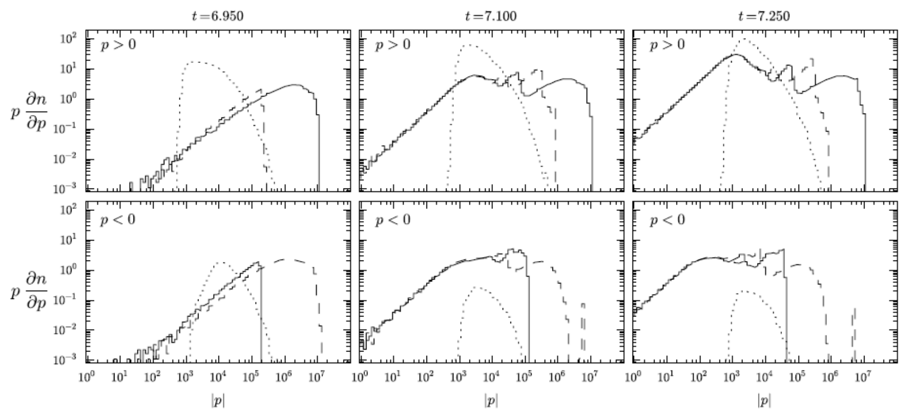
$p = \gamma\beta$

Quasi-stationary non-neutral warm beam + trapped cloud particle spectra

$J_{||}/c\eta_R = -1.5$

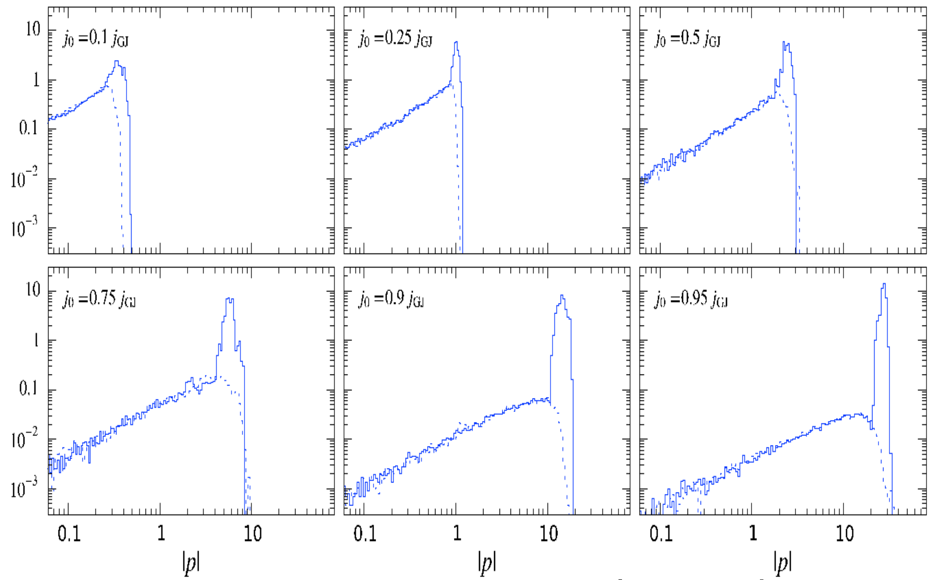


Direct radio emitter?



Positron (solid), electron (dashed) & gamma ray (dotted) spectra with unsteady clouds

$J_{||}/c\eta_R$=+0.5



/λ_D

p=γβ

Quasi-stationary non-neutral warm beam
+ trapped cloud particle spectra

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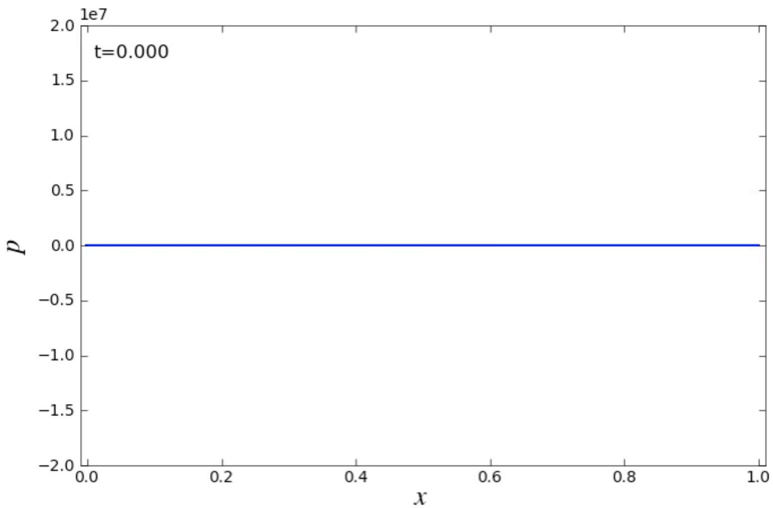

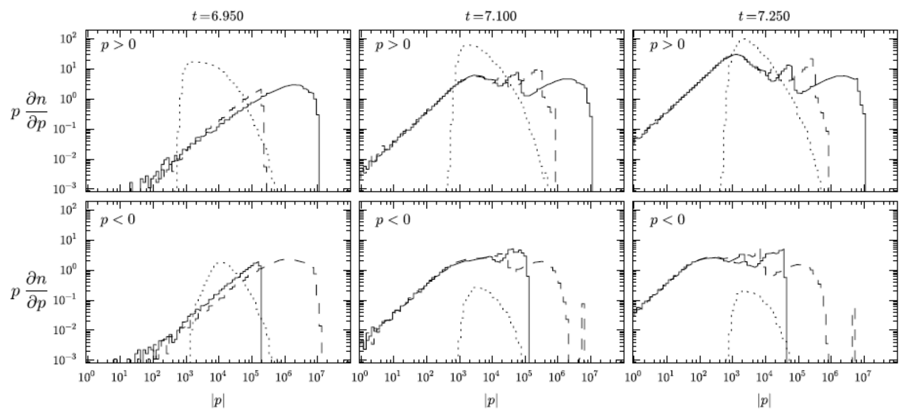

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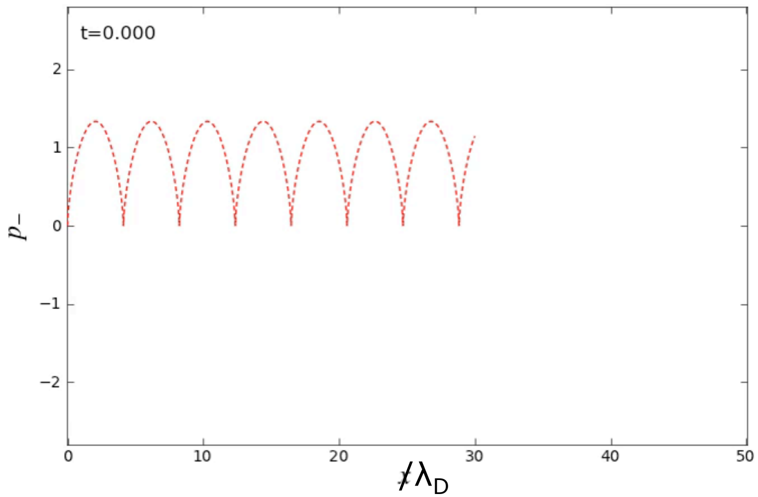
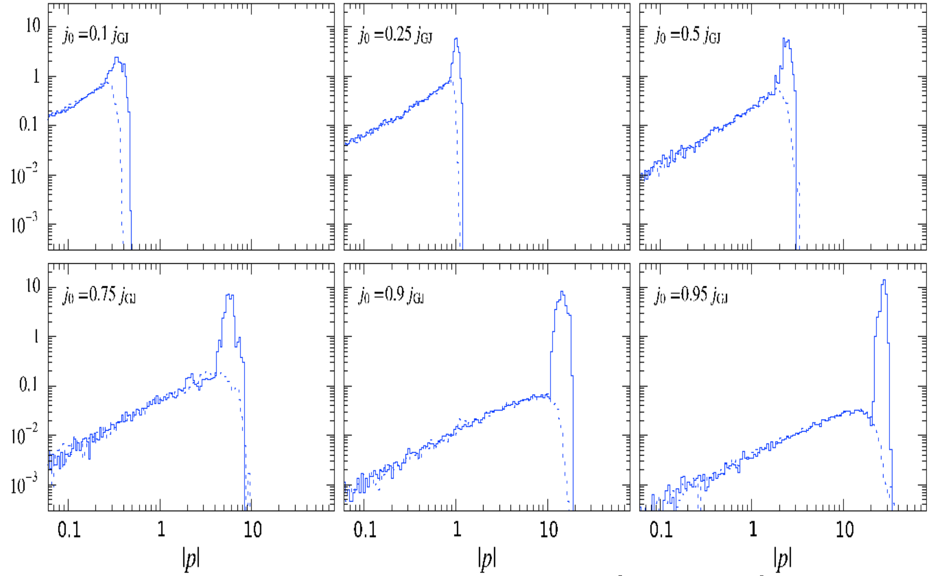
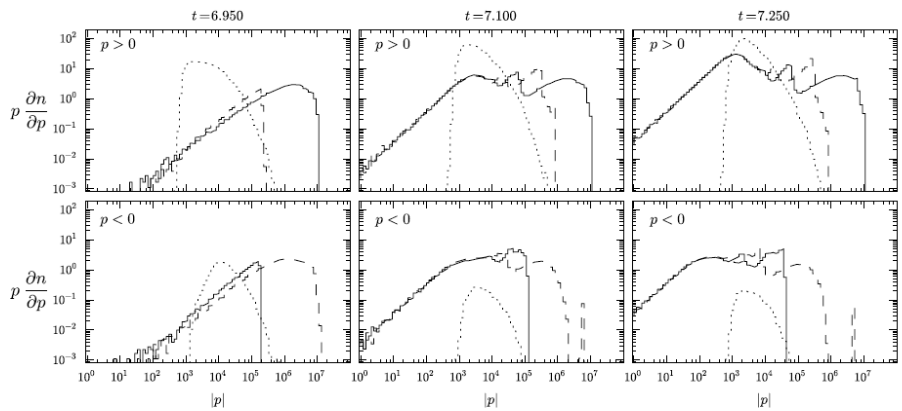




p=γβ

Quasi-stationary non-neutral warm beam + trapped cloud particle spectra

$J_{||}/c\eta_R$=-1.5



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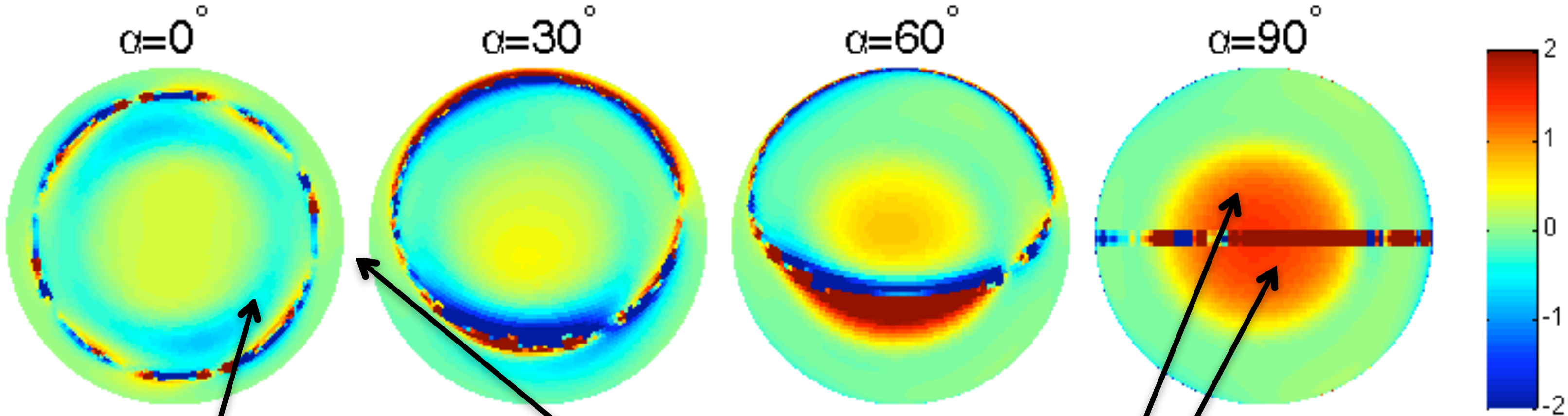

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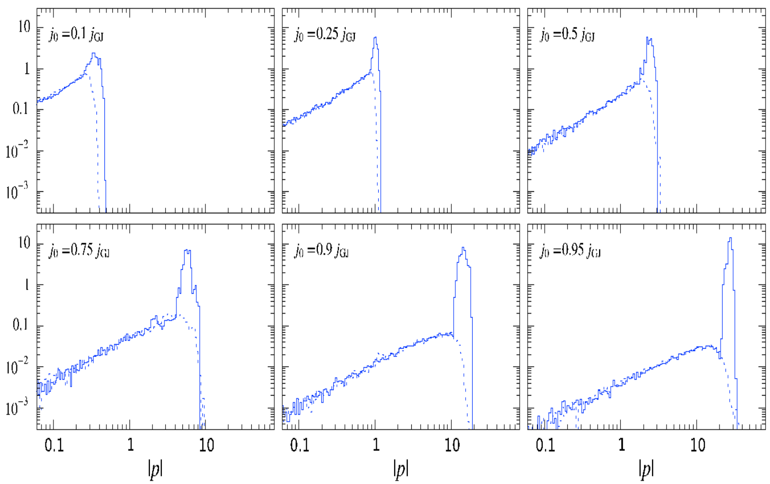

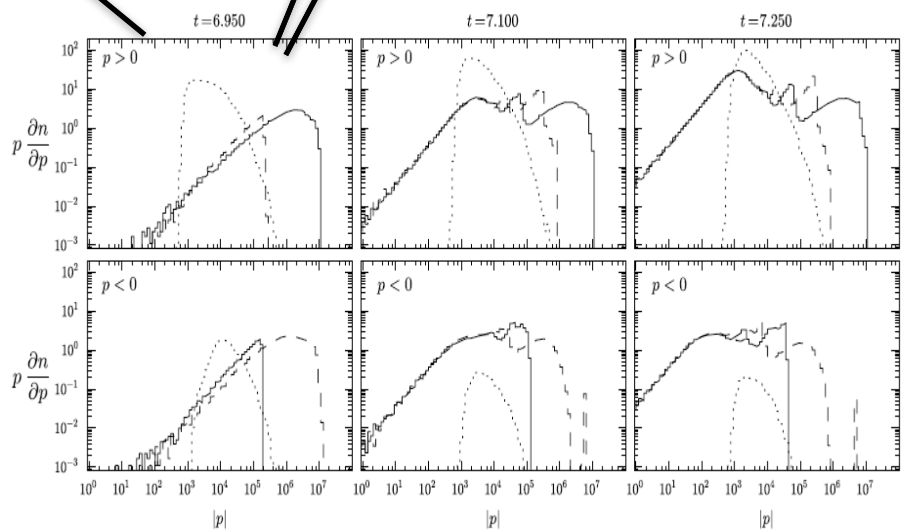

Mostly escapes to wind

All escapes to wind

Many unanswered questions – what happens to non-neutral outflow

SUMMARY

PeVatron: Pulsar Wind Nebulae – Wind Termination Working Surface
is time dependent, associated with nebular synchrotron emission
textbook transverse shocks don't work,
shock + some kind of reconnection shows promise
shock + external turbulence needs study
- gamma rays in flares need region with E/B > 1 (like X-lines)

TeVatron: Pulsed Gamma Rays from Magnetosphere
Force Free MHD Model for Spindown
return current: current sheet + extra distributed current in magnetosphere & wind
possible formation of return current from reconnection at cusp
possible auroral model for acceleration in current sheet
pair creation at polar caps (needed for MHD to work)
30 year old polar beam model being replaced by
discharges in return current, MHD in main volume of wind
by fully charge separated flow (?) – force free just needs enough charge to make $E \cdot B=0$, does not need quasineutrality
time dependent discharges make radio emission?