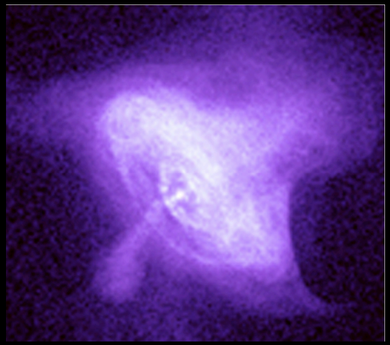
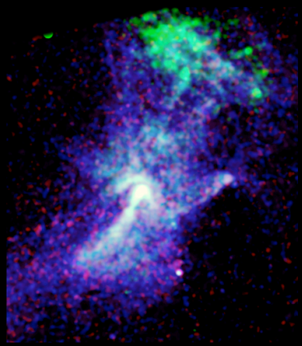
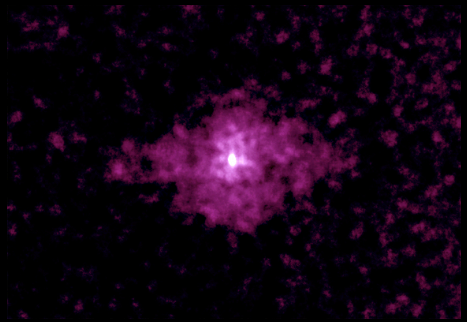
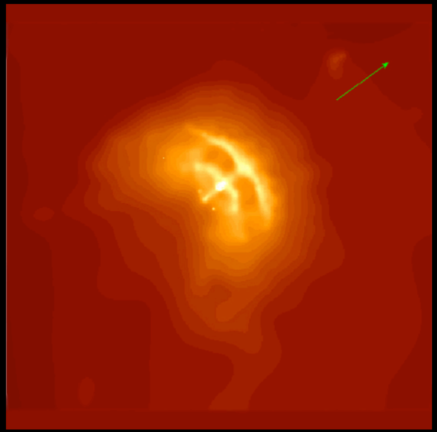




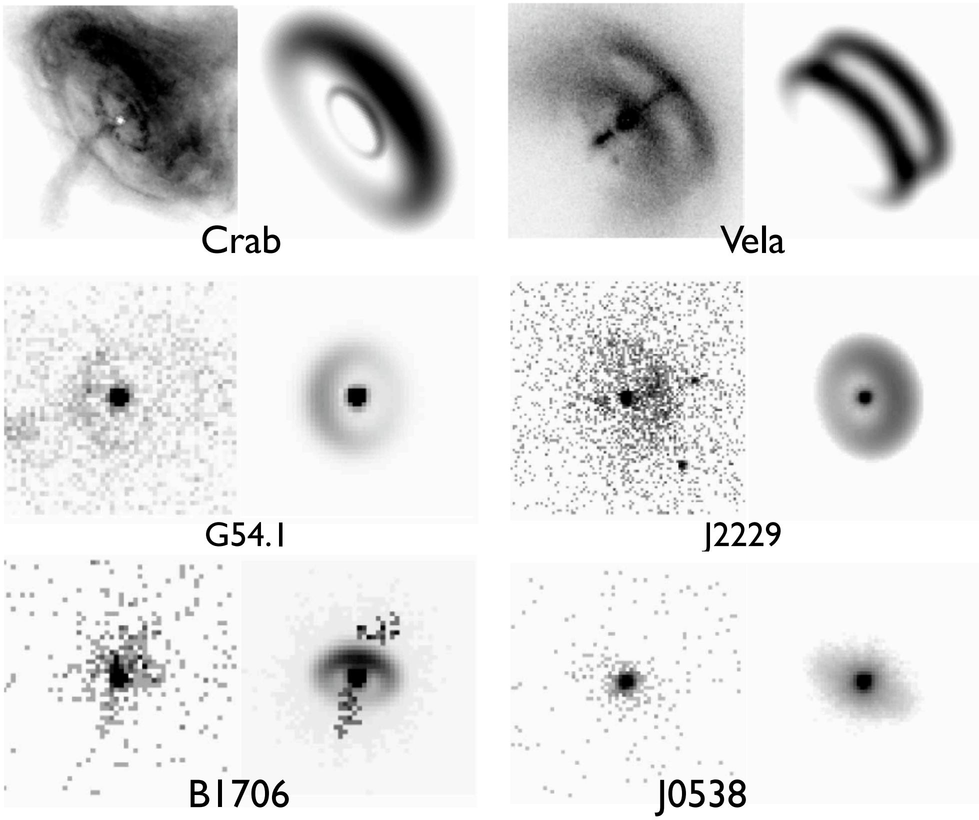
Multiple Sheet Beam Instability of Current Sheets in Striped Relativistic Winds

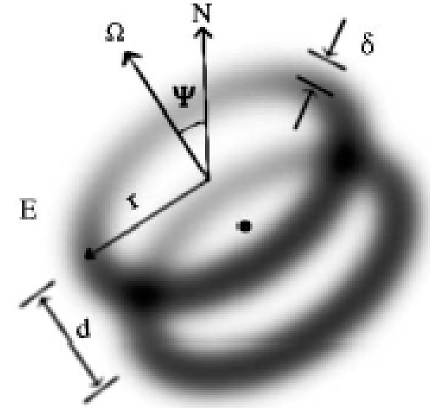
Jonathan Arons
University of California, Berkeley





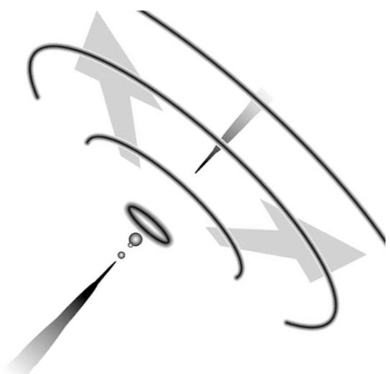
Rings and Torii





Ng & Romani

Torii in rotational equator - small aspect ratio - $\delta/r \sim 0.1$ (Crab), smaller in others

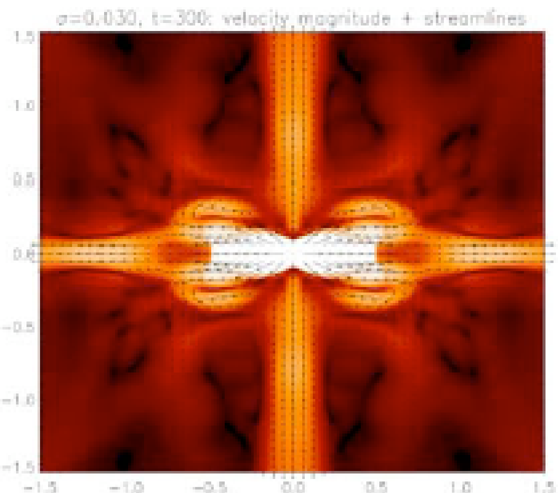


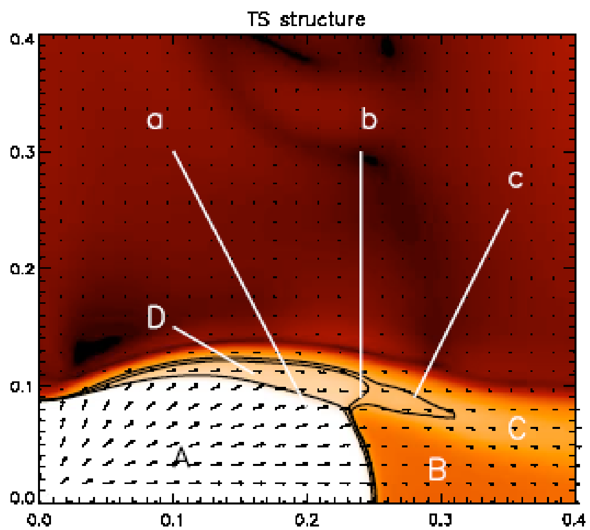
As if energy flux $\dot{E}/4\pi r^2$ in a narrow latitude sector $|\lambda| < \delta/r$

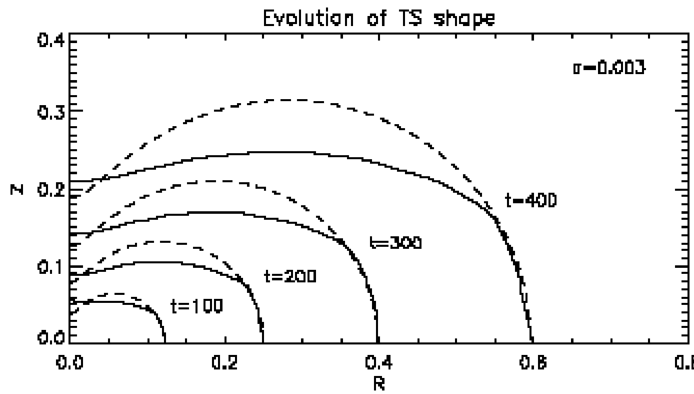
Poynting Flux dominated wind strongest toward equator

$$F_{upstream} = \frac{\dot{E}}{4\pi r^2}\cos^2\lambda = c\left(\frac{B^2}{4\pi}\right)_{upstream}\left(1+\frac{1}{\sigma}\right)$$

Magic: If $\sigma = \left(\frac{B^2}{4\pi m c^2 n \gamma \beta^2}\right)_{upstream} \ll 1$, nebular response ~ images







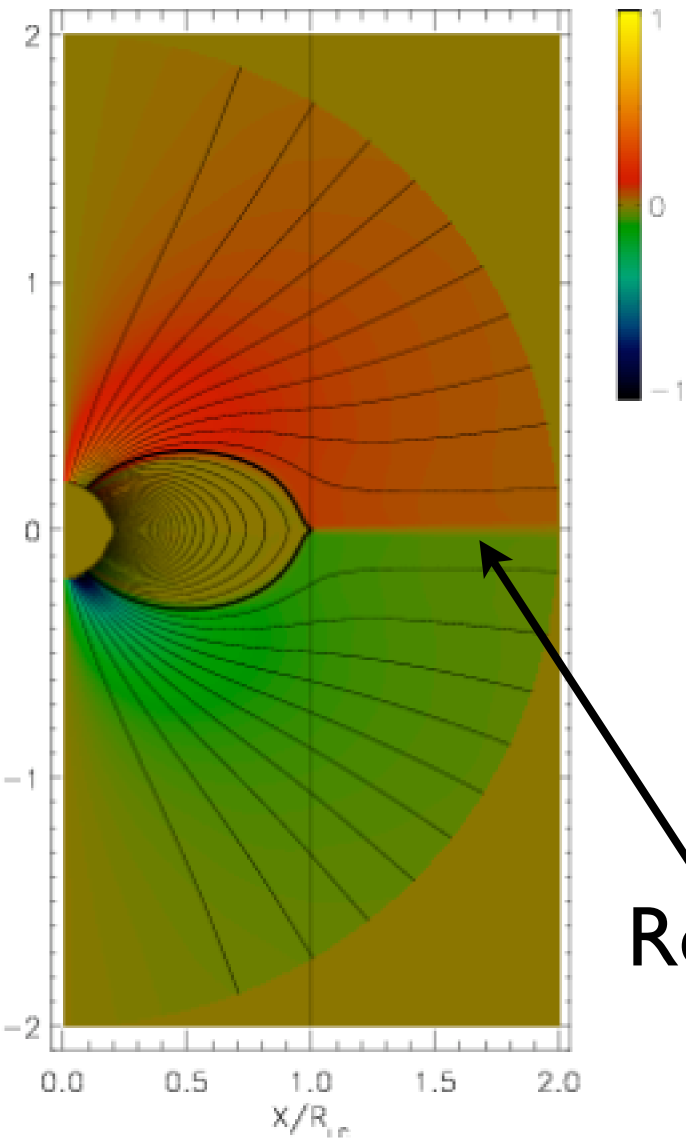
$$B(r,\lambda) = B_0\left(\frac{r_0}{r}\right)\cos\lambda\tanh\left(\frac{\lambda}{\lambda_0}\right),\ \sigma = 0.03,\ \lambda_0 = 5^\circ$$

"Unmagnetized" equatorial channel

(Komisssarov & Lyubarsky 2003; del Zanna et al 2004; Bogovalov et al 2005)

Outer Wind Properties, $r \gg R_L = c/\Omega$:

Like Split Monopole of Aligned Rotator Without Dissipation:



$$B_\phi = \mp \frac{\mu}{R_L^2 r} \cos\lambda = \mp \frac{\Phi}{r} \cos\lambda, \quad |\lambda| > \Delta\lambda$$

$$B_r = \pm \frac{\mu}{R_L r^2} = \pm \frac{\Phi R_L}{r^2}, \quad B_\theta = 0$$

$$F = \frac{\dot{E}}{4\pi r^2} \cos^2\lambda, \quad \dot{E} = I\Phi = c\Phi^2$$

$$\Gamma_{wind} \approx \left(\frac{q\Phi}{2m_{eff}c^2} \right)^{1/3} = \sigma_0^{1/3} \approx 100 \left(\frac{\Phi}{10^{15}\ V} \frac{m_{proton}}{m_{eff}} \right)^{1/3}$$

Current Sheet, carries return current

$$I = c\Phi = \mu\Omega^2/c$$

Relativistic Beam: "protons" (i=0), e- (i=p)

Sheet Opening Angle: $\Delta\lambda = ?$

4

Observed PSR = oblique rotators

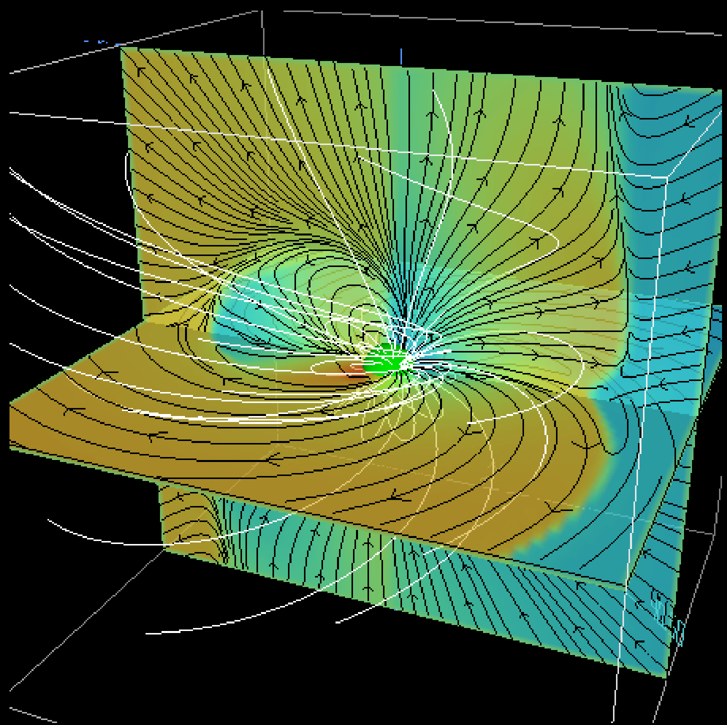
PSR	i
Crab	80°
Vela	65°
1509-58	60°
1706-44	40°
0630+17	25°
1055+08	70°

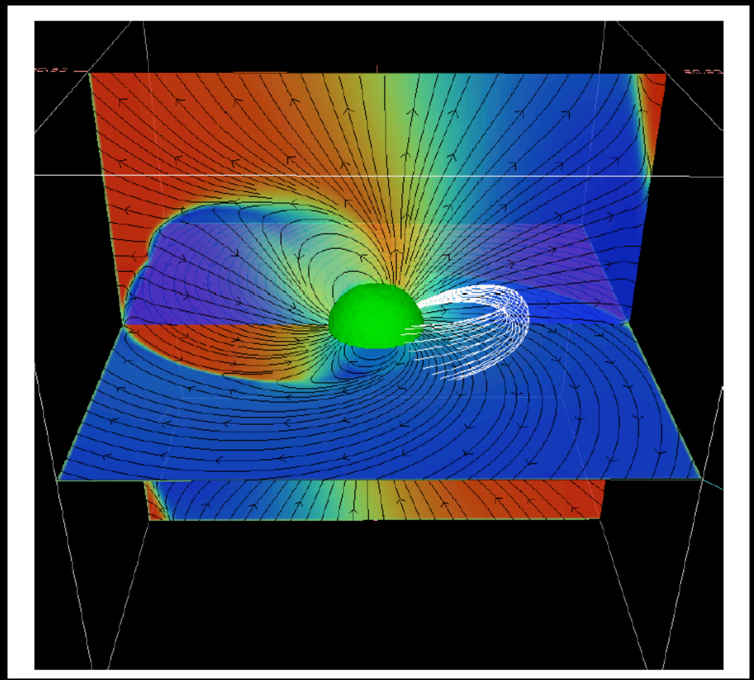
Gamma Ray PSR, i from Romani and Yadigarglou outer gap model

Equatorial Current Sheet ⟶ Frozen-in wave

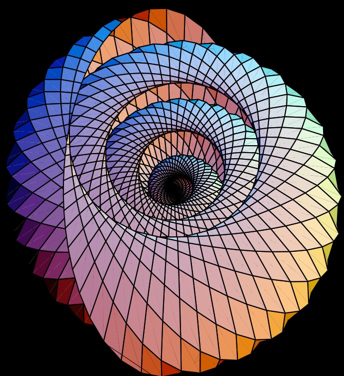
Inner Wind: Magnetically Striped

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

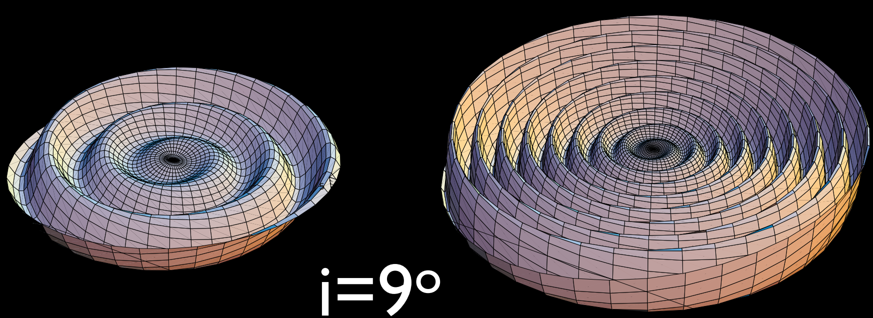




Current Sheet Separating Stripes (Bogovalov)



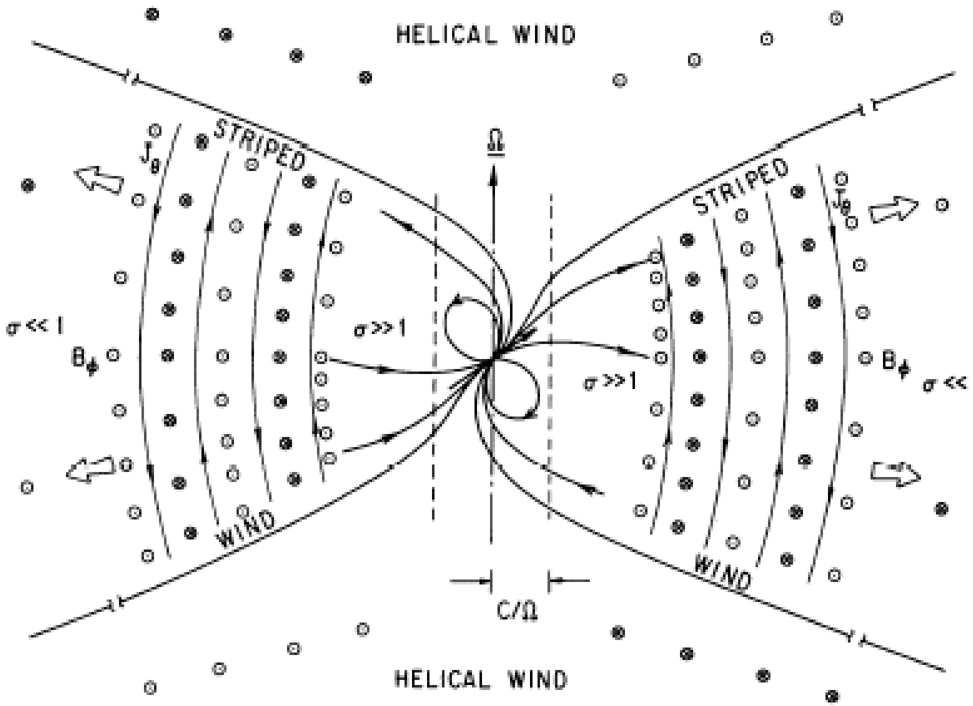
i=60°

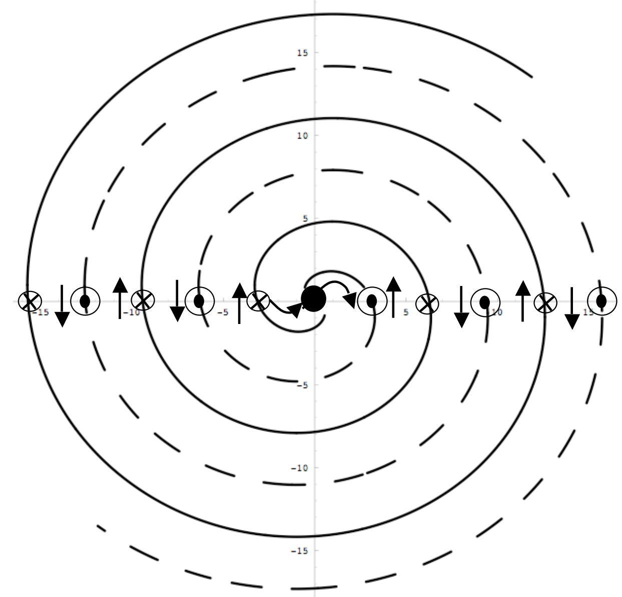


i=9°

Stripe Dissipation

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





Sheet Dissipation: Tearing of **one** locally ~ plane sheet?

(Coroniti; too slow? - Kirk & co.)

Insufficient Current? (everybody)

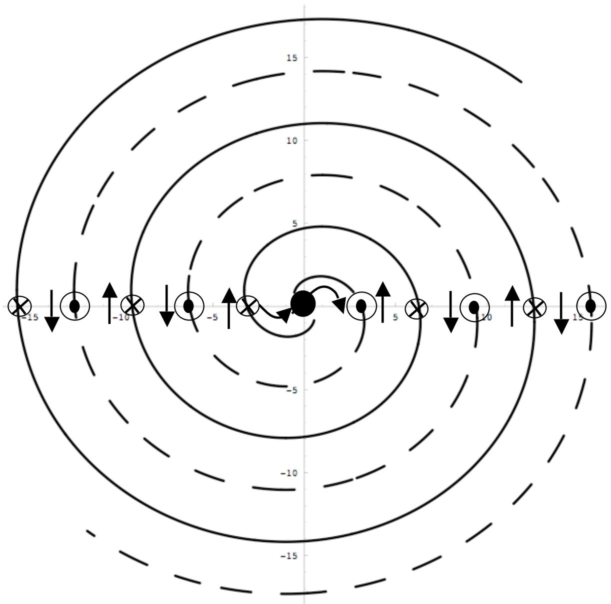
sheet ⟶ strong waves? - Melatos-vacuum)

Other Effects Leading to Dissipation:

Toroidal Sheets: kink instability, growth rate ~ c/r ~ expansion rate - slow? saturates at nonlinear kink, then tearing?

MHD detonation - explosive growth of ballooning modes, creates small scale turbulence - perhaps applies if wind acceleration large

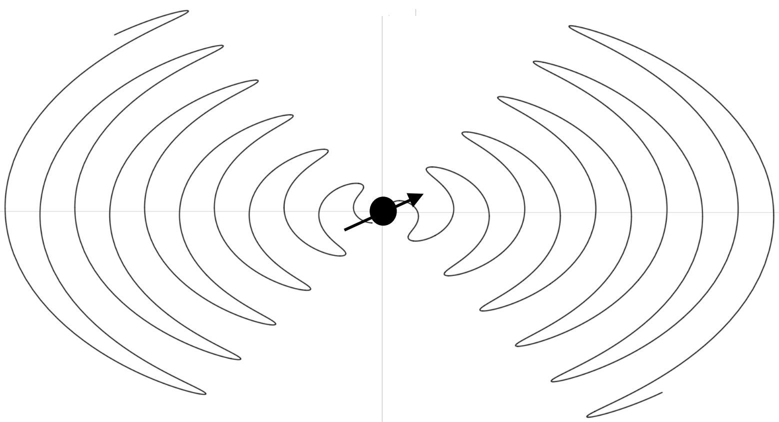
Stream Instability of Multiple Sheets



Current sheets = transmission lines
Current = charged particle beam
injected by source - Y or X line at LC

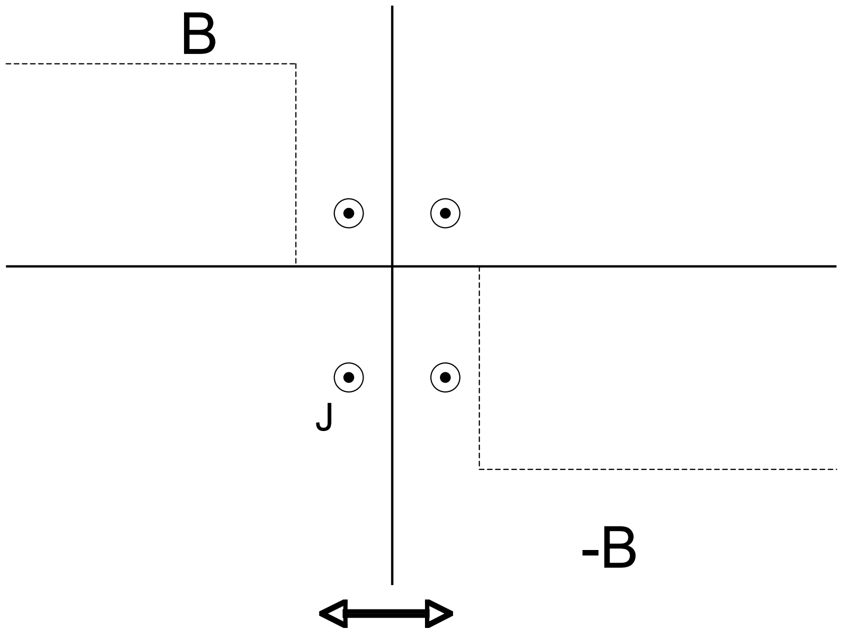
$$j_n = qc\beta_b\Sigma_b = c\frac{B(r_n)}{2\pi} = \pm\frac{c\Phi}{2\pi r_n}\cos i$$

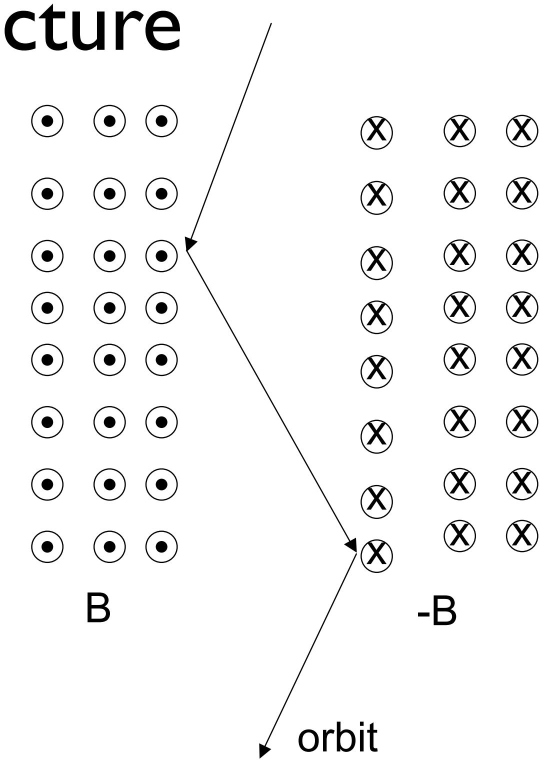
$|2\pi r_n j_n|$ =I_{GJ}=Goldreich-Julian Current



In absence of dissipation, beams flow adiabatically in narrow channel

Simplified Sheet Structure





$$H \approx r_{Lb} = \frac{mc^2\gamma_b\beta_b}{qB} \qquad \Sigma_b = \frac{j}{cq\beta_b} = \frac{cB}{2\pi q\beta_b}$$

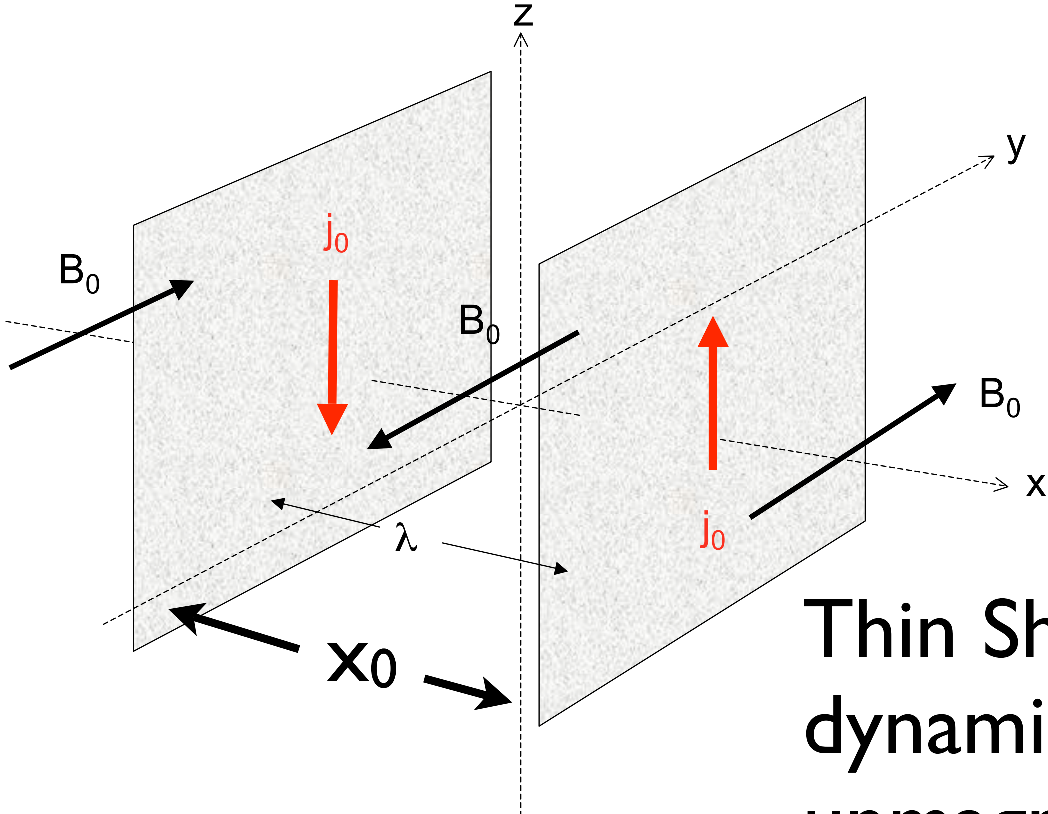
$$P_b = \frac{\Sigma_b}{2H}\gamma_b\beta_b^2 mc^2\langle\sin^2\psi\rangle = \frac{B^2}{8\pi} \Rightarrow \frac{H}{R_L} \approx \frac{2mc^2\gamma_b}{q\Phi}\left(\frac{r}{R_L}\right)^{1/2}$$ (adiabatic EOS)

Sheets swallow stripes ($H > R_L$): $r > R_m = R_L\left(\frac{q\Phi}{2mc^2\beta_b\gamma_b}\right)^2 = \frac{3\times 10^{14}}{\gamma_b^2}R_L$

(Crab) $R_m < R_{shock} \approx 10^9 R_L$ only if $\gamma_b > 600 > \sigma_0^{1/3}$ (protons)

- sheets survive?

Sheets Interact - Two Stream (Weibel-like) instability



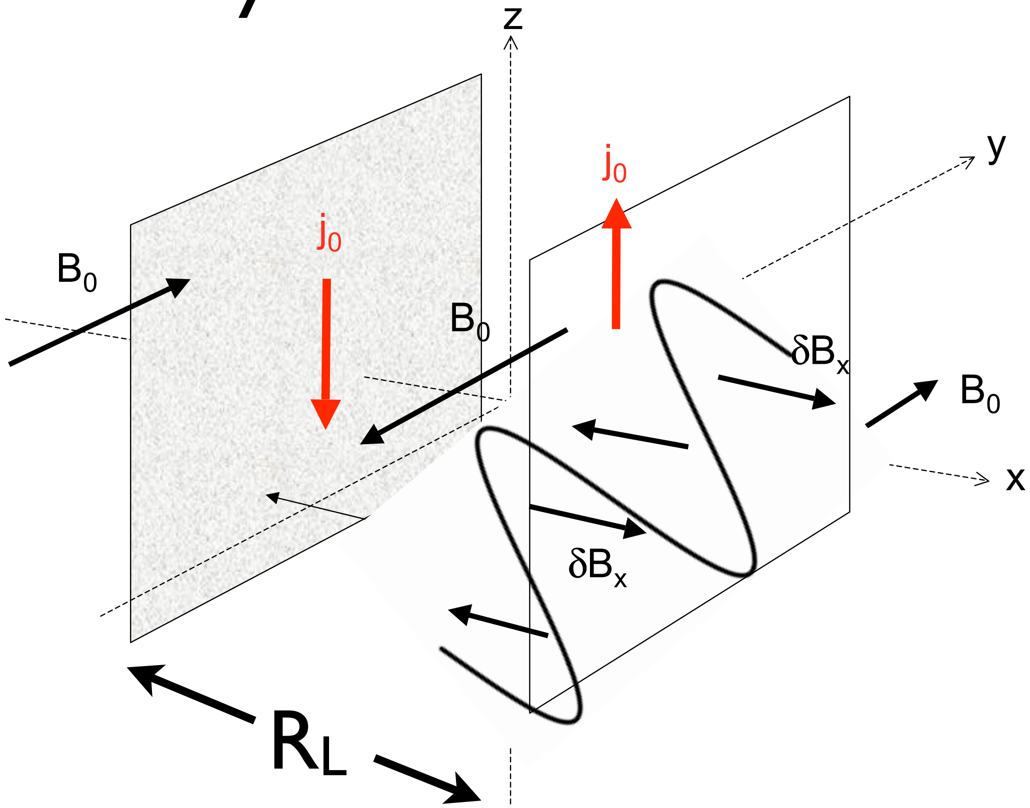
$x_0 = R_L << r$

Thin Sheet (kr_L<<1)
dynamics as if each sheet is unmagnetized
although intersheet medium MHD $(B^2 \gg 4\pi\rho_0 c^2)$

$$\langle f(x_n)\rangle = \frac{1}{2}[f(x_n^{(+)}) + f(x_n^{(-)})]$$

$$mc\Sigma_b \frac{D(\gamma_b\beta_b)}{Dt} = q\Sigma_b(\langle E\rangle + \beta_b \times \langle B\rangle) = q\Sigma_b(\langle \delta E\rangle + \beta_b \times \langle \delta B\rangle),\ \langle B_0\rangle = 0$$

Two Symmetric Sheet Instability



Imagine Magnetic disturbance at each sheet - Alfven pol

$$\langle \delta B_x(y) \rangle \propto \exp[i(k_y y - \omega t)]$$

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

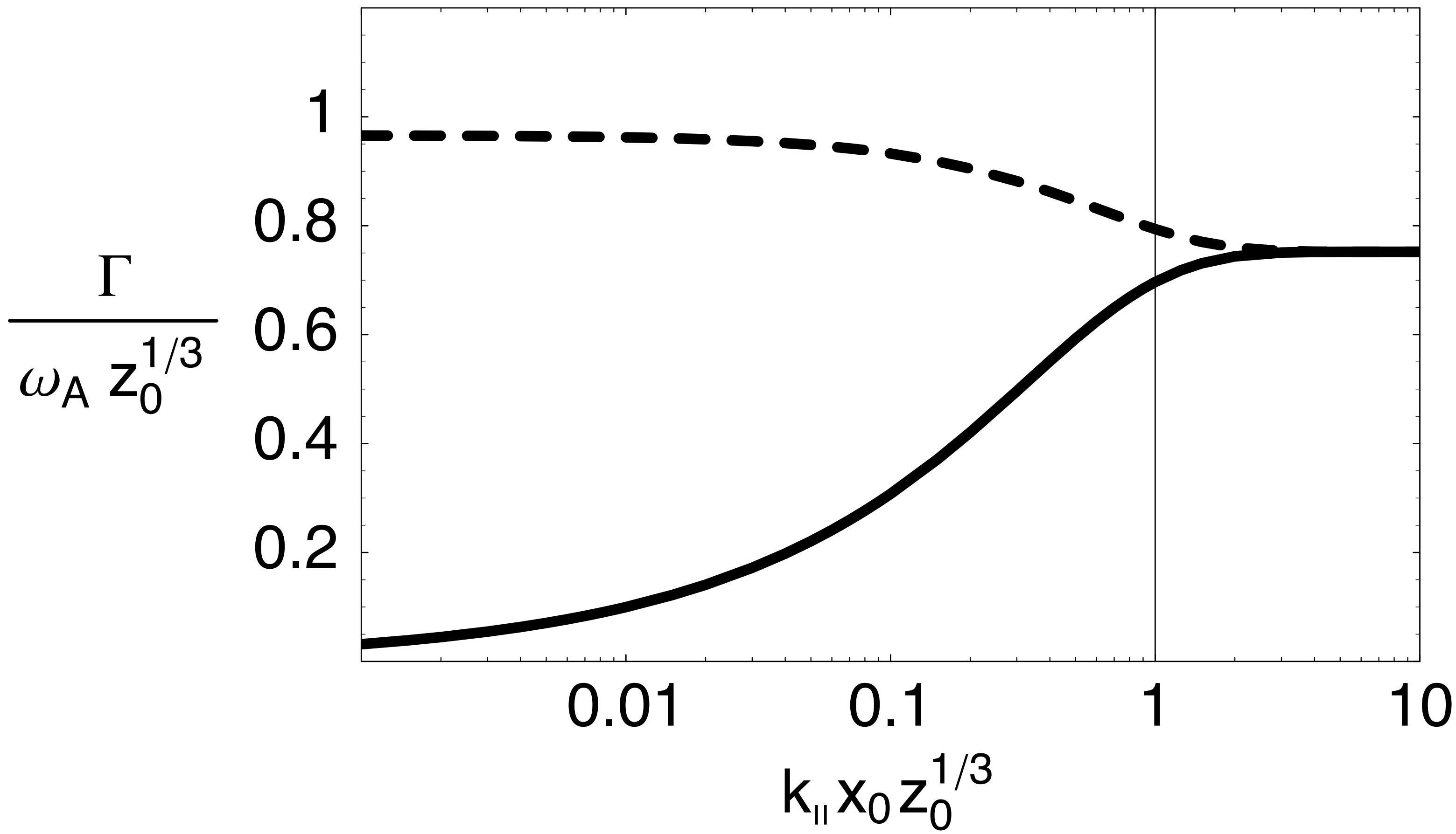
Growth Rate

2 symmetric sheets = purely growing in proper frame

Surface current filaments reinforce δB_x - Weibel instability in flatland

Proper Growth Rate (v_A=c, v_{beam}=c, sheet thickness = c/ω_{pb})

$$\Gamma = \frac{\omega_A}{(kr_{Lb})^{1/3}} = kcz_0^{1/3} = \frac{c}{x_0}(kx_0z_0^{1/3}) = k^{2/3}c\left(\frac{\omega_{pb}}{c}\right)^{1/3}, \quad z_0 = \frac{1}{kr_{Lb}}$$



$$(\Gamma T_{flow})_{max,lab} = \left(\frac{m_b c^2}{q\Phi}\right)^{2/3} \frac{r}{R_L}$$

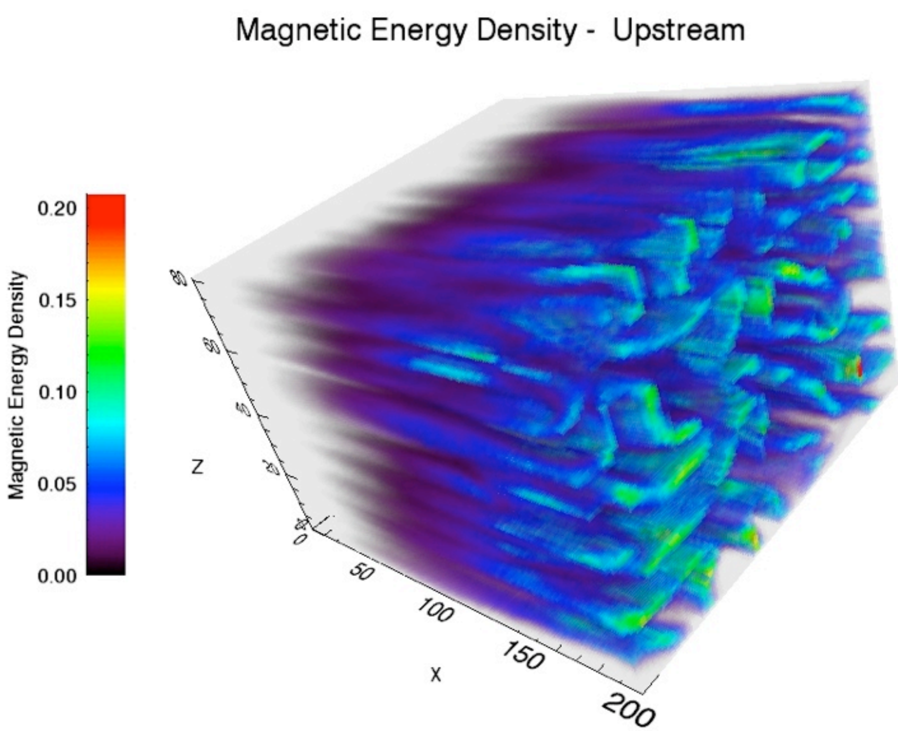
Growth rate > expansion rate for

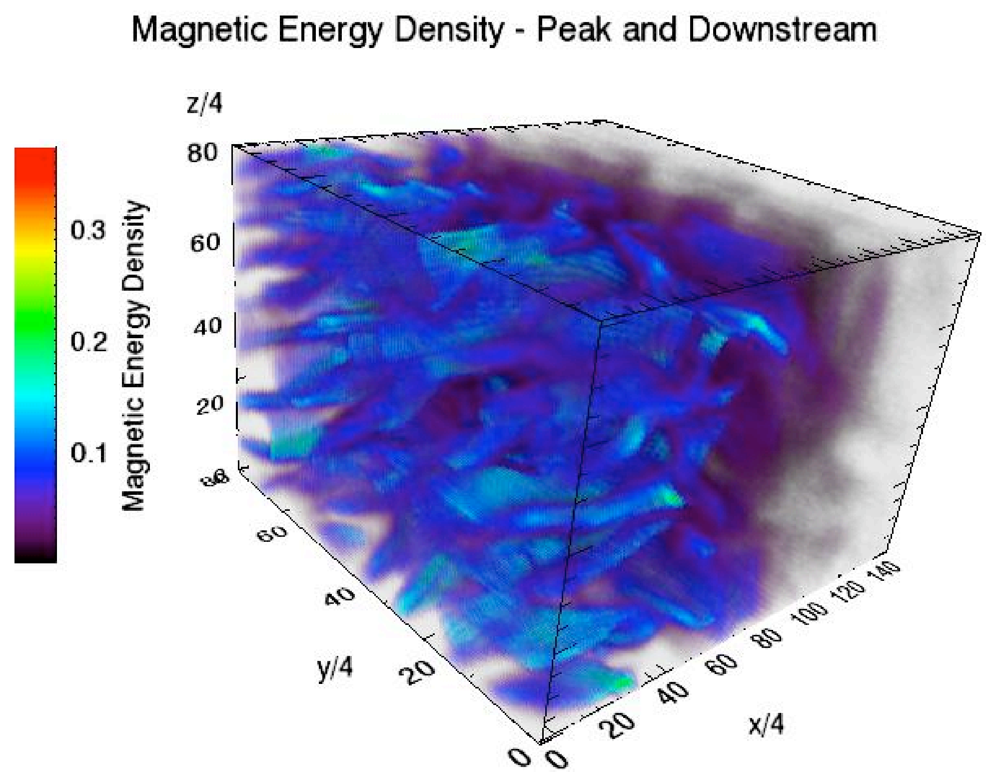
$$r > R_{fast}(q\Phi/m_b c^2)^{1/3} = R_L \sigma_0^{2/3}(m_{eff}/m_b)^{2/3}$$

Saturation - Magnetic Trapping beam particles scattered by self fields

$$\frac{q\delta B}{m_b\gamma_b c} \sim \Gamma$$

Growth & Trapping Saturation of Spatially Distributed Weibel (Spitkovsky & JA)





shock - transient growth and decay; current sheet is driven but end result will "always" be magnetic turbulence that scatters particles

Anomalous Resistivity in Sheets - rapid expansion of sheets, destruction of intersheet field? (Coroniti's model)

Resistive electric field in sheet - equilibrium beam energy (?)

$$\gamma_b \sim \left(\frac{q\Phi}{m_b c^2} \right)^{1/3}$$

Anomalous resistance, scattering: radiation (synchroton), sheets radiate - pulsed emission? (Kirk et al; historically, JA)

Many sheets, sheet strength j_0 declines with r: radiation of long wavelength EM waves (fast modes $\longrightarrow$ shocks) of relativistic amplitude?

Conclusion(?)

Asymptotically low s due to dissipation, sheets don't survive even to R_m = current starvation radius, $R_m = R_L \left(\frac{q\Phi}{2 m_b c^2 \beta_b \gamma_b} \right)^2$ never mind to termination shock

Dissipation broadens sheets much faster than in adiabatic expansion (sheet beams much denser than Coroniti's sheets)

- if stripe death due to anomalous resistivity, rate may decline as sheets broaden?;

- reconnection (tearing modes, drift-kink,....) maintains high dissipation rate (shortens length scale along B_0 directions)

- conversion to strong waves (and surfing acceleration) exists? competes with/exceeds resistive dissipation?

Inner wind ($r << R_m$) creates observable synchrotron emission from sheets, observable pulses? Or, steady emission? (low level unpulsed emission exists)

Jets - striped jets exist? (Konigl, Spruit) - related dissipation mechanisms