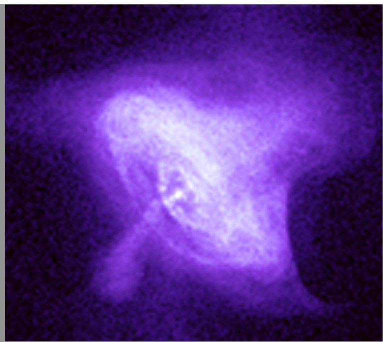
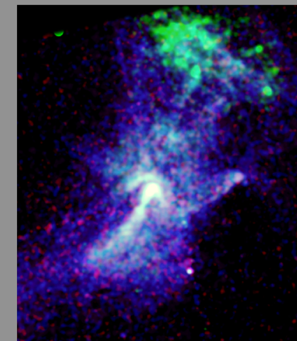
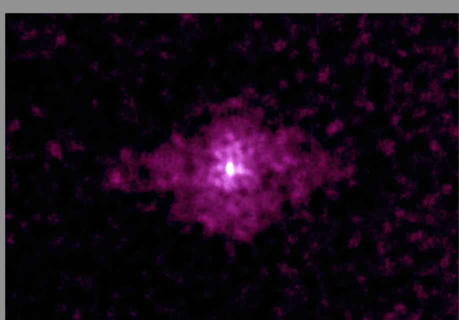


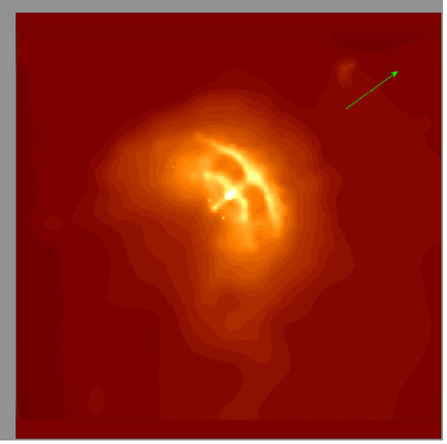


PULSAR WINDS – COSMIC PEVATRONS

Jonathan Arons
UC Berkeley

With a little help from my friends: D. Alsop, E. Amato, B. Gaensler, Y. Gallant, M. Hoshino, V. Kaspi, B. Langdon, C. Max, A. Spitkovsky, M. Tavani

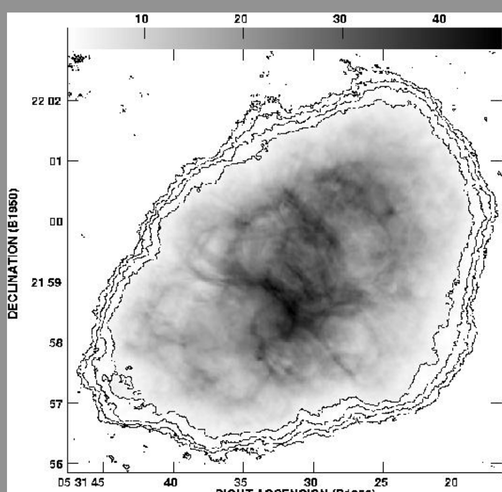




The Eponymous Crab Nebula
a prototype for all Pulsar Wind Nebulae and (a lot of) AGN and GRB physics – magnetar version: UHECR?

O-X

Powered by relativistic outflow
 electrons-positrons + ions (?)
Energy extracted electromagnetically
 from rotating neutron star
Radiation: Synchroton (TeV: IC,
 hadronic emission not yet seen)



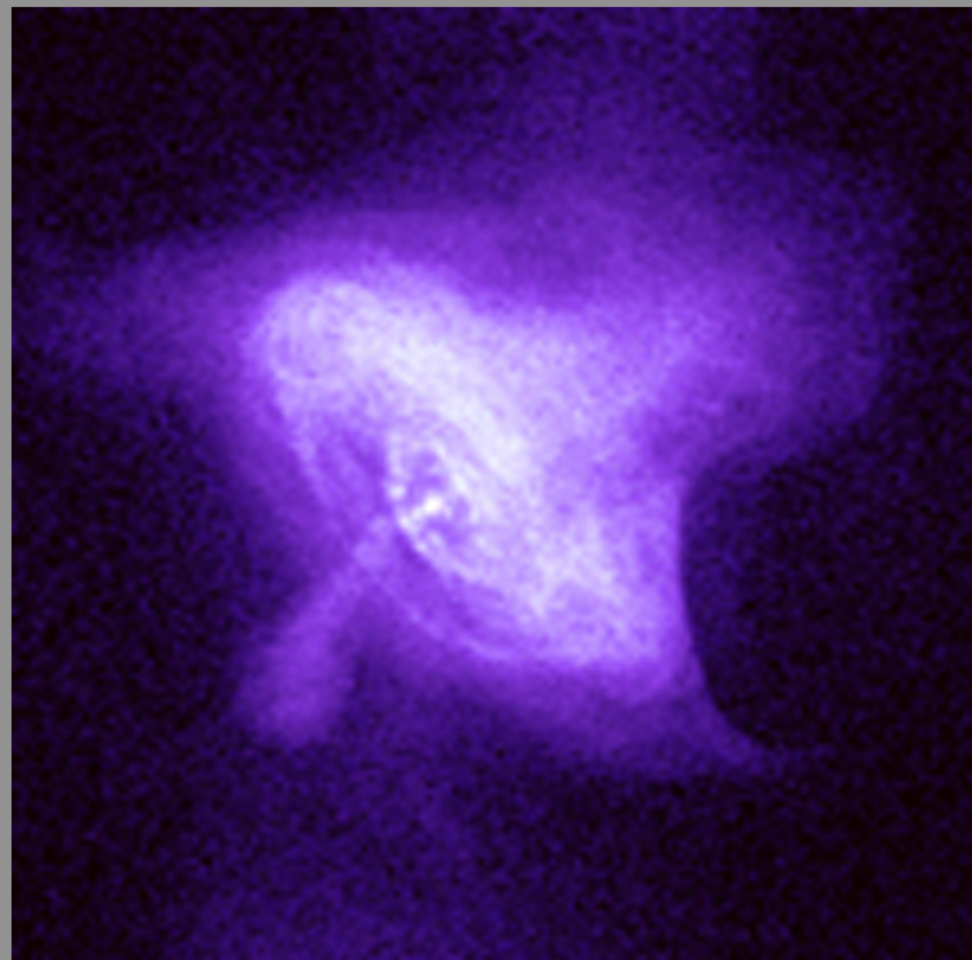
Radio

D: 2 kpc
Size: 2x1 ellipsoid,
 radio – 6pc x 3 pc
 optical – 4 pc x 2 pc
 X-ray (10 kev): 0.6 pc x 1 pc
 synch: ε up to 100 MeV

X + g-rays measure current energy input from the pulsar

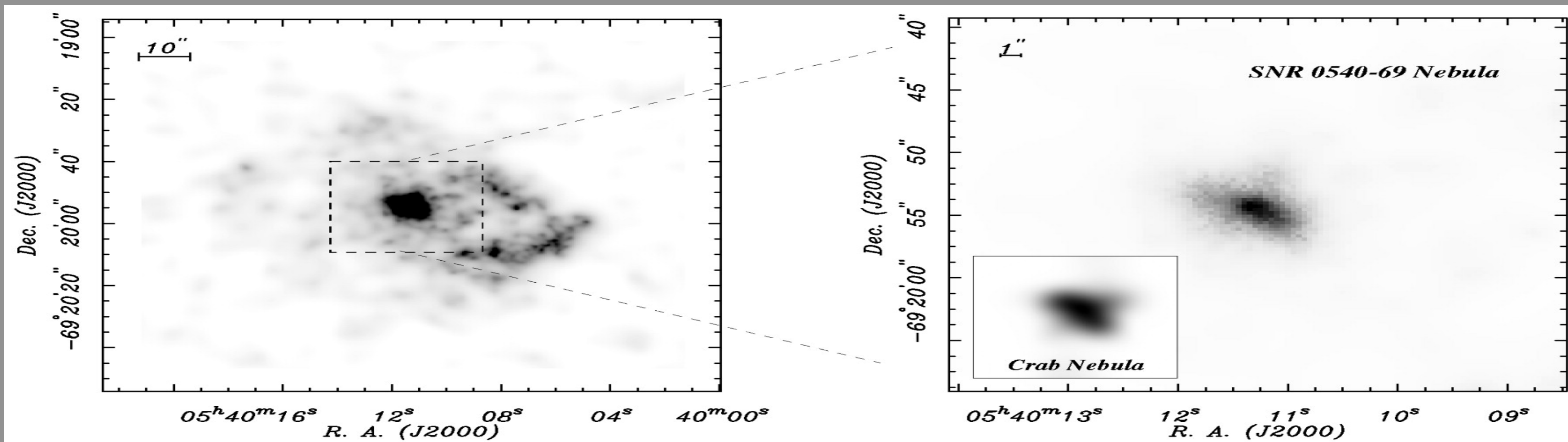
$L_X + L_g = 10^{38}$ erg/s

$L_{spindown} = 5 \times 10^{38}$ erg/s

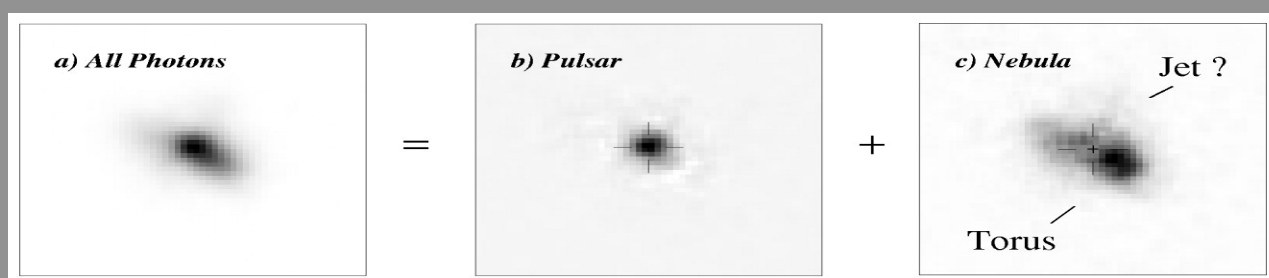


Main X-ray Source = Torus; Polar Pinch(es) along rotation axis; created by backflow B in nebula, not by hoop stress in wind

The Crab is Not Alone - Nebula of B0540 is Similar



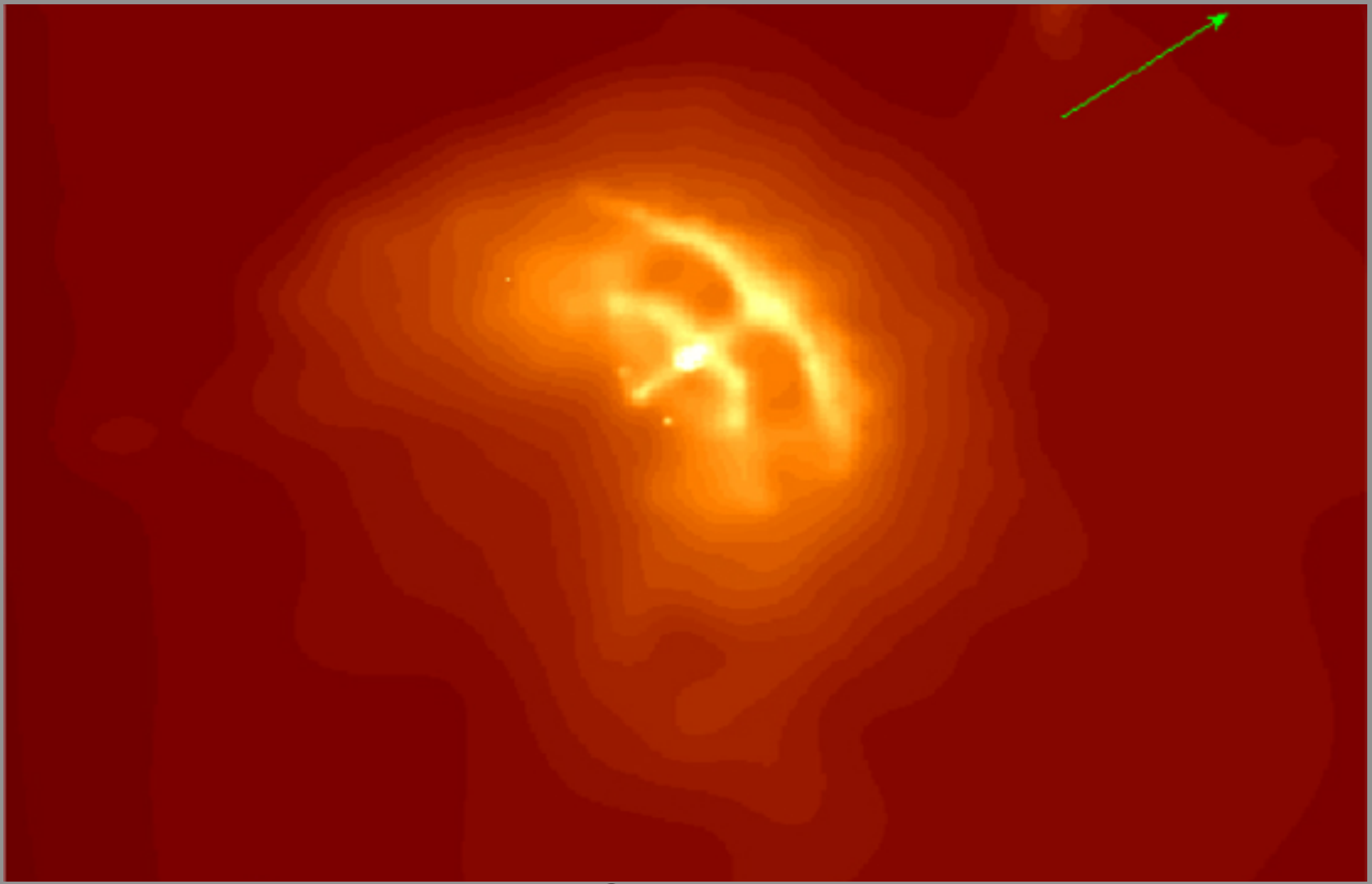
B0540 Nebula also shows Torus, perhaps Jet



Chandra Images, Gotthelf and Wang 2000

B0540 too distant (55 kpc) for detail

Vela Pulsar (T ~ 10^4 yr)has X-ray nebula with structure like Crab,
perhaps distorted by proper motion induced ram pressure (Chandra)

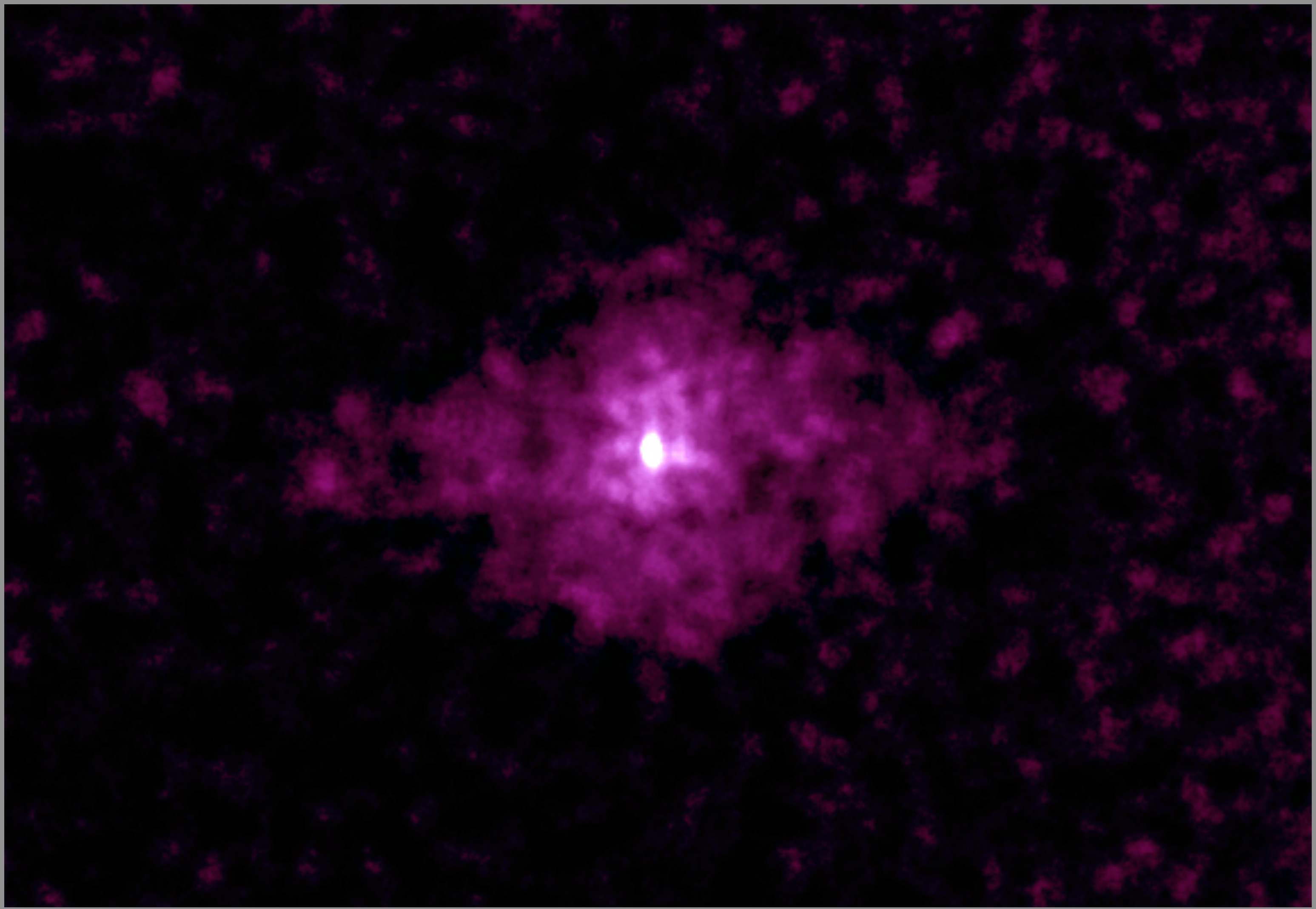


Rings = two torii at equal radii? Partial Inner Ring and larger radius torus? Embedded in larger PWN (Vela X)

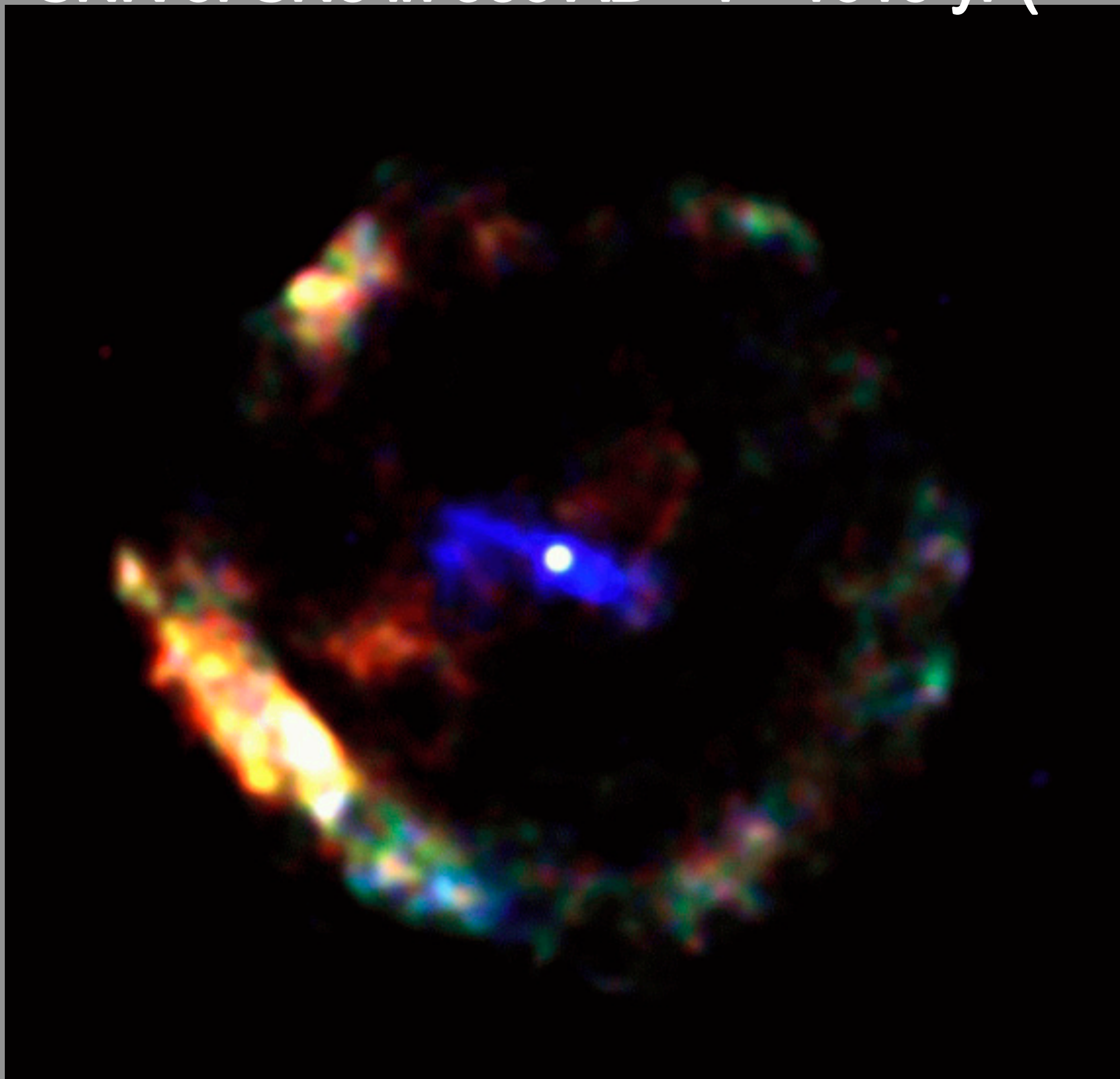
A Soft Shelled Crab

Chandra Image of P=$0^s.067$ pulsar in 3C58

SNR of 1181 Sne? - T = 815 yr ($P/2\dot{P} = 3335$)



A Hard Shelled Crab
Chandra Image of P=0s.0714 pulsar (ASCA) in G11.2-0.3
SNR of SNe in 386 AD - T =1615 yr ($P/2\dot{P} = 24{,}000$ yr)



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

$$T = \frac{P}{(n-1)\dot{P}}\left[1-\left(\frac{P_i}{P}\right)^{n-1}\right]$$

“theory”: n = 3

Obs: 2<n<3

Crab: $P_i \approx P/2$

Vela: $P_i << P$

(T_{SNR}~10^4 yr))

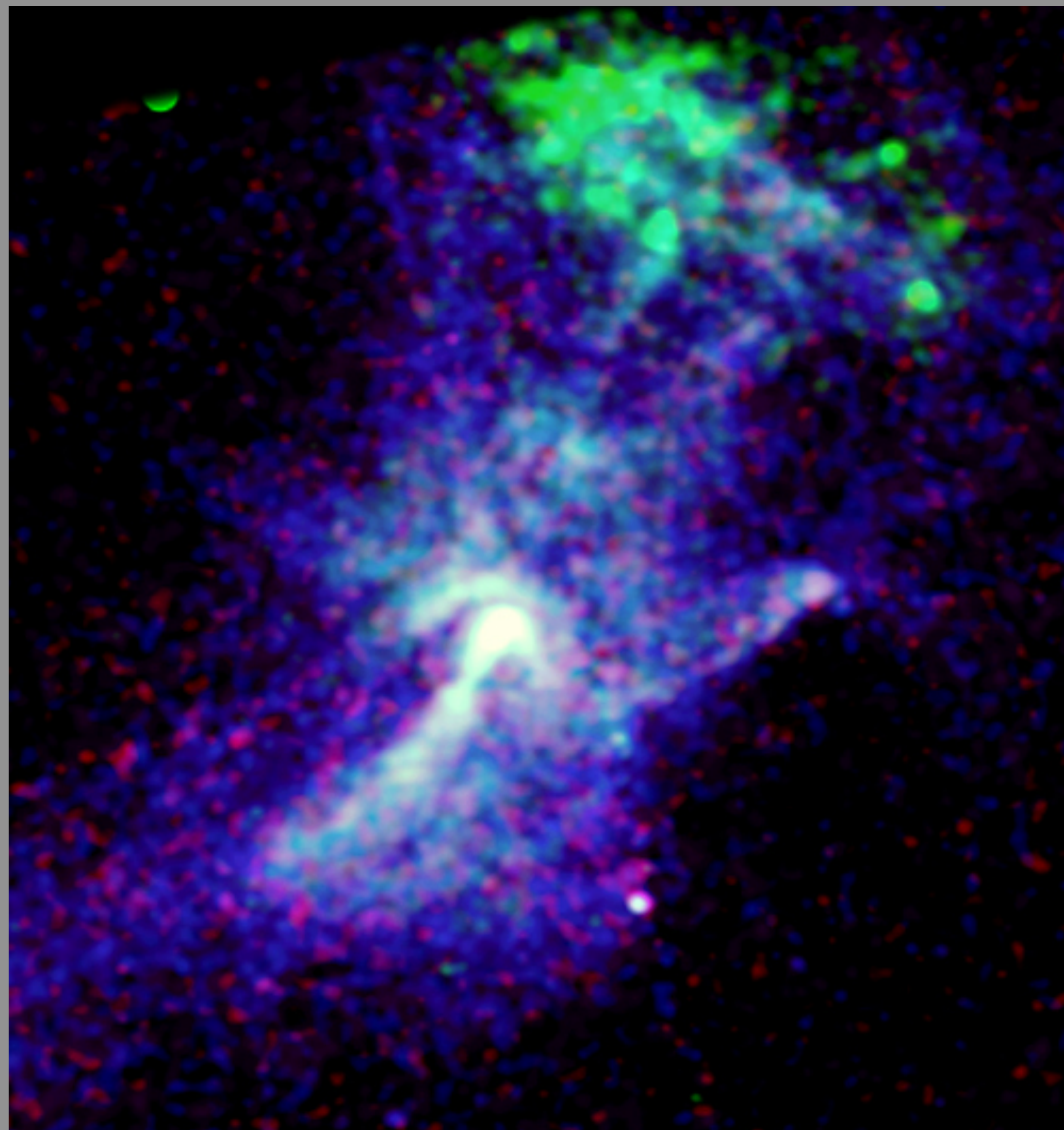
3C58, G11.2:

$P_i \approx P$

(3C58: 87%

G11.2: 97%))

G320.4/PSR1509-58(T_{spin}~1250 yr) from Chandra



Crab cools radiatively at high energy:
t(flow) ~ t(rad) in X-ray, gamma ray

Nebula smaller at high energy: Pulsar emits particles
shrinkage not universal: e.g., 3C58 has $R_X \sim R_{radio}$: B field weaker – environment? + somewhat weaker pulsar

Name	Period (msec)	Spin-Down Luminosity (erg/s)	Voltage (Volts)
Crab	33	5.0E+38	4.0E+16
3C58	67	6.5E+37	1.4E+16
1509-58	110	1.8E+37	7.4E+15
Vela	89	1.2E+37	6.0E+15
G11.2	71	7.7E+36	4.8E+15

Pulsars: Pulsed Radio (and IR, optical, X, gamma) Sources

1.6 msec < P < 9 sec
dP/dt > 0

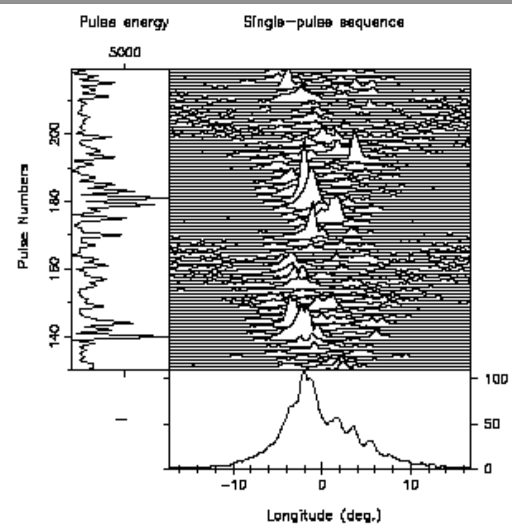
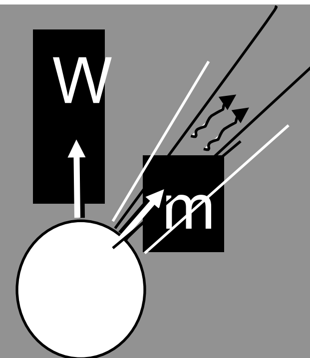


FIG. 1.—A series of individual pulses from the pulsar B0943+10 (*center panel*) along with their average (*bottom panel*) and energy (*left panel*) as a function of pulse number and longitude (360° longitude corresponds to 1 stellar rotation). Note the drifting subpulses, the alternate pulse modulation,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

Pulsar Radio Emission: Lighthouse Beam



Model: Rotating Neutron Star (1 msec < P < 10 sec)
Unipolar Inductor
Polar Beam: Electron-Positron Pairs, Charge Neutralized
Electron Current, Ion return current in "walls" (flipped in opposite geometry) - Ultrarelativistic Outflow

Polar models have voltage across B~10^{12} Gauss of F $\approx W^2 m/c^2 > 10^{13}$ V.
Polar current I ~ $W^2 m/c$ ~ 10^{12} Amps and created by acceleration through potential DF << F (space charge limited beam): DF $> 10^{12}$ V: pair creation
Rotating magnet sends out EM Poynting flux + particle flux, spins down (dP/dt > 0)
("Wind") Energy deposited in surrounding interstellar medium, creates nebula
USE NEBULAE TO CHARACTERIZE OUTFLOW

Necessity of Magnetospheric Plasma

Star = good conductor

Electric field vanishes **inside** star in co rotating frame:

(works in GR, co-rotating frame not inertial)

$$\boldsymbol{E} + \frac{1}{c}(\boldsymbol{\Omega} \times \boldsymbol{r}) \times \boldsymbol{B} = 0, r < R$$

Co-rotation electric field (inertial frame)

$$\mathrm{v_E} = c\frac{\mathsf{E}\times\mathsf{B}}{B^2} = -\frac{[(\Omega \times r)\times B]\times B}{B^2} = \Omega \times r$$

$$\mathrm{v} = \mathrm{v}_E + \mathrm{v}_{\|}\boldsymbol{b}, \boldsymbol{b} = \frac{\boldsymbol{B}}{B}$$

Non-zero E requires charge density:

$$\nabla \cdot E = 4\pi\eta_R, \quad \eta_R = -\frac{\boldsymbol{\Omega}\cdot\mathrm{B}}{2\pi c} + \dots$$

$$\frac{\eta_R}{e} = 7\times 10^{10}\frac{B_{12}}{P}\ \mathrm{cm}^{-3}$$

Parallel electric field reduced to small compared to vacuumto vacuum

$$\Phi = \int_0^{r_{cap}} dr_\perp E_{co} = \frac{\mu}{r_{LC}^2} = \sqrt{\frac{\dot{E}_R}{c}} \approx 10^{13}\sqrt{\frac{\dot{P}_{15}}{P^3}}\ \text{Volts (Crab: } 10^{16.5}\ \text{V,...)}$$

$$I = \int_0^{r_{cap}} dr_\perp r_\perp c\eta_R = c\Phi \approx 10^{12}\sqrt{\frac{\dot{P}_{15}}{P^3}}\ \text{Amps}$$

B_f = F/r

Goldreich-Julian density = I/c*Area

$$\dot{E} = I\Phi = c\Phi^2 = \dot{E}_R\ \text{(without details of angles)}$$

Atmosphere scale height = 1 cm- no thermal filling of magnetosphere

Nebulae require Number Loss Rate >> Goldreich-Julian rate

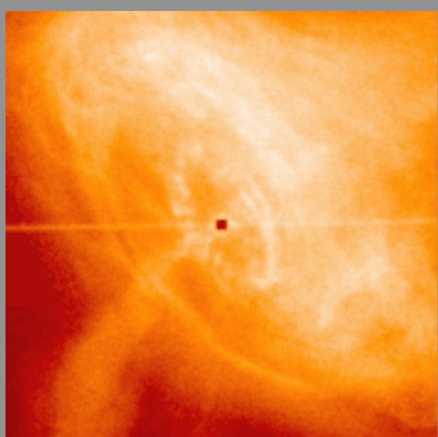
$$\dot{N}_{\pm} \gg \frac{c\Phi}{e} \approx 10^{34} \frac{\Phi}{10^{16.6}\,V} s^{-1}, \quad \Phi = \sqrt{\frac{\dot{E}_R}{c}} = 3.9 \times 10^{16} \frac{\dot{P}/10^{-12.35}}{(P/33\,\mathrm{msec})^3} \text{ Volts,}$$

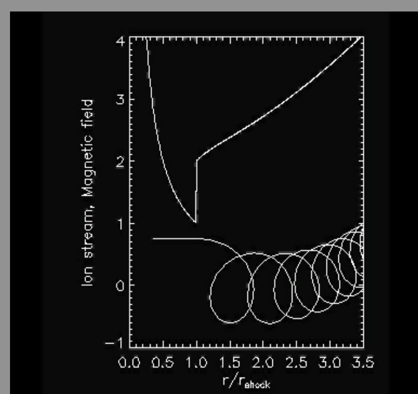
$$\mathrm{I} = c\Phi = 3.9 \times 10^{16} \frac{\dot{P}/10^{-12.35}}{(P/33\,\mathrm{msec})^3} \text{ Amp, } \dot{E}_R = I\Phi = c\Phi^2 = \frac{\Omega^4 \mu^2}{c^3} \text{ (~ dipole to LC)}$$

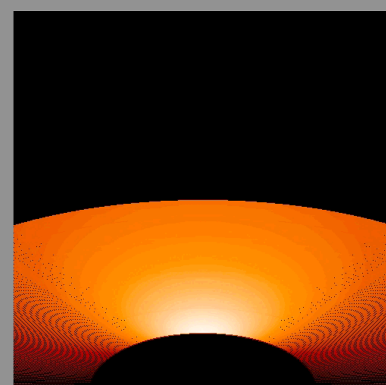
Feeding Nebulae needs particle outflow > > cF/e: large multiplicity

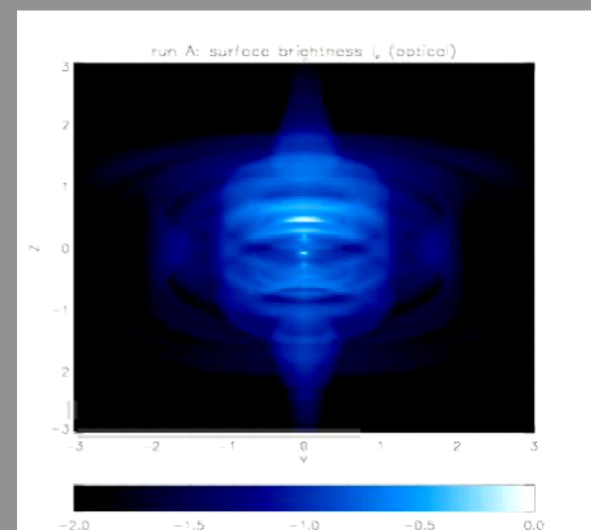
Composition = electron-positron plasma

Termination Shock (TS) located at $R_{TS} = F/(4pP_{neb})^{1/2} >> R_L$









Chandra variability

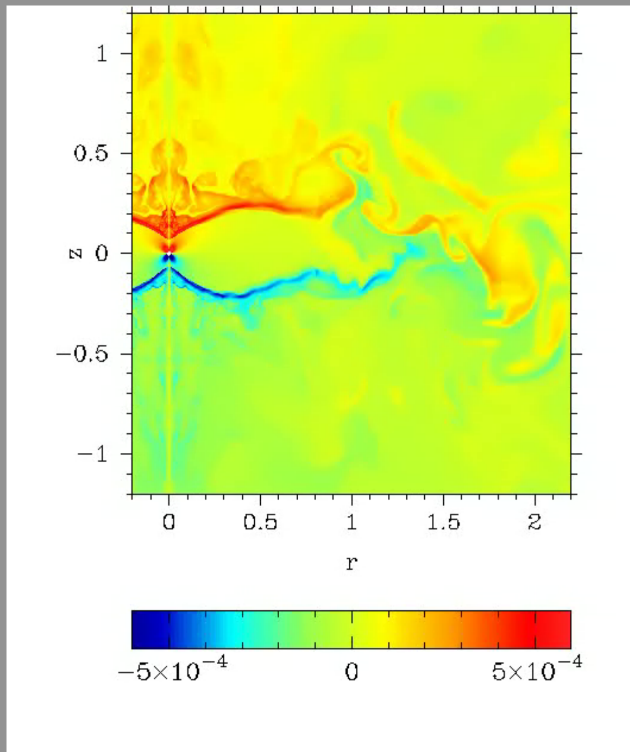
Runaway equatorial beam + pairs
(Spitkovsky & Arons – original version
= frozen in ions + pairs)

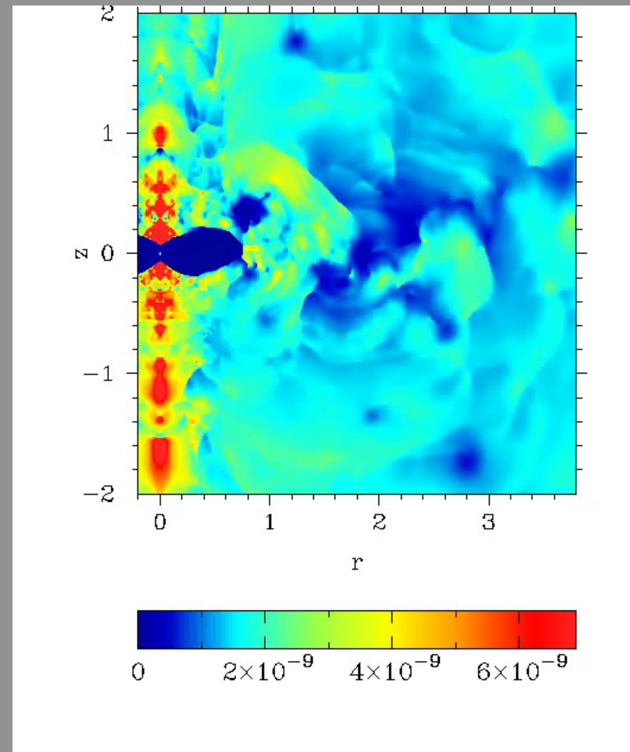
Like SASI (STerSI?)Instability
(Bucciantini & Kommisarov)

$$\sigma \equiv \frac{B^2}{4\pi\rho\gamma c^2}$$

All Models behave as if s << 1 at TS; s large at NS

STerSI makes termination shock flow “turbulent”:





B from Camus et al 2009 pressure

If turbulence cascades to short wavelength, fast 2nd order Fermi acceleration creates radio emitting spectrum (Fermi 1948, Kardashev 1962 – magnetic eddies; Stawarz 2008 (eddies, waves)

$Q_{inject} \propto E^{-(1+p)}, \; p = \frac{\tau_{accel}}{\tau_{esc}} \sim 0.5$ plausible: diffusion in space, energy from same eddies/waves, $v_{eddy/wave}/c \sim 1$

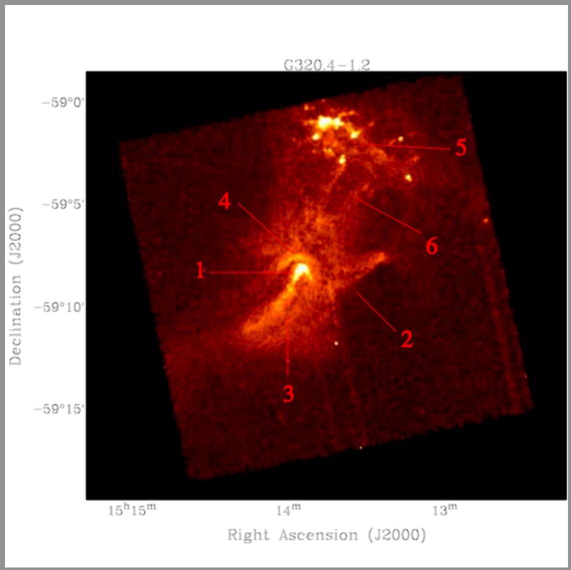
Follow the Mass Loss: From Whence all the Pairs?

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 (starvation) gap rates $k_{\pm} \lesssim 10^4$ pairs/GJ

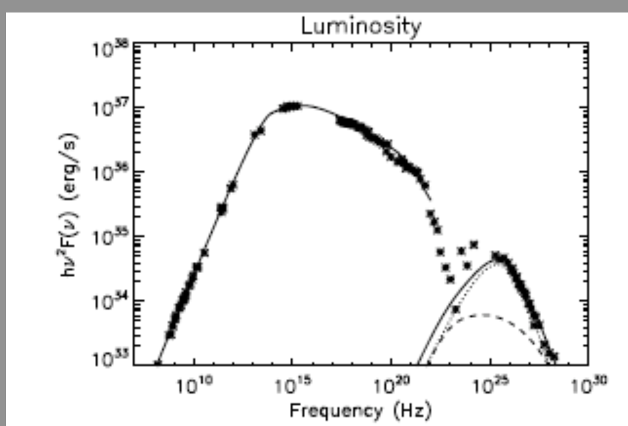
Radio measures injection rate averaged over nebular histories, $\langle k_{\pm} \rangle > 10^6$



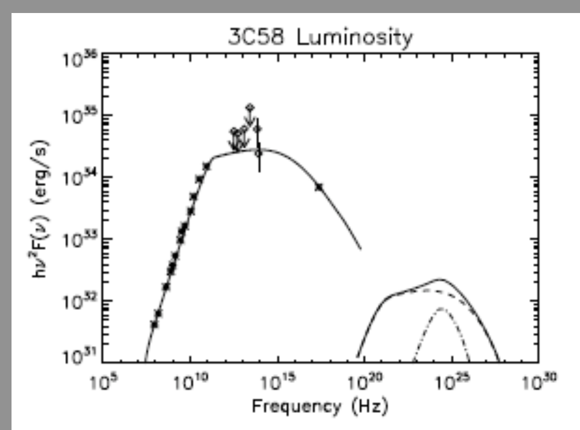
Low $s = B^2/8pm_{\pm}c^2n_{\pm}G_w$ at termination → $G_w = eF/2m_{\pm}c^2k_{\pm} = s_0$

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

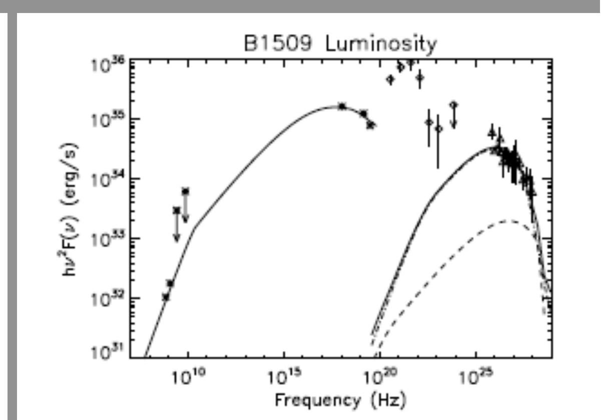
From one zone evolutionary model of observed spectrum <u>including</u> radio (with Bucciantini, Amato) – injection spectrum <u>convex, $g^{-1.5}$ (radio) → $g^{-2.3}$ (X)</u>



Crab



3C58



PSR B1509/MSH 15-52

Low s ($G_w \rightarrow s_0$) in <u>unconfined</u> wind requires magnetic dissipation somewhere

Ideal MHD, poloidal field lines almost radial:

acceleration parallel to velocity, inertial force for change of speed proportional to longitudinal mass mg^3:

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

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

Unconfined Relativistic MHD winds accelerate to

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

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

Observations (models) require stronger, non-radiative (<u>equatorial</u>) acceleration for $r >> R_F \sim 10^2\ R_{LightCyl}$

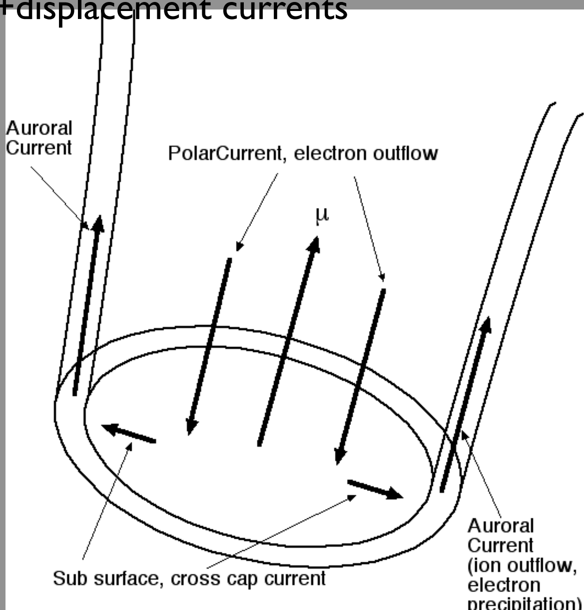
Current Sheet: Return Current Particle Beams with Pair Content

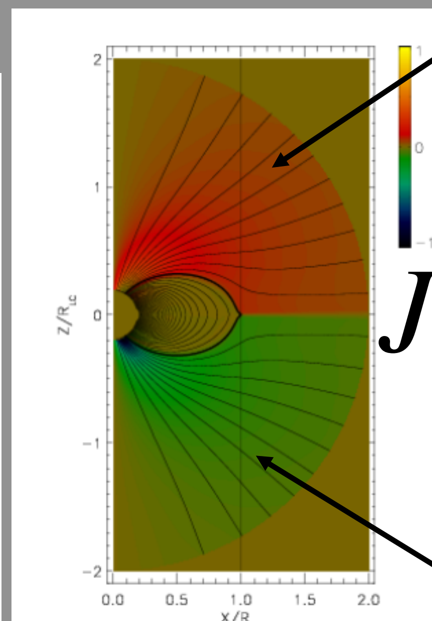
Inner wind magnetically dominated (s >> 1) – has generic return current sheet

Circuit is open – net electrons (protons) on central path, protons & positrons (electrons) on auroral path –current "closes" in "earth" = external nebula (interstellar medium) through eddy currents

Aligned rotator geometry makes physics easier, results generic (+displacement currents)

)

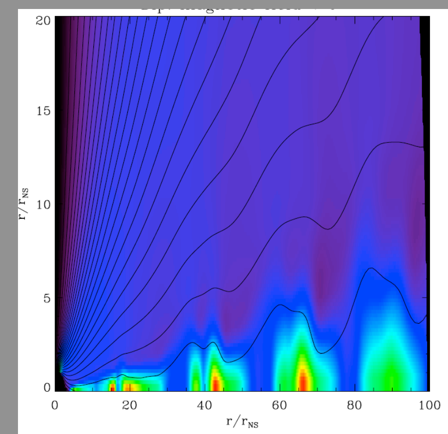




J

J_r →

J



Reconnection flow supports return current: pairs from wind into layer - electrons flow down, contribute to the return current - rest is particles (protons in geometry shown) attracted up from the surface by precipitating charge - current outflow in equatorial sheet (plasmoids) = ions from surface + positrons from reconnection singular region

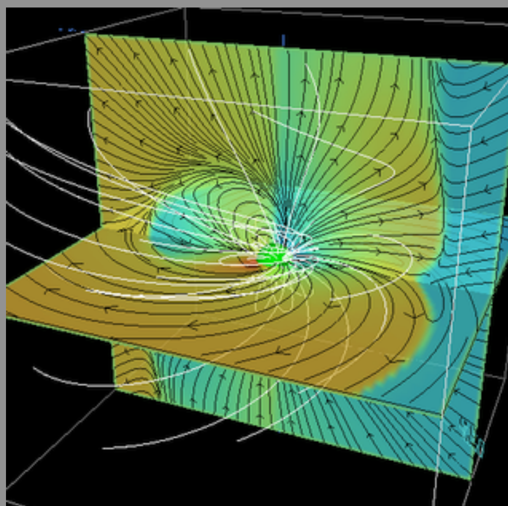
Relativistic MHD Simulation of Aligned Rotator – dissipation = numerical resistivity - limit cycle reconnection in current sheet (Bucciantini et al 2006)

O Regions recede relativistically - Recurrence time ~ rotation period

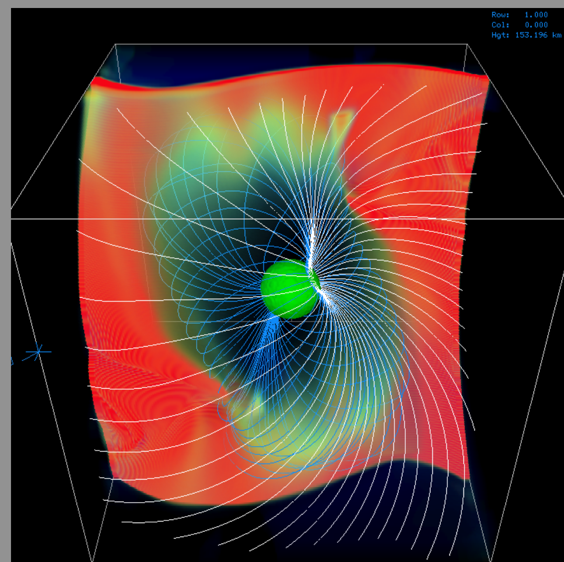
Observed PSR = oblique rotators

Equatorial Current Sheet ⟶ Frozen-in Transmission Line

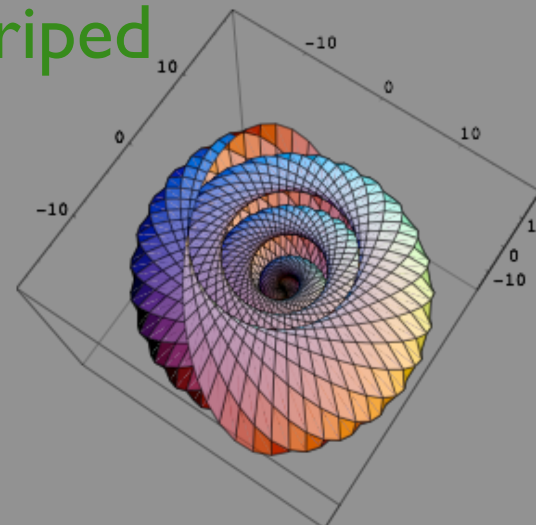
Inner Wind: Magnetically Striped



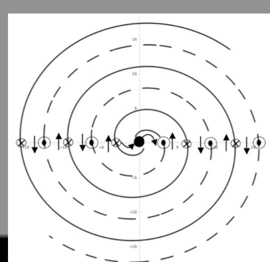
Force Free Simulation of i=60° Rotator (Spitkovsky)



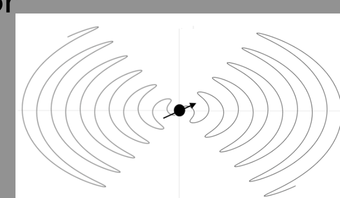
i=60° - topology = aligned rotator (Bai and Spitkovsky)



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



Equatorial cross-section



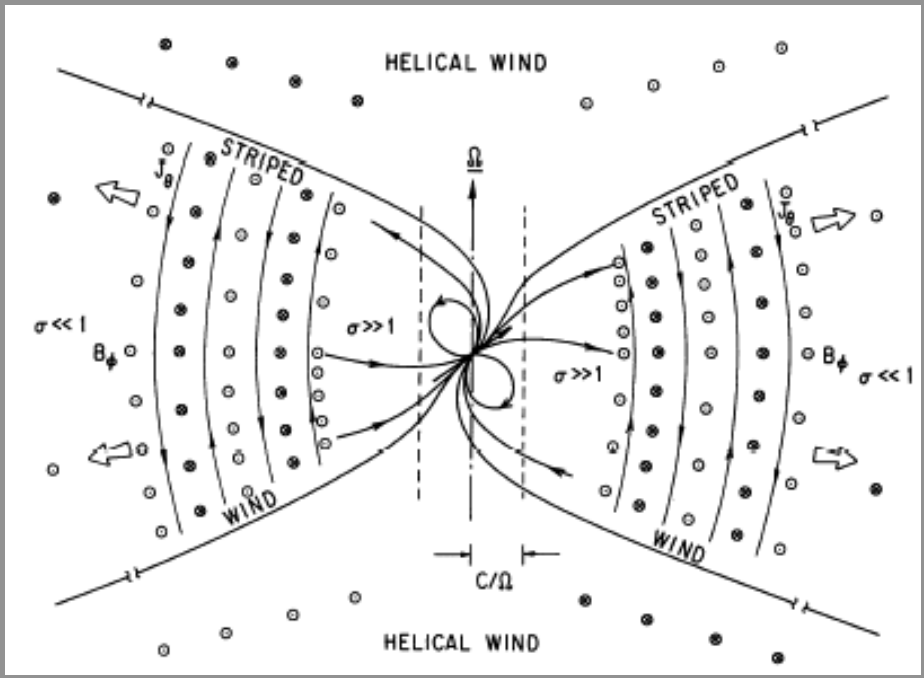
Meridional cross-section

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

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

Stripe Dissipation Kills B_f, restores aligned rotator thick CS

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



From Coroniti 1990

Sheet spacing: v/W − cold between sheets

Sheet separation = R_L, wavelength = $2G_\omega$ RL

TS at many R_L (10^9 R_L for Crab)

Ideal MHD: Intersheet s >> 1 conserved

Current sheets' dissipation:

1) Anomalous resistivity forms, plasma in sheets heats, current channels widen, merge at $r \ll R_{TS}$

2) Reconnection (also needs resistivity/ inertia) collapses field onto sheets, energy goes to hot islands, sheets spread and merge, devour field upstream of TS

3) Mode conversion - sheet converts to relativistically strong EM waves in flow frame

Plasma pressure in sheets causes wind acceleration as G_ω drops

Maximum dissipation

Heating: sheet expansion in wave frame = wind flow rest frame

spreads at speed v_s < c; sheets expand, merge, s ⟶ "0"

sheet separation in wave frame: $l/2 = pG_{wind}R_L$,

Merger time in PWN frame:

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

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

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

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

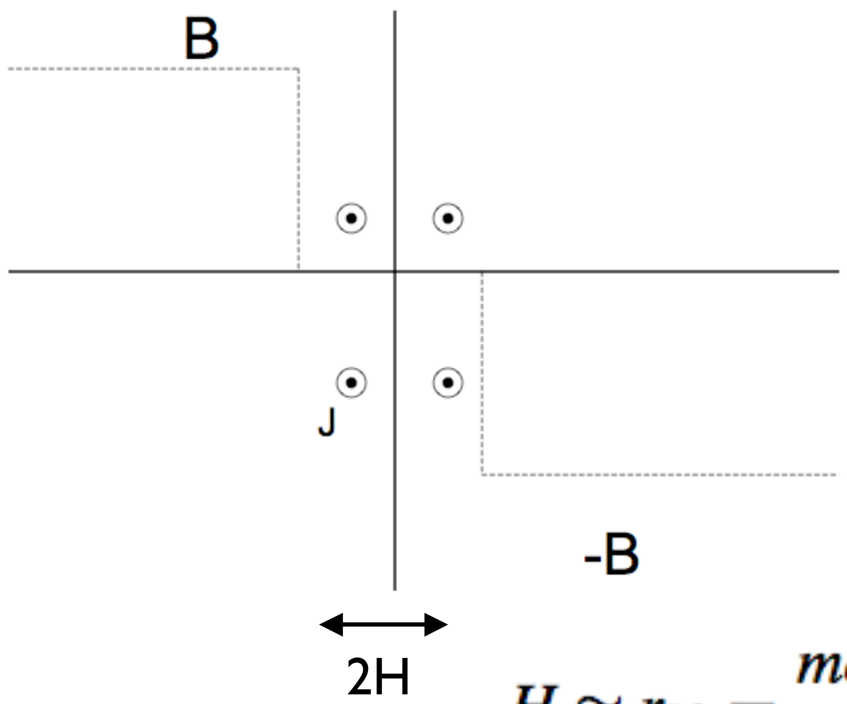
Low s wind at TS $\Rightarrow \dot{E}_R = \dot{N}_\pm m_\pm c^2(\Gamma_{wind}-1) \Rightarrow \Gamma^{(max)}_{wind} = \frac{\dot{E}_R}{2\dot{N}_\pm m_\pm c^2} = 3\times 10^3\,\frac{10^{41}\,s^{-1}}{\dot{N}_\pm}(Crab\ radio)$

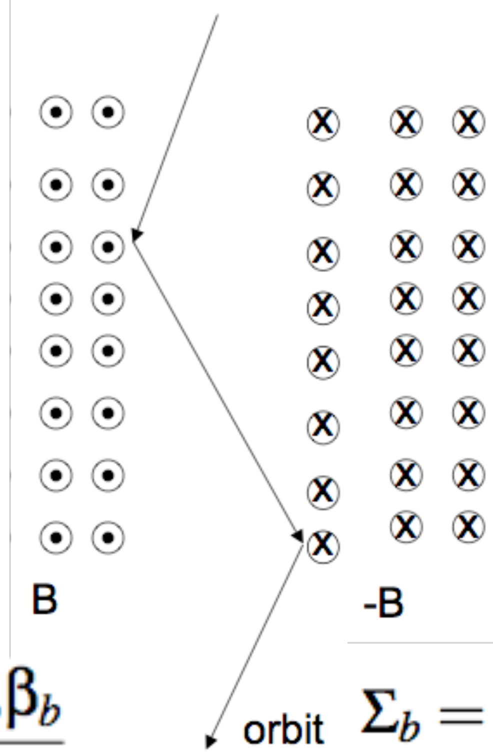
Sheet dissipation upstream of TS may work if

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

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

Simplified Sheet Structure





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

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

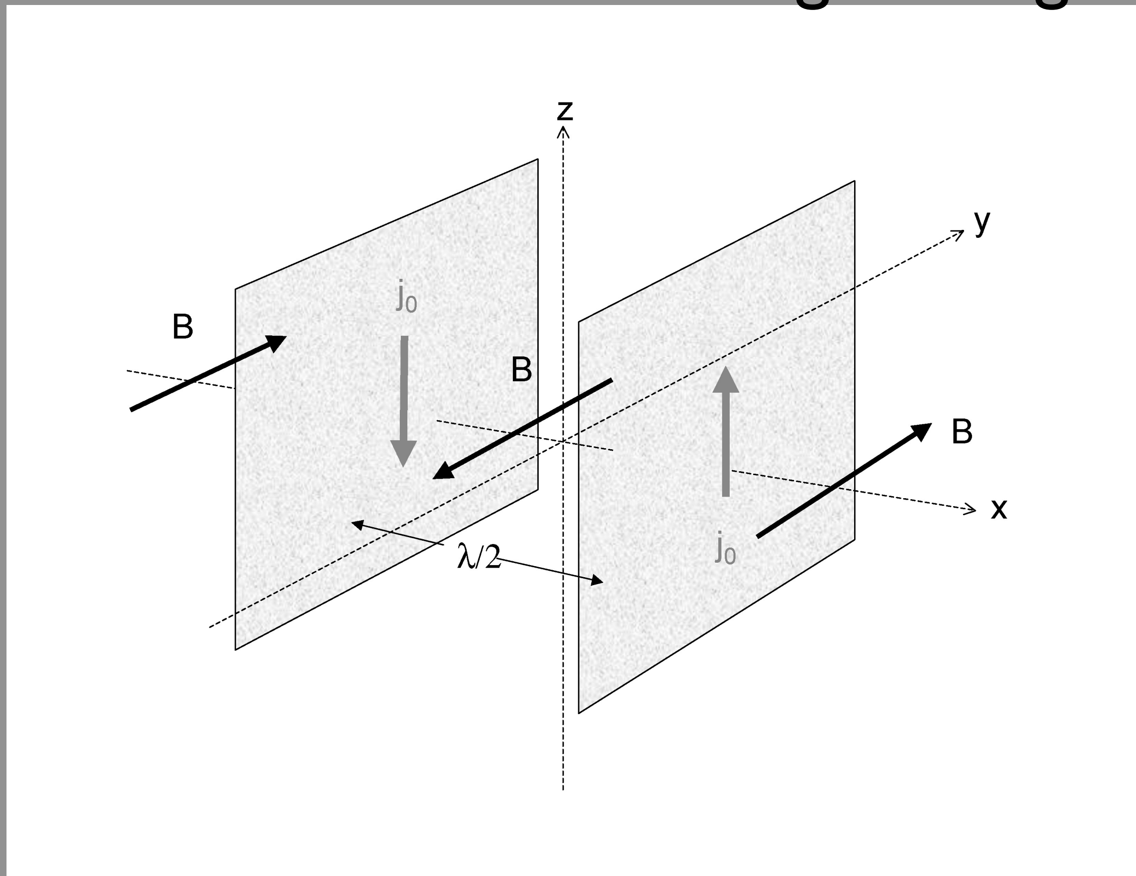
$$P_b = \frac{\Sigma_b}{2H}\gamma_b\beta_b^2 m_b c^2\left\langle\sin^2\psi\right\rangle \equiv \frac{\Sigma_b}{2H}T_{b\perp} = \frac{B^2}{8\pi} \Rightarrow \frac{H}{R_L} \approx \frac{2T_{b\perp L}}{q_b\Phi}\left(\frac{r}{R_L}\right)^{1/3}$$ *(adiabatic 2D EOS)*

Sheets swallow stripes: $r > R_m = R_L\left(\frac{q_b\Phi}{2\beta_b T_{b\perp L}}\right)^3 = \frac{8\times10^{21}\dot{P}_{12.4}P_{33}^{-3}}{\left(T_{b\perp L}/m_pc^2\right)^3}R_L$ (Crab) >> R_{shock}

(Crab) $R_m < R_{shock} \approx 10^9 R_L$ only if $\frac{T_{b\perp L}}{m_pc^2} > 2\times10^4$ - sheets survive?

<u>Rapid Dissipation Mechanism: Anomalous Resistivity</u>

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

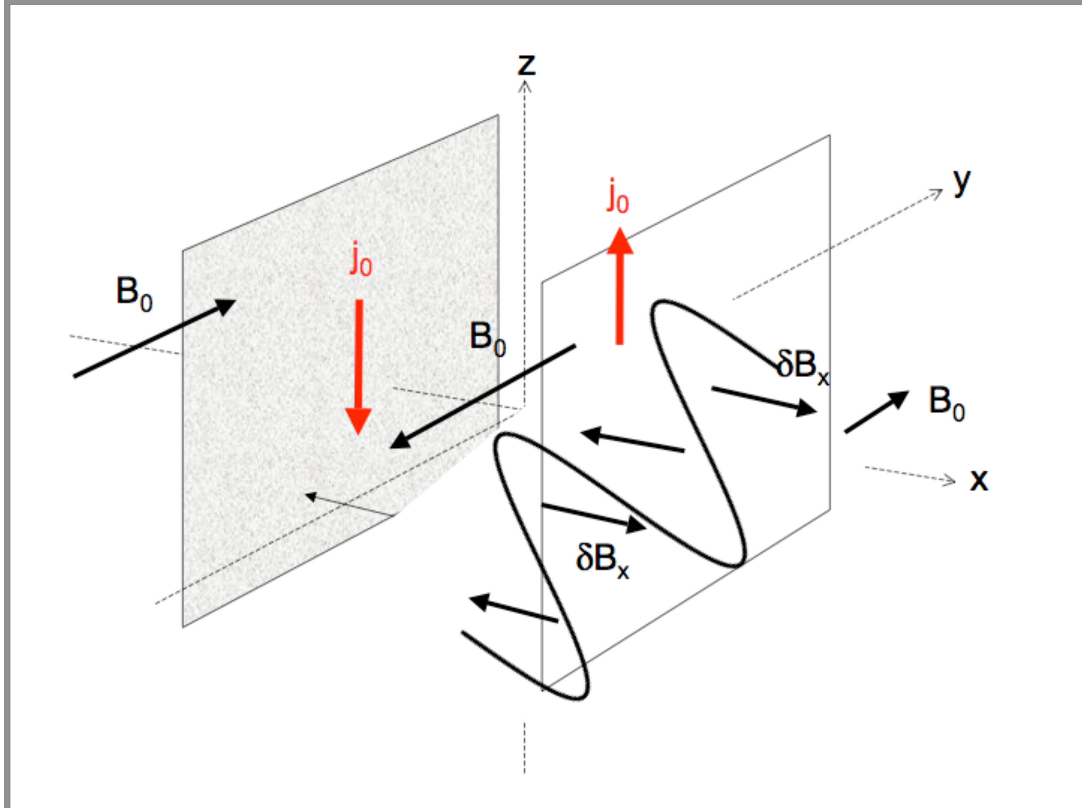


$l = 2pG_w R_L << G_w r$

Dynamics of plasma inside thin sheets as if each sheet is unmagnetized; intersheet medium is high s MHD

$(B^2 \gg 4\pi\rho_0 c^2)$ - <u>sheet current = runaway beam</u>

Two Symmetric Sheet Instability



Growth Rate

2 symmetric sheets = purely growing in proper frame

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

Alfvenic magnetic ripple at each sheet

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

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

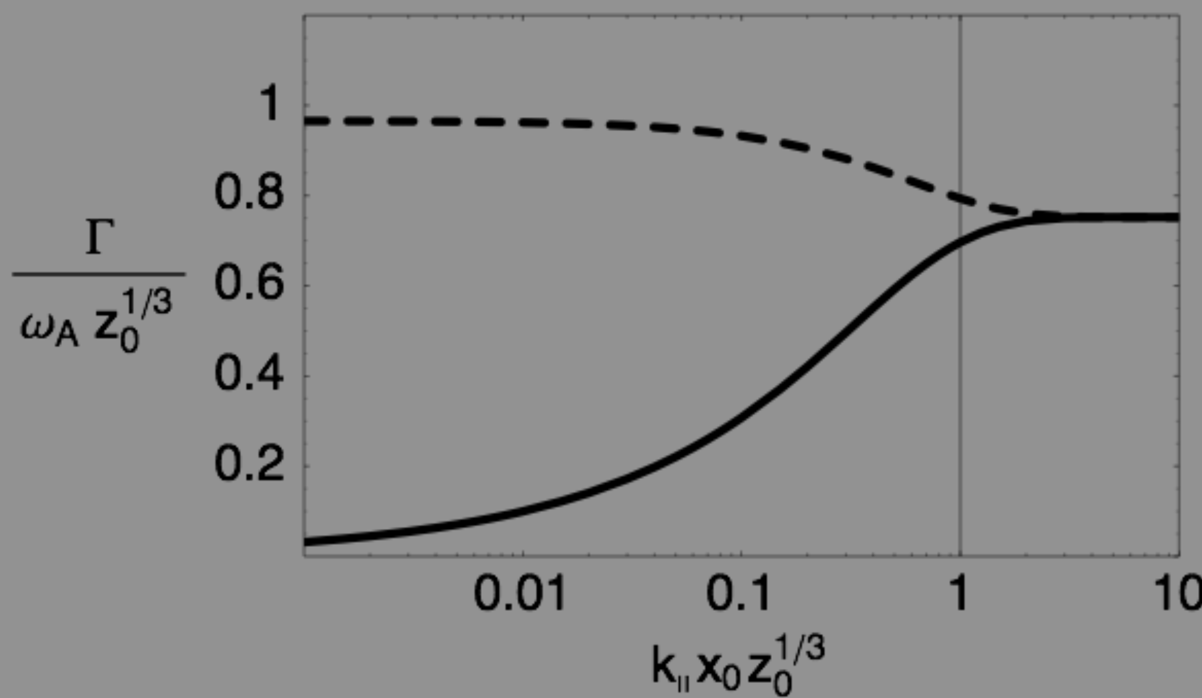
$j_0 \times dB_x$ force compresses each sheet's surface density into filaments parallel to j_0

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

Weibel instability in flatland

Proper Growth Rate ($v_A = b_A$, $v_{beam} = cb_b$)

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



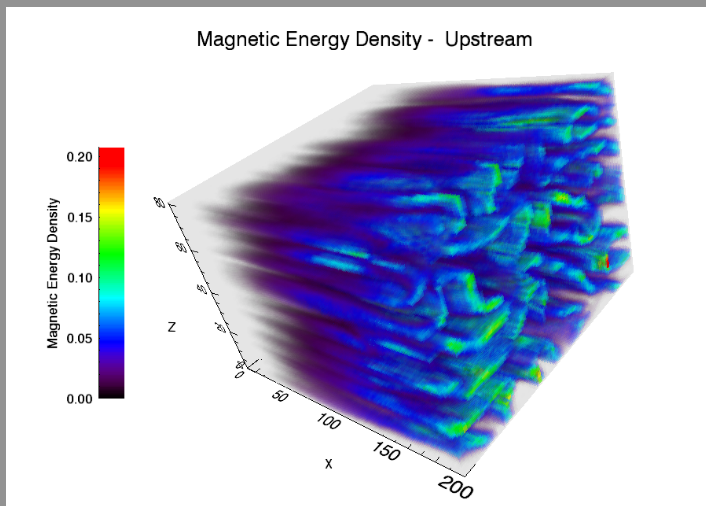
$$\omega_A = k_{\|}c\beta_A$$

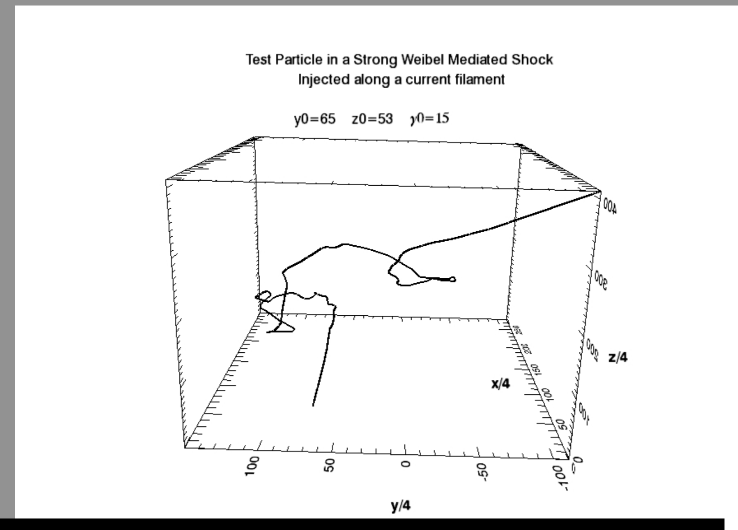
$$z_0 = \frac{\beta_A^2\beta_b^2}{k_{\|}H}$$

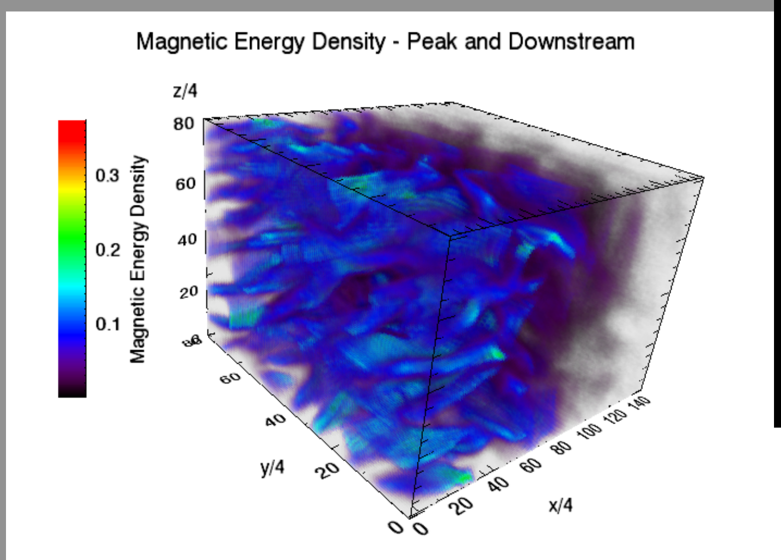
$G_{2sheet}T_{flow} >> 1$, Sustained Weibel turbulence inside current sheets in wind

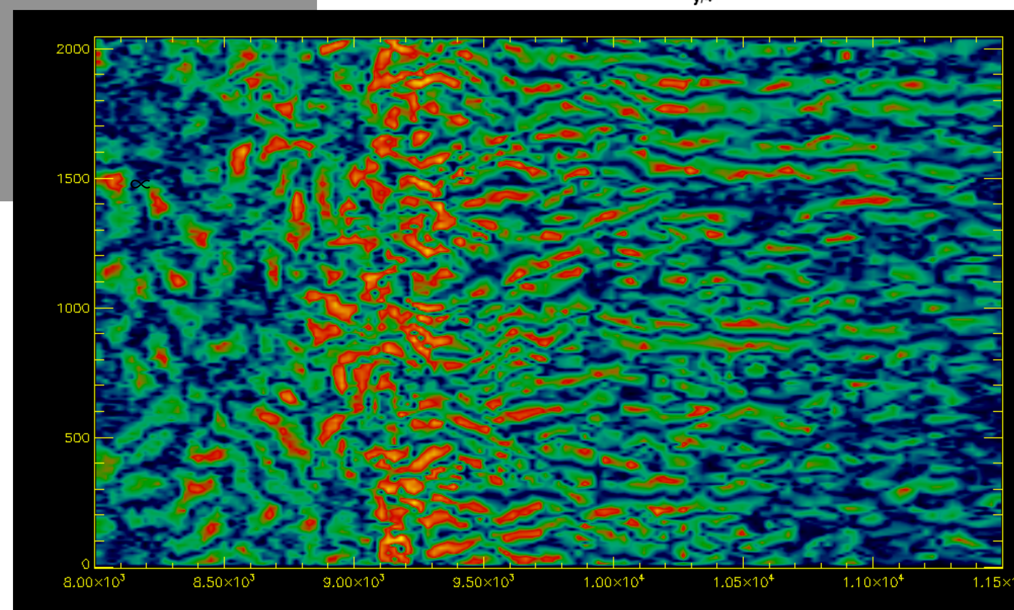
Weibel scatters particles

Weibel in pairs, colliding shells (shock simulations)









Large 2D shock PIC simulation
Labeled plasma particles show scattering

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

Current carriers scattering nonresonant, $t_{scat} \propto \pi^2 \Rightarrow$ ρυναωαψ βεαμσ
G_{beam} may be as high as qF

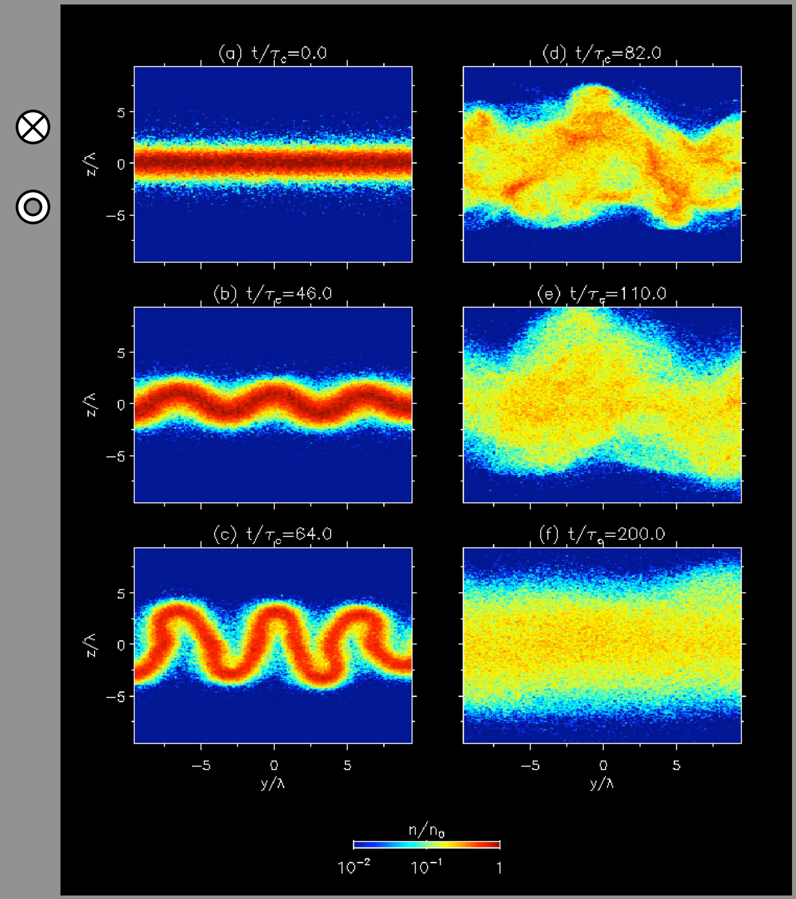
Alternate model – currents are in main body of sheet plasma, not very relativistic,
dissipation = internal Instabilities of Sheets: Collisionless Tearing, Drift Kink (stronger for pairs)

Relativistic Harris-Hoh Equilibrium instead of unidirectional charge neutralized beam

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

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

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



Counterstreaming electrons/positrons in channel
drives kinking perpendicular to B

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

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

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Anomalous Resistivity in Sheets & Sheet Merging (beam model)

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

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

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

Magnetic Diffusivity

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

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

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

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

Heating accelerates the wind

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

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

Energy Conservation:

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

Similarity Solution:

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

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

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

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

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

Radiation from Wind

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

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

if $m_{beam} = m_\pm$

Synchrotron emission (observer frame):

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

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

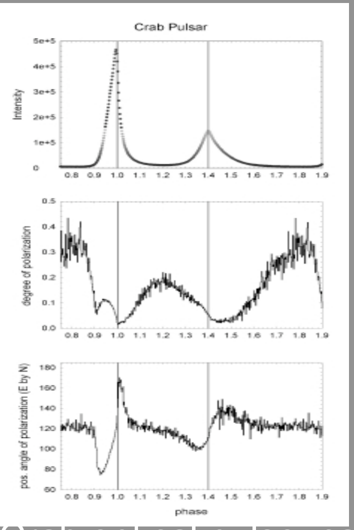
old ion beam
Idea generalized to all possibilities (e^-, e^+, ions – depends on PSR geometry, coupling of current flow to * surface, Y line

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

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

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

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



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

Conclusions

Current sheets in striped high s winds decay due to anomalous resistance, sheets in striped pulsar winds don't survive to termination shock - requires large mass loading (observed in Crab, others)

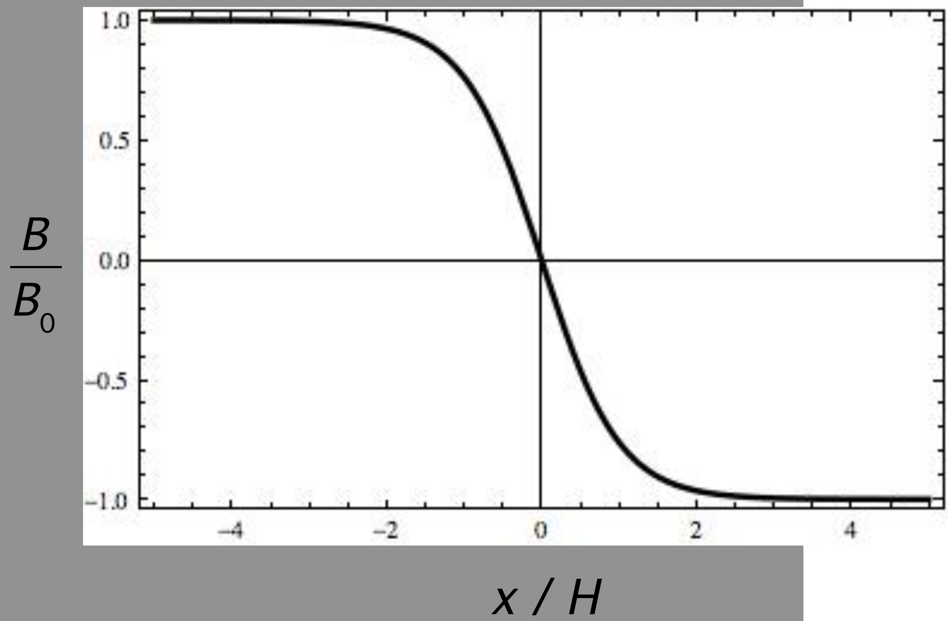
Termination Shock in macro-turbulent medium: shock accel (X-rays) coupled to Fermi II accel of radio emitting pairs?

Inner wind ($r < R_{merge}$) creates synchrotron emission from sheets.
Bolometric luminosity small fraction of total energy loss.

Unpulsed? Pulsed? Detectable now or in near future?

Application to jets? Confined (by disk wind?) jets can see $G_w \rightarrow s_0$ without magnetic dissipation ⇒ (?) emission from shocks

Lab: sheet spacing = $v/W << 1$ m – $v=1$ km/s needs $W > 10^4\ s^{-1}$
cold: $c_s << v$ (ion, electron; bucky ball pair plasma?) – termination shock?
$r_L <<$ spacing, transonic inner flow: B >> kiloGauss – less if supersonic

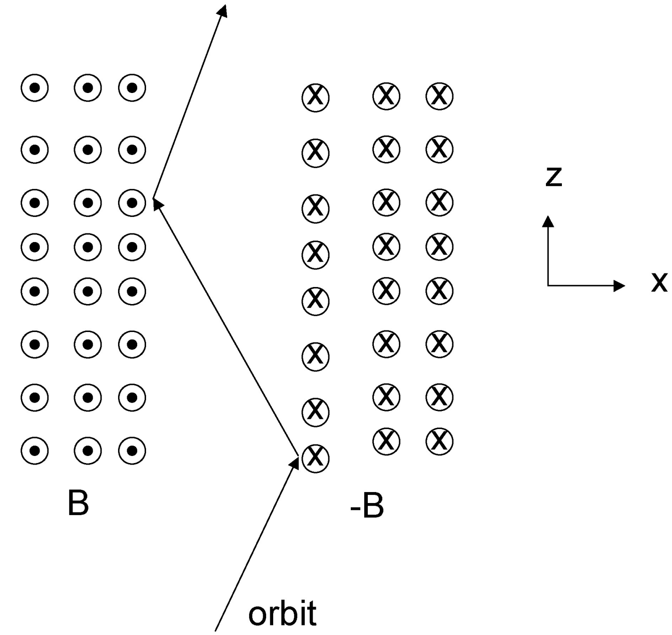


Profile of Magnetic Field in a Current Sheet - Harris Model

$$B = B_0 \tanh\left(\frac{x}{H}\right)$$

$$2H = \text{Larmor radius} = \frac{T}{qB},$$

T = beam "temperature"



Schematic of particle beam orbits *within* a single current sheet
Momentum transfer at magnetic "walls" = "pressure" keeping field Lines separated

Beams flow in central unmagnetized channel