UHECR from Pulsars/Magnetars based on An "Auroral" Accelerator Model for Gamma Ray Pulsars

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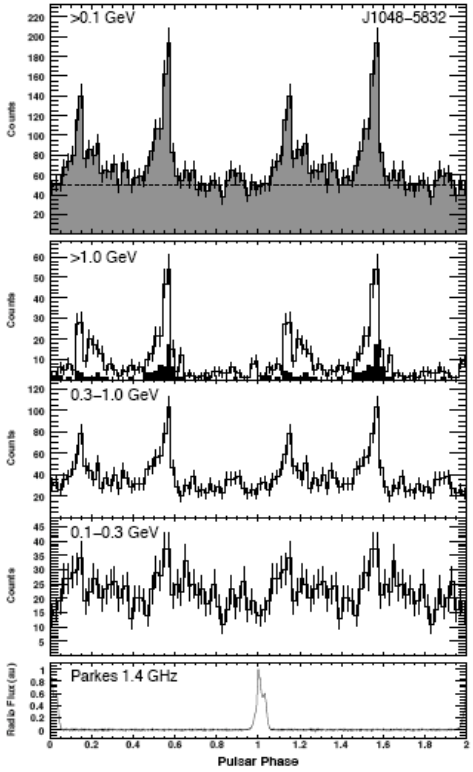
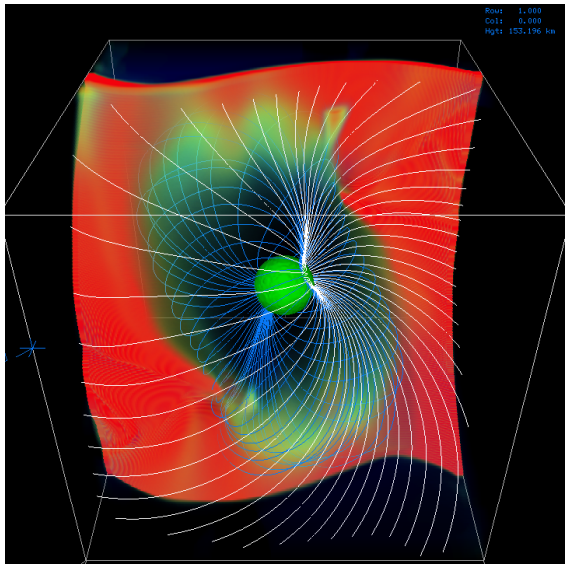
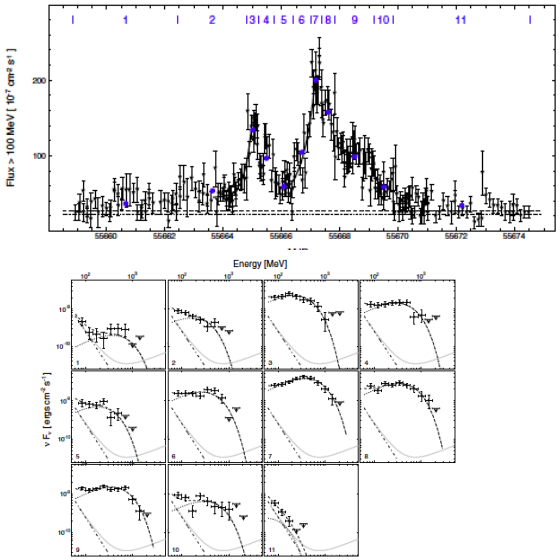


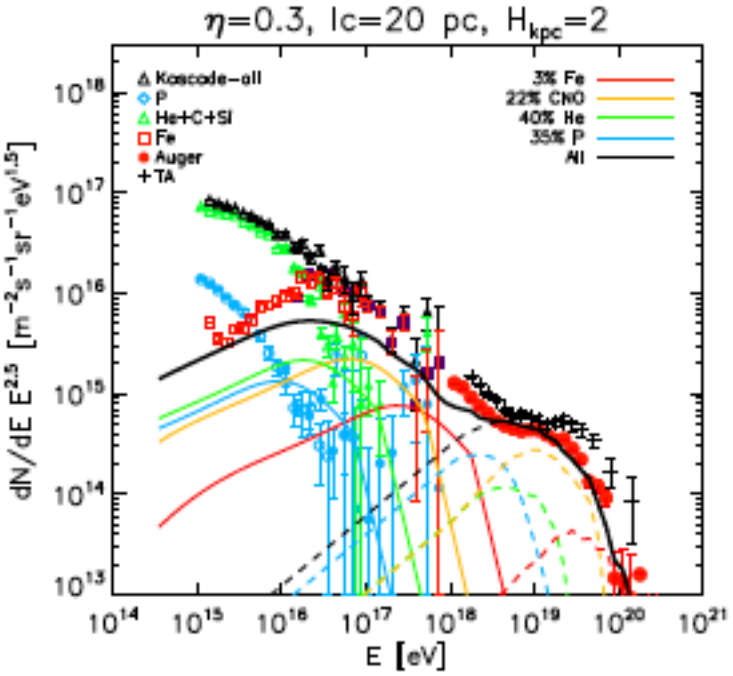


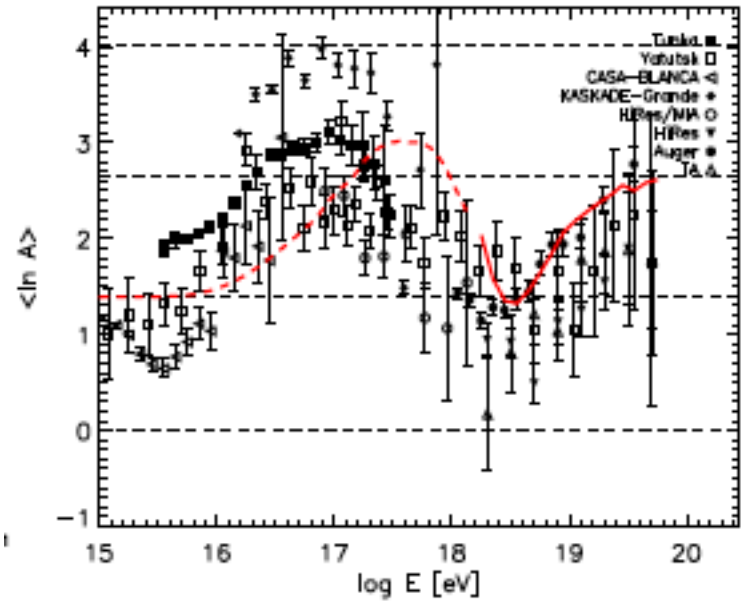
Bai & Spitkovsky 2010



Collaborators: N. Bucciantini, A. Spitkovsky

Heavy UHECR: a neutron star source?





Energy Spectrum
GZK cutoff or source
Ends above $10^{19.5}$ eV

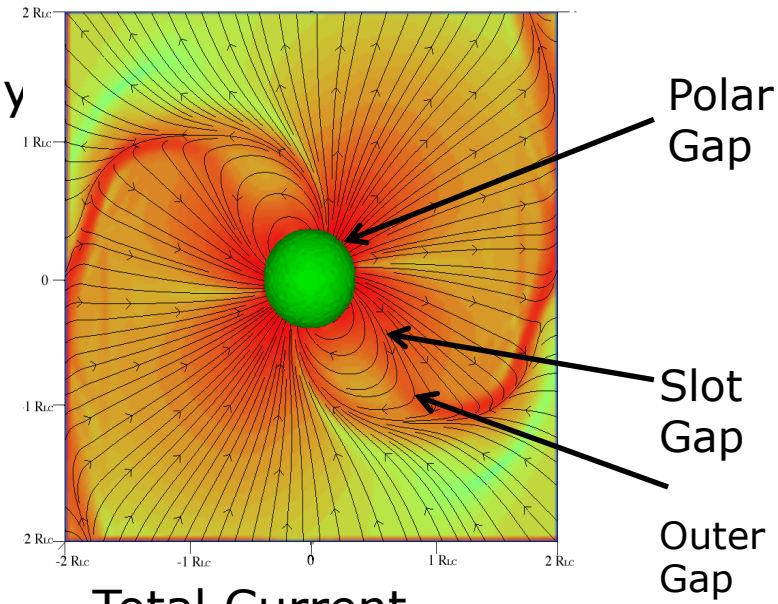
Composition; or hadronic interactions in air shower model not understood

Pulsars/Nebulae can accelerate ($e^{\pm}$) to PeV; have (Fe) crust/ocean

Magnetospheric Current System Requires Ion Extraction from Star (Atmosphere? Ocean? Crust?)

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 into vacuum B** to model gamma ray emission and pair creation – by construction, gaps carry small fraction of total current $I \Rightarrow L_{gap}$ small; Accelerate test particles along B

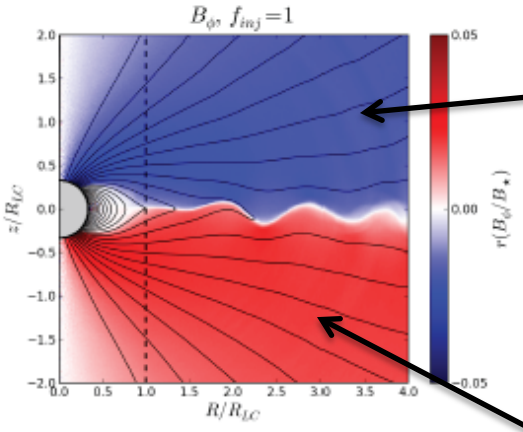
rotation ➔ lighthouse $\Rightarrow$ beamed photons (lighthouse)

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

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

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

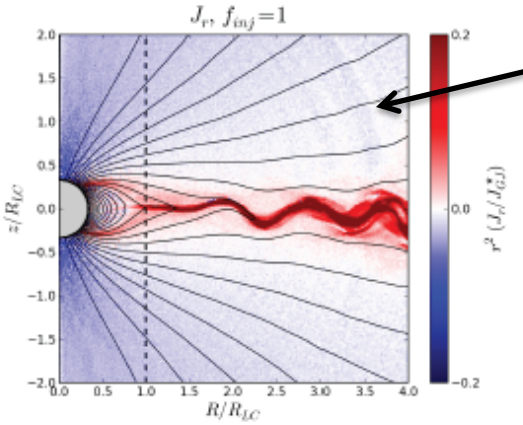
Force Free model has no accelerator: pure MHD (Alfven's ghost angry): Gap Models with vacuum $E_{||}$ have too little energy



Wind

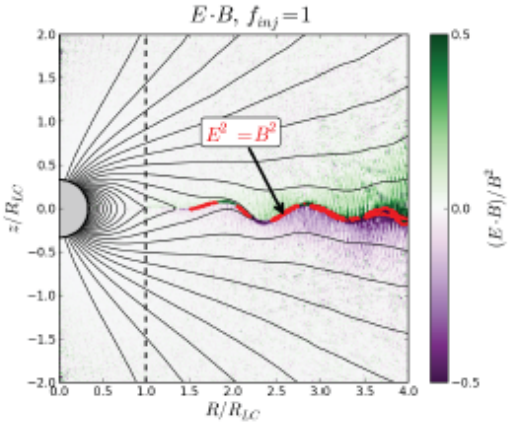
PIC aligned rotator simulation
e± pairs, low altitude pair creation (Cerutti+2015) - ~force-free + active current sheet (dynamics, particle acceleration)

rB_ϕ/B_*

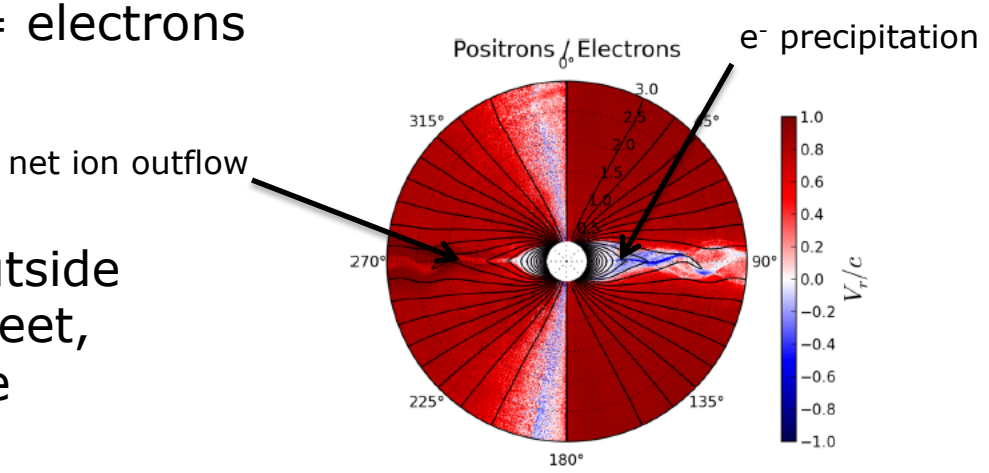


Poloidal field lines

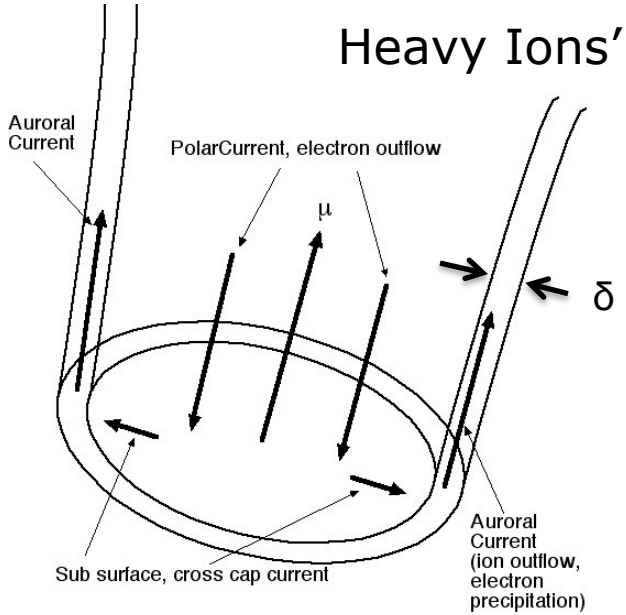
r^2J_r/J_{GJ*} - radial positive current = positive charge outflow (return current in equatorial current sheet) – radial volume current = electrons



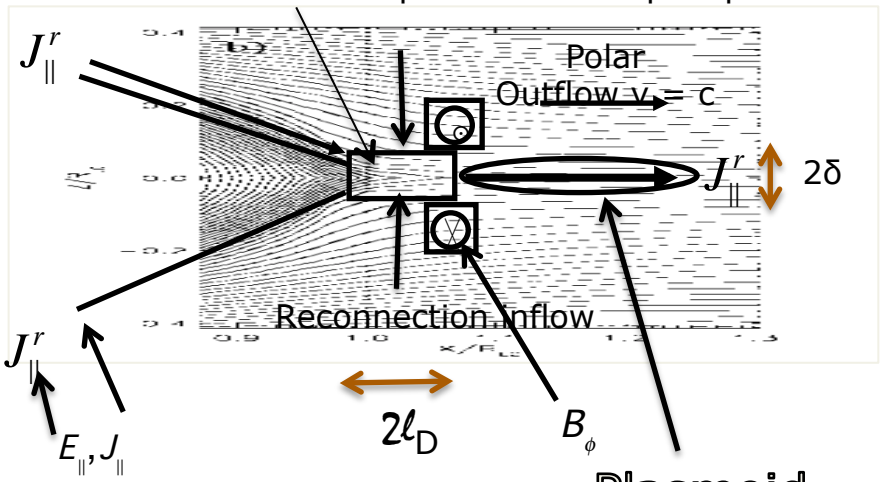
$E_{||}/B$ – B outside current sheet, B=0 inside



Heavy Ions' Source(14-17)

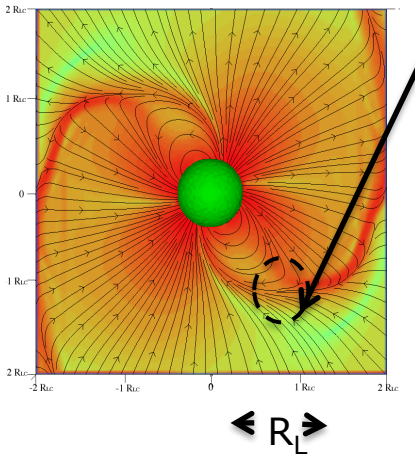


Unmagnetized Diffusion region & CS center: fed by reconnection inflow from wind thermal evaporation forms precipitation beam



Field Aligned Return Current

Magnetic Y-line



Electron precipitation density$_*$ = $I/r_{cap}\delta$ ≫ GJ
attracts upward ion beam from upper atmosphere (p^+,He^+,CNO^+?) Or ocean (Fe^{+many}?)
Electron precipitation current ≪I =cΦ≈I_{ion}

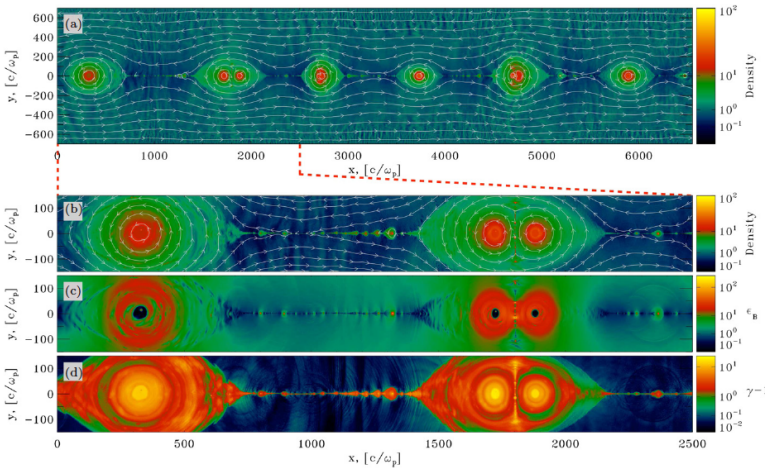
Acceleration along <u>radial</u> (r≫<u>R_L</u>) X-lines of reconnecting current sheet ~ linear accelerator

Electric return **current channel**

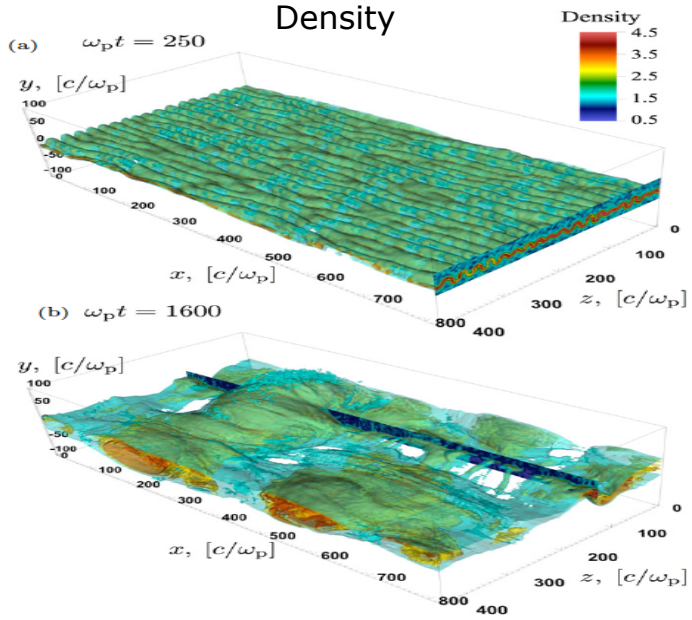
$\Omega \cdot \mu > 0$ Downward electron beam, upward ion beam

$\Omega \cdot \mu < 0$ Downward positron beam, upward electron beam

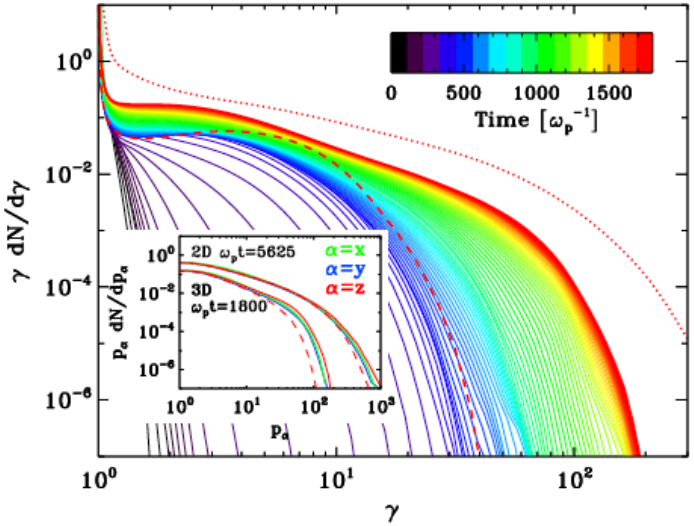
3D PIC e± (Sironi2014+)

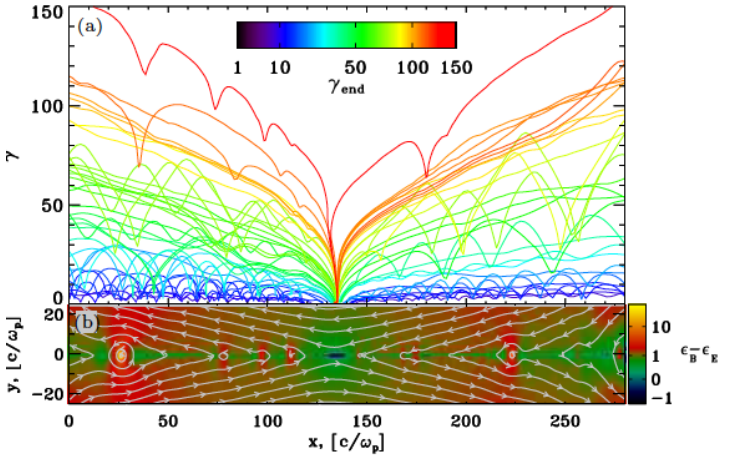


Density



Spectrum (whole box – radial, height, width ~ 6000 $r_L \ll r_{wind}$ ~$10^9 R_L$)





Energy Histories

$dN/d\gamma \sim \gamma^{-1.3}$ - ~ monoenergetic, highest energy particles have most energy

Linear Accelerator = current sheet in wind; carries electric return current

Particle rate:

$$\dot{N}_i(t) = \frac{I_{return}(t)}{Ze} = \frac{\Omega^2(t)\mu}{Zec} \quad \propto \frac{\Omega_i^2}{1+\frac{t}{t_{EM}\left(\Omega_i\right)}}$$

Decays as star spins down (EM after initial 10s, neutrino heated wind gone):

$$t_{EM} = \frac{I_M c^3}{2\Omega^2\mu^2} = \frac{10\,\mathrm{yr}}{\mu_{30}^2}\left(\frac{P}{1\mathrm{msec}}\right)^2$$

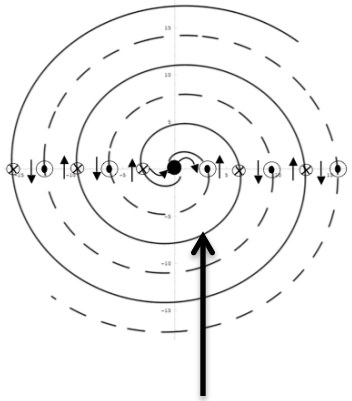
Maximum Energy: radial electric field E_r= reconnection = $(v_{rec}/c)B_\varphi$

$B_\varphi = \Phi/r$, $\Phi=\mu\Omega^2/c^2=1.3\times10^{19}\ \mu_{30}/P_{msec}^2$ Volts (magnetar: $\mu_{30}\sim10^3$)

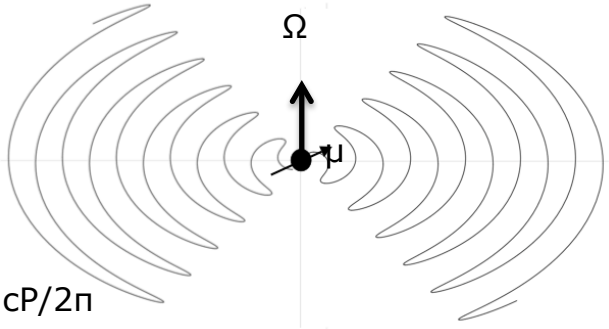
V_{rec} (simulations; simple 2 fluid theory) $=0.8\pm0.2v_A$,
v_A = c after initial 10s

$$\varepsilon = \gamma mc^2 = Ze\int_{r_{min}}^{r_{max}} E_r dr = Ze\left(\frac{v_{rec}}{c}\right)\int_{r_{min}}^{r_{max}} \frac{\Phi}{r} dr = Ze\left(\frac{v_{rec}}{c}\right)\Phi \ln\left(\frac{r_{max}}{r_{min}}\right)$$

Oblique Rotators: Inner Wind Magnetically Striped

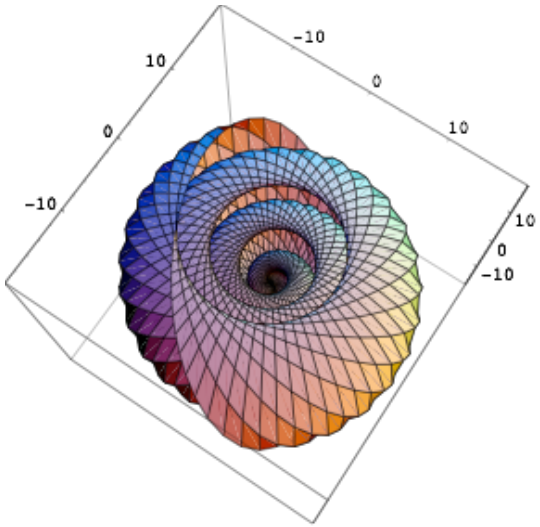


Equatorial cross-section



Meridional cross-section

Wavelength = $R_L = cP/2\pi$



Current Sheet

Dissipated in Wind Zone if

$$\Gamma_{wind} \le \sigma_0 = \sqrt{\frac{\dot{E}_R}{\dot{M}c^2}} \qquad \ll 10^6$$

for Crab Nebula, $\sigma_0 \sim 10^{3\text{-}4}$

Suggests stripes gone outside

$r = R_{diss} = r_{min} \sim 10^{6\text{-}7} R_L = 10^{-(3\text{-}2)} R_{TWS}$

R_{TWS} = wind termination radius = r_{max}

Mass loading of millisecond PSR = ?

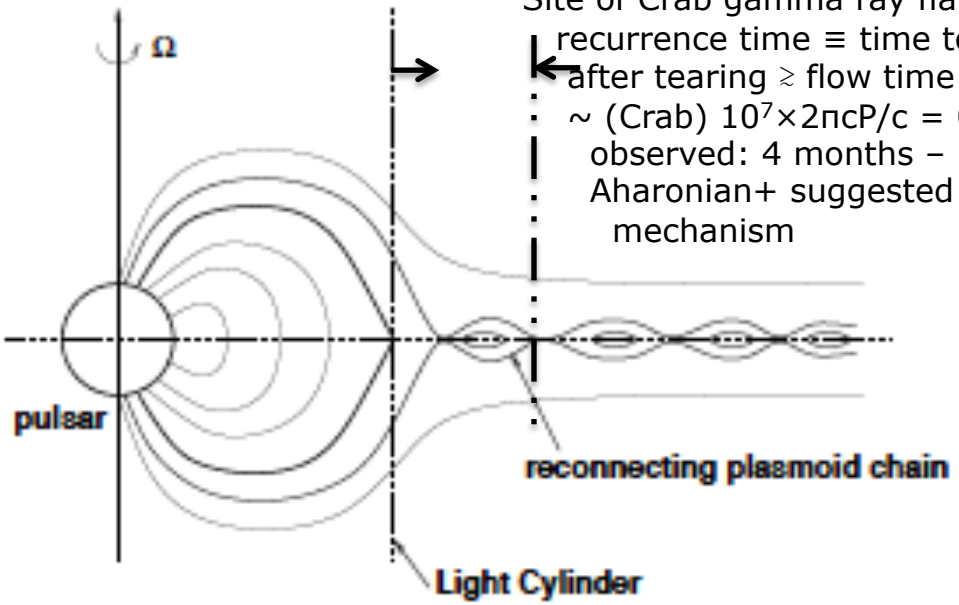
Outside R_{diss}, current sheet flat = linear accelerator to R_{TWS}

$$\varepsilon_{max}(t) = \gamma mc^2 = Ze\int_{r_{min}}^{r_{max}} E_r dr = Ze\left(\frac{v_{rec}}{c}\right)\int_{r_{min}}^{r_{max}} \frac{\Phi}{r} dr = Ze\left(\frac{v_{rec}}{c}\right)\Phi(t)\ln\left(\frac{r_{max}}{r_{min}}\right)$$

R_{diss} = stripe dissipation radius

$10^7 R_L$ based on fast reconnection of striped current sheet

Site of Crab gamma ray flares? –
recurrence time ≡ time to restore current sheet
after tearing ≳ flow time from LC = R_{diss}/c
~ (Crab) $10^7 \times 2\pi cP/c$ = 0.9 months –
observed: 4 months – 1 year
Aharonian+ suggested dissipation at 30 R_L, without mechanism



$R_{TWS} \sim 10^9 R_L$(Crab)

Particle Spectrum ∝ $E^{-1.3}$ from one star too hard for UHECR
Heavy ion source appealing, so
Superpose many stars/galaxies with a spectrum of voltages? (Kotera)
Process heavy ions (Fe?) in SNe ejecta shell? (Fang+)

BLOWOUT

possible relation to hypernova models of GRBs -
fast rotating magnetic core forms in core collapse supernova; magnetic pressure explodes stellar envelope, Compton upscatter of radiation field as wind escapes creates (slow) GRB?

Rare compact objects: $\nu_m = 10^{-4}\nu_{m4}\ yr^{-1}$ Suggests unusual core collapse SNe - Ib/c?

Newly formed magnetic core dumps EM energy (B fields,…) in a few minutes - initial spin down by GW emission,

$$t_{GR}(\Omega_i) \approx \frac{30}{\Omega_4^4\left(\varepsilon/10^{-2}\right)^2}\ \mathrm{sec},$$

$$\Delta E_{EM}(t < t_{GR}) \approx 5\times10^{51}\left(\frac{\mu_{33}}{\varepsilon/10^{-2}}\right)^2 ergs = 0.1\left(\frac{1}{2}I\Omega_i^2\right) \quad \left(\Omega_i \sim 10^4\ s^{-1}\right)$$

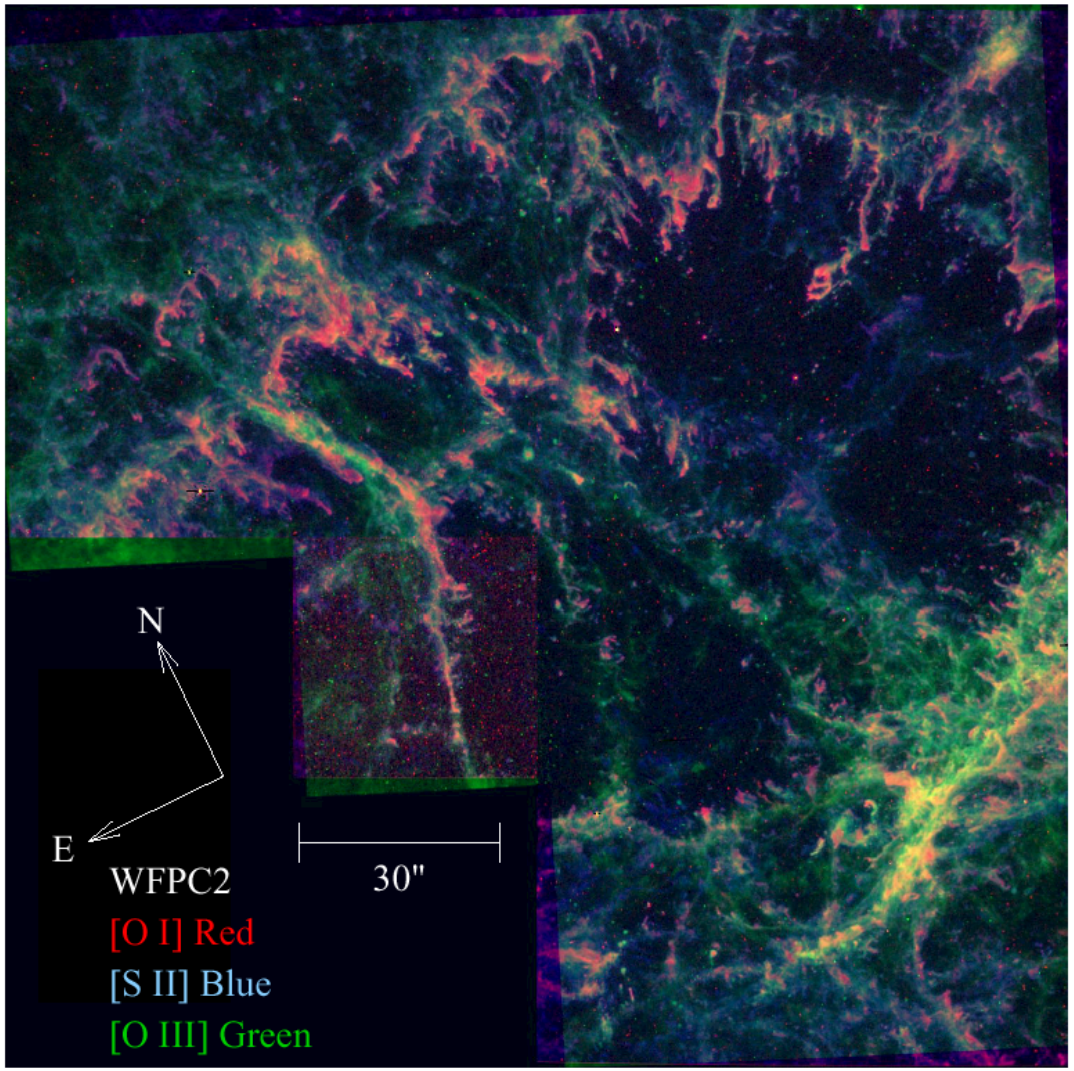
Pre SN star likely compact, with fairly short dynamical time
Wheeler et al 2000 model:

$$t_d \sim 20\frac{(R_* / 10^{5.5}\ km)^{3/2}}{(M/M_{sun})^{1/2}}\ \mathrm{sec}$$

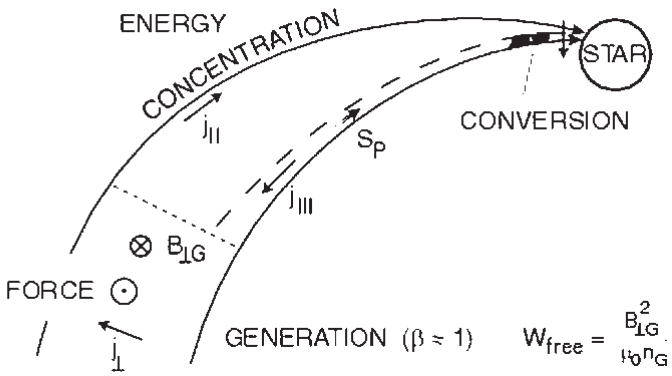
Injected EM Energy disrupts pre SN envelope in the dynamical time

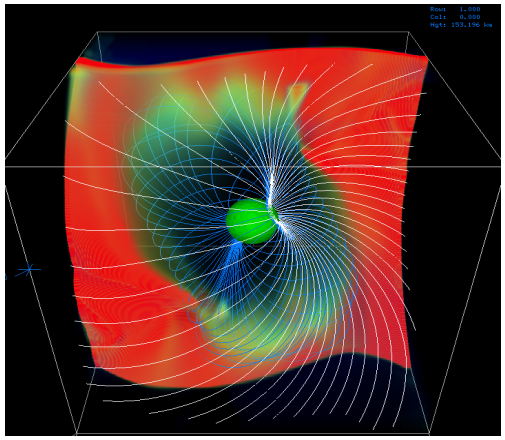
Rayleigh-Taylor of light EM energy shreds envelope in time t_{dyn}, short compared to standard SN,

Wind then expands freely, blows bubble in ISM, expansion non-relativistic after 1 year – deposits ~2-5 x $10^{50\text{-}51}$ ergs/neutron * in the ISM, limited by gravitational wave loss



Crab filaments - RT shredded ejecta (Sankrit Hester et al); also Gamma ray leakage from '87a


ENERGY
CONCENTRATION
STAR
CONVERSION
j_{II}
S_p
j_{III}
$\otimes B_{\perp G}$
FORCE $\odot$
$j_\perp$
GENERATION ($\beta \approx 1$)
$W_{free} = \frac{B_{\perp G}^2}{\mu_0 n_G}$



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