Cosmic Pevatrons in the Galaxy

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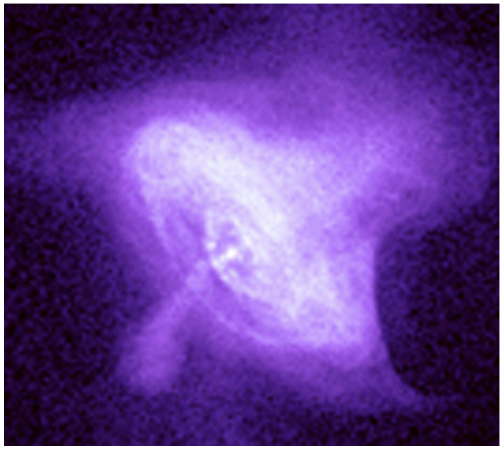
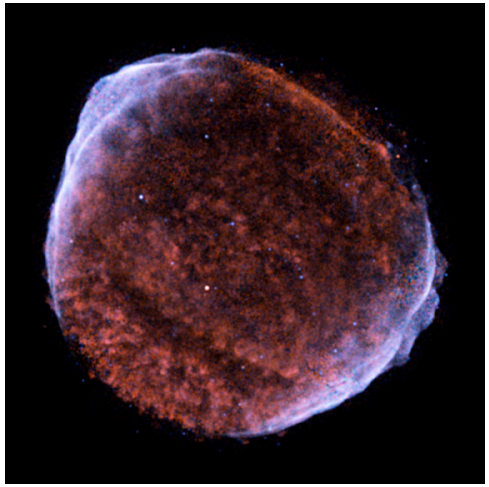
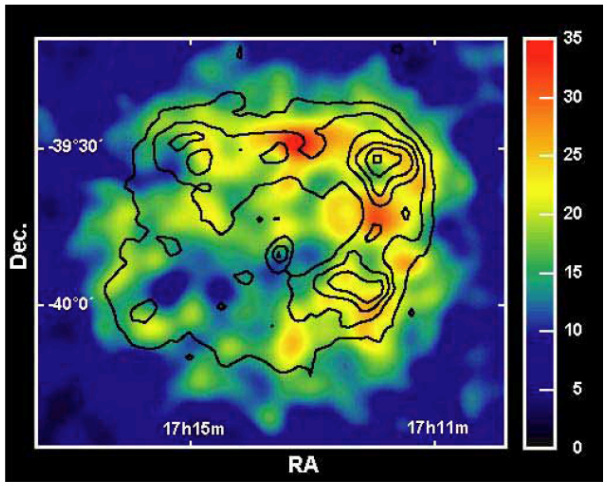


Cosmic Rays
Acceleration in Supernova Remnants
Pulsar Wind Nebulae





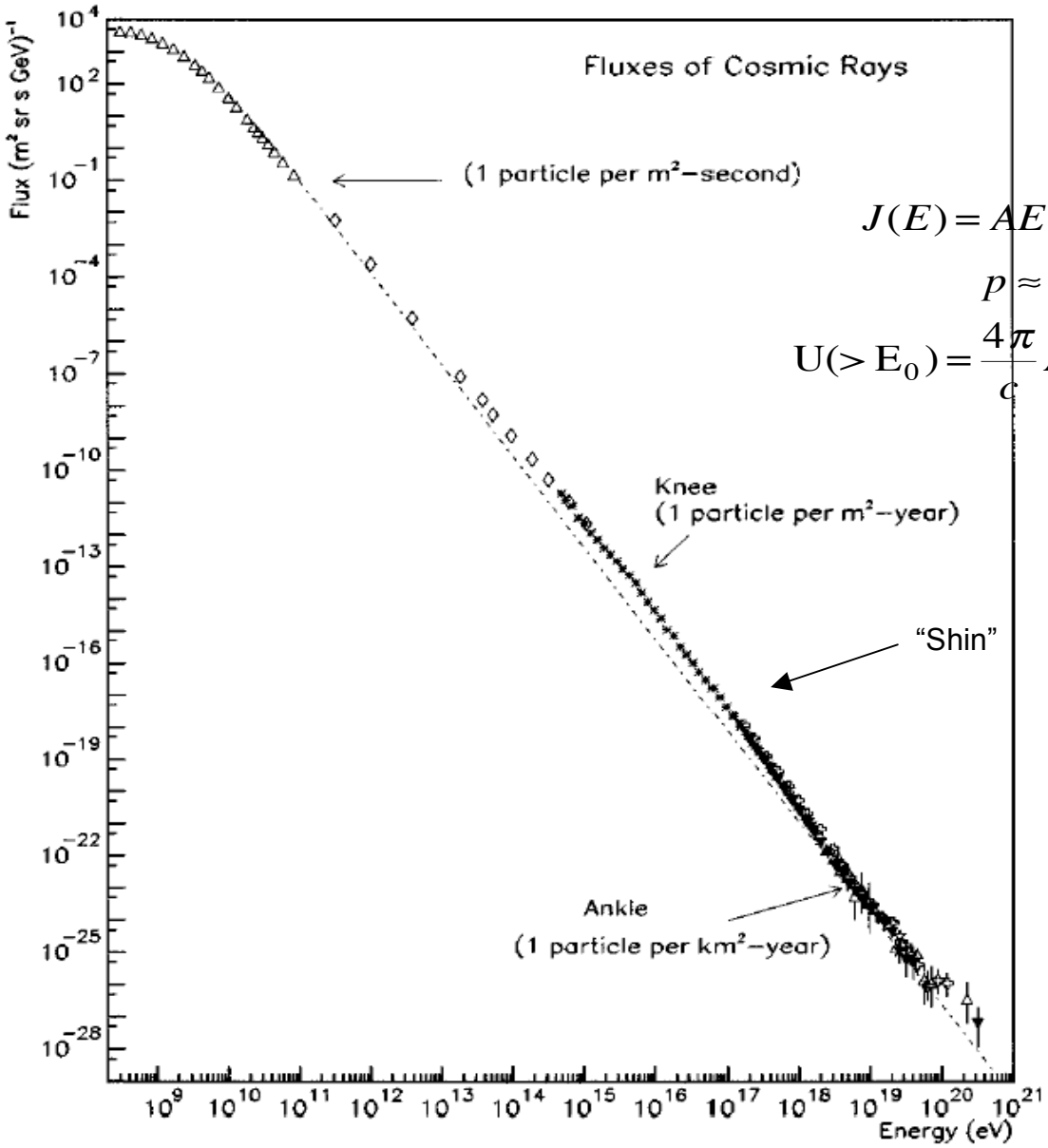


FIG. 1. Spectrum of cosmic rays greater than 100 MeV. This figure was produced by S. Swordy, University of Chicago.

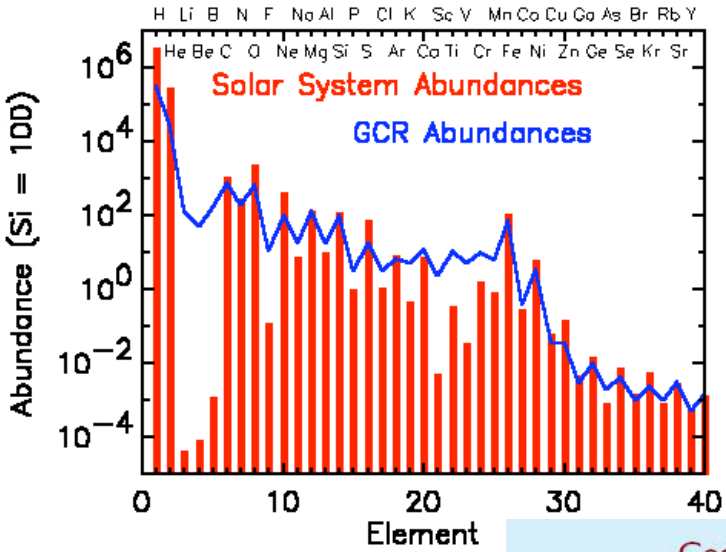
Cronin, 1999, RMP, 71, S165

$$J(E) = AE^{-p},\ p \approx 2.7, 1\,GeV < E < 10^6\ \text{GeV};$$

$$p \approx 3,\ 10^6\ \text{GeV} < E < 10^9\ \text{GeV}$$

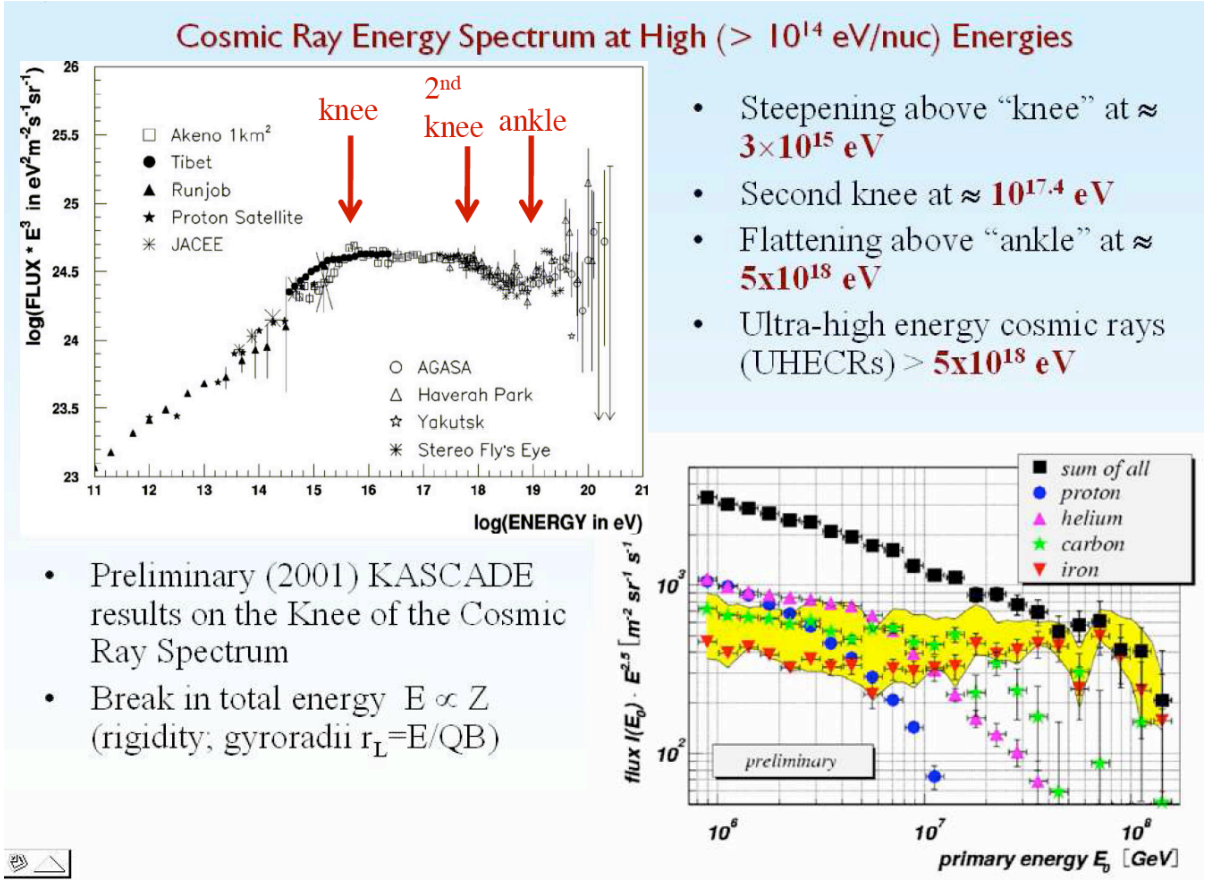
$$\mathrm{U}(>\mathrm{E}_0) = \frac{4\pi}{c} A \int_{E_0}^{\infty} dE E^{-(p-1)} \approx 1\,\text{eV/cm}^3 (E_0/1\,\text{GeV})^{-1}$$

Mostly protons (E < 1 TeV)

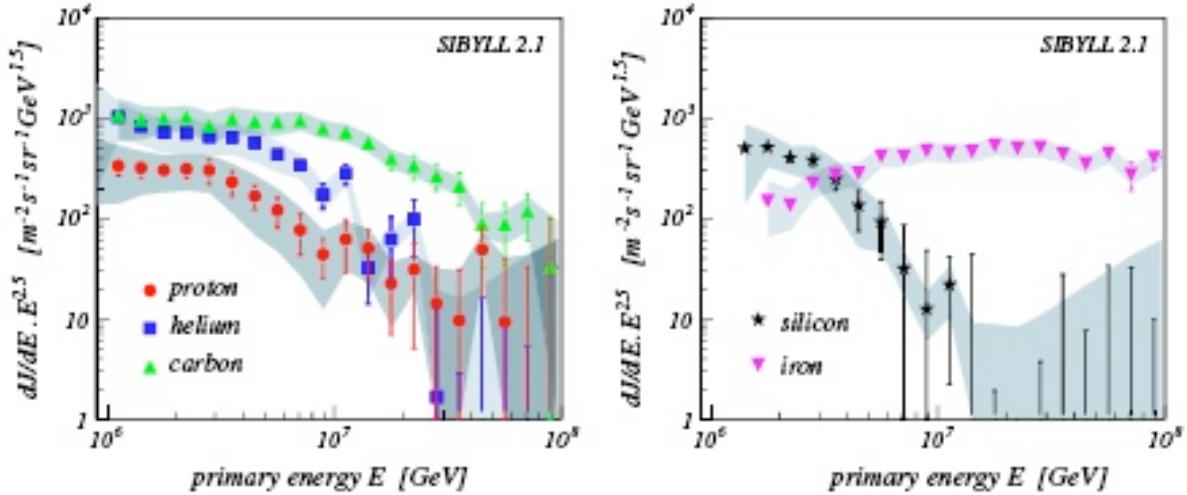


Composition: Maps "Normal" Matter - anomalies (e.g., Li, Be, B) = secondaries created during transport from sources (low energy data)

High energy composition constrains accelerator



Kascade Final Spectra



Accelerator works to a fixed E/Z = pc/Z

Accelerator requires electric field

Magnetized Cosmic Plasmas: Motional EMF of frozen-in B

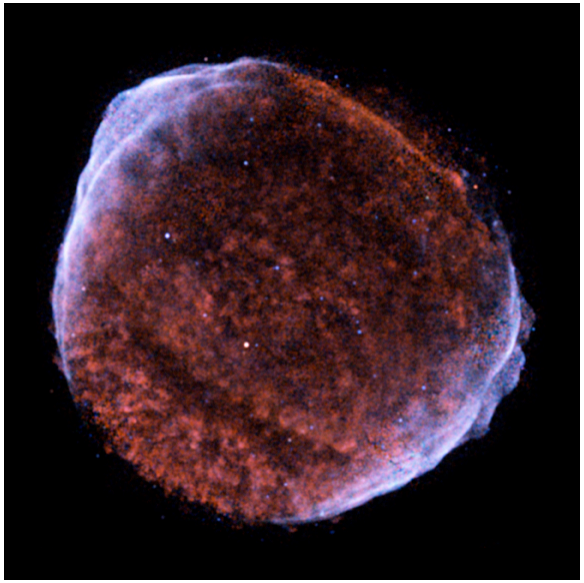
$$E = \frac{v}{c} B$$

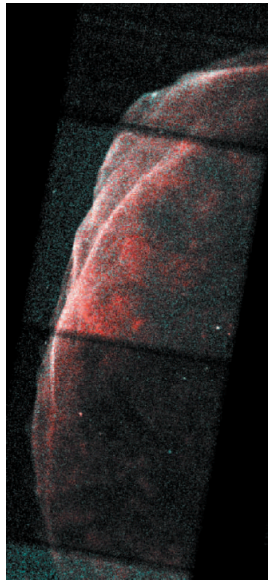
$$+$$

E ⊥ B : Need Finite Larmor Radius (particles untied from field lines)

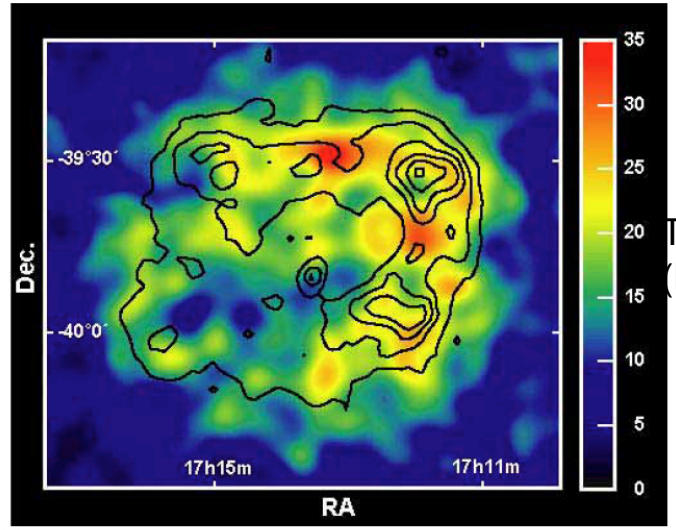
$$r_L = \frac{pc}{ZeB} : \quad r_L = R \Rightarrow (pc / Z)_{\max} \; fixed \; (eRB \; fixed)$$

Energetics: Supernovae and their Remnants (long known)





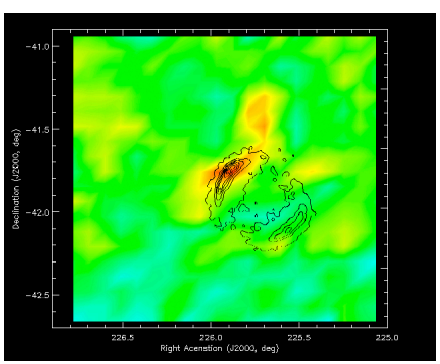
X-ray (Chandra)



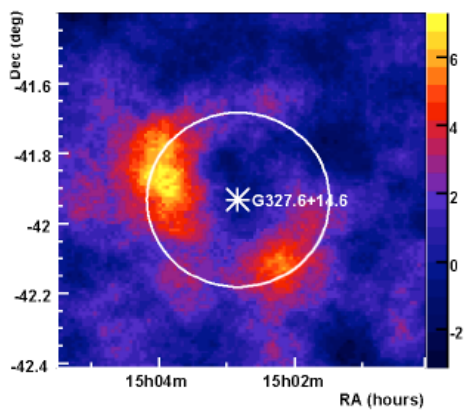
TeV (HESS)

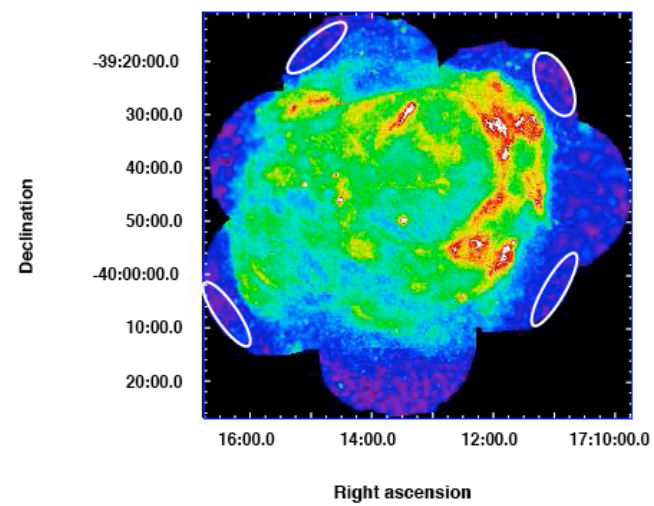
20 pc

Radio



TeV (HESS)





X-ray (XMM)

SNR 1006

Synchrotron - B ~ 100 μG >> $4B_{ISM}$; PeV e^-

RX J1713

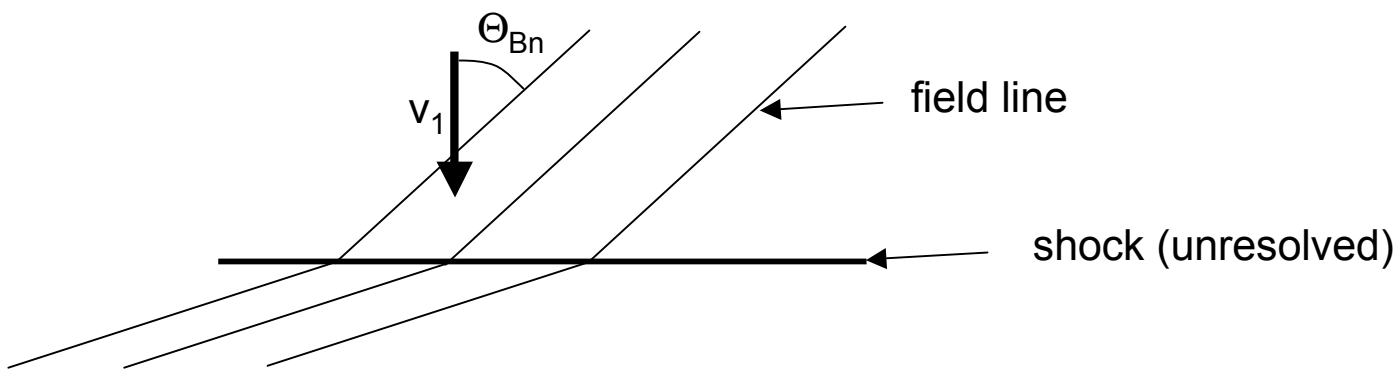
Synchroton X-Ray

TeV: pp->π^0->γ (probably)

Thin X-ray filaments -> fast synchrotron cooling -> strong B

Accelerator: Diffusive Fermi Acceleration (DFA)
Diffusive Shock Acceleration (DSA)

efficient (>10%) conversion of flow energy to nonthermally heated broad (in energy) downstream particle population - particles must access upstream from downstream many times while following B - reflection diffusive, rate = time to scatter back into shock front



Many crossings - particles like tennis balls between converging walls, gain energy+ removal by flow downstream yields (non relativistic test particle model) $N(E) \propto E^{-2}$ with upper cutoff determined by age of system or by radiative or other loss

Nonlinear variants (cosmic ray pressure modifies upstream dynamics) yield curved spectra

Mechanism effective if time to accelerate to momentum p < age of SNR

Acceleration rate determined by the time to cycle across shock (simple quasi-linear version; see Morlino et al for nonlinear flow - but still quasi-linear kinetic theory version applied to RX J1713)

$$\frac{dp}{dt} \sim \frac{\Delta p}{T_{\text{cycle}}} = \frac{u_1 - u_2}{3} \frac{p}{\frac{D_1}{u_1} + \frac{D_2}{u_2}}$$

$u_{1,2}$ = up(down) stream flow speeds
$D_{1,2}$ = up(down) stream diffusion coefficients

$$D_i = \frac{r_L(p, B_i) c\beta}{3} \left(\frac{B_i^2}{\langle \delta B^2 \rangle_i} \right)_{k r_L(p)=1}, \; i = 1,2$$

$$r_{Li}(p) = \frac{cp}{ZeB_i}$$

Toy Model (Bohm diffusion) short circuits modeling δB: $\frac{B_i^2}{\langle \delta B^2 \rangle_i} = 1$

Then

$$D_i \propto r_L \propto \frac{1}{B} \Rightarrow \frac{1}{p}\frac{dp}{dt} \propto B :$$

Large B means small Larmor radii, diffusion coefficients, partcicles scatter back into shock quickly, fast acceleration

Inferred 100 μG B from synchrotron model yields fast enough acceleration to create PeV e^-, p^+ - acceleration to CR knee solved (conclusion preserved in non-linear flow models)

Large B >> compressed Interstellar Medium B - due to cosmic ray streaming with respect interstellar plasma incoming upstream of the shock

Modeling cosmic ray driven turbulence - beyond Bohm diffusion, beyond Quasi-linear theory

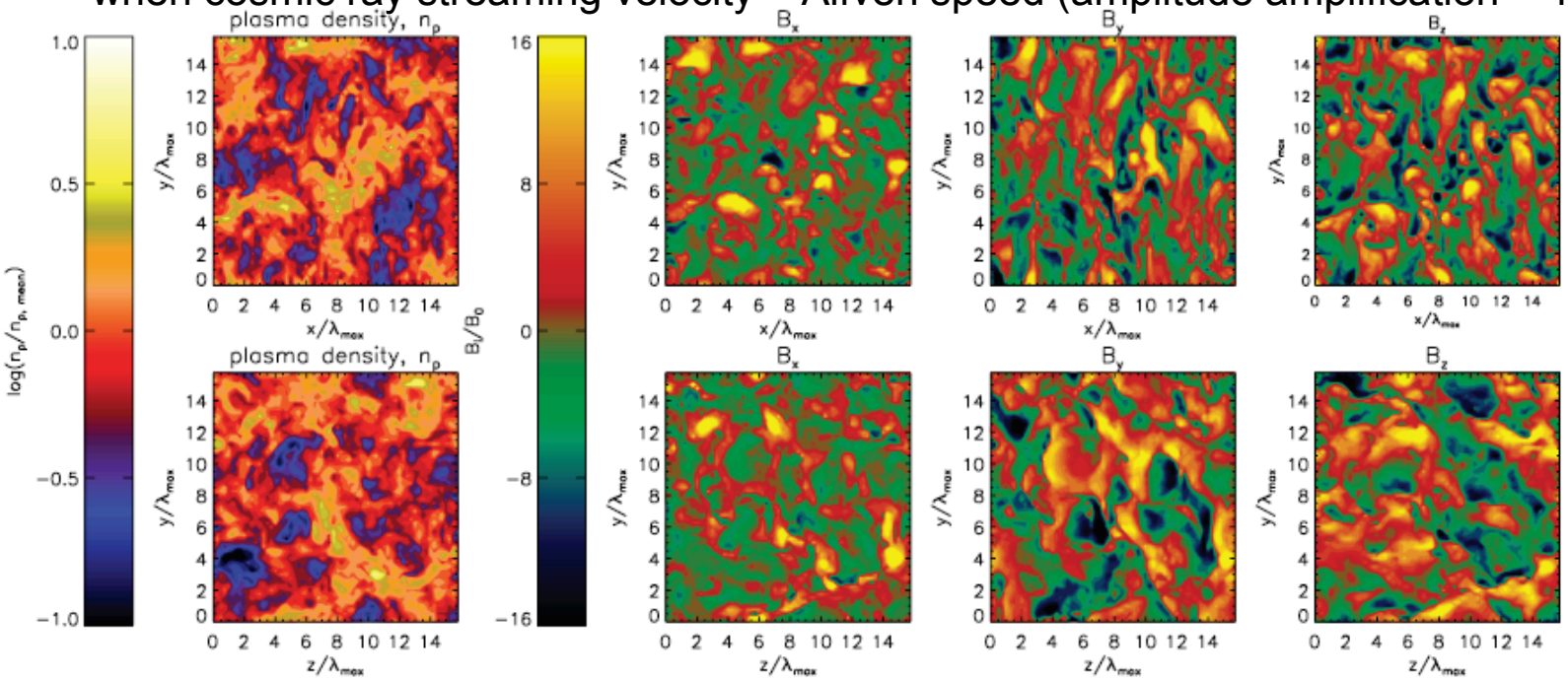
Several mechanisms (“instabilities”) studied/propounded:

1. cosmic rays resonate with Alfven waves, streaming creates maser amplifier (Lerche, Kulsrud & Pearce - 60s) - $r_L(p) \sim$ wavelength λ
2. cosmic ray streaming induces electric current in medium, unstable circularly polarized magnetic waves generated (Bell - 2000-2005) - faster than #1 in linear growth phase - requires $r_L(p) >>$ wavelength λ
3. firehose instability driven by anisotropic pressure of streaming cosmic rays (implicit in 70s work by Eichler, recent suggestion by Blandford - nothing quantitative in print to date) - requires $r_L(p) <<$ wavelength λ

Mechanism 2 recently studied using fully nonlinear computational kinetic (PIC) simulations (Riquelme & Spitkovsky 09 ApJ) in 1D, 2D and 3D

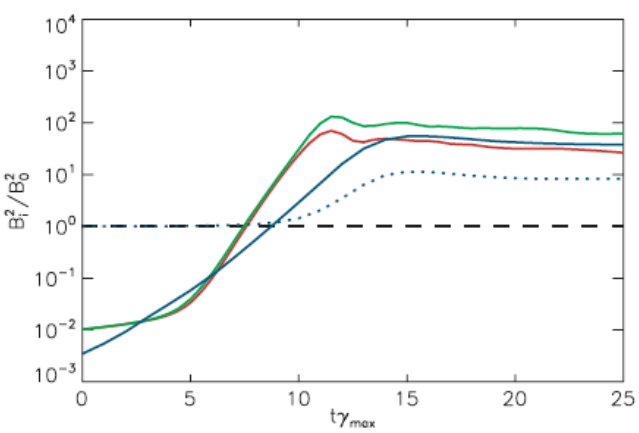
Solved initial value problems: cosmic rays stream through uniform medium, instability grows, saturates, usually (for SNR like conditions) by turbulence reacting on CR streaming, reduces streaming velocity to Alfven speed

Magnetized turbulence driven by cosmic ray streaming, short wavelength: saturation when cosmic ray streaming velocity ~ Alfven speed (amplitude amplification ~ 10)



3D

Amplitude(t): 3D (blue; 1D(others)

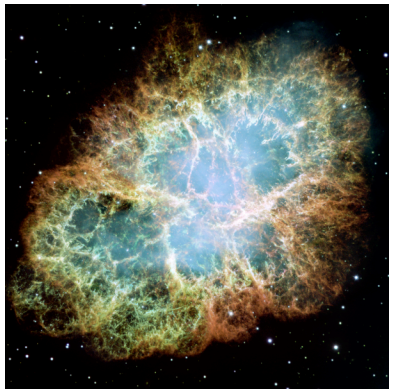


Magnetic amplifications in upstream medium ~ 10 driven by cosmic rays are physical. Shock compression gives extra factor of 4 downstream, good for synchrotron cooling model of thin filaments

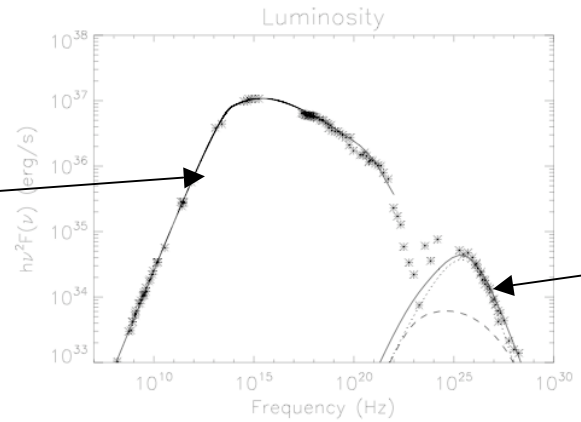
Also good for acceleration of protons to the knee

Pulsar Wind Nebulae - Electron-Positron Pevatrons

The Eponymous Crab Nebula = archetype (in most respects)



~1.5 pc



Synhcrotron (R, IR, O, X,γ) ε < 100 MeV

ε ~100 MeV requires PeV electrons, positrons (B~10^{-4} G, accumulated from pulsar)

Inverse-Compton (self-Compton in Crab, from CMB in most others)

Powered by electromagnetic braking of central pulsar. Strong electric field ***parallel*** to B over pulsar's polar cap accelerates e^- (and e^+) parallel to curved B, $\gamma + B \rightarrow e^{\pm} + B$ cascade

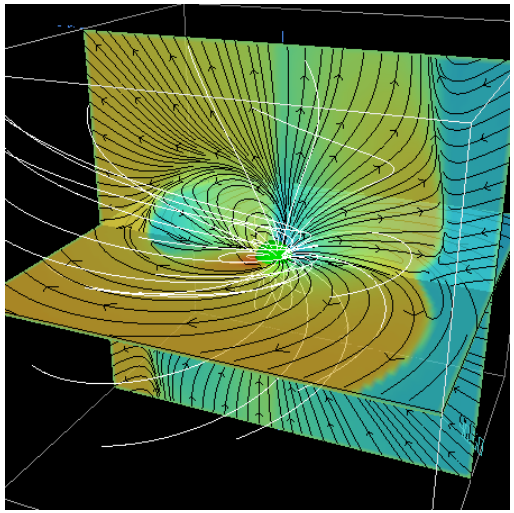
$$\dot{N}_{\pm} \gg \frac{c\Phi}{e} \approx 10^{34} \frac{\Phi}{10^{16.6}\,V} s^{-1}, \quad \Phi = \sqrt{\frac{\dot{E}_R}{c}} = 3.9 \times 10^{16} \frac{\dot{P} / 10^{-12.35}}{(P / 33\,\text{msec})^3} \text{ Volts,}$$

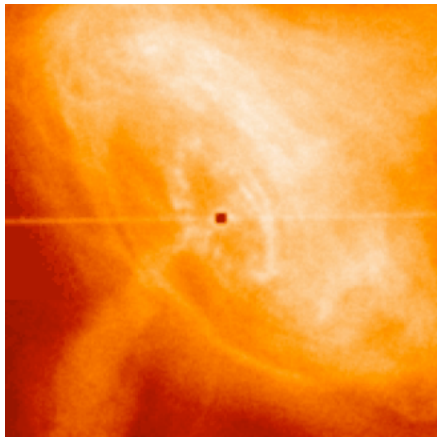
$$I = c\Phi = 3.9 \times 10^{16} \frac{\dot{P} / 10^{-12.35}}{(P / 33\,\text{msec})^3} \text{ Amp, } \dot{E}_R = I\Phi = c\Phi^2 = \frac{\Omega^4 \mu^2}{c^3} \text{ (~ dipole to Light Cylinder)}$$

μ = magnetic moment, Ω = angular velocity

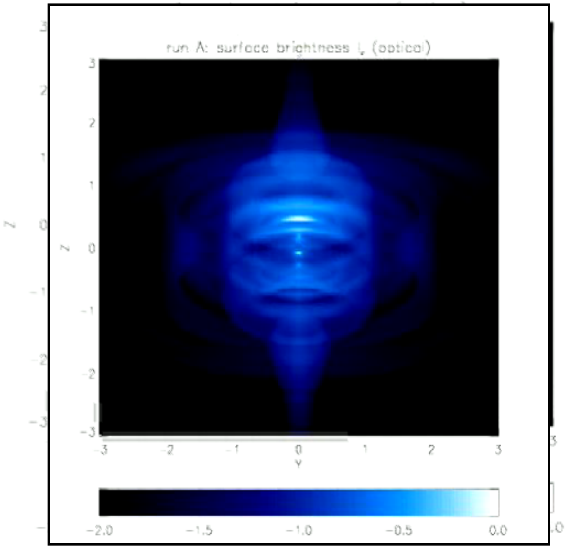
Pairs and B flow out as magnetized relativistic wind - cold MHD flow stops at relativistic termination shock, shock acceleration (DFA?) converts flow energy to broken power laws of emitters - that's the idea, how?

3D Force-Free MHD simulation (Spitkovsky)





Time Varying Termination Shock (Chandra/Mori)



Unstable MHD flow downstream of termination shock (Bucciantini)

Shock geometry transverse - B perp to flow

Relativistic DFA in very weakly magnetized shocks

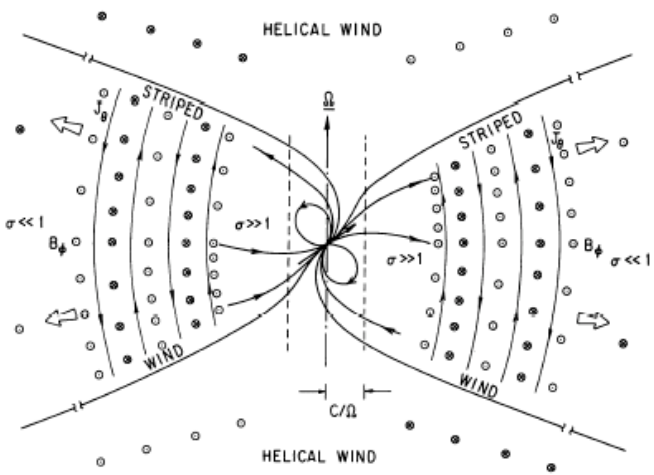
does succeed - $\sigma_1 = (B^2 / 8\pi m_\pm n_\pm c^2)_1 < 10^{-3}$ upstream - relativistic multi D PIC

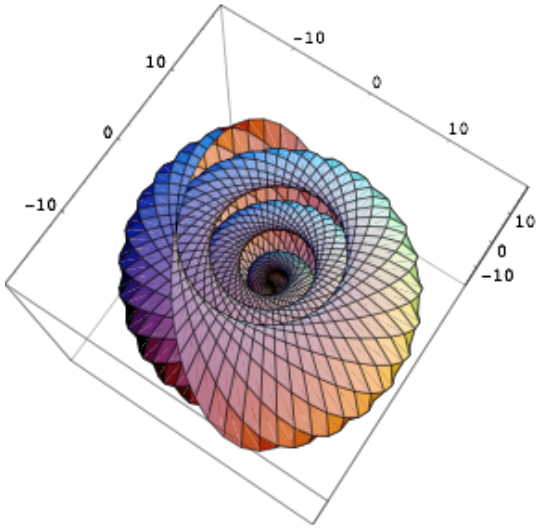
Nebular MHD model requires $\sigma_1 \sim 0.02$ to get X-ray jet-torus structure correct (magnetic hoop stress compresses downstream flow, focuses onto axis)

PIC simulations show DFA ineffective at magnetizations > 10^{-3}

Pair Cascade models yield $\dot{N}_\pm \sim 10^4 (c\Phi / e) \sim 10^{38}$ / s, OK for X-rays, 100-1000 too small for radio, problem common to young pulsars/nebulae (where we have data)

Likely Solution: Acceleration probably related to upstream wind being structured ("striped"), B field at low rotational latitude decays upstream, weakly magnetized angular sector feeds torus, very low σ shock





Large Pair outflow rate perhaps related to intrinsic time dependence of cascdes inside the magnetospheres - but not clear

Pulsar contribution to positron content of cosmic rays (as seen by PAMELA, perhaps by FERMI) hard to predict, since existing theory applied to well studied systems has problems - improvements are in the works, perhaps will help

Secondary positrons made in p-p interactions inside SNR may be able to account for PAMELA/FERMI with no free parameters (Blasi)