Cosmic-ray Streaming Instabilities at supernova shocks

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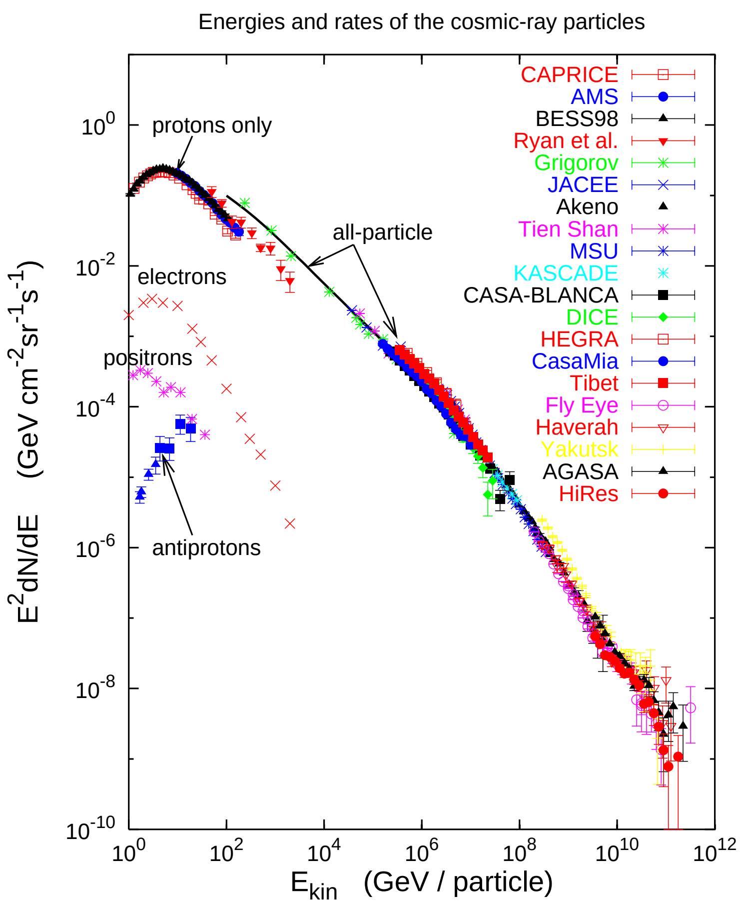
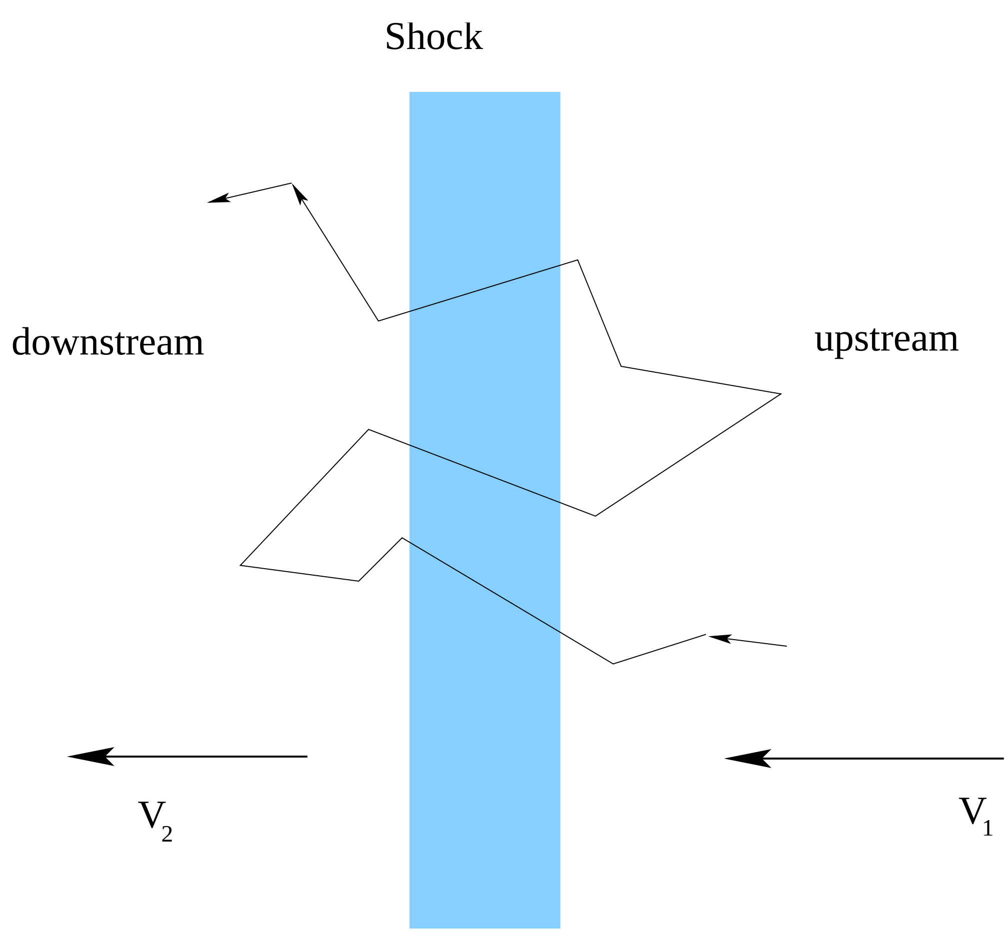
Cosmic ray spectrum



(from Hillas [2006])

Diffusive shock acceleration (DSA)

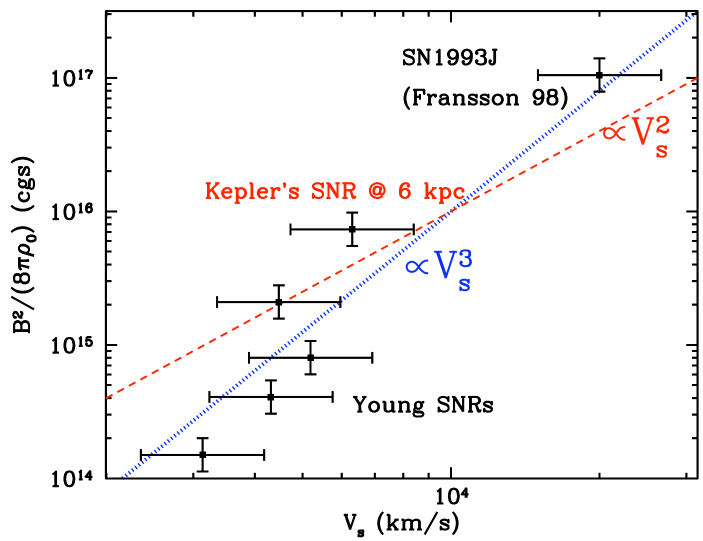


DSA in SNRs

- SN forward shocks
- DSA very efficient, predicting $dN/dE \sim E^{-\delta}$, $\delta \sim 2$
- Turbulence needed, but resonant wave growth due to CR not sufficient
- Maximum energy obtainable at SNR shock
  limited by the Bohm diffusion $D_B \sim v r_g/3$ (Lagage & Cesarsky 1983):
  $D \sim \Delta L^2/t \sim v_s \Delta L$
  $\Rightarrow E_{\max} \sim 3 \times 10^{14}\,\mathrm{eV}$ for $\Delta L \sim 10^{16}\,\mathrm{m}$, $B \sim 2 \times 10^{-10}\,\mathrm{T}$, $v_s \sim 10^7\,\mathrm{m\,s^{-1}}$
- Large B needed to reduce Larmor radius r_g

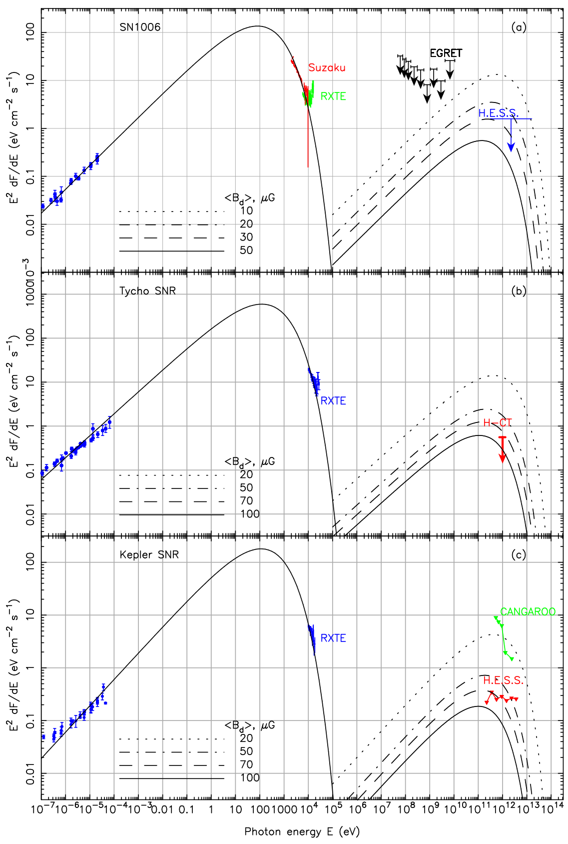
Magnetic fields in SNRs

$B \gg B_{ISM}$ implied by X-ray observations of SNRs
(Berechko et al. 2002; Vink & Laming 2003; Völk et al 2005)



(Vink 2008)

TeV gamma-rays



(Völk et al. astro-ph 0809.2432)

Origin of magnetic fields

- Bell's model (2004)

  $\delta B \gg B_0$ generated by CR streaming instability
  very efficient at $1/k_{||} \ll r_g$
- Nonresonant growth of Alfvén waves dominant over resonant growth at short wavelenth ($1/k_{||} \ll r_g$)

CR streaming instability

- Plasma physics?
  Bell's model in MHD
  Kinetic theory (Melrose 2005, Amato & Blasi 2008)
- Linear mode
- Saturation?
  MHD simulation $\delta B/B_0 \sim 10^3$ (Bell 2004)
  PIC simulation $\delta B/B_0 \sim 1$ (Niemiec et al 2008)
  Full PIC $\delta B/B_0 \sim 3-30$ (Riquelme & Spitkovsky 2008)
- Effects on DSA: Nonresonant scattering $k_{\|}r_g \gg 1$?

Interpretation

- CR current $J_{CR} = qn_{CR}v_{CR}$
- A model:
  background plasma+CRs with $v_{CR} \neq 0$
  Neutralization conditions:

$$e(n_e - n_p) = qn_{CR}, \quad e(n_e v_e - n_p v_p) = qn_{CR} v_{cr}$$

- Compensating current, equal to $-J_{CR}$
- Instability driven by the compensating current
- Condition for instability

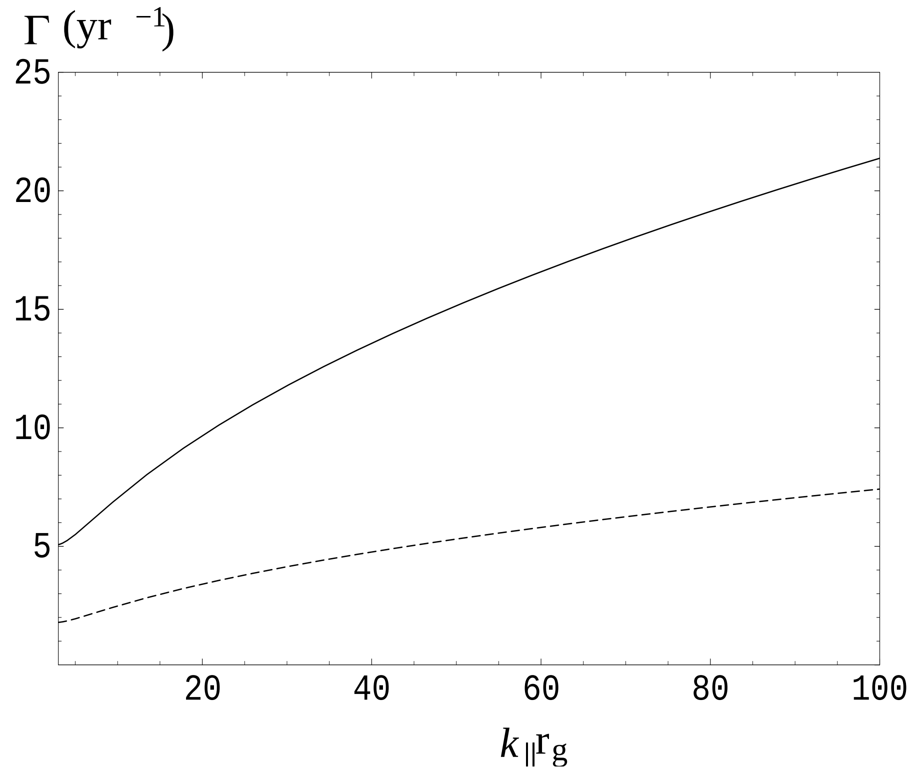
$$J_{CR} > \frac{k_{\parallel} B_0}{\mu_0}$$

- The instability grows rapidly at $k_{\parallel} r_g \gg 1$

- Growth rate

$$\Gamma \approx (6\eta_s k_0 r_{g0})^{1/2} \left(\frac{v_s}{c}\right)^{3/2} \frac{\Omega}{\gamma_0}$$

($B_0 = 10^{-10}$ T
$v_s = 5 \times 10^6, 10^7$ m s^{-1}
$\gamma_0 = 100$)



Saturation

- A streaming model

$$f(p,\alpha) = n_{CR}\left(1 + 3\frac{v_{CR}}{v}\cos\alpha\right)\frac{g(p)}{4\pi p^2}$$

$$g(p) = \begin{cases} \dfrac{b-1}{p_1}\left[1-\left(\dfrac{p_1}{p_2}\right)^{b-1}\right]^{-1}\left(\dfrac{p}{p_1}\right)^{-b}, & p_1 \le p \le p_2, \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

- Streaming velocity $\langle v_{\|} \rangle = v_{CR}$

- Quasilinear diffusion
  Feedback on CR current
- $v_{CR}(t)$ evolves due to nonresonant/resonant diffusion
- Nonresonant diffusion, similar to the firehose instability
- Resonant diffusion, pitch angle scattering
- Scattering time

$$t_s \sim \frac{\gamma}{\Omega}\frac{B_0^2}{\delta B^2}k_0 r_{g0}$$

compared to growth time $1/\Gamma$

- Saturated magnetic energy

$$\frac{\delta B^2}{B_0^2} \sim \frac{12}{\pi}(6\eta_s)^{1/2}\left(\frac{v_s}{c}\right)^{3/2}\left(k_0 r_{g0}\right)^{3/2}\ln\left(\frac{v_{CR0}}{v'_{CR}}\right)$$

- Magnetic amplification modest

$$\frac{\delta B^2}{B_0^2} \sim 18\left(\frac{\eta_s}{0.1}\right)^{1/2}\left(\frac{v_s}{10^7\,\mathrm{m\,s^{-1}}}\right)^{3/2}\left(\frac{k_0 r_{g0}}{100}\right)^{3/2}$$

Summary

- Physical interpretation. The instability driven by compensating current
- Limit by saturation due to diffusion. Modest amplification possible
- Implication for DSA. Only small fraction of CRs in resonance with amplified magnetic fields