Type II Supernova Remnants and Cosmic-Ray Spectrum

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SNR accelerate Galactic Cosmic Rays

How can we reach PeV energies?

Upstream magnetic field amplification.

How?

Resonant instability ($\lambda \sim r_L$)

(Skilling 1975)

Not enough

(Lagage&Cesarsky83)
NRH Instability: How Does It Work?

In presence of high CR acceleration efficiency, current driven regime and fast growing non-resonant modes (Bell 2004)

High energy particles escape the remnant balistically because $\lambda << r_L$.

The scale of the instability is too small and there is no particle scattering → magnetic field perturbations grow up to resonant scales $\lambda \sim r_L$.

Particles with the same energies are scattered resonantly by perturbations towards the downstream.

Efficient acceleration.
Current driven regime

Simulation results about growth rate (Bell, Schure 2013)

Ejecta and Medium density profile

Current driven regime

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**MAXIMUM ENERGY**

$$E_M(R) = \frac{2Z\epsilon}{10} \sqrt{4\pi\rho R^2} \frac{\xi_{CR}}{c\Lambda} v_{sh}^2(R) = 130 \left( \frac{\xi_{CR}}{0.1} \right) \left( \frac{M_{ej}}{M_*} \right)^{-2/3} \left( \frac{E_{SN}}{10^{51} \text{ erg}} \right) \left( \frac{n_{ISM}}{\text{cm}^{-3}} \right)^{1/6} \text{ TeV}$$

$$E_M(R) = \frac{2Z\epsilon}{5} \sqrt{4\pi\rho R^2} \frac{\xi_{CR}}{c\Lambda} v_{sh}^2(R) = 1 \left( \frac{\xi_{CR}}{0.1} \right) \left( \frac{M_{ej}}{M_*} \right)^{-1} \left( \frac{E_{SN}}{10^{51} \text{ erg}} \right) \left( \frac{M}{10^{-5} \text{ km / yr}} \right) \left( \frac{V_w}{10 \text{ km / s}} \right)^{-1/2} \text{ PeV}$$

**Type I (ISM)**

**Type II (wind)**

**Sedov Time**
Power-law time dependence of the SNR radius, changing during the whole SNR evolution $\Rightarrow N_{\text{esc}}(E) = N_{\text{esc}}(\xi_{\text{CR}}, E_{\text{SN}})$

- Type I
  - $N_{\text{esc}}(E) = \begin{cases} E^{-(5+4\varepsilon)} & \text{ED} \\ E^{-(2+\varepsilon)} & \text{ST} \end{cases}$

- Type II
  - $N_{\text{esc}}(E) = \begin{cases} E^{-(4+3\varepsilon)} & \text{ED} \\ E^{-(2+\varepsilon)} & \text{ST} \end{cases}$

- If injection spectral index $p \leq 2 \Rightarrow \varepsilon = 0$
- If injection spectral index $p > 2 \Rightarrow \varepsilon \neq 0$

- The escape spectrum reproduces the injection spectrum only if $p = 2$ or steeper

- The spectrum is a broken power-law $\Rightarrow$ There is no sharp cut-off for energies above $E_M$
Taking into account diffusion and spallation contributions,
Using B/C ratio in order to estimate the grammage:

\[ N_{\text{obs}}(E) = N_{\text{esc}}(E) \times \frac{\mathcal{R}}{2\pi R_D^2 n_D h c m_p} \times \left(1 + \frac{X(E)}{m_p/\sigma_{sp}}\right)^{-1} \]

\[ X(E) = n_D h c m_p \frac{H^2}{D_0} \left(\frac{E}{eZ}\right)^{-\delta} \]

\[ E_M > 1 \text{ PeV} \]

\[ E_{\text{SN}} = 10^{51} \text{ erg} \]

\[ R = 1/30 \text{ yrs} \]

\[ v_0 = 15.700 \text{ km/s} \]
$E_{SN} = 2 \times 10^{51} \text{ erg}$
$R = 1/110 \text{ yrs}$

$E_M = 3.7 \text{ PeV}$
$\xi_{CR} = 20\%$
$t_0 = 60 \text{ yrs}$
$v_0 = 22.200 \text{ km/s}$
$E_{SN} = 10^{51}$ erg
R = 1/15 yrs

Cardillo, Amato & Blasi 2015
AND SO?

✧ Type II SNRs can accelerate particles up to the knee through the NRH instability

✧ NHR instability leads to the release of a steep power-law spectrum in the ejecta dominated phase → no sharp cut-off!

✧ KASCADE Grande and ARGO data can be fitted with reasonable values of SN parameters.

BUT..

✧ Type II SNRs can accelerate particles up to the knee at very early time → detection problem.

✧ No model that can fit both ARGO and KASCADE-Grande data → need a better data understanding with a consequent theory improvement.
Thank you very much!