Acceleration of Cosmic Rays and Non-Thermal Radiation in Middle-Aged Supernova Remnants

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Gamma and X-ray observations of young SNRs testify that particles are accelerated up to ~ 100 TeV by the diffusive shock acceleration mechanism in Type IIP SNRs.

Rare Type IIb and IIn SNRs can accelerate particles up to PeV energies.

turbulent magnetic field is produced by cosmic ray streaming instability
Middle-aged SNRs \((t > 10^4 \text{ yr})\) in the dense partly ionized interstellar medium

see for reviews: Space Sci, Rev 2013, 178, 599 (Bykov et al.), 2015, 188, 187 (Slane et al.).

Ackermann et al. 2013

Spectral shapes at < 1 GeV favors hadronic origin of gamma-emission. Spectra steepens above few GeV that is natural because of the MHD wave damping on neutrals: \(E_{\text{max}} \approx u_8 n_H^{1/2} n_n^{-1} \text{ TeV}\) Drury et al 1996, Ptuskin & Zirakashvili 2003.

Very high energy protons are not accelerated at present but why do not we see the cutoffs?
IC433 images
Veritas, Fermi LAT
Humensky et al 2015
multi-TeV protons accelerated earlier are probably confined yet in the SNR shell

W28 images
HESS, Fermi LAT
Hanabata et al 2014

The code was used for explanation of energy spectrum and composition of Galactic cosmic rays Ptuskin, Zirakashvili, Seo 2010, 2013; explanation of IceCube observations through the production of very high energy neutrinos in extragalactic Type IIIn SNRs Zirakashvili, Ptuskin 2016.


The present version includes
• spherically symmetric hydrodynamic eqs.;
• diffusion-convection transport equation for cosmic rays with particle injection at forward and reverse shocks and the energy loss term;
• eq. for MHD wave pressure with dissipation on neutrals;
• circumstellar neutral gas density \( n_n \) is constant (without study of gas ionization by radiation and the gas heating in shock precursor).

Cosmic ray diffusion with Bohm scaling:

\[
D = D_B \quad \text{downstream}, \\
D = D_B \frac{(P_{m0} + P_m)}{P_m} \quad \text{upstream}, \\
D_B = \frac{cvp}{3ZeB} \quad \text{Bohm diffusion coefficient}, \\
B = \left(8\pi(P_{m0} + P_m)\right)^{1/2}, \quad P_m = \frac{(\delta B)^2}{8\pi}, \quad P_{m0} = \frac{B_0^2}{8\pi}.
\]
Eqs. for gas and wave pressures include radiative cooling and wave damping on neutrals

\[ P_c = 4\pi \int dpp^3 vN / 3, \]
\[ P_m = (\delta B)^2 / 8\pi. \]
\[ \gamma_g = 5 / 3, \quad \gamma_m = 3 / 2 \]

\[ V_{Ar} = V_A / \sqrt{3}; \]
\[ h_m = 1 \text{ at } P_m < 10P_{m0}, \quad \text{McKenzie,Voelk1982} \]
\[ h_m = 0.5 \text{ at } P_m > 10P_{m0}; \quad \text{Beresnyak,Li 2014} \]
\[ \Gamma_m = 0, \quad V_a = 0 \text{ downstream.} \]

\[ w = u + \xi_A V_{Ar}, \]
\[ \xi_A = 1 / -1 \text{ upstream of forward/reversed shocks,} \]
\[ \xi_A = 0 \text{ downstream of forward and reverse shock at } R_b < r < R_f. \]
Physical parameters of SNRs W28 (G6.71-0.05), W44 (G34.7-0.4) and IC433 (G189.1+3.0, 3C157).

Most probably, they are Type IIP supernovae exploded in the clumpy molecular clouds and evolve primarily in the interclump medium with the gas density $n_H = 5-25 \text{ H atoms cm}^{-3}$ (Chevalier 1999).

<table>
<thead>
<tr>
<th></th>
<th>$d$</th>
<th>$R_f$</th>
<th>$E_{SN}$</th>
<th>$M_{ej}$</th>
<th>$n_H$</th>
<th>$n_n$</th>
<th>$K_{ep}$</th>
<th>$T$</th>
<th>$V_f$</th>
<th>$B_f$</th>
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<tbody>
<tr>
<td>W28</td>
<td>1.9</td>
<td>13.4</td>
<td>1.3</td>
<td>6.8</td>
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<td>0.2</td>
<td>0.008</td>
<td>37</td>
<td>121</td>
<td>79</td>
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<tr>
<td>W44</td>
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<td>12.4</td>
<td>1.6</td>
<td>7.1</td>
<td>6.0</td>
<td>0.3</td>
<td>0.006</td>
<td>33</td>
<td>130</td>
<td>102</td>
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<tr>
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<td>1.5</td>
<td>9.9</td>
<td>0.9</td>
<td>6.3</td>
<td>3.0</td>
<td>0.15</td>
<td>0.008</td>
<td>17</td>
<td>196</td>
<td>110</td>
</tr>
</tbody>
</table>

calculated from observed gamma-ray fluxes, spectral shapes of gamma-ray emission, observed radio fluxes
SNR W28

\[ \log(P_c/\rho_0 \dot{R}_f^2), \log(P_g/\rho_0 \dot{R}_f^2), \log(P_m/\rho_0 \dot{R}_f^2) \]

\[ u, 10^2 \text{ km s}^{-1}, \log(p/\rho_0), \log(T_e/\text{keV}) \]

\[ T=37000 \text{ yr} \]

run-away particle spectrum

integrated over the volume
particle spectrum

\[ n_f=10^{-3} \]

Photons from cold outer shell

X-rays from hot interior

\[ d=1.9 \text{ kpc}, E_{SN}=1.3 \cdot 10^{51} \text{ erg}, M_{ej}=6.8 \text{ M}_{\odot}, t=37 \text{ kyr}, n_H=4.0 \text{ cm}^{-3}, n_n=0.2 \text{ cm}^{-3} \]

\[ V_r=120 \text{ km/s}, B_r=8 \times 10^{-5} \text{ G}, K_{ep}=0.008 \]
calculated and observed spectra of electromagnetic radiation

W44

\[ d=2.8 \text{ kpc}, E_{SN}=1.6 \cdot 10^{51} \text{ erg}, M_{ej}=7.1 \text{ M}_{\odot}, t=33 \text{ kyr}, n_{n}=6.0 \text{ cm}^{-3}, n_{r}=0.3 \text{ cm}^{-3} \]
\[ V_{r}=130 \text{ km/s}, B_{r}=10^{-4} \text{ G}, K_{ep}=0.006 \]

IC443

\[ E_{SN}=0.9 \cdot 10^{51} \text{ erg}, M_{ej}=6.3 \text{ M}_{\odot}, t=17 \text{ kyr}, n_{H}=3.0 \text{ cm}^{-3}, n_{n}=0.15 \text{ cm}^{-2} \]
\[ V_{r}=200 \text{ km/s}, B_{r}=1.1 \cdot 10^{-4} \text{ G} \]
Conclusion

The main part of gamma emission in IC 443, W28, W44 supernova remnants is produced by energetic protons via $pp$ collisions. The gamma emission at GeV energies is generated by particles recently accelerated at the forward shock. Their energies are determined by the neutral damping of MHD waves upstream of the shock. High energy gamma-ray emission is produced by particles accelerated earlier when the shock speed was higher. The confinement of these particles is very efficient because of the Bohm-like diffusion in the ionized remnant interior. Thus, the damping of MHD waves on neutrals in the shock precursor naturally explains the gamma-ray spectra in the middle-aged SNRs.

[different mechanisms of production of steep power law “tails” in gamma ray spectra were suggested by Malkov et al 2011 and Cardillo et al 2016]