Non-linear acceleration at supernova remnant shocks and the hardening in the cosmic ray spectrum

S. Recchia
S. Gabici

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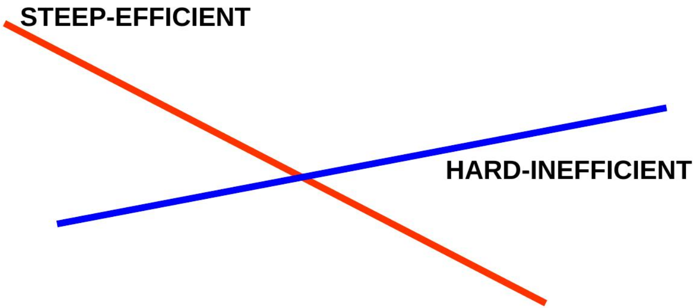
Overview

Observed spectral hardening in the p and He spectra

NLDSA revisited

- dispersion in the spectral slope of cosmic rays
- steeper spectra corresponding to larger acceleration efficiencies



Cosmic ray spectral hardening

...data

- Proton and He spectra (and heavier)
- $\sim 200 - 300$ GeV
- $\Delta\gamma \sim 0.1 - 0.2$
- ATIC-2, PAMELA, CREAM, AMS-02

...possible explanations

- break in the CR diffusion coefficient
- the effect of a nearby source
- NLDSA: concavity and reverse shocks
- distinct populations of CR sources

Cosmic ray acceleration

efficient magnetic field amplification detected in several SNRs

- necessary for acceleration of CRs to the knee

observation of γ-rays in SNRs

- large dispersion in the slope of CRs in SNRs
- steep CR spectra $\propto E^{-2.1} - E^{-2.5}$

in contrast with standard predictions of NLDSA

- test particle DSA predicts $\propto E^{-2}$
- CR pressure generate precursor in the upstream region
- concave spectra, hard ($\propto E^{-1.5}$) above few GeV
- large acceleration efficiencies

NLDSA revisited

Caprioli (2012)

- NLDSA
- + B amplification by CR streaming instability
- + B in the jump condition at the shock
- + velocity of Alfvèn waves (computed in amplified B)

...found

- B amplification self-regulating mechanism
- maximum $\xi_{CR} \approx 30\%$
- compression factor close to 4 (test particle limit of DSA)
- spectra close to power laws
- spectral slope $\sim 2.1 - 2.6$
- steeper spectrum at larger ξ_{CR}

NLDSA revisited: simple calculation

- ξ_{CR} input parameter $\sim 0.03 - 0.3$
- small shock modification neglected ($\xi_{CR} \lesssim 30\%$)
- power law spectrum
- amplified B by CR streaming instability

compression factor R= u_1/u_2

$$\frac{M_1^2}{2}\frac{\frac{\gamma+1}{R}-(\gamma-1)}{1+\Lambda_B} \approx 1$$

compression factor + v_A

$$R_{eff} = \frac{u1 - v_{A1}}{u2} + R\left(1 - \frac{1}{M_A}\right)$$

B amplification $M_{A1} = u_1/v_{A1}$

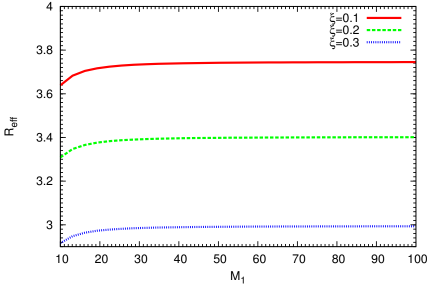
$$M_A^2 = \frac{4}{25}\frac{\left[1-(1-\xi_{CR})^{\frac{5}{4}}\right]^2}{(1-\xi_{CR})^{\frac{3}{4}}}$$

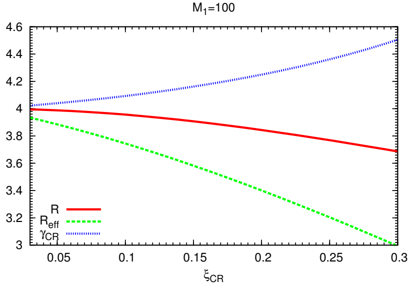
$$\Lambda_B = W\left[1 + R\left(\frac{2}{\gamma} - 1\right)\right]$$

$$W = \frac{\gamma}{2}\frac{M_1^2}{M_A^2}$$

Results: $\gamma(\xi_{CR})$

$$\gamma_{CR} = \frac{3R_{eff}}{R_{eff} - 1}$$





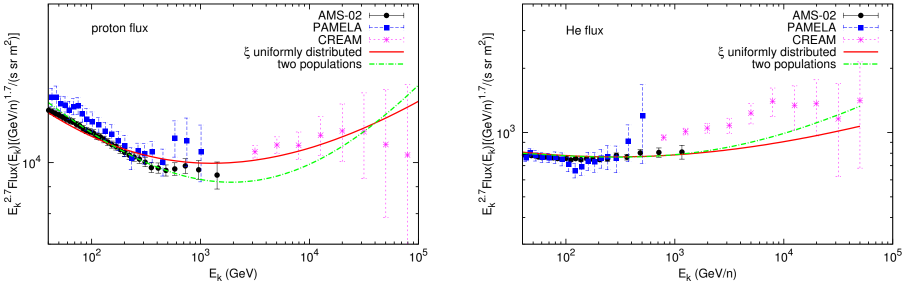
Results: comparison with data

- diffusive propagation $D(R) = D_0(R/\mathrm{GV})^{\delta}$
- $+$ spallation for He
- spectral slope of accelerated particles depends on ξ_{CR}
- case with ξ_{CR} flat distributed in $\sim 0.03 - 0.3$
- case with two populations of sources with $\xi_{CR} = 3\%$ and 30%

Results: comparison with data

$\delta \sim 0.4$ $\quad D_0 \sim 8 \times 10^{28} \mathrm{cm}^2/\mathrm{s}$

$H \sim 4\,\mathrm{kpc}$ $\quad$ grammage $\sim 10 - 12\ \mathrm{g/cm}^2$ at 10 GeV/n



Conclusions

- Revisited NLDSA
- dispersion in the CR acceleration efficiency and spectral slope
- steeper spectra correspond larger efficiencies
- CR spectra at the sources in agreement with $\gamma-$ray data in SNRs
- spectral hardening in the proton and helium spectrum can be naturally accounted for