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Time Evolution of Parallel Shock Accelerated Particle Spectrum Bend-over Energy

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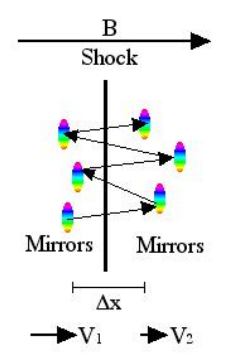
Outline

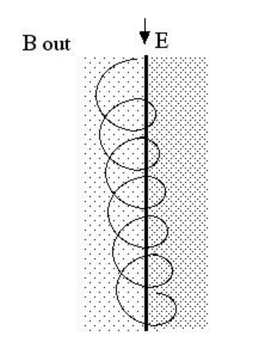
Shock acceleration mechanism

diffusive shock acceleration (DSA) theory explains the power-law cosmic-ray spectrum.

first-order Fermi acceleration(FFA)



shock drift acceleration(SDA)



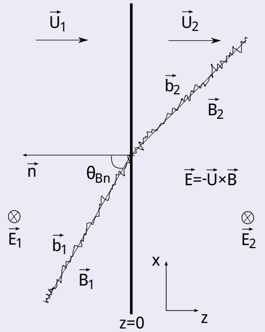
Shock acceleration model

The control equation:

$$\frac{d\boldsymbol{p}}{dt} = q[\boldsymbol{E}(\boldsymbol{r}, t) + \boldsymbol{v} \times \boldsymbol{B}(\boldsymbol{r}, t)], \tag{1}$$

where $\boldsymbol{E} = -\boldsymbol{U} \times \boldsymbol{B}$, and $\boldsymbol{B}(x, y, z) = \boldsymbol{B}_0 + \boldsymbol{b}(x, y, z)$.
The turbulent magnetic field (Matthaeus et al. 1990, Zank & Matthaeus 1992, etc.):

$$\boldsymbol{b}(x, y, z) = \boldsymbol{b}_{\text{slab}}(z) + \boldsymbol{b}_{\text{2D}}(x, y) \tag{2}$$



- left: upstream
- right: downstream

Bend-over energy model

The average acceleration time for each cycle of a particle crossing of the shock front (Drury, 1983, Rep. Prog. Phys.) $\Delta t = \frac{4}{v}\left(\frac{\kappa_1}{U_1} + \frac{\kappa_2}{U_2}\right)$

average increased momentum: $\Delta p = \frac{4}{3}\frac{U_1 - U_2}{v} p$

the average momentum change:

$$\frac{dp}{dt} \approx \frac{\Delta p}{\Delta t} = \frac{1}{3}(U_1 - U_2)\left(\frac{\kappa_1}{U_1} + \frac{\kappa_2}{U_2}\right)^{-1} p \tag{3}$$

Assume the diffusion coefficient

$$\kappa_i = \kappa_{Ri}\left(\frac{p}{p_{ref}}\right)^{\xi_i} \tag{4}$$

Bend-over energy model

$$\left(\frac{p_{acc}}{p_{ref}}\right)^{\xi_1} + g\left(\frac{p_{acc}}{p_{ref}}\right)^{\xi_2} = \left(\frac{p_0}{p_{ref}}\right)^{\xi_1} + g\left(\frac{p_0}{p_{ref}}\right)^{\xi_2} + \frac{1}{3}\frac{U_1^2}{r\kappa_{R1}}\xi_1(r-1)t, \quad (5)$$

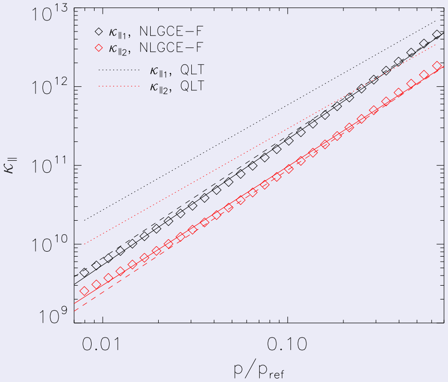
$g = \xi_1 \kappa_{R2} r / \left(\xi_2 \kappa_{R1}\right)$. $\xi_1 = \xi_2 \equiv \xi$

$$p_{acc} = p_{ref}\left[\left(\frac{p_0}{p_{ref}}\right)^{\xi} + \frac{U_1^2 \xi}{3}\frac{r-1}{r(\kappa_{R1} + r\kappa_{R2})}t\right]^{1/\xi}. \quad (6)$$

bend-over energy E_0:

$$E_0 \equiv E_{acc} = \sqrt{p_{acc}^2 c^2 + E_p^2} - E_p. \quad (7)$$

Parallel diffusion coefficients

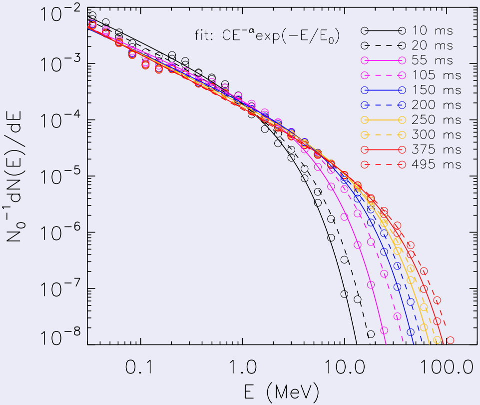


		upstream	downstream
NLGCE-F	ξ_i	1.60	1.51
	$\kappa_{Ri}(m^2/s)$	8.48×10^{12}	3.10×10^{12}
QLT	ξ_i	1.33	1.33
	$\kappa_{Ri}(m^2/s)$	1.26×10^{12}	6.32×10^{12}

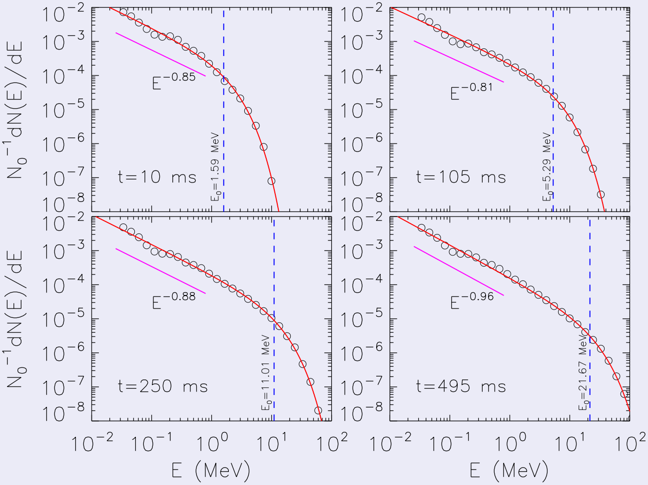
The accelerated spectrum from the simulations

Main parameters

$B_{10} = 50$ G, $U_1 = 3.3 \times 10^6$ m/s, $s = 3.85$, $\theta_{Bn} = 0°$, $\lambda_{slab} = 10^3$ m, $E_{\rm in} = 30$ keV, $(b/B_0)^2 = 0.19, 0.38$. $z_0 = -1.1 r_g$ isotropically injected, $t_{acc} = 500$ ms.



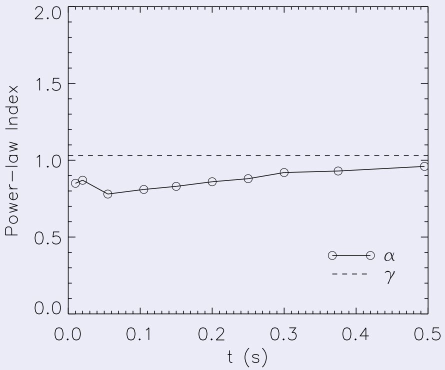
Fits of accelerated spectra at different times



red fit line: $j(E) = cE^{-\gamma}\exp(-E/E_0)$

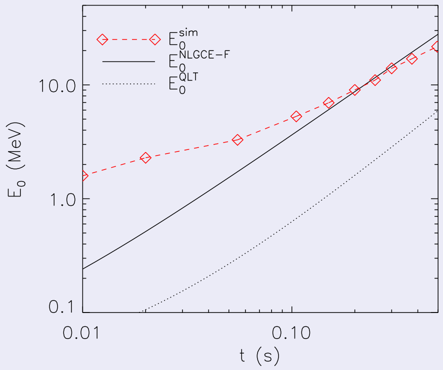
Comparisons between the simulations and theoretical results

simulated, theoretical index α, γ



$\gamma = (s+2)/(2s-1)$ (DSA theory, s is the shock compression ratio.)

time evolution of bend-over energy



red: simulation,
QLT: Jokipii, ApJ, 1966
NLGCE-F: Qin & Zhang ApJ, 2014

Conclusions

- The accelerated particle spectrum at the parallel shock: a power-law with exponential tail.
- Bend-over energy from the simulations fits better to the model result based on the NLGCE-F model than on QLT. This indirectly illustrates that the NLGCE-F model is a better diffusion model than QLT.

- Results published in
Study of time evolution of the bend-over energy in the energetic particle spectrum at a parallel shock, F.-J. Kong, G. Qin, et al., ApJ, 877, 97, 2019

Thank you very much