Coronal Shock Acceleration of Protons and Minor Ions In Self-generated Turbulence

Battarbee, M.[1,2], Laitinen, T.[2], Vainio, R.[3]

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[1] markus.battarbee@utu.fi
[2] Department of Physics and Astronomy, University of Turku, Finland
[3] Department of Physics, University of Helsinki, Finland

Motivation

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- How do CME/shock properties affect particle entrapment?
- *What is the evolution of swept up minor ion populations?*

Upstream simulation of particles

- Numerically solve the Fokker-Planck equation
- Single particle propagation using guiding centre approximation in 1D
- Pitch-angle independent resonance condition $f_{res} = f_{cp} \frac{u_{sw} + v_A}{v}$
- Scattering frequency $\nu = \pi^2 f_{cp} \frac{fP(f)}{B^2}$
- Focusing due to adiabatic invariance, isotropic scattering from turbulence

Upstream simulation of turbulence

- Waves transported as spectra with
  $\frac{\partial P}{\partial t} + \frac{B v_A}{V} \frac{\partial}{\partial r} \left(\frac{V^2}{B v_A} P \right) = \Gamma P + \frac{\partial}{\partial f} D_{ff} \frac{\partial P}{\partial f}$
- Wave growth from particle scatterings: $\Gamma = \pi^2 f_{cp} \frac{p S_p(r,p,t)}{n v_A}$
- Ad-hoc linear frequency diffusion mimics wave-wave interactions
  $D_{ff} = \frac{V}{1\,\mathrm{AU}} f_b^{-2/3} f^{8/3}$
  which modify the spectral shape to a broken power law

Shock & simulation parameters

- Step-profile shock, plasma compression ratio 4
- Parallel shock
- Shock-normal velocity of $V_s = 1250$, 1500 or 1750 km/s.
- Cross helicity of -1 (upstream) and 0 (downstream).
- Particle mean free path (10 keV P+) is 1 AU.

Injected particles

Model for realistic particle injection

- Radial density & temperature profiles from Cranmer & Ballegooijen, 2005.
- Simulation follows a shock through the solar corona (from 1.5 $R_\odot$), sweeping up ambient particles.
- Ambient particle velocities follow a kappa distribution: $\kappa = 6 \ldots 2$ between $1.5 \ldots 3\ R_\odot$.

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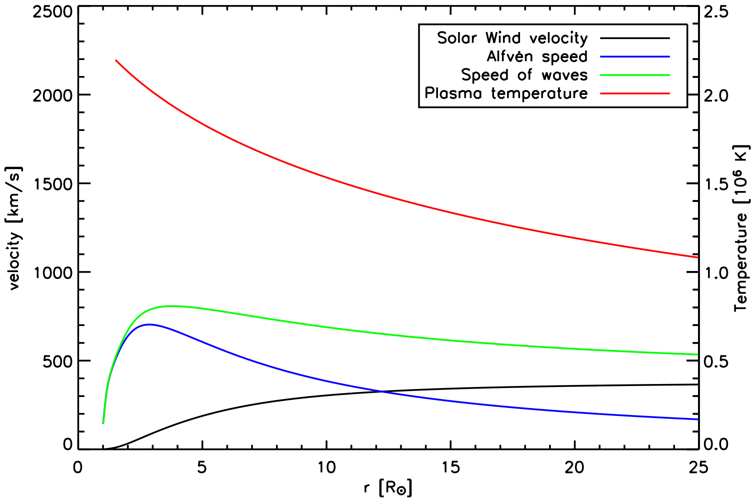
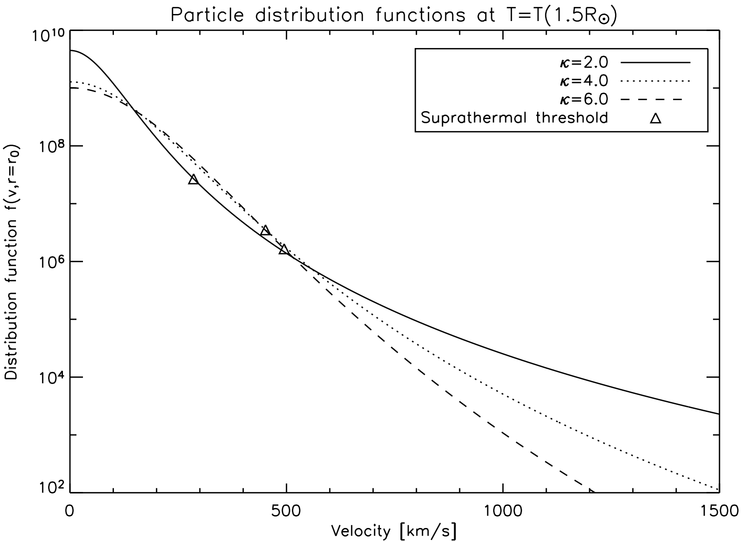
Minor ion abundances

- P+: *1·10*$^{-2}$ of given density
- He3: *1,6·10*$^{-5}$ of P+
- He4: *0,04* of P+
- Fe56: *1,0·10*$^{-4}$ of P+
- Fe is partially ionized to *Q=14*

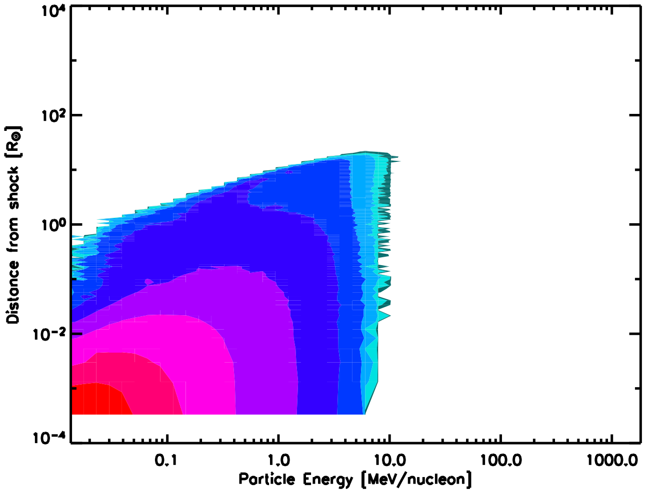
Model velocities & temperature



Sample κ-distributions



Proton intensities, 1.0 magnitude intervals ($V_s = 1500 km/s$, 550 s)



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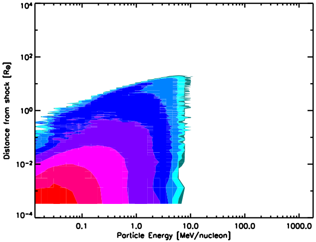
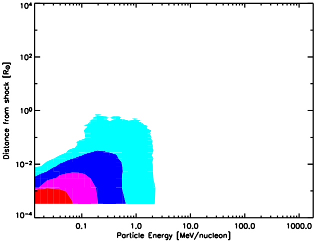
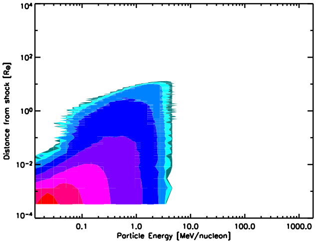


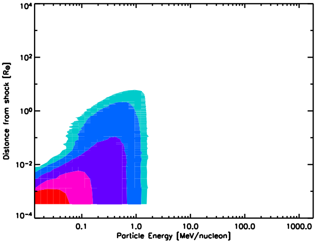
(a) Suprathermal P+



(b) He3

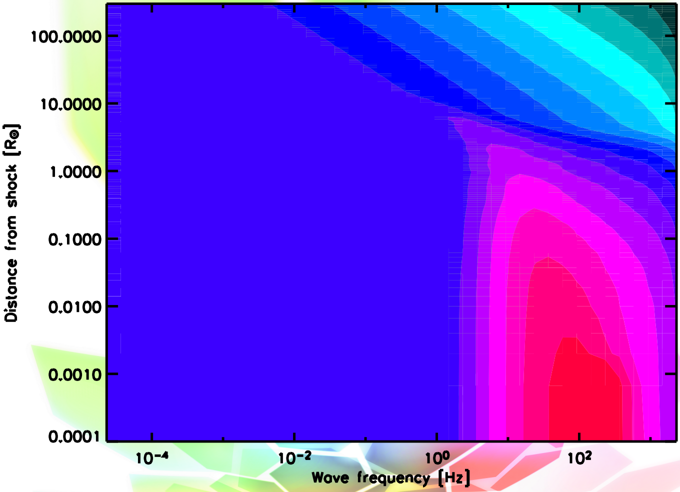


(c) He4

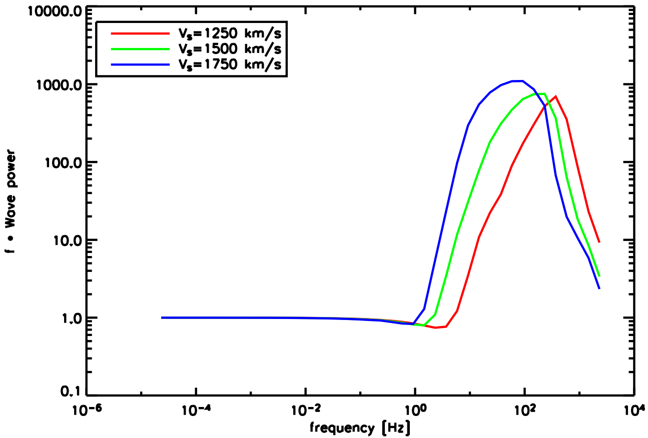


(d) Fe56, Q=14

Log Wave power, 0.5 contour interval ($V_s = 1500 km/s$, 550 s)



Wave power spectra at the shock



Results

Expectations

- A faster shock leads to increased acceleration.
- Increased acceleration leads to increased trapping and a *bootstrapped process*.

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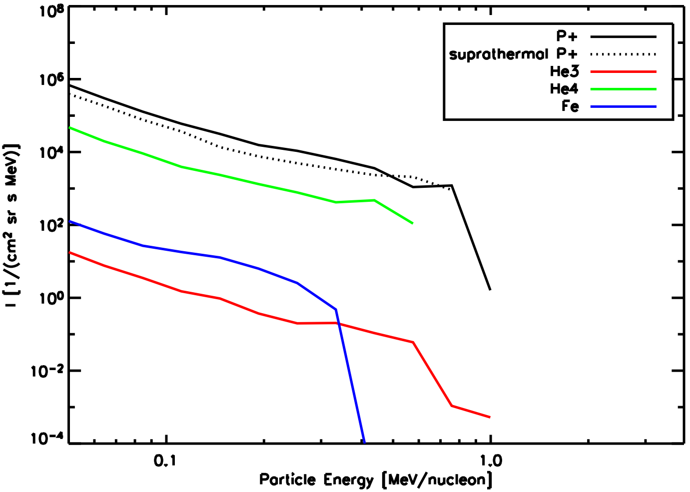
Questions

- How hard are the particle spectra?
- How is the maximum attained energy (per nucleon) proportional to the charge/mass ratio?
- How does the source ion abundance correlate with accelerated particles?

Particle spectra ($V_s = 1250 km/s$, 550 s)



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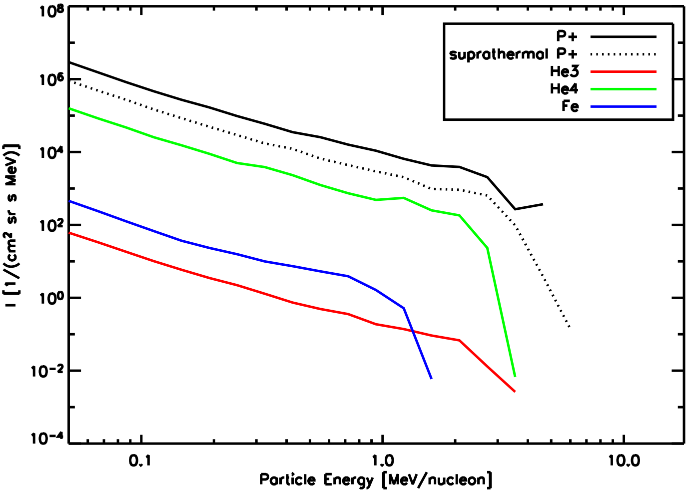
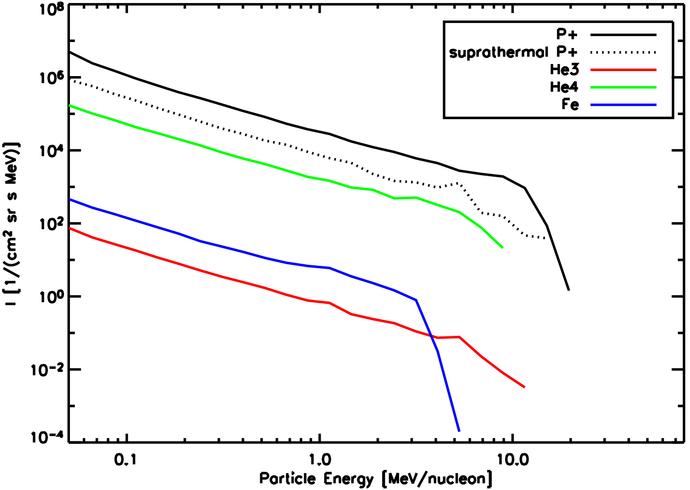
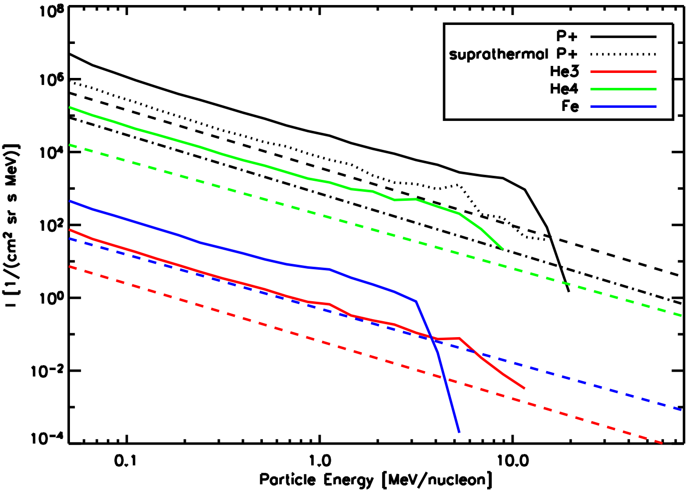


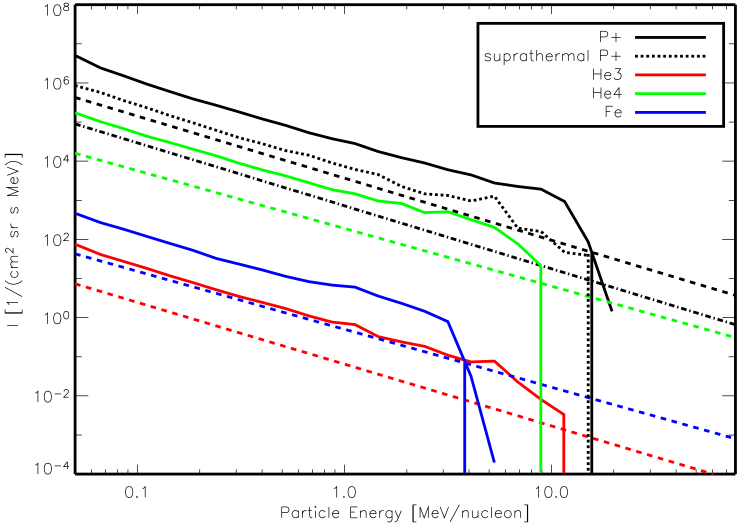
Particle spectra ($V_s = 1750 km/s$, 550 s)



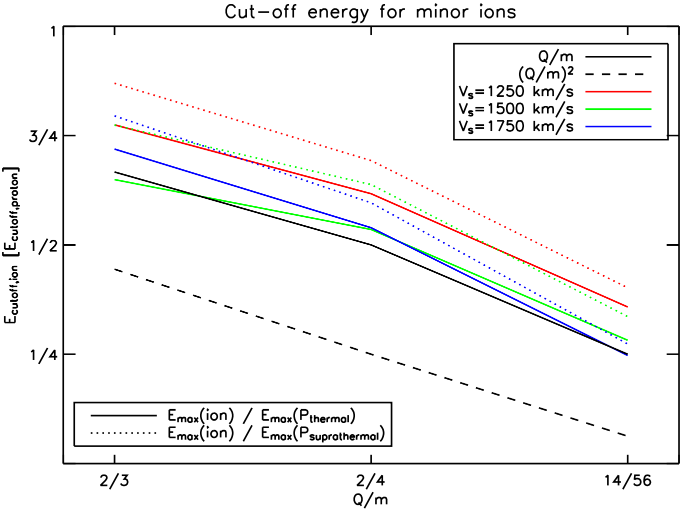
Spectra & power laws ($V_s = 1750 km/s$)



Spectra, power laws & energy cutoffs



Energy cutoffs



SEP power laws & ion abundances

Power laws, averaged over time steps 549 . . . 559

	P+	P(suprathermal)	He3	He4	Fe
$V_s = 1250 km/s$	-2.77	-2.70	-2.76	-2.78	-2.90
$V_s = 1500 km/s$	-2.00	-1.94	-1.94	-1.90	-1.93
$V_s = 1750 km/s$	-1.63	-1.63	-1.57	-1.50	-1.50

Accelerated ion abundances relative to proton abundances

	P+	He3	He4	Fe
Seed pop.	1.0	1.6-05	0.04	1.0e-4
$V_s = 1250 km/s$	1.0	1.16e-05	0.031	1.18e-4
$V_s = 1500 km/s$	1.0	1.15e-05	0.030	1.17e-4
$V_s = 1750 km/s$	1.0	1.13e-05	0.029	1.10e-4

Conclusions

- A high shock-normal velocity leads to greater cutoff energies and harder particle spectra.
- Ion acceleration cut-off energies scale roughly as $(Q/m)^n$, $n \lesssim 1$.
- The accelerated particle population has an increased abundance of Fe and decreased abundance of He3 and He4.
- At high energies, He4 is cut off before He3, which leads to an "enrichment" of He3.

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Future work

- What can we expect to detect far away from the shock (eg. $0.3 \ldots 1$ AU)?
- What can parameter studies of eg. oblique shocks reveal?