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Shock Acceleration in the Solar Corona

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Outline

- Introduction
- Unusual Abundances & Charge States
    - Numerical Modeling
- Ground Level Enhancements
    - Numerical Modeling
- Conclusions and Summary

Introduction

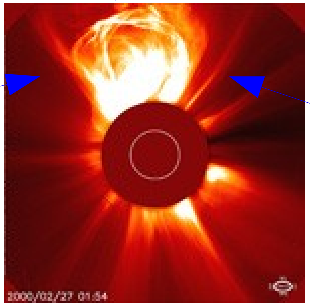
The ions with the highest energies (>100 MeV/nucl) are in general accelerated near the Sun within ~10 mins of the CME onset, culminating in >1 GeV protons producing GLEs.

Kahler (1994) found that 60+ MeV/nucl ions are released into IP space when the CME leading edge reaches 5-15 solar radii.

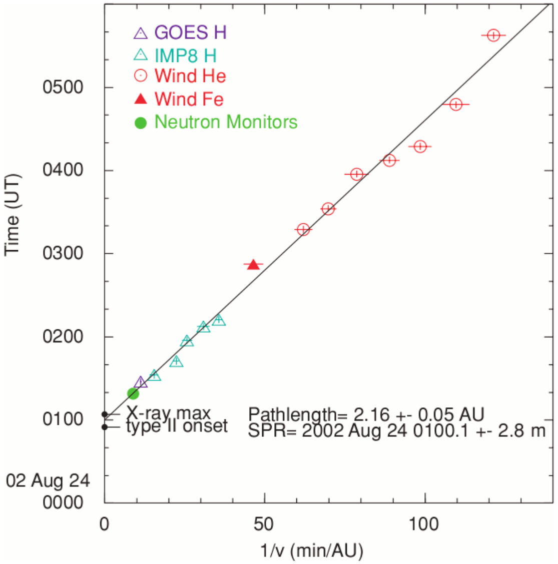
- IP propagation effects neglected
- Leading edge may not be the accelerator

Leading edge at ~5 solar radii

1st connection to observer's field line at flanks



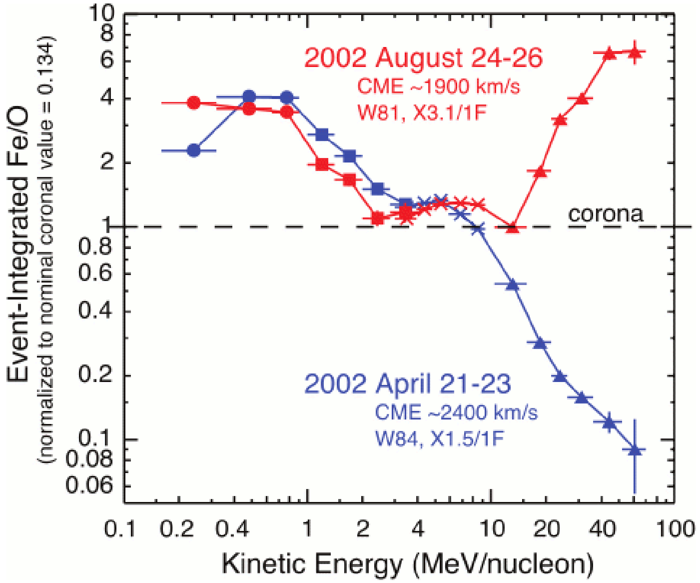
Streamer deflection



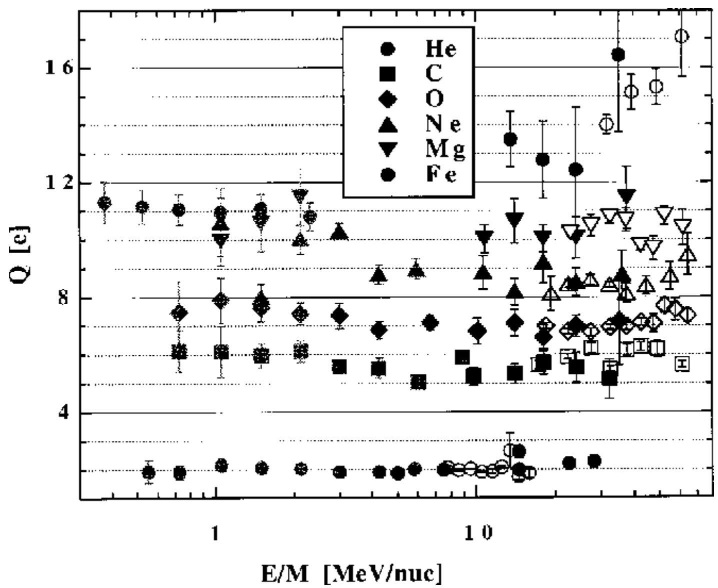
Onset time analysis of a GLE event (Reames 2009).

Abundances & Charge States

Some larger gradual events have abundance ratios and charge states which are typically associated with impulsive events. What is the role of flares?



Fe/O ratios from two similar large gradual SEP events (Tylka et al. 2006).



Ionic charge states observed by SAMPEX (Oetliker et al. 1997).

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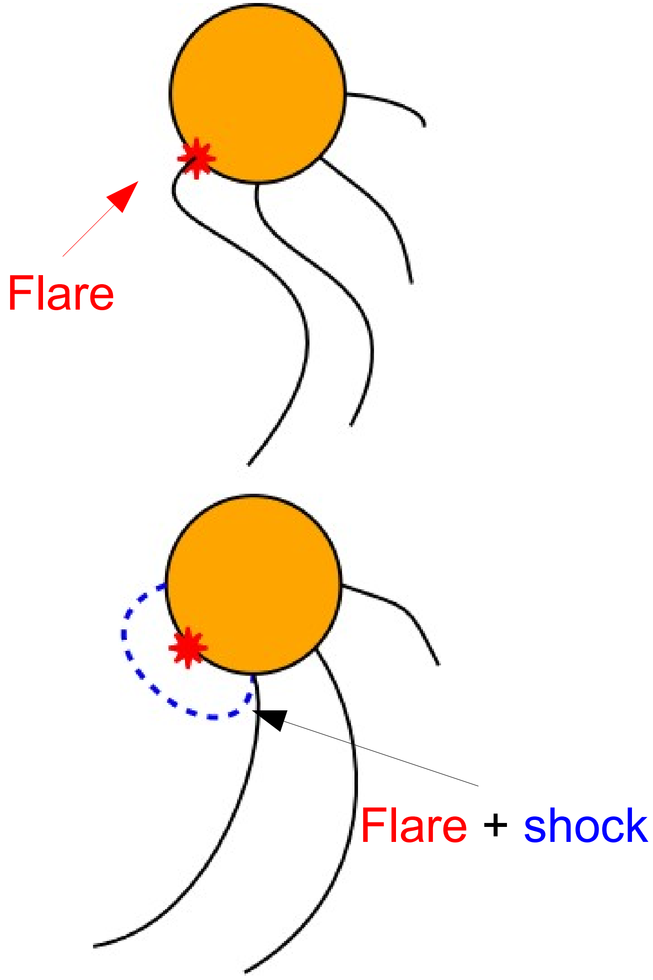
Abundances & Charge States

Two explanations have been proposed:

a) Associated flare accelerates the "unusual" ions, highly disturbed IP field provides the connection to spacecraft (Cane et al. 2003, 2006)

b) CME-driven shock selectively accelerates ions from a compound seed population (Tylka et al. 2005, Tylka & Lee 2006)

Interaction between flares & CMEs? How important is coronal magnetic geometry?

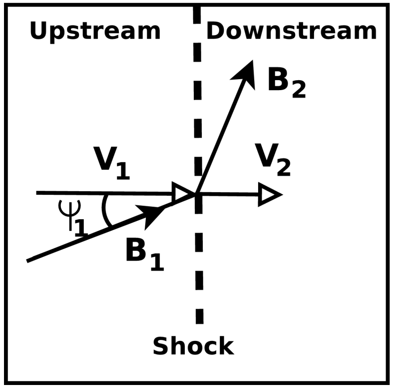


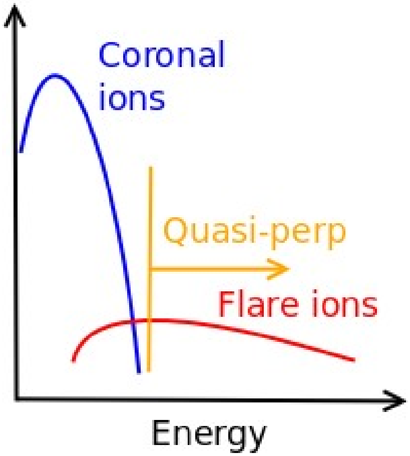
Abundances & Charge States

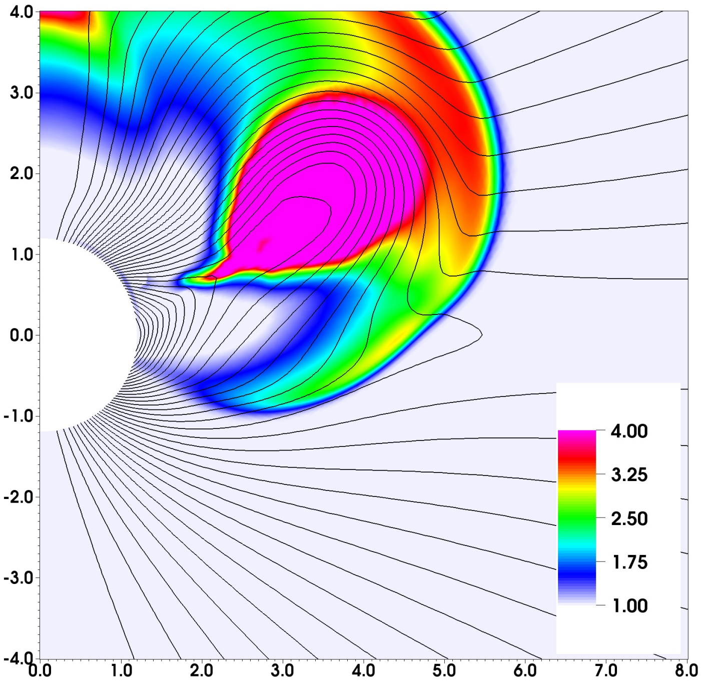
A key aspect of selective DSA is the change of shock obliquity angle over time + quasi-perp. shocks are rapid accelerators.

Energetic flare remnants can overcome the geometry-based injection threshold $v_{thr} \propto V_{shock}/\cos\psi$ more easily than coronal ions.

We modeled this process using a Monte-Carlo simulation using an expanding coronal shock.







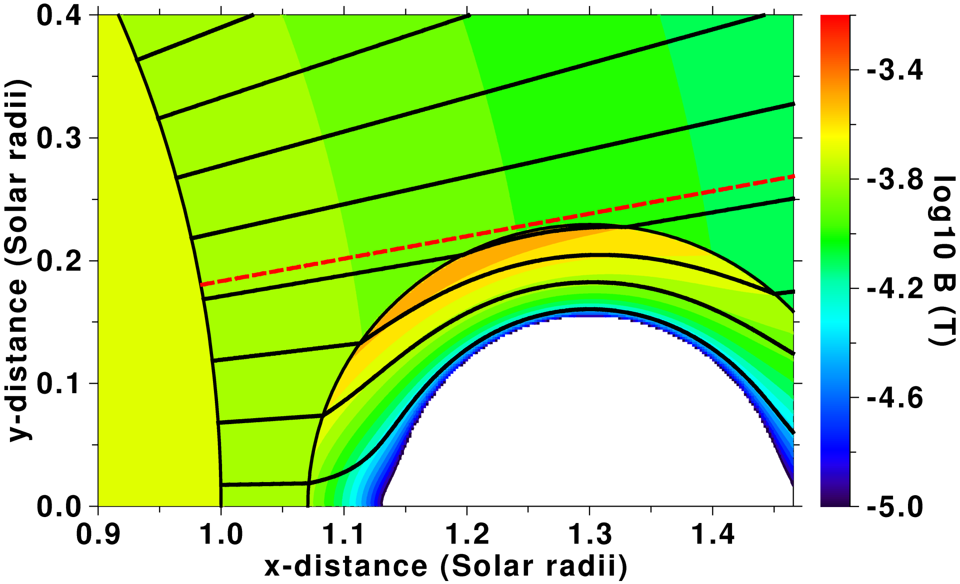
A coronal shock and some field lines, coloring shows the compression ratio (Poster by Pomoell et al.)

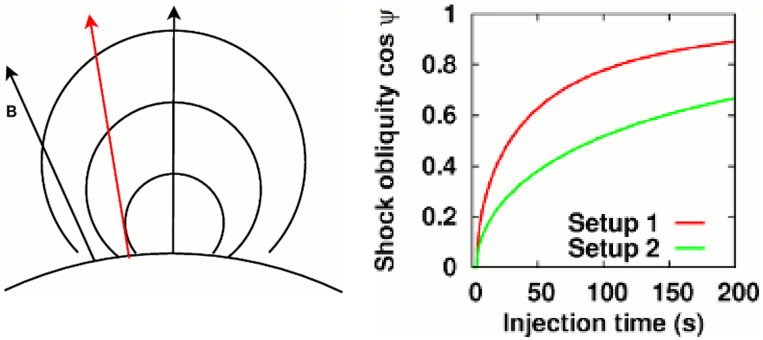
Numerical Modeling

Power law turbulence spectrum $P(k) = P_0(k/k_0)^{-q}$.

Injected ions: mixture of lower energy coronal ions (10-100 keV/nucl) & energetic flare remnants (0.1-1 MeV/nucl) with higher charge states.

Shock speed ~1000 km/s.





Shock obliquity changes due to expansion

Sandroos & Vainio (2007, 2009)

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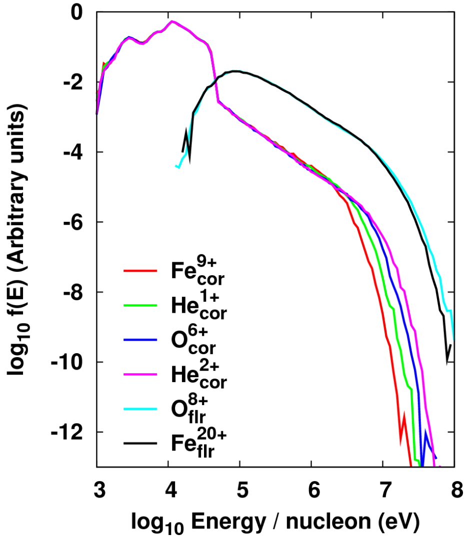
Numerical Modeling

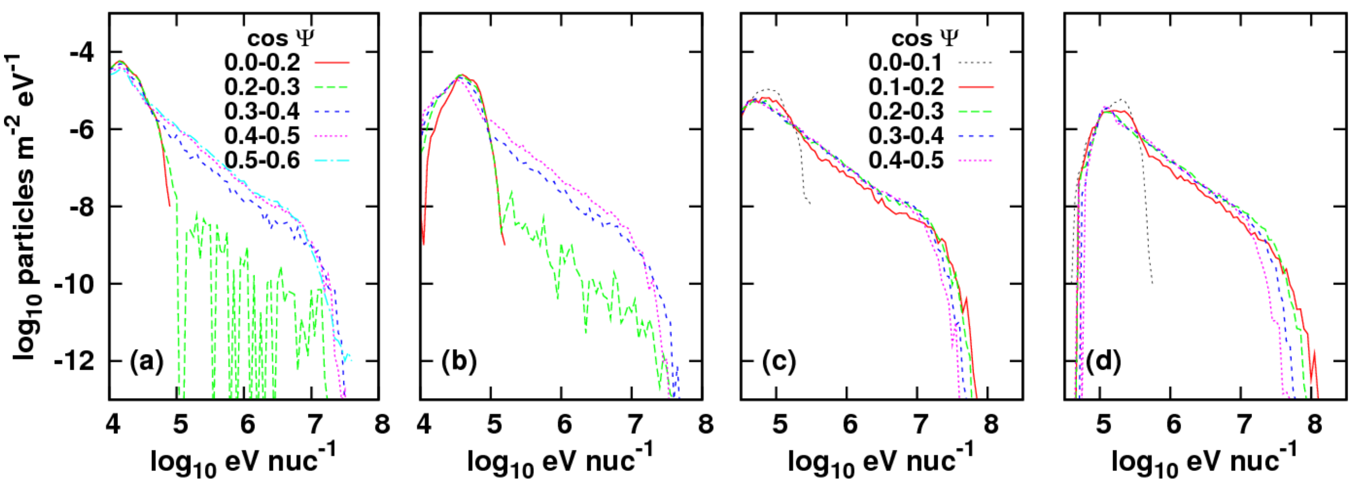
Fluence spectra are power laws with rigidity-dependent cutoffs.

Injection of coronal ions stops when shock obliquity angle exceeds ~80 deg.



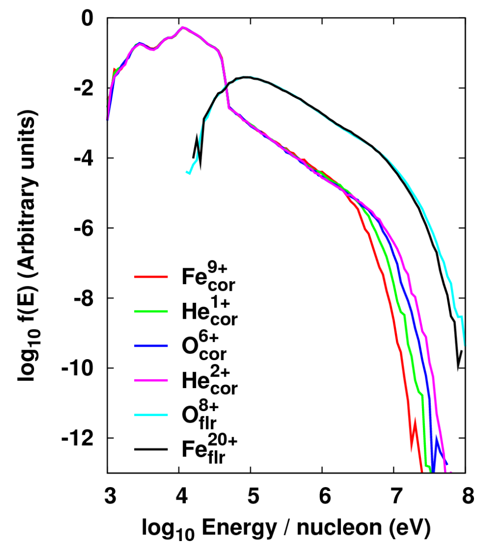
Coronal ions

Flare ions



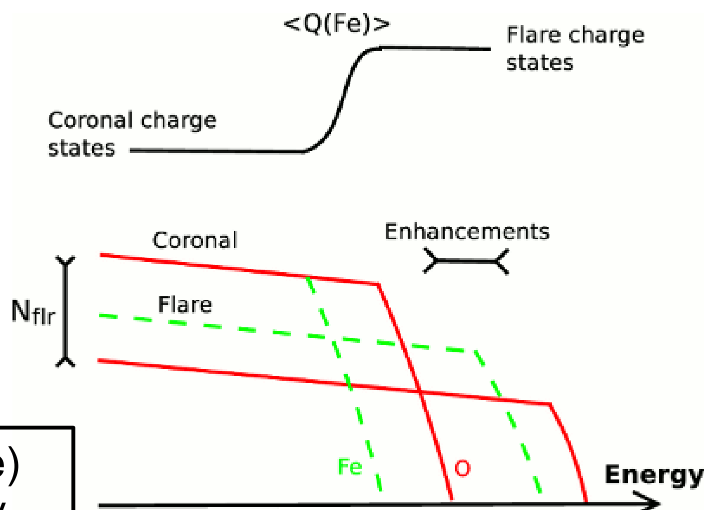
Sandroos & Vainio (2007, 2009)

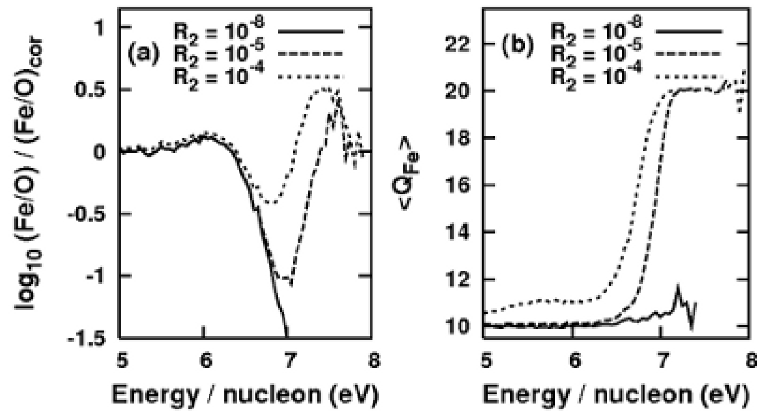
Numerical Modeling



Observed fluence spectra are constructed from the individual ion spectra.

Ratio of coronal to flare ions R2 is a free parameter.





Elevated Q(Fe) does not imply elevated Fe/O

Sandroos & Vainio (2007, 2009)

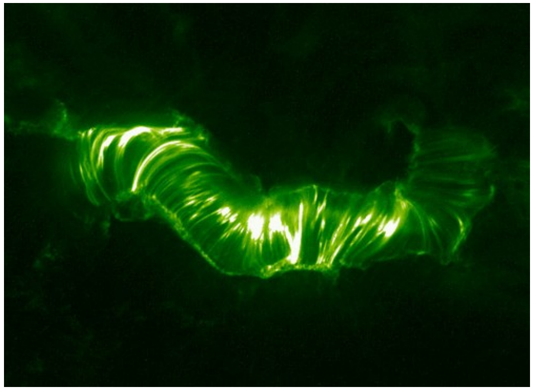
Ground Level Enhancements

GLEs are the most energetic SEP events. They are associated with the fastest CMEs (avg. >1800 km/s) and X-class flares (Gopalswamy et al. 2005). Numerous timing studies (Kahler et al. 2003, Gopalswamy et al. 2005, Tylka et al. 2003, Reames 2009a,b) indicate that

- GLE protons are released when CME leading edge is at 2-4 solar radii
- Type II radio bursts precede the release times by several minutes

GLEs often occur from an active region that has previously produced a SEP event, even with modest M-class flares and ~800 km/s CMEs (Cliver 2006)

- Energetic seed ions available
- Enhanced levels of turbulence



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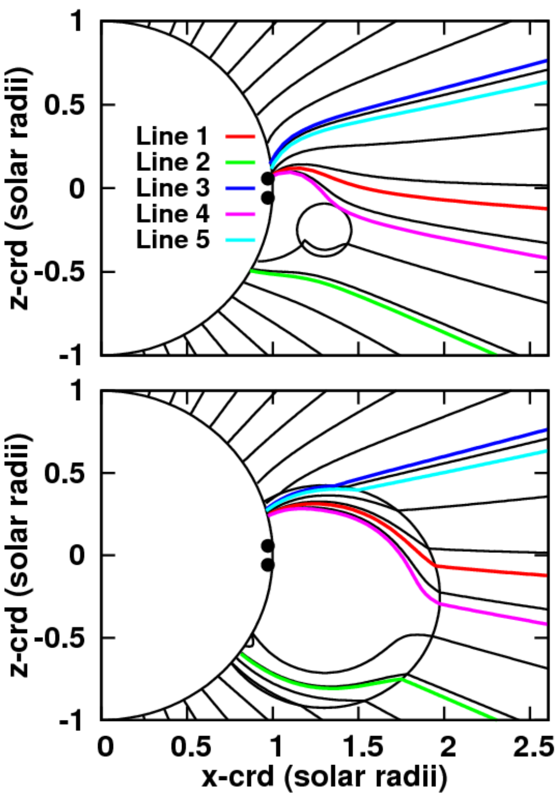
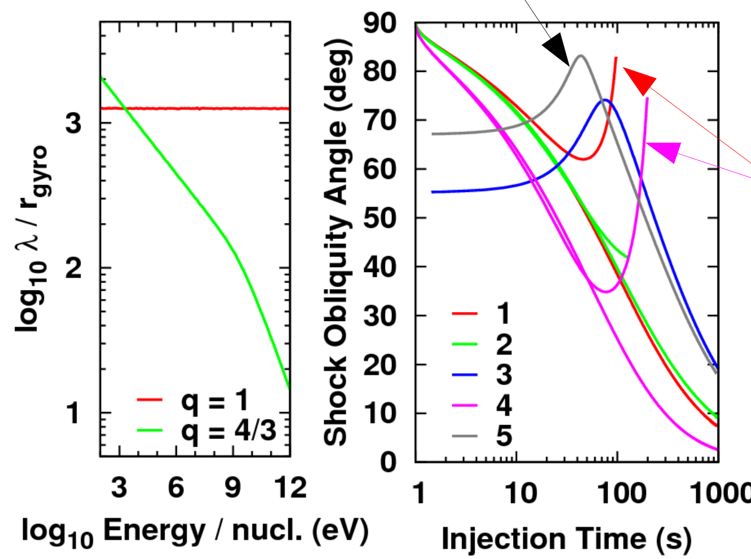
Ground Level Enhancements

Bipolar active region is assumed to launch a CME driving a coronal shock



Quasi-perp. phase after injection onset



At the surface

Acceleration studied on selected field lines (1-5)

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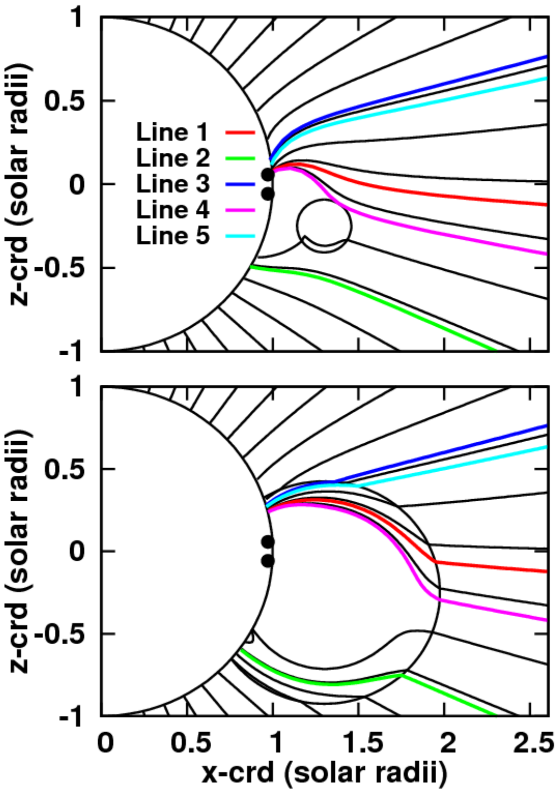
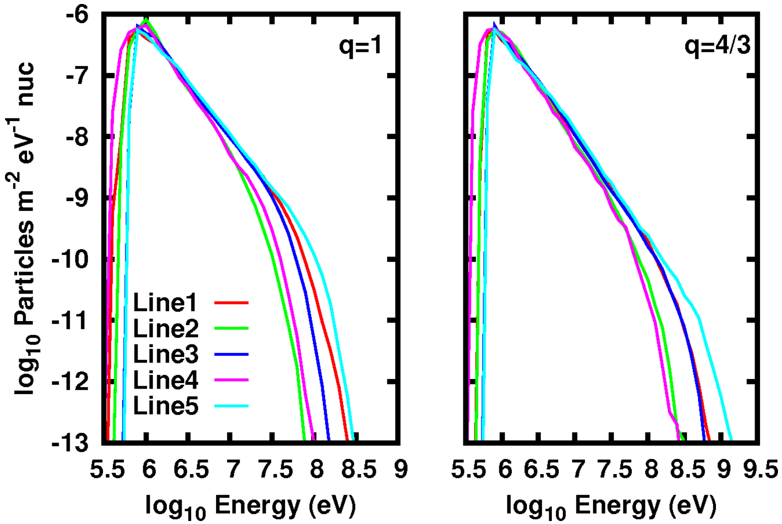
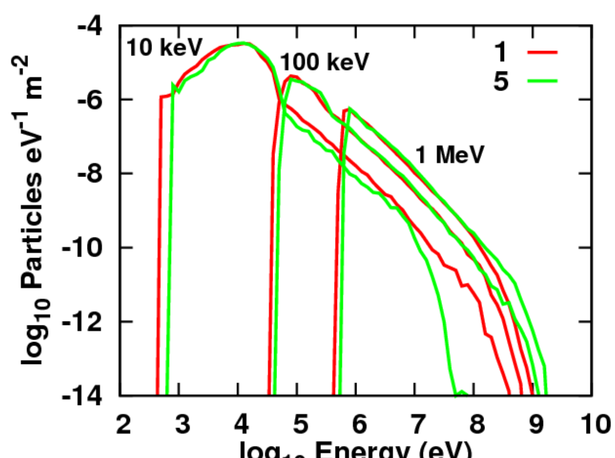
Ground Level Enhancements





L2: Cutoff ~10 MeV

L5: Energy > 1 GeV



High energy seed ions are needed!

Sandroos & Vainio (2009)

Conclusions and Summary

Coronal magnetic geometry has a significant impact on the efficiency of DSA:

- Acceleration into higher energies
- Quasi-perpendicular regions can explain variability in high energy abundance ratios and charge states
- Important aspect of SEP modeling

Preconditioning by preceding activity can turn a “regular” event into a GLE:

- Energetic seed ions + elevated turbulence
- Favorable geometry
- Many special requirements → rare

Important to know the properties of suprathermal populations