High energy particles from the Sun

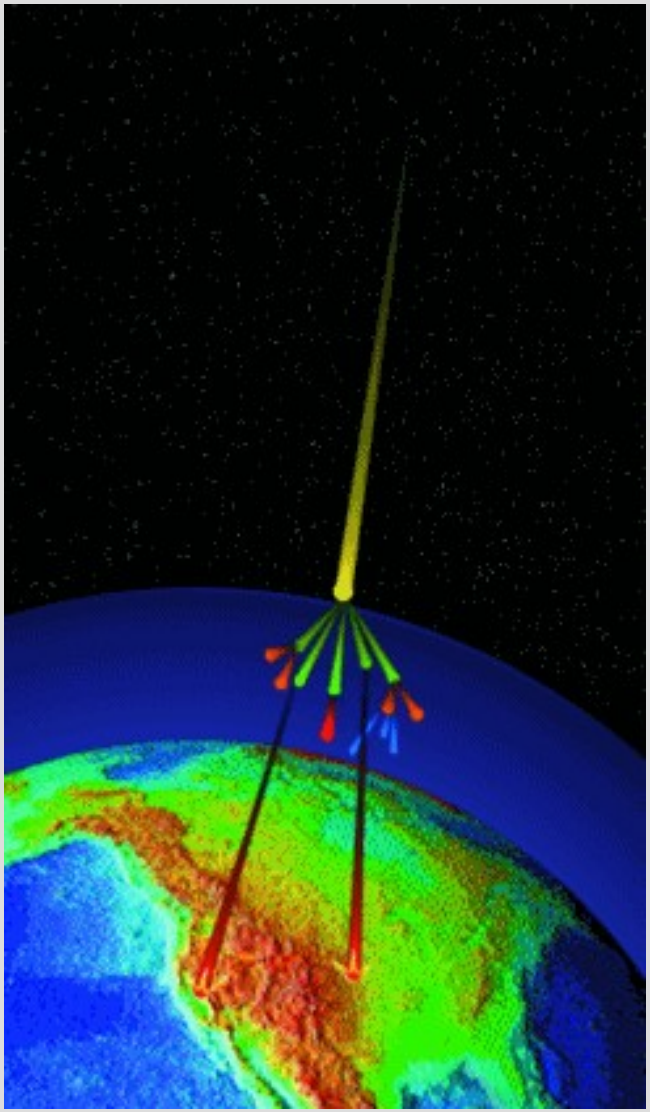
Arto Sandroos

Sun-Earth connections

25.1.2006

Background

- In addition to the solar wind, there are also particles with higher energies emerging from the Sun.
- First observations in 1940s.
- For a long time it was though that all solar HEPs were accelerated in flare eruptions (the flare myth), since coronal mass ejections (CME) were not found until 1970s.



Background

- HEPs hitting the ionosphere directly create particle showers, increasing the radiation level at high altitudes.
- Most solar high energy particles (HEP) cannot penetrate into the ionosphere, but they increase the radiation levels in interplanetary space and at Earth orbit.
- Potential danger for astronauts, communication satellites etc.

Background

- Nowadays solar energetic particles (SEP) are understood to be produced by two mechanisms.
  - Flare acceleration vs. CME-driven shock waves.
- Solar wind observations are categorized roughly as impulsive (flares) and gradual (CMEs) events.
- Connection between SEP events and active phenomena is not entirely clear.

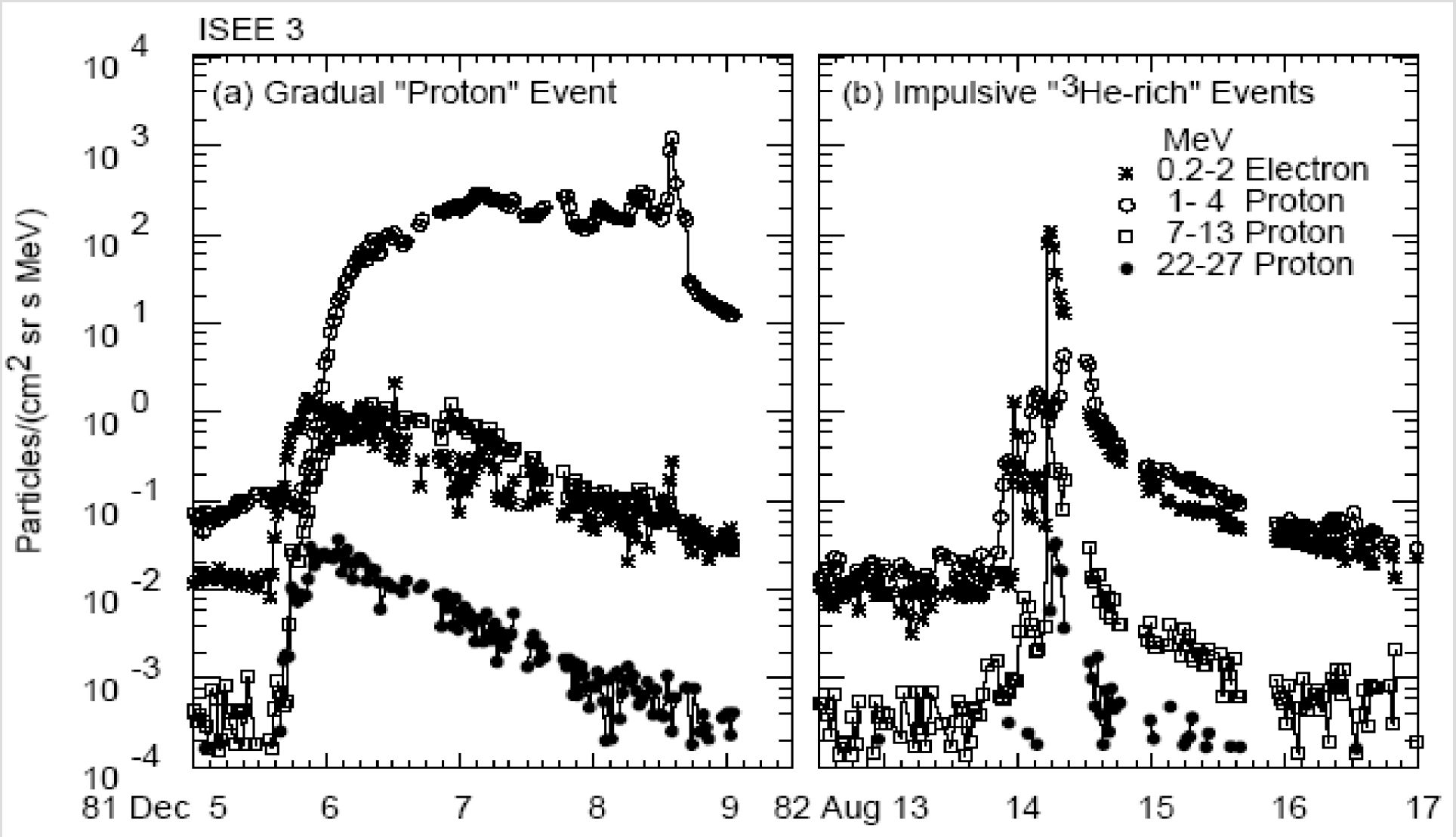
Background

- Ambient plasma densities can be so low that the only information of the acceleration are the observed high energy particles.

Gradual and impulsive events

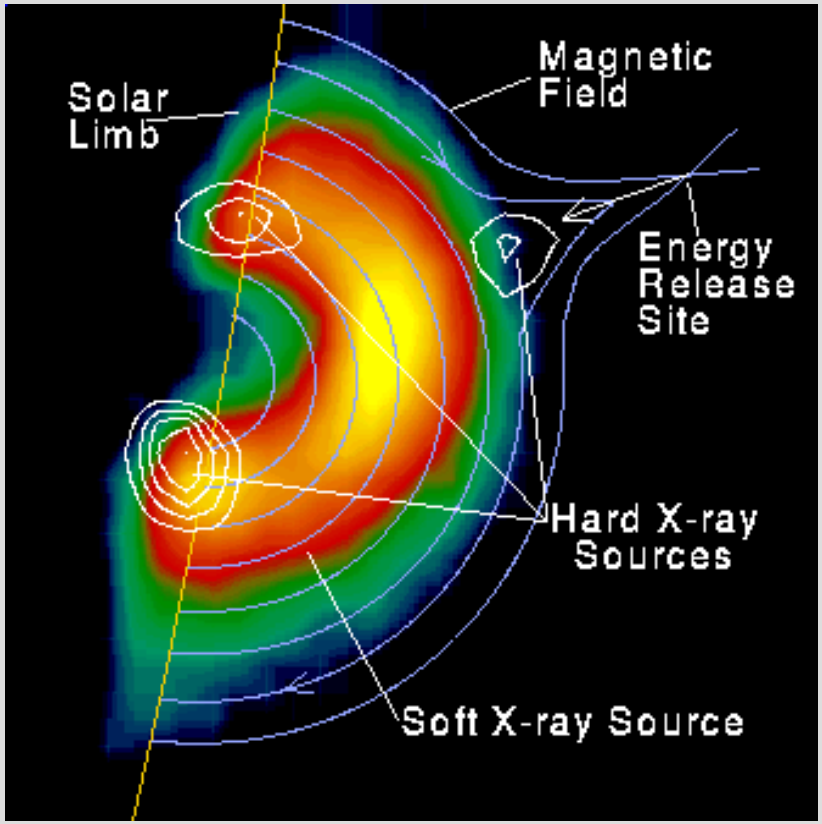
- Gradual events typically show higher particle energies than impulsive ones.
- However, both types have maximum proton and electron energies ~1 GeV and ~100 MeV, respectively.
- Solar wind speed range 450-900 km/s corresponds to energies of 1-4 keV for protons and 0.6-2.3 eV for electrons.
- The fluxes of HEP are a lot smaller than SW particles.

Gradual and impulsive events as observed from solar wind



Flares and impulsive events

Flares occur when reconnection converts magnetic energy to particle energy.

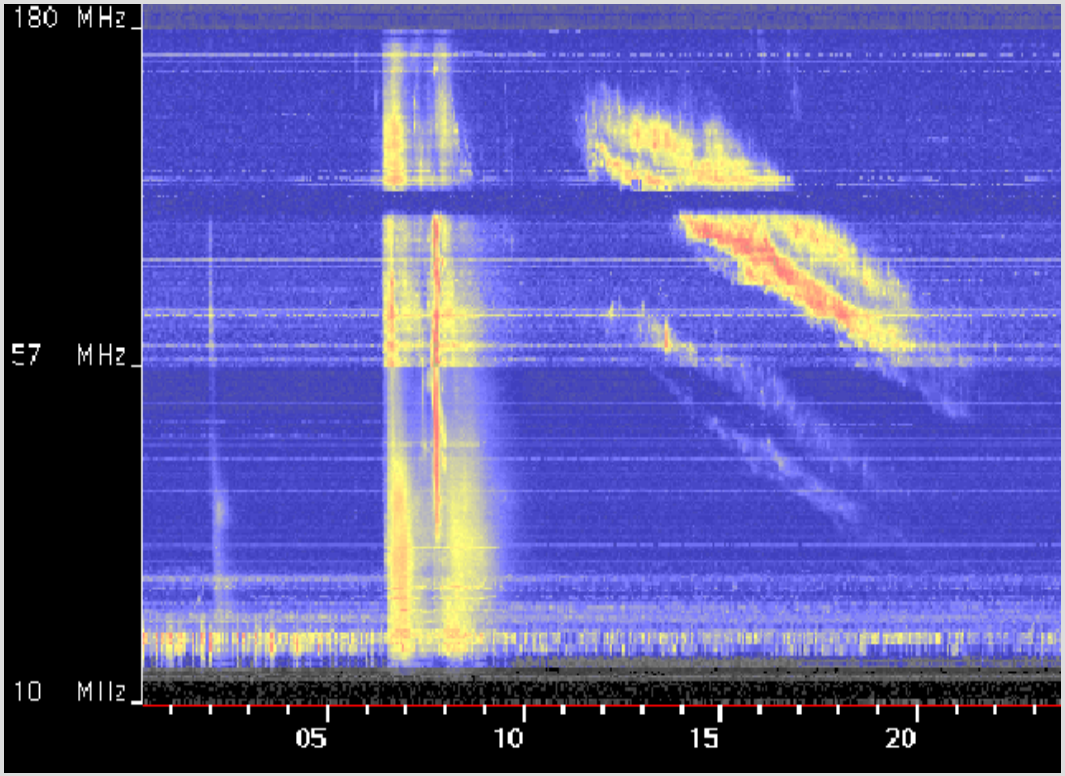


- Electrons are quickly ($t < 1s$) accelerated to relativistic energies.
- Electron beams emit X-ray bremsstrahlung at the reconnection site and loop footpoints.

Flares and impulsive events

- Ions are also accelerated through somewhat selective wave-particle resonances.
- Especially abundances of ^{3}He are enhanced.
- Electron beams enhance plasma oscillation -> type III radio bursts.
- Beams travel along interplanetary magnetic field (IMF) lines.
- Beams can be used to map IMF field lines.

Flares and impulsive events



- Type II (vertical) and type III (diagonal) radio bursts.
- Time axis in minutes.
- Frequency proportional to plasma frequency.

Flares and impulsive events

- Impulsive events observed only if flare site is magnetically connected to the spacecraft.
- Hevy ions (up to Fe) are often completely ionized and their abundances enhanced.
- Ionization degree of particles correspond to temperature ~10 MK, suprathermal even in hot corona (~2 MK).
- Impulsive events are short, since flares erupt quickly.
- Flares are common -> lots of impulsive events.

Flares and impulsive events

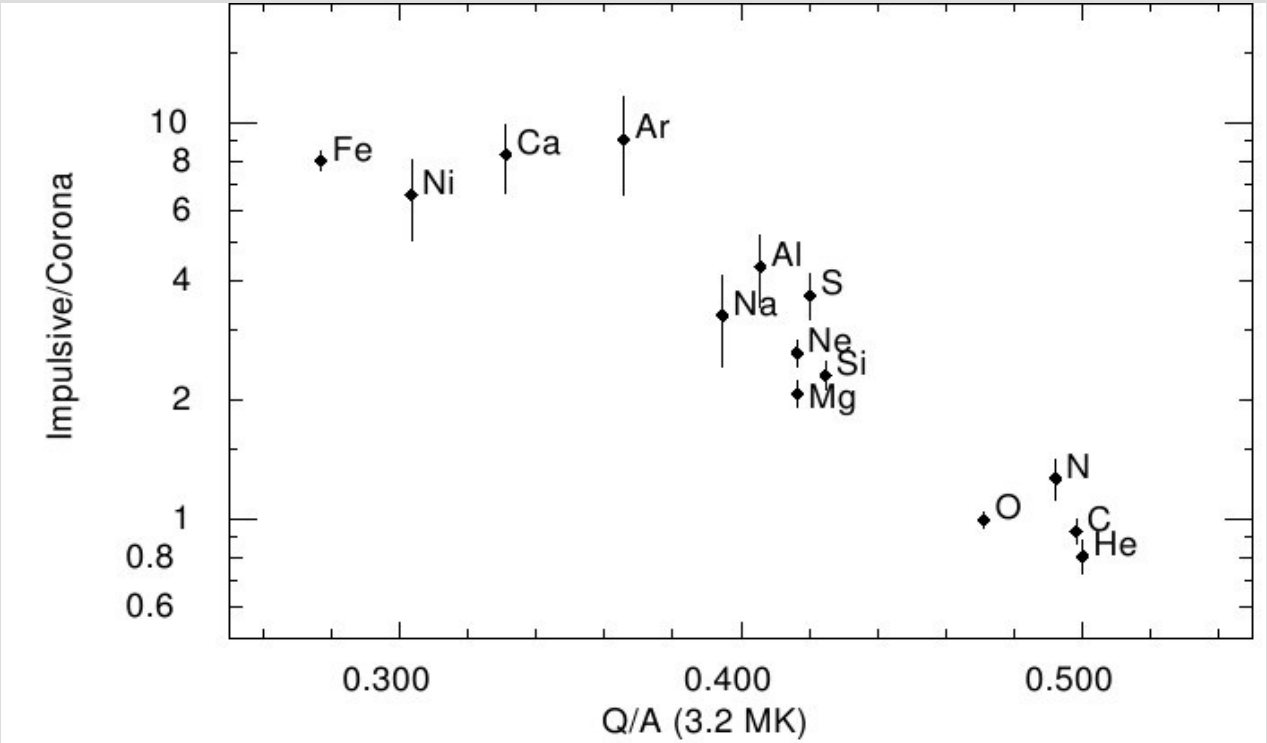


Figure 4.4. Average abundance enhancements in impulsive events, relative to coronal abundances, v
Q/A for a 3.2 MK thermal plasma.

- Average ion abundances in impulsive events (Reames 1999).

This figure also tells about the resonant waves present in flares as Larmor frequency is proportional to Q/A (charge / mass ratio).

Flares and impulsive events

- Impulsive events associated with:
  - Type III radio bursts (from fast electron beams).
  - Hard X-ray flares, gamma rays (acc. ions collide with coronal plasma).
  - Energy-time-dispersion measured from HEP match observed flare onset times.

CMEs and gradual events

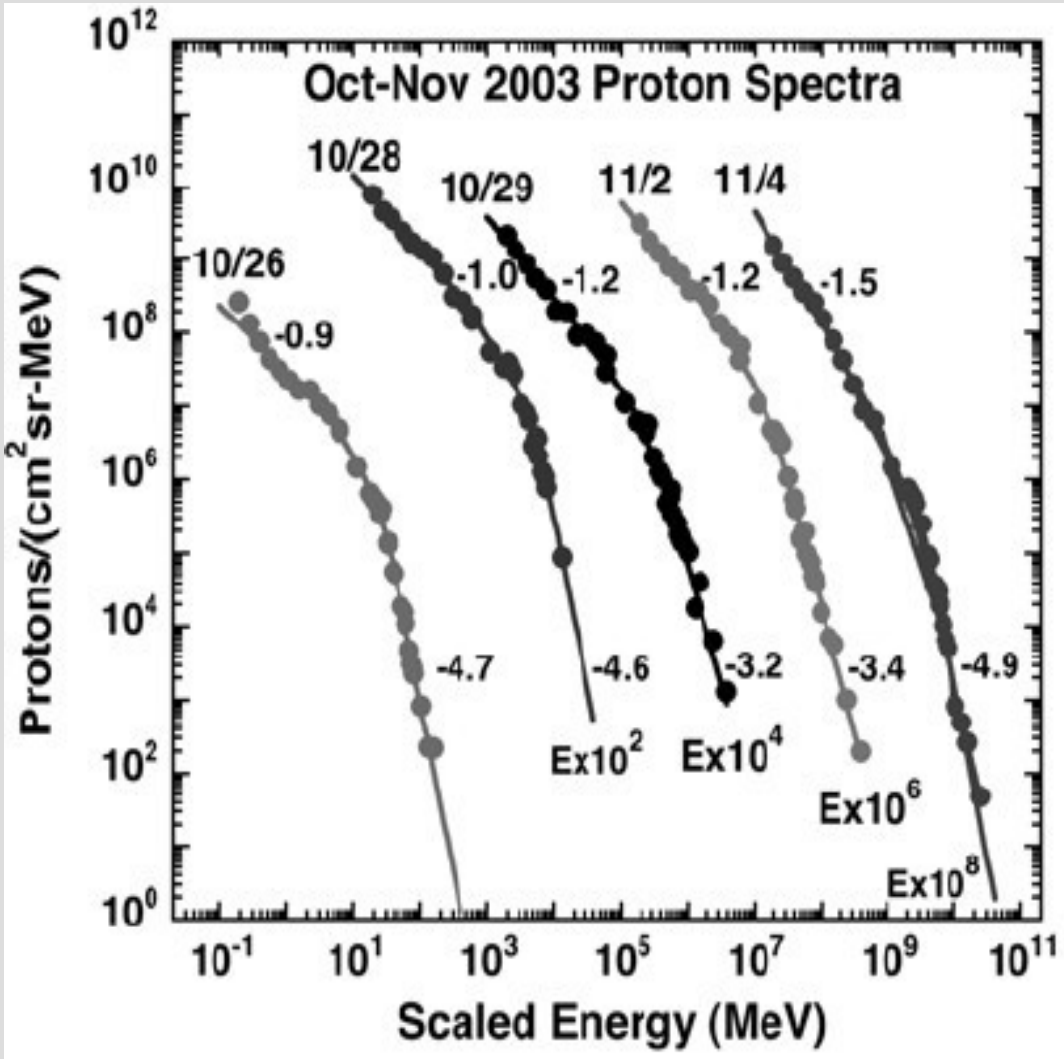
- Gradual SEP events can persist for several days.
- The acceleration mechanism should also operate for roughly the same time period.
- Flares erupt in a fraction of second, so it would take a large number of flares to get ~continuous acceleration.
- 96% of gradual events can be connected to a CME, but only a small number of CMEs cause gradual events.

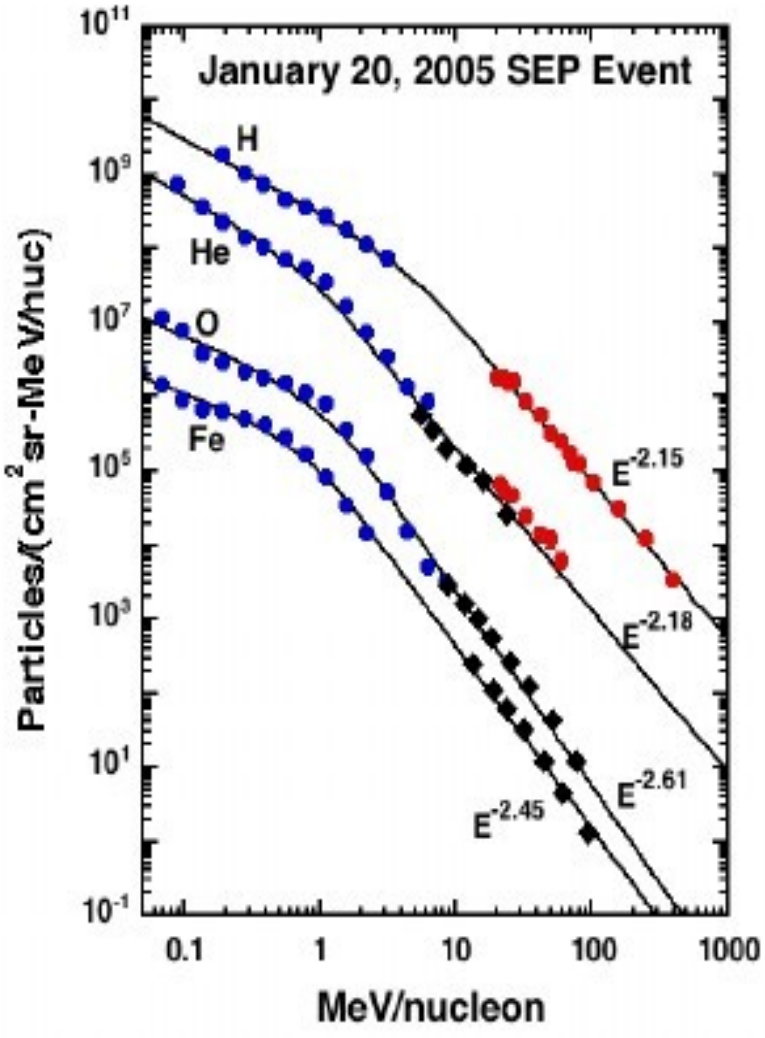
CMEs and gradual events

- Gradual events are typically dominated by high energy protons vs. electron-dominated impulsive events.
- In a typical event the energy spectrum of HEP is a simple power law,

$$dN/dE \sim E^{-s}$$

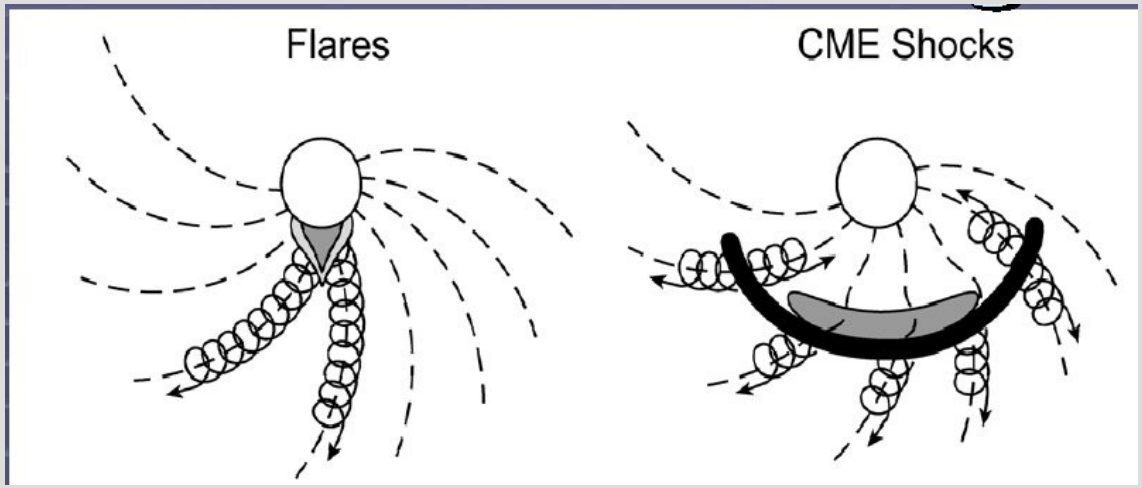
CMEs and gradual events





CMEs and gradual events

- CMEs can usually be associated with gradual soft X-ray flares, which are used to determine the launch site.



- A source site anywhere on solar disc can lead to an observable gradual event -> acceleration in wide area around the source.

CMEs and gradual events

- Superalfvenic CMEs drive shock waves.
- Shocks are magnetic mirrors moving through the ambient plasma.
- If an ion is imagined to be a ping-pong ball, the shock is a bat which hits incident particles, thus increasing their energies.
- Magnetic mirrors are not perfect, i.e. there are always particles in the loss cone etc.

CMEs and gradual events

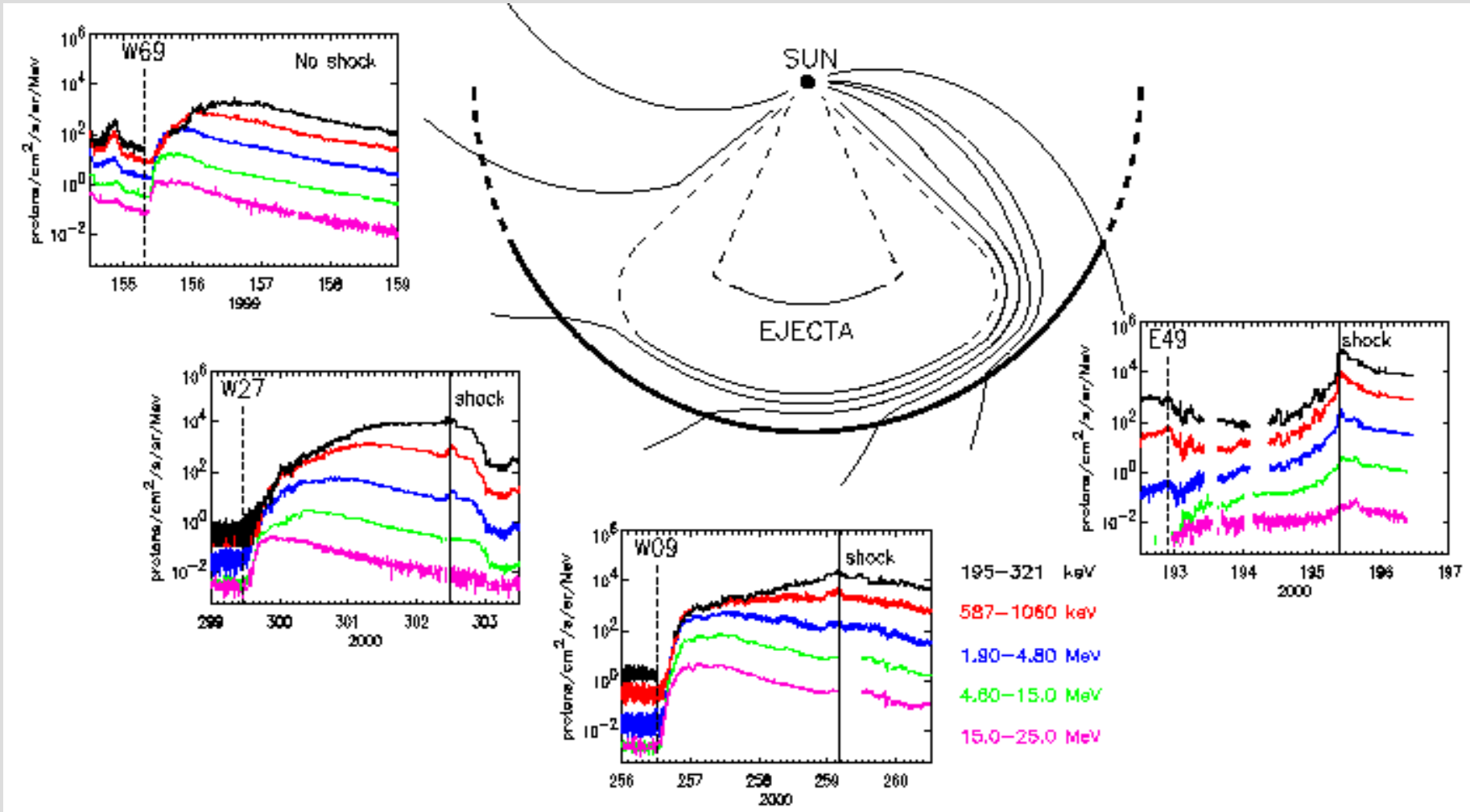
- The energy gain for a particle encountering the shock depends on the plasma parameters and shock speed.
- However, for a single encounter the particle may increase it's energy by a factor of ~4, so multiple encounters are required to produce e.g. MeV protons.
  - Suitable magnetic geometry or scattering from (possibly self-induced) plasma turbulence.
  - Different models: diffusive shock acc., shock drift acc., ...

CMEs and gradual events

- In general one can say that the shock is better accelerator near the nose of the CME than in the flanks.
- Fast CME required (> 500 km/s).
- The time profile of observed particle fluxes depend on the spacecraft's magnetic connection to the shock.
- The connection point can change as the CME moves away from the Sun.

CMEs and gradual events

Gradual events observed by ACE and IMP-8



CMEs and gradual events

Left flank

- Initial connection to the nose.
- Later connection to weaker flank.

Right flank

- Initial connection to weak flank.
- Later connection to nose from behind the shock.

Center

- Connection stays close to strong shock.

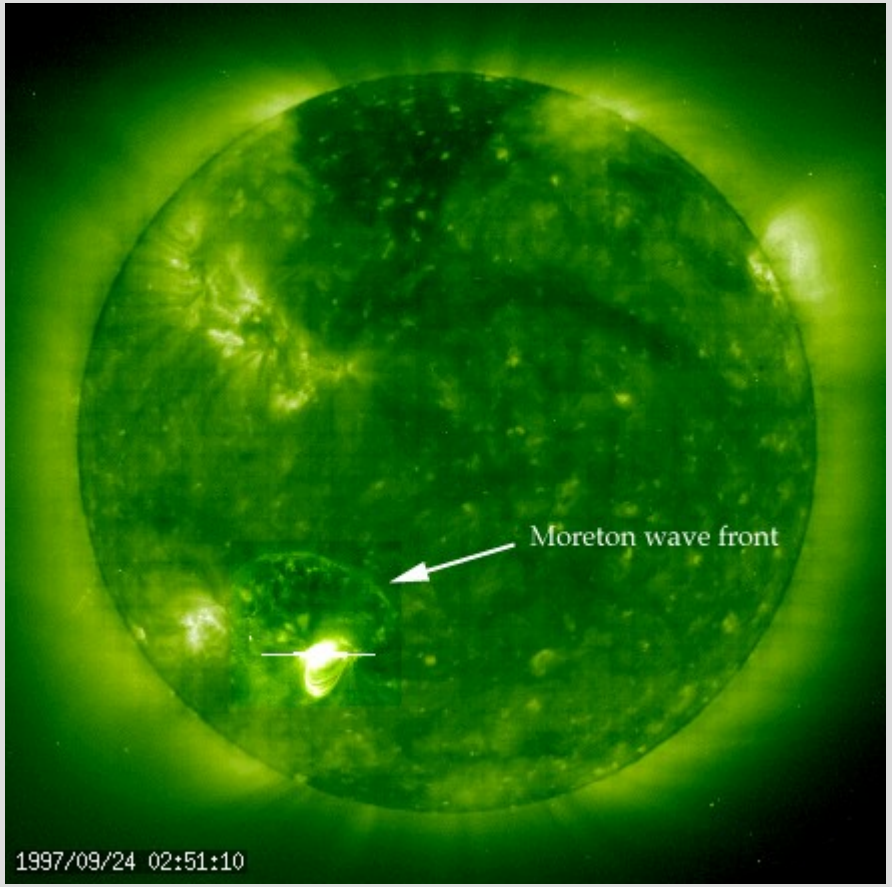
Particles with higher energies reach the spacecraft in shorter time.

CMEs and gradual events

- Ion abundances and ionization states in gradual events correspond well to coronal values.
- From these it has been deduced that the most efficient acceleration occurs at 5-10 solar radii.
- The shocks also propagate through the corona.
- The particles accelerated at corona can act as seed particles for new acceleration.

CMEs and gradual events

- This should probably be called as an EIT wave.
- Find out more about EIT and Moreton waves from www.



Similar active phenomena occur also on other stars.

Sources

- http://www.am.ub.es/~blai/enginmodel/SEP_History.html
- Klein, Trottet: “The origin of solar energetic particle events: Coronal acceleration versus shock wave acceleration”, Space Science Reviews 2001, 95:215-225.
- Reames: “Particle acceleration at the Sun and in the heliosphere”, Space Science Reviews 1999, 90:413-491.
- Reames: “Solar energetic particles: Sampling coronal abundances”, Space Science Reviews 1998, 85:327-340.

Images

- HEP cascade in ionosphere:
  http://www2.slac.stanford.edu/vvc/cosmicrays/cratmos.html
- Energy spectras in gradual events
  http://www.srl.caltech.edu/ACE/ASC/DATA/bibliography/ICRC2005/usa-mewaldt-RA-abs3-s
- Radio bursts
  http://solar.physics.montana.edu/home/www/nuggets/2002/020823/020823.html