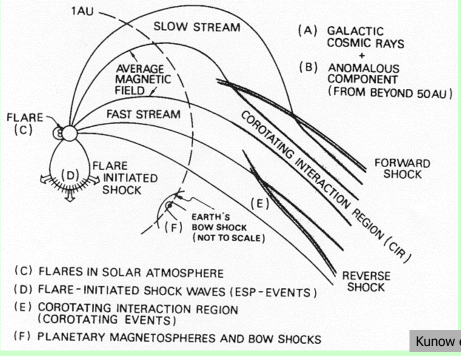
Solar energetic particles and cosmic rays

- Solar energetic particles and cosmic rays
- Energy spectra and acceleration
- Particle propagation and transport
- Pick-up ions, origin and distribution
- CIRs and the outer heliosphere
- Modulation of cosmic rays in the solar cycle

Energetic particles in the heliosphere



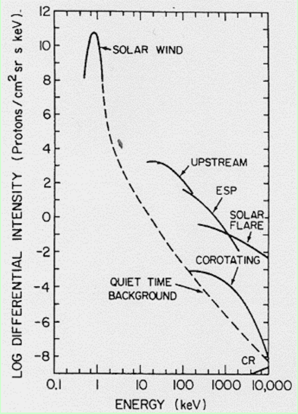
Kunow et al., 1991

Energy spectra of heliospheric ion populations

- How are they accelerated?
- What is their composition?
- How do they propagate?
- What are their source spectra?

Energies: 1 keV - 100 MeV

Sources: Mainly shock acceleration at flares/CMEs and CIRs



Gloeckler, Adv. Space. Res. **4**, 127, 1984

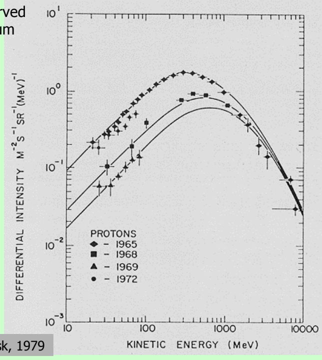
Properties of particle populations

	Temporal scales	*Spatial scales*	*Energy range*	*Acceleration mechanism*	*Population*
A	continuuous	global	GeV – TeV	Diffuse shock	Galactic cosmic rays GCR
B	continuous	global	10 – 100 MeV	Shock?	Anomalous cosmic rays ACR
C	many	many	keV – 100	Reconnection, shock, stochastic heating	Solar energetic particles SEP
D	days	extended	keV – 10 MeV	Diffusive shock, shock drift	Energetic storm particles ESP
E	27 days	large	keV – 10 MeV	Diffusive shock	Corotating interaction region
F	continuous	local	keV - MeV	Shock drift	Planetary bow shock

Galactic cosmic rays I

Proton energy spectra observed at 1 AU (1965, solar minimum and 1969, maximum)

High-energy ions coming from the galaxy penetrate the inner heliosphere.

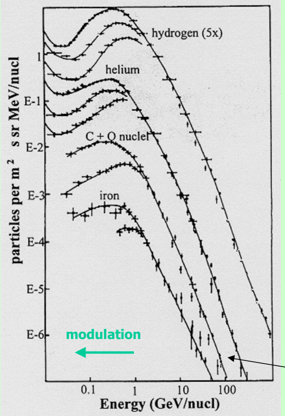


Fisk, 1979

Interactions with solar wind magnetic field lead to:

- Radial intensity gradients
- Temporal variations

Galactic cosmic rays II



- Where do they come from?
- How are they accelerated?
- What is their composition?
- How do they propagate?

Energies: 100 MeV - 10^{20} eV

Sources: Shock acceleration at supernova remnants

$J \sim E^{-\gamma}$ with $\gamma = -2.5$

Meyer et al., 1974

Galactic cosmic rays III

Energies: 100 MeV - 10^{20} eV

- Sources: Mainly **shock acceleration** at supernova remnants, yielding energies up to about 10^{15} eV
- Higher energies unexplained......
- Electron spectra are similar to proton spectra and show also modulation
- Relativistic electrons generate cosmic radio waves (synchrotron emission in the galactic magnetic field)

GCR energy density $\approx$ 0.5 - 1.0 eV cm^{-3}
......compare with starlight $\approx$ 0.5 eV cm^{-3}

Differential flux or intensity: particles/(m^2s str MeV/nucleon)

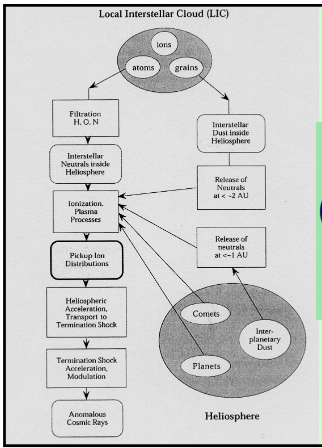
Particle transport processes

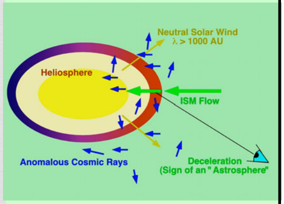
Heliosphere (solar wind) is highly variable and structered on all spatial scales (R_s or 1 AU) down to particle gyroradius (>100 km)

- Stream structures (fast and slow steady wind, transient flows)
- Corotating interaction regions (shocks) and their mergers (MIRs)
- Coronal mass ejections (CMEs) and magnetic clouds
- Alfvén waves, magnetosonic waves and travelling shocks
- Discontinuities and heliospheric current sheet

- Convection and adiabatic decelerartion with expanding wind
- Reflection and acceleration at shocks and discontinuities
- Pitch-angle scattering and (resonant) diffusion
- Gradient drifts and local displacements

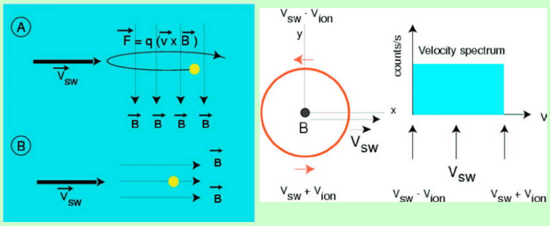
Reservoirs for pick-up ions





Inner source from interplanetray dust

Ion pick-up velocity distribution



A: perpendicular,
B: parallel pick-up

Resulting spectra:

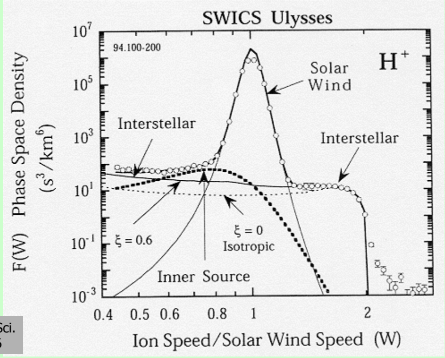
- Ring in velocity space
- Box in energy space

Mall, 1999

Interstellar hydrogen pick up

Time-averaged spectrum over 100 days from SWICS Ulysses in fast wind at 785 km/s

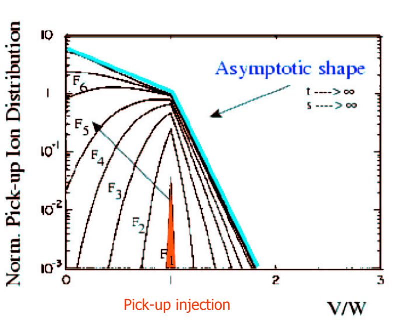
Drop at W=2 indicates: little energy diffusion



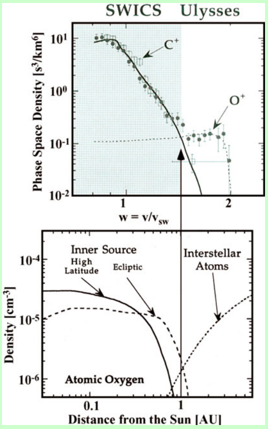
Gloeckler, Space Sci. Rev. **89**, 91, 1996

Energy diffusion of pick-up ions

Spreading in speed (V) by diffusion of a (ring) shell velocity distribution (W, the solar wind speed).



Isenberg, 1999



Pick-up ion spectra

SWICS Ulysses at 1.4 AU

- Inner source from dust, comets etc., ions are singly ionized!
- Outer source from interstellar atoms

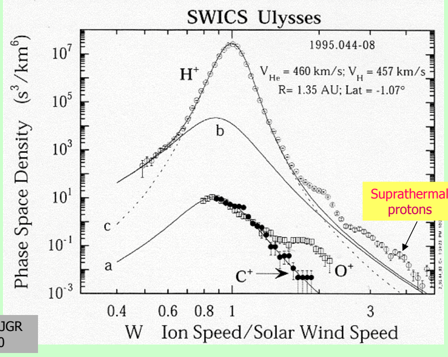
Gloeckler & Geiss, Space Sci. Rev. 86, 127, 1998

Speed distributions of pick-up ions

40 days of Ulysses SWICS observations at 1.35 AU

V = 460 km/s

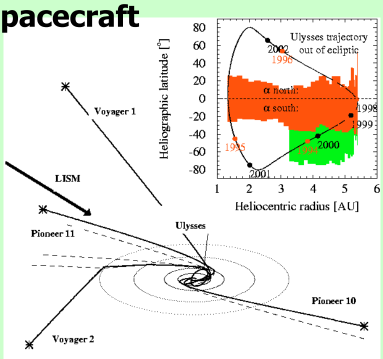
The Carbon C^+ and O^+ (beyond W=1,4) ions are all from an inner source!



Suprathermal protons

Gloeckler et al., JGR **105**, 7459, 2000

Heliospheric trajectories of various spacecraft



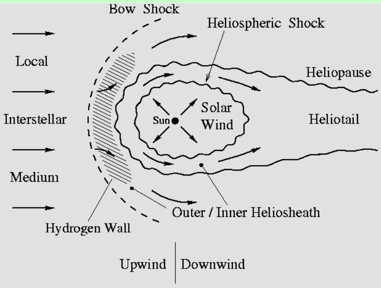
Maximum latitudinal extent of the HCS angle α

α at minum

α at maximum

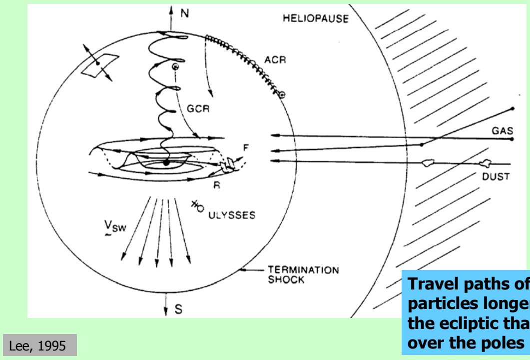
Local interstellar medium LISM

Schematic of the heliosphere



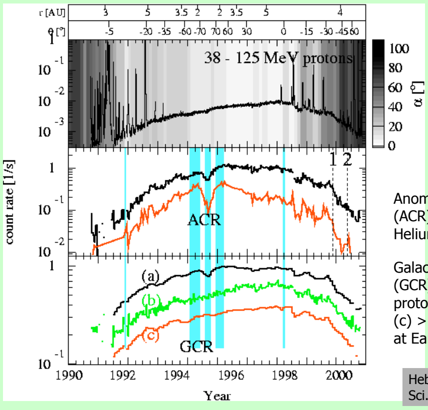
- **Basic plasma motions in the restframe of the Sun**
- **Principal surfaces (wavy lines indicate disturbances)**

Particle motions in the heliosphere



Lee, 1995

Travel paths of particles longer in the ecliptic than over the poles



Cosmic rays

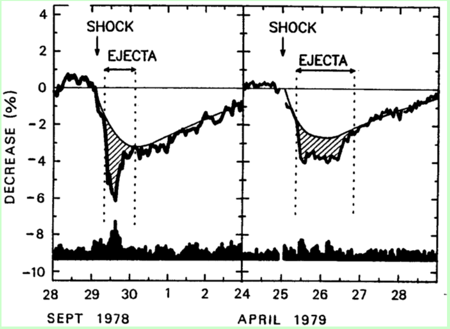
Maximal angle of current sheet latitude, α

Anomalous cosmic rays (ACR): 34-50 MeV/N Helium; 8-27 MeV/N O^{+1}

Galactic cosmic rays (GCR): (a) 2.5 GeV protons, (b) electrons, (c) >100 MeV protons at Earth

Heber & Marsden, Space Sci. Rev. 97, 309, 2001

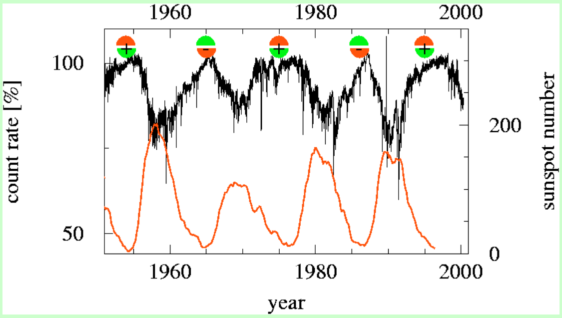
Forbush decrease in neutron data



Wibbeerenz, 1998

Short term CR modulation by solar ejecta (CME, shocks)

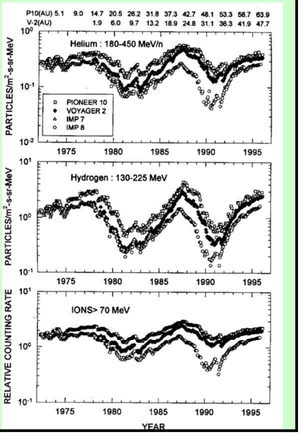
Cosmic ray solar cycle modulation



Heber & Marsden, Space Sci. Rev. 97, 309, 2001

CLIMAX neutron monitor; rays at > 3 GeV

CR varations caused by plasma structures

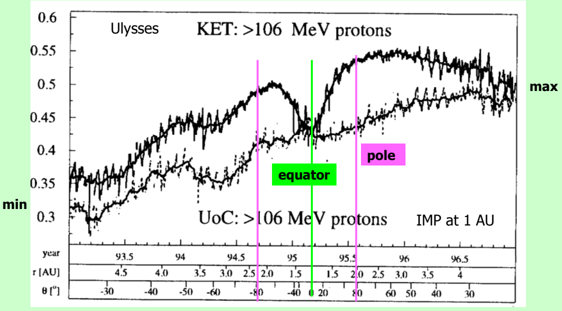


Local, corotating or global merged interactions regions in the (outer) heliosphere cause decreases in CR intensities.

MIRs are spiral „walls" produced by coalescence of two CIRs.

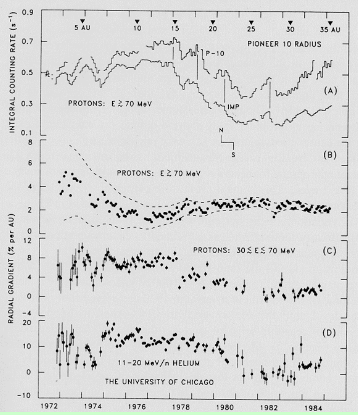
Fujii &McDonald, JGR **102**, 24101, 1997

Latitudinal gradients of CRs



Heber et al., JGR **103**, 4809, 1998

Little (10%) variation with latitude!



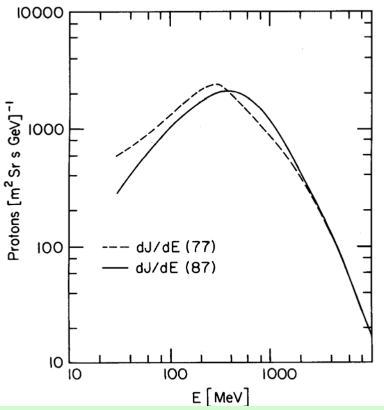
CR radial gradients

- (A) 27-day average of integral proton flux (E>70 MeV)
- (B) **radial gradient** for integral proton flux
- (C) for integral low energy proton flux
- (D) for integral low energy helium flux

A few % per AU

McKibben, 1986

Spectrum of CRs at minimum



Some spectral variations at subsequent solar activity minima occur at lower (<400 MeV) energies.

Lockwood & Webber, JGR **101**, 21573, 1996

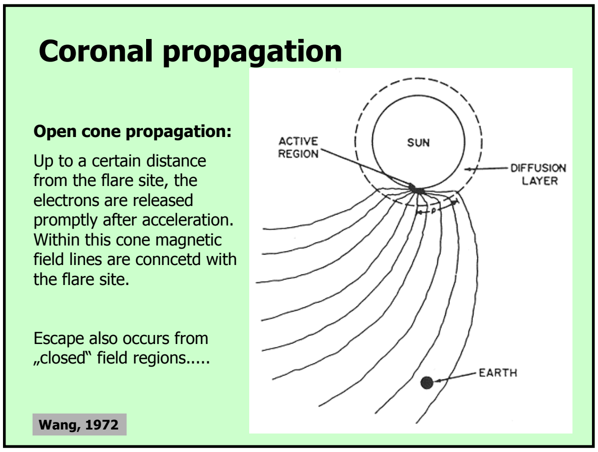
Basic transport processes of CRs

- Diffusion in wave fields and turbulence, κ (r)
- Convection and adiabatic deceleration, $V_{sw}(r)$
- Drift (curvature, gradient) induced by field nonuniformity, $V_D(r)$

$$\partial U/\partial t = \nabla\bullet(\kappa\bullet\nabla U) - (V_{sw}+V_D)\bullet\nabla U + 1/3(\nabla\bullet V_{sw})\,\partial(\alpha TU)/\partial T$$

U=U(r,t,T), is the number density of particles with kinetic energy, T, and $\alpha=(T+2mc^2)/(T+mc^2)$; here $\nabla\bullet V_{sw} < 0$ means compression (acceleration) and > 0 expansion (deceleration).

Parker, 1958, 1965



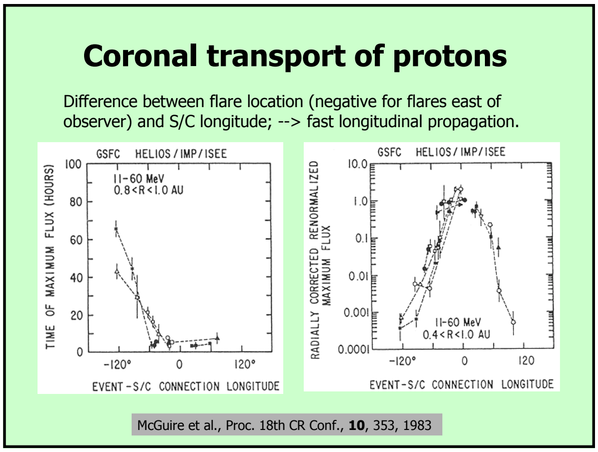
Coronal propagation

Open cone propagation:

Up to a certain distance from the flare site, the electrons are released promptly after acceleration. Within this cone magnetic field lines are conncetd with the flare site.

Escape also occurs from „closed" field regions.....

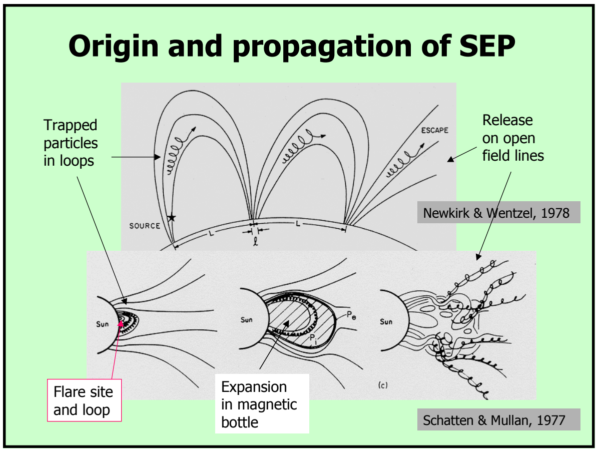
Wang, 1972



Coronal transport of protons

Difference between flare location (negative for flares east of observer) and S/C longitude; --> fast longitudinal propagation.

McGuire et al., Proc. 18th CR Conf., **10**, 353, 1983



Origin and propagation of SEP

Trapped particles in loops

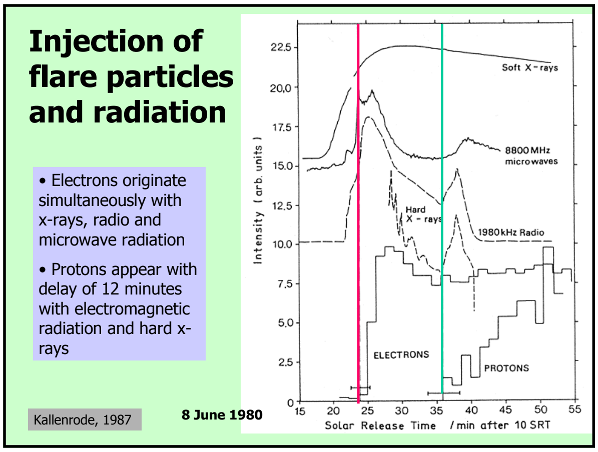
Release on open field lines

Newkirk & Wentzel, 1978

Flare site and loop

Expansion in magnetic bottle

Schatten & Mullan, 1977

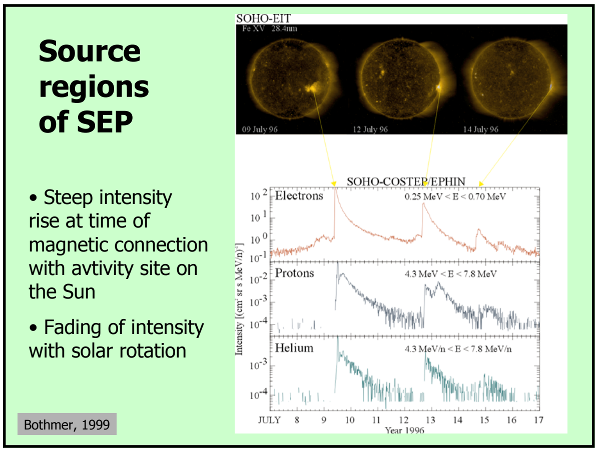


Injection of flare particles and radiation

- Electrons originate simultaneously with x-rays, radio and microwave radiation
- Protons appear with delay of 12 minutes with electromagnetic radiation and hard x-rays

Kallenrode, 1987

8 June 1980



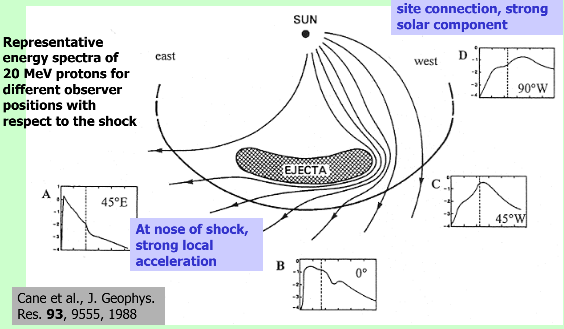
Source regions of SEP

- Steep intensity rise at time of magnetic connection with avtivity site on the Sun
- Fading of intensity with solar rotation

Bothmer, 1999

Spectra varying with magnetic connection

Representative energy spectra of 20 MeV protons for different observer positions with respect to the shock

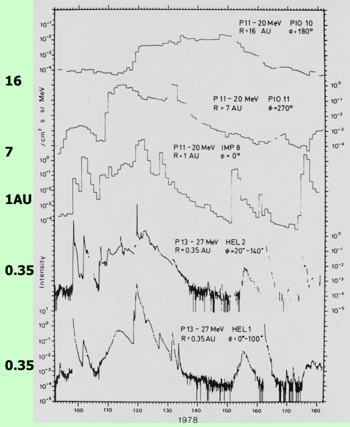


Flank of shock, but flare site connection, strong solar component

At nose of shock, strong local acceleration

Cane et al., J. Geophys. Res. **93**, 9555, 1988

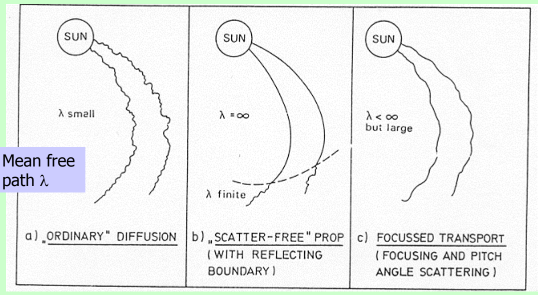
Cosmic ray super event



Intensity time profiles of energetic protons during a rare super event April/May 1978 at various r and ϕ

- **Intensity enhancement occurring in whole heliosphere for protons > 10 MeV**
- **Flare/CME generated multiple shocks**
- **Interplanetary merged shells or IRs related with CMEs and shock waves**
- **Stream coalescence and merging blocks GCRs**

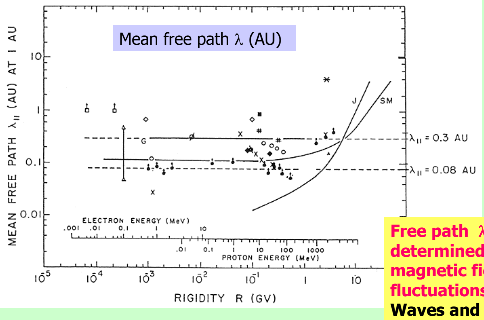
Interplanetary propagation I



Mean free path λ

Strong turbulence — Magnetic moment conserved — Weak turbulence

Interplanetary propagation II



Mean free path λ (AU)

Rigidity = relativistic energy/charge, R = E/q ≈ cp/q

Free path λ is determined by magnetic field fluctuations: Waves and structures

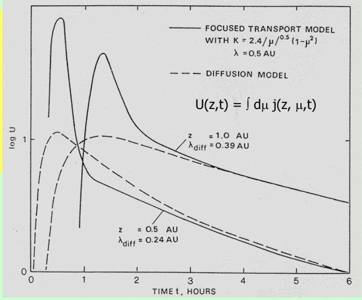
Interplanetary propagation III

$$\partial j/\partial t + \mu v \partial j/\partial z + (1-\mu^2)/(2L)\, v \partial j/\partial \mu - \partial/\partial \mu(\kappa\, \partial j/\partial \mu) = Q(t)$$

Ingredients:

- Spatial diffusion: $\kappa(z, \mu)$ magnetic field fluctuations
- Focusing length: $1/L(z) = -\partial/\partial z \ln B(z)$
- Source term: $Q(t, z_0)$

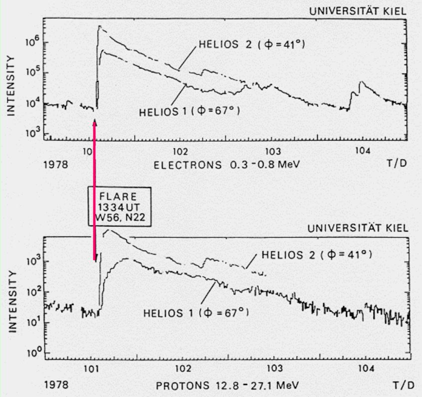
Intensity: $j(z, \mu, t)$ for particles with speed $v >> V_{sw}$



$U(z,t) = \int d\mu\, j(z, \mu, t)$

Wong et al., 1982

Particles at flares

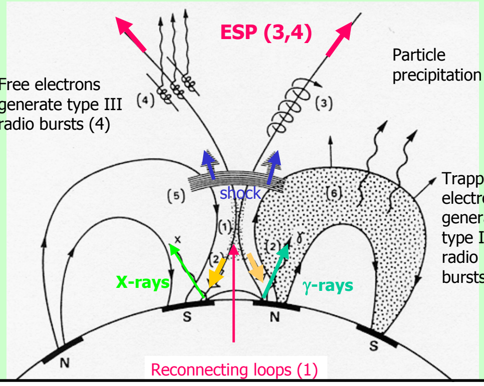


The 11 April 1978 flare seen by Helios 1 and 2

Larger distance to flare in solar longitude causes event to be delayed and weaker at Helios 1

Kunow et al., 1991

Particle acceleration in flares



Free electrons generate type III radio bursts (4)

Particle precipitation (2)

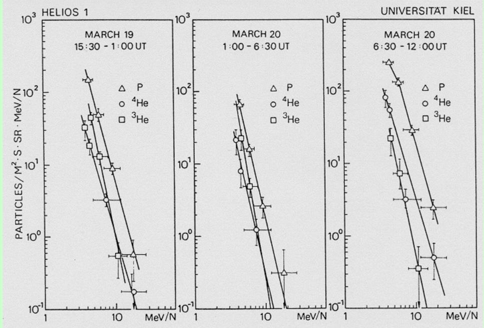
Trapped electrons generate type III radio bursts (6)

Energetic particles from flares

Feature	***impulsive***	***gradual***
rich in	electrons	protons
^{3}He/^{4}He	~1 (2000 times)	~0.0005
H/He	10	100
Q_{Fe}	+20	+14
duration	hours	days
longitudinal extent	<30^0	<180^0
corona	--	CME
event rate	~1000/a	~10/a

Kallenrode, 1998

Spectra of Helium in flare



Kunow et al., 1991

Helios 1 in March 1975

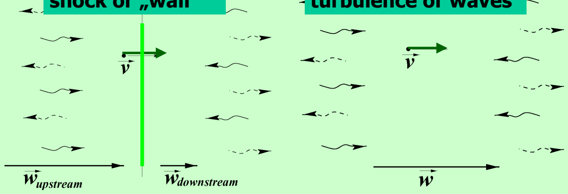
Concept of Fermi acceleration

Fermi I ~ (v/c)

shock or „wall"

Fermi II ~ $(v/c)^2$

turbulence or waves

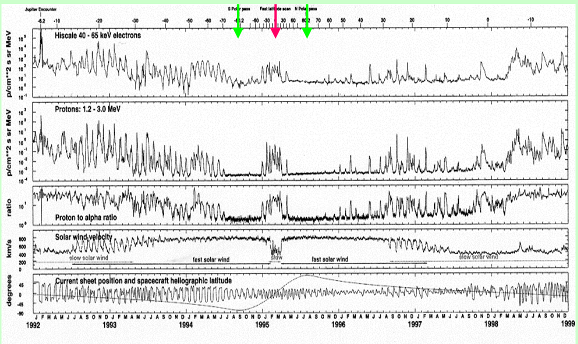


For an upstream (downstream) particle crossing the shock there are only downstream (upstream) waves propagating toward it, --> always head-on collisions!

Fermi, 1949

For a particle there are both waves moving in the same and opposite direction, --> heading and trailing collisions!

Ulysses low energy particles

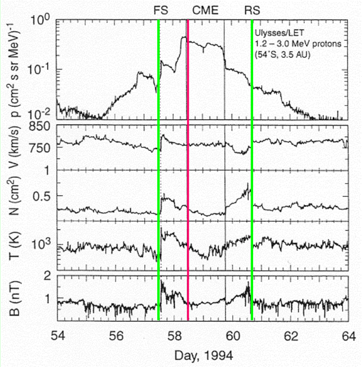


Lanzerotti & Sanderson, 2001

Energetic protons at CME

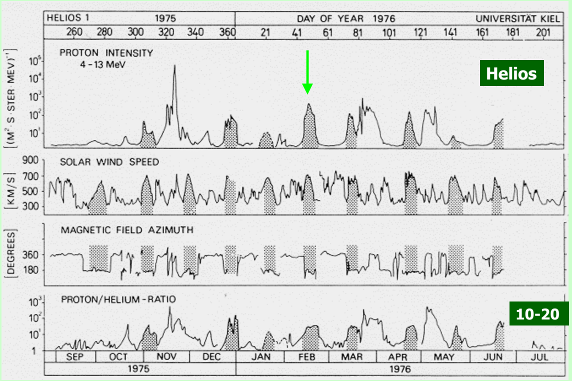
Protons associated with forward (FS) and reversed (RS) shock at CME. Top: ten-minute average of 1.2-3.0 MeV proton flux.

Bottom: solar wind parameters.



Bothmer et al., Geophys. Res. Lett. **22**, 3369, 1995

Corotating events at CIRs

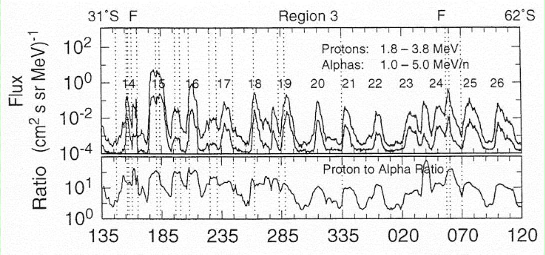


Helios

10-20

Ions at CIRs at high latitudes

Dotted lines: reverse shocks; two forward shocks are indicated by F.

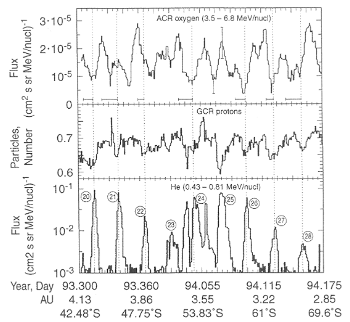


Sanderson et al., Space Sci. Rev. **72**, 291, 1995

Ulysses

Relationship between ACRs and CRs at CIRs

Intensities of anomalous cosmic ray oxygen (top), galactic protons (middle) and helium (bottom) at nine CIRs



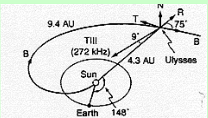
Anticorrelation between the variations of the ACRs and GCRs and the variations in the CIR-induced He fluxes. Comic rays are excluded from the inner heliosphere by CIRs!

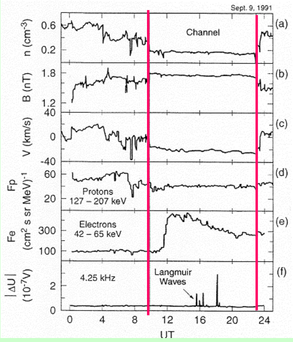
Reuss at el., Ann. Geophysicae **14**, 585, 1996

Ulysses

Propagation of particles in interplanetary structures

Below: Sketch showing the field geometry of the channel at the time of the event. **Right:** Note the extremely smooth wind characteristics in the channel guiding the energetic particles. **Panel (f)** shows Langmuir waves excited by beam electrons.





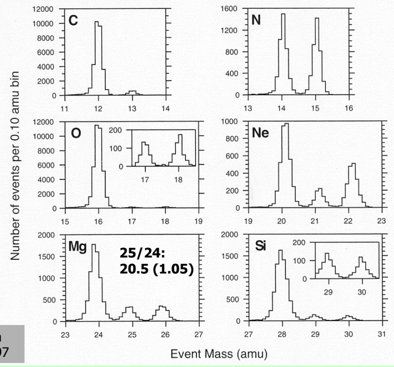
Buttighoffer, A&A, **335**, 295, 1998

CR isotopes

13/12: 6.3 (0.8)

15/14: 49.8 (0.6)

Cosmic ray isotopes at typical energies of 100-200 MeV/amu; measured by stopping in a physical detector.



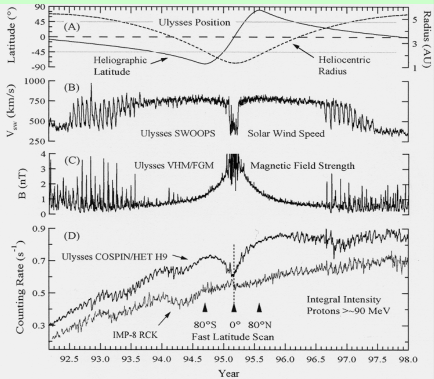
25/24: 20.5 (1.05)

Isotope ratios [%] reflect CR history from injection and acceleration, through interstellar propagation and finally heliospheric modulation.....

Connel & Simpson, Proc. 25th Cosmic Ray Conf. **3**, 381, 1997

CR heliospheric modulation

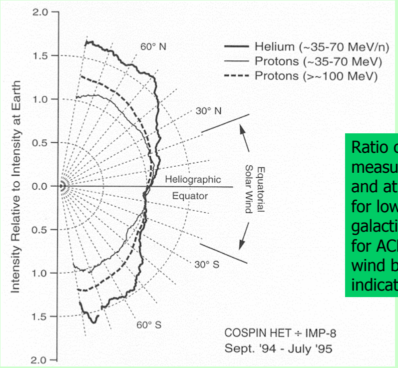
Integral intensity of CRs at energies > 90 MeV with mean response at 2 GeV. Modulation for electrons looks similar.



Note the overall steady increase in flux towards activity minimum in late 1997!

McKibben, 2001

Polar plot of CR intensities



- Weak asymmetry!
- No gradient over poles!

Ratio of intensities measured at Ulysses and at Earth on IMP-8 for low-energy and galactic CR protons and for ACR helium. Solar wind boundaries are indicated as well.

McKibben et al.,
A&A **316**, 547, 1996