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ICTP-COST-USNSWP-CAWSES-INAF-INFN
International Advanced School
on
Space Weather
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Cosmic Rays in the Heliosphere

Marisa STORINI
Istituto di Fisica dello Spazio Interplanetario
Via fosso del Cavaliere, 100
Tor Vergata
00133 Rome
ITALY

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

M. Storini – INAF/IFSI_Rome Trieste - 5 May 2006

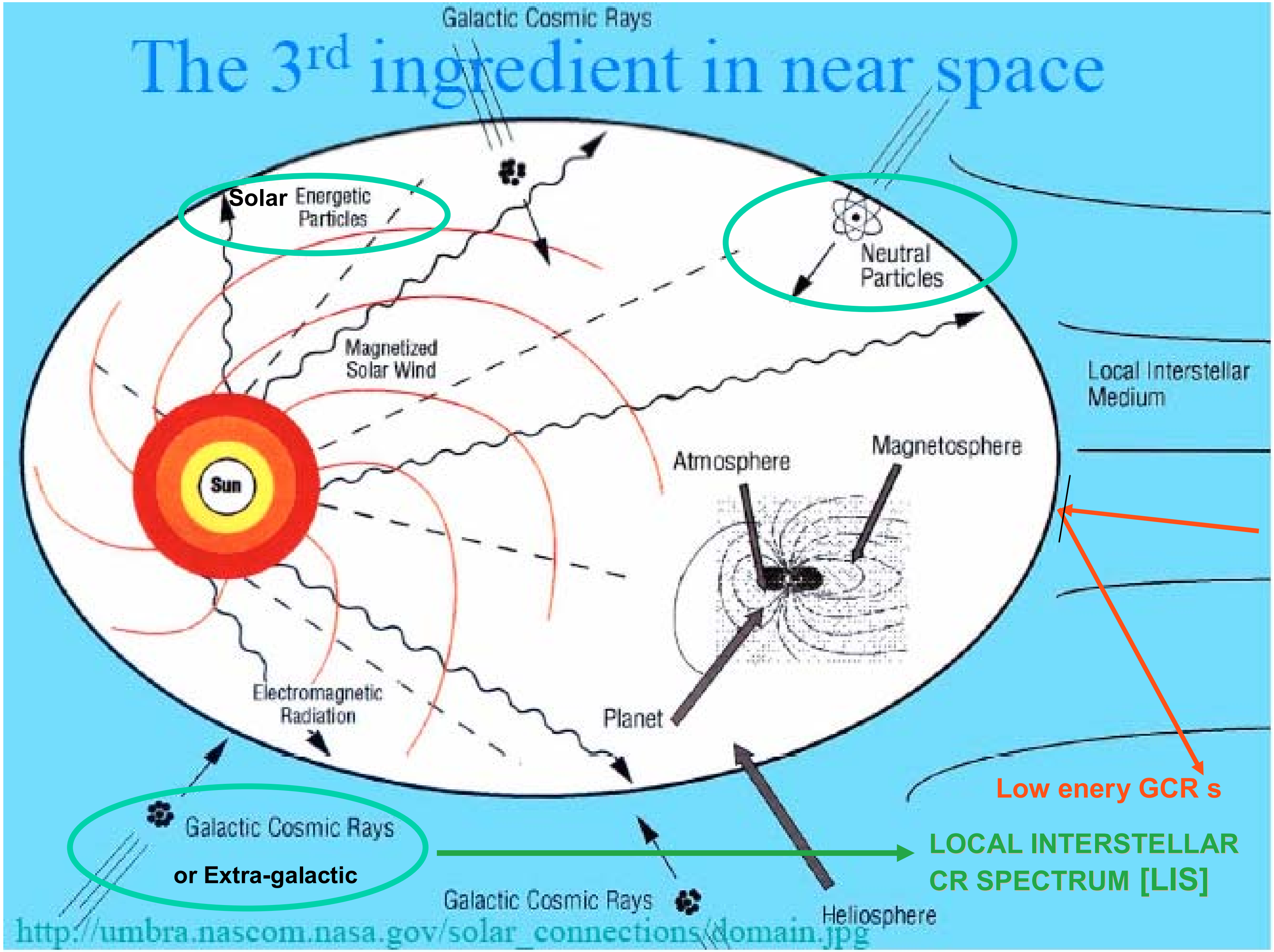
E-mail: storini@ifsi-roma.inaf.it

ICTP-COST-CAWSES-INAF-INFN
International Advanced School on Space Weather

Lecture 2. COSMIC RAYS IN THE HELIOSPHERE

- CR populations
- CR propagation
- CR modulation (long-, medium- and short-term)
- Solar CR events

CR POPULATIONS



CR POPULATIONS

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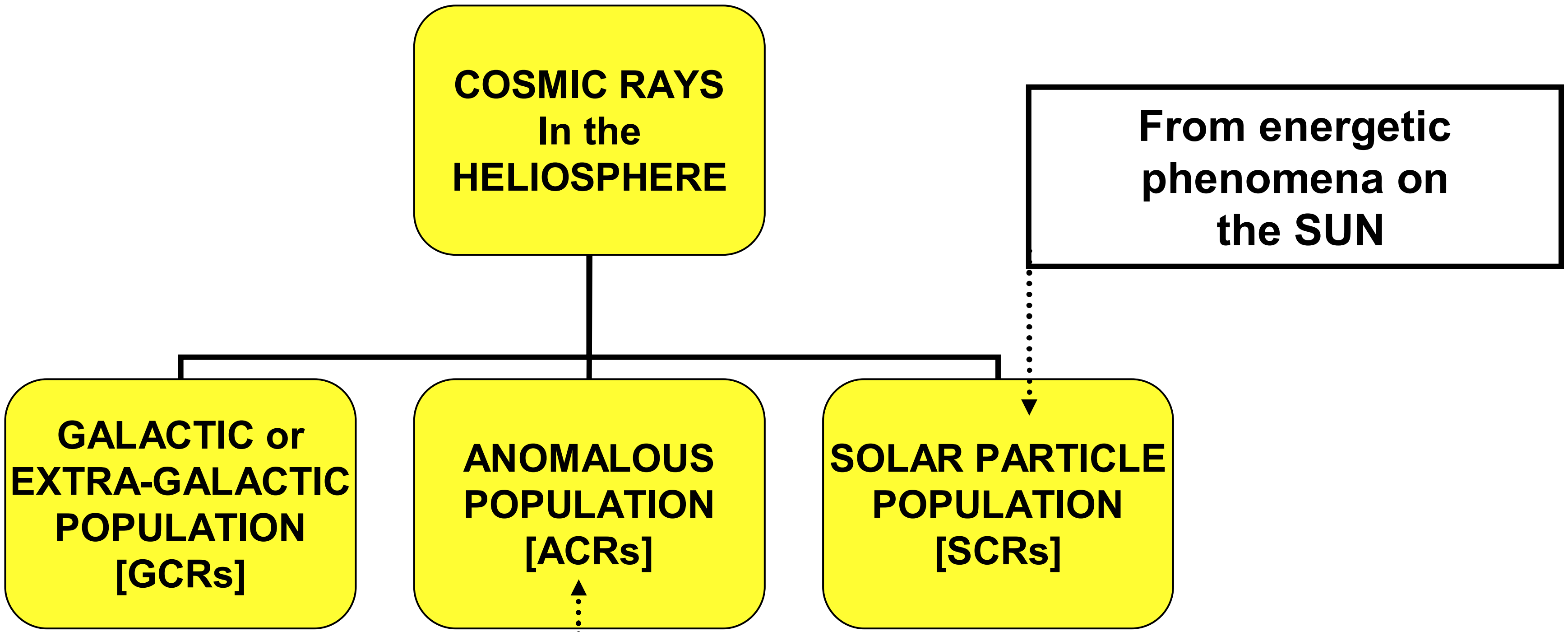

From ionized neutral interstellar atoms by

- Photoionization induced by solar UV photons
- Charge exchange collisions with protons

} **INNER HELIOSPHERE**

📖📖 IMF (frozen in solar wind) picks up and carries them (PICKUP IONS)

📖 SW TERMINATION SHOCK
(acceleration up to tens of MeV/nucleon)
✎ IN SITU MEASUREMENTS CONTRADICT ???

} **OUTER HELIOSPHERE**

CR POPULATIONS

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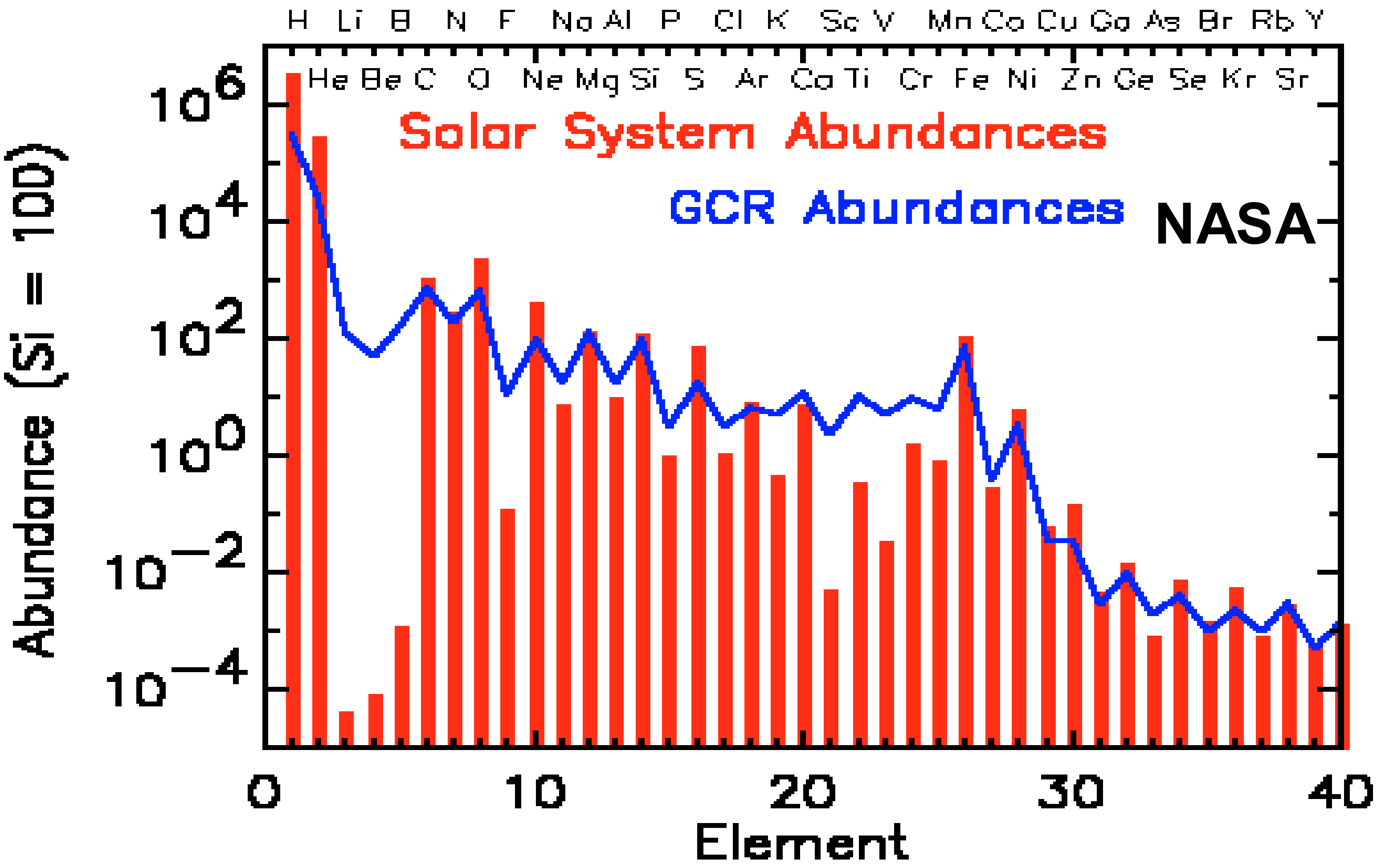
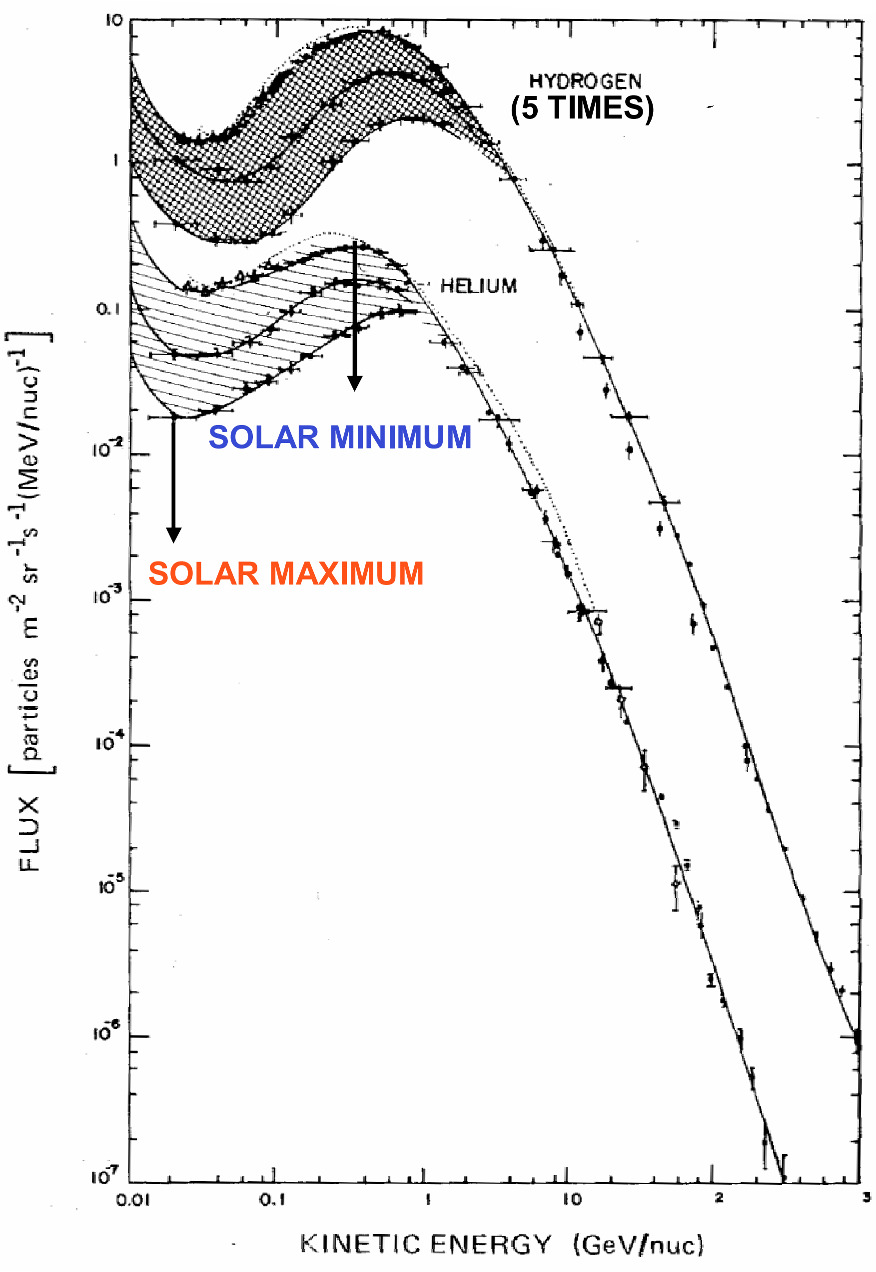
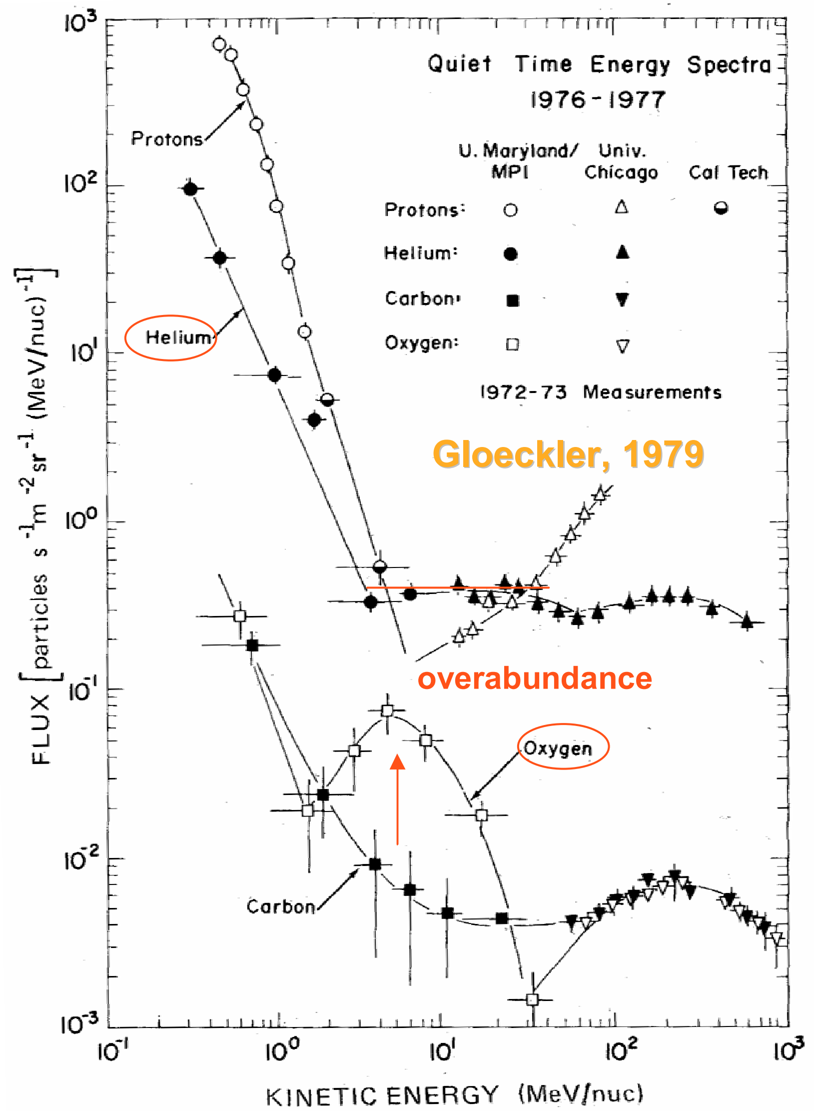


CR POPULATIONS





Taken from Smart D.F. and Shea M.A. , Chapt.6 in Handbook of Geophysics and the Space Environment, A.S. Jursa (ed.), AF Geophys. Lab., 1985.

CR POPULATIONS

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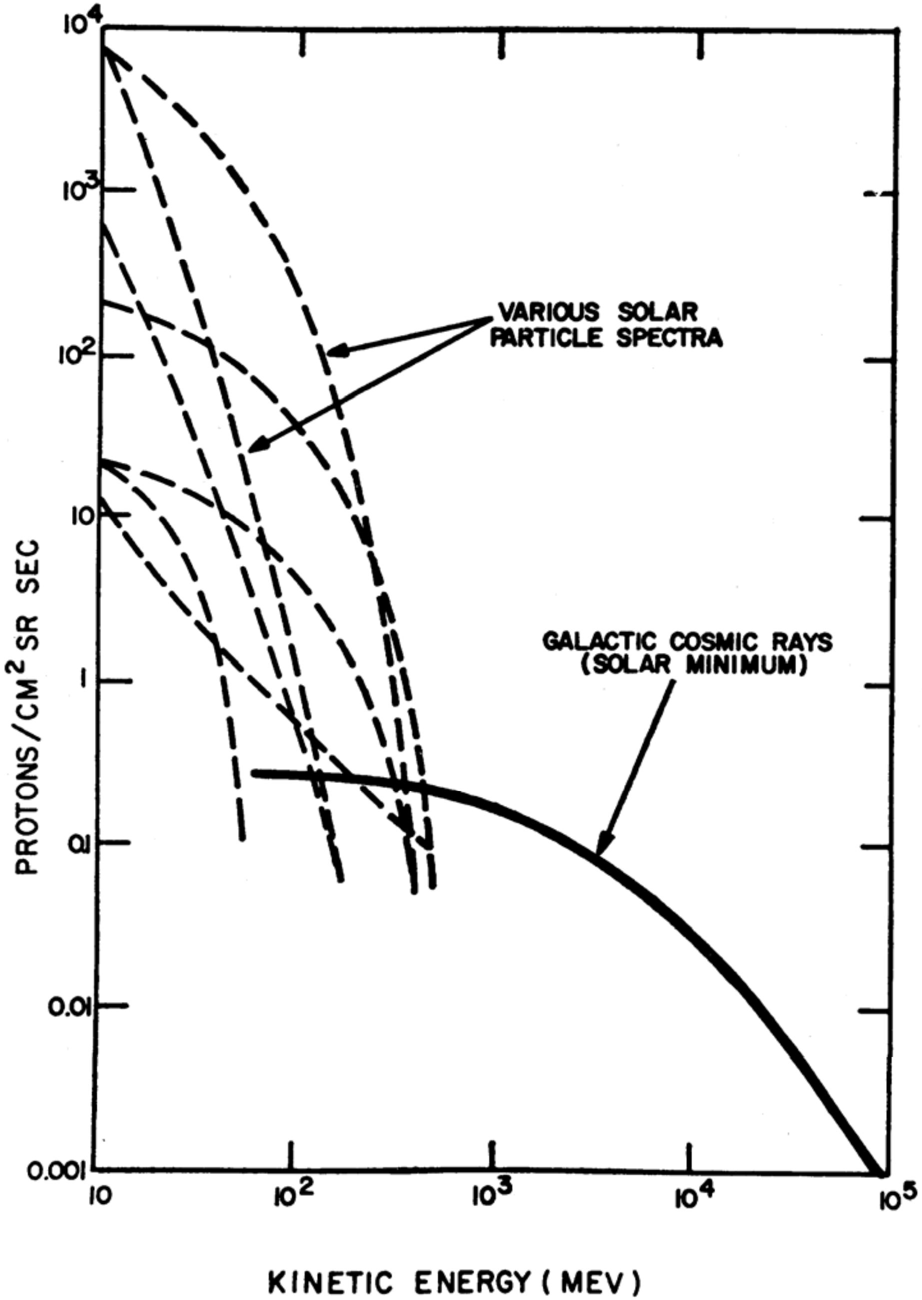
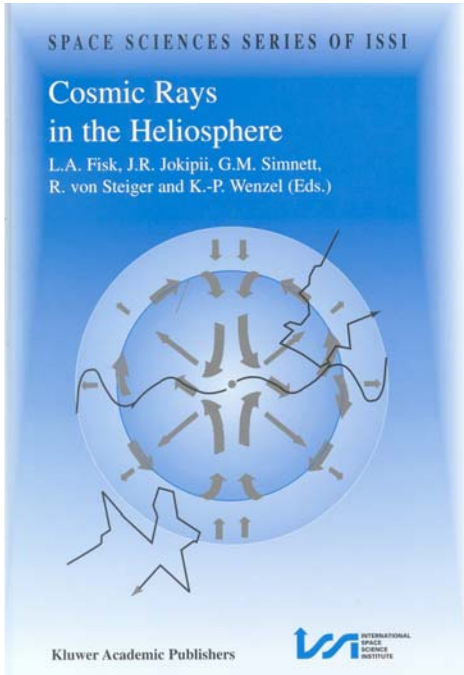


Energy spectra from several moderate-size SCR events compared with the galactic CR spectrum.

(Fitchel and McDonald, Ann. Rev. Astron. Astrophys. 5, 351, 1967)

CR PROPAGATION



The CR transport theory was described, for the first time in 1965, by E.N. Parker*. There are four involved phenomena related with the solar wind (SW) outflow:

- SW convected turbulence ✐ CR CONVECTION
- SW expansion ✐ ADIABATIC DECELERATION
- IMF turbulence ✐ CR DIFFUSION
- IMF gradient and curvature ✐ CR DRIFT

CR COLLISIONS WITH SOLAR WIND PARTICLES ARE COMPLETELY NEGLIGIBLE

Note that SW is either expanding (outward solar flows) or compressing (at shock structures). Therefore, IMF irregularities are moving apart or closer together ✐ CRs undergo adiabatic cooling or heating.

(local deceleration or acceleration)

* E.N. Parker, Planet. Space Sci. Rev. 13, 9-49, 1965.

Assuming *f* (r, R, t) as the CR distribution function (with r: position, R: particle rigidity and t: time) the transport equation is:

convection — diffusion

$$\frac{\partial f}{\partial t} = -\Big(\underbrace{\mathbf{V}}_{a} + \underbrace{\langle \mathbf{v}_D \rangle}_{d}\Big) \cdot \nabla f + \underbrace{\nabla \cdot \left(\mathbf{K}_{(s)} \cdot \nabla f\right)}_{c} \qquad (1)$$

$$+ \underbrace{\frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln R}}_{b} + \underbrace{Q}_{e},$$

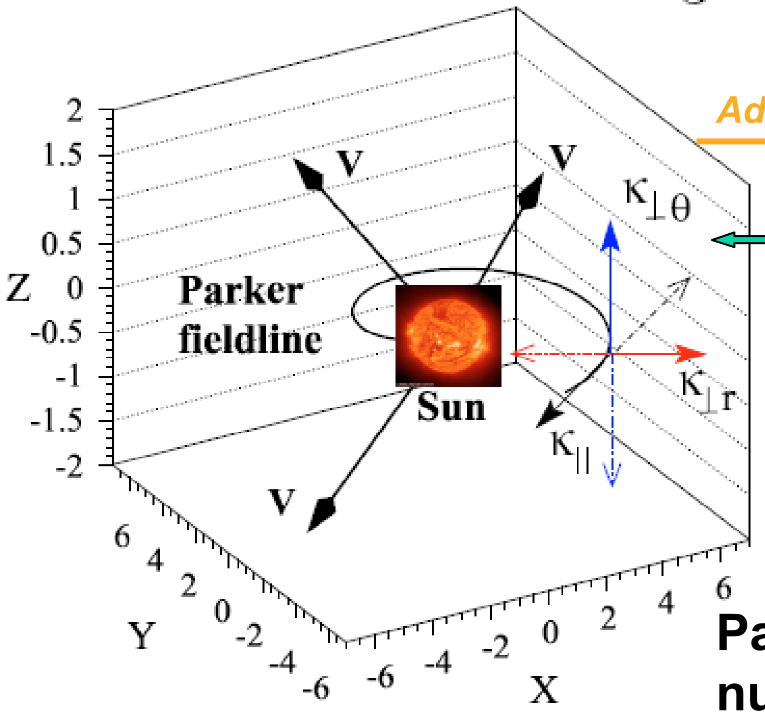
drift

Solar wind speed

Diffusion tensor

Adiabatic loss

Additional internal sources

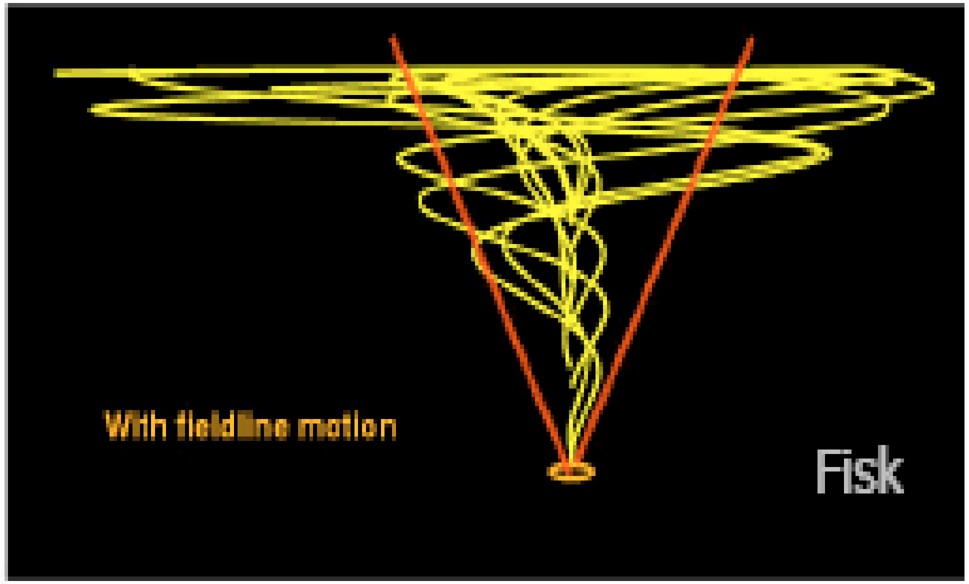


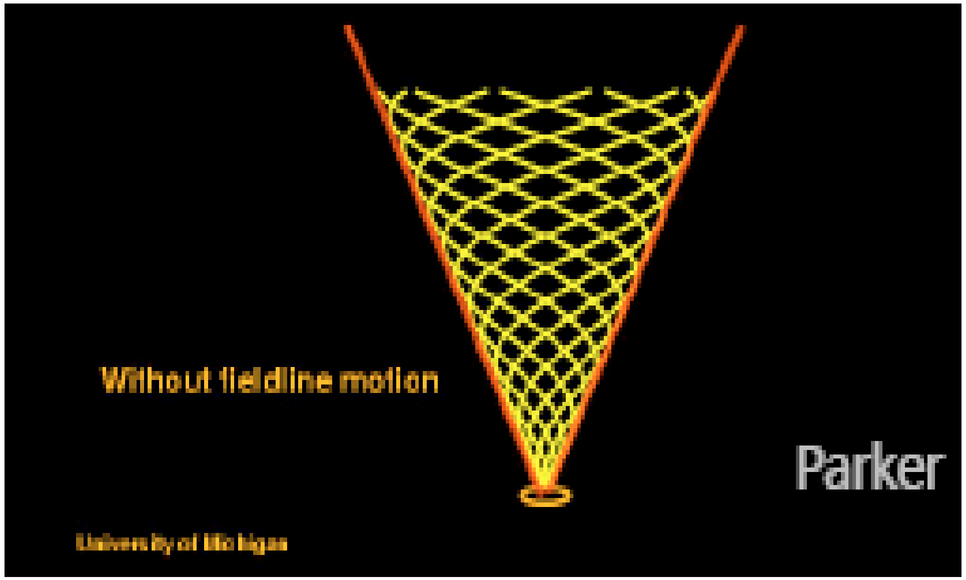
The different elements of the diffusion tensor with respect the Parker spiral.

[taken from Heber, B., IJMPA 20 (29), 6621-6632, 2005]

Parker’s equation (1) is usually solved by the numerically approach.

CR PROPAGATION





Fisk in 1996 introduced a heliospheric MF model, which includes a meridional field component, absent in the Parker model.**

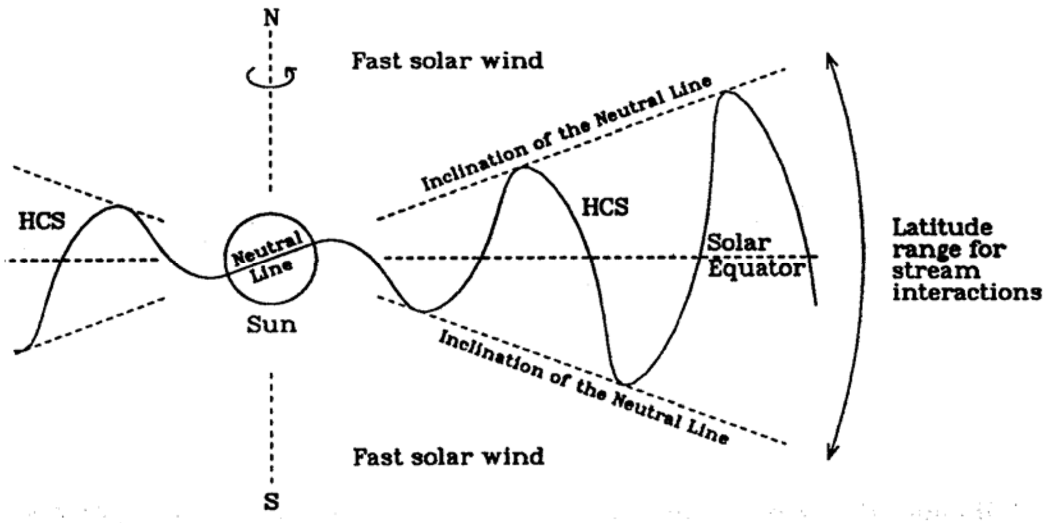
Relevant for the reorganization of the heliospheric MF

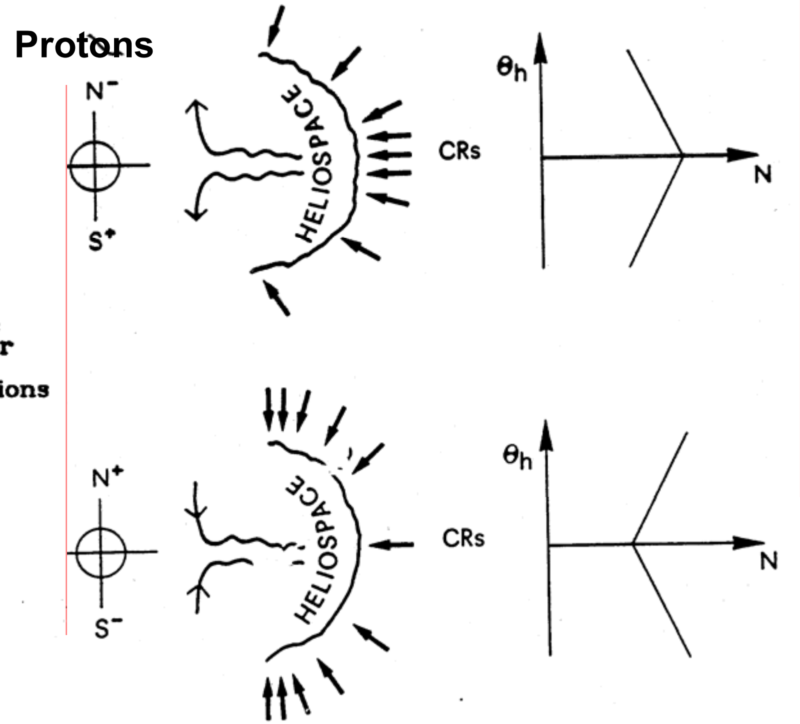
But difficult to handle in numerical models

** L.A. Fisk, JGR 101 (7), 15547-15553, 1996.
* E.N. Parker, Planet. Space Sci. Rev. 13, 9-49, 1965.

OTHER TWO "INGREDIENTS" FOR CR PROPAGATION STUDIES:

- Tilt angle of the current sheet and charged-particle propagation (drift effects)





Gaziz, P.R., Rev. Geophys. 34 (3), 379-402, 1996.

- Magnetic helicity [the measure of magnetic fieldline twisting, linking and kinging (also called writhing)]

CR MODULATION

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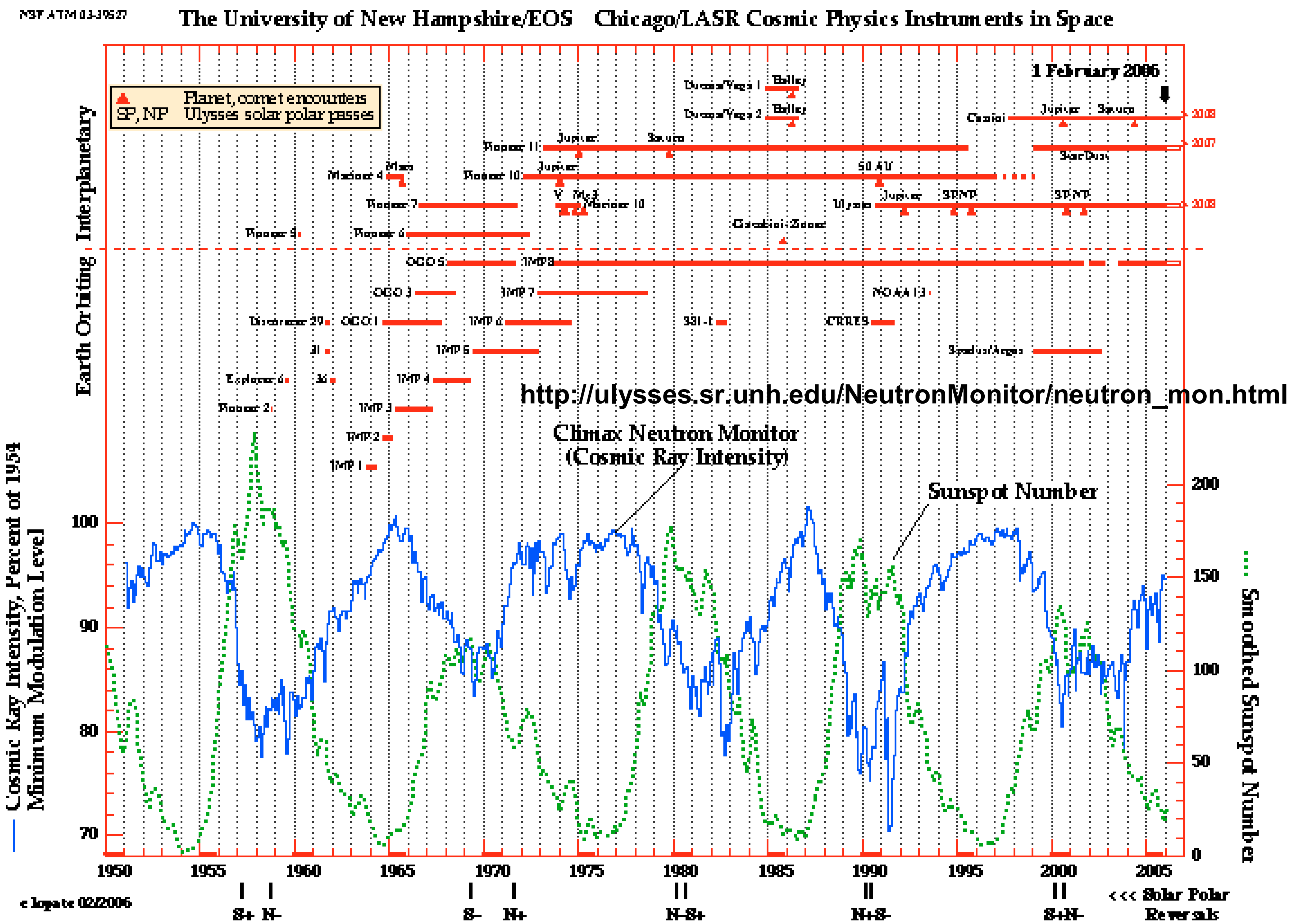


http://ulysses.sr.unh.edu/NeutronMonitor/neutron_mon.html

MODULATION POTENTIAL or MODULATION STRENGTH (Φ)

The total amount of CR modulation observed in the heliosphere can be described by a single parameter (Φ), if in the phase-space an isotropic CR density distribution is assumed (Force-Field approximation).

Introduced Φ in the CR transport equation, it is possible to obtain an analytical solution in which Φ is the variable parameter. Such solution needs the knowledge of the LIS spectrum.

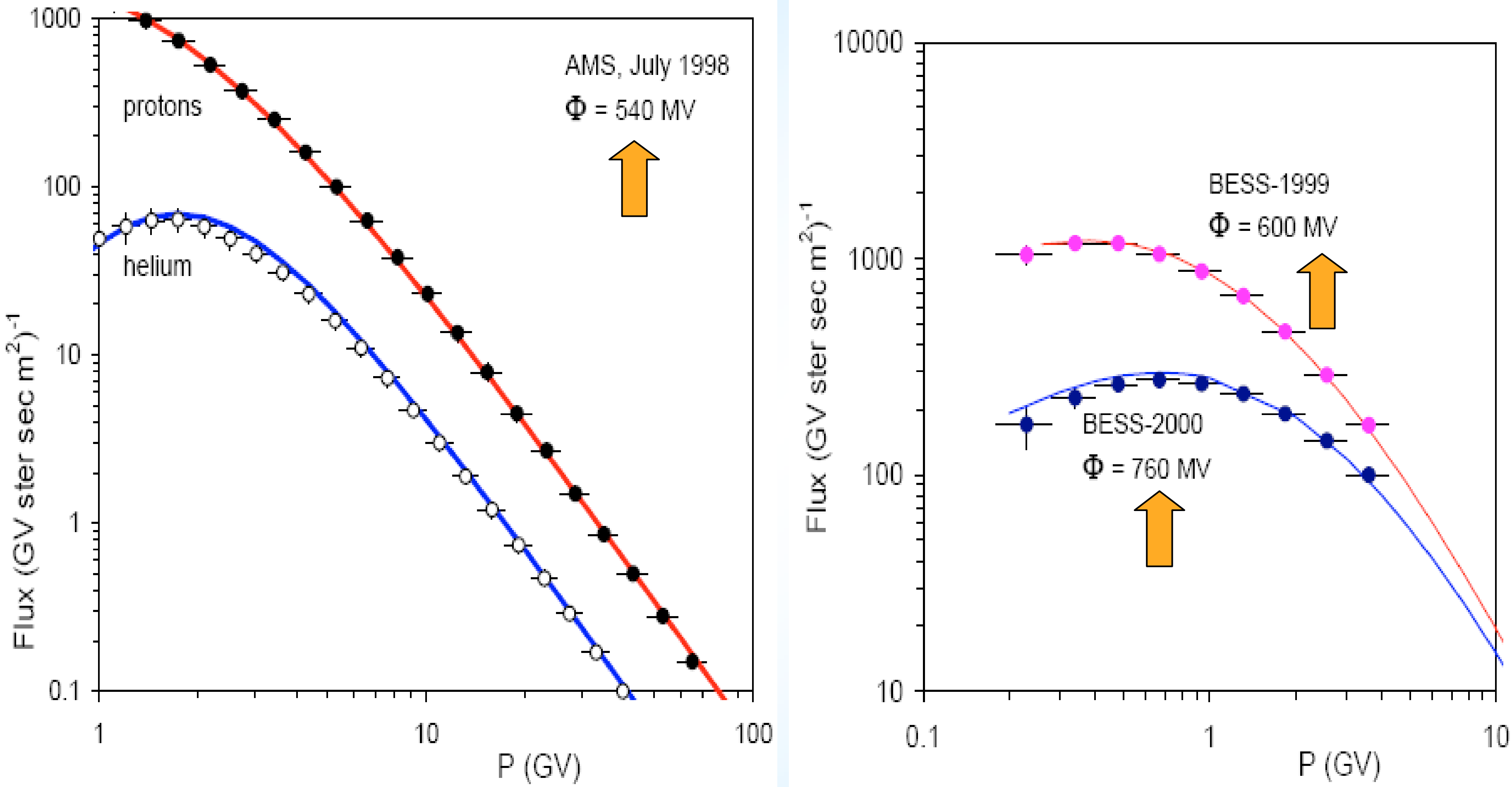
✐ It can be derived also from direct measurements (no assumption for LIS is needed)

✐ It gives better results in the inner heliosphere than in the outer one, where numerical solutions of the CR transport equation work better

✐ EXAMPLE

CR MODULATION

➡ Leaving physical interpretation aside, the force-field formalism provides a very good approximation of the shape of the differential CR energy spectrum, for both p and α, in a wide range of parameters.



SPECTRA PARAMETERIZATION
I.G. Usoskin, Heliospheric modulation of galactic cosmic rays
COST 724 – Trieste Meeting - 2004

MAIN CR VARIABILITIES

ORIGIN

- 22-yr modulation 🕮🕮 HALE CYCLE (heliomagnetic field time history)
- 11-yr modulation 🕮🕮 SCHWABE CYCLE (solar activity)

- Forbush decrease 🕮🕮 TRANSIENT INT. PERTURBATION
- Regular decrease 🕮🕮COROTATING STREAMS (27-day periodicity)
- Diurnal anisotropy 🕮 🕮 CONVECTION + DIFFUSION (24-h periodicity)
- GLE event 🕮🕮 RELATIVISTIC SOLAR PROTONS (sporadic)

CR MODULATION

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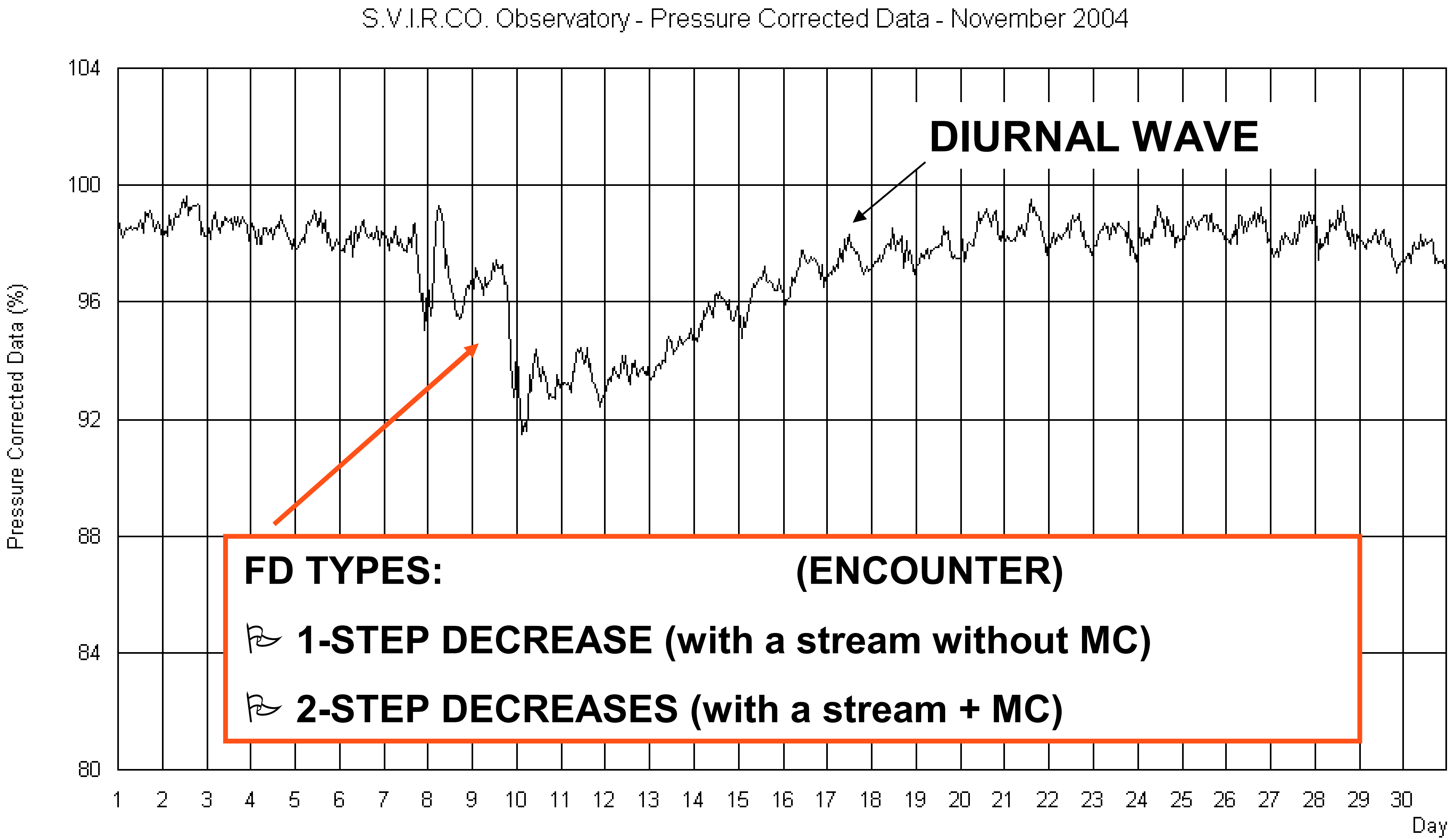
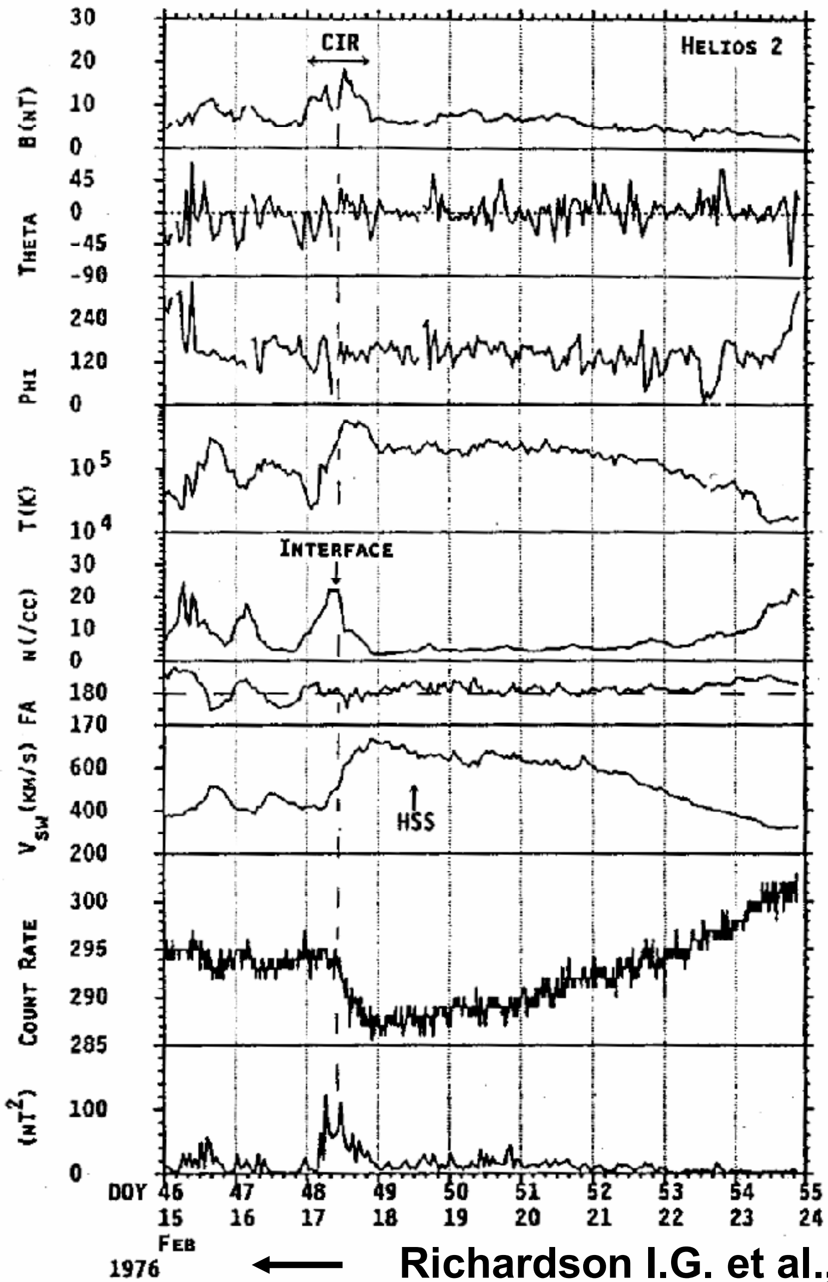
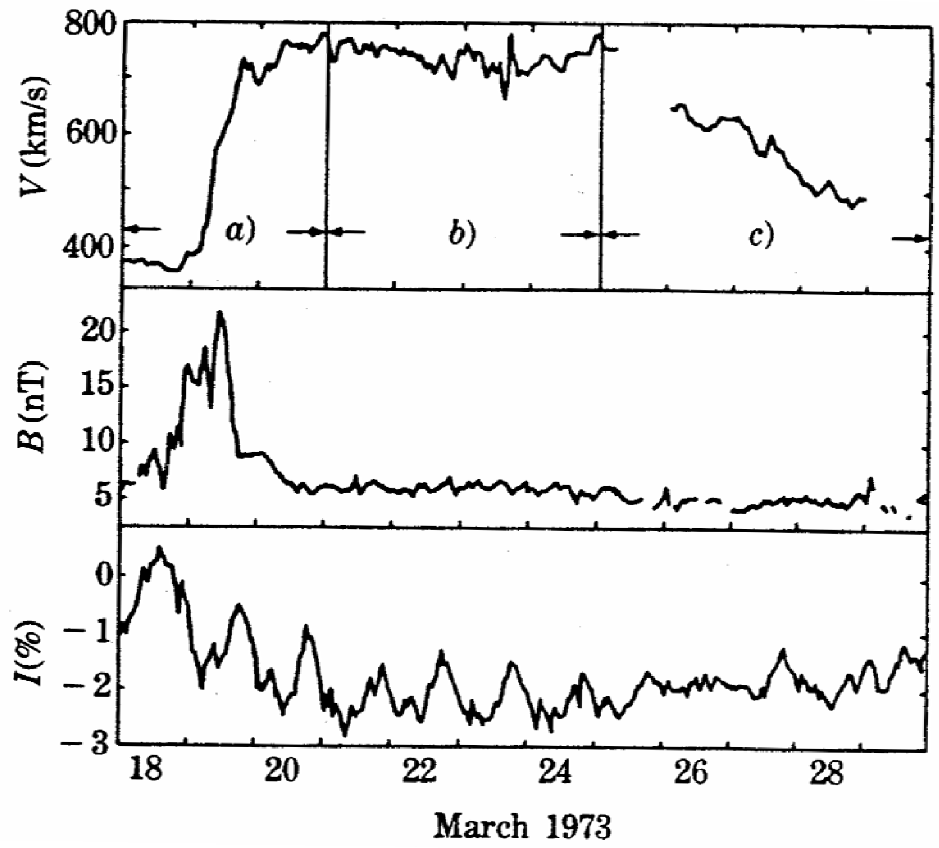


INAF/IFSI_UNIRomaTre collaboration at http://www.fis.uniroma3.it/~svirco/

CR MODULATION





Azimuthal encounter: N-S CR anisotropy + Diurnal wave

(see Storini M.: Galactic cosmic-ray modulation and solar-terrestrial relation-ships, Il Nuovo Cimento, 13C, 103-124, 1990 &14C, 211, 1991).

⟵ **Richardson I.G. et al., JGR 101 (6), 13483-13496, 1996.**

SOLAR CR EVENTS

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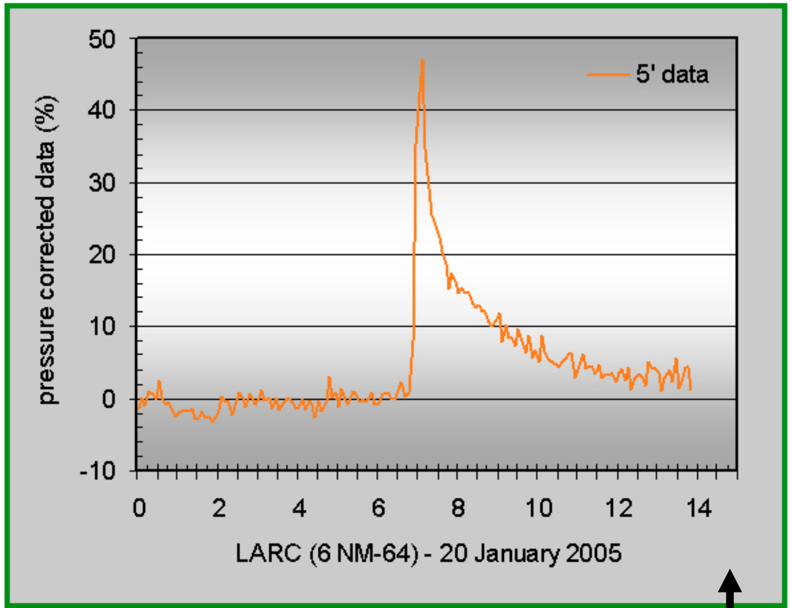
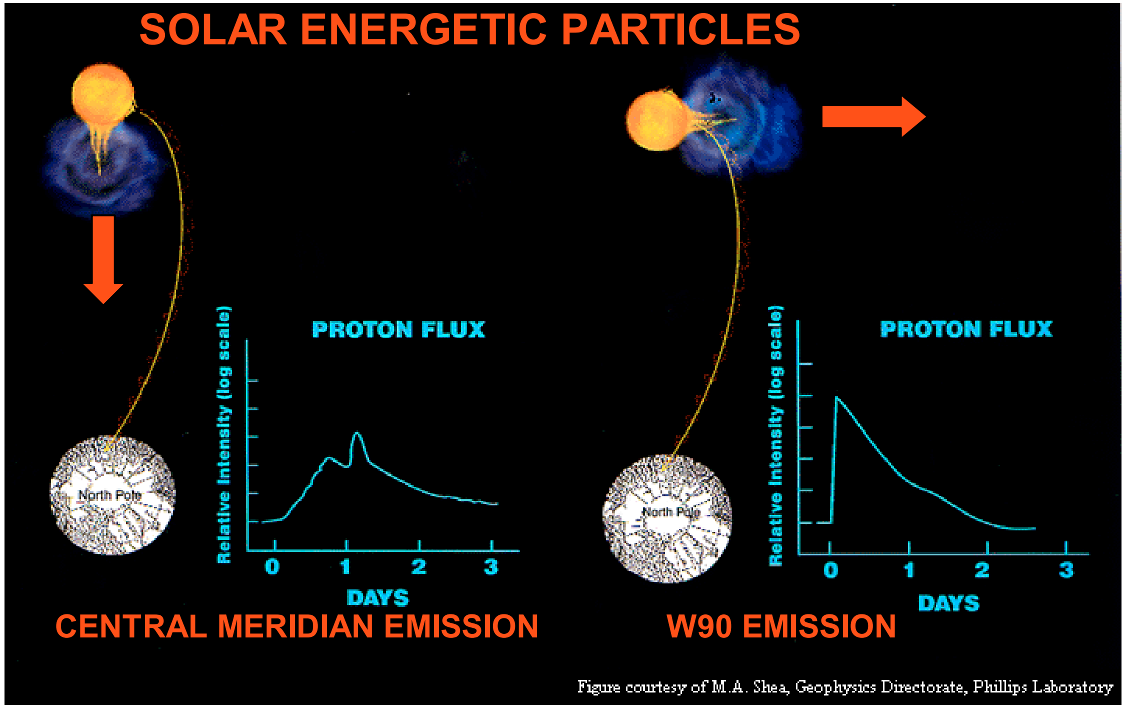


- Distinct increase in the counting rate related to solar activity.
- Particles with near solar wind energies to relativistic ones.
- Catalogues of proton events generally concerns E > 1 MeV.

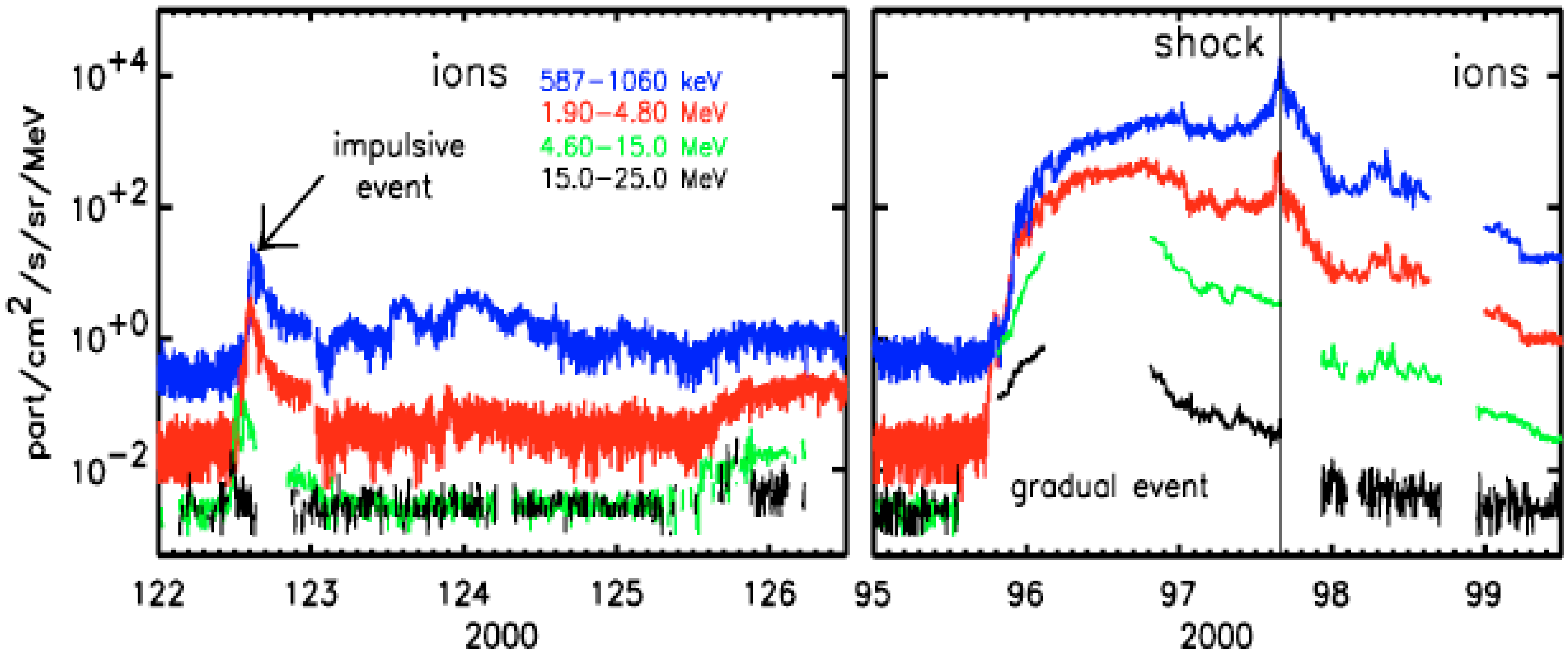


RELATIVISTIC PROTONS

Antarctic Laboratory for Cosmic Rays –

King George Island

SOLAR CR EVENTS



Time profiles of protons for an impulsive (left) and a gradual (right) SEP event as measured by ACE/EPAM (two lower energy channels) andIMP-8/CPME. (two high energy channels)

From Aran et al.:

ESA/ESTEC Contract 14098/99/NL/MM (TOS-EES)
(the final report can be downloaded from the web of the group:
http://www.am.ub.es/~blai)
DGU/MECD Spain

SOLAR CR EVENTS

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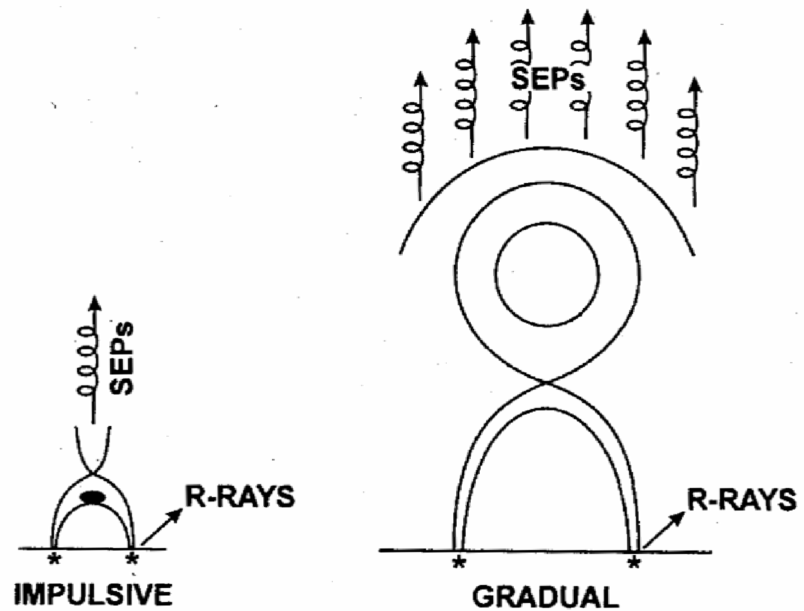
PROPERTIES OF IMPULSIVE AND GRADUAL EVENTS

	IMPULSIVE (FLARE)	GRADUAL (CME - SHOCK)
PARTICLES:	ELECTRON-RICH	PROTON-RICH
$^3He/^4He$	~1	~0.0005
Fe/O	~1	~0.1
H/He	~10	~100
Q_{Fe}	~20	~14
DURATION	HOURS	DAYS
LONGITUDE CONE	<30°	~180°
RADIO TYPE	III, V(II)	II, IV
X-RAYS	IMPULSIVE	GRADUAL
CORONAGRAPH	---	CME
SOLAR WIND	---	IP SHOCK
EVENTS/YEAR	~1000	~10



Taken from Cliver E.W., AIP Conf. Proc. 516, 103-119, 2000.

Present scenario more complex:

Also mixed events!!!

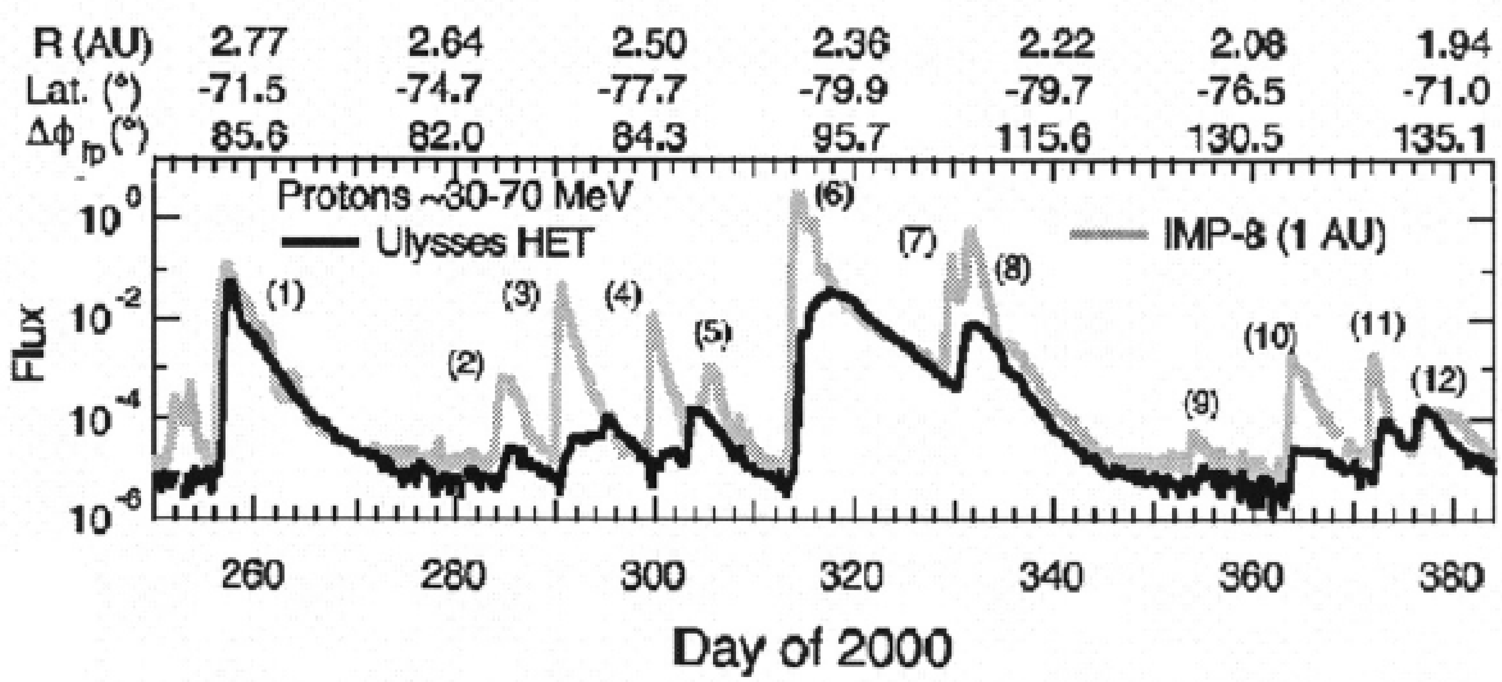
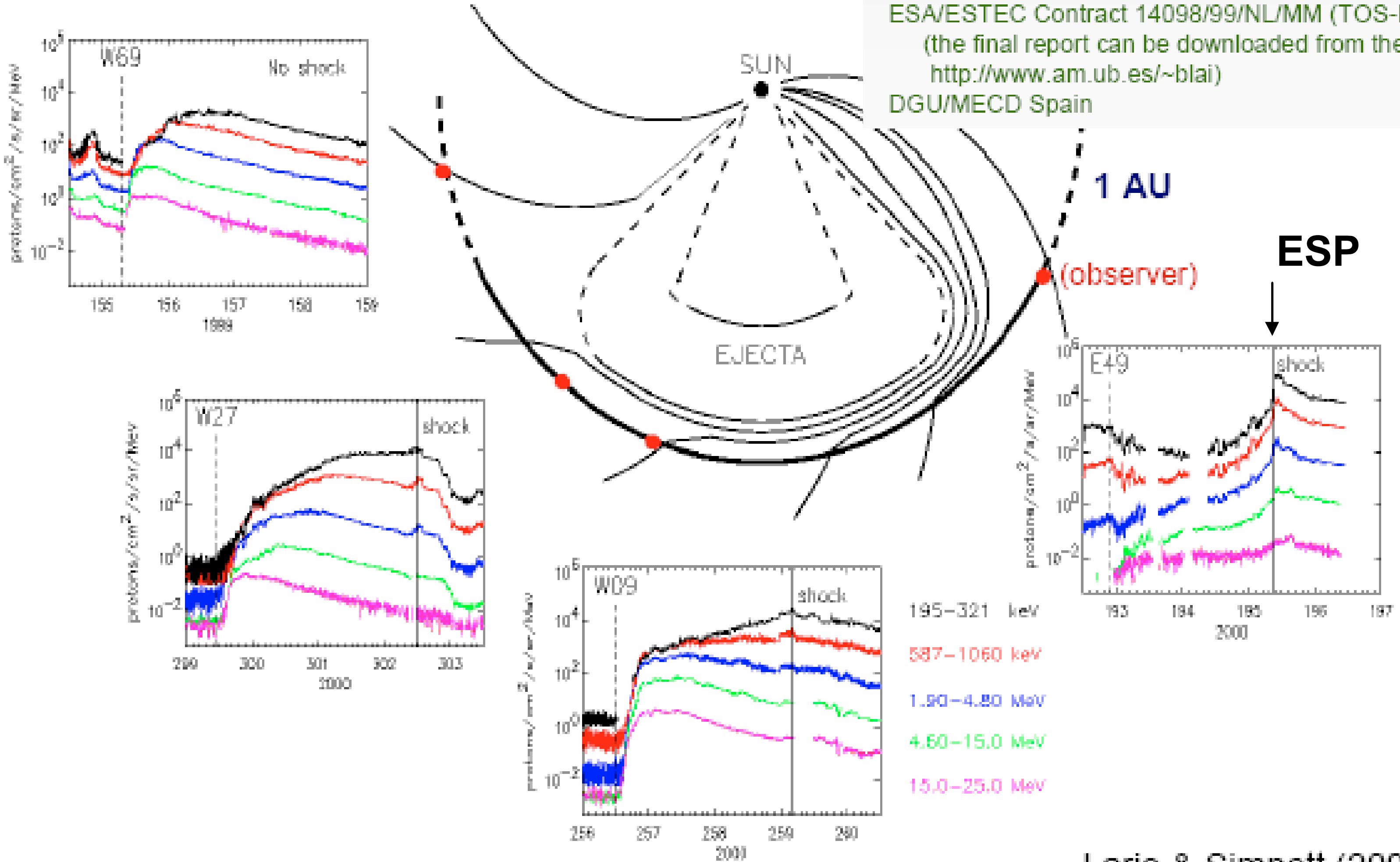


Fig. 22. Time profiles of protons from Ulysses at high latitudes and IMP-8 in the ecliptic **McKibben et al., Space Sci. Rev. 97, 257, 2001**

Taken from Cohen C.M.S, Proc. 28th ICRC, 8, 113-133, 2004

Typical flux profiles of SEP events generated from different solar longitudes relative to the observer

ESA/ESTEC Contract 14098/99/NL/MM (TOS-EES)
(the final report can be downloaded from the web of the group: http://www.am.ub.es/~blai)
DGU/MECD Spain



Lario & Simnett (2004)

ACE/EPAM and IMP-8/CME data. Dashed vertical lines: occurrence of the parent solar event. Solid vertical lines: arrival of the interplanetary shock

SOLAR CR EVENTS

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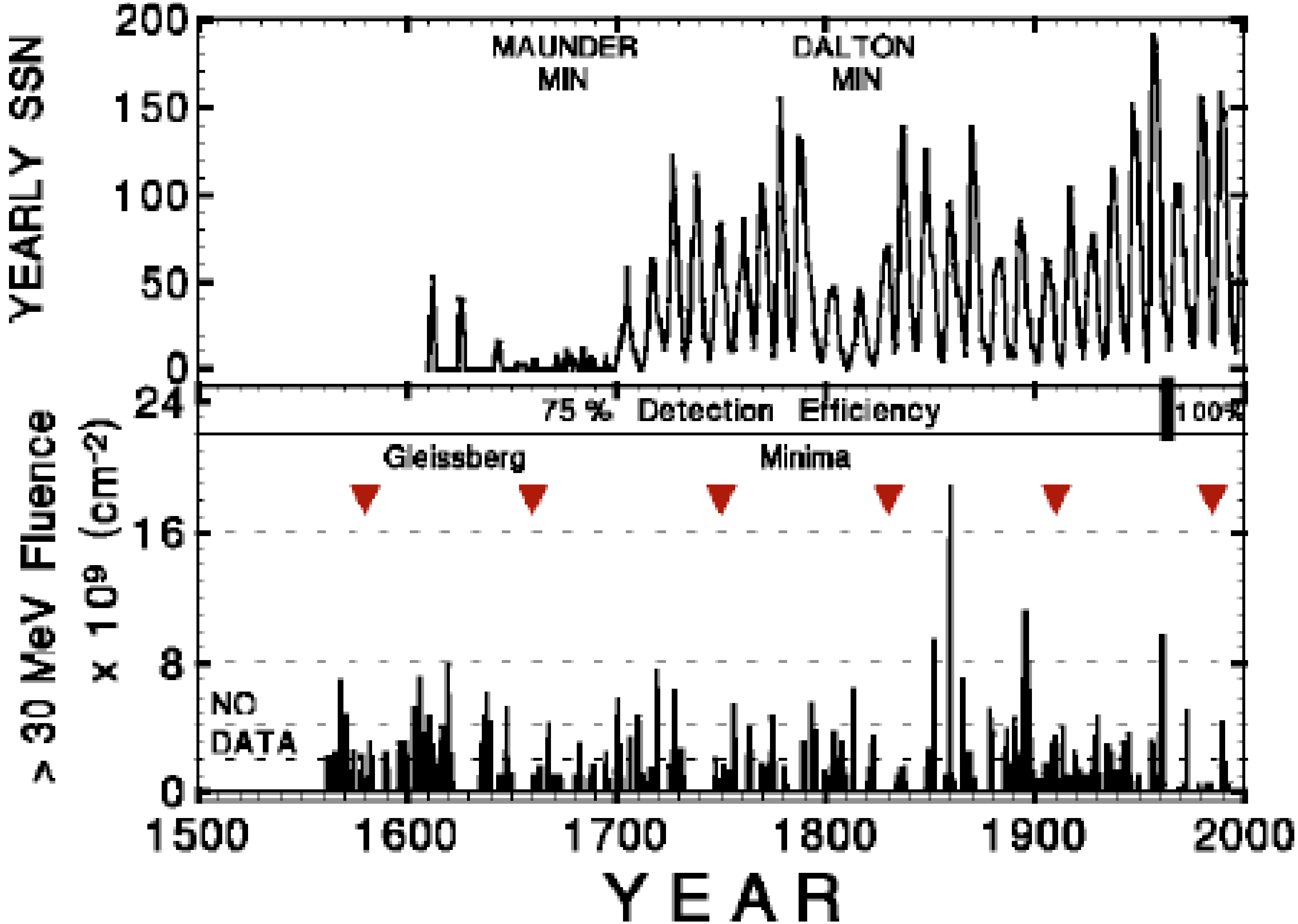

Solar particle FLUENCE derived from ice cores (see McCracken K.G. et al., JGR 106 (10), 21585-21598 & 21599-21609, 2001).

In summary

POPULATIONS

Galactic CRs

Anomalous CRs

Solar CRs,

but also:

- pick-up ions
- energetic storm particles (ESP)
- diffuse upstream ions (bow shocks of planets and comets)
- corotating ions

CONCLUSION

These lectures intend to give only the background knowledge of the field, with special attention on topics related to Space Weather. No completeness should be expected due to the few hours allowed.

Students are encouraged to read the Proceedings of the International Cosmic Ray Conferences (specially the volume INVITED, RAPPORTEUR, AND HIGHLIGHT PAPERS, 29 meetings from 1947).