Solar Extreme Events 2007: Fundamental Science and Applied Aspects

SEE 2007: International Symposium
Athens, Greece
Monday 24 September– Thursday 27 September
2007

COSPAR Colloquia

On the Early Phase of Solar Energetic Particle Events. Are there signatures of acceleration mechanism?

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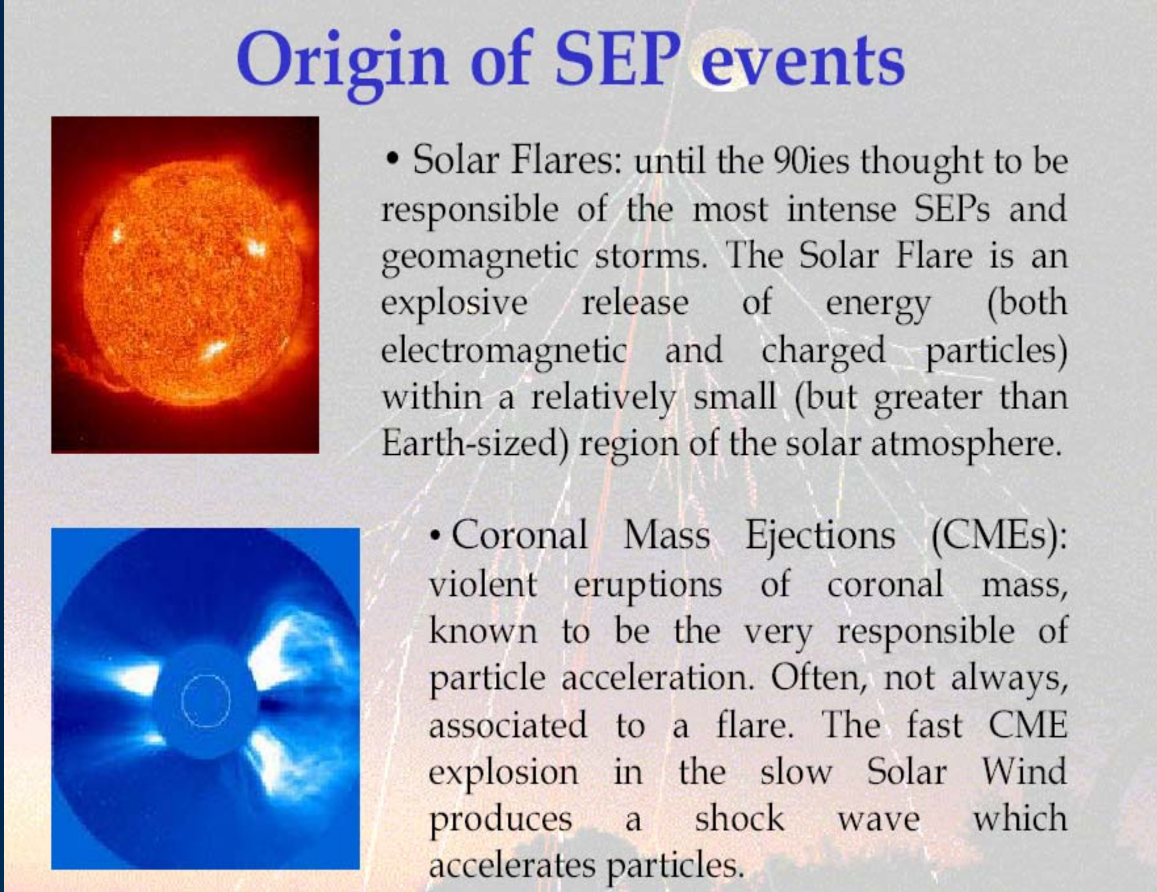
Motivation

The most interesting problem: **Where and how are solar energetic particles generated?** There is no generally accepted opinion about the place of acceleration and dominant mechanism of acceleration

The observed SEPs are influenced by many processes of multiple and/or prolonged acceleration, and propagation in the corona and interplanetary space. Therefore, it is difficult to distinguish signatures of acceleration mechanisms from particle observation

The early phase of the SEP events is most close to the time of acceleration, and the role of interplanetary transport is minimal for the first arriving particles. Extreme events provide the best oportunity for study of the early phase because of high signal to noise ratio. Relativistic solar protons are are the most proper candidate for approach to a problem of particle acceleration



Origin of SEP events

- Solar Flares: until the 90ies thought to be responsible of the most intense SEPs and geomagnetic storms. The Solar Flare is an explosive release of energy (both electromagnetic and charged particles) within a relatively small (but greater than Earth-sized) region of the solar atmosphere.

- Coronal Mass Ejections (CMEs): violent eruptions of coronal mass, known to be the very responsible of particle acceleration. Often, not always, associated to a flare. The fast CME explosion in the slow Solar Wind produces a shock wave which accelerates particles.

Concerning the powerful SEP events (GLEs), fast CMEs and flares always occur together, which makes it difficult to directly identify the actual source of SEP events detected near Earth orbit..

Plan of the talk

- Current status of the problem
  - Main acceleration mechanisms
  - Recent obseravational works
- Early phase of GLEs (set of 9 recent events)
  - Definition of first particle arrival
  - Solar phenomena to be considered
  - Timing of particle injection
  - Correlations of particle Intensity and spectra with expected from shock acceleration
- Discussion:
  - flare vs shock;
  - stochastic vs reconnection
- Conclusion

Generally considered acceleration mechanisms for generation of solar energetic particles

- Shock acceleration
- Stochastic acceleration
- Acceleration in the DC electric fields

$$\frac{dJ}{dE} \propto (E^2 + 2Em_0c^2)^{-(\sigma+2)/(\sigma-1)}$$

Shock acceleration

- **Diffusive shock acceleration (first-order Fermi acceleration):** charged particles stream into magnetic perturbations in the post-shock region, reflect, and are scattered back across the shock by the pre-shock Alfvén waves.
- $dE/dt \propto v_c/v$, where P and v are energy and velocity of the particle and v_c is velocity of magnetic compression.

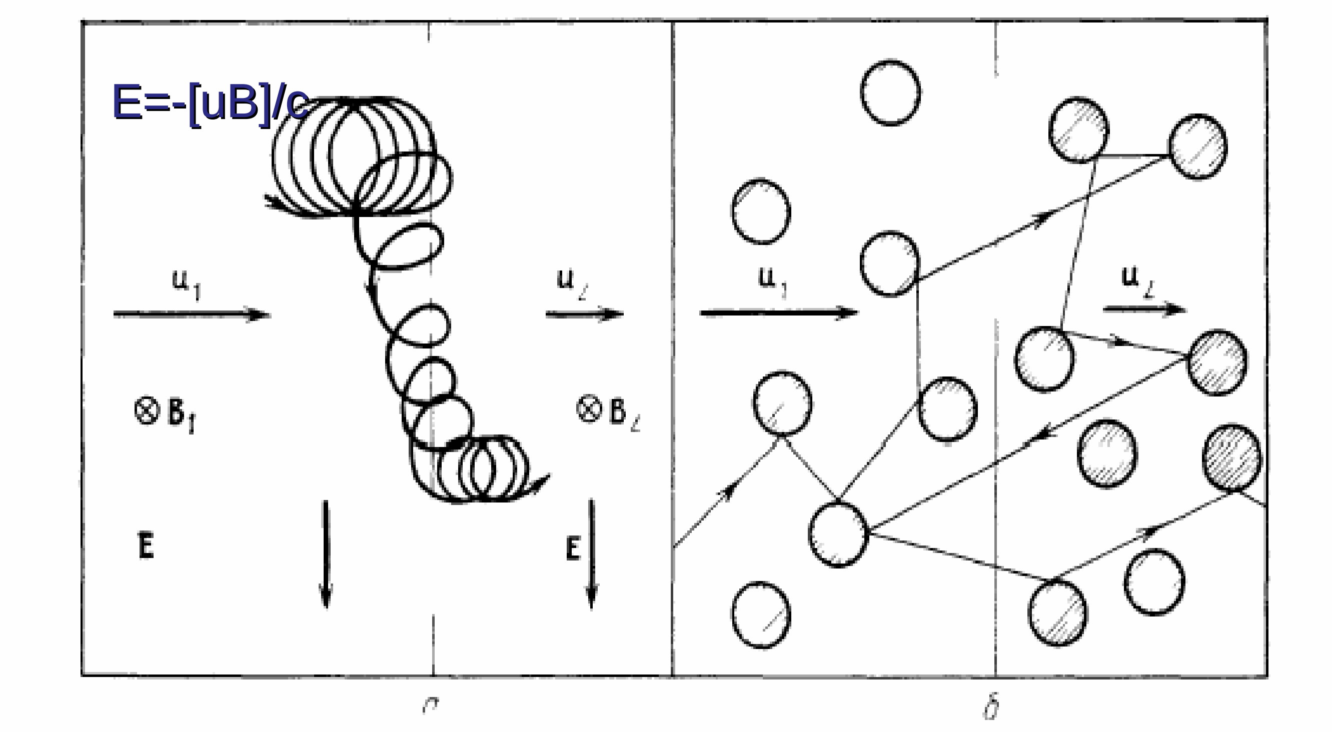
Spectral form:

$$\frac{dJ}{dE} \propto (E^2 + 2Em_0c^2)^{-(\sigma+2)/(\sigma-1)}$$

Shock acceleration

Laminar perpendicular shock wave

Shock with the turbulent perturbations



1 – upstream region, 2 – downstream region;

u is bulk plasma flow velocity;

$\sigma = u_1/u_2 = B_2/B_1 = \rho_2/\rho_1$ is the compression ratio;

spectral index $\gamma = (\sigma+2)/(\sigma-1)$

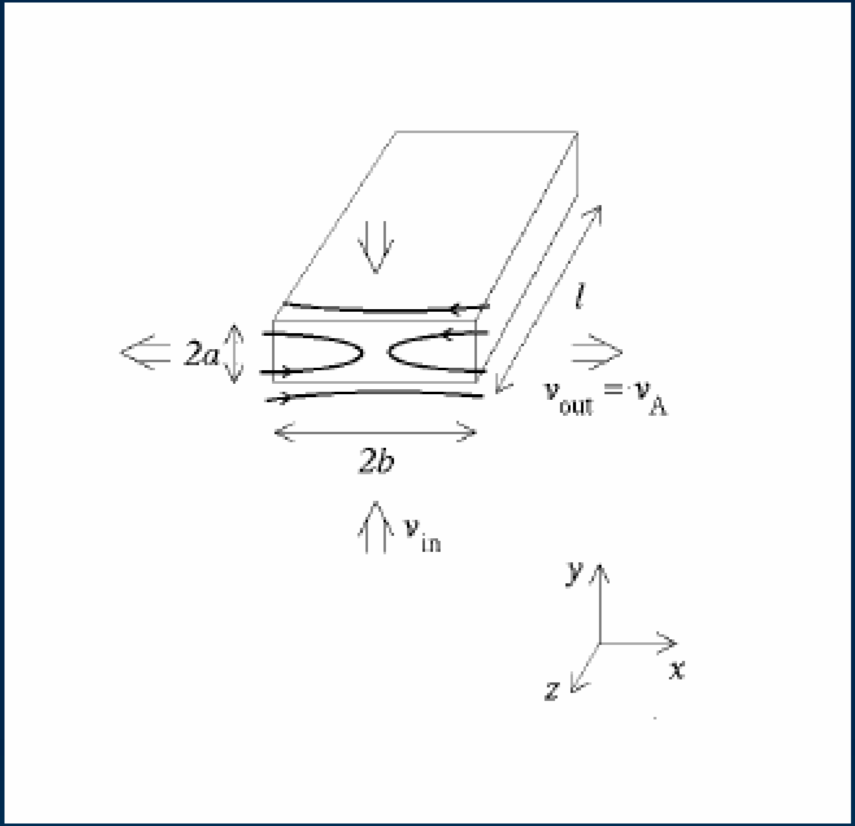
Stochastic acceleration

Second-order Fermi acceleration: particles gain or lose energy while scattering in the turbulent plasma, but they systematically gain energy over long times. This is because the head-on, energy-gaining, collisions happen more often than the overtaking, energy-losing, collisions

$dE/dt \propto (v_c/v)^2$, where P and v are energy and velocity of the particle and v_c is velocity of magnetic compression.

$\frac{1}{c}$

➢Acceleration in the DC electric fields



The magnetic energy may be released via reconnection of oppositely directed magnetic field

$$\mathcal{E} = -\frac{1}{c}[V_{in}B]$$

$$E = e\,\mathcal{E}\,L_{ac}$$

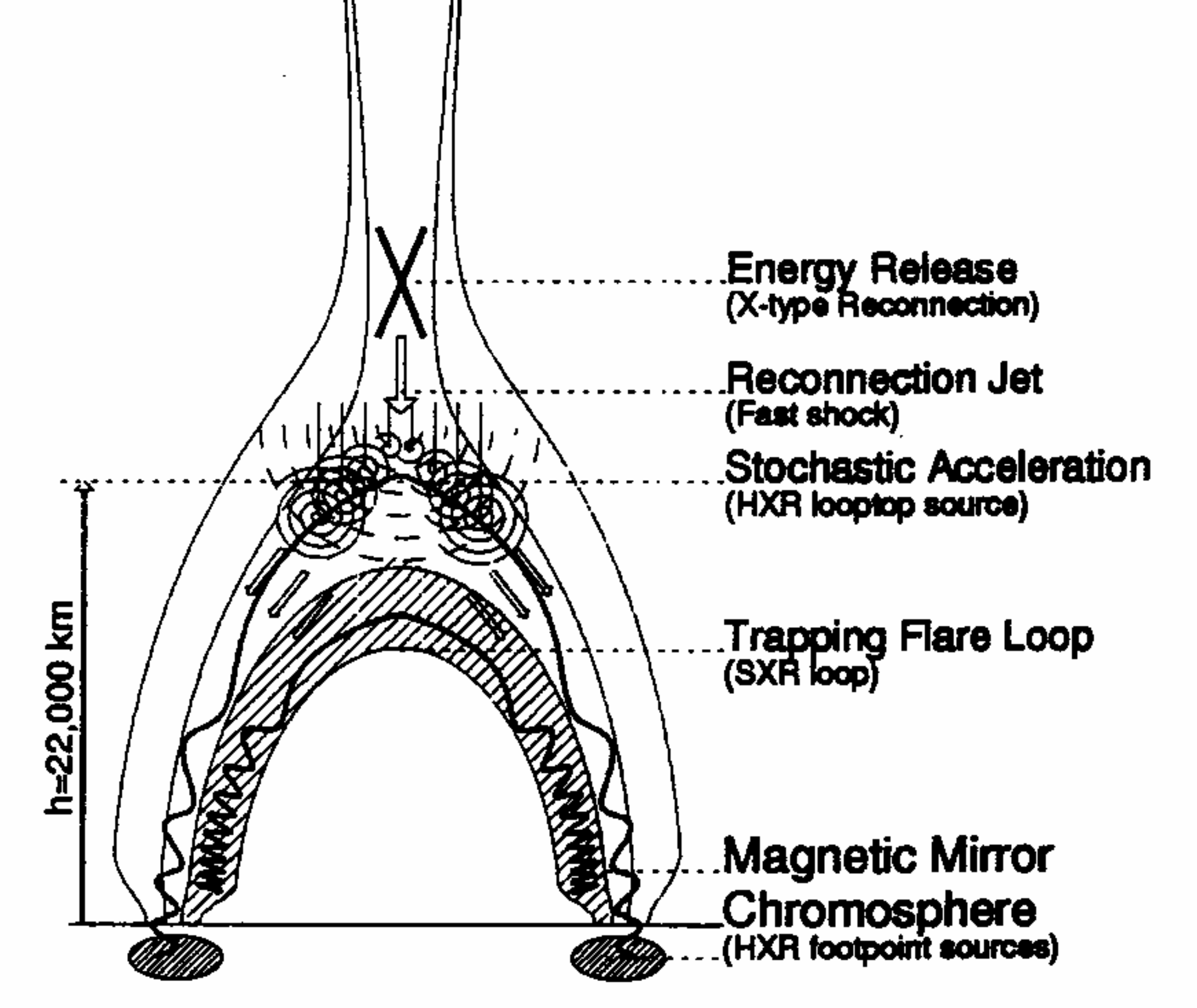
$$L \approx 10^9 cm,$$
$$V_{in} \approx 10^5\text{–}10^6\ cm/s,$$
$$B \approx 100\text{–}300\ G$$

$$L_{ac} \ll L$$

Projection of the magnetic field in the reconnecting current sheet

(length *L*, thickness 2*a*, width 2*b*) on the *XY* plane. The electric field ε and the longitudinal magnetic field *Bk* are along the *Z*-axis.

Y. Litvinenko (2003)



**Taken from
J.-I. Sakai and
C. de Jager,
1996**

Model of the flare (Aschwanden et al., 1995): reconnection i the X-point is followe by a downward directed shocks and MHD turbulence. (Selective He^3 acceleration may occu here) . Timing is sec – min, E is up to GeV, spectrum is a power law.

Stochastic acceleration – diffusion in the momentum space. $dE/dt \propto (v_c/v)^2$, where E and v are energy and velocity of the particle and v_c is velocity of magnetic compression.

The observational consequences of proton-generated by CME-driven shock waves

- The streaming limit
- The spectral knee position vs. Q/M
- Peculiar abundance variations
- Ionic charge state relevant to relatively low temperature

These features are really observed but at nonrelativistic energies and not at early phase of event.

Flare or shock?

If flare, then
DC or stochastic?

Adherents of shock acceleration of Relativistic Solar Protons

S.W. Kahler, G. M. Simnett, M.J. Reiner. Onsets of solar cycle 23 Ground Level Events as probes of Solar Energetic Particle Injections at the Sun, Proc 28 ICRC,3415-3418, 2003.

J. W. Bieber, P.Evenson, W. Droege, R. Pyle, D. Ruffolo, M. Rujiwarodom, P. Tooprakai, T. Khumlumlert, Spaceship Earth observations of the Easter 2001 solar particle event (15/04/2001), Ap.J., 601:L103–L106, 2004.

N. Gopalswamy, H. Xie, S. Yashiro, I. Usoskin, **Coronal Mass Ejections and Ground Level Enhancements,** Proc. ICRC 29, Pune, 1, 169-172, 2005.

N. Gopalswamy, S. Yashiro, M. L. Kaiser, R. A. Howard, Coronal mass ejection interaction and particle acceleration during the 2001 April 14-15 events. Adv. Space Res., 32(12), 2613-2618, 2005.

D. Bombardieri, K. Michael, M. Duldig, J. Humble, Relativistic Proton Production during the 2001 April 15 Solar Event The Ap. J., 665(1), 813-823, 2007.

Main arguments:

- Delay between a flare and the particle escape into IMF
- Close connection with type II radio emission
- Long injection comparatively to the impulsive phase of a flash
- Connection with most powerful CME
- Modeling of particle injection and transport: good fitting of intensity time profile and form of energy spectrum

Adherents of flare acceleration of Relativistic Solar Protons

E.V. Vashenyuk, Yu.V. Balabin, L.I. Miroshnichenko, J. Perez-Peraza , A. Gallegos-Cruz, Relativistic solar cosmic ray events (1956-2006) from GLE modeling studies. Proc. 30 ICRC, 2007

C. Li, Y.H. Tang, Y. Dai, W.G. Zong, C.Fang– Two acceleration characteristics of solar energetic particles in the 2000 July 14 event. A&A, arXiv:astro-ph/0609682v4 25 Jun 2007.

S.N. Kuznetsov, V.G. Kurt, B.Yu. Yushkov, K. Kudela CORONAS-F satellite data on the delay between the proton acceleration on the Sun and their detection at 1 AU. Proc. 30 ICRC, 2007

G. M. Le*; Y. H. Tang, Y. Q. Tang. What did the occurrence of relativistic solar neutrons on 28 October 2003 mean? Proc. 30 ICRC. 2007.

K.G. McCracken, H. Moraal.Two acceleration mechanisms for ground level enhancements. Proc. 30 ICRC, 2007

Etc.

Arguments in favor of flare origin

Obligatory powerful flare presence

Fast timing without correlation with CME velocity or radial distance

Presence of prompt component with peculiar characteristics (Vashenyuk et al.)

Longitudinal distribution of the parent flares

Early phase of GLEs (as observed at 9 recent events)

Relativistic protons are the fastest to arrive after acceleration. So the events recorded by the ground based neutron monitors (GLEs) are the main object of analysis.

Extreme events are the most proper because of high signal to noise ratio on the early phase

Information from the accompanying solar phenomena:

Solar γ and neutrons
Soft and hard X-rays bursts (sX and hX)
Solar radio emission of the II and III types
Coronal mass ejections (CME)

Timing of first-arriving relativistic solar particles

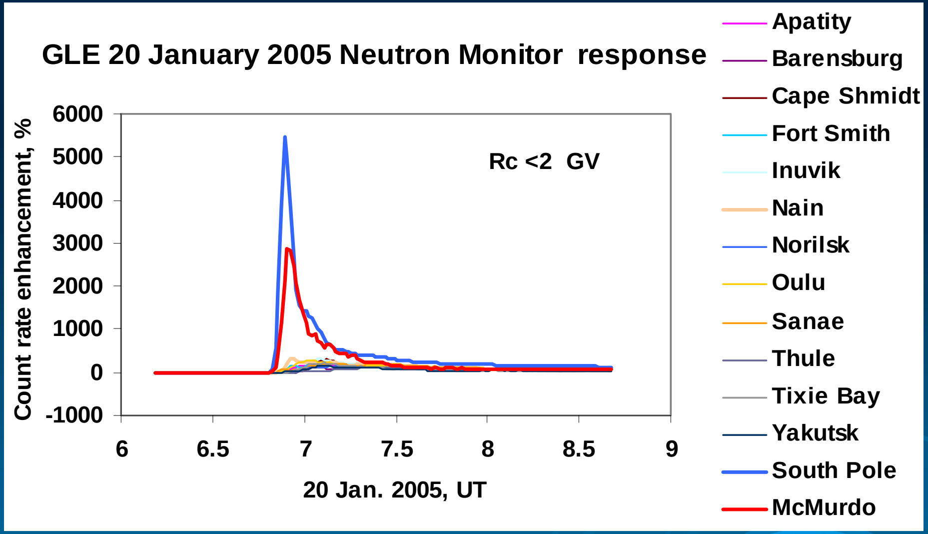
Earlier works: E.W. Cliver, S.W. Kahler, M.A. Shea, D.F. Smart, Ap.J., 260,362-370, 1982

And many others afterward

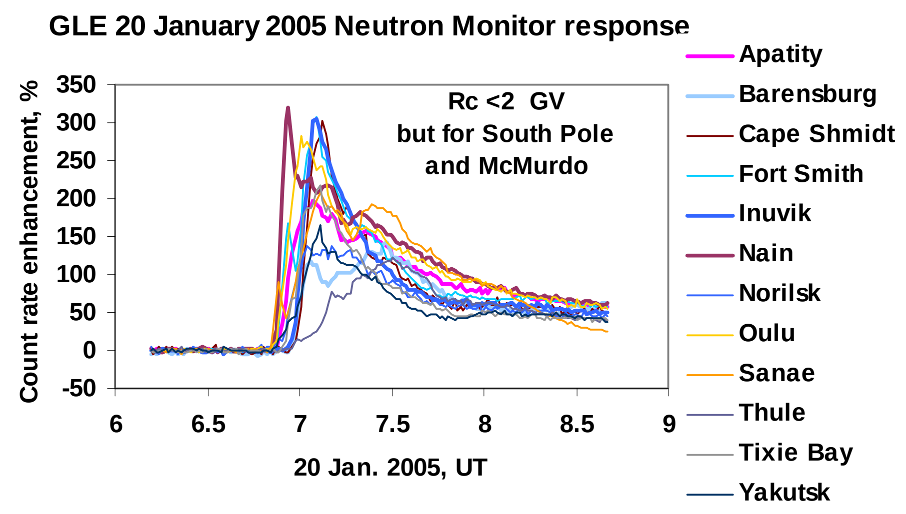
- Definition of first particle arrival

1. Choise of station with earliest arrival
2. Determination of the path length with account of solar wind velocity value
3. Determination of solar time of escaping (assuming that effective energy was around 1.5 GeV)

GLE 20 January 2005



All stations

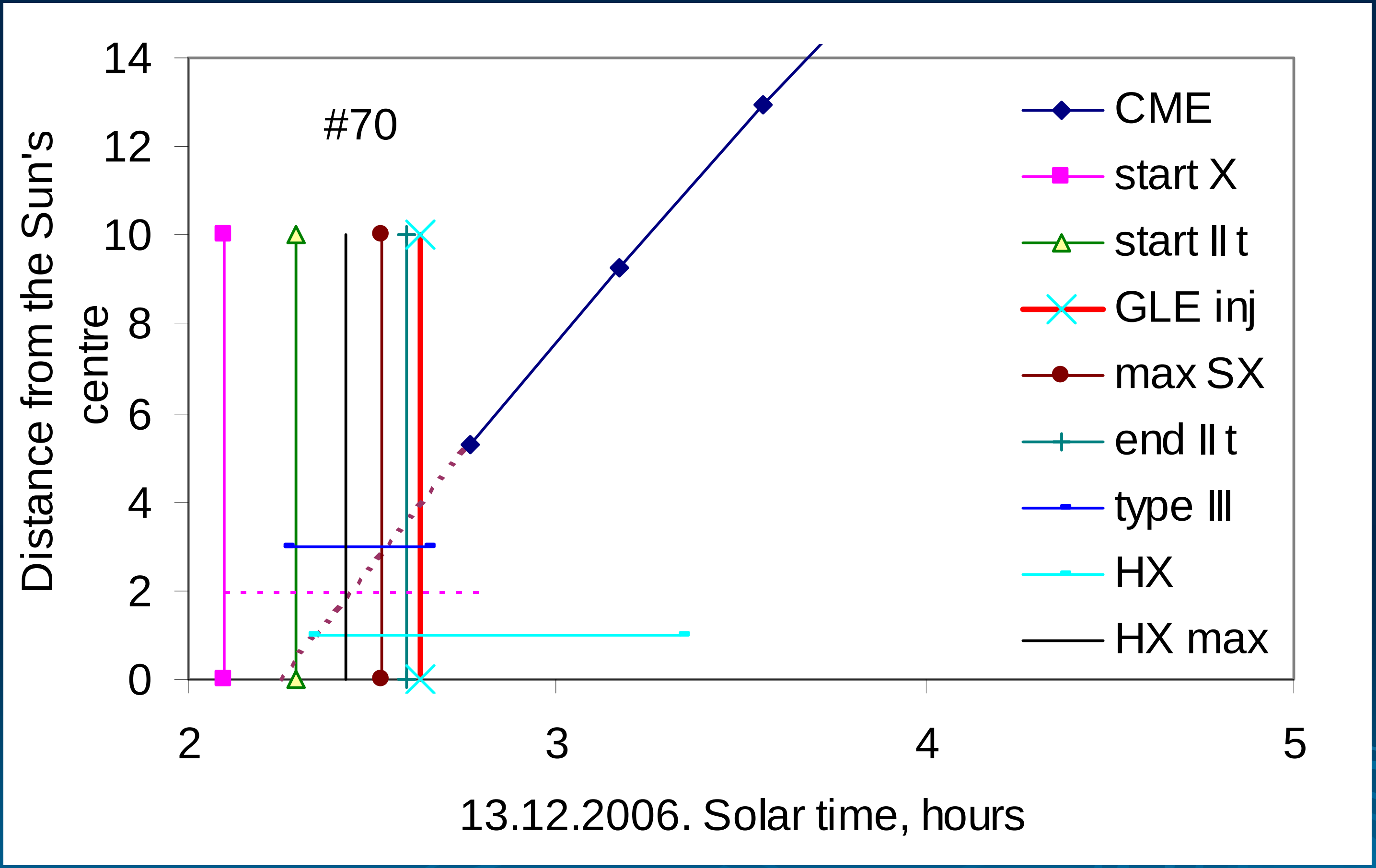


without South Pole and McMurdo

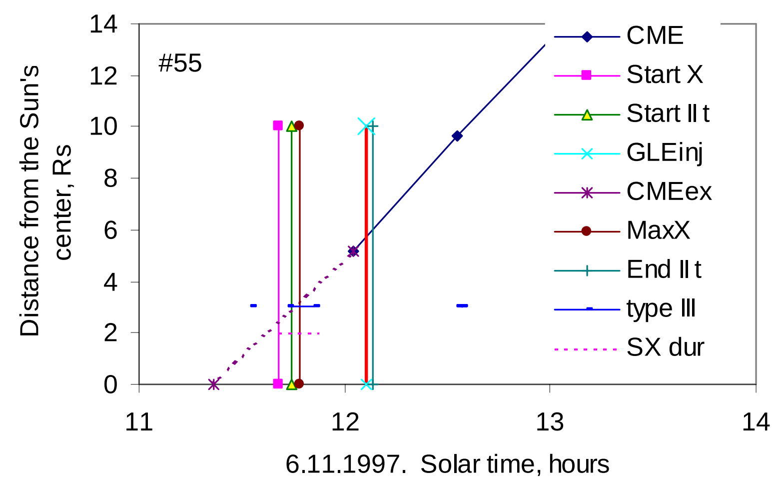
Choice of station with earliest arrival of relativistic solar protons

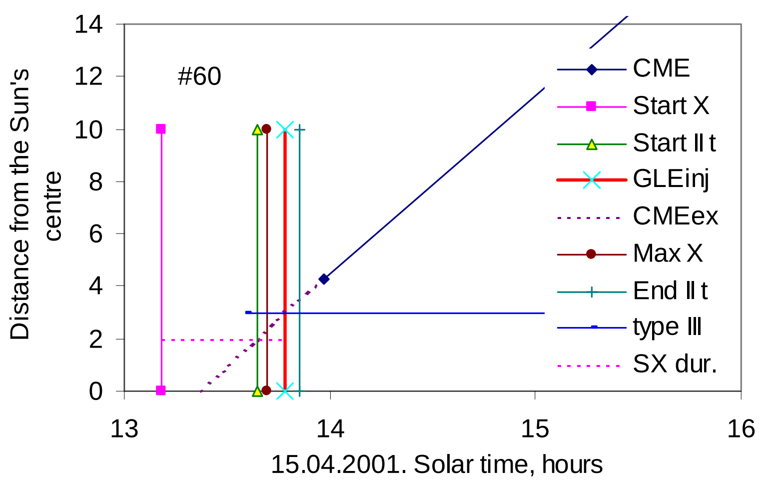
GLE number	Date	Flare		The earliest arrival, UT	Station	Solar wind velocity km/s	Time of propagation, min
55	6.11.1997	S18 W63	2B/X9.4	12:17	South Pole	349.66	10.94
59	14.07.2000	N22 W07	3B/X5.7	10:32.5	Oulu	593.47	9.76
60	15.04.3001	S20 W87	2B/X14.4	13:57	South Pole	498.85	10.04
61	18.04.2001	S20 W120	.../C2.2	2:33	South Pole	490.15	10.07
65	28.10.2003	S16 E08	4B/X17.2	11:13.5	Moscow	774.26	9.47
66	29.10.2003	S19 W09	2B/X10	20:58	South Pole	no data	11.00
67	02.11.3003	S14 W56	2B/X8.3	17:21	Lomn. Stit	525.97	9.95
69	20.01.2005	N12 W58	2B/X7.1	06:48.5	South Pole	855.40	9.39
70	13.12.2006	S06W23	4B/X3.4	02:47.5	Oulu	641.36	9.66

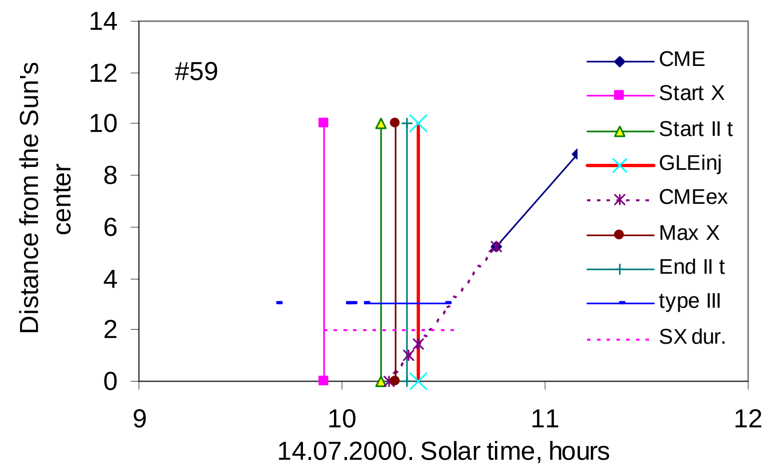
Timing of GLE 13.12.2006

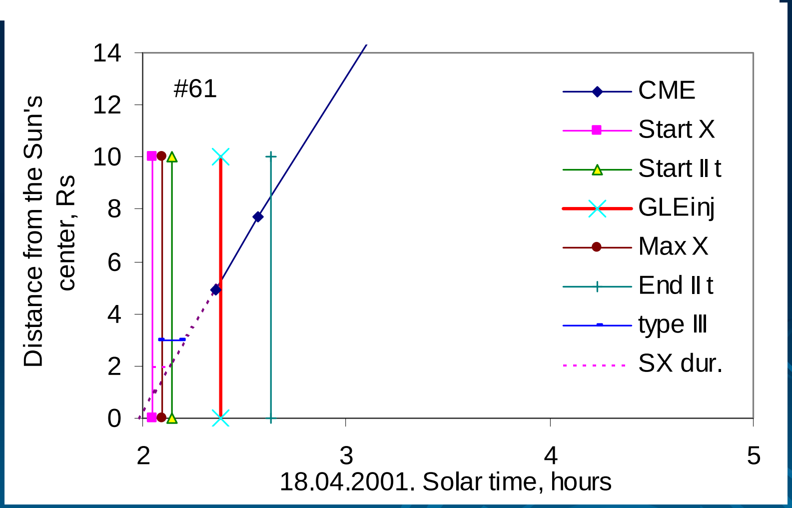


Timing of some GLEs (I)



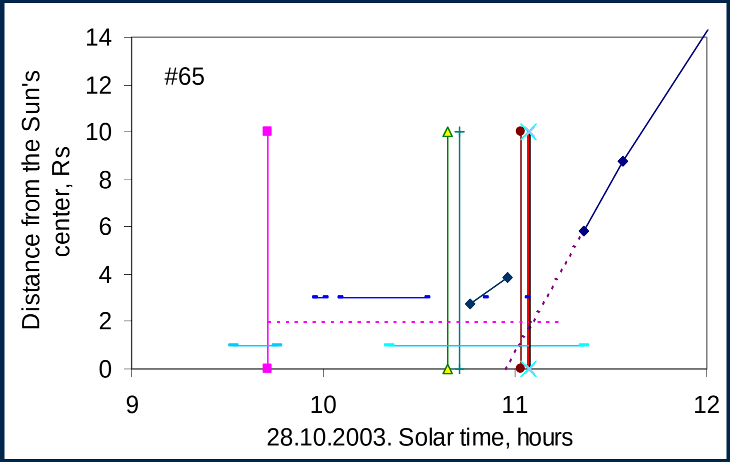


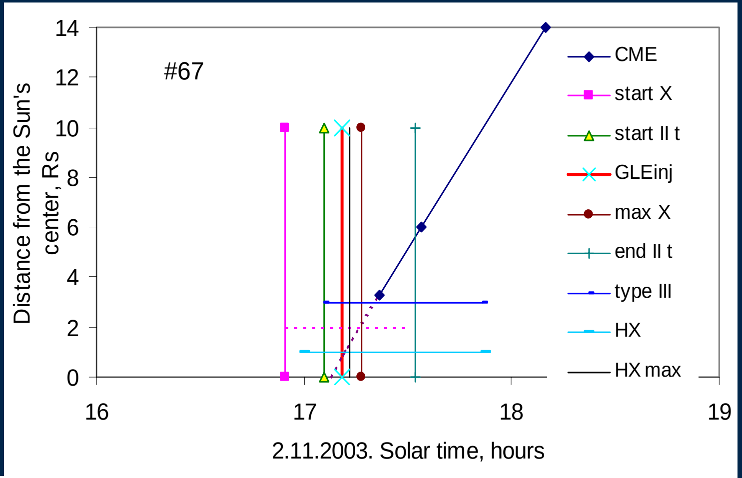


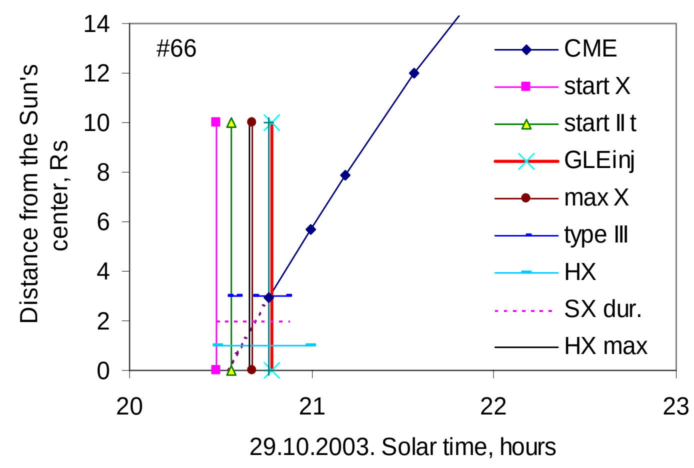


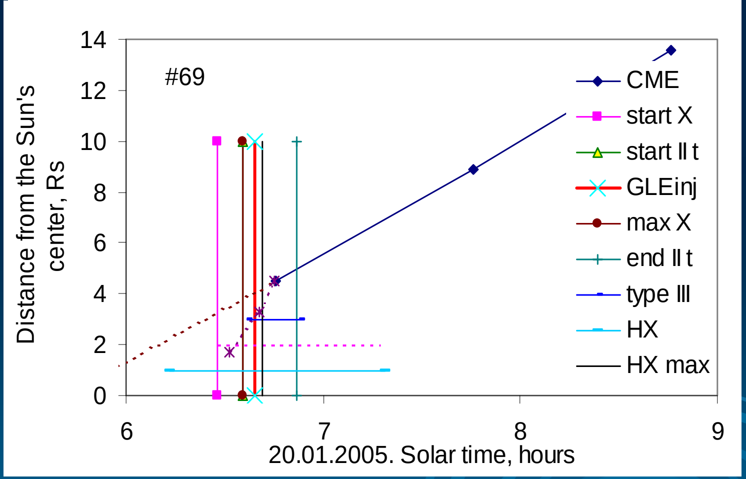
Height from the Sun’s center, Rs

Timing of some GLEs (II)



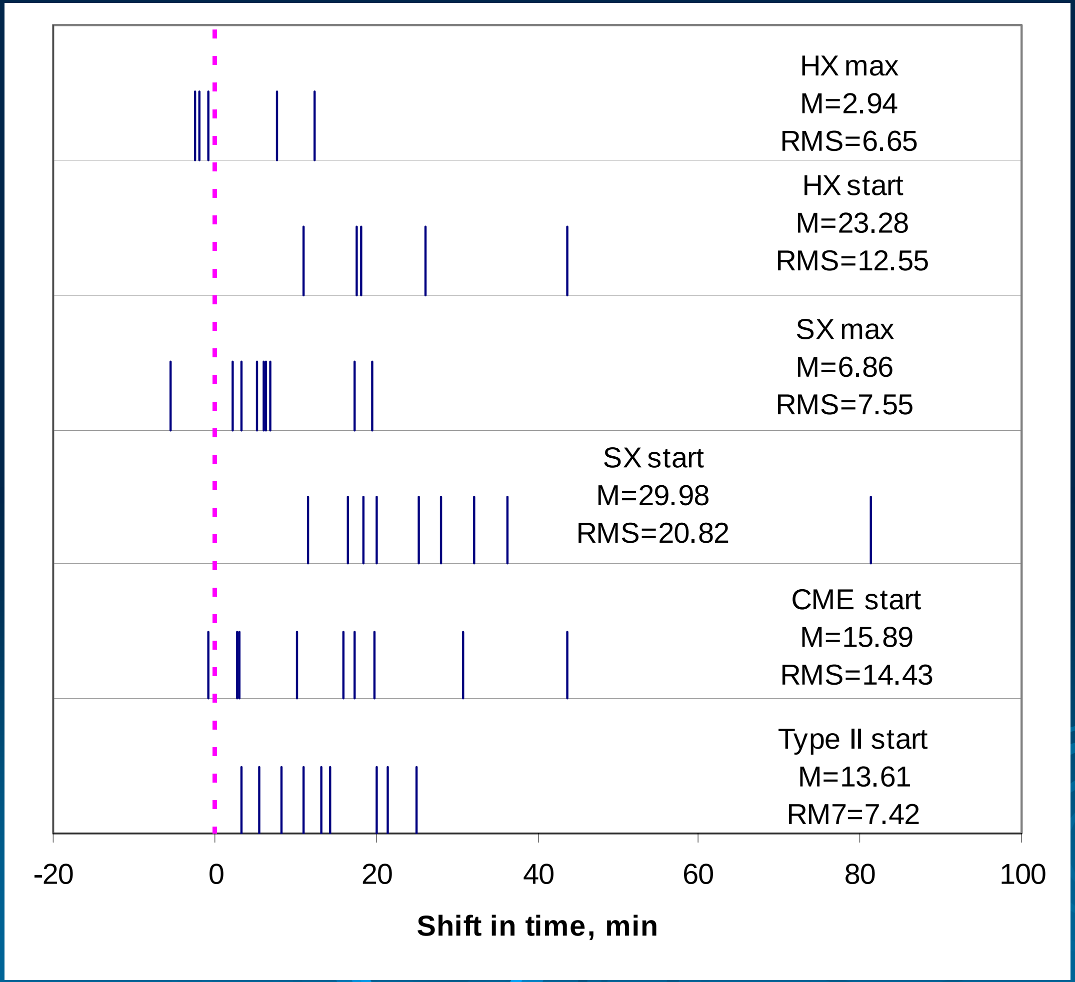






Height from the Sun's center, Rs

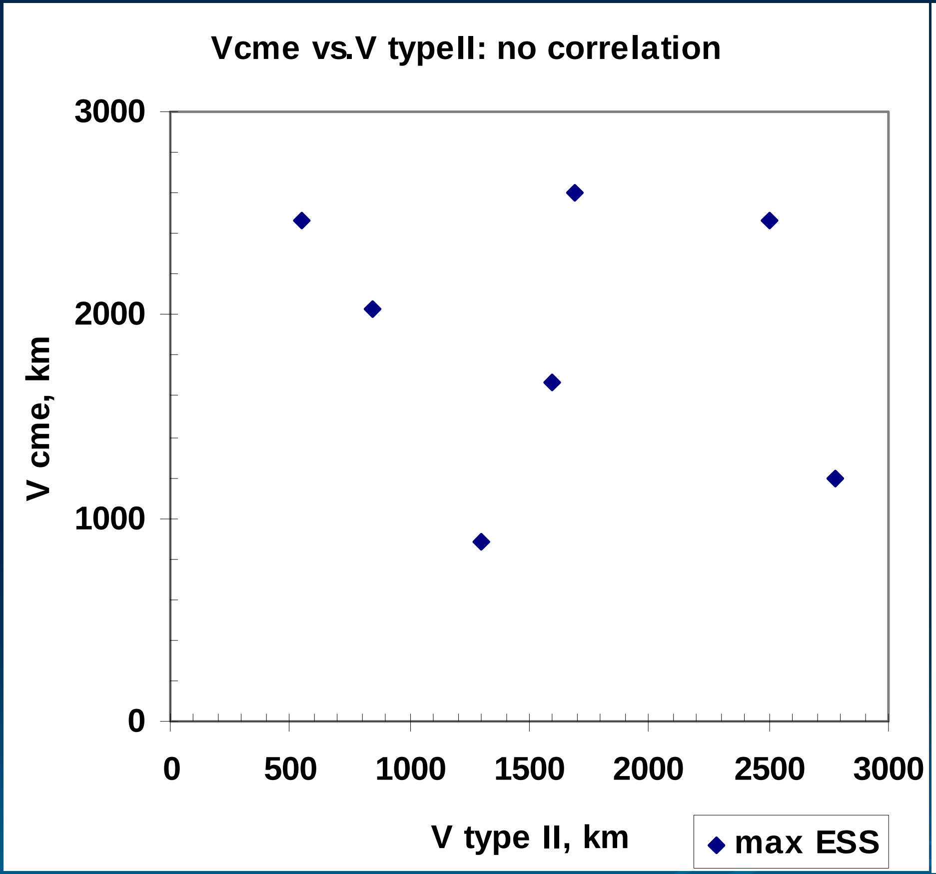
Temporal shift between some phenomena on the Sun and relativistic protons escape

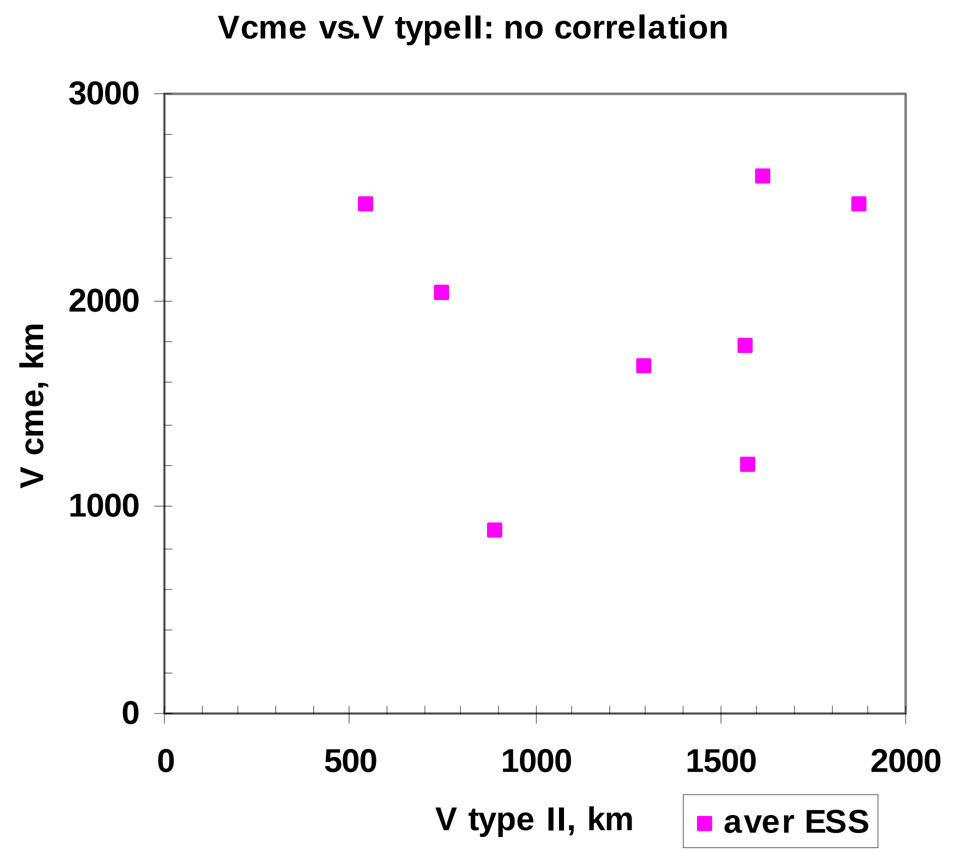


Delay of relativistic protons escape relative to solar phenomena, min

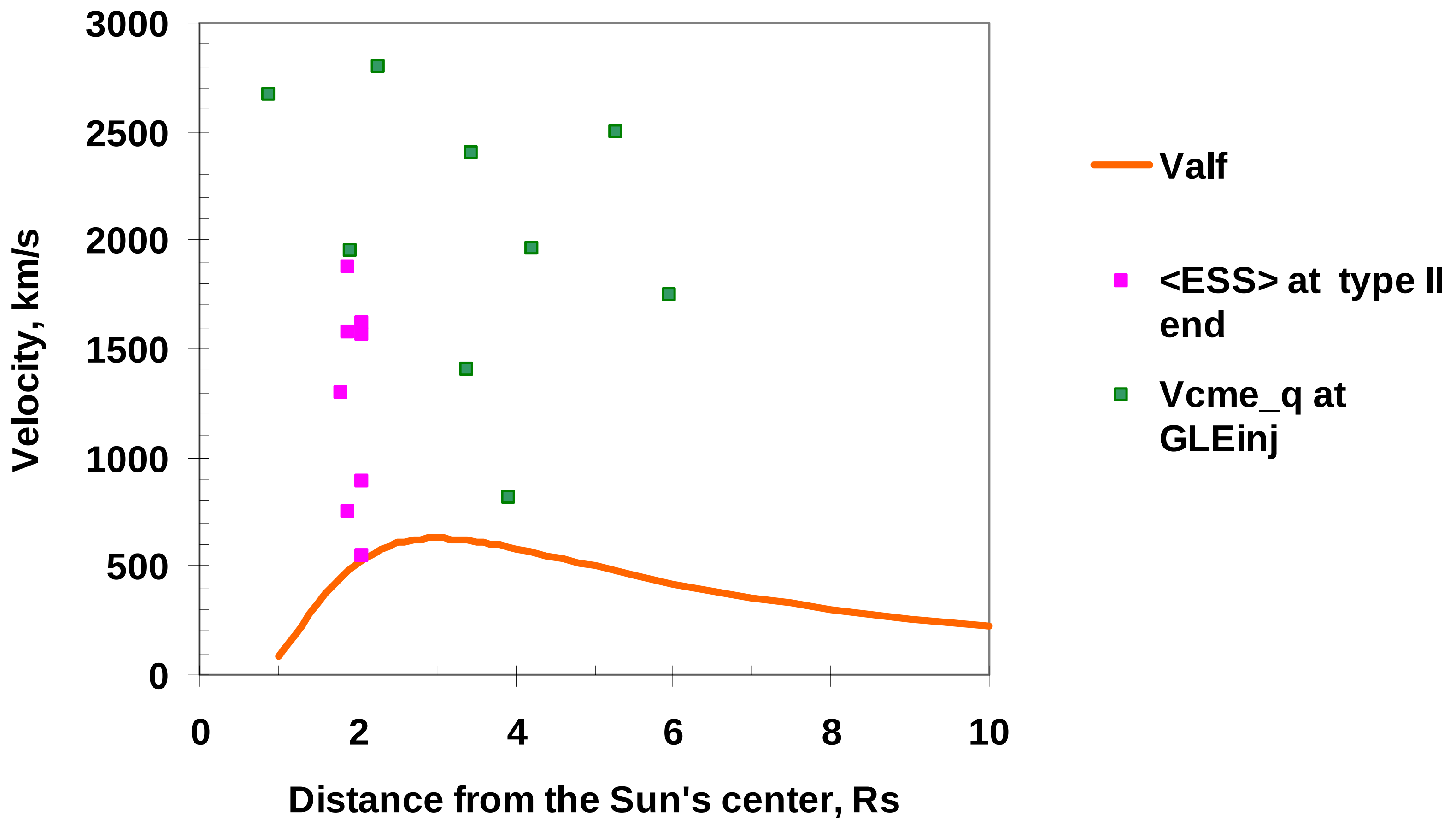
Phenomenon	Mean	Stand. deviation
hX start (5events)	23.28	12.55
hX max (5events)	2.94	6.65
sX start	29.98	20.82
sX max	6.86	7.55
CME start	15.89	14.43
type II start	13.61	7.42

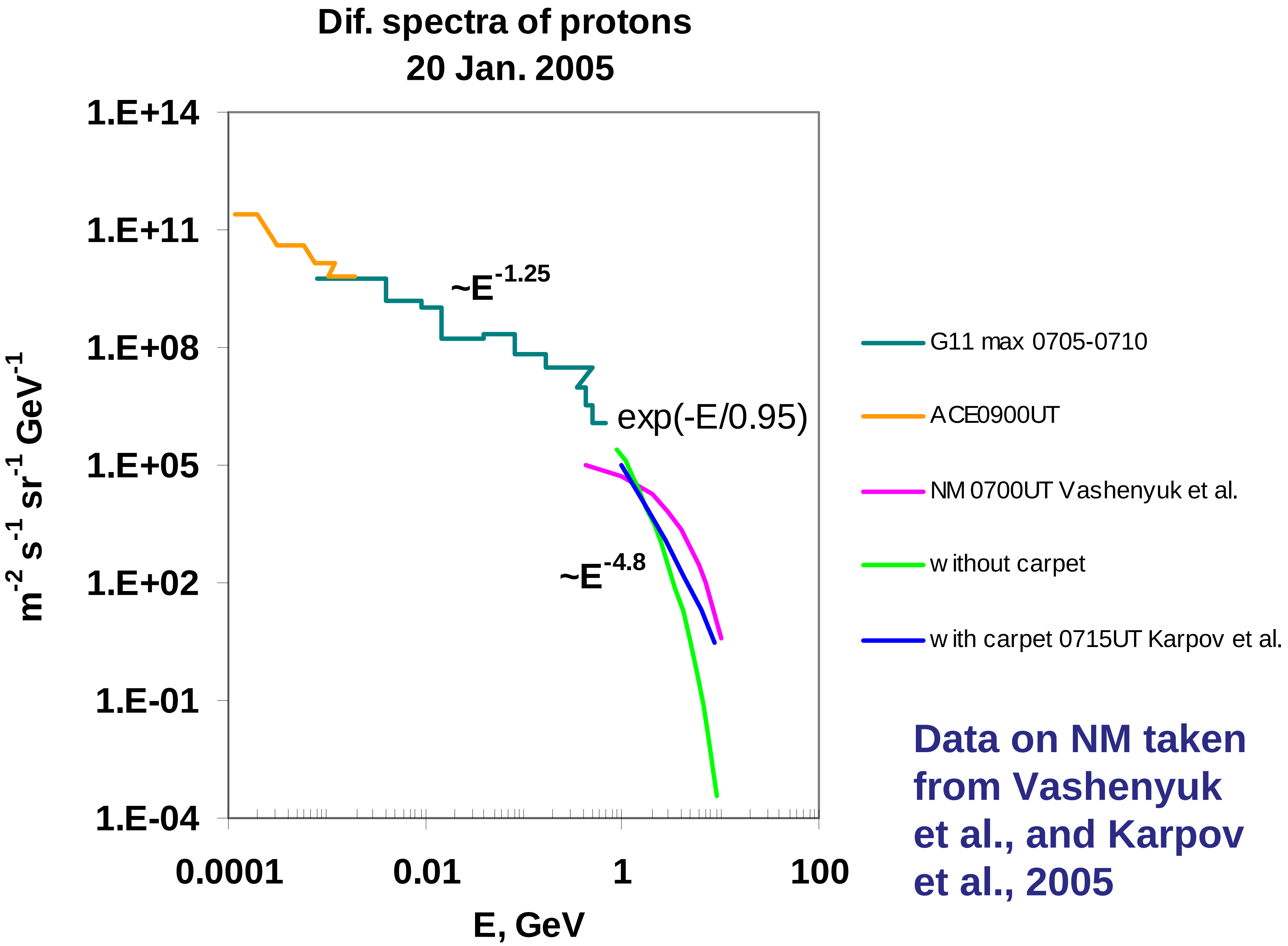
Relation between the CME speed and the Estimated Shock Speed according to type II radio bursts observations





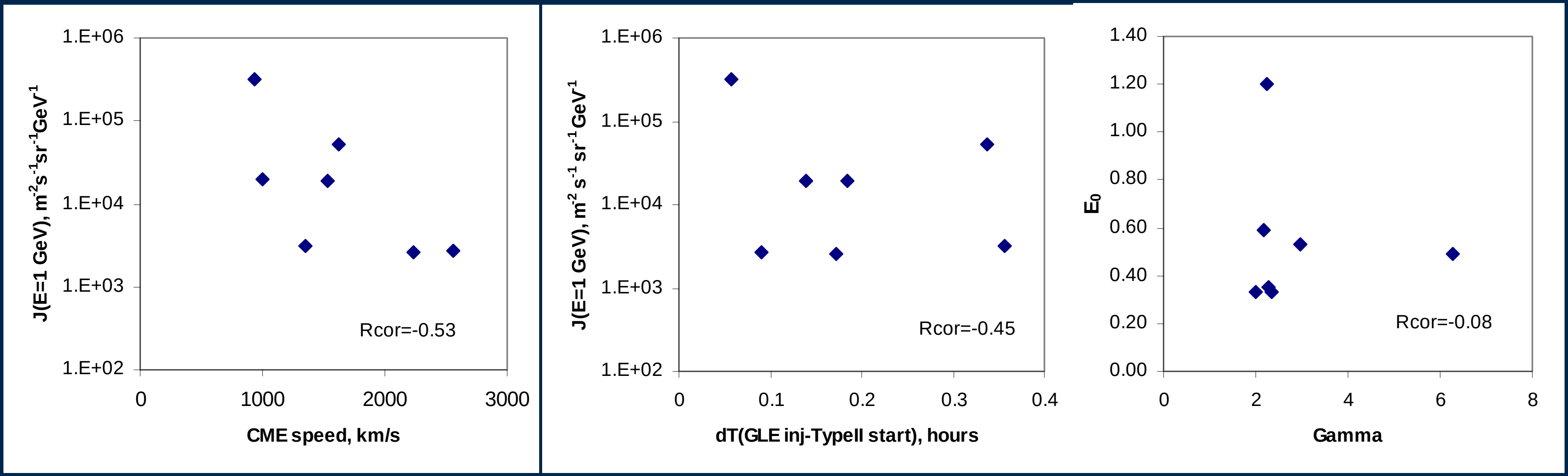
Alfven velocity and estimation of shock velocities





Data on NM taken from Vashenyuk et al., and Karpov et al., 2005

Parameters of relativistic solar protons and CMEs



Intensities of first arriving protons are taken from information on prompt component of GLEs (Vashenyuk et al., 2007) as J(E) =J0 exp(-E/E0)

Gamma is a power law spectral index, expected from the shock acceleration Gamma = $(\sigma+2)/(\sigma-1)$, $\sigma = (\gamma+1)M^2/((\gamma-1)M^2+2)$, $\gamma = 5/3$, M is the Mach number.

A word of precaution: CME speed is just only the plane-of-sky projection!

Conclusion from this study

- Timing shows more close connection of relativistic solar protons to the flare-connected phenomena than to the shock-connected phenomena
- The intensities and energy spectra of first arriving relativistic solar protons do not correlate with the expected from the shock acceleration.

Is it possible to make any conclusion about particle acceleration mechanism on the Sun from the observed features of first arriving particles?

DC or stochastic?

J. Pérez-Peraza, A. Gallegos-Cruz , L.I. Miroshnichenko, E.V. Vashenyuk. Solar Particle Source Energy spectrum: Stochastic acceleration *vs* Neutral Current Sheet acceleration *vs* Shock Wave acceleration. Proc. 30 ICRC, 2007:

Prompt component is accelerated by the deterministic electric fields produced in the process of magnetic reconnection. The energy spectra of the PC adequately reproduced by an exponential type spectrum from MNCS acceleration.

The spectra of Delayed component may be adequately reproduced by stochastic acceleration.

D. Bombardieri, K. Michael, M. Duldig, J. Humble, Relativistic Proton Production during the 2001 April 15 Solar Event The Ap. J., 665(1), 813-823, 2007: “at the rise, peak, and decline phases of the event… the spectrum between 120 MeV - 10 GeV is best fitted by a shock acceleration spectral form”;

But for the 2000 July 14 solar event “MHD turbulence arising from magnetic reconnection from a dissipating neutral current sheet was important in relativistic proton production”.

Spectral form from selected works

Reference	Mechanism	Spectral form
Litvinenko, 2003	reconnection	$E^{-\gamma}$ ϒ=2-3
Vashenyuk et al., 2003,	reconnection	$\exp(-p/p_0)$
Zharkova, Gordovsky, 2005	reconnection	$E^{-\gamma}$ ϒ=1.5
Browning, Vekstein , 2001	reconnection	Broken power law
Veselovsky, 2002	inductive el. field in electrojets	Exp with power law tail
Mori et al., 1998	reconnection	$E^{-\gamma}$ ϒ=2-2.2
Ellison D.C., Ramaty R. 1985,	More realistic diffusive shock acceleration	$j(E) = J_0 E^{-\gamma} \exp(-E/E_0)$,
J. Niemiec, M. Ostrowski, M. Pohl, 2006	Shock acceleration with downstream short-wave turbulence	Concave spectra with cutoffs

The spectral form is strongly dependent on realistic conditions in the site of acceleration.

For example:

- Topology and strength of magnetic fields
- Local turbulence
- Seed population and injection function
- Finite shock size and lifetime
- Magnetic field inclination with respect to the shock normal (perpendicular, parallel, oblique wave)
- Long –wave background turbulence
- Short-wave turbulence generated at the shock downstream

Etc.

Therefore, it is difficult to get the acceleration mechanism signatures from the observational data

CONCLUSION

- Majority of arguments argue for the flare origin of the first arriving relativistic solar protons.

  First-arriving relativistic particles can hardly be generated without a flare.

- At the moment, the conclusions about acceleration mechanism drawn from the results of the first – arriving relativistic particles are rather speculative.

- More sophisticated observations of solar processes are needed to get insight into real conditions of particle acceleration (3D images of CMEs from STEREO)

Thank you for attention

Acknowledgement

I would like to express my sincere gratitude to the organizing committee for inviting me here

Observational characteristics of Solar Energetic Particles

Particle intensity, energy spectrum (form of the spectrum, maximal energy) depends on the mechanism of acceleration, efficiency and duration of particle escaping

Angular distribution depends on the duration of particle escaping and condition of space of propagation

Elemental and isotope abundance and ion charge state (not observed for GLEs)

Intensity-time profile versus heliolongitude of the suggested particle source

Correlation of the observed particle features relative to concomitant solar (X rays, gamma, neutrons, radio, CMEs) and interplanetary phenomena (shock front arrival)

Event frequency rate

All the characteristics may change with time and depend on energy of particles

Processes being reflected on the observed SEP fluxes

- **Acceleration on the Sun (in the flare and/or in the corona)**

- **Propagation in the corona and injection of particles onto IMF line connecting the Sun and an observer**

- **Propagation through interplanetary space including:**
  interplanetary shock acceleration,
  Alfvén wave generation and wave-particle interaction in shock's vicinity,
  diffusion,
  adiabatic focusing,
  convection,
  adiabatic deceleration

$f(kHz) = 9\sqrt{n(cm^{-3})}$

Type II.

Type II radio emissions are caused by electrons accelerated by shocks at the local plasma frequency and/or at its harmonics. Emissions begin at frequency of ***f*** ~300 MHz (metric range) and shifted to the ***f***~10 MHz (decametric range) during (tens of) minutes. This is associated with a shock moving through the solar atmosphere.

Plasma wave with frequency

$f(kHz) = 9\sqrt{n(cm^{-3})}$

$$f(\mathrm{kHz})=9\,[n(\mathrm{cm}^{-3})]^{0.5}$$

Corresponds to moving from ~ 1Rs outward.

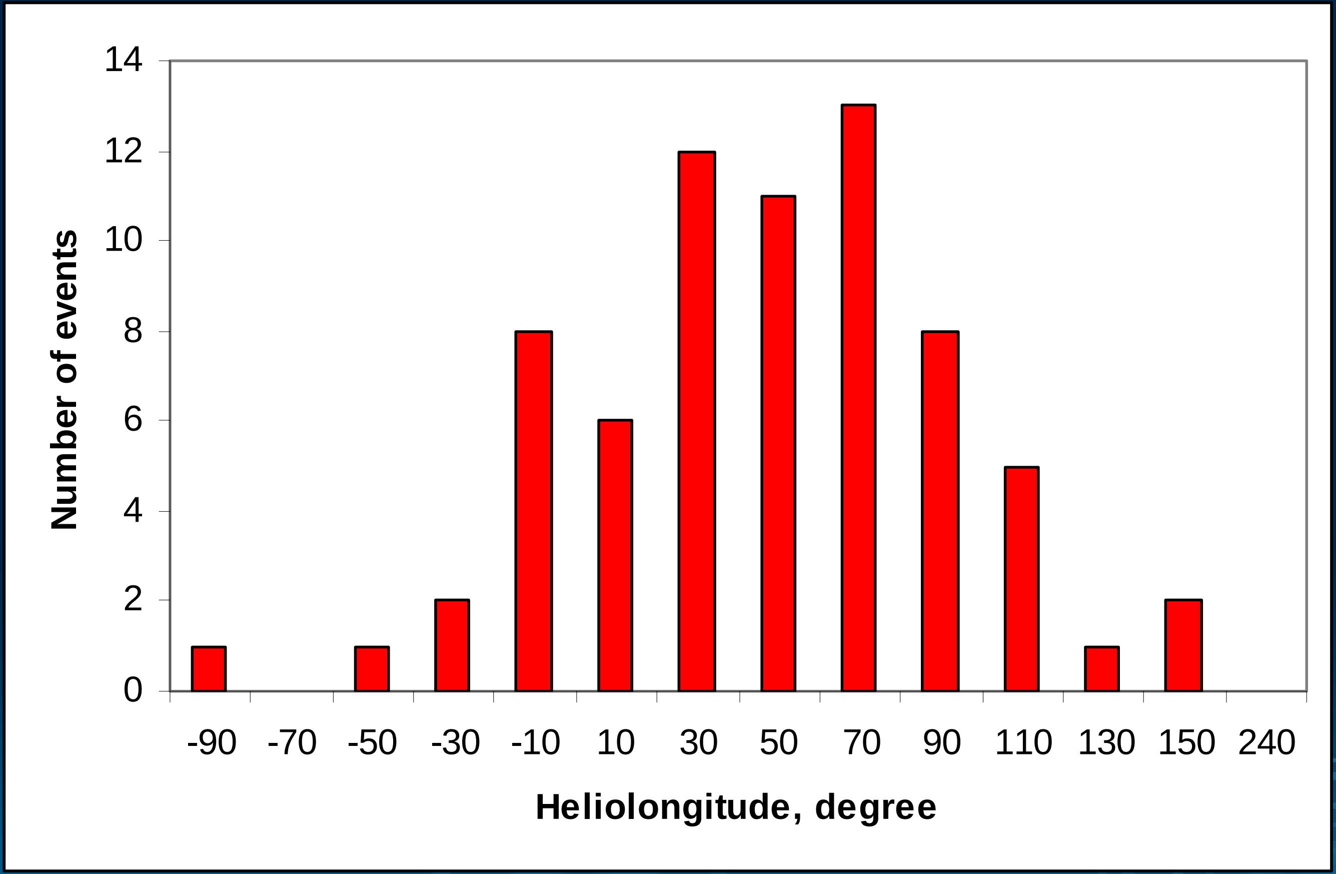
Type II start was considered as evidence of a shock formation.
A heliospheric density model of Mann et al., (1999) was used to find heights of start and end of the type II bursts

Type III

Frequency narrow-range bursts fast moving from decimeter to decameter (500-0.5 MHz) range during several seconds. Their generation is due to energetic electrons (tens of keV) streaming outward through the corona and the interplanetary medium along the open magnetic field lines.

Type III is considered as indication on direct field line connection from the acceleration region to Earth.

Heliolongitudinal distribution of the GLE parent flares (1942-2006)



Particle acceleration in the DC electric fields

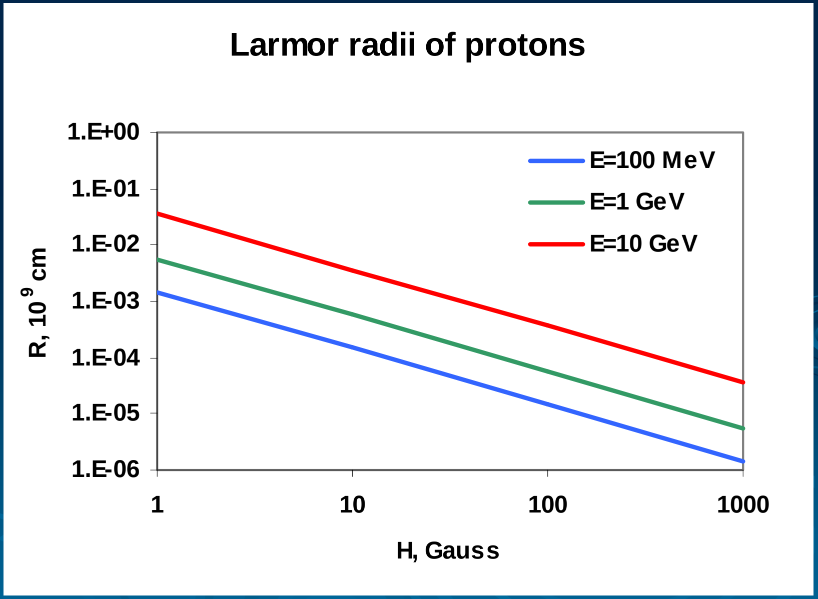
Reference	Electr. field, ε, V/cm	Length, cm max/prob.	Energy, eV max/prob.	Time of acceler., s	Spectral form
Litvinenko,2003, reconnection	≤ 10	10^9	10^{10}/ $3\text{x}10^8$		$E^{-\gamma}$ $\gamma=2\text{-}3$
Vashenyuk et al., 2003, reconnection	$4\text{x}10^2$	10^{10}	10^{12}	$<10^{-3}$	$\exp(-p/p_0)$
Zharkova, Gordovsky, 2005, recon.	1	$10^9/10^6$	$10^9/10^6$	10^{-3}	$E^{-\gamma}$ $\gamma\sim 1.5$
Browning, Vekstein, 2001, reconnection	30	10^8	$/10^6$		Broken power law
Veselovsky, 2002, inductive el. field in electrojets	3	10^9	10^9	$\sim 10^{-2}$	Exp with power law tail

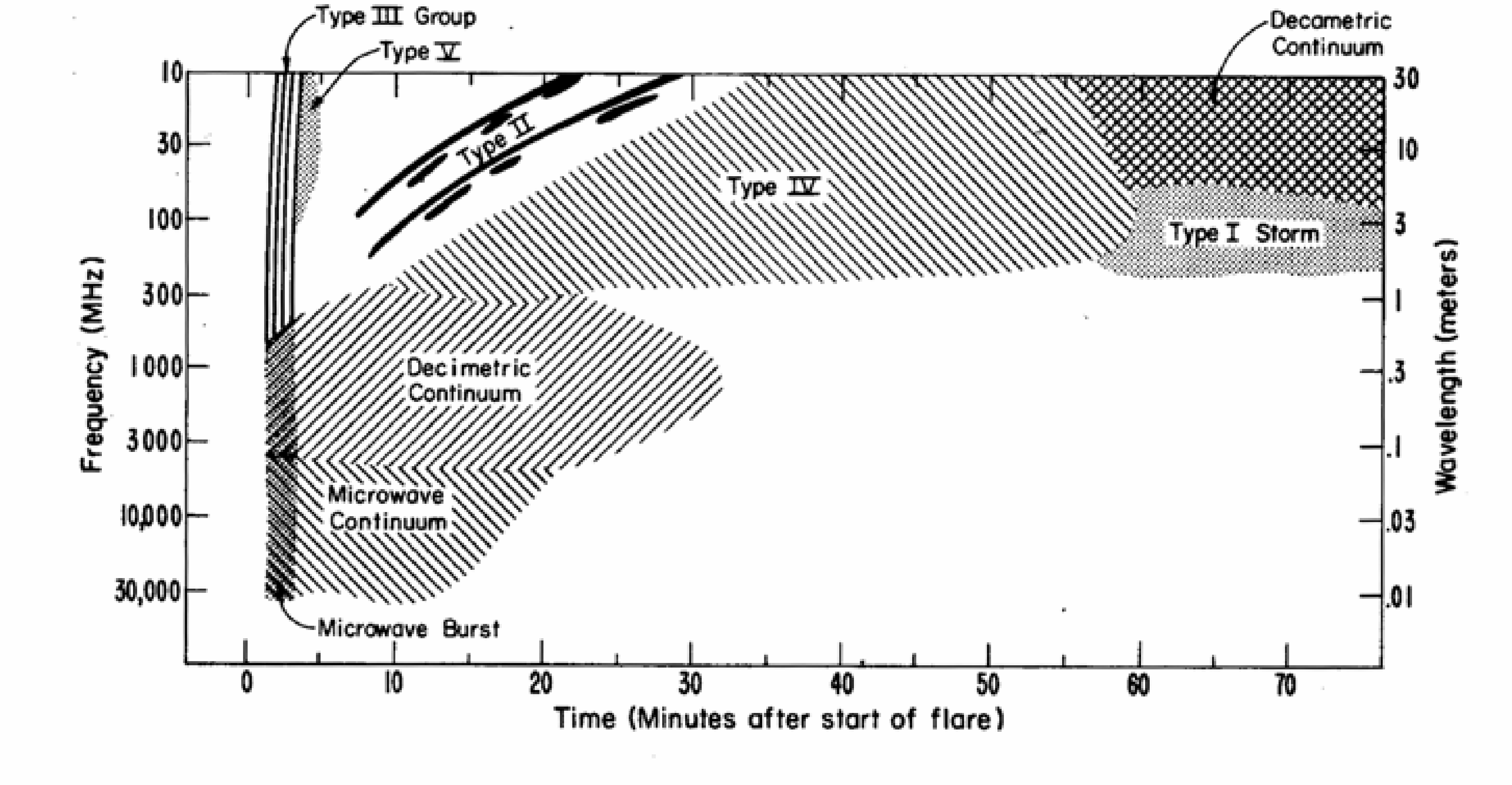
Relativistic Particles are the best candidates to enable the observer to look at the acceleration processes

Relativistic Particles are the first to be observed, so the time elapsed from the acceleration is minimal

Fast arriving is usually observed indicative of scatter-free propagation (minimal effect of self-generated Alfvén waves)

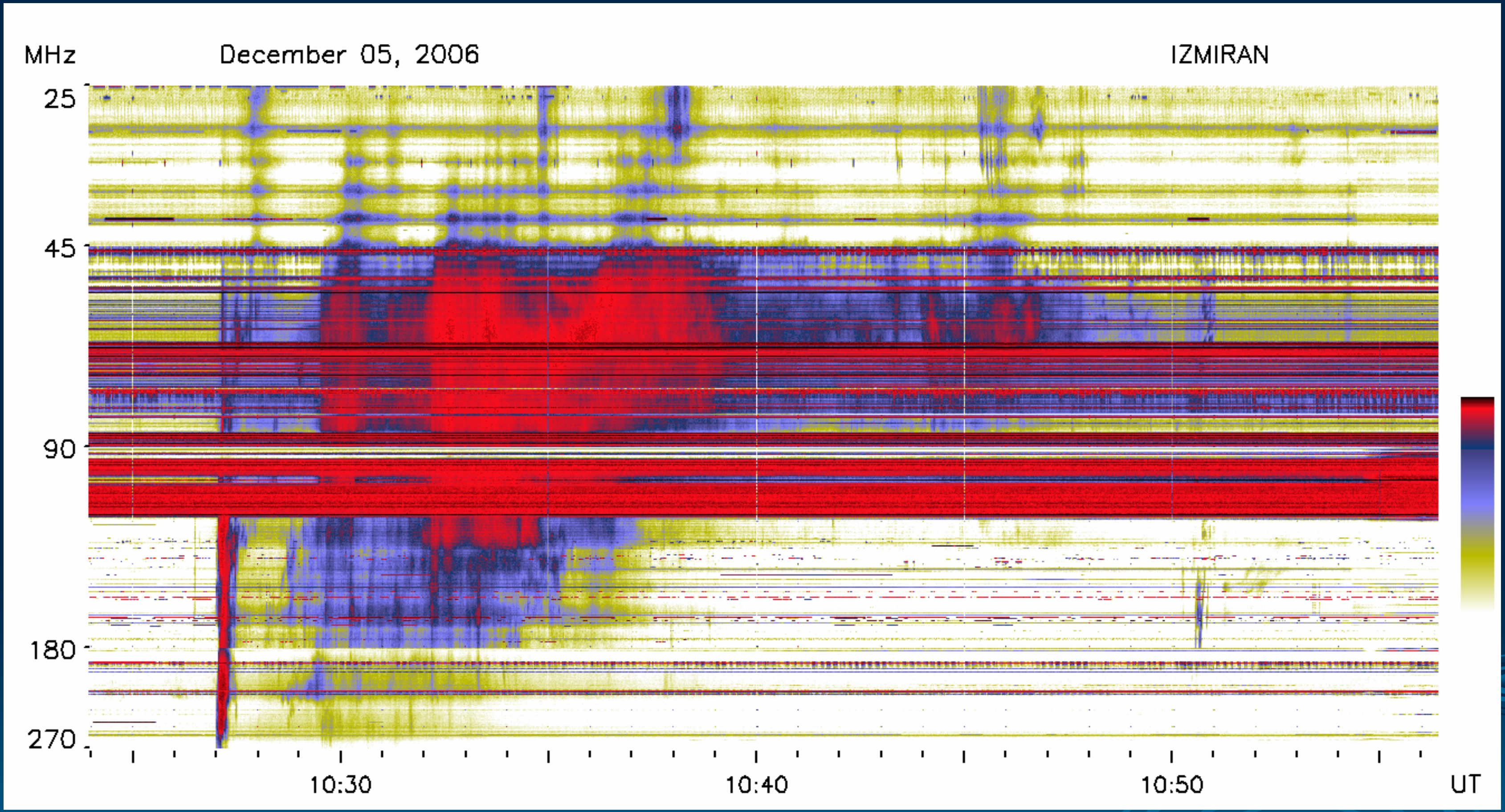
Larmor radii of Relativistic Particles are << scale lengths of coronal structures. The observed Relativistic Particles were accelerated or fast transported on the open field lines and freely escaped into interplanetary space.





Fast–drift bursts (type III) can be used to trace field lines from the Sun into the interplanetary medium. Emission above 100 MHz originates within 0.5 solar radii of the photosphere whereas emission at 10 MHz originates at about 2 solar radii. If the bursts extend to the lowest frequencies seen near Earth (typically ~30 kHz) then there must be direct field line connection from the acceleration region to Earth (Cane et al., 2002)

Radiobursts of type II and III



20 January, 2005

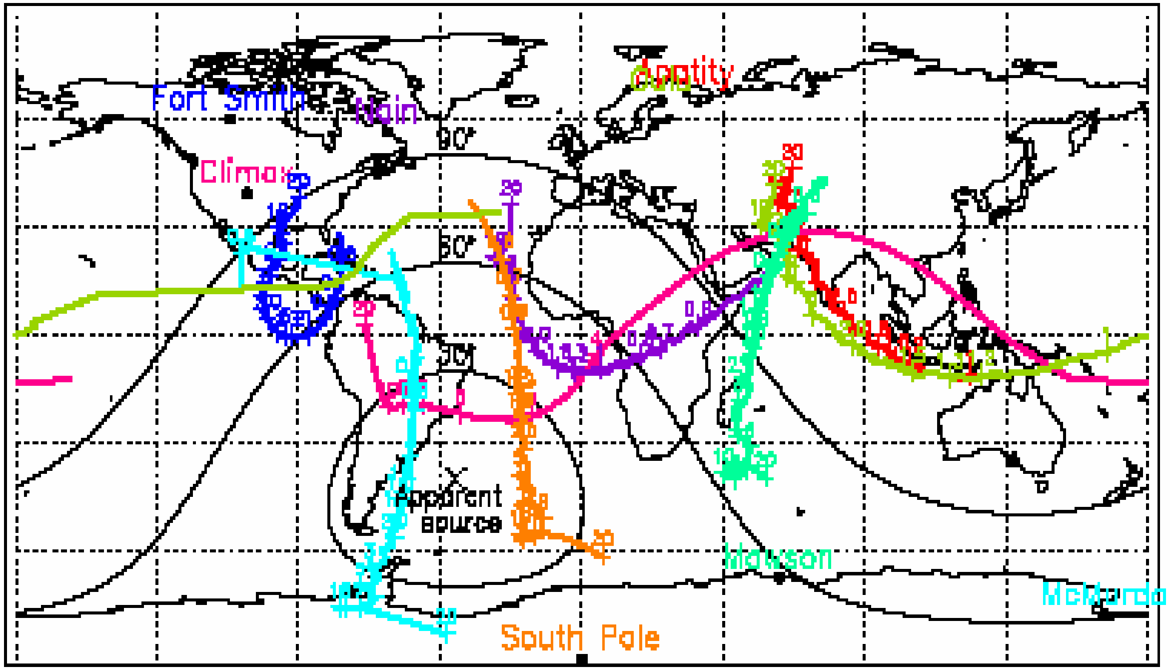
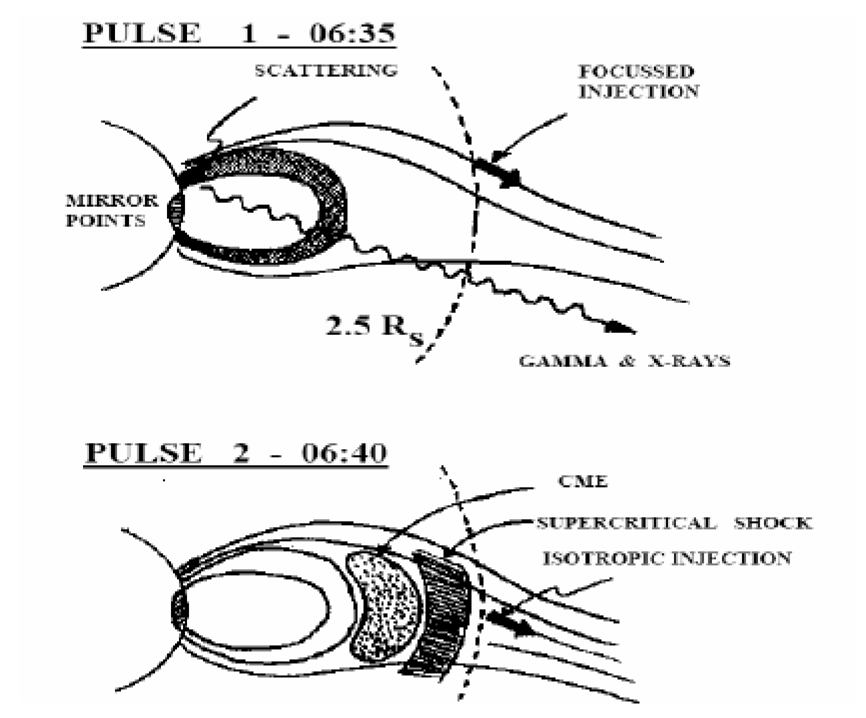


Figure 4. Asymptotic directions of NM stations with high count rate increases in the time interval 0655–0657 UT during the GLE on January 20, 2005. For further details see text.

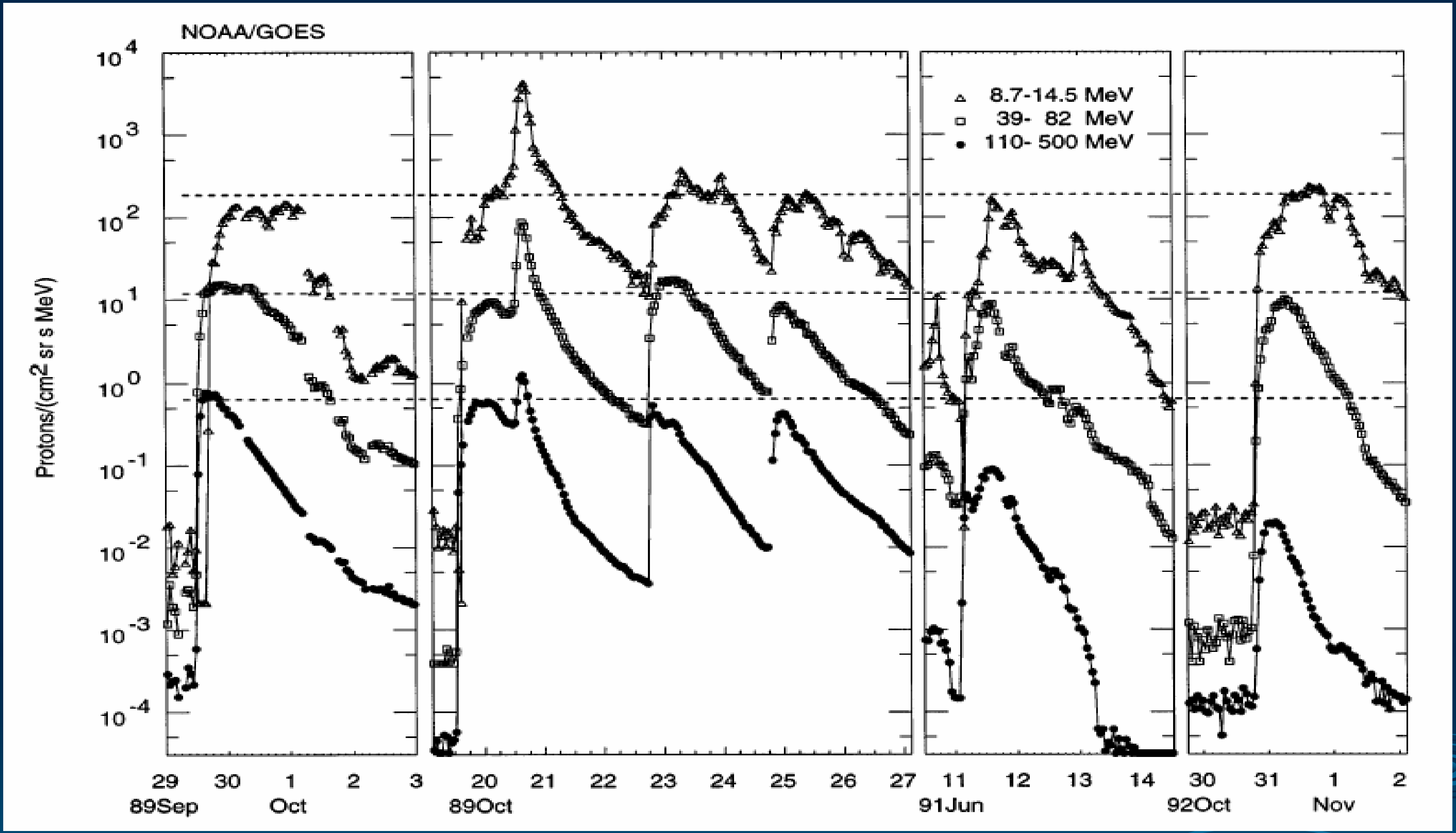
Vashenyuk et al. 2005

K.G. McCracken, H. Moraal, Two acceleration mechanisms for ground level enhancements,

Proc. 30 ICRC, 2007

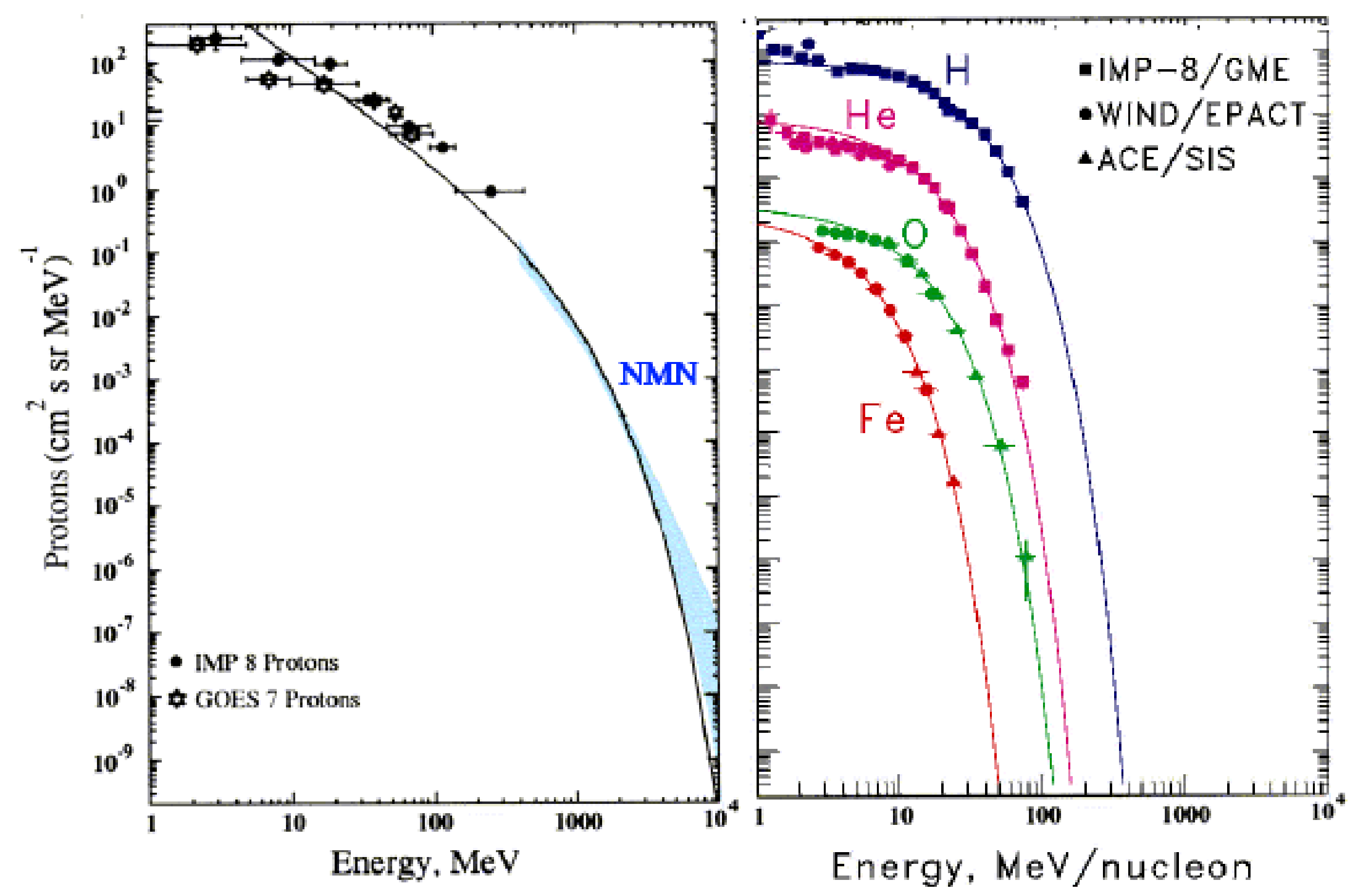


D. V. Reames, 1998 . The streaming limit

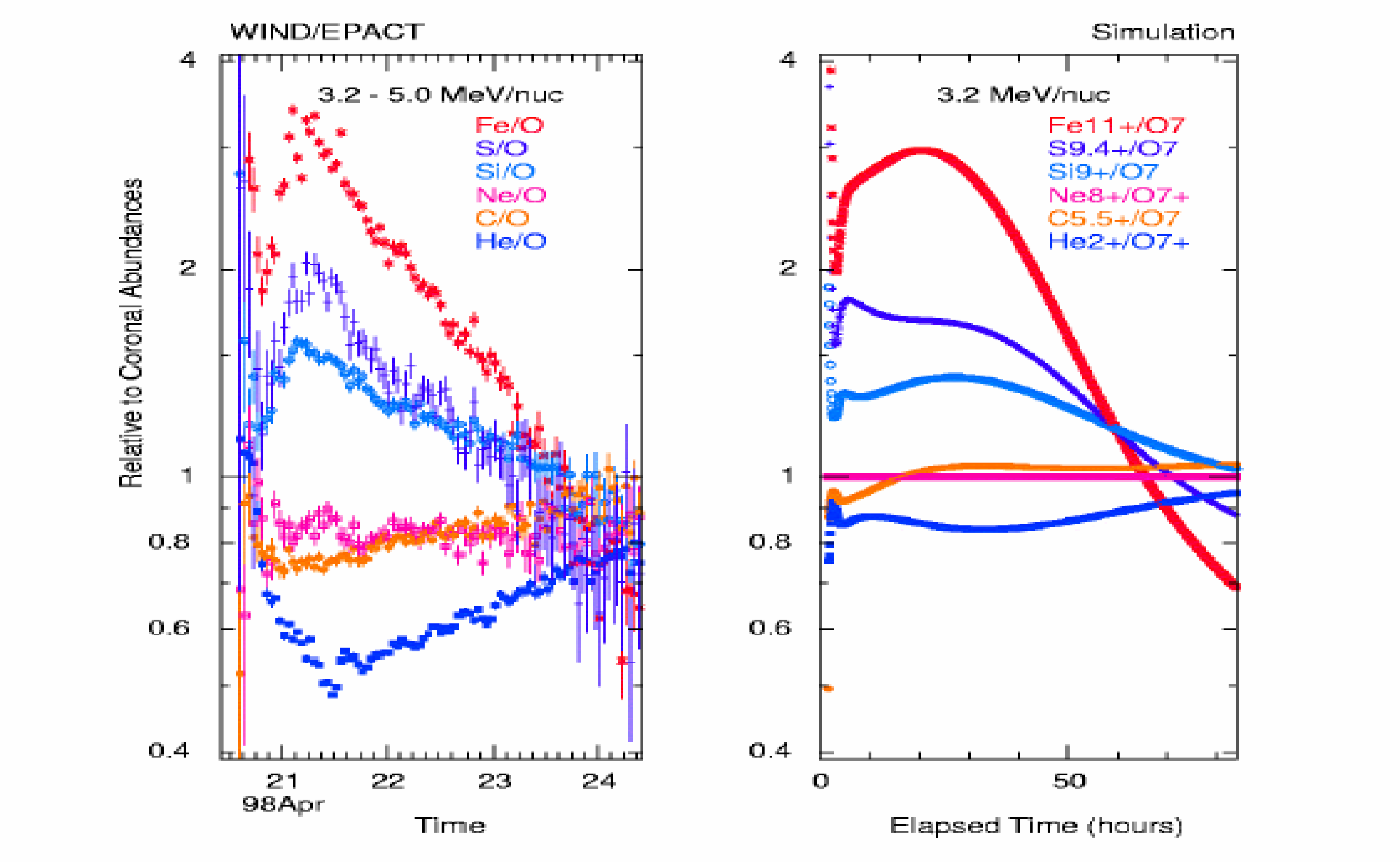


Intensity-time profles of protons in three energy channels are shown for six large SEP events during the last solar cycle as measured on the GOES spacecraft. Streaming-limited intensity values for each energy channel are shown as dashed lines.

The spectral knee



Left: A spectrum from spacecraft and the neutron monitor network in the 29 September 1989 event with *Eo* = 1 GeV. Right: spectra from the 20 April 1998 event with *Eo* = 15 MeV. (**Reames, 2000**). Proton intensities below ~50 MeV are similar in the both events.



Left: Wind/EPACT hourly averaged abundance ratios normalized to reference coronal values, during 20.04.1998 event [Reames, 1995]. Right: Simulation of these abundances [Ng et al., 1999]

D. V. Reames, 2000.