Solar cosmic ray acceleration and propagation

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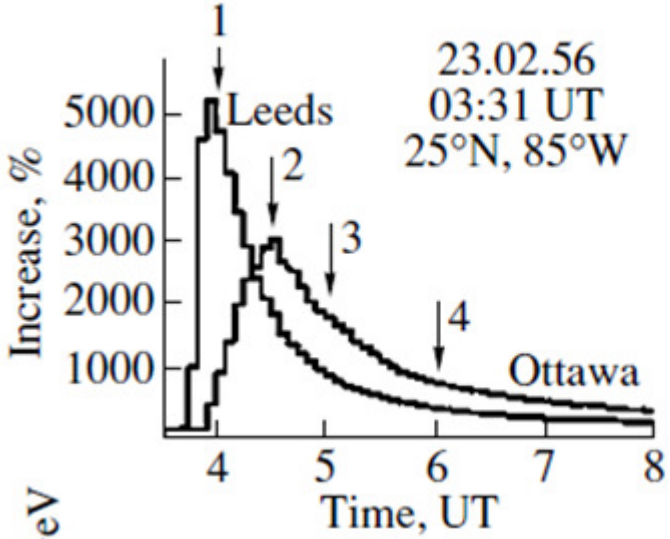
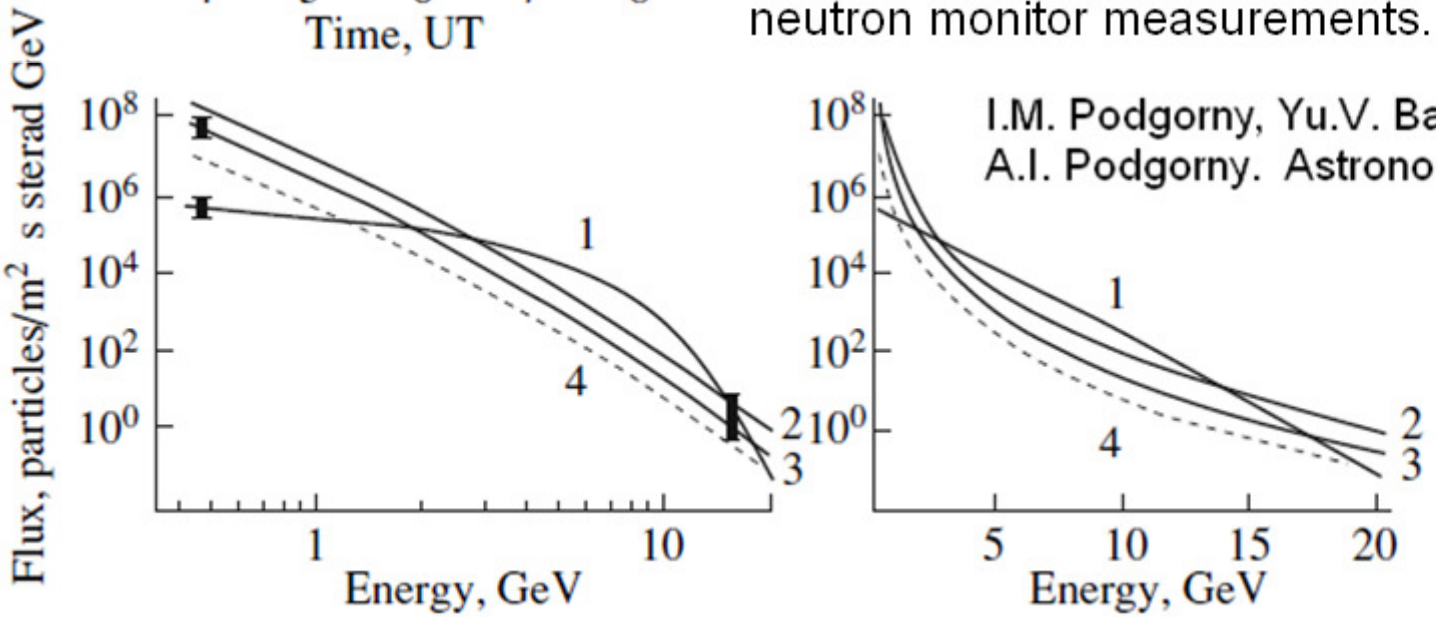
Flare protons, which have been previously executed jointly with E. C. Vashenjuk and Y. Balabin, demonstrate the acceleration in the flare current sheet along a singular magnetic field Line. The accelerated protons have an exponential spectrum. From the analysis of GOES measurements it follows that the characteristics of accelerated protons reaching the Earth depend on the flare position on the solar disk. The so-called fast proton component arrives from the Western flares with a sharp (~5 min) front. The time delay is determined by the time of flight (~20 min) along lines of an Archimedean spiral. Protons from Eastern flares are transferred across the field lines with the solar wind velocity and diffuse due to scattering on the magnetic inhomogeneities. The proton stream lasts 2 - 3 days, which corresponds to the average velocity of ~5 10^7 cm/s. The front of proton flux from the Eastern flares is gently sloping. Its duration is more than 10 hours. The fast component is not recorded by the GOES spacecraft from flares that occurred in the Eastern part of the solar disk. The observed facts are explained by a single mechanism of proton acceleration in the current sheet. The maximum proton energy in a shock wave cannot reach 100 MeV



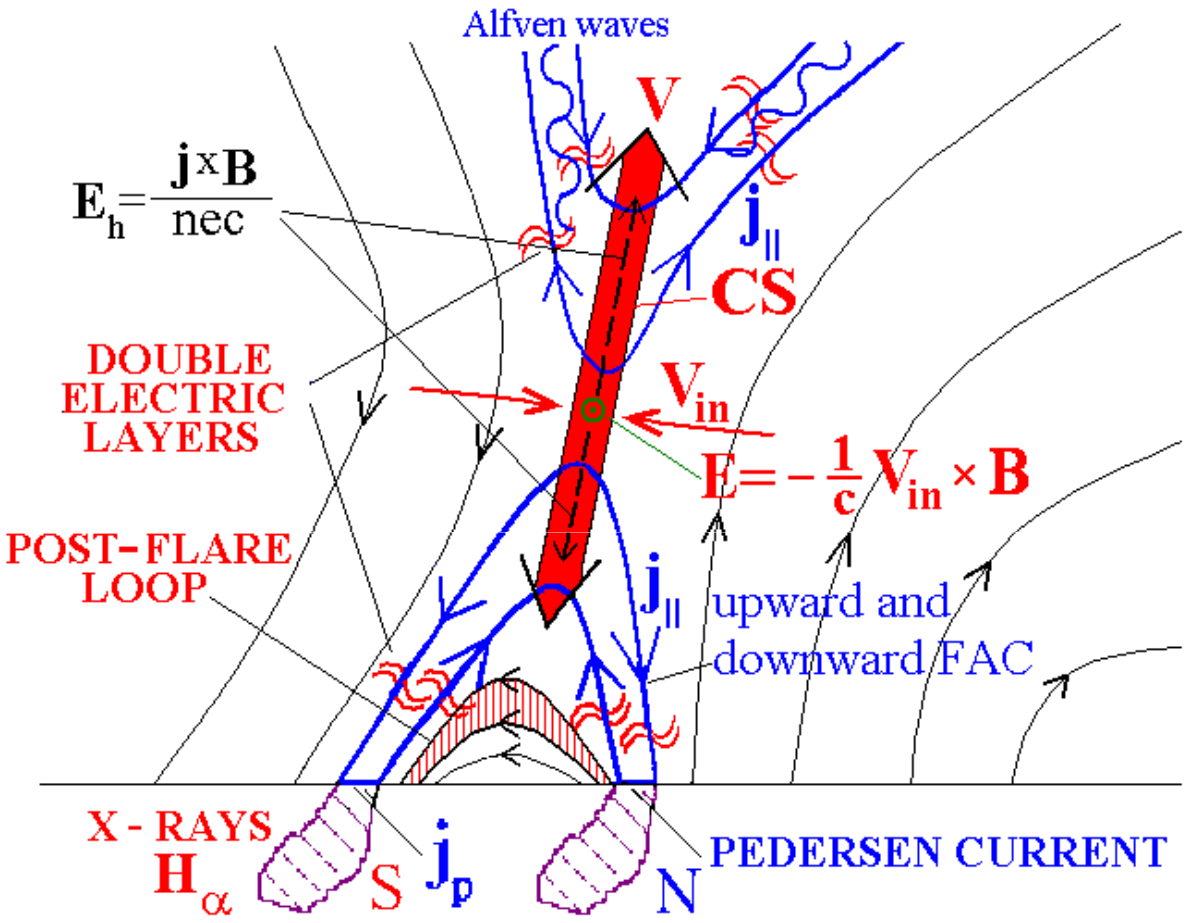
1 Fast component
$\sim e^{-E/E_0}$ $E_0 \sim 1.3$ GeV

2–4 Delayed component $\sim E^{-\gamma}$
$\gamma \sim 5$

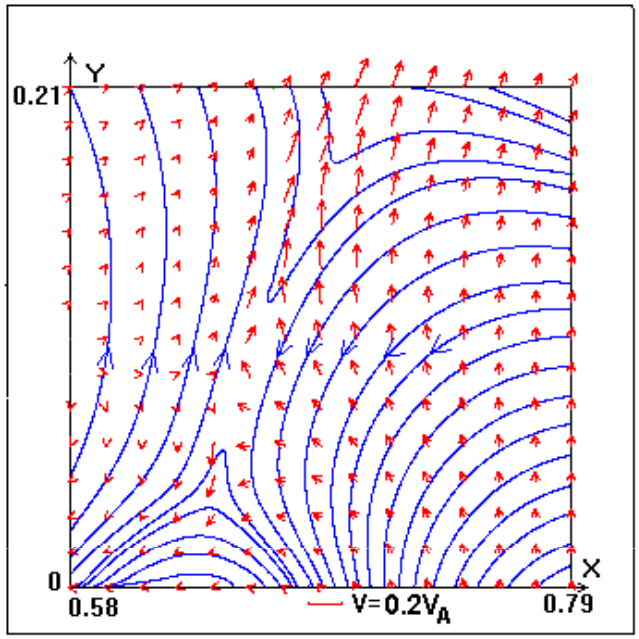
Spectra of solar flare relativistic protons according to neutron monitor measurements.



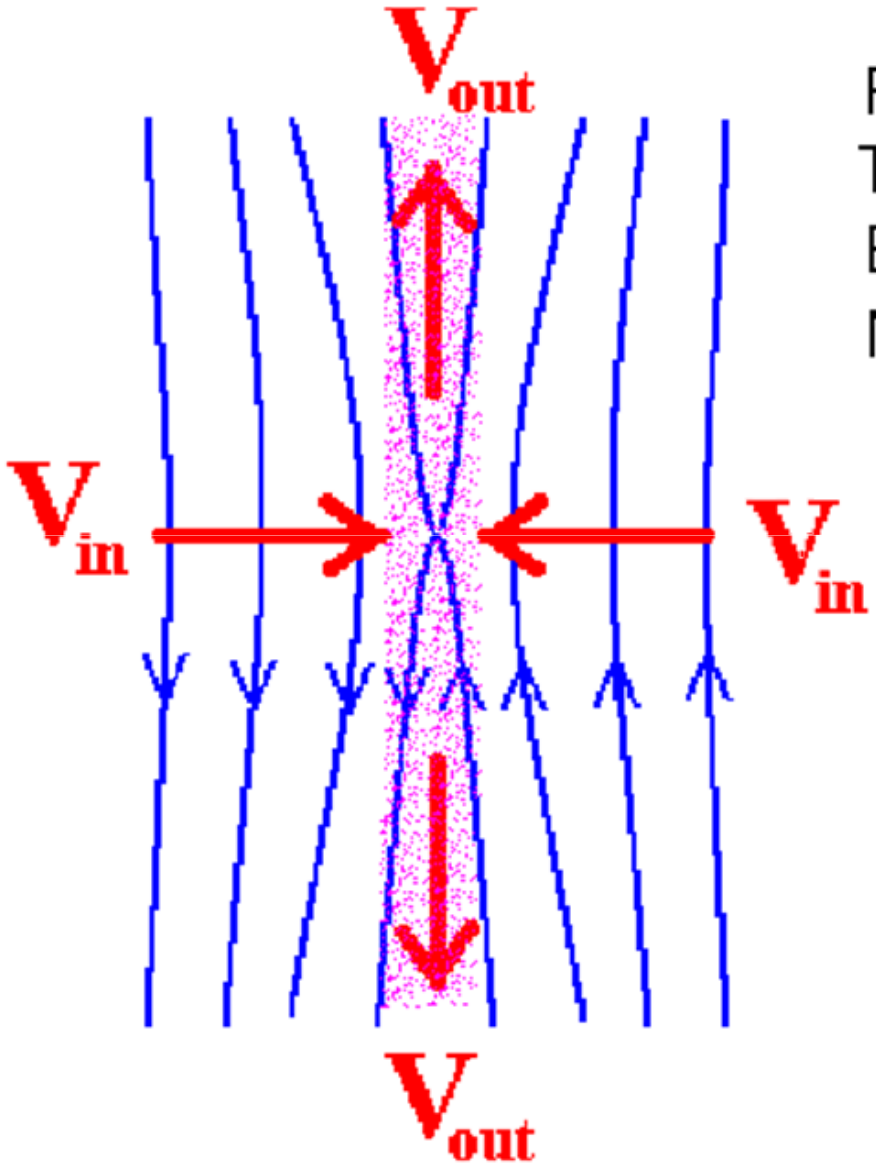
I.M. Podgorny, Yu.V. Balabin, E.V. Vashenyuk, A.I. Podgorny. Astronomy Reports. 2010.



Electrons accelerated in FAC produce hard X-ray.



Results of current sheet creation in numerical MHD simulation. A sheet appears above an active region in the preflare state. Plasma inflows into a current sheet. Inside the sheet plasma acceleration takes place by $\mathbf{j} \times \mathbf{B}$ force producing CME.



From RHESSI: $(ME)=5\cdot10^{49}\,cm^{-3}$.
$T=3.1$ keV $n=10^{11}\,cm^{-3}$.
$B^2/8\pi = nkT \rightarrow B = 110\,G$.
$M = Nm_p \sim 10^{15}\,g$ --- CME.

At $V_{in} = 2\times10^{7}$ cm/s and $L=10^{9}$ cm.

$E = V \times B/c$. $E=20$ V/cm.

$W=2\times10^{10}$ eV.

The three-dimensional distribution of **E** and **B** are obtained by numerical solution of the full system of MHD - equations. The initial and boundary conditions are taken for the Bastille flare. No assumptions about the mechanism of the flare has been done.
Proton spectrum was calculated by test particles

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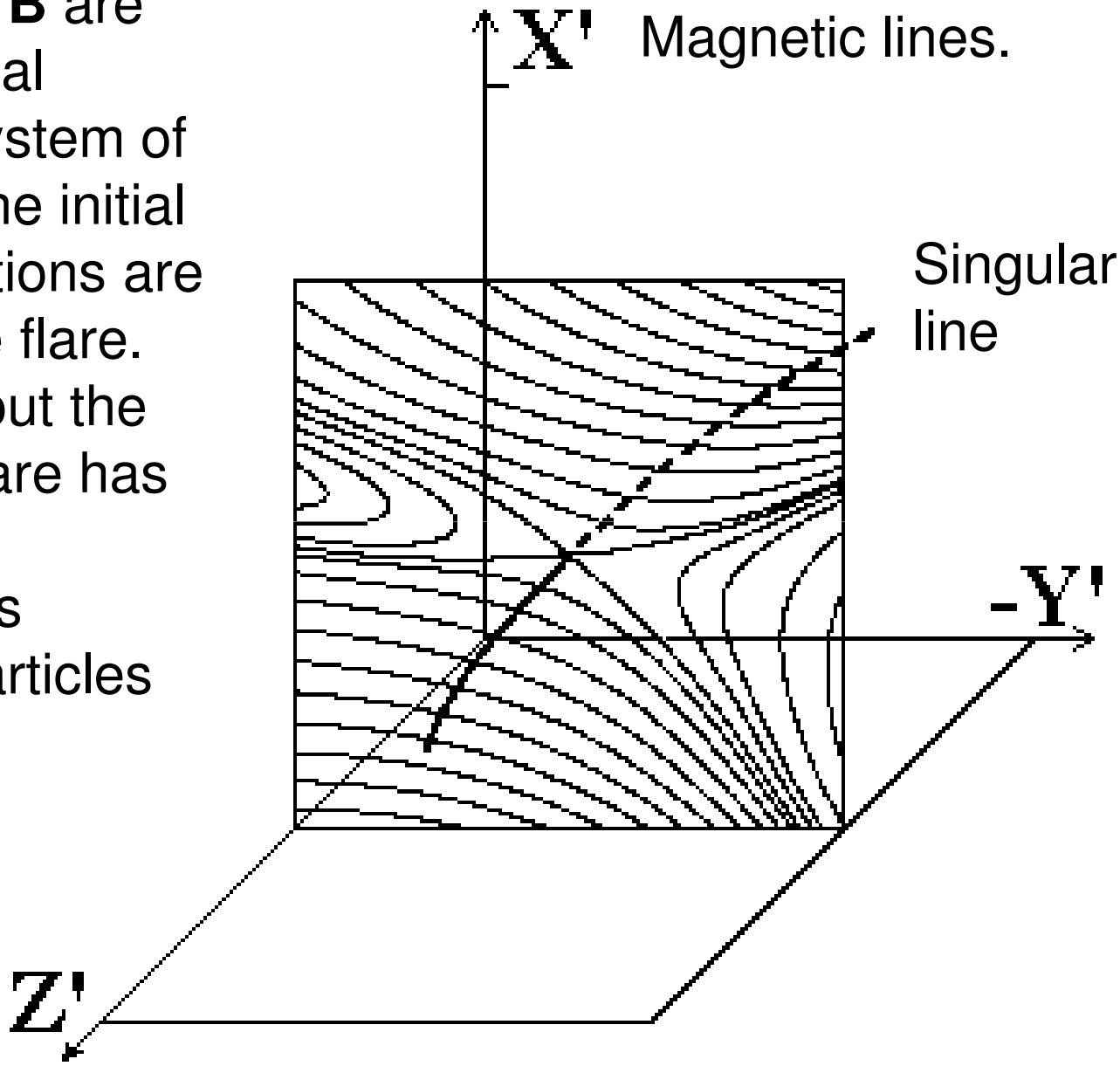
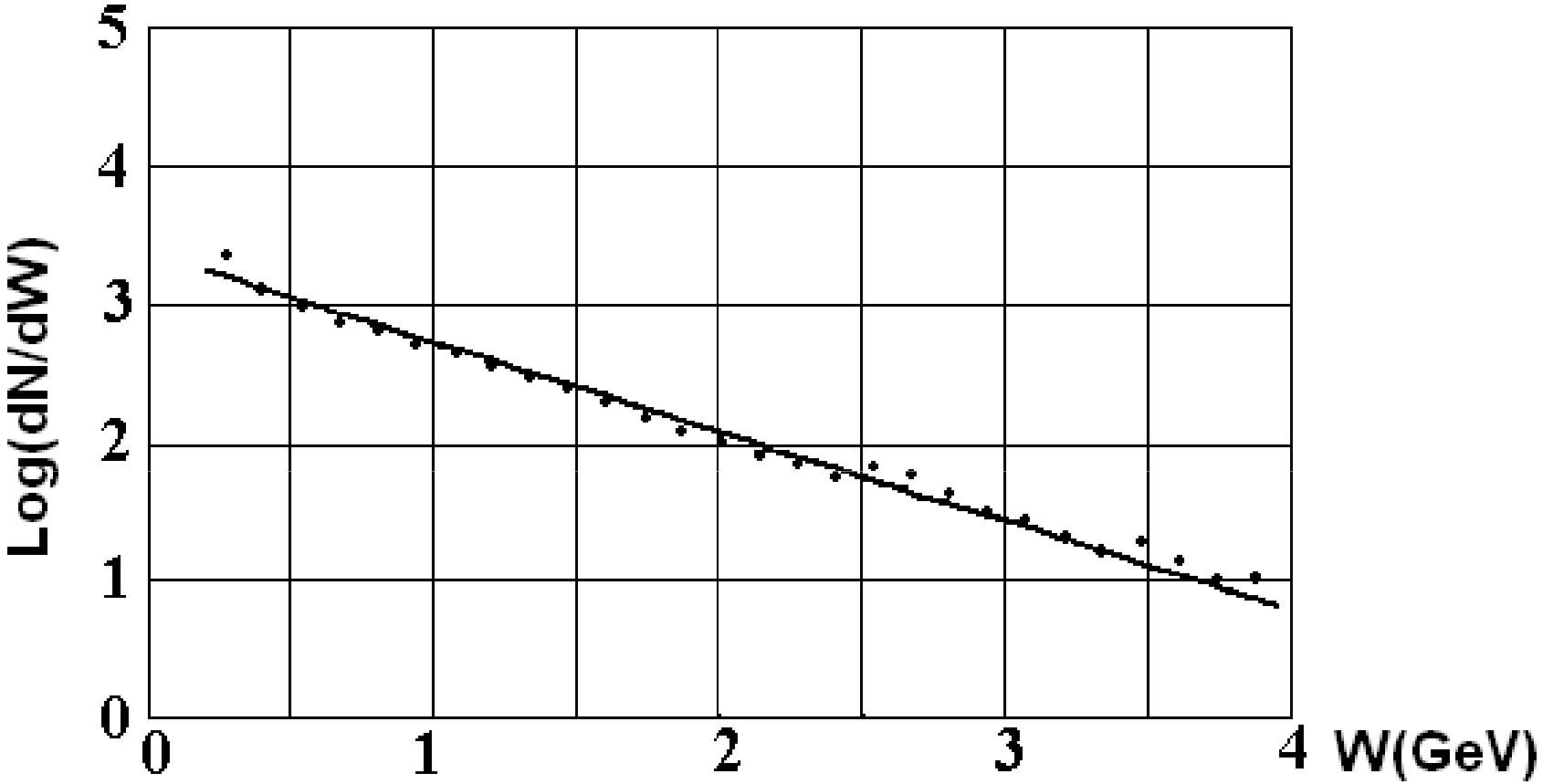
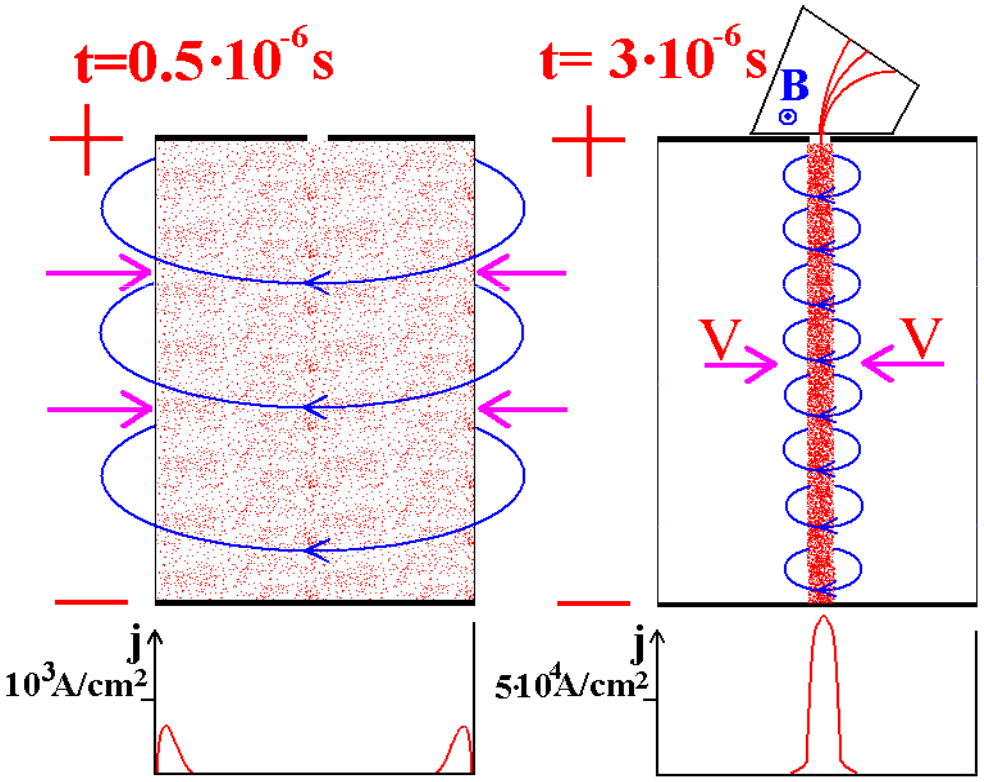




THE CALCULATED AND MEASURED SPECTRA OF RELATIVISTIC PROTONS COINCIDE AT THE PLASMA VELOCITY INFLOW IN THE CURRENT SHEET, I.E. THE VELOCITY OF MAGNETIC RECONNECTION, $\sim 2 \cdot 10^7$ CM/S

The compression of the gas discharge by its own magnetic field at the currents of the hundreds of 500 kA leads to generation of the Lorentz electric field, directed along the axis of discharge. The energy of accelerated particles ~300 KeV at an applied potential difference of ~15 KV.



$\varphi = 15$ kV

$dI/dt = 10^{11}$ A/s

$I_{max} = 200$ kA

$W > 300$ keV

$\mathbf{E} = -\mathbf{V} \times \mathbf{B}/c$

$V \sim 10^7$ cm/s

$B_{max} \sim 4 \cdot 10^4$ G

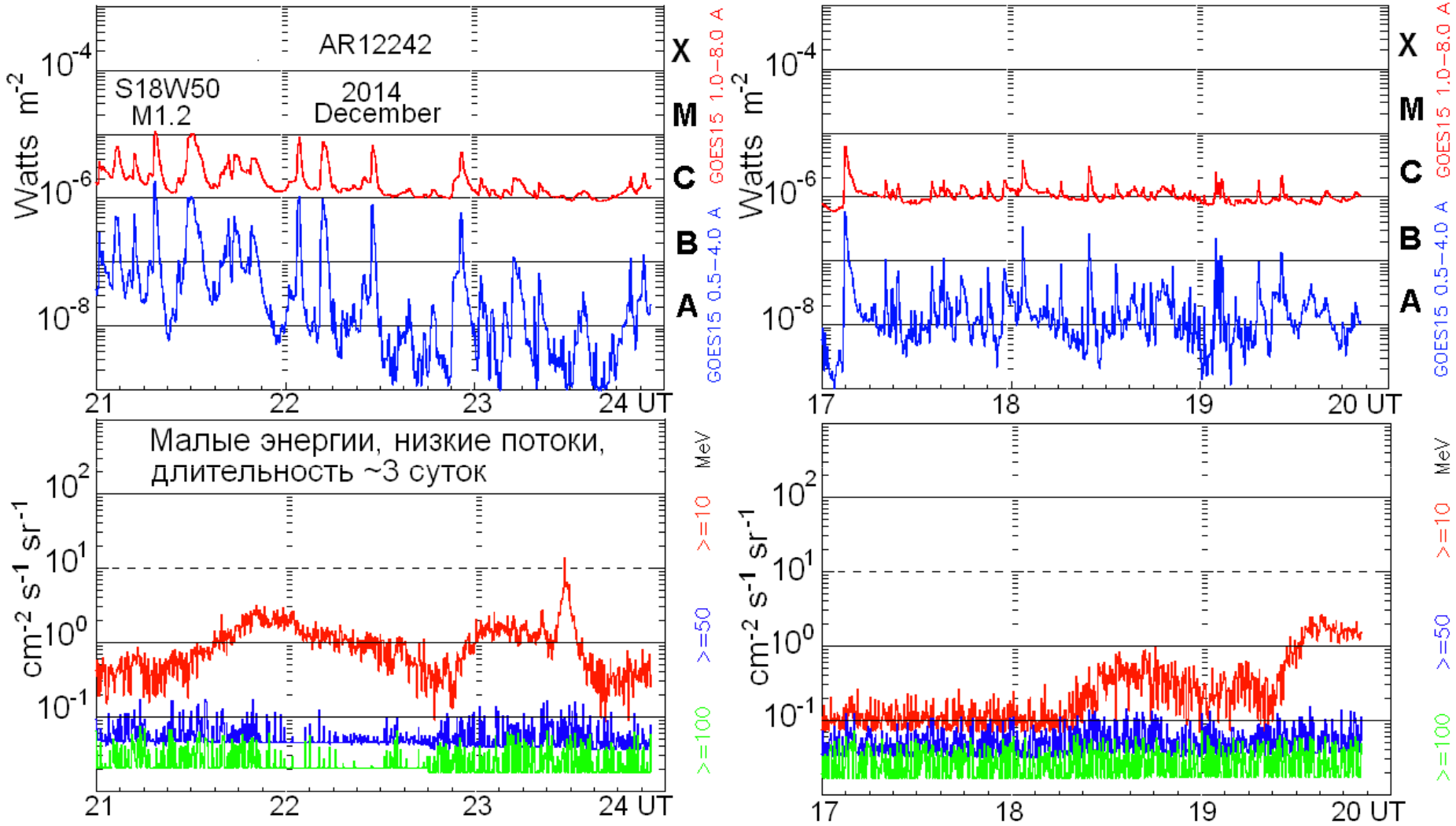
$E \sim 4 \cdot 10^3$ V/cm

Lab. № 2. 1954.
Atomnaja energija
№ 3. 1956.
Artsimovich et. al. P. 84.
Lukjanov, Podgorny. P. 93.

НИЯФ МГУ 1957.
Podgorny, Kovalsky, Palchikov.
DAN SSSR. 123, 825 (1958).

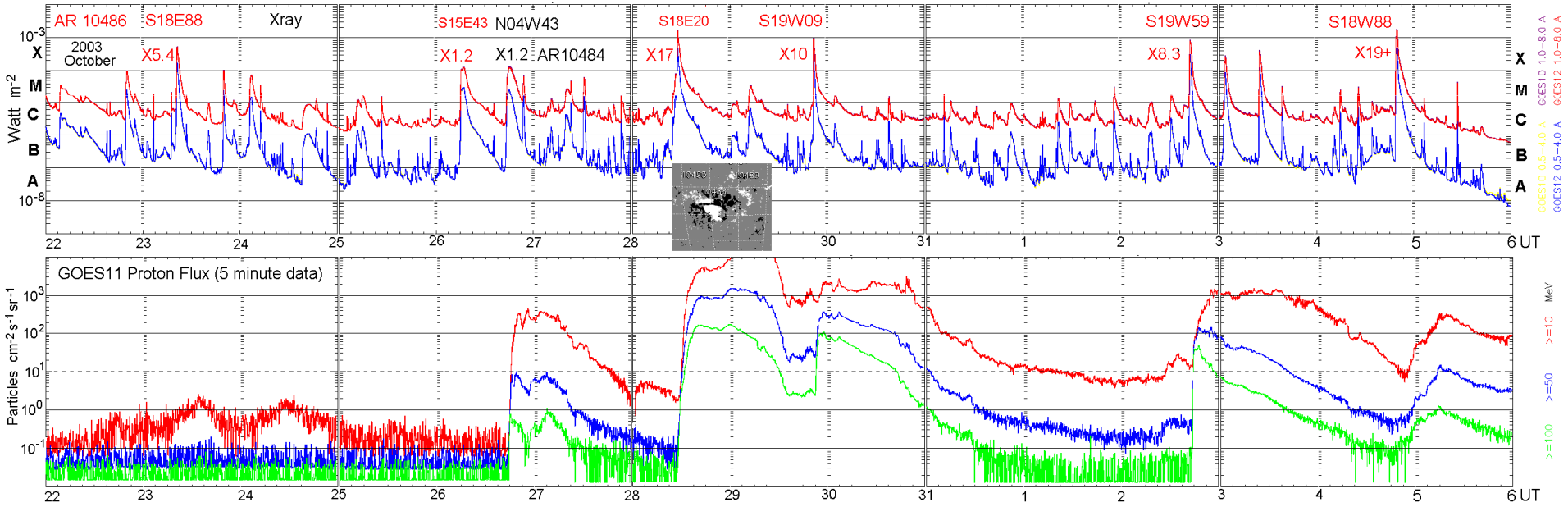
1957.
Severny, Toneman } Electric discharge in solar corona.

С. Н. Вернов

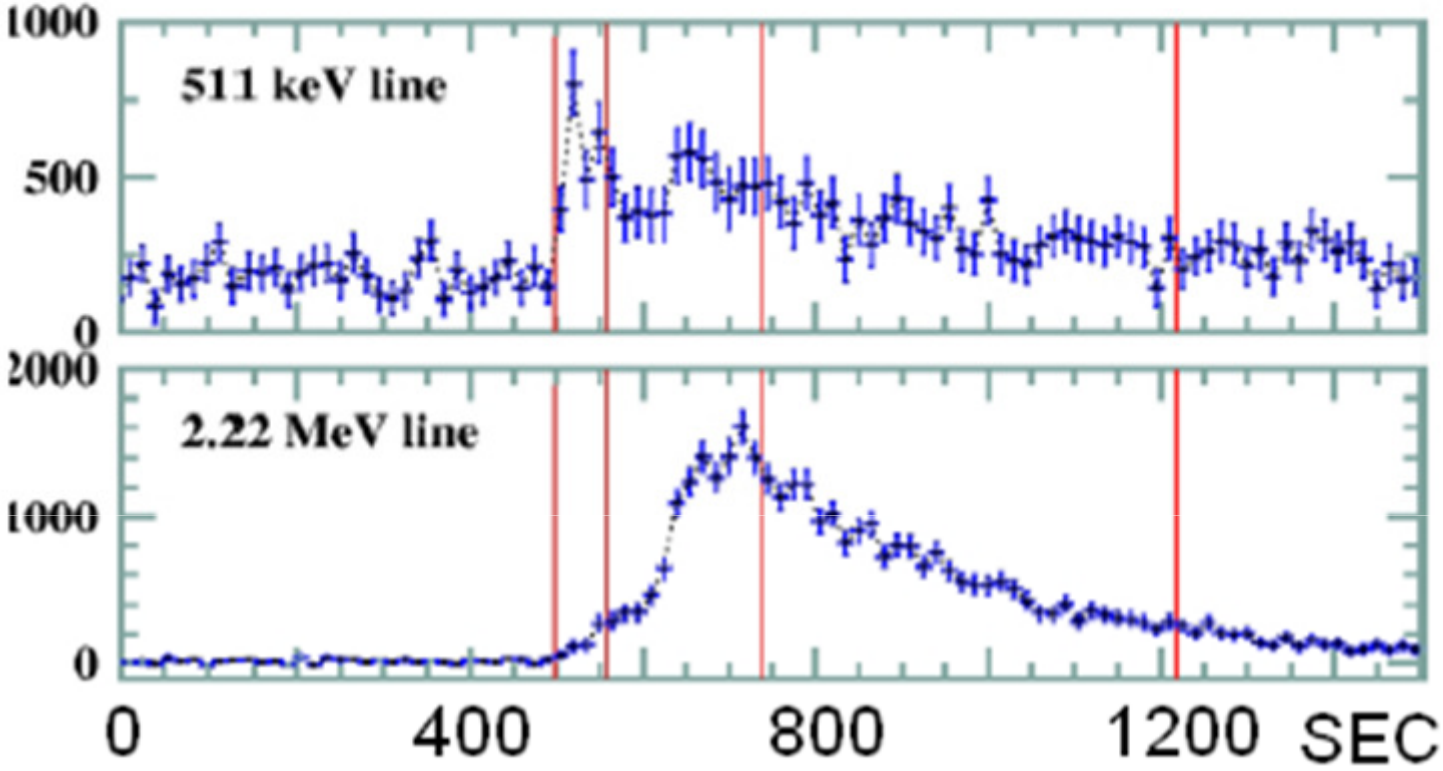


The relationship of small proton flux and solar flares is not detected.

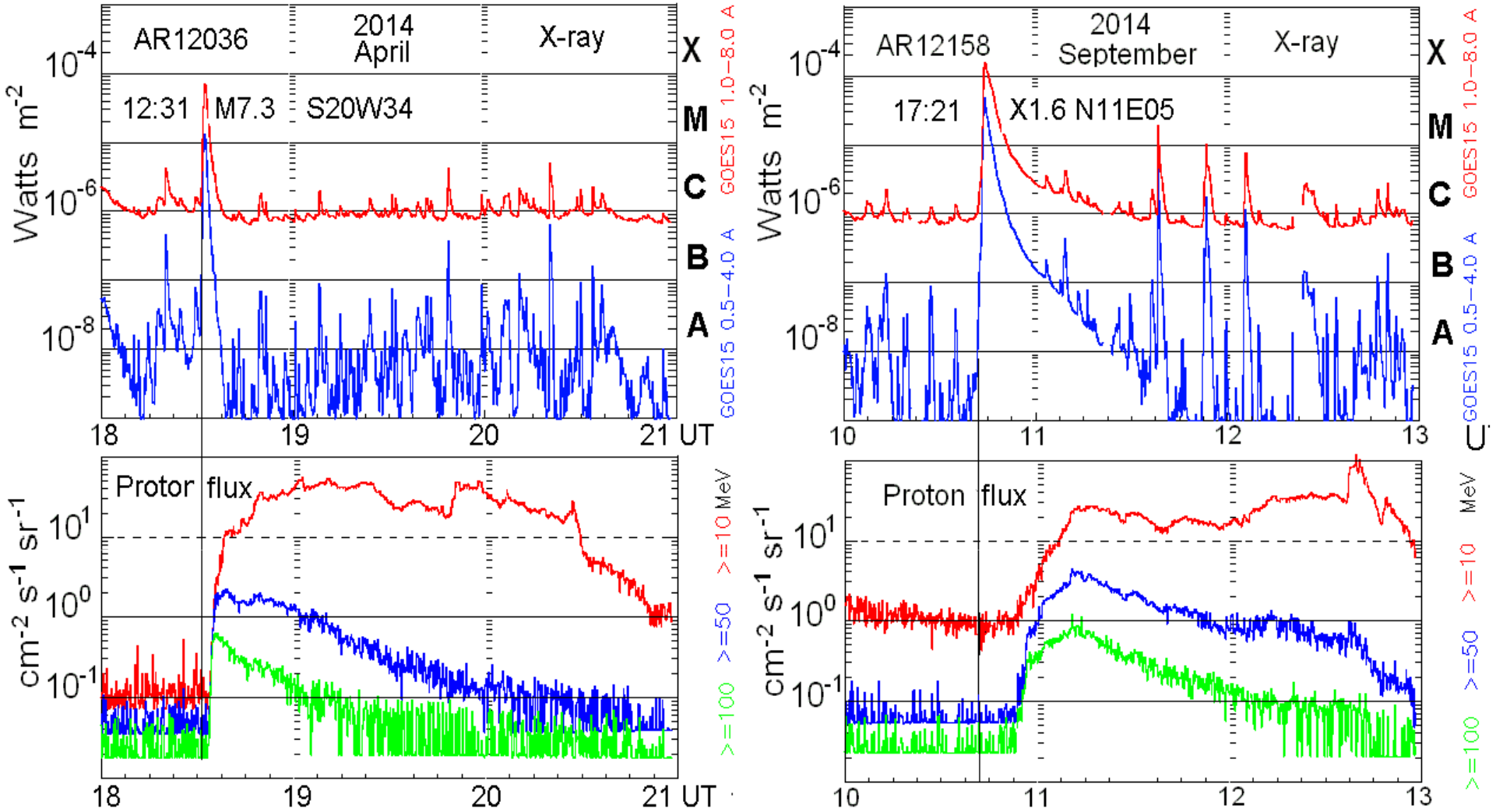
A series of large proton events in October and November 2003 above the complex active region (it is typical). There is no correlation between the values of flares and proton fluxes. Not all X class flares generate proton flux.



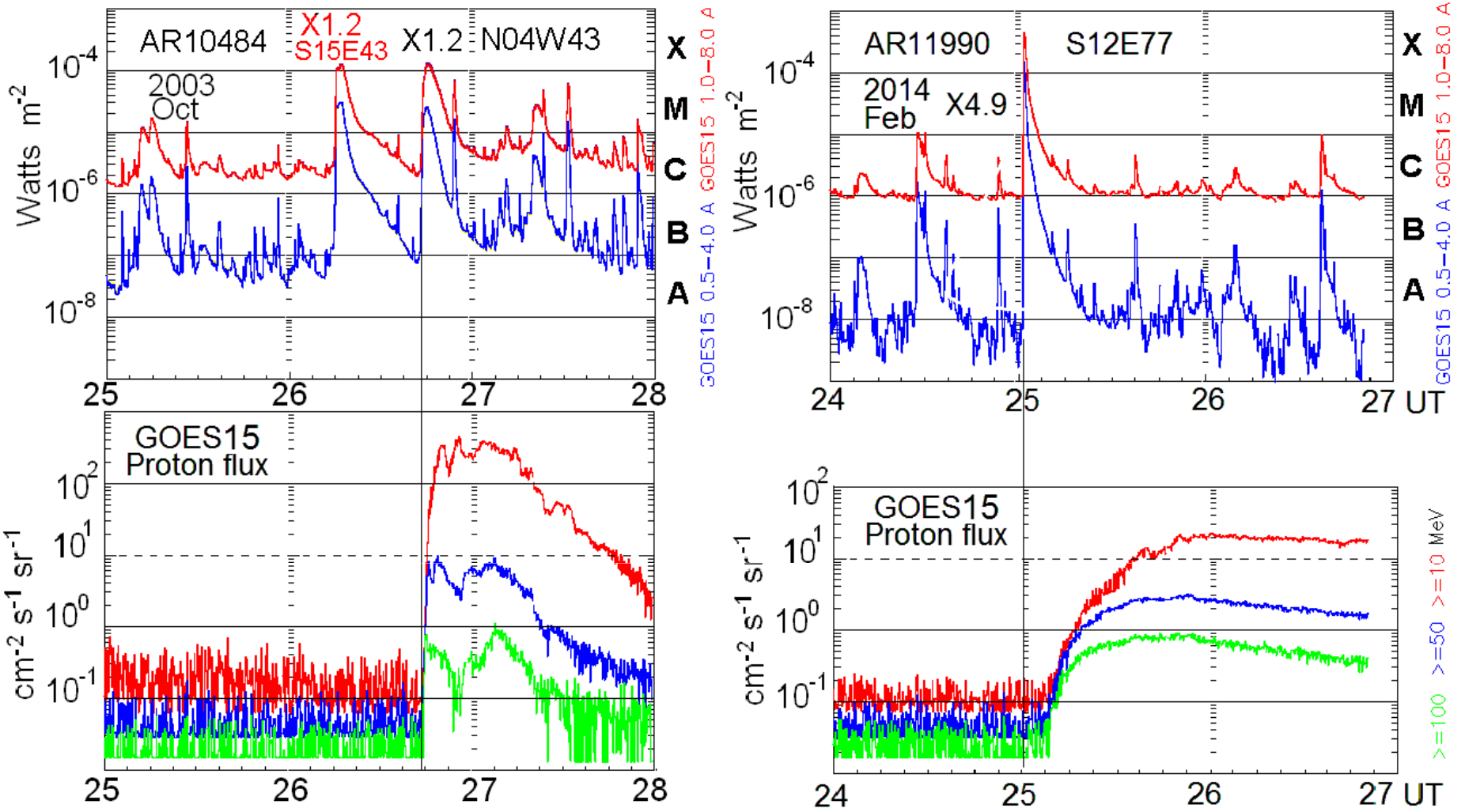
INTEGRAL October, 28. 2003.
H + n = D + 2.22 MeV



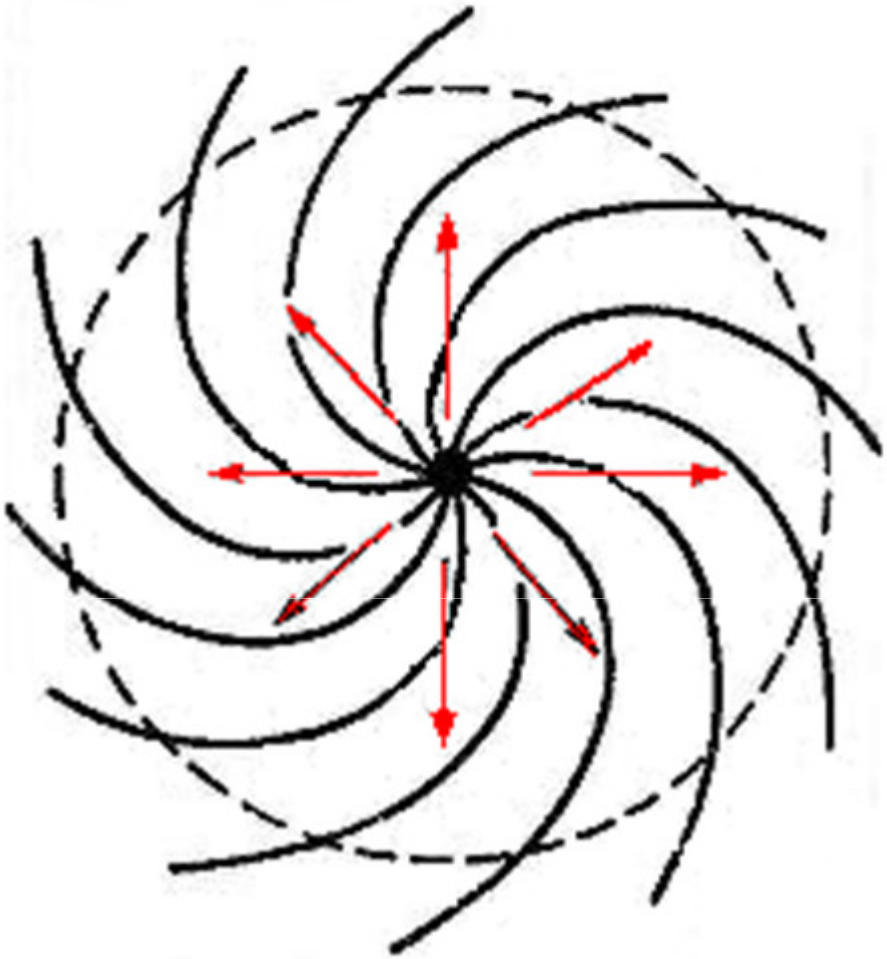
The duration of nuclear reactions in proton events and solar flares are almost identical, but they are ~100 times smaller than the duration of the recorded stream of protons



The Eastern flare X1.6 N11E05 occurred near the center of the solar disk, but the proton front reached Earth only after 5 hours, while the steep front of protons from the Western flare M7.3 S20W34 came after ~20 minutes. The last protons come after ~ 3 days. They propagate with the speed of the solar wind. The protons in the middle of the stream propagated with a velocity less than the particle velocity, but the greater velocity than the solar wind. Diffusion across the field due to scattering on of the magnetic field inhomogeneity??

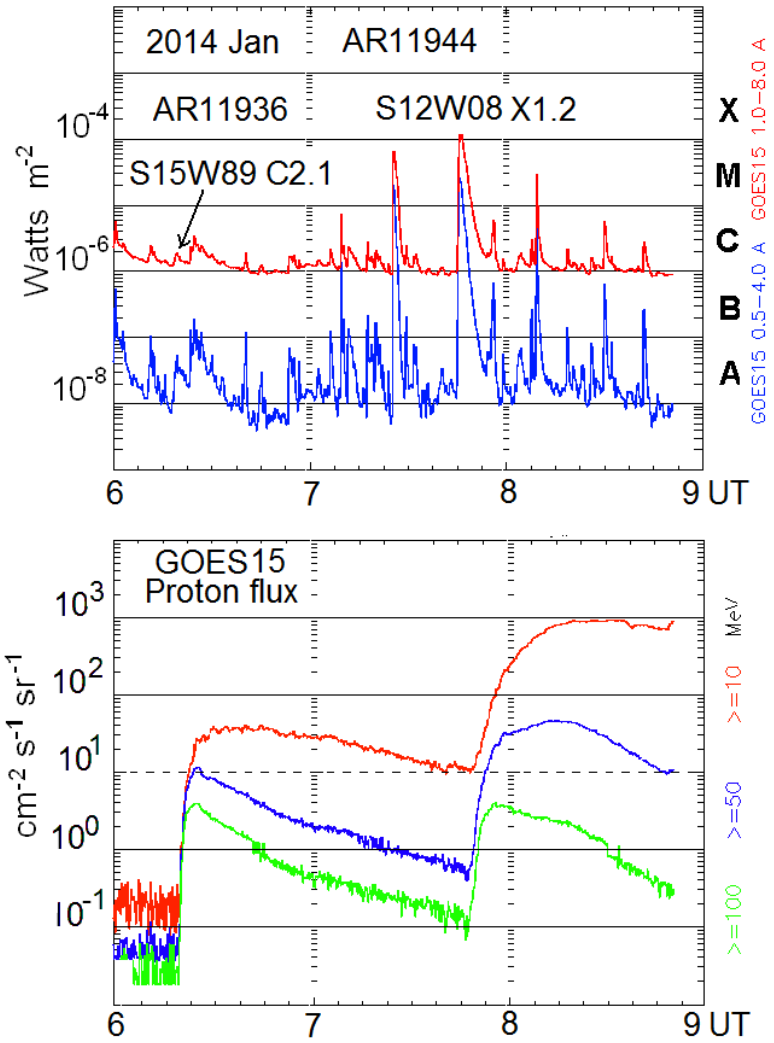


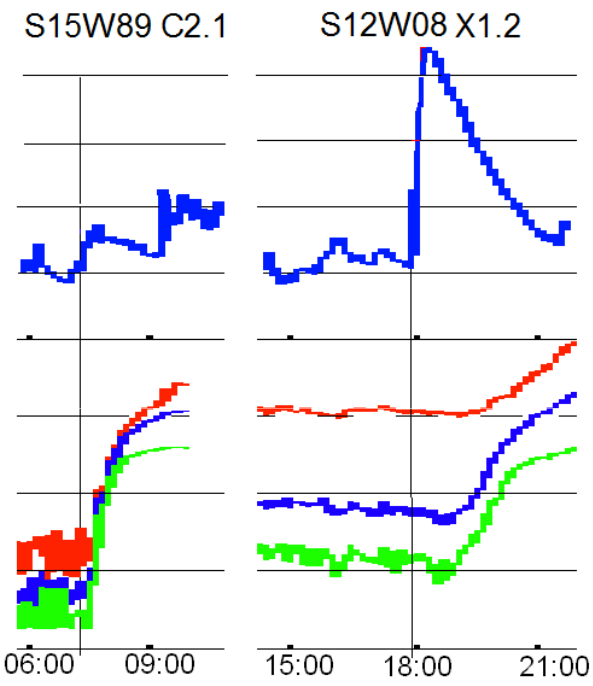
The typical proton event from the Western flare (sharp ~ 13 min front and the time of arriving from the flare with the proton velocity) and proton event from the Eastern flare (wide ~10 hours front and 3 - 5 hours delay).



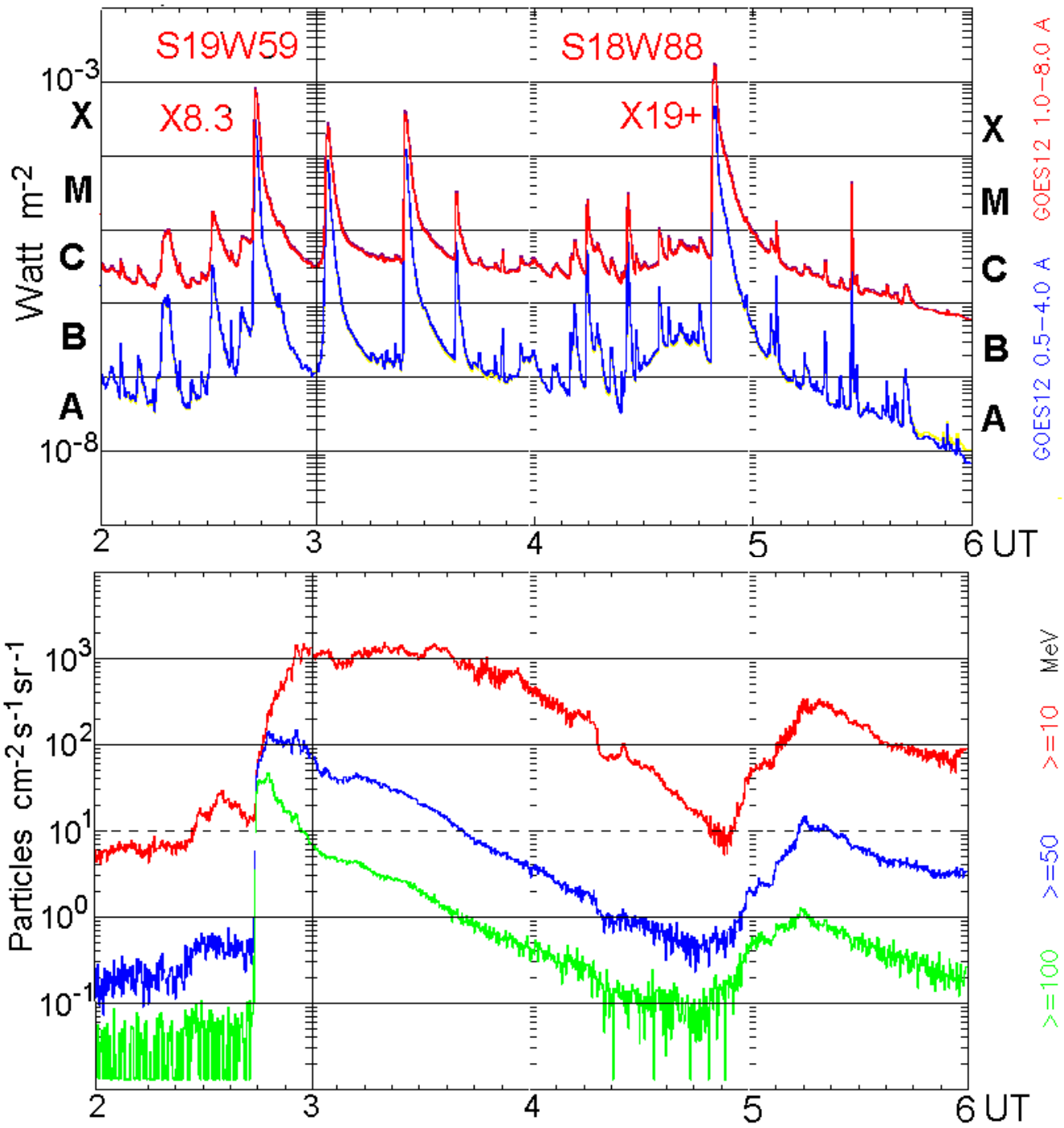
SOLAR WIND - THE PLASMA EXPANSION IN VACUUM IN THE MAGNETIC FIELD AT

$$8\pi nW/B^2 > 1.$$





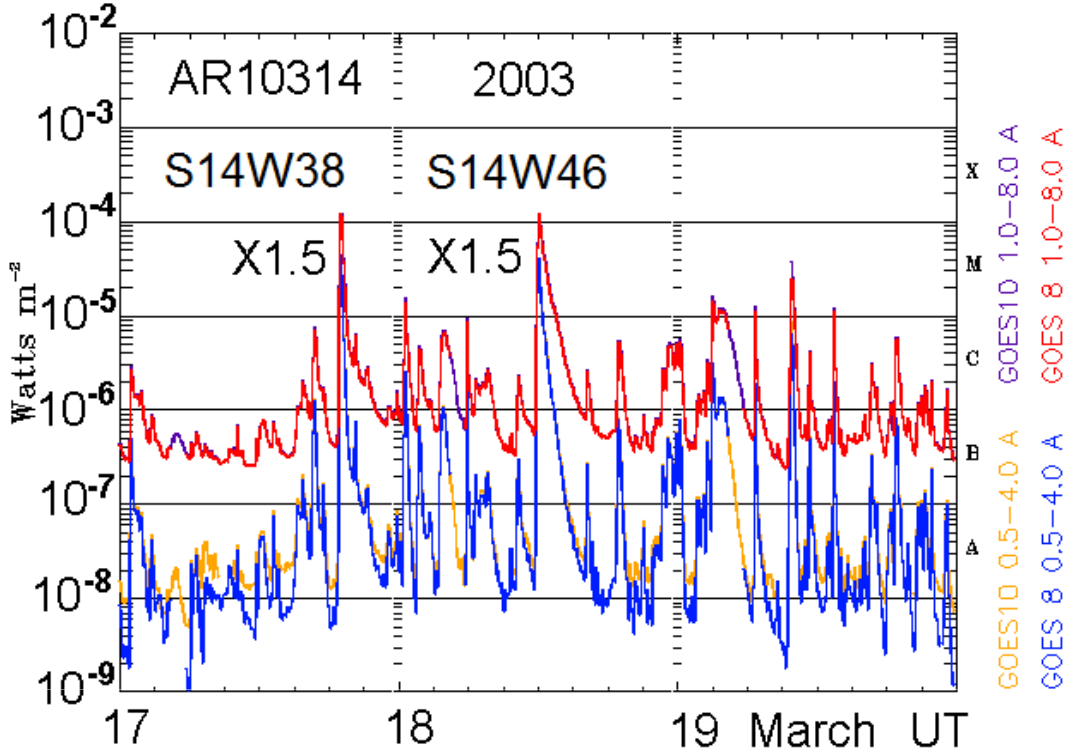
The flare C2.1 is very weak. Such flares never cause a proton flux. Apparently, the flare primary x-ray radiation appeared on the back side of the Sun. The protons came to Earth along magnetic lines of the Archimedean spiral from the back side of the Sun.

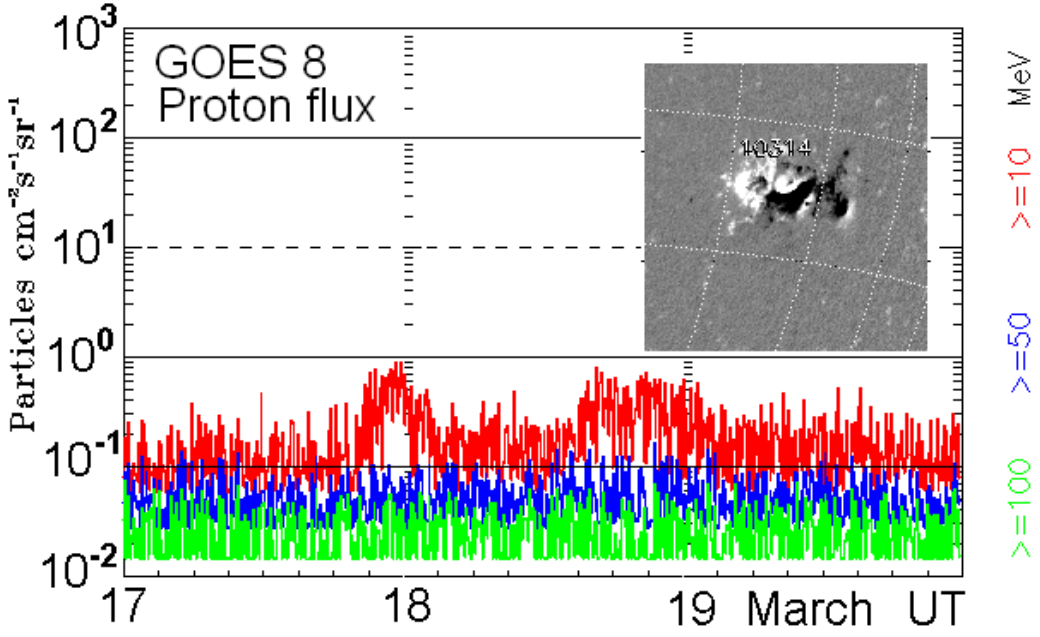


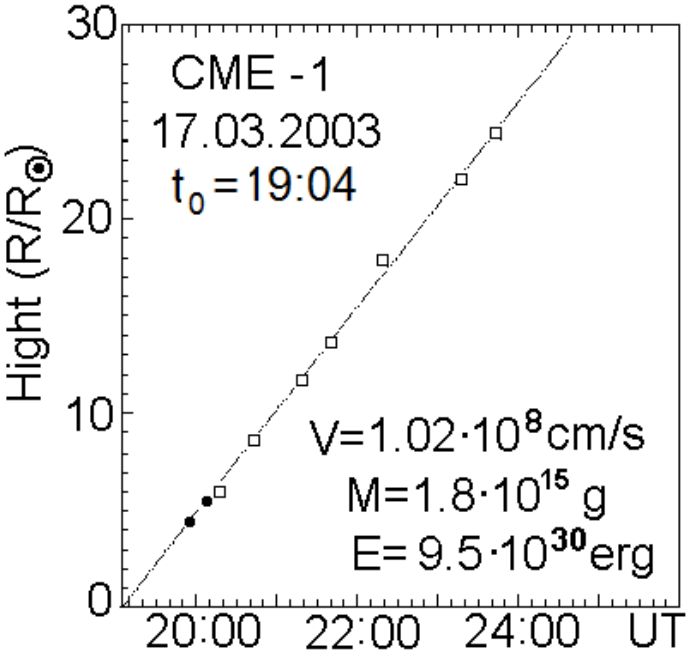
Unusual event !

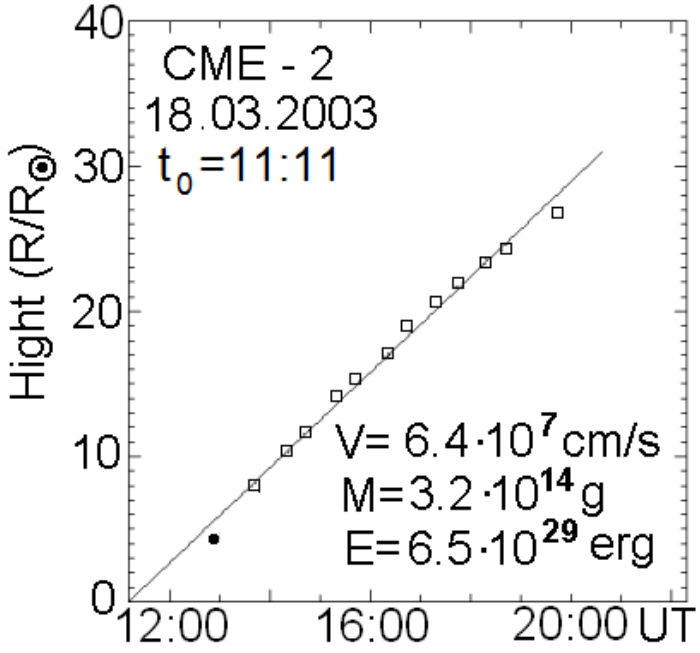
The front of proton flux from the giant Western flare is stretched for ~10 hours.

Three big flares and a large CME can distort the spiral form of magnetic lines of the interplanetary field.

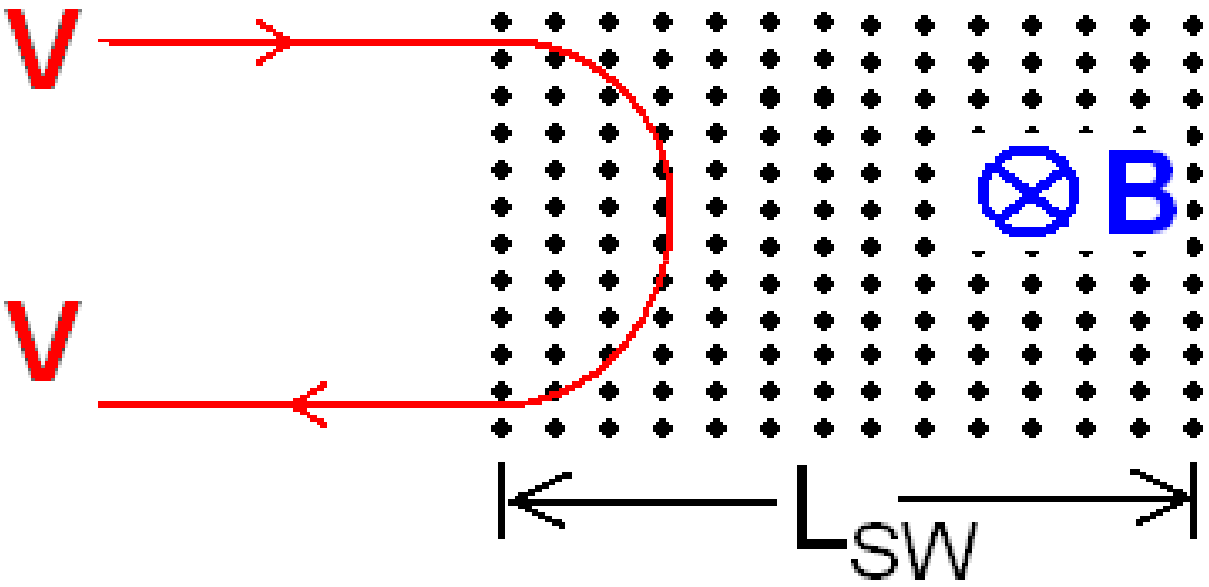

AR10314
2003
S14W38
X1.5
S14W46
X1.5
Watts m⁻²
GOES10 0.5–4.0 A
GOES 8 0.5–4.0 A
GOES10 1.0–8.0 A
GOES 8 1.0–8.0 A
X
M
C
B
A
17
18
19 March UT


GOES 8
Proton flux
10314
Particles cm⁻²s⁻¹sr⁻¹
MeV
>=10
>=50
>=100
17
18
19 March UT


CME -1
17.03.2003
t0 =19:04
V=1.02·10⁸cm/s
M=1.8·10¹⁵ g
E= 9.5·10³⁰erg
Hight (R/R⊙)
20:00
22:00
24:00 UT

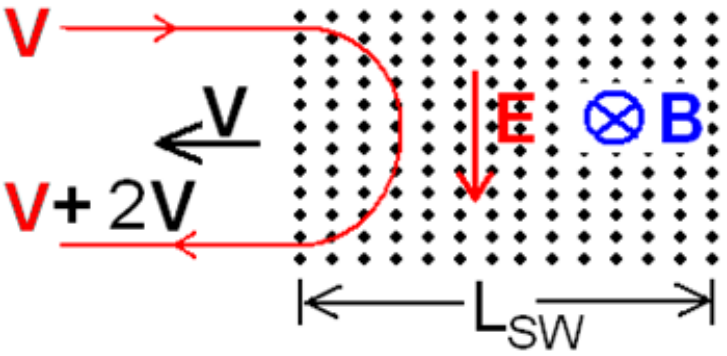

CME - 2
18.03.2003
t0 =11:11
V= 6.4·10⁷ cm/s
M=3.2·10¹⁴ g
E=6.5·10²⁹ erg
Hight (R/R⊙)
12:00
16:00
20:00 UT

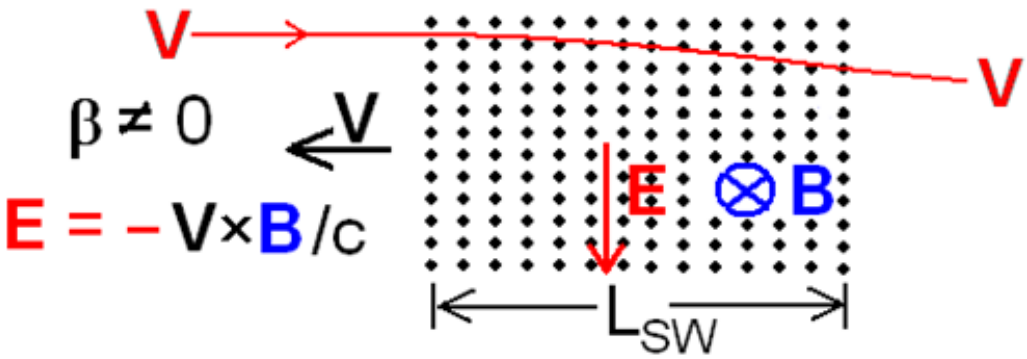
Independent of $\beta = \frac{8\pi nkT}{B^2}$



W= const

Fermi acceleration is a reflection of a particle from moving magnetic clouds with velocity **V**.





$$\delta W = 2\rho E e \qquad \rho = \frac{MVc}{eB} \qquad \delta W = 2\frac{MVc}{B} V \times B/c$$

$$W = \frac{MV^2}{2} \qquad \delta V = \frac{\delta W}{MV} \qquad \delta V = 2V$$

For Fermi acceleration the shock front width L_{SW} must be greater than the Larmor radius ρ. **Otherwise, the particle penetrates the shock front is not gaining energy. The maximum of achievable energy corresponds to the equality of the Larmor radius and the size of the magnetic cloud.**

Conclusion.

1.Large proton events are generated in the flare current sheet.
2. Four time scales of proton events :
a). The duration of generation of accelerated protons is equal to the duration of the flare t_{SF}~20 - 30 min.
b). The typical duration of the proton flux at the Earth orbit is equal to the time of propagation of the solar wind t_{SW} =1a.u./V_{SW}~ 3 days.
c). The arrival time of the sharp front of the stream of relativistic protons from the Western flare to the Earth orbit is equal to the flight time of the protons along the Archimed spiral t_F = 1a.u./c ~15 - 20 minutes.
Collisionless flow carries information about the spectrum of the flare protons.
d). Gentle increase of the proton flux front from Eastern flare (? diffusion across the field ?) t_D ~ 3 - 5 hours.

IT IS INSTALLED:

1.Flare proton acceleration takes place in the Lorentz electric field along the magnetic X-line in the current sheet at the reconnection velocity ~2×10^7 cm/s.

2. The duration of the observed proton flux (~3 days) significantly exceeds the flare duration. It is equal to the time of solar wind transfer to the Earth.

3. Protons from the Western flares arrive to Earth along the helical magnetic field lines.

4. Protons from the Eastern flares can arrive to the Earth with the solar wind flow across magnetic field lines. However, the delay due traveling with solar wind velocity must be greater than observed one. Apparently, some of the protons arrive ahead of the solar wind due to diffusion.

5. Large flares can distort the interplanetary magnetic field.

6. Small proton event not find clear patterns.

Thank you!

БЛАГОДАРЯ!