Solar cosmic ray generation by solar flares.

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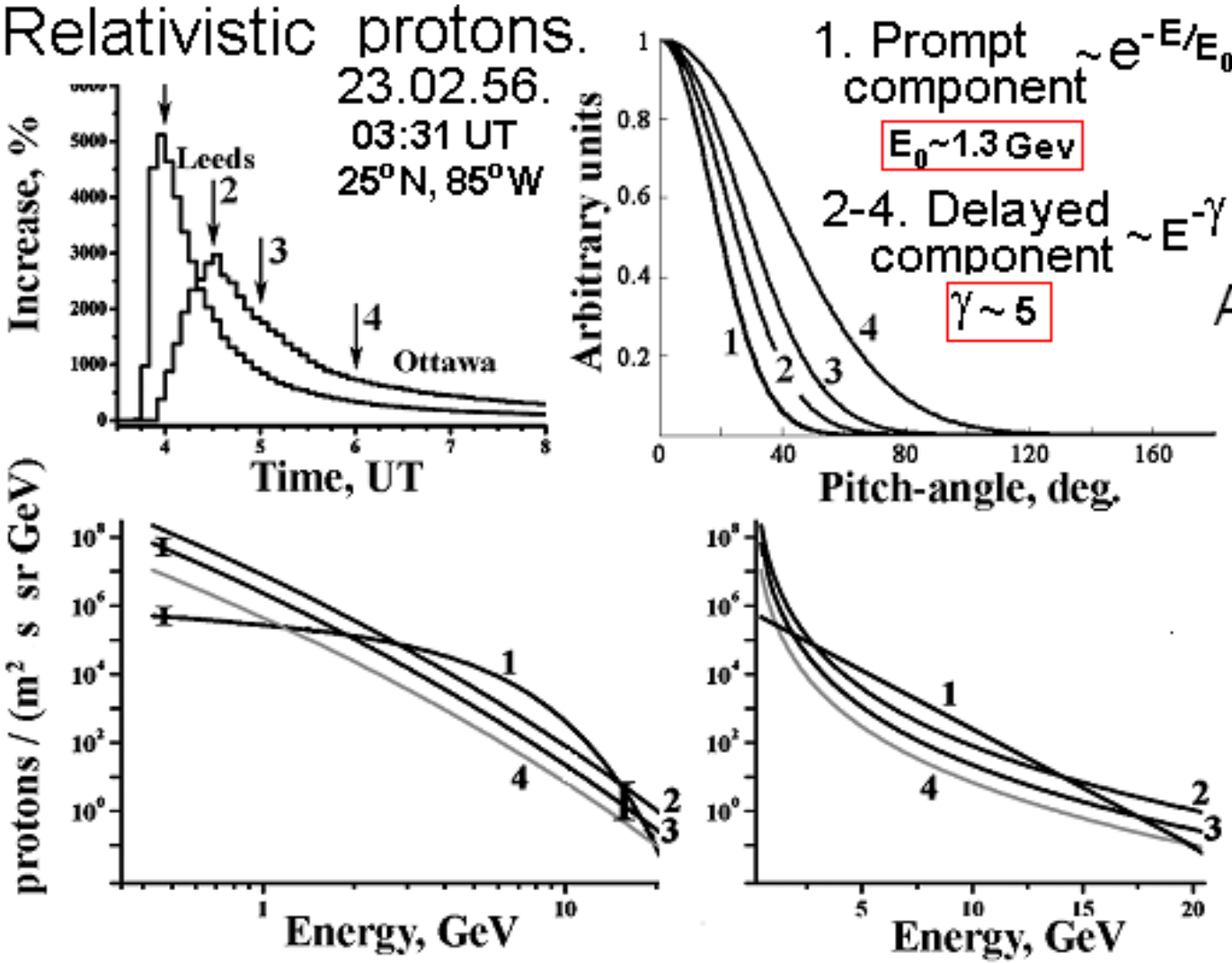
[1] Institute of Astronomy RAS, Moscow, Russia;

[2] Lebedev Physical institute RAS, Moscow, Russia

Some solar flares are accompaniment by pulses of protons with the energy up to 20 GeV. The proton acceleration takes place during the magnetic reconnection at a solar flare. The duration of prompt proton ejection from the Sun is ~10 min. It does not exceed time of a solar flare. But the duration of proton pulses arriving to the Earth orbit and measured with the GOES spacecraft is order of several days. This time is determined by solar wind flow and diffusion in the interplanetary space. The proton flux tail is not depended on the flare position, but the measured proton flux demonstrates two types of the front structure. The sharp front ~20 min is observed if the flare appears on the West of the solar disk. The long front order of several hours is demonstrated the proton flux generated by eastern solar flares. The sharp front appears at particle traveling along magnetic line connecting the flare and the Earth. These particles arrive without Columbus scattering. They initiate the beam instability, and following particles are transported due to diffusion. The scattering initiate the change of the spectrum. The protons traveling across the magnetic lines arrive to the Earth orbit after the delay of 3 - 5 hours. It is much faster than the solar wind. One of possibility for such fast arriving is the turbulent diffusion initiated by beam instability of the prompt proton component.

- Cosmic rays are studied for 100 years, but their origin is still not clear.
- Sun - is an astronomical observatory. Due to its proximity to the Earth, we can get information, which does not come to us from other stars.
- John N. Bahcal

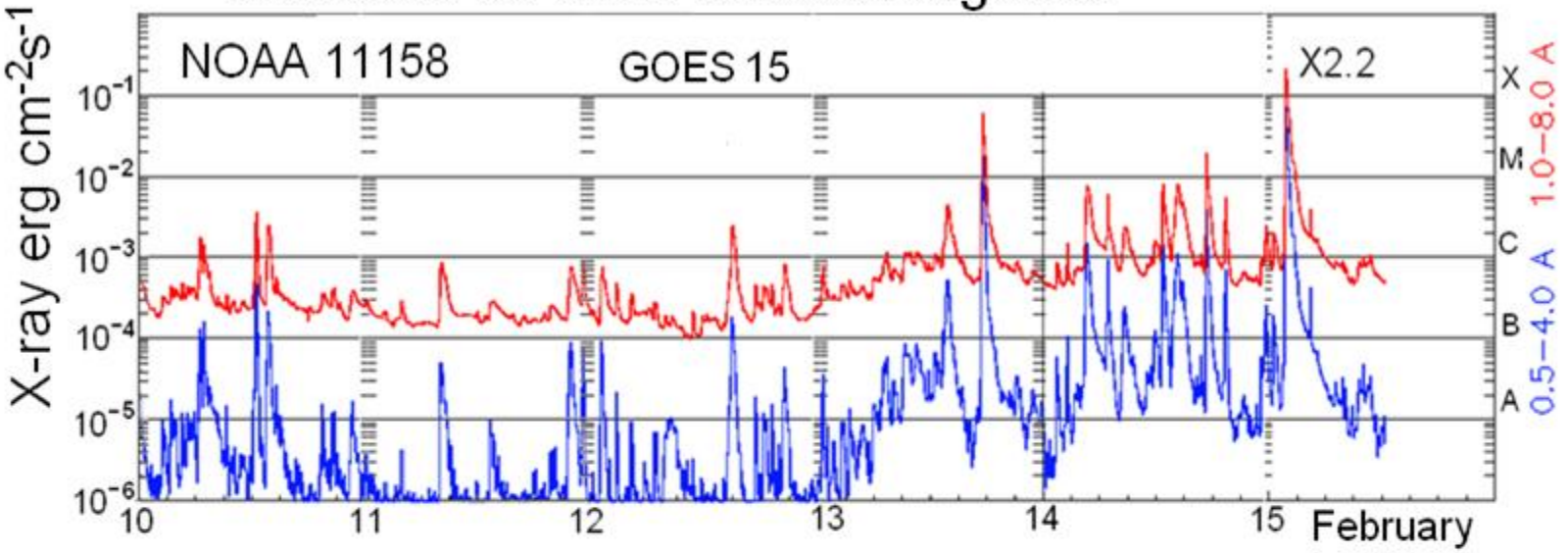
Measurements with world wide net of neutron monitors

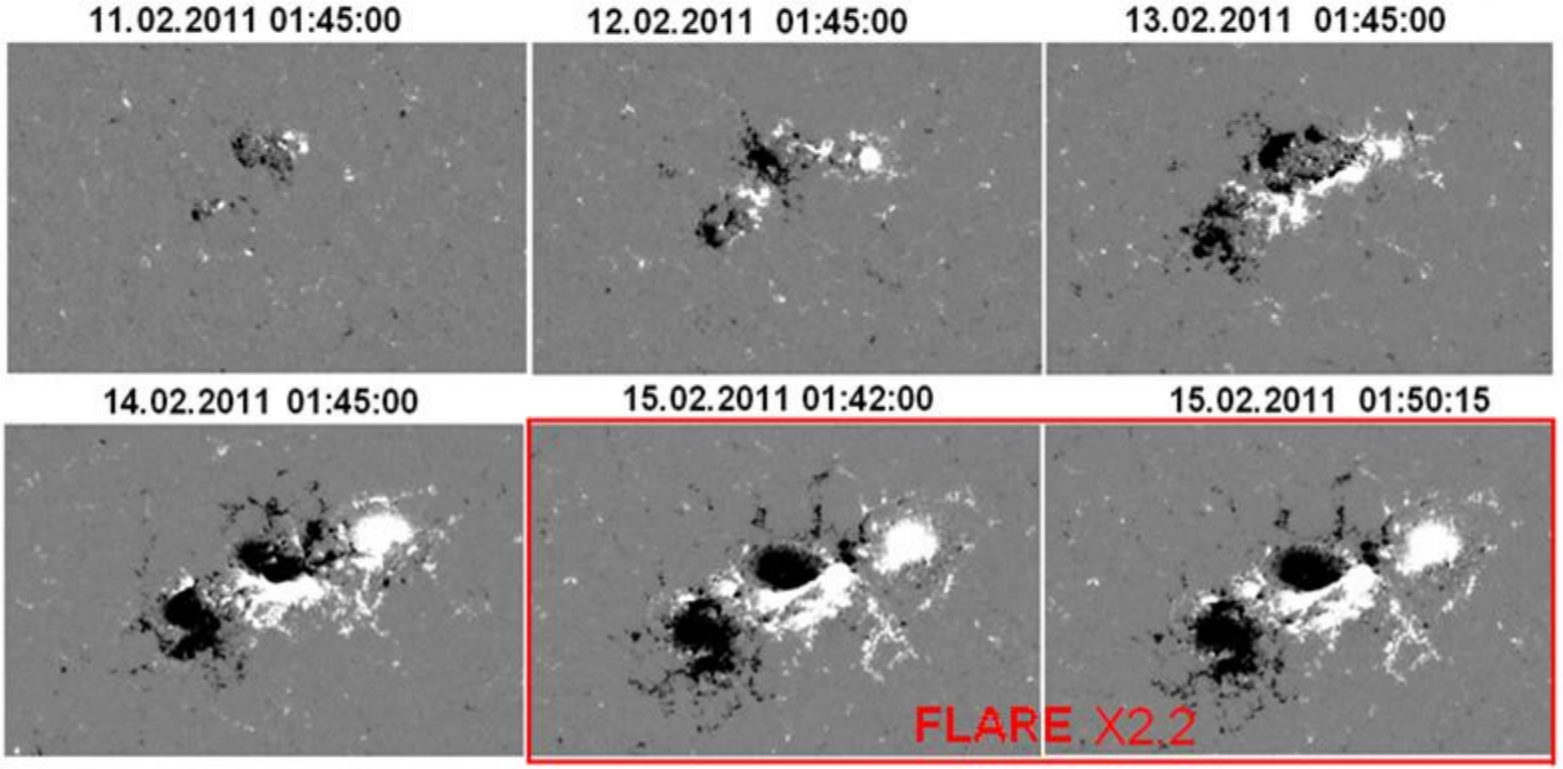


Podgorny at al. 2010, Astronomy Reports.

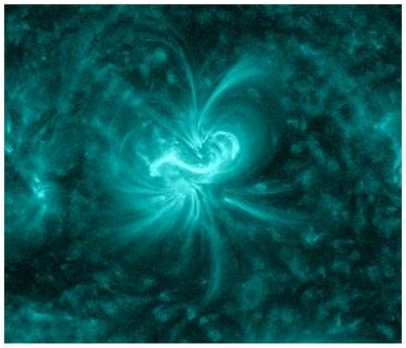
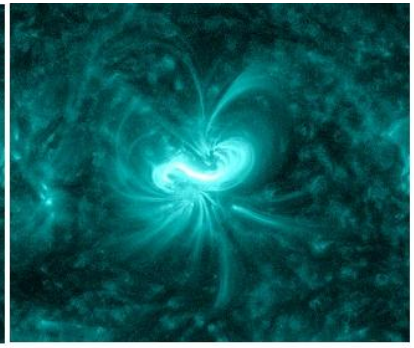
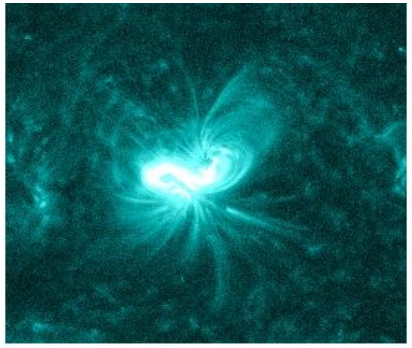
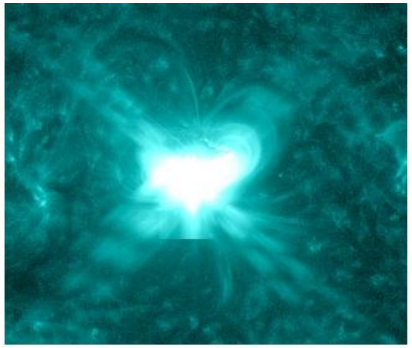
Prompt proton component arrives without collisions along magnetis lines.They move with the proton velocity.

Large and complex magnetic field is necessary but not sufficient for solar flare emergence



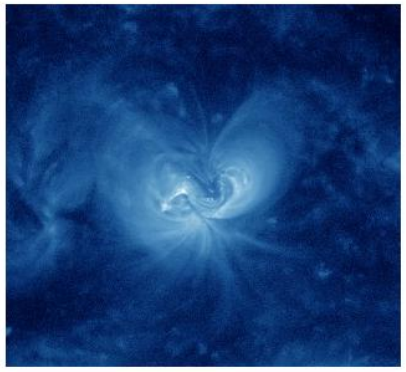
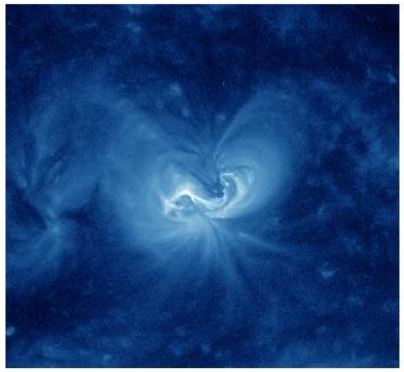
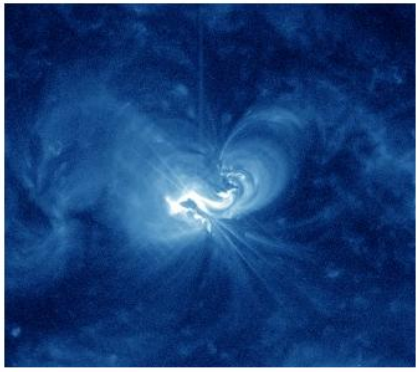
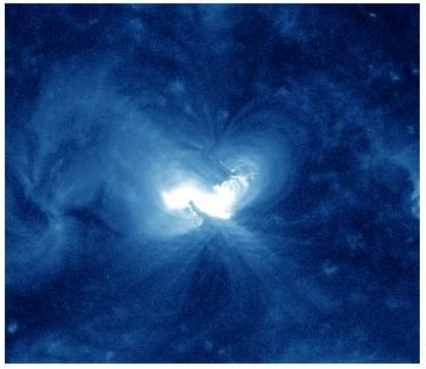


SDO measurements

16:57:46 17:12:46 17:28:19 17:43:26

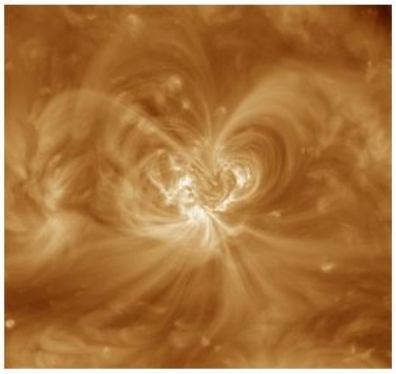
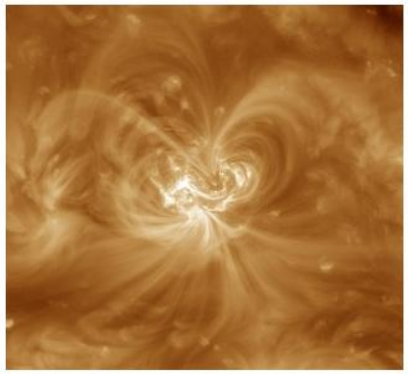
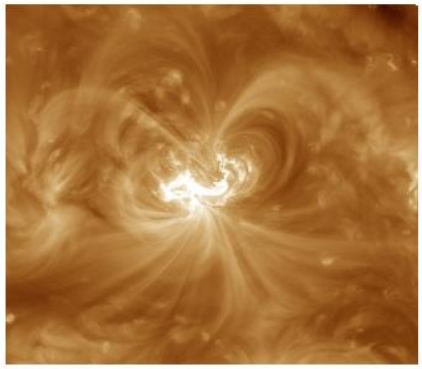
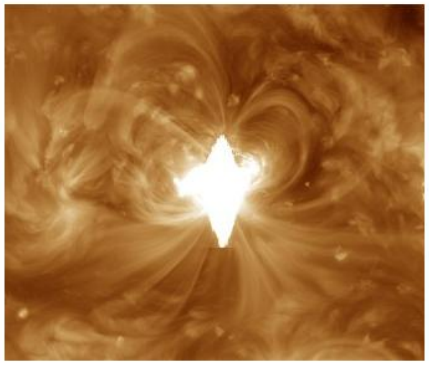
X1.6 AR12158
N11E05
t_0=17:21
10.09.2014 UT
131A FeVIII, FeXX, FeXXIII
0.4 MK, 10 MK, 16 MK

17:00:52 17:16:28 17:31:04 17:47:28

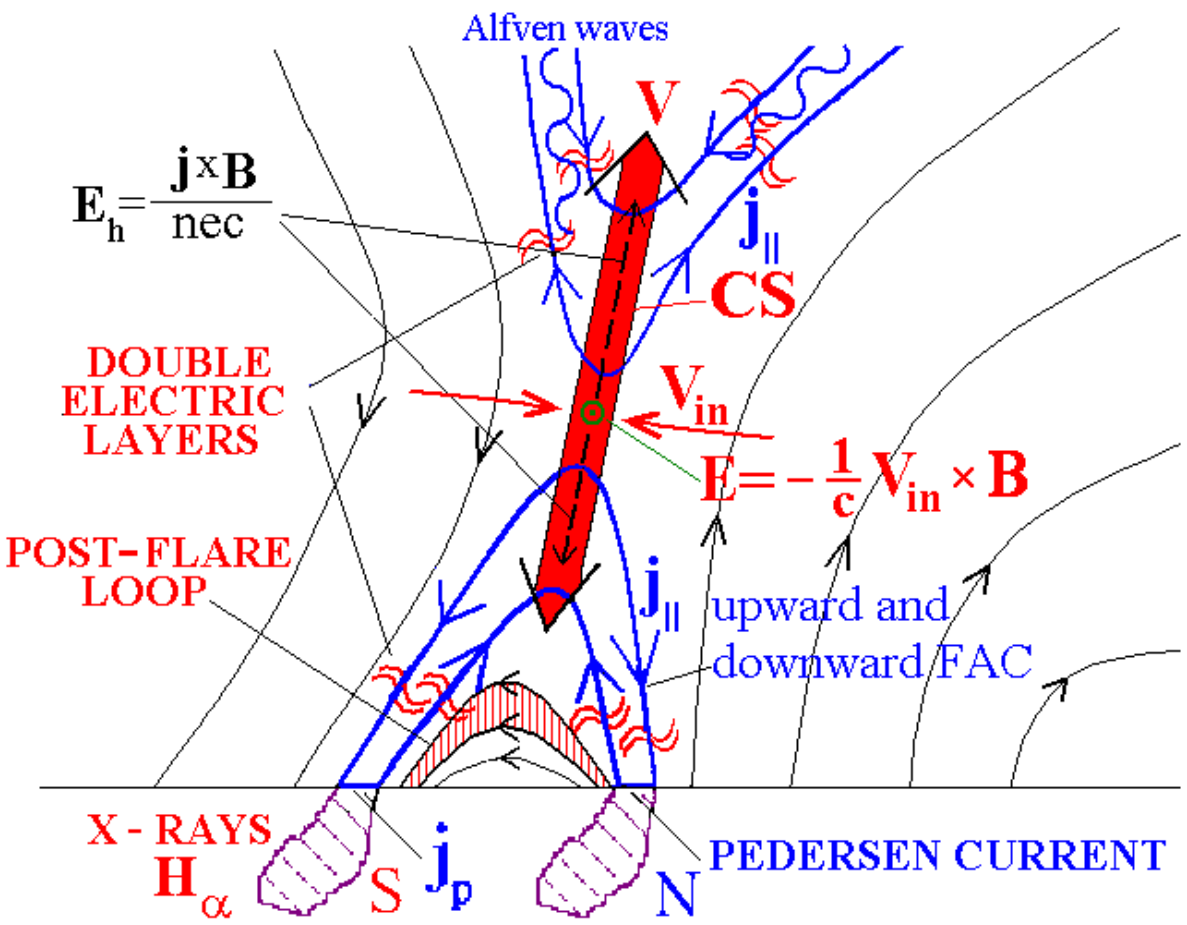
335A FXVI
2.5 MK

211XIV ac-reg cor 2 MK
335XVI ac-reg cor 2.5 MK

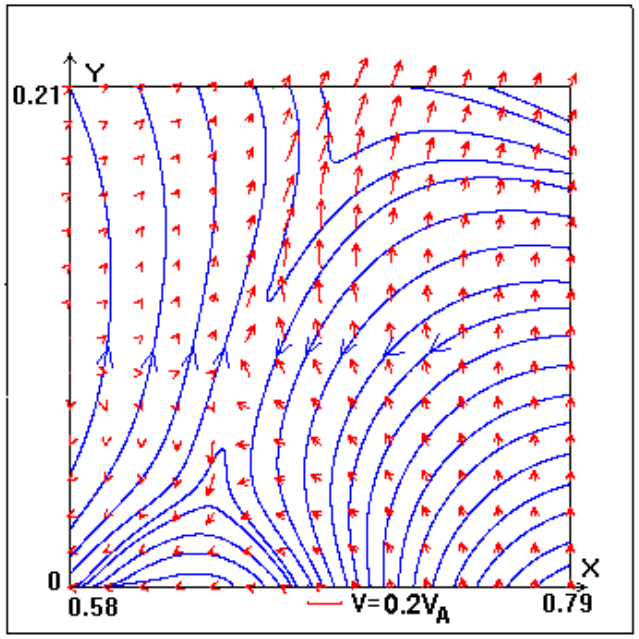





16:55:07 17:10:55 17:26:19 17:40:43

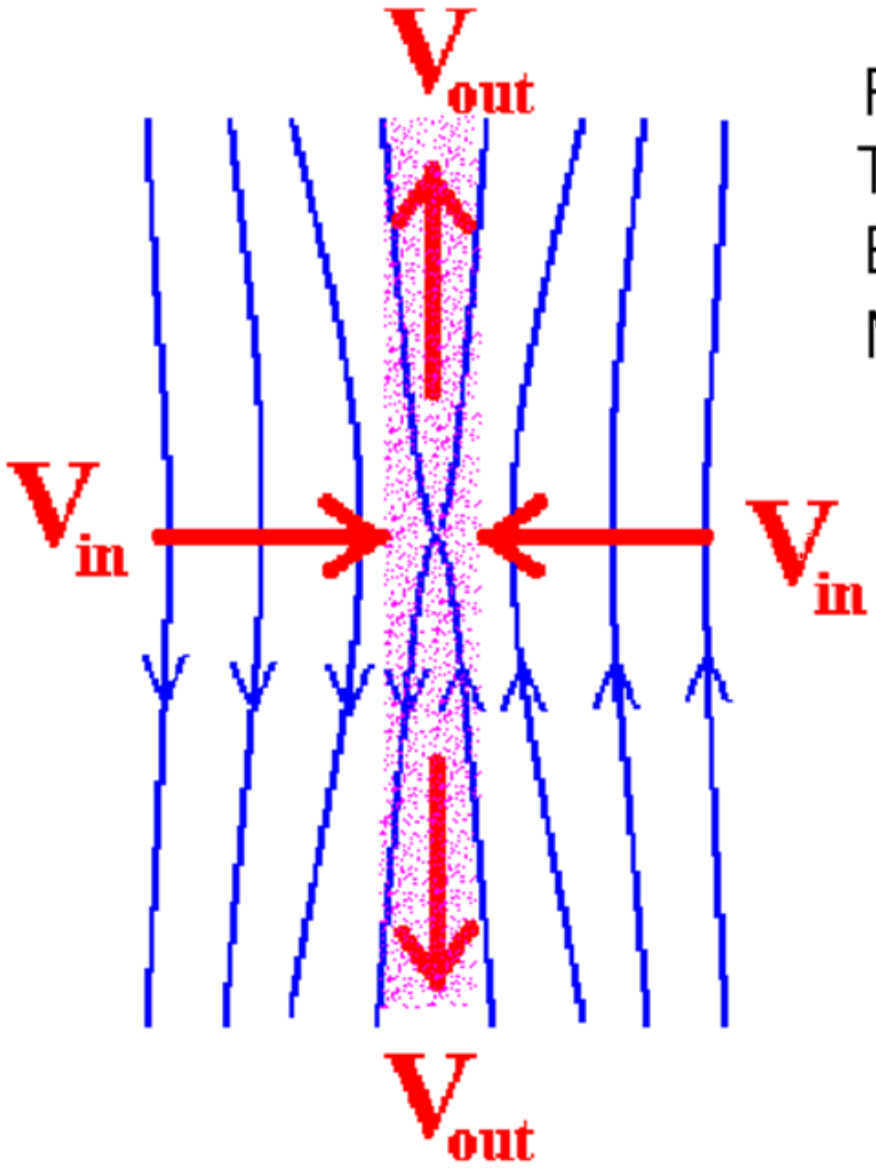
193A Fe XII
FeXXIV



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 **j**x**B** force producing CME.



From RHESSI: $(ME)=5\cdot10^{49}\,cm^{-3}$.

$T=3.1$ keV $n=10^{11}\,cm^{-3}$.

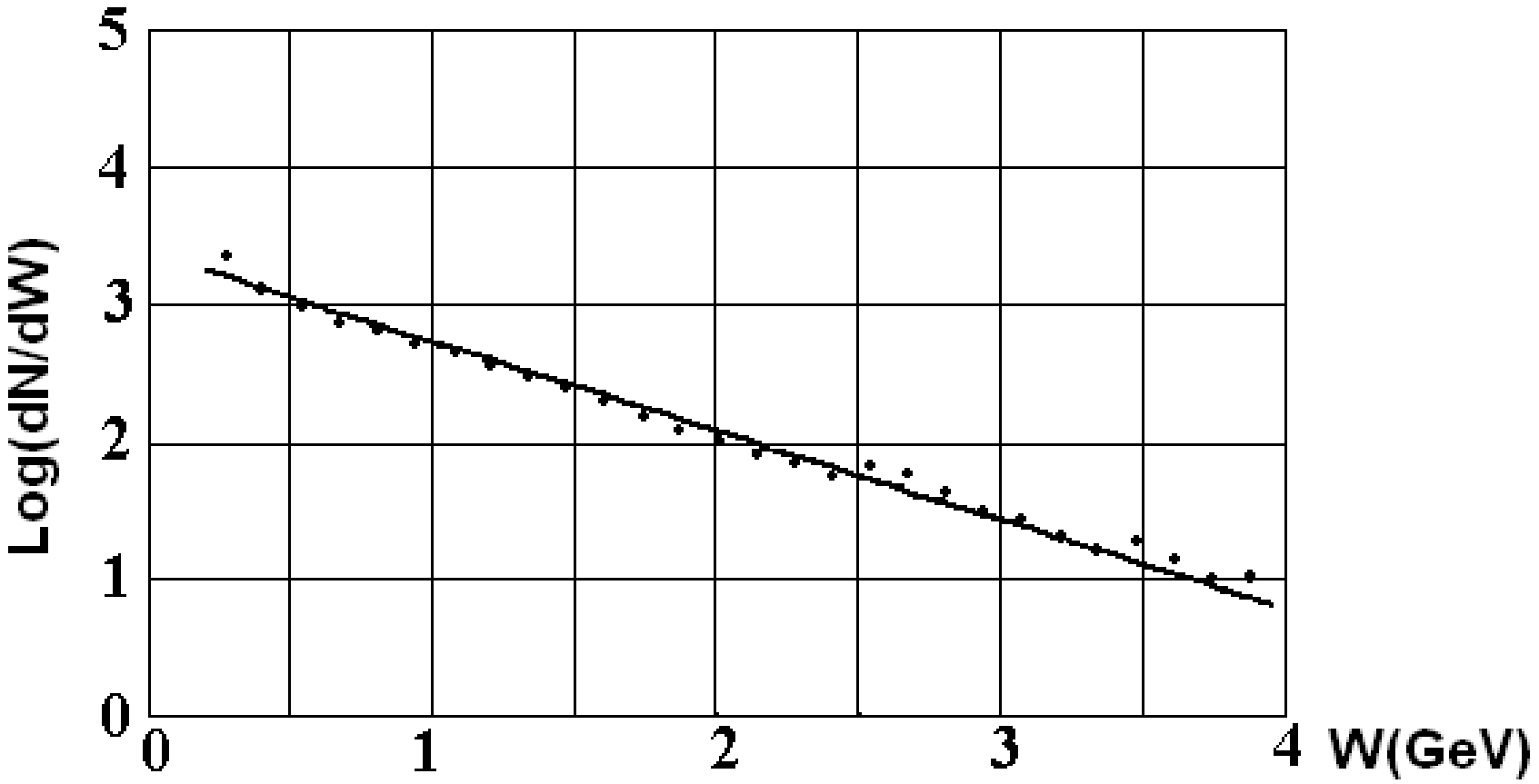
$B^2/8\pi = nkT \rightarrow B = 110\,G$.

$M = Nm_p \sim 10^{15}\,g$ --- CME.

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

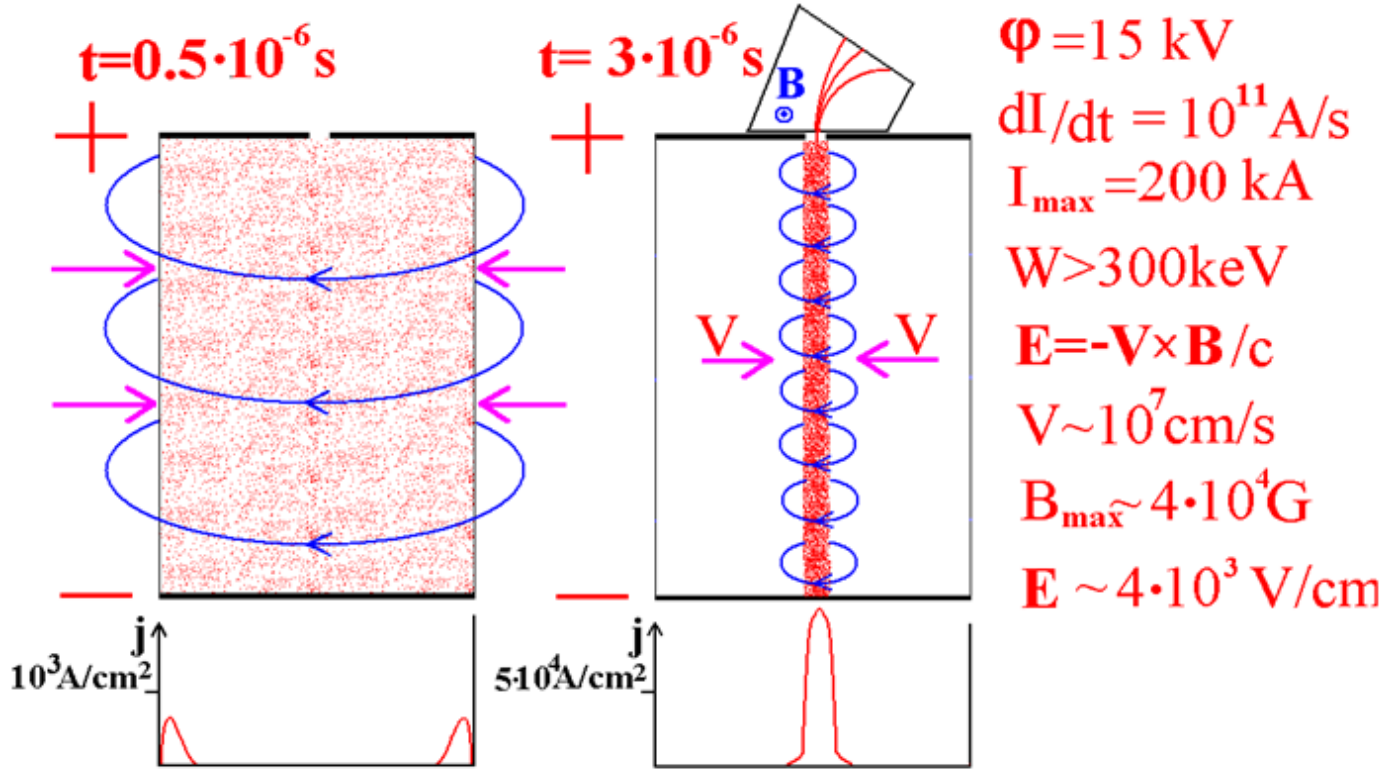
$E = V \times B/c$. $E=20$ V/cm.

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



THE 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 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>300keV

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

$V \sim 10^7$ cm/s

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

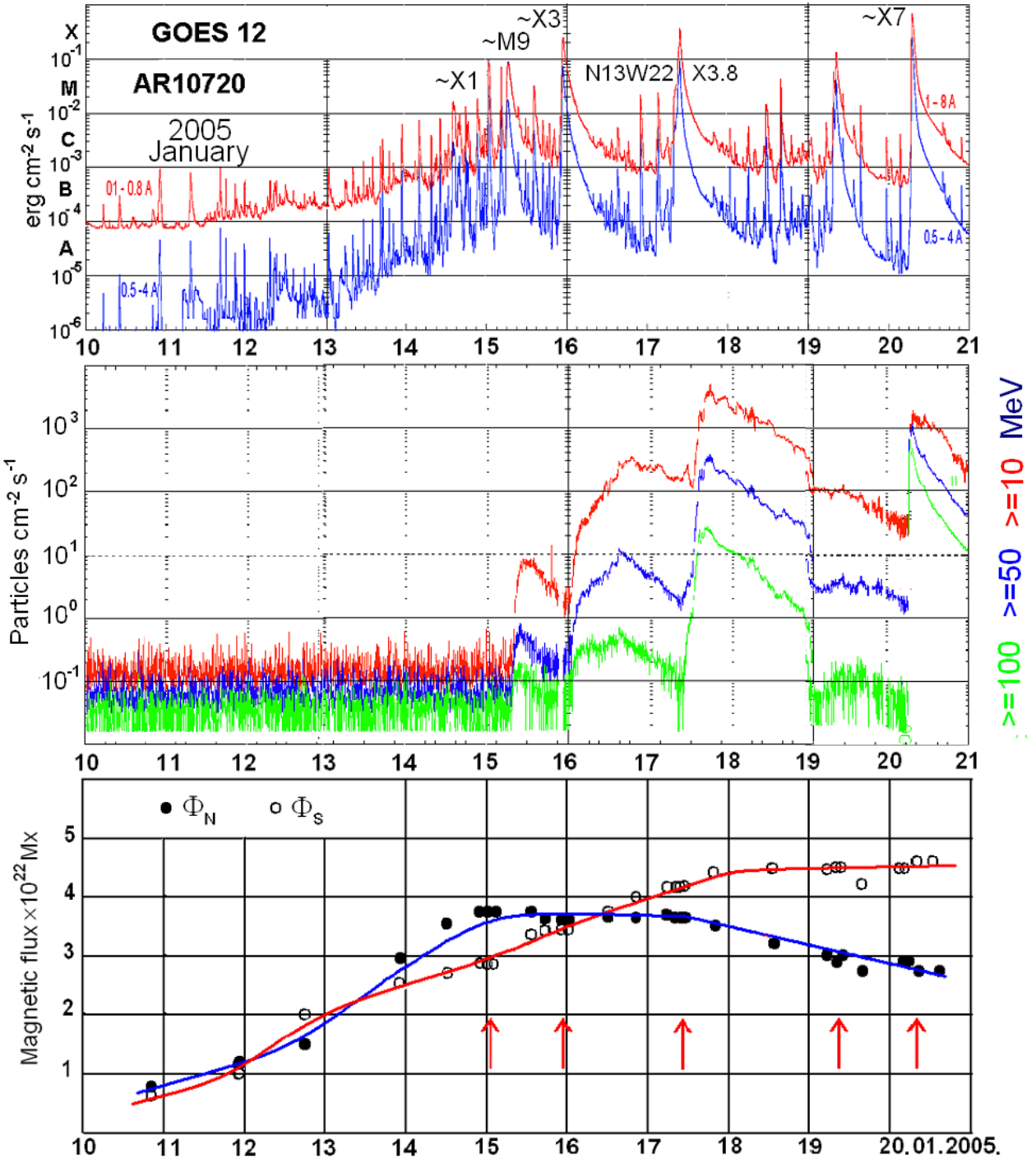
$E \sim 4 \cdot 10^3$ V/cm

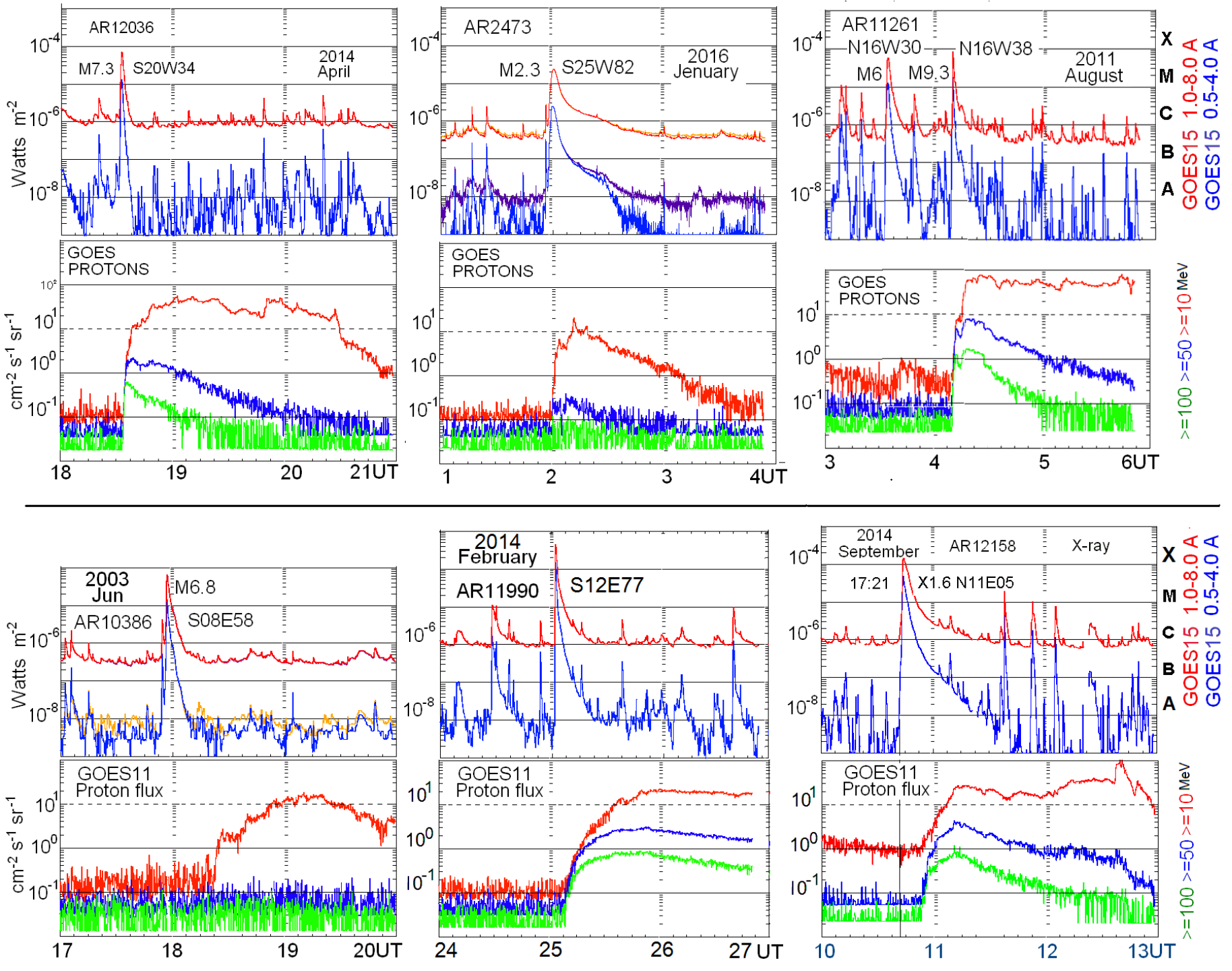
Lab. № 2. 1954.
Atomnaja energija
№ 3. 1956.
Artsimovich et. al. P. 84.
Lukjanov, Podgorny. P. 93.

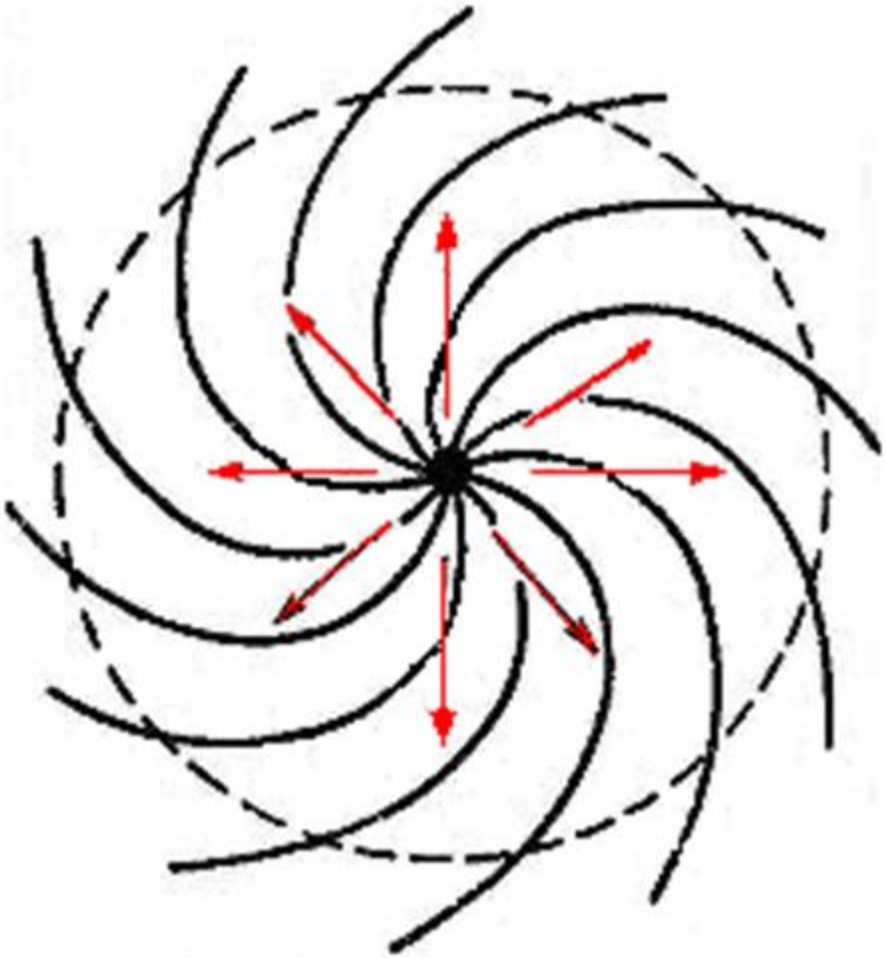
SINP MSU 1957.
Podgorny, Kovalsky, Palchikov.
DAN SSSR. 123, 825 (1958).

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

S. N. Vernov

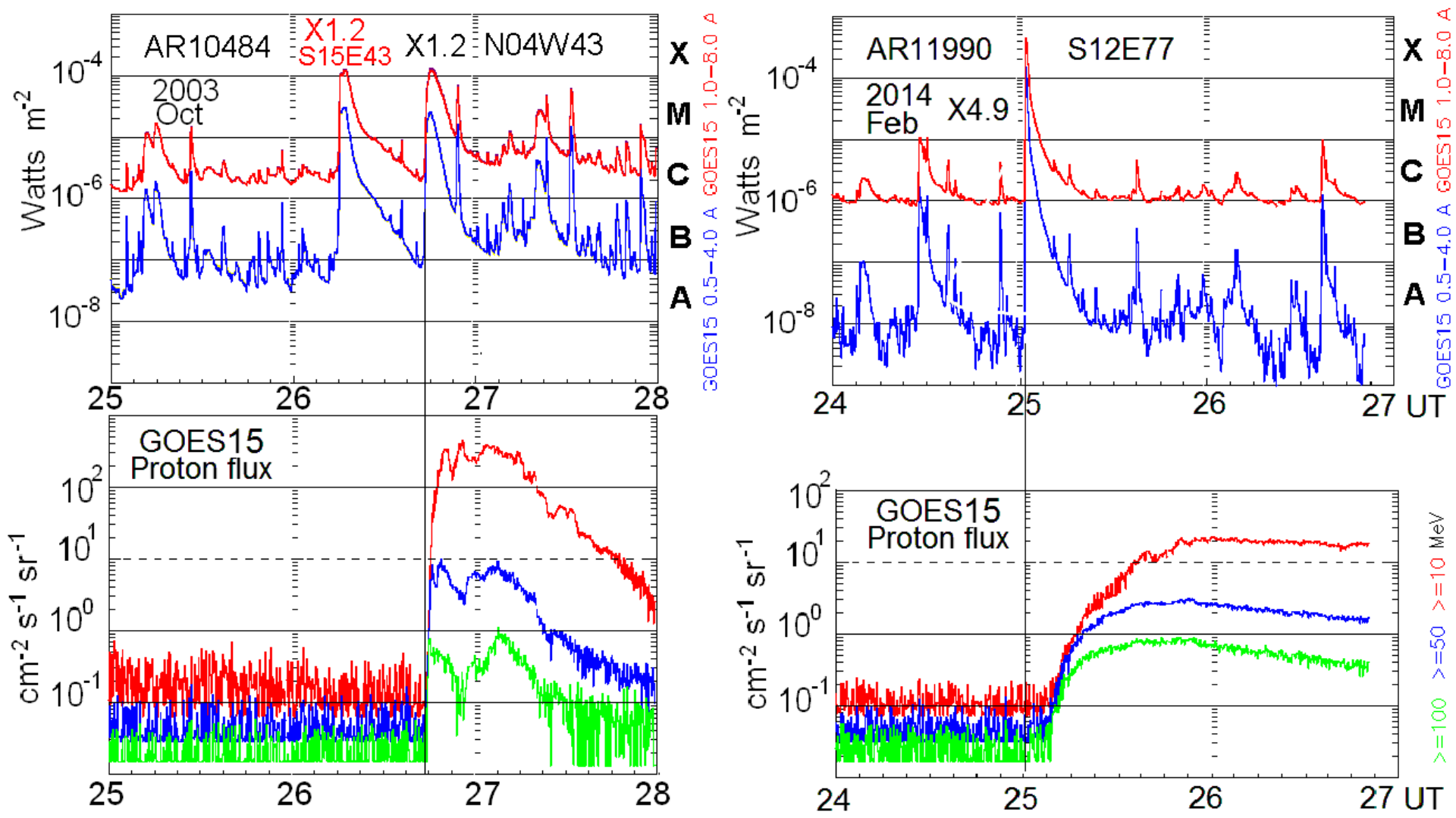

GOES 12
AR10720
2005
January
~X1
~M9
~X3
N13W22
X3.8
~X7
X
M
C
B
A
erg cm-2 s-1
01-0.8A
0.5-4A
1-8A
Particles cm-2 s-1
>=100
>=50
>=10 MeV
Magnetic flux ×10^22 Mx
Φ_N
Φ_S
10
11
12
13
14
15
16
17
18
19
20
21
20.01.2005.


AR12036
M7.3 S20W34
2014 April
AR2473
M2.3 S25W82
2016 Jenuary
AR11261
N16W30 N16W38
M6 M9.3
2011 August
Watts m-2
GOES PROTONS
cm-2 s-1 sr-1
GOES15 1.0-8.0 A
GOES15 0.5-4.0 A
>=100 >=50 >=10 MeV
2003 Jun
M6.8
AR10386 S08E58
2014 February
AR11990 S12E77
2014 September
AR12158
X-ray
17:21 X1.6 N11E05
GOES11 Proton flux

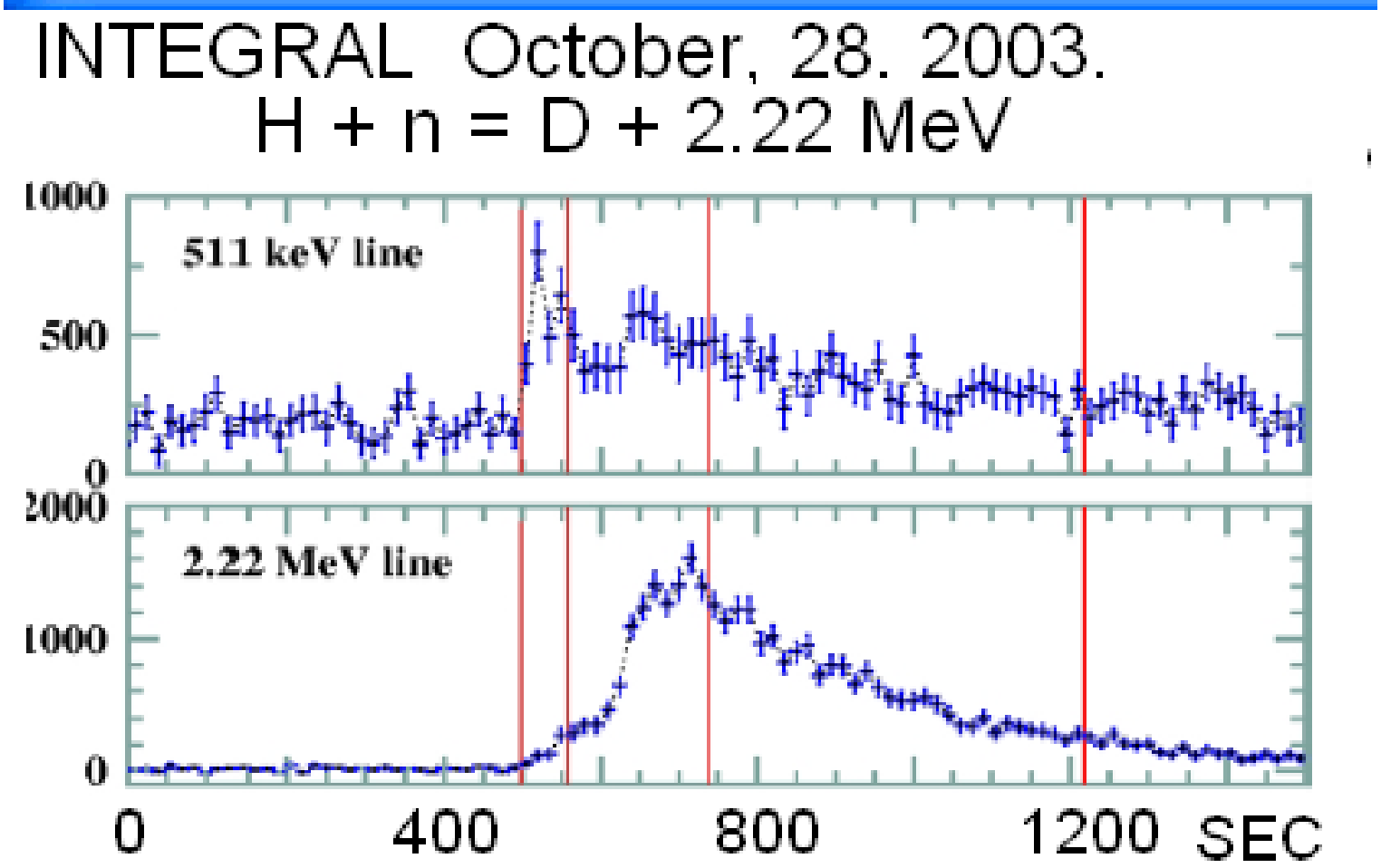


SOLAR WIND - THE PLASMA EXPANSION IN VACUUM IN THE MAGNETIC FIELD AT

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



Large proton streams from western and eastern flares. Very large prompt proton stream with very steep front is observed only from a western flare.

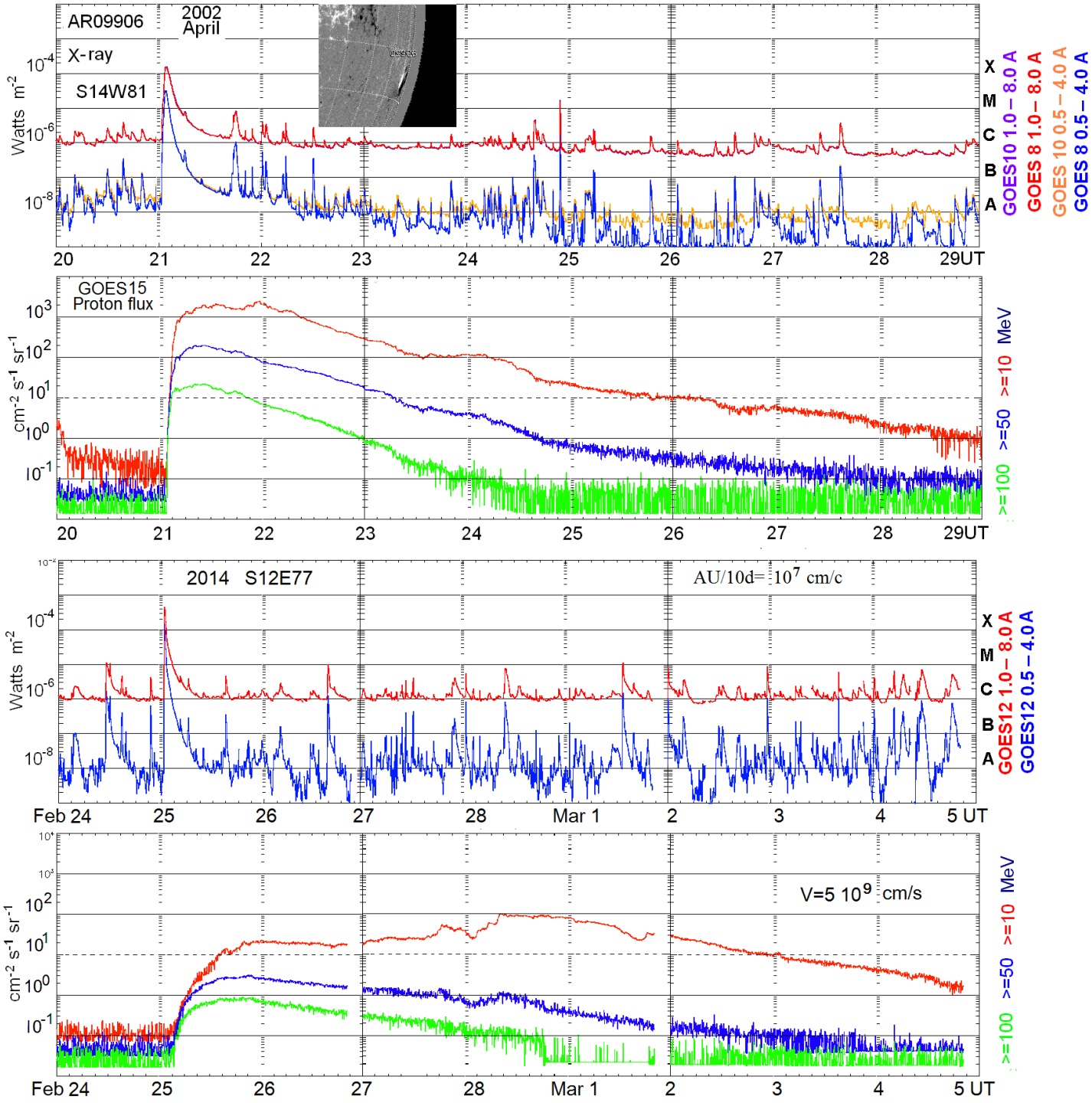


The durations of nuclear reactions in the Sun and flare X-ray radiation are the same, but they are 100 times smaller than the duration of the recorded proton flux.

Protons from western flares. The front of prompt collisionless anisotropic proton flux with proton velocity can arrive to the Earth moving along the magnetic lines. The prompt proton flux is accompanying by isotropic diffusion flux.

Protons from eastern flares. Can arrive moving across the magnetic lines. The front arrives with the velocity 10^9 cm/s.

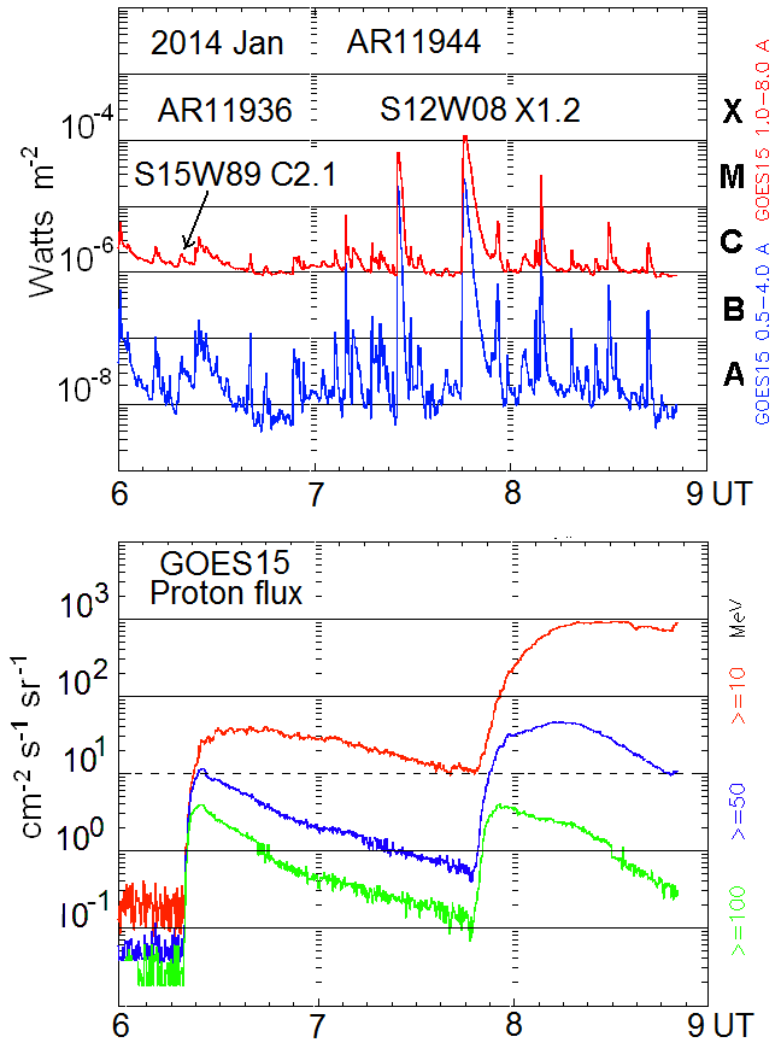
Why the collisionless flux is converted into diffusion one?
Are electromagnetic fluctuations appeared due to beam instability of the prompt component?
Why the proton delayed flux along magnetic lines from the western flares and delayed flux across the magnetic lines from the eastern flares are demonstrated the similar time dependence?
How the proton flux front of the eastern flares can move so fast ($V \sim 10^9$ cm/s) across the magnetic lines?

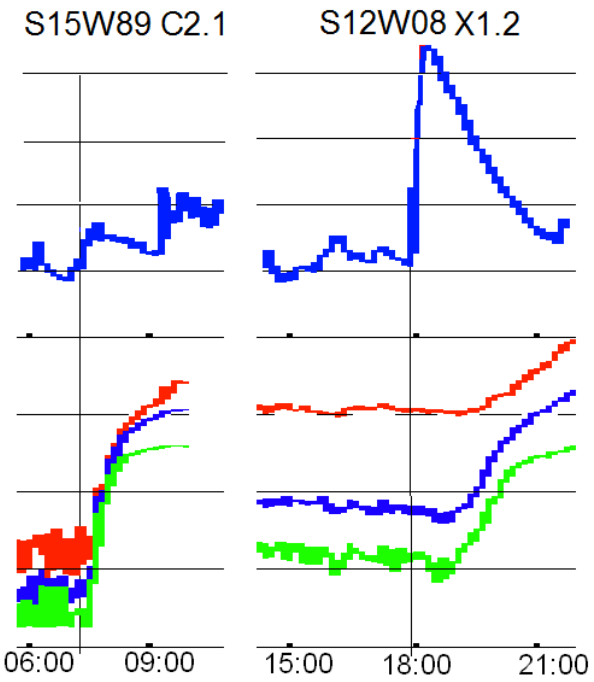

AR09906
2002
April
X-ray
S14W81
Watts m-2
10-4
10-6
10-8
X
M
C
B
A
GOES10 1.0 – 8.0 A
GOES 8 1.0 – 8.0 A
GOES 10 0.5 – 4.0 A
GOES 8 0.5 – 4.0 A
20
21
22
23
24
25
26
27
28
29UT
GOES15
Proton flux
cm-2 s-1 sr-1
103
102
101
100
10-1
>=100
>=50
>=10
MeV
2014 S12E77
AU/10d= 10^7 cm/c
GOES12 1.0 – 8.0A
GOES12 0.5 – 4.0A
Feb 24
25
26
27
28
Mar 1
2
3
4
5 UT
V=5 10^9 cm/s

The front structure of proton fluxes from western and eastern flares are determined by interplanetary magnetic field, but there are no differences for the long delayed proton components of these flares.

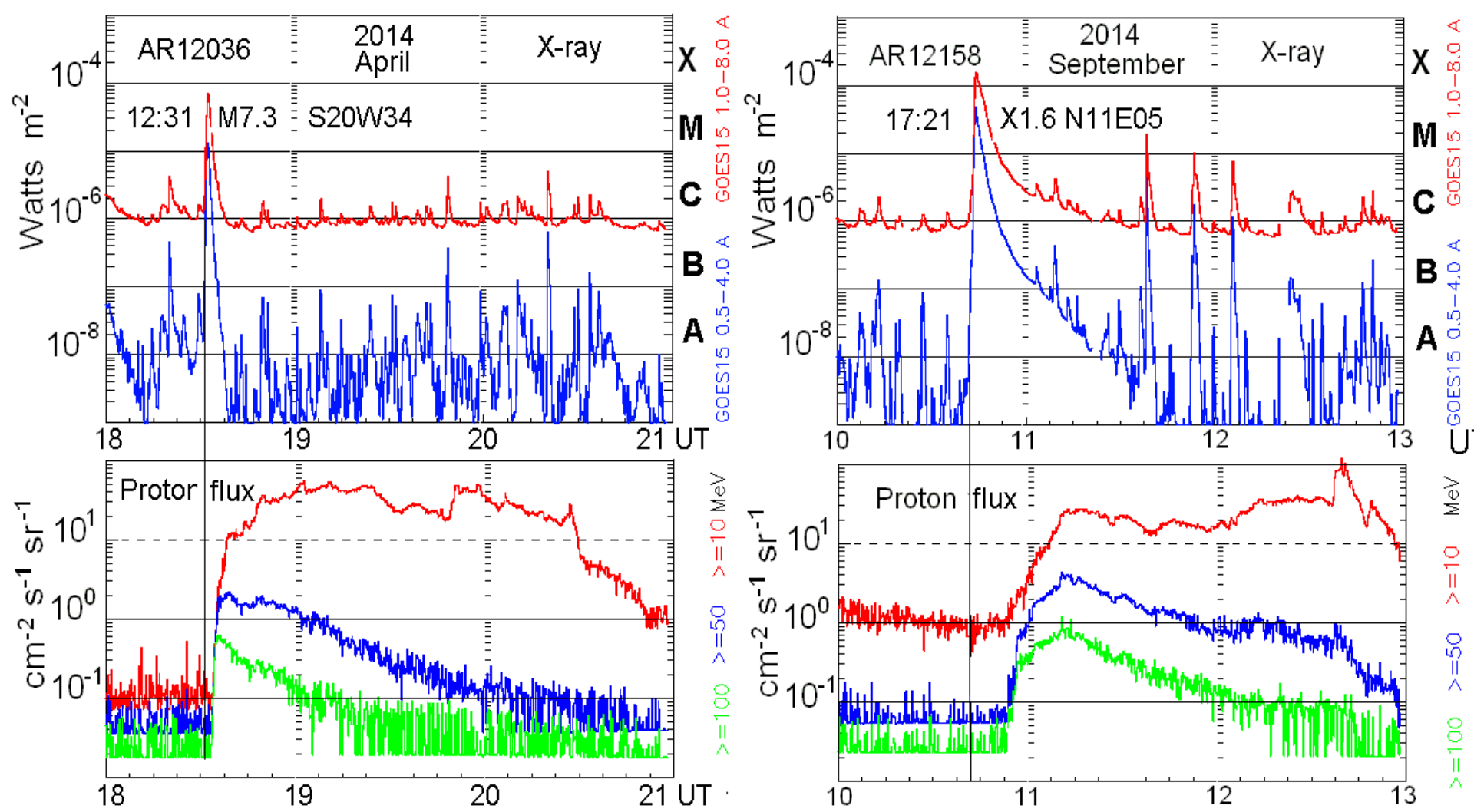
The possible explanation:

Diffusion can not depend on the magnetic field, if scatterings on electromagnetic fluctuation are very strong ($\lambda<\rho$). Such fluctuation can appear at beam instability of the prompt proton component.

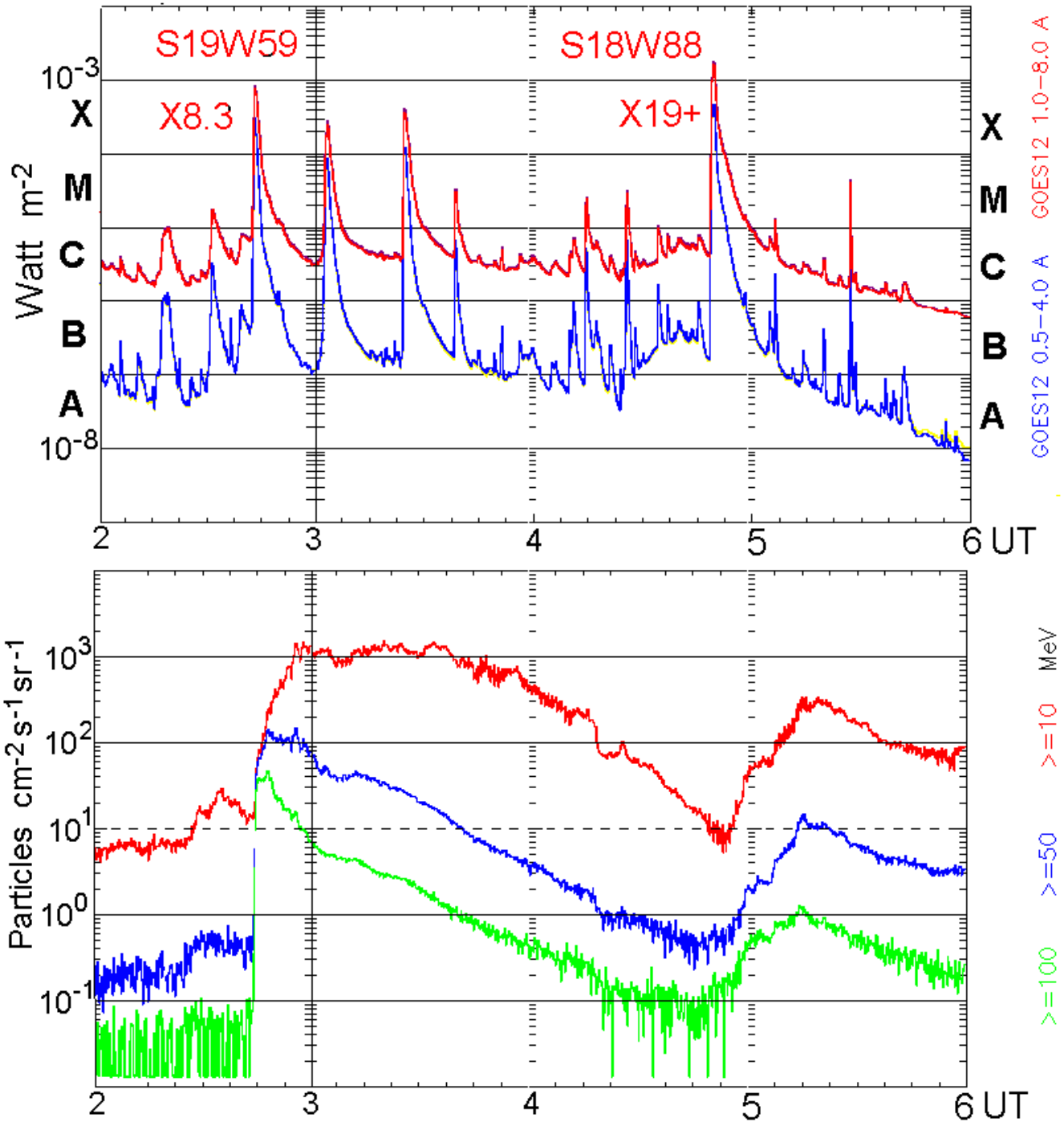




A VERY WEAK C2 FLARE NEVER CAUSES A PROTON FLUX. APPARENTLY, THE MAIN X-RAYS WAS ON THE BACK SIDE OF THE SUN. PROTONS HAVE ARRIVED TO EARTH ALONG MAGNETIC FIELD LINES OF ARCHIMEDES SPIRAL FROM THE BACK SIDE.

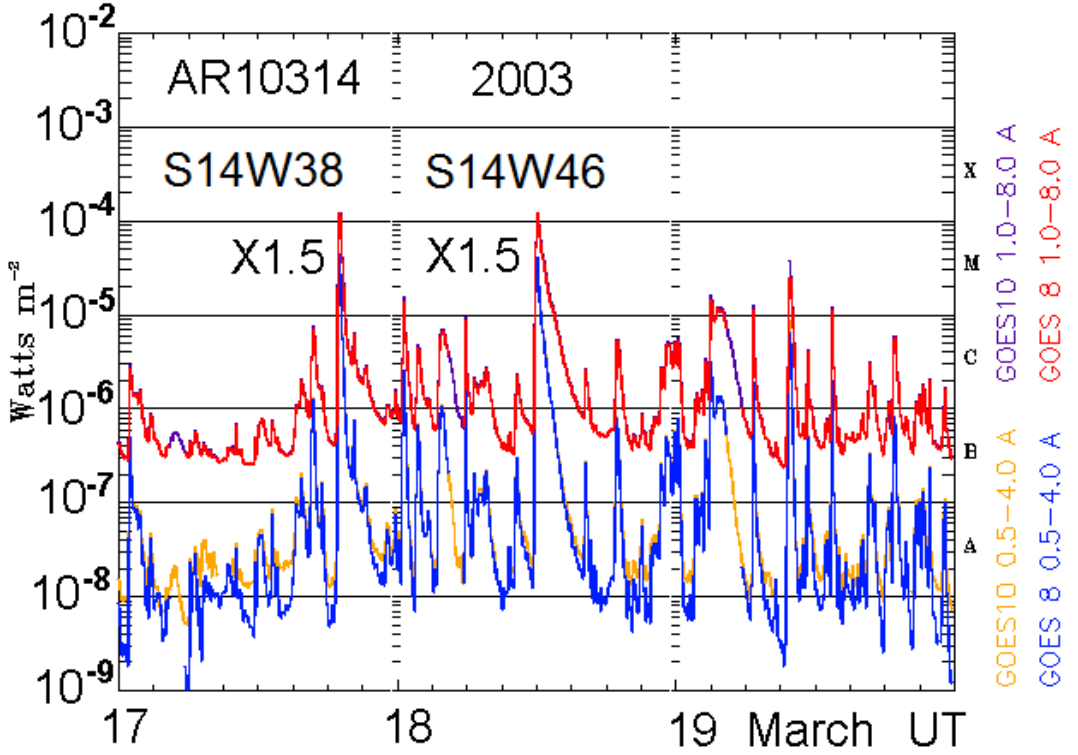


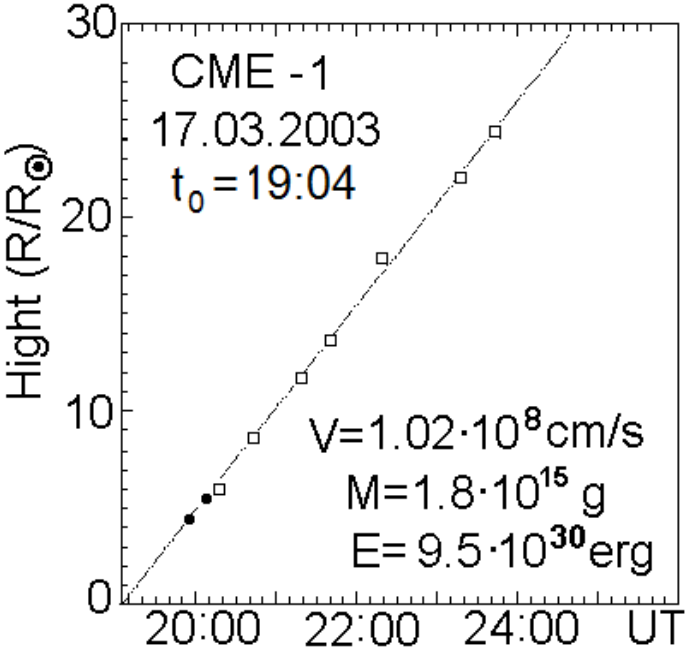
X1.6 N11E05 flare occurs near the center of the solar disk, but protons are reached the Earth only after 5 hours, whereas a steep front of protons from the western flare M7.3 S20W34 arrives through about 20 minutes. Delayed protons come through ~ 3 days.

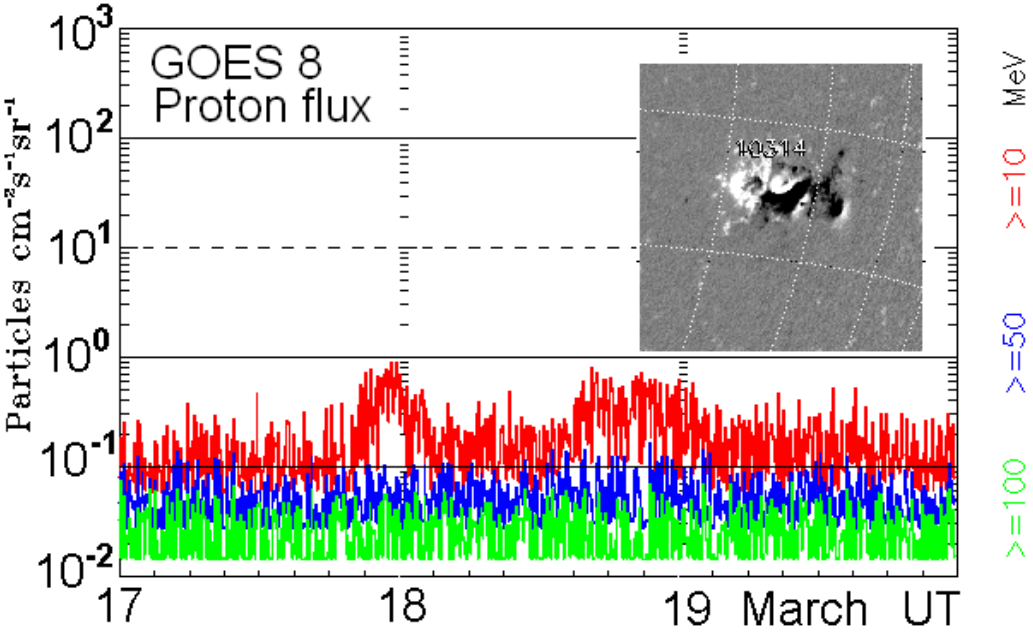


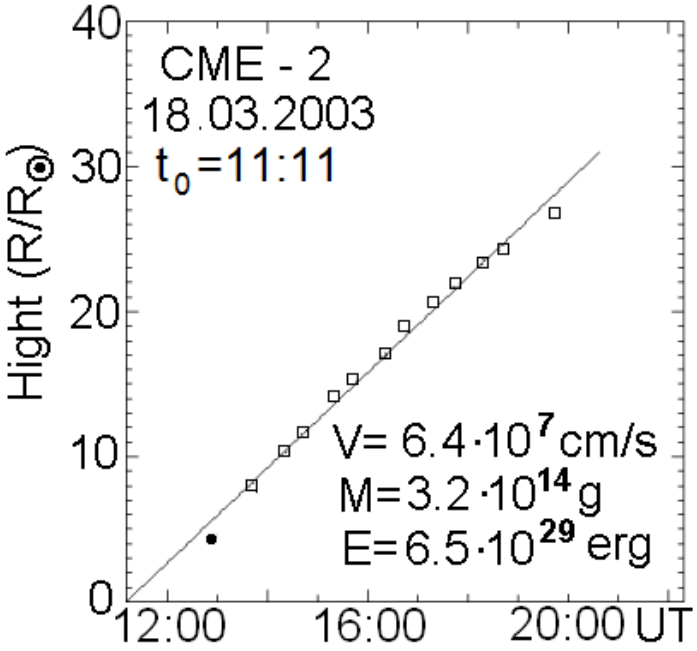
UNUSUAL EVENT!

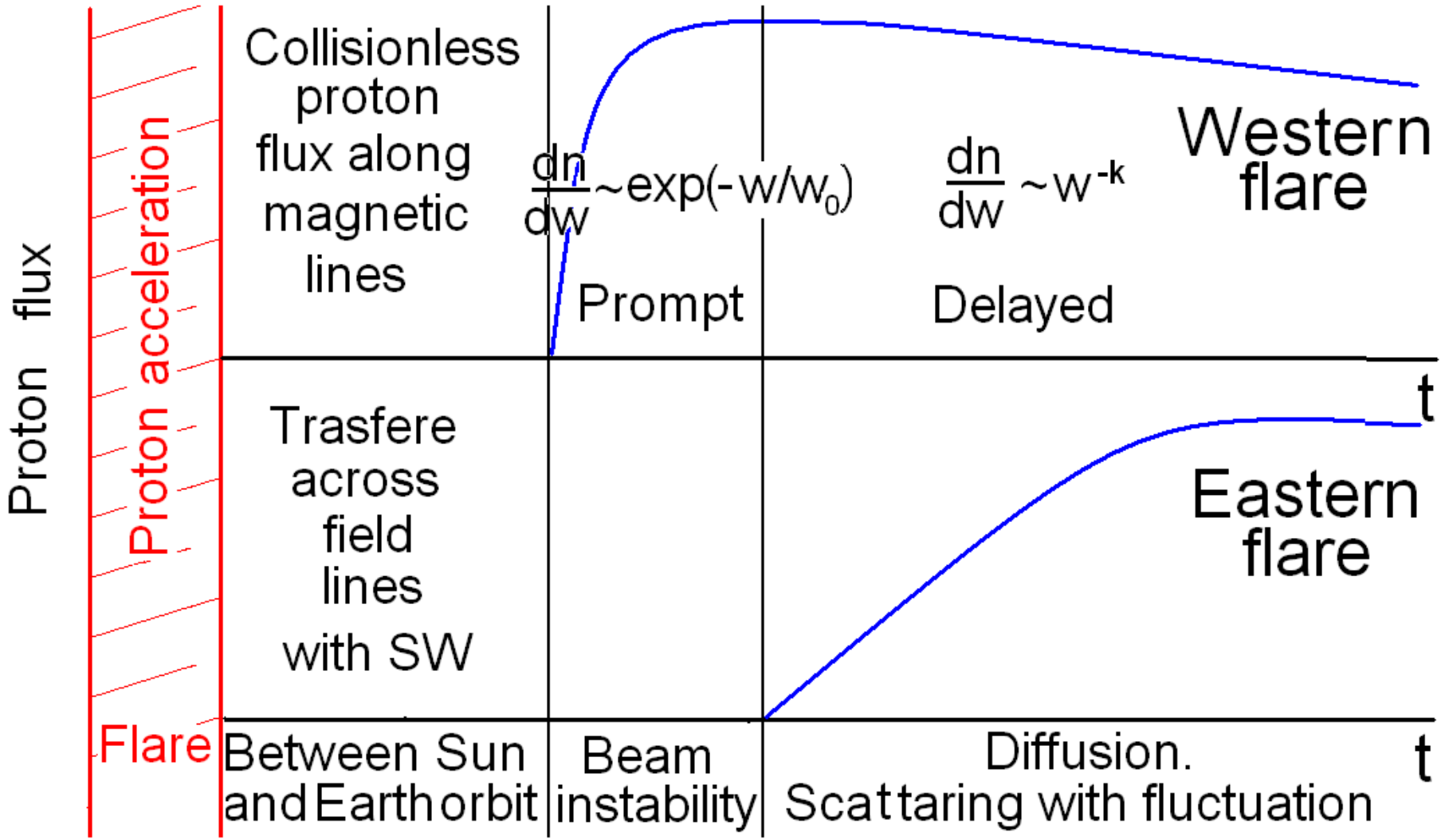
THE FRONT OF THE GIANT WESTERN PROTON STREAM IS EXTENDED TO ABOUT 10 HOURS. THREE BIG FLARES AND THE LARGE CME CAN DISTORT THE SPIRAL SHAPE OF INTERPLANETARY FIELD LINES.


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


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


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


Proton flux
Proton acceleration
Flare
Collisionless proton flux along magnetic lines
Trasfere across field lines with SW
Between Sun and Earth orbit
Beam instability
Diffusion. Scattaring with fluctuation
dn/dw ~exp(-w/w0)
dn/dw ~w-k
Prompt
Delayed
Western flare
Eastern flare
t
t

CONCLUSION.

1. The proton events are generated in the flare current sheet.
2. Four time scales of proton events:

a). The duration of the generation of accelerated protons is equal to the duration of the flare t_{SF} ~ 20-30 min.

b). The typical duration of the proton stream at the Earth orbit is equal to the propagation time of the solar wind t_{SW} = 1A.U. / V_{SW} ~ 3 days.

c). Time of arrival of the sharp front of relativistic proton from the western flare to the Earth's orbit is equal to the time of flight of protons along the Archimedes spiral $_F$ ~ 1A.U. / c ~ 15 -. 20 min. The collisionless anisotropic stream carries information about the spectrum of protons.

d). Arrival of a gentle front of relativistic protons front from the eastern flare (across the magnetic lines) to the Earth's orbit is t_D ~ 3 - 5 hours. The diffusion initiated by beam instability ???

БЛАГОДАРЯ!

Thank you!