Energy and Mass Transports During Extreme Events on the Sun and in the Heliosphere

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Solar Extreme Events:
Fundamental Science and Applied Aspects
(SEE-2005)
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Nor Amberd, Armenia
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Contents

DATA and ANALYSIS

- APEV Data Base
  http://dbserv.sinp.msu.ru/apev
- All geomagnetic storms with daily Ap> 20

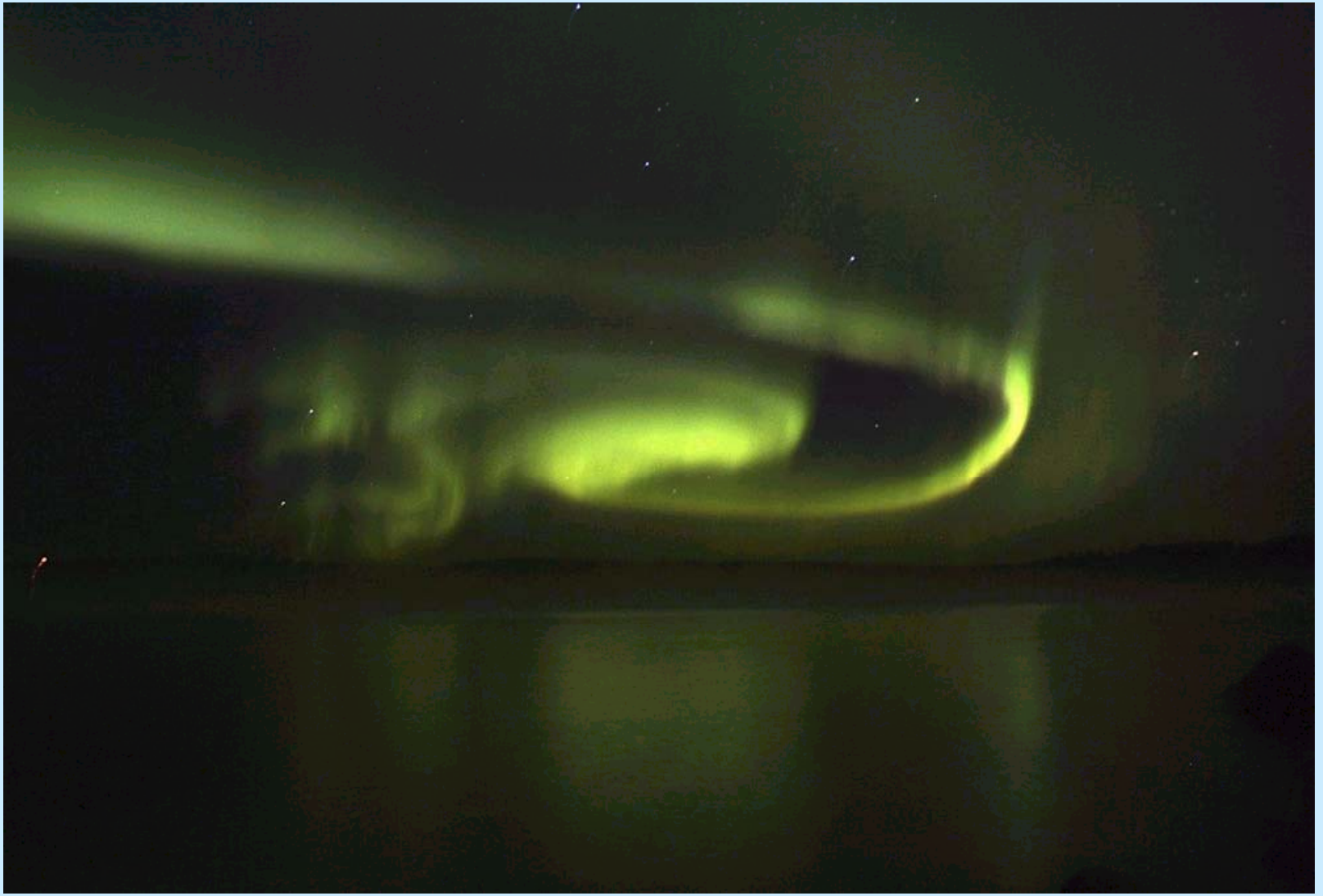
(1997 – 2004 - continued)

- Part of INTAS Project 03-51-6206 (MPI SSR/Lindau; ROB; AI/Prague; IZMIRAN/Moscow; SINP MSU/Moscow)

September 10, 2005

Jarkko Rosenstrцm, Saarijarvi FINLAND

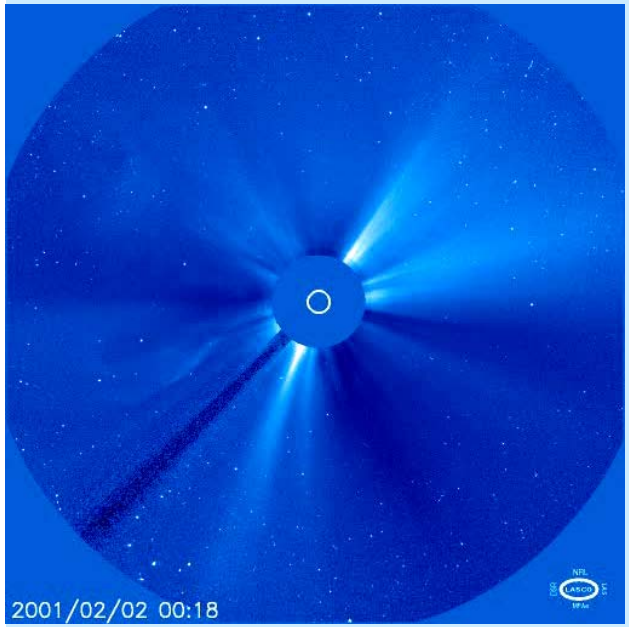
http://www.spaceweather.com/aurora/gallery_01sep05_page5.htm

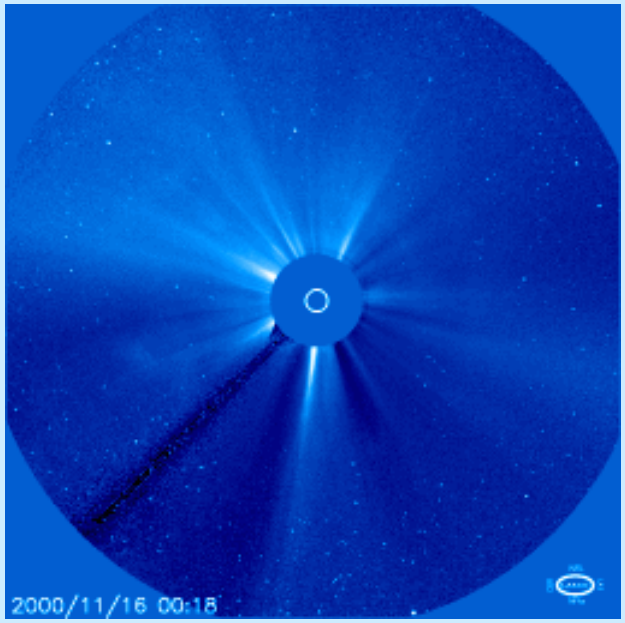


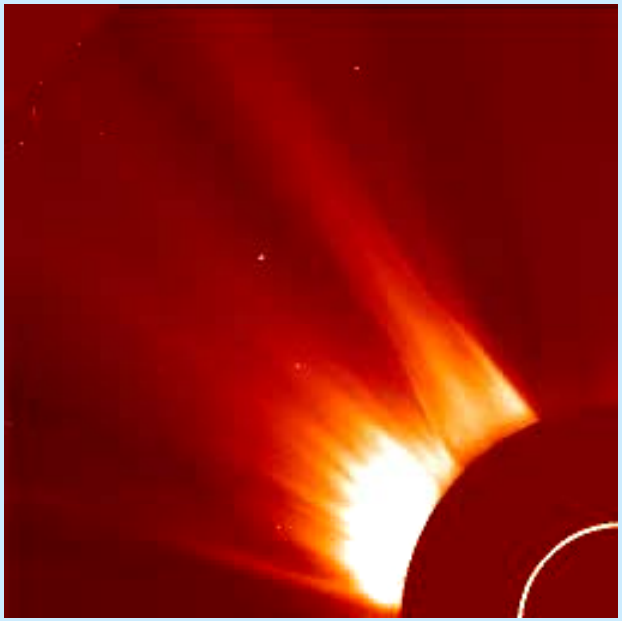
September 11, 2005

Philippe Moussette, Iles d'orlйand Quйbec, Canada
http://www.spaceweather.com/aurora/gallery_01sep05_page5.htm

Magnetically open structures in the solar corona: rays and steramers



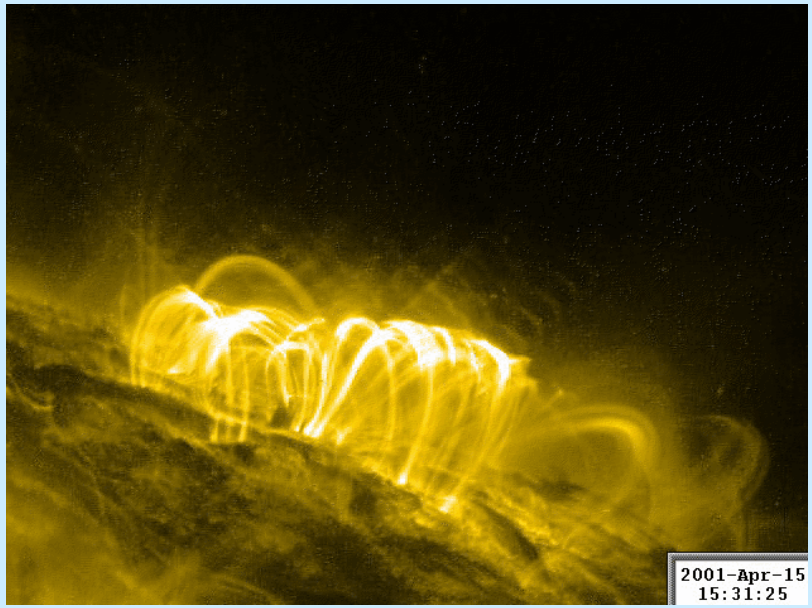


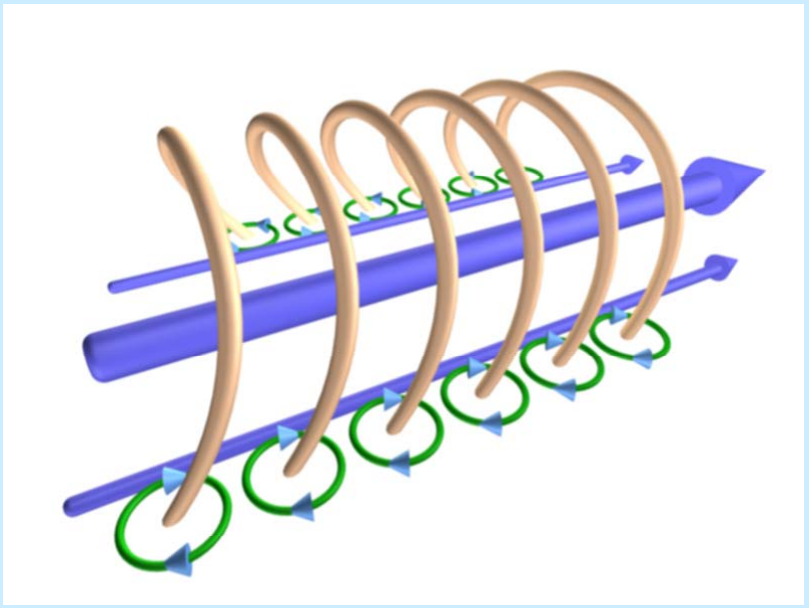


SOHO/LASCO

Coronal streamers and rays are due to the electric currents in the solar corona with non-potential magnetic fields

Magnetically closed structures in the solar corona: loops and arcades

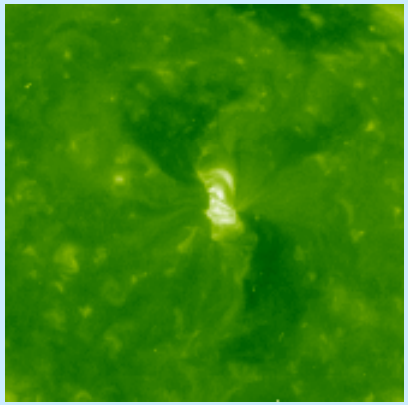




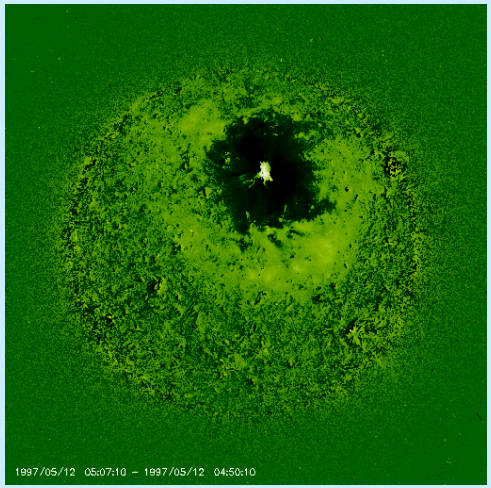
TRACE: dynamic arcades and thin loops: electric currents along and across the system

CME SIGNATURES IN EUV

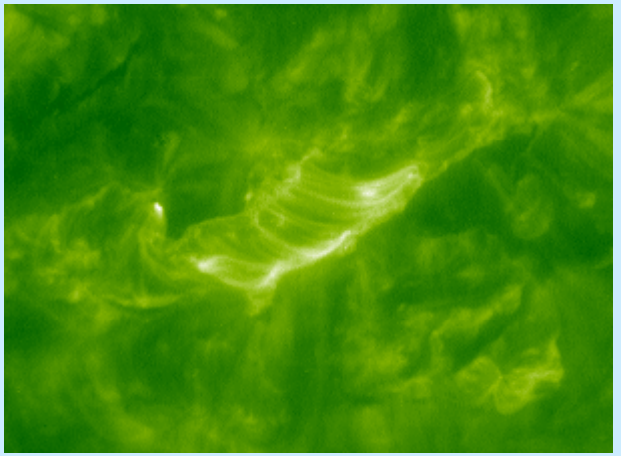
(by the courtesy of Dr. A.N.Zhukov)



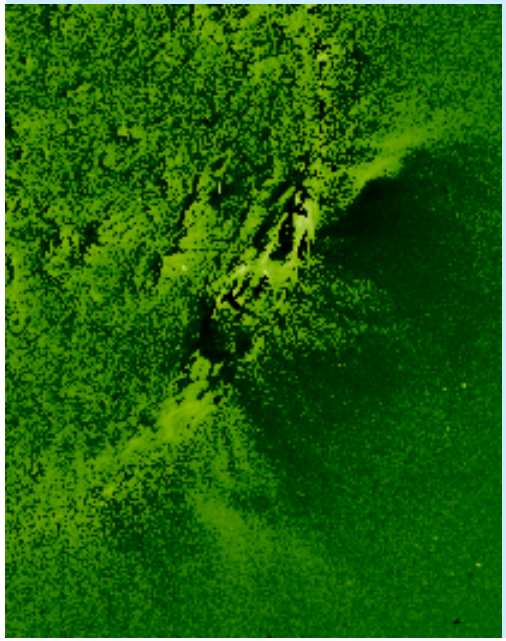
Dimmings
(including TCHs)



EIT wave

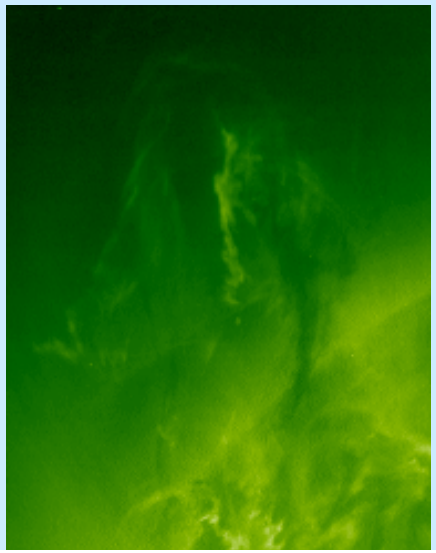


Post-eruption
arcade



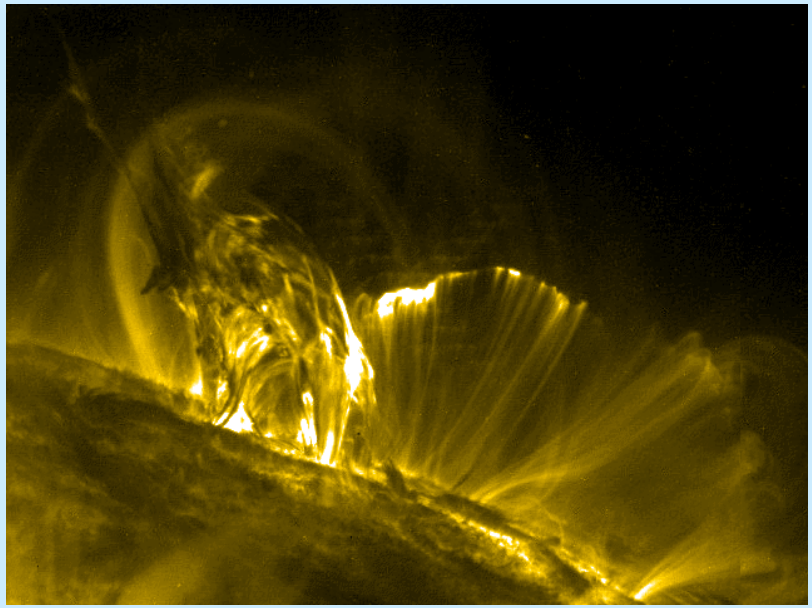
Limb signatures:
opening of loops,
plasmoid lifting
etc.

SOHO/EIT
195 Å



Erupting
prominence
(filament)

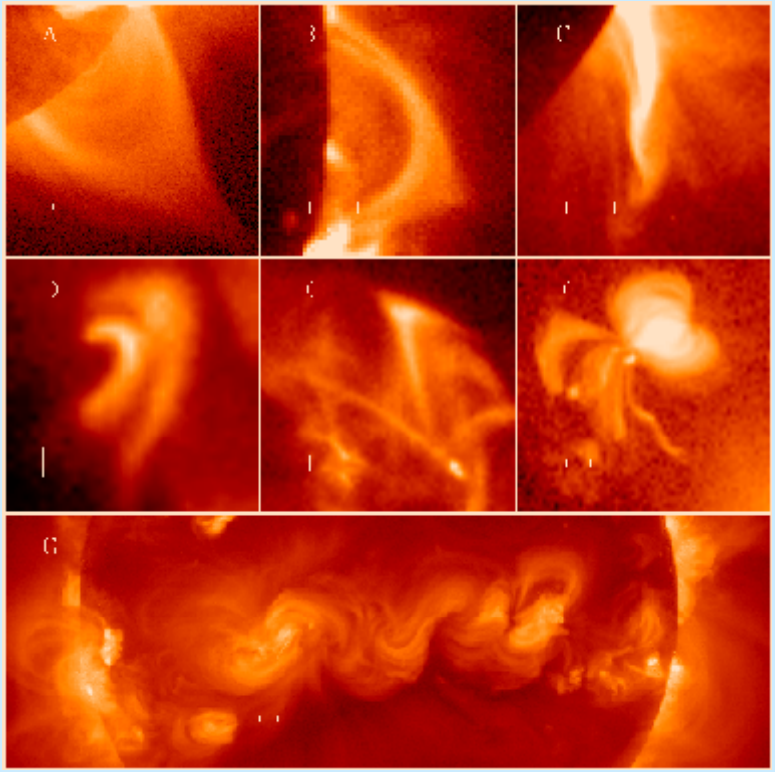
Complicated dynamical geometry of arcades:



- Spurious "reconnections" and X-points: projections of twisted loops
- Spurious "crossings of the loops": the same as above
- Spurious "plasmoids": brighter summits of the loops

(an example from the TRACE "gold mine")

YOHKOH gallery



- Caution: Some of these fuzzy and not well resolved (integrated over a broad spectral range) images could be sometimes wrongly interpreted as manifestations of topological changes or singularities in the large scale magnetic field being in reality projection effects

Plasma drifts
in the time dependent magnetic fields B(t): (E cross B drift)

$\mathbf{V} \sim c\mathbf{E}\times\mathbf{B}/BB \sim c\ E/B$

Faraday induction electric field
$E \sim BL/ct$

L-length scale, t – time scale

E cross B drift estimates

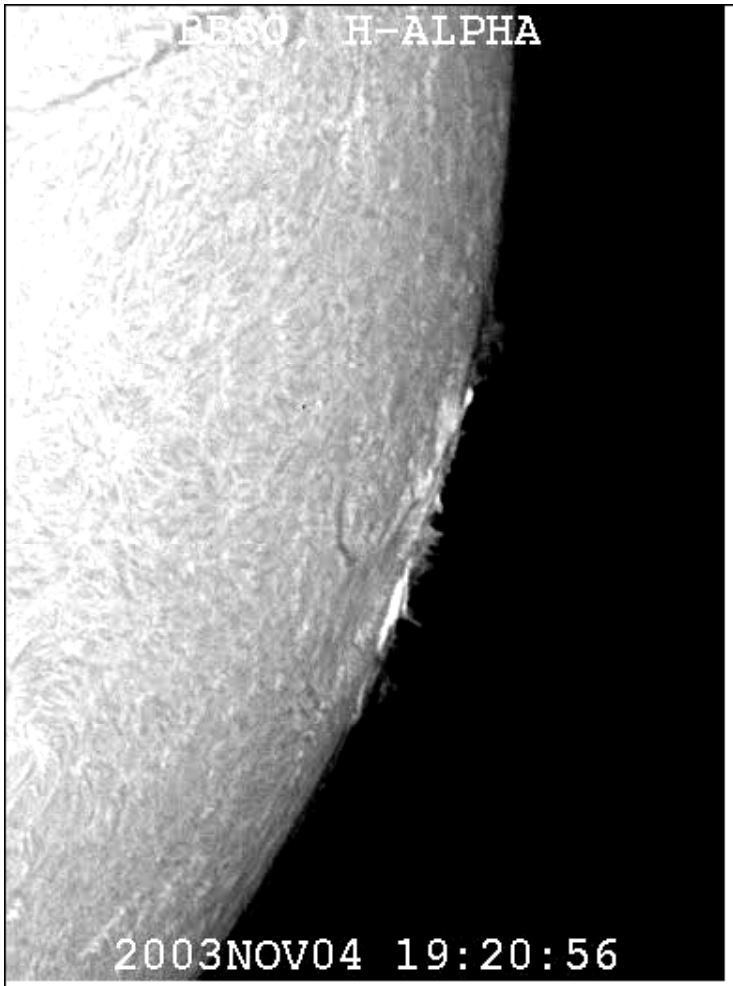
- $V \sim c(E/B) \sim L/t$

  Larger (higher) loops drift faster
  (self-similar motion is independent on the B strength!)

  L~1 Gm t~1 hour V~300 km/s
- The time scale is important

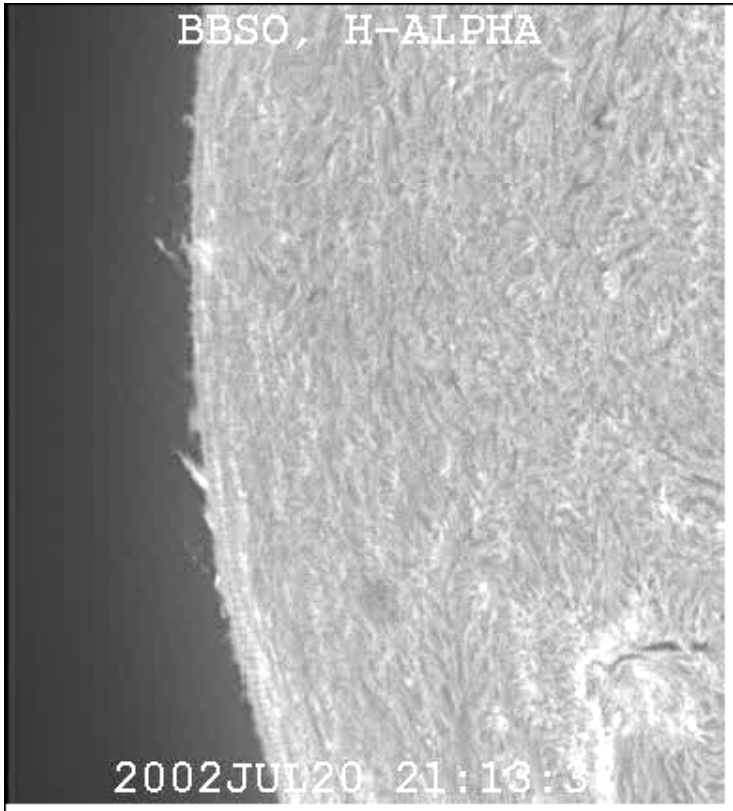
Example of an H-alpha flare without «magnetic reconnections»: it was also the biggest X-ray flare well documented by TRACE

- http://www.bbso.njit.edu/Images/03nov04.mpg



Нет рисунка

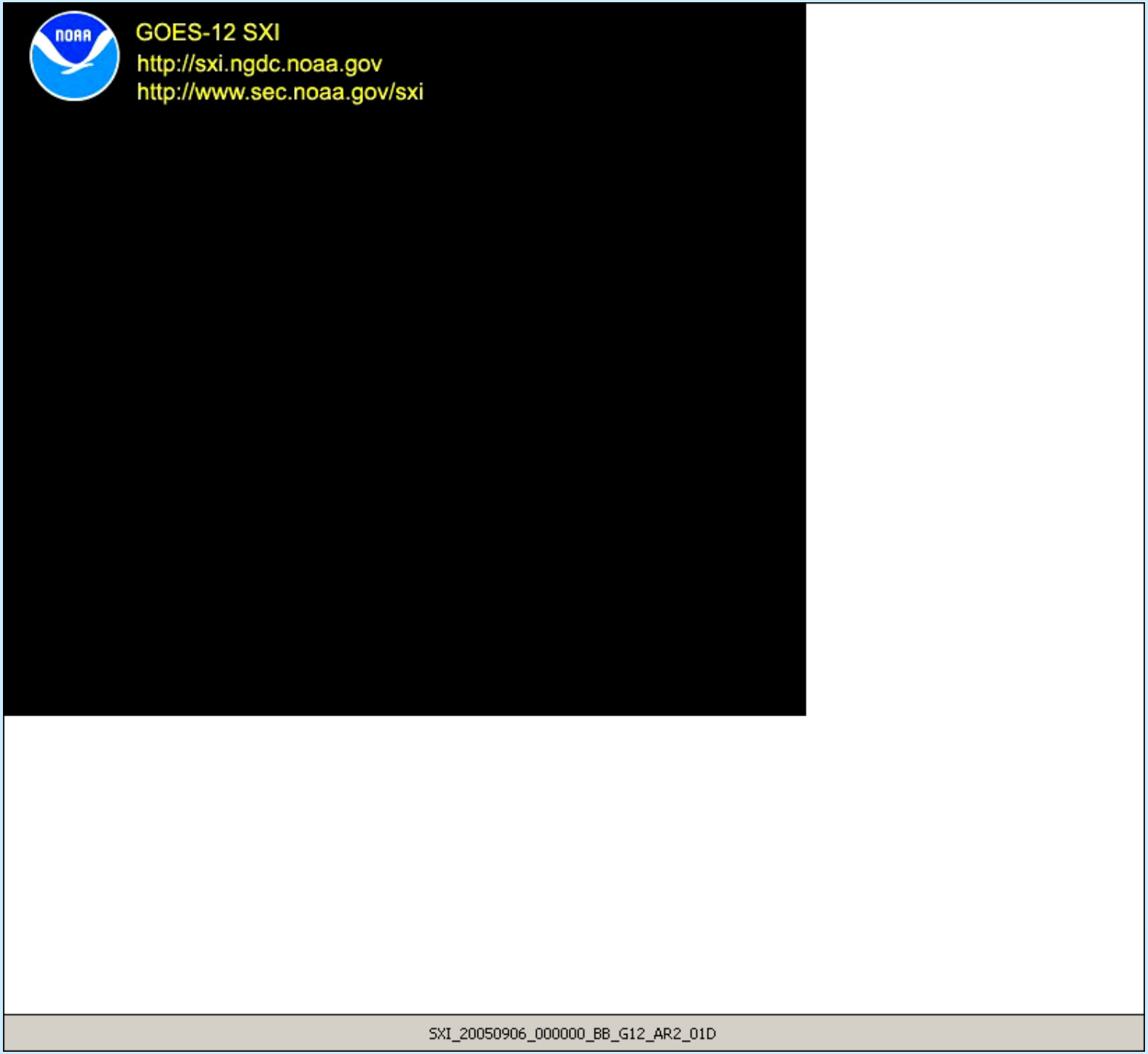
One more example of a flare without any large-scale topological changes



Нет рисунка

September 6, 2005:
The case of a “slow” flare
in round shaped loops
without large-scale
“magnetic reconnections”

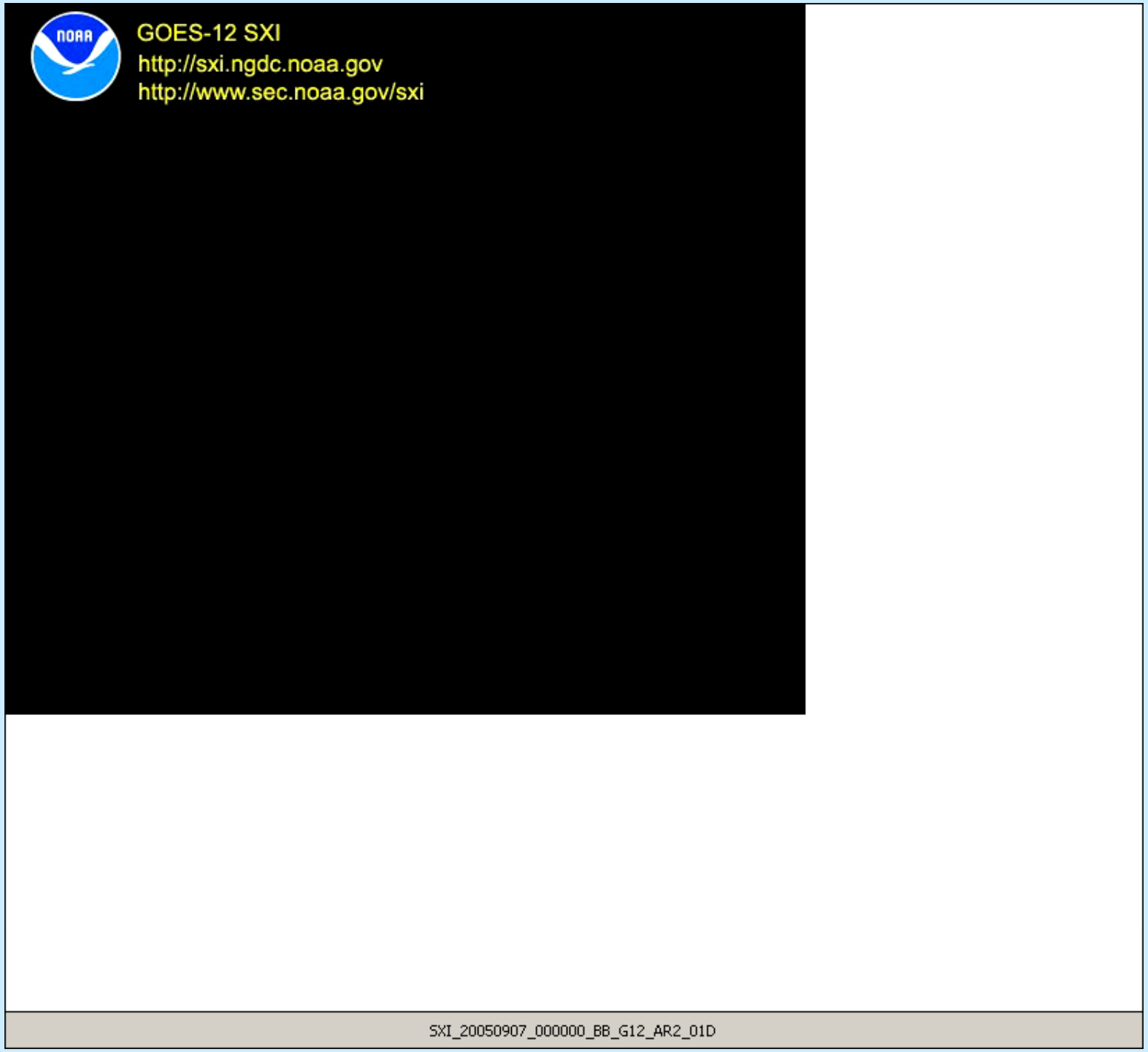
4 min time resolution


GOES-12 SXI
http://sxi.ngdc.noaa.gov
http://www.sec.noaa.gov/sxi
SXI_20050906_000000_BB_G12_AR2_01D

CME and Flare of September 7, 2005: events without any signatures of «magnetic reconnections»

4 min time resolution

(case «number 4» in the list of X-ray flares)


GOES-12 SXI
http://sxi.ngdc.noaa.gov
http://www.sec.noaa.gov/sxi
SXI_20050907_000000_BB_G12_AR2_01D

September 1-11, 2005:

Global asymmetry of the Sun and the super-long duration energy release with multiple CME and flare onsets

(partially recurrent and sporadic activity)

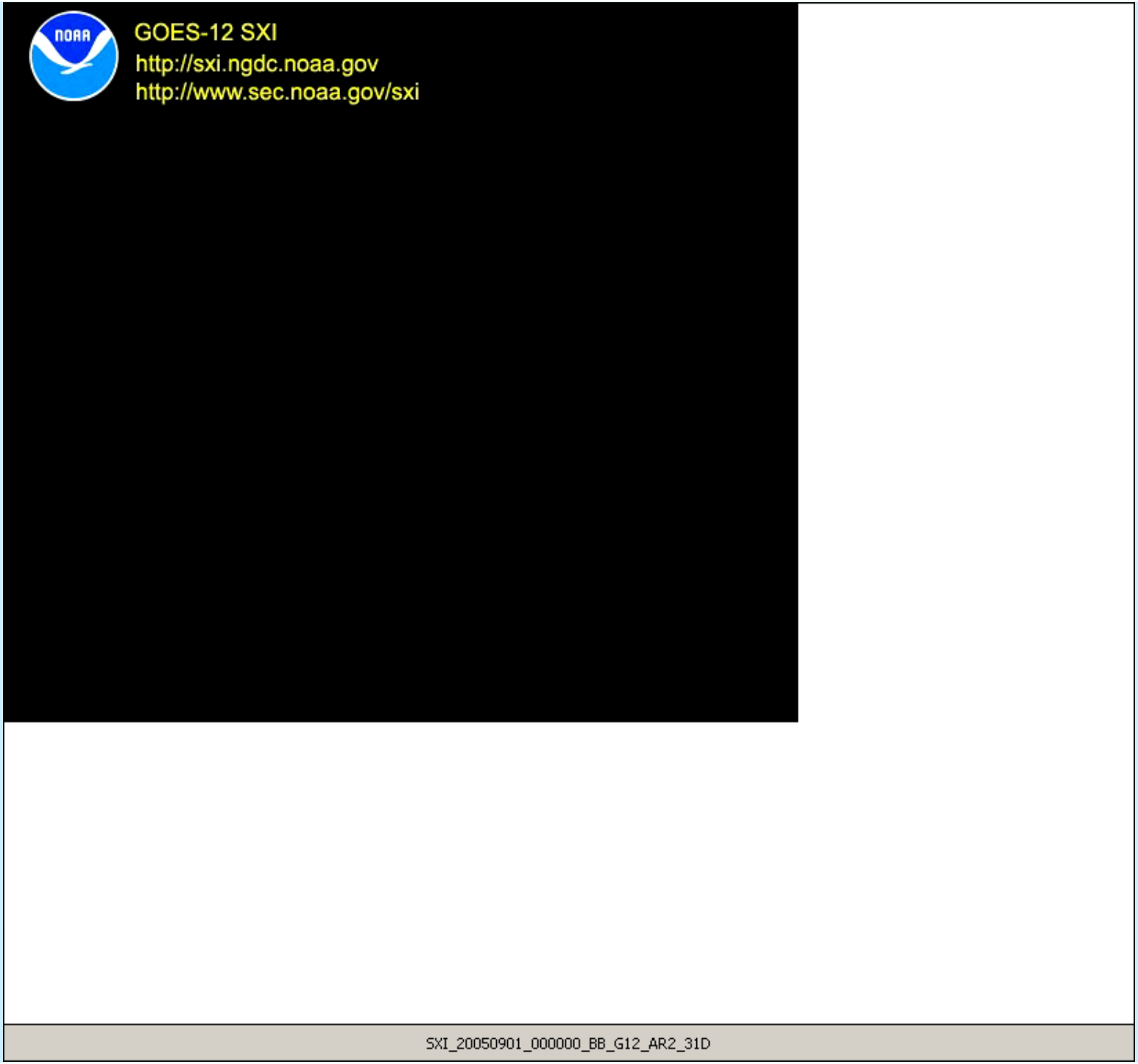
Not predicted

EIT/SOHO bakout from 02.09.05

GOES 12 up to 11.09.05

CORONAS-F

Please note some errors in the time sequence of frames in the movie!!!


GOES-12 SXI
http://sxi.ngdc.noaa.gov
http://www.sec.noaa.gov/sxi
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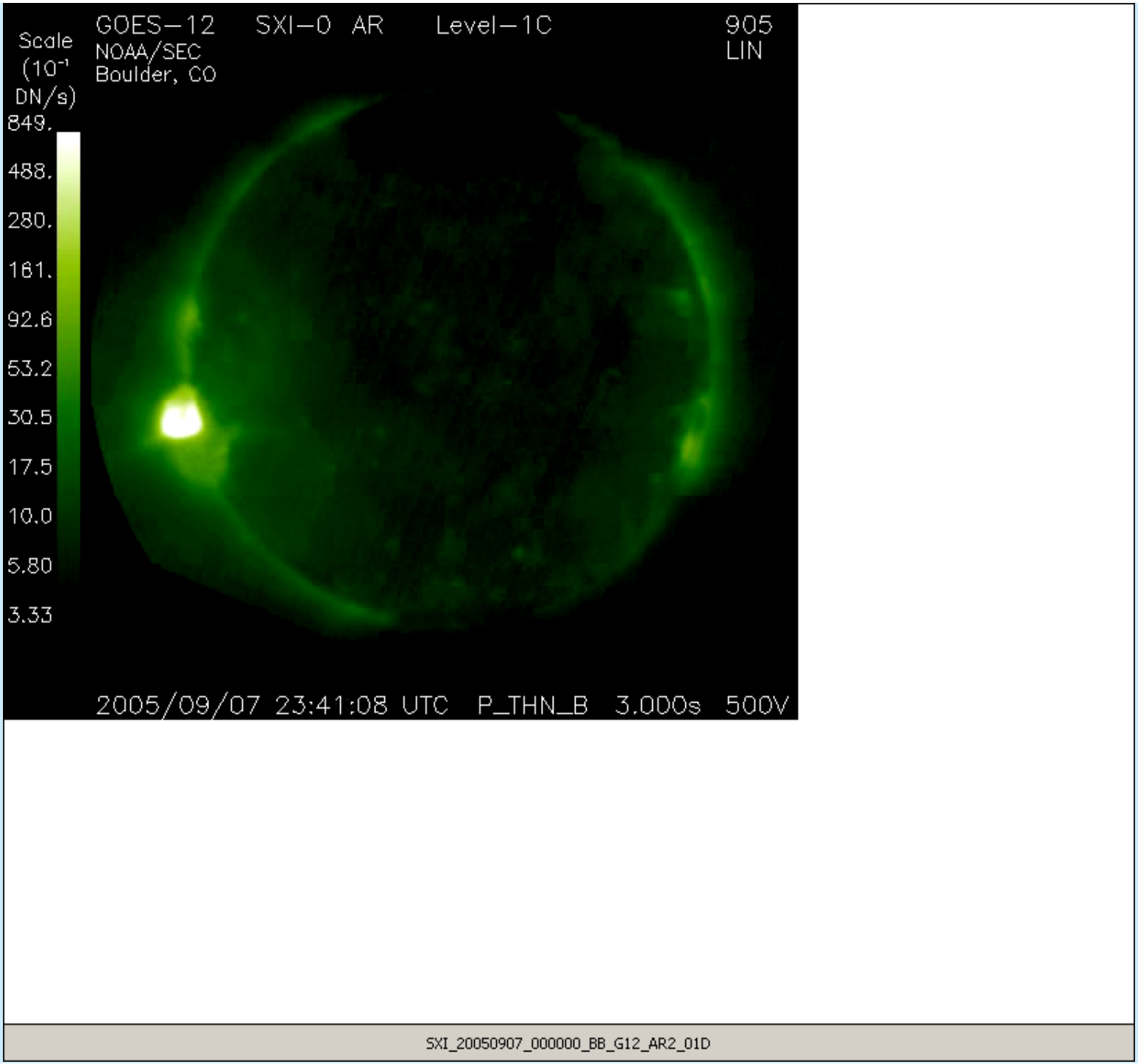
September 7, 2005
Big solar flare in the foot points of expanding loops on the E limb

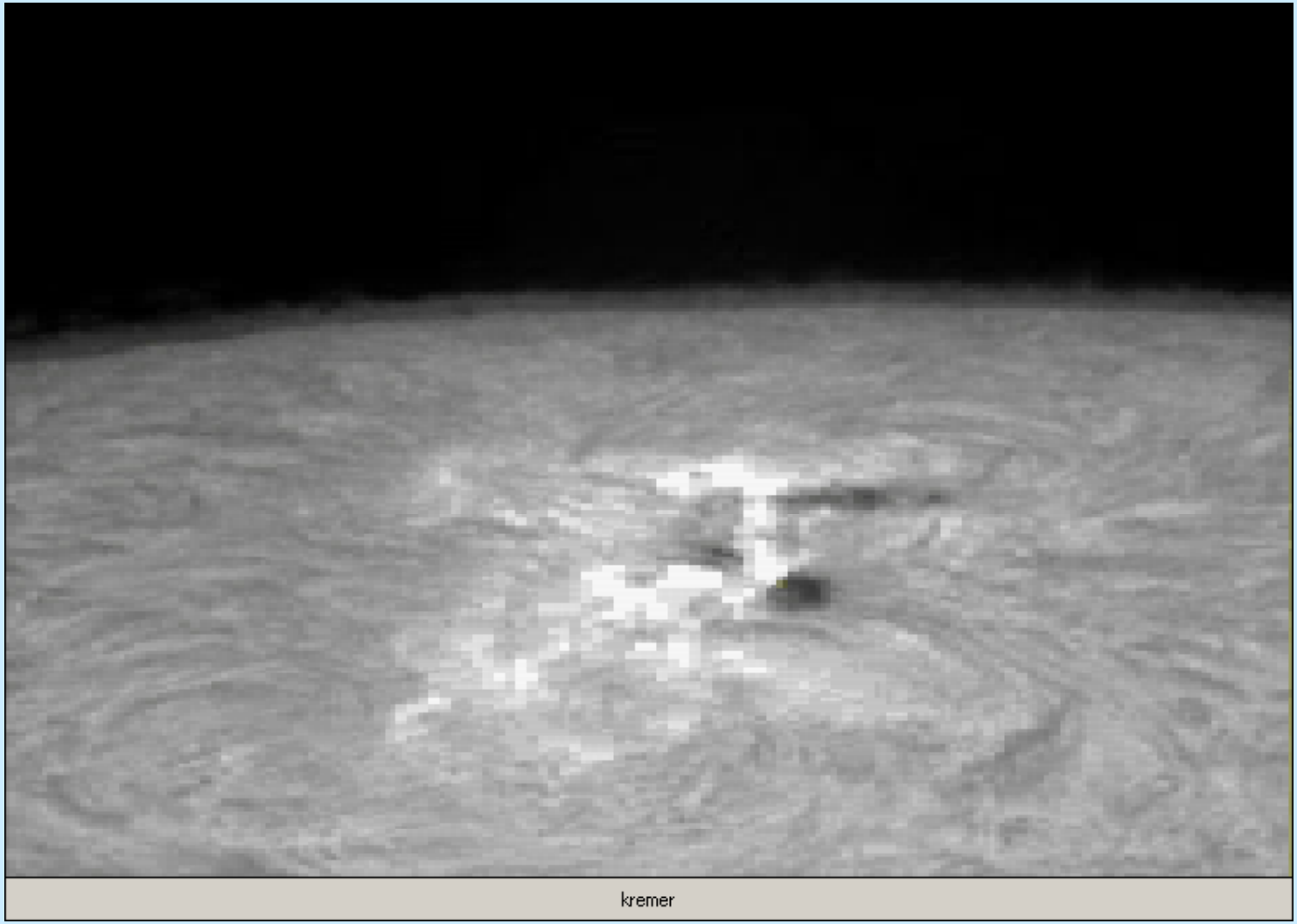
Preserved round-shaped large-scale magnetic topology with no “cusps” nor magnetic “islands”


GOES–12 SXI–0 AR Level–1C 905
NOAA/SEC
Boulder, CO
Scale
(10⁻¹
DN/s)
849.
488.
280.
161.
92.6
53.2
30.5
17.5
10.0
5.80
3.33
2005/09/07 23:41:08 UTC P_THN_B 3.000s 500V
SXI_20050907_000000_BB_G12_AR2_01D

Chromospheric Flare Development

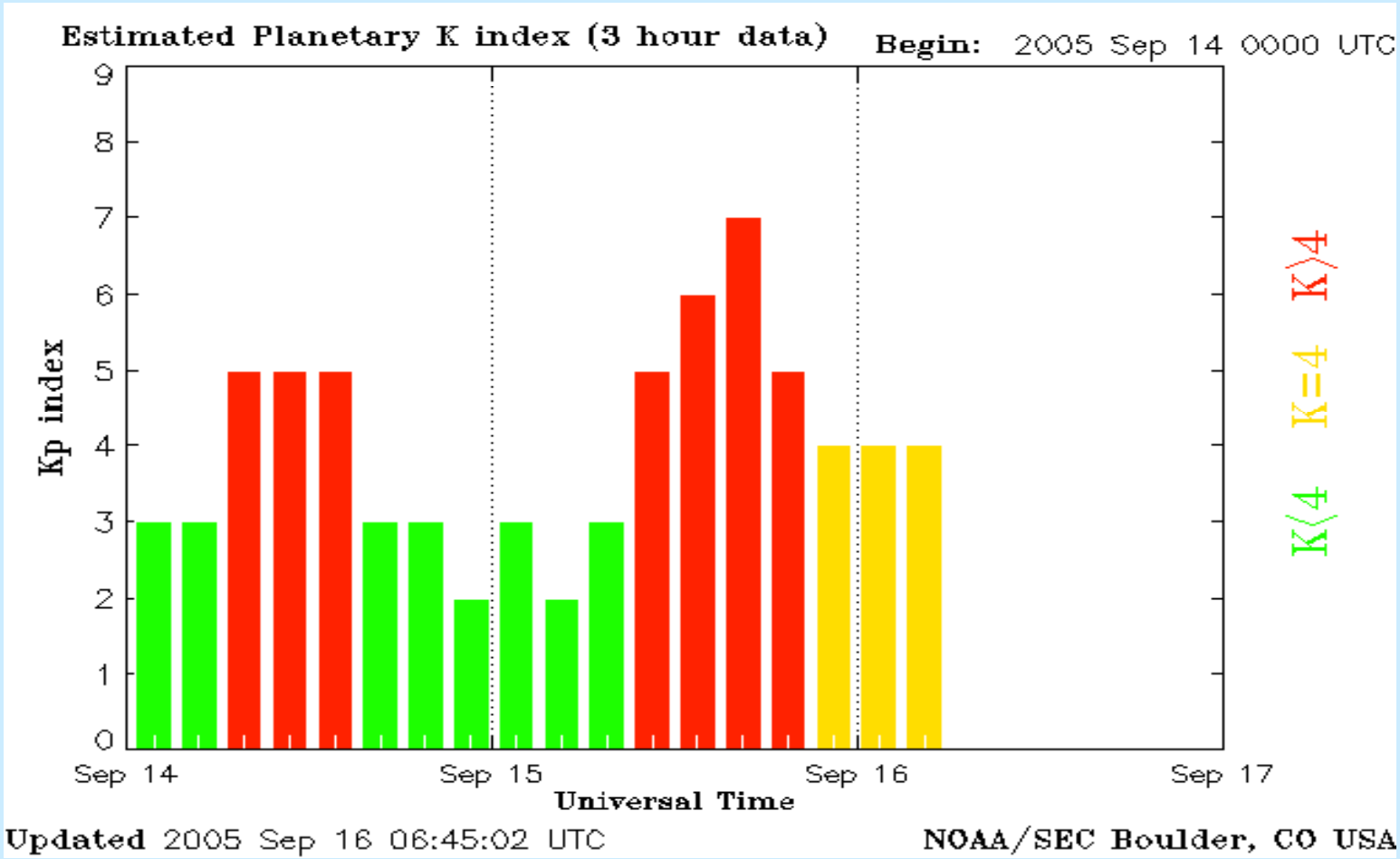
- Initiation from legs to summits of the loops
- Surges (up and down plasma flows)
- Gravity, magnetic forces, thermal pressure gradients, inertia
- Multi-scale nature in space and in time
- Electric currents along and across magnetic fields
- Plasma drifts along and across B

An X-flare photographed on Sept. 9th, 2005 by
Birgit Kremer of Marbella, Spain. [movie]
http://science.nasa.gov/headlines/y2005/15sep_solarminexplodes.htm?list168061



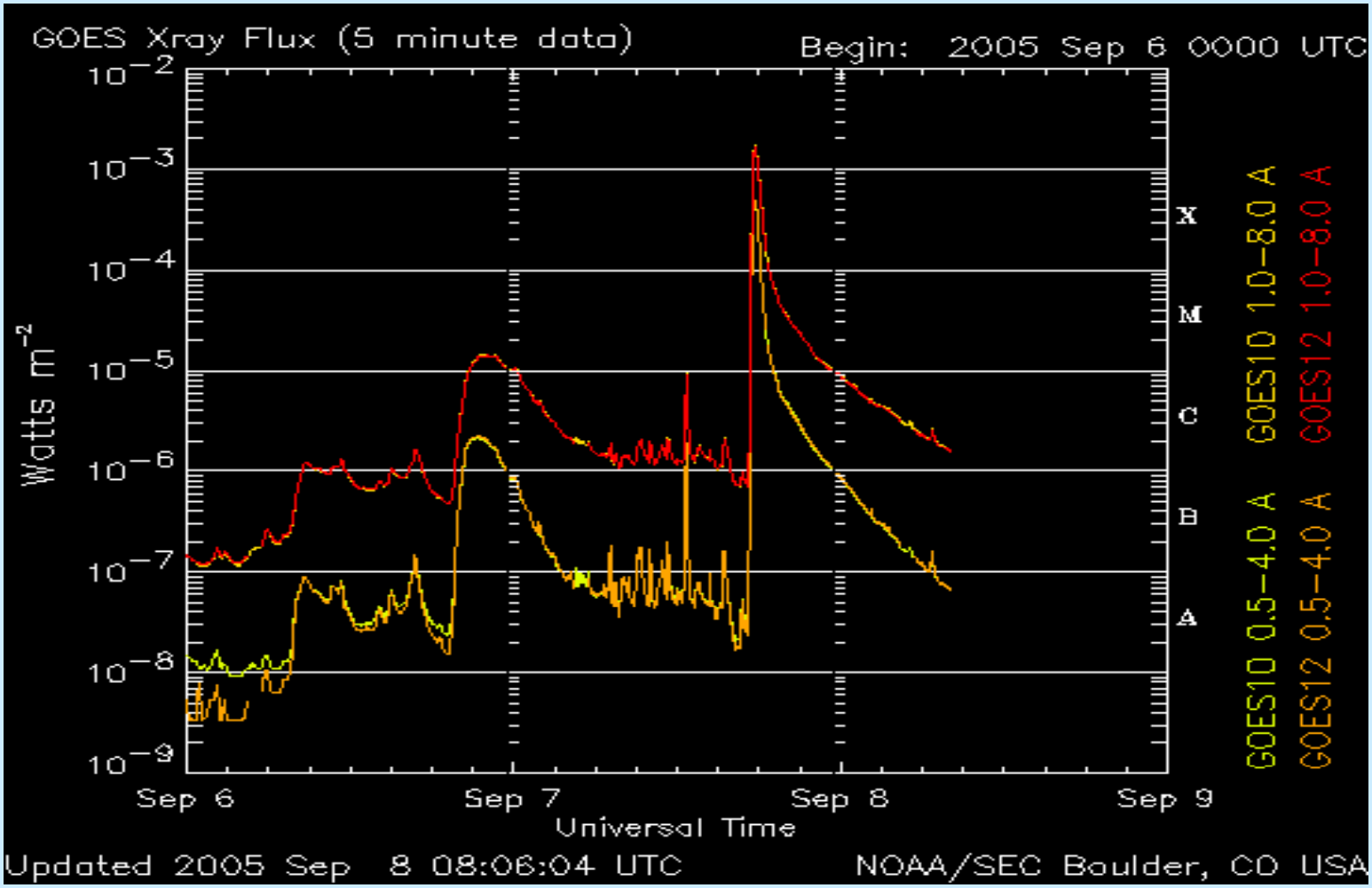
Geomagnetic perturbations of September 2005

superposition of crotating and multiple sporadic storrms



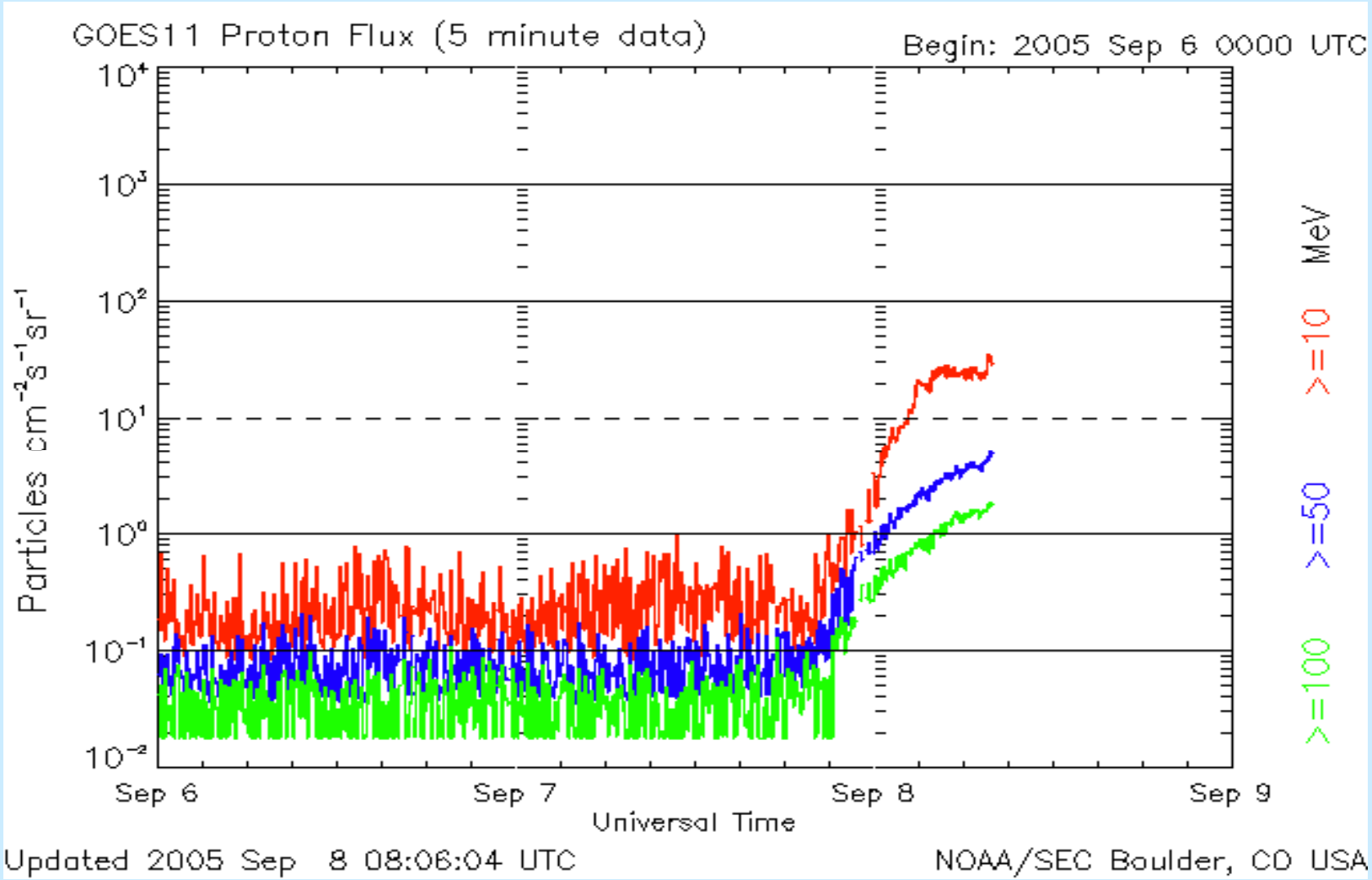
September 2005 CMEs and Flares:

an example of super-long duration events in energy releases lasting for many days with multiple CMEs and flare onsets



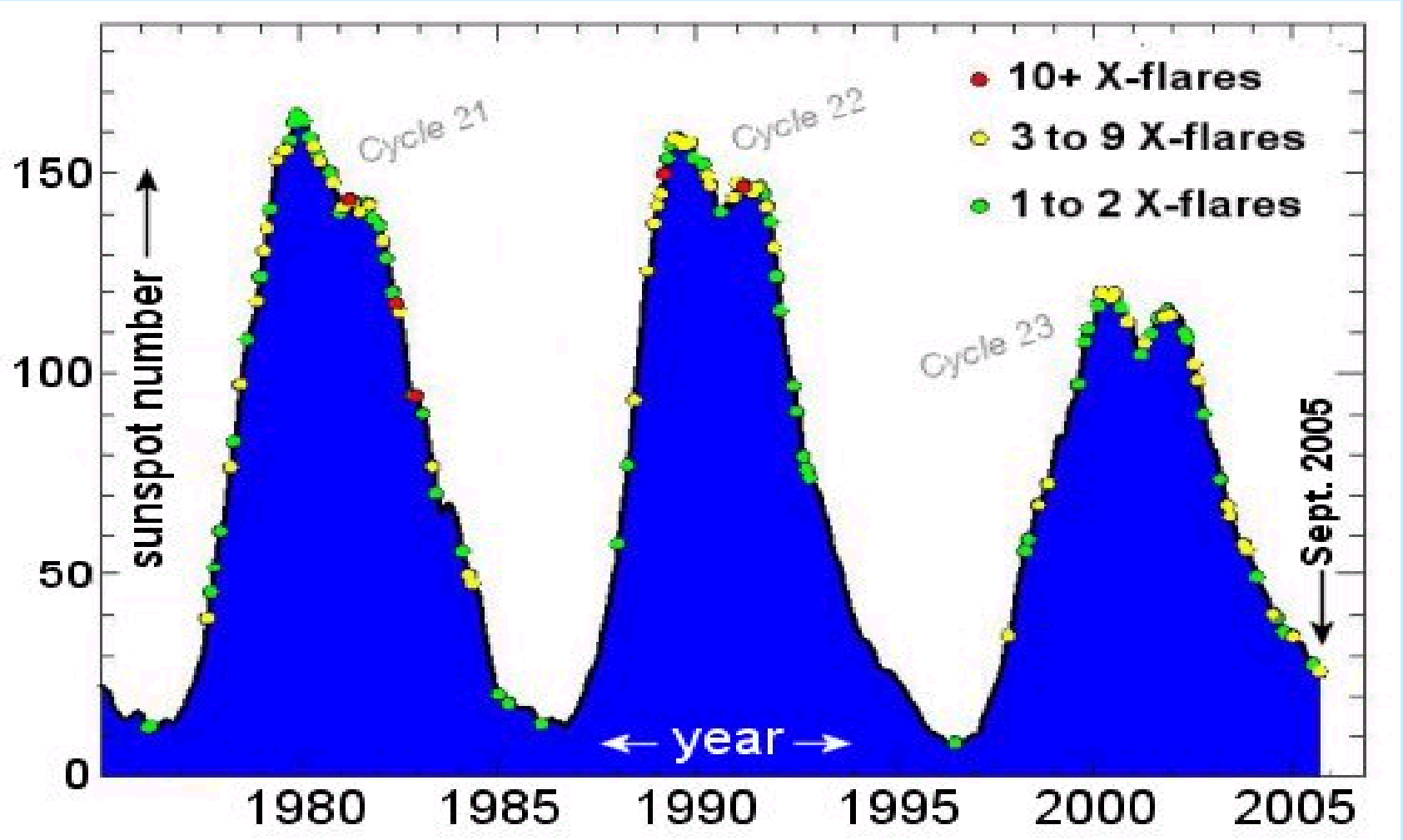
Proton event of September 2005:

slow rise, Eastern limb,



Sunspot counts and X-flares during the last three solar cycles

Note how solar activity
continues even during solar minimum. Credit: David Hathaway, NASA/NSSTC.
http://science.nasa.gov/headlines/y2005/15sep_solarminexplodes.htm?list168061



US$30 in the USA, Canada & Mexico
Aurora Special
6 months of space weather alerts.
This is for aurora-lovers.
We'll call when things are exploding on the sun and when auroras are about to appear over your home town.

Severe heliospheric and geomagnetic storms in November 2004

Not Predicted:

NOAA Space Weather Outlook 03-29 November 2004

- "Solar activity is expected to be low to moderate throughout the most of forecast period due to possible M-class flare activity from Regions 691 and 693"
- SWO PRF 1522 02 November 2004
- http://www.sec.noaa.gov/weekly/prf2004/prf1522

What is missing in predictions?

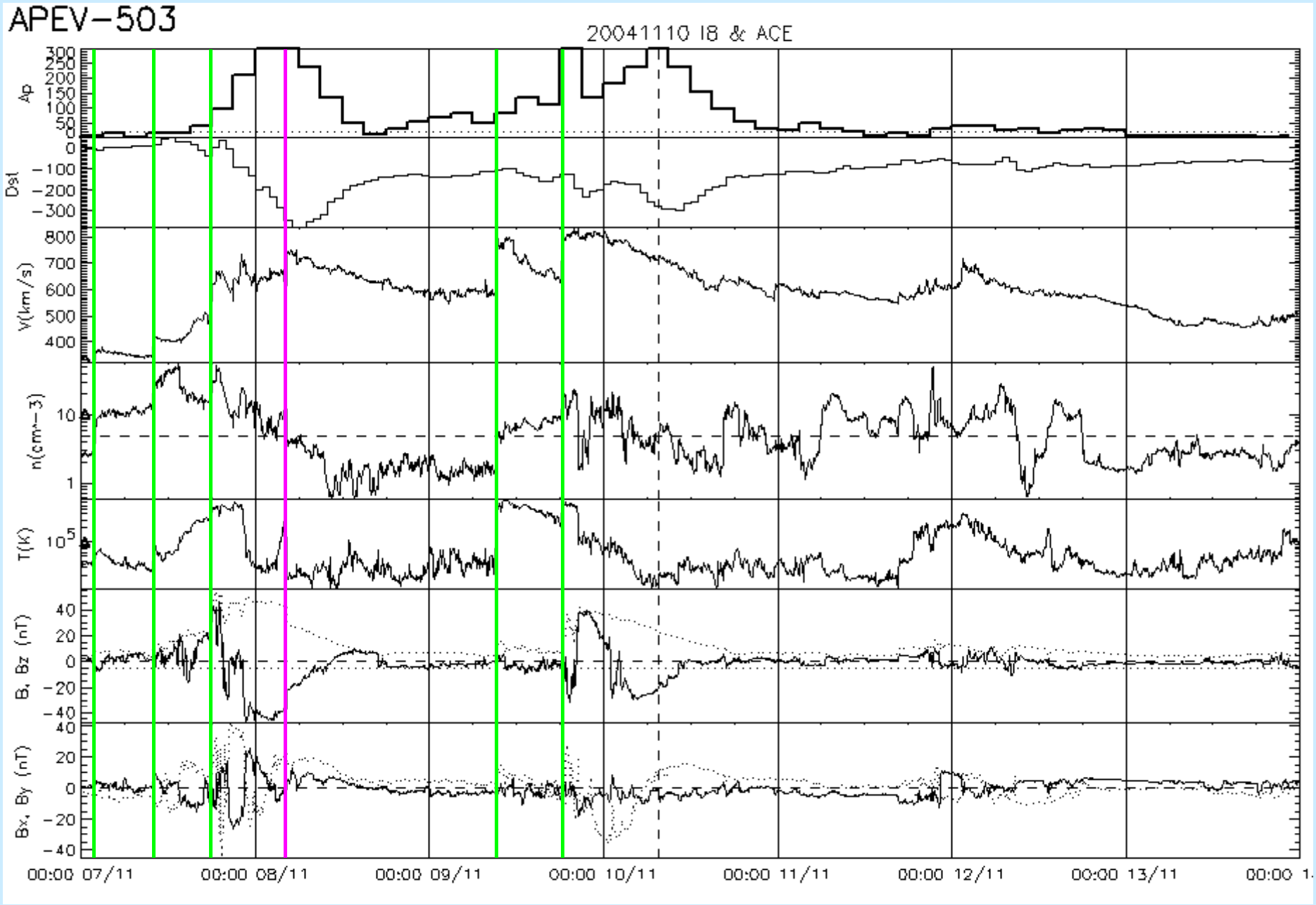
- Rapid development of new electric and magnetic fields globally on the Sun less then in a few days.
- Global activity complex encompassing at least AR 0696/0695/0699 and their surroundings unexpectedly appeared and worked in concert on the visible side during days: **a global phenomenon**
- V.N. Ishkov's method is promising for the evaluation of inductive electric fields

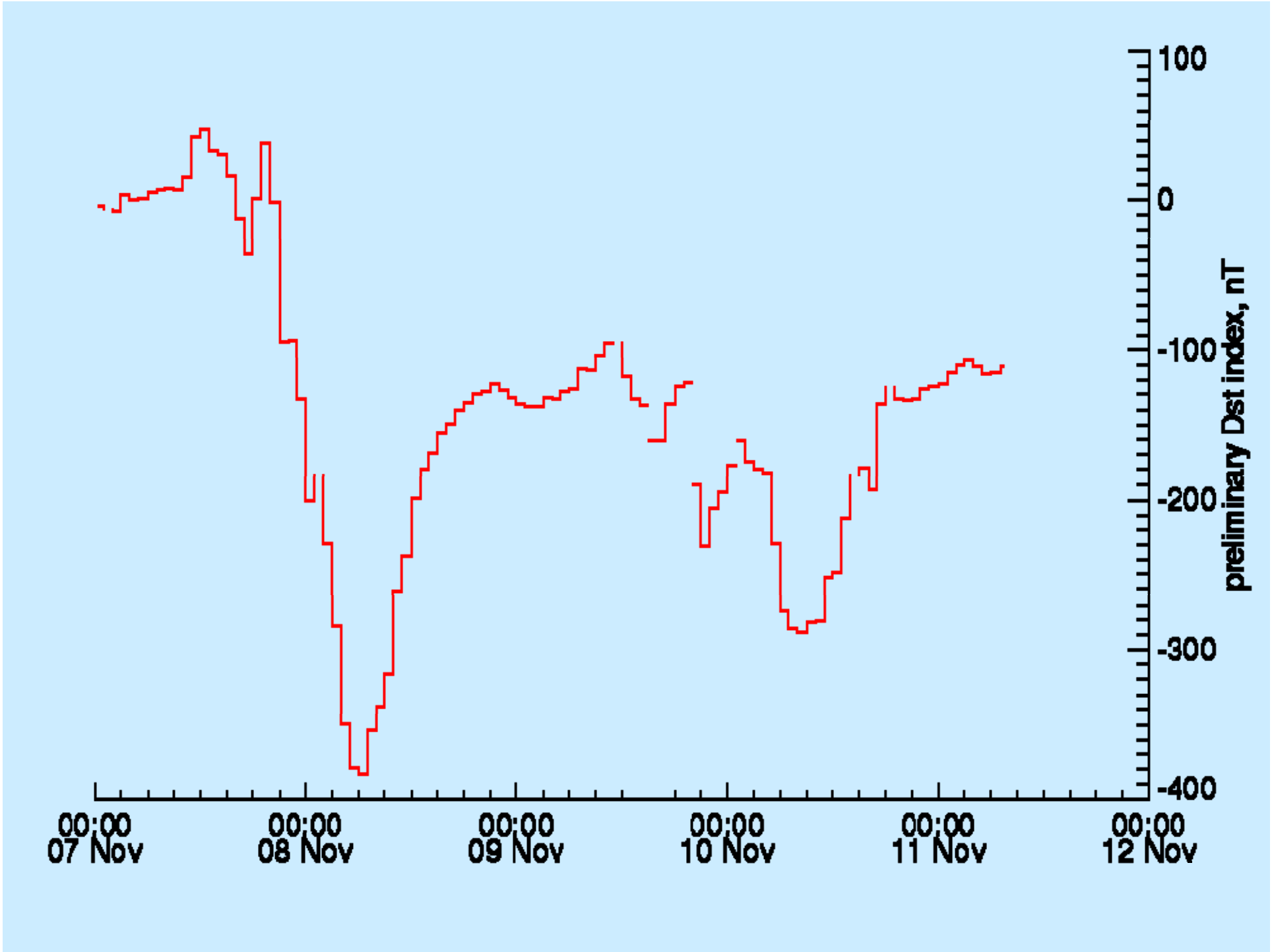
What is needed for attempts of a better prediction starting from the Sun?

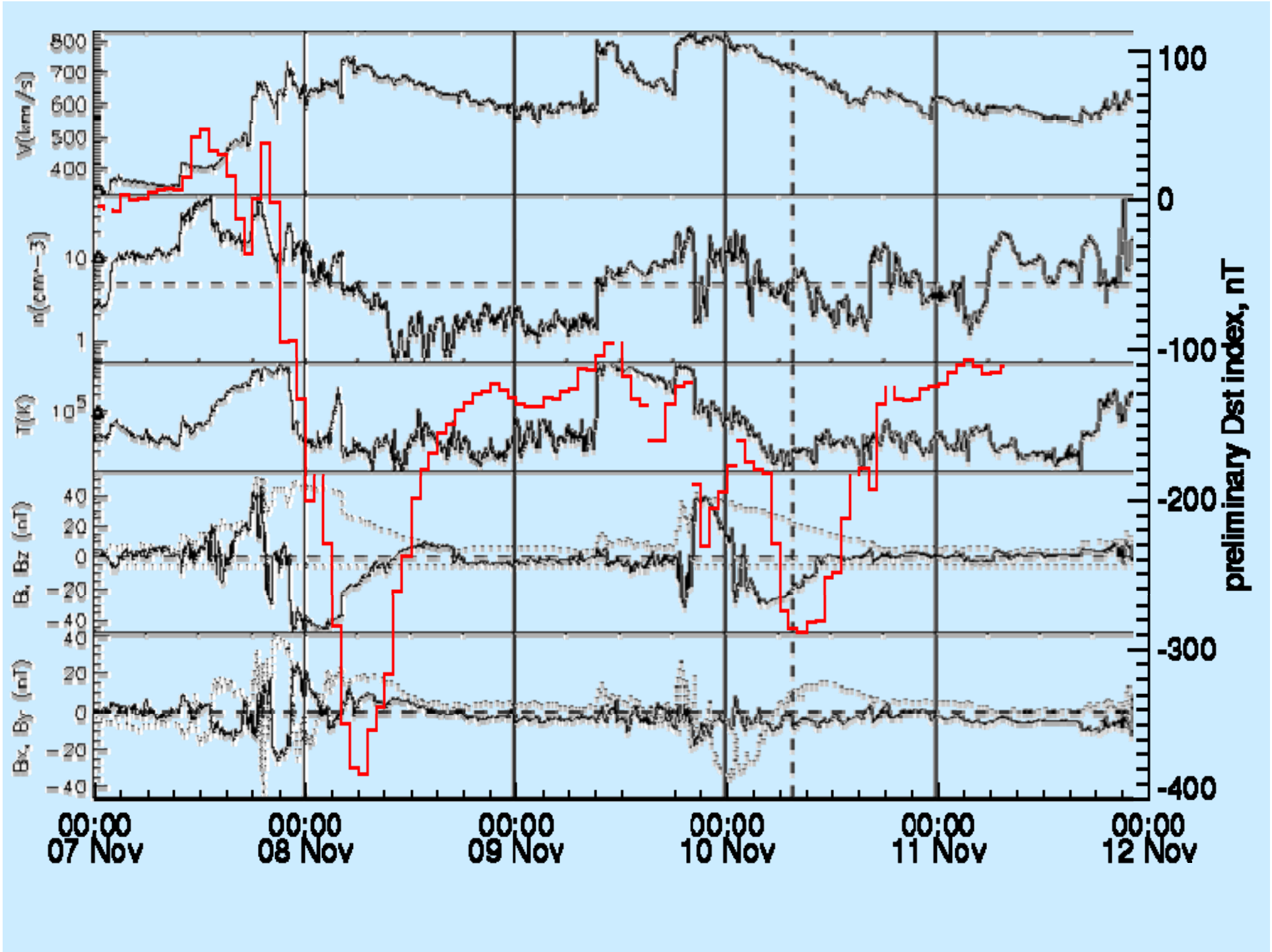
- More accurate knowledge of input parameters in the existing models:
- magnetic field and velocity vectors as functions of time at some boundary level around the Sun. Not existing now.
- density and temperature distributions as functions of time. Not existing now.
- More realistic macroscopic models (including kinetic effects) beyond the standard dissipative MHD codes. Not existing now and difficult in future.

Multiple storm onsets

- Multiple interplanetary traveling shocks (4 well developed forward and 1 reverse) + several other nonlinear perturbations (not developed shocks) during November 7-12, 2004
- Superposition of corotating perturbations and HCS crossings (~ 20% contribution in Dst amplitude) with sporadic ICMEs (~80% contribution)


APEV-503
20041110 I8 & ACE
Ap
Dst
V(km/s)
n(cm^-3)
T(K)
B, Bz (nT)
Bx, By (nT)
00:00 07/11
00:00 08/11
00:00 09/11
00:00 10/11
00:00 11/11
00:00 12/11
00:00 13/11


100
0
-100
-200
-300
-400
preliminary Dst index, nT
00:00
07 Nov
00:00
08 Nov
00:00
09 Nov
00:00
10 Nov
00:00
11 Nov
00:00
12 Nov


V(km/s)
800
700
600
500
400
n(cm^-3)
10
1
T(K)
10^5
B, Bz (nT)
40
20
0
-20
-40
Bx, By (nT)
40
20
0
-20
-40
100
0
-100
-200
-300
-400
preliminary Dst index, nT
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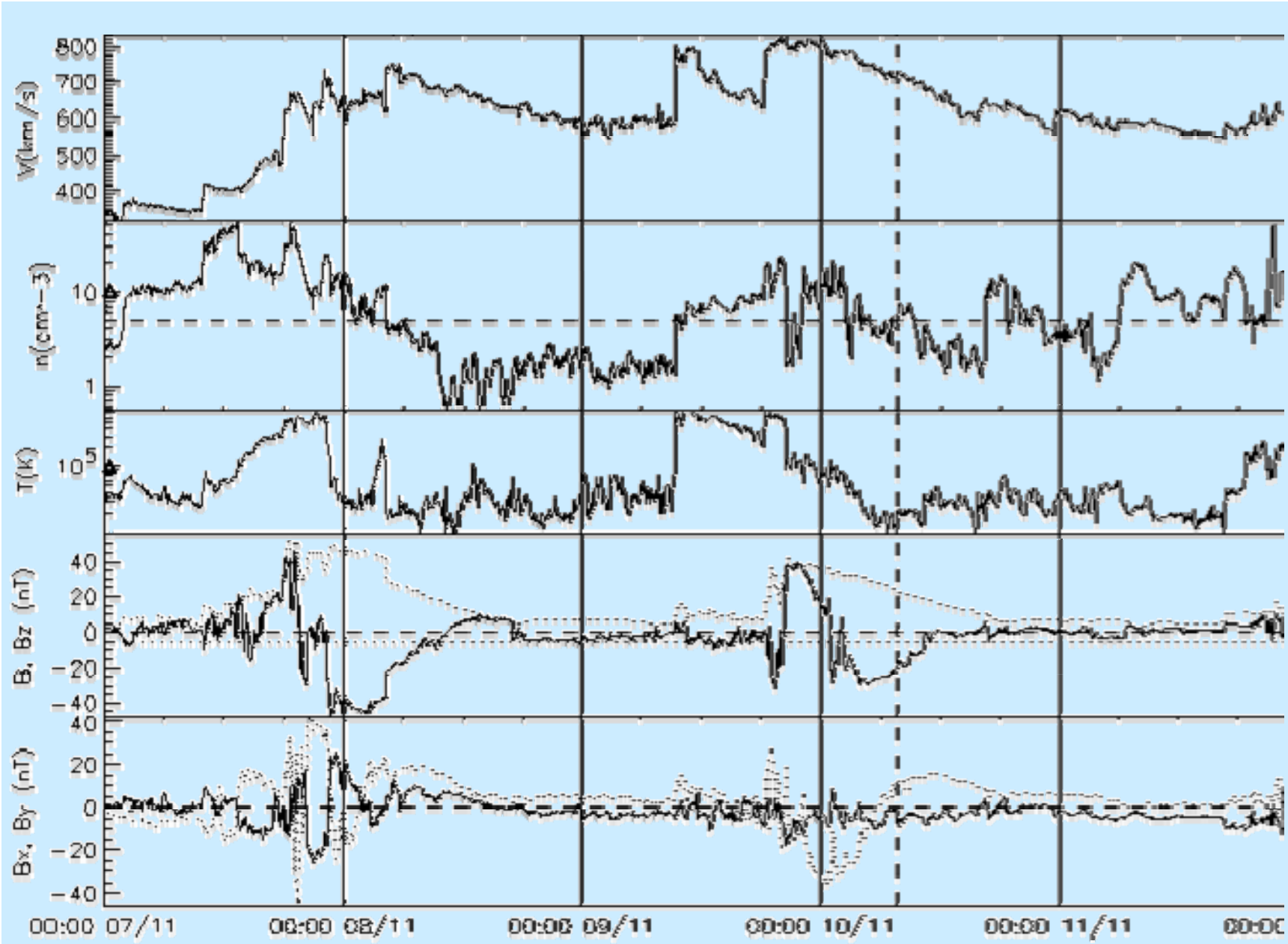
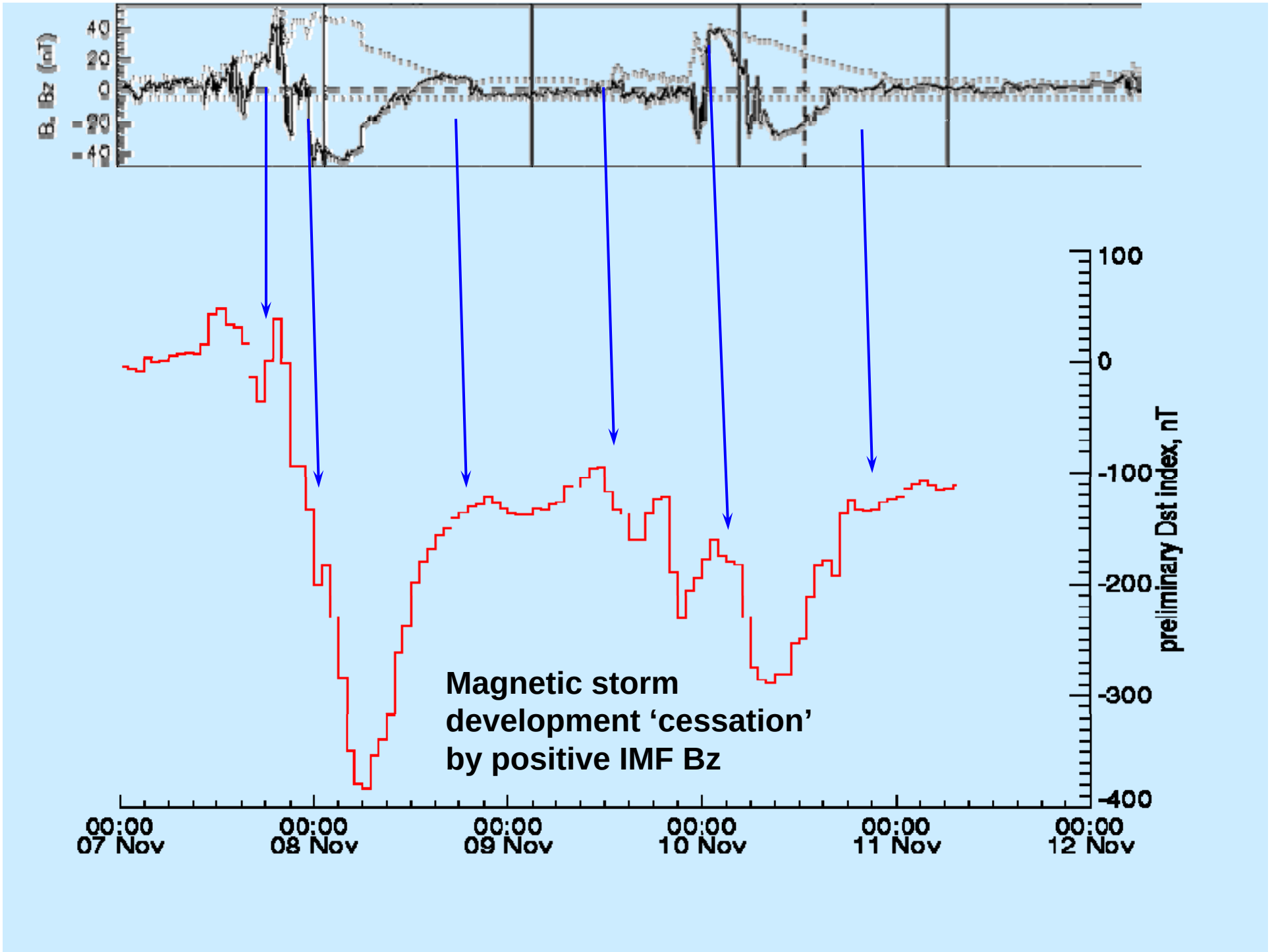
09 Nov
00:00
10 Nov
00:00
11 Nov
00:00
12 Nov


V(km/s)
800
700
600
500
400
n(cm^-3)
10
1
T(K)
10^5
B, Bz (nT)
40
20
0
-20
-40
Bx, By (nT)
40
20
0
-20
-40
00:00 07/11
00:00 08/11
00:00 09/11
00:00 10/11
00:00 11/11
00:00


B, Bz (nT)
40
20
0
-20
-40
100
0
-100
-200
-300
-400
preliminary Dst index, nT
Magnetic storm
development ‘cessation’
by positive IMF Bz
00:00
07 Nov
00:00
08 Nov
00:00
09 Nov
00:00
10 Nov
00:00
11 Nov
00:00
12 Nov

Interplanetary Causes

- S.-I. Akasofu
- M. Temerin and X. Li (ACE News#86)
- Max Dst ~ 8 (6-10) Max Bz
- Storm onsets when large Bz<0 for several hours
- ‘Cessation attempts’ when Bz>0
- Reconstruction of IMF Bz(t) using past historic records of Dst(t) (in the way similar to the Svalgaard-Mansurov effect for IMF sectors)

Physics of interplanetary drivers

- Non-linear, coupled MHD convective, propagating and standing (trapped) wave modes
- **TA = 0** - the set of MHD equations
- **T -** MHD propagator (ideal or dissipative)
- **A {**n**(r,**t**),** **V(r,**t**),** T**(r,**t**),** **B(r,**t**), …}** generalized MHD vector of state
- Linear case: dispersion relation, eigen modes:
  - ω=0 non-propagating dissipative branches (convective modes: streams, vortexes)
  - ω– kv =0 wave branches (Alfven, Fast, Slow…)
- Non-linear case: solitary solutions (large manifold, not separable mixture of flow streams, vortexes and oscillations, guided and trapped MHD waves)

Partial loss of memory about parent conditions on the Sun

- Kinetic and macroscopic **mixing** processes
- Vortexes (convective complexity) – twist and **rotation** of currents
- Elliptic polarization plane of Alfven waves with periods from hours to a day can rotate during the propagation in the corona and in the heliosphere (B.Tsurutani et al. : for shorter periods ¾ of a whole turn)
- **Hence:** Bz sign in solitary perturbations **is not always** conserved on the way from the Sun

Parent situation on the Sun

- Global activity complex encompassing at least AR 0696/0695/0699 and their surroundings worked in concert on the visible side: **a global phenomenon**

- **Distant and trans-equatorial** connections in the upper corona are involved in producing ejections/dimmings

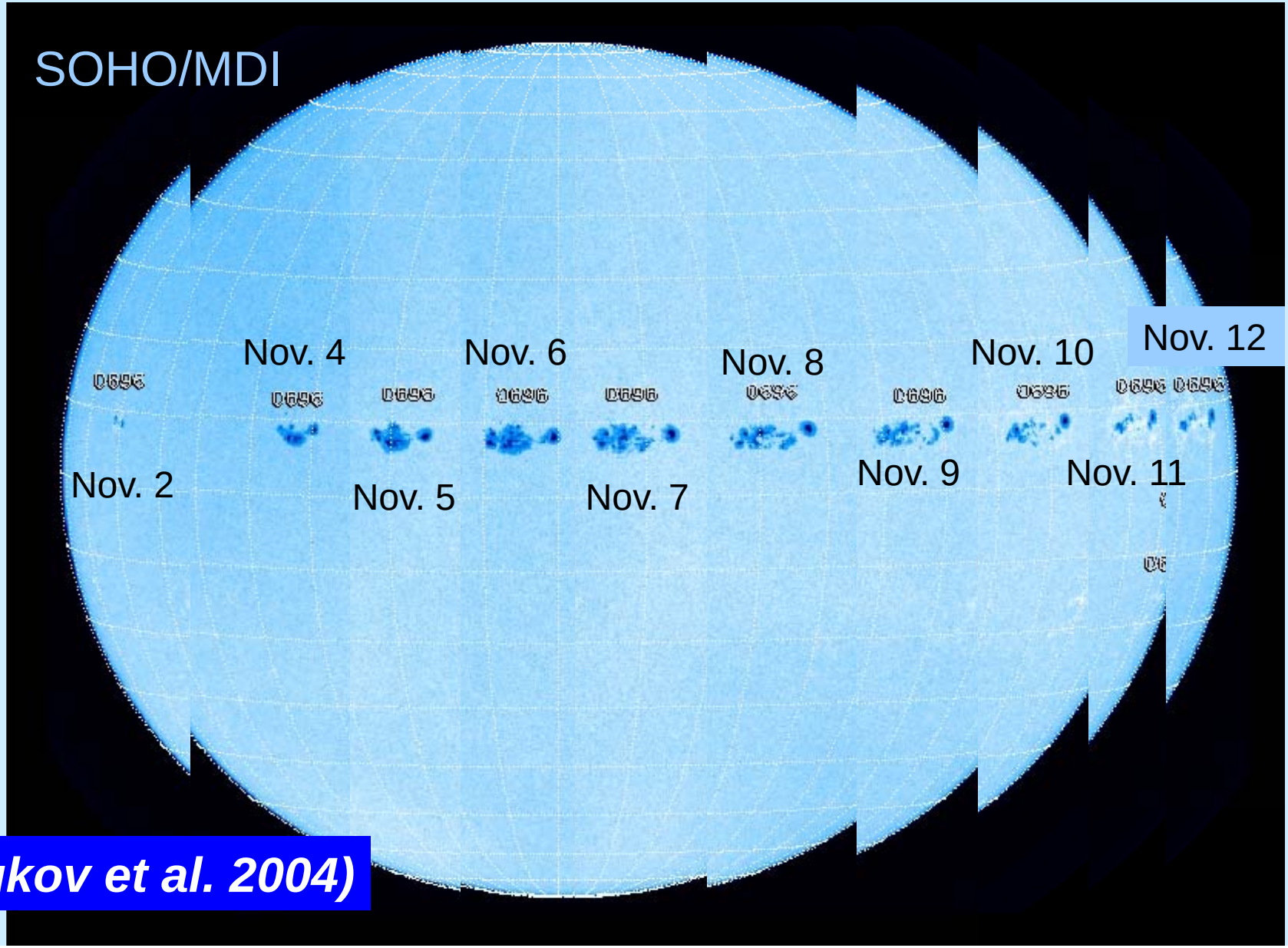
- **Geometry** and time history are complicated
- Super-long **duration** (days)
- + long-duration (hours)
- + impulsive (minutes) free energy releases

- **Hence: non-local sub-photospheric sources**

Important note

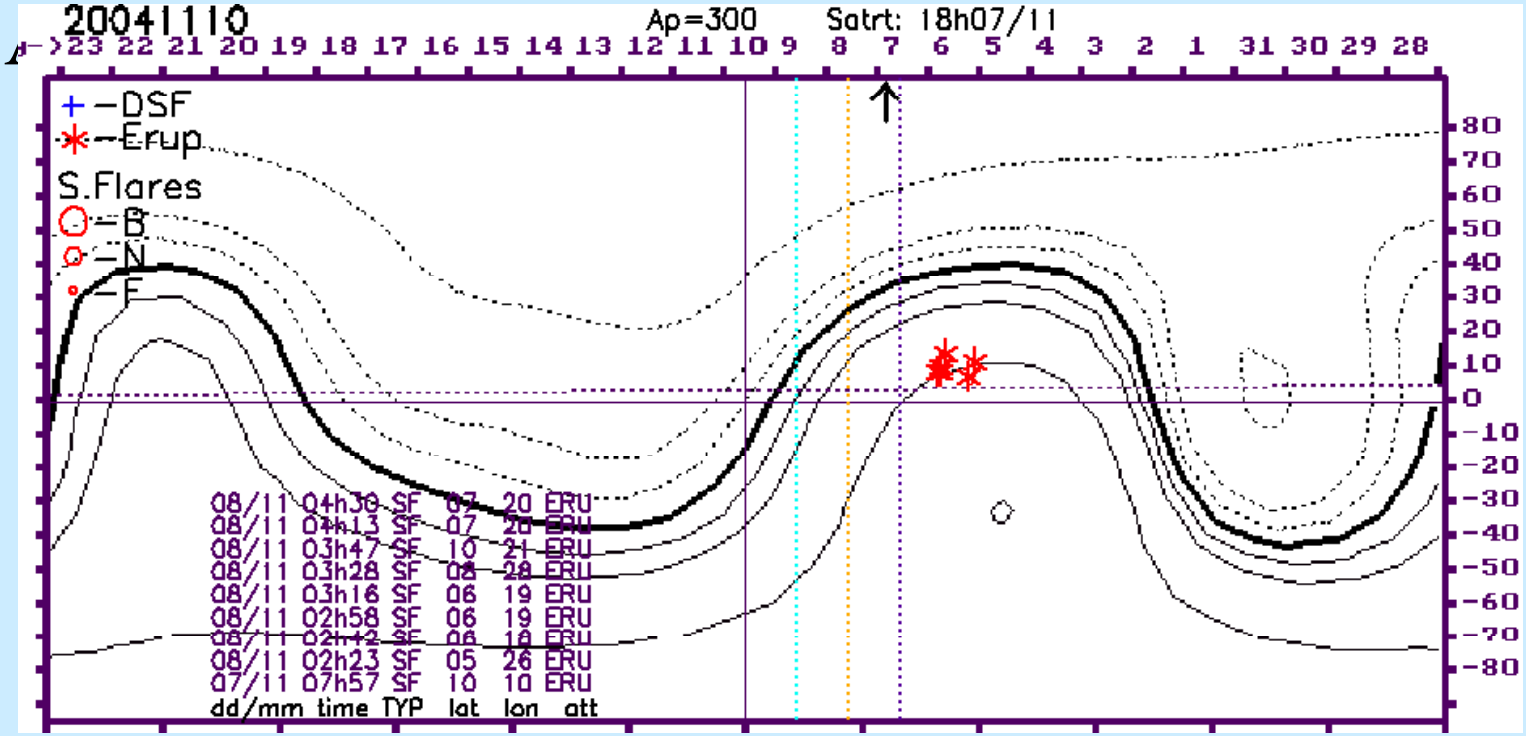
- Initially, observers (A. Zhukov et al., 2004; V. Yurchyshyn, 2004 – presentation at the Sonoma meeting, 2004) reported the coronal, heliospheric and geomagnetic phenomena of interest and focused the attention on eruptions in and around AR 0696 (early attempts to "localize the sources of CMEs" and corresponding IMF flux ropes with Bz<0)
- But:
- Please note that not only one AR 0696 was involved in producing the compound coronal and interplanetary perturbations of interest (non-local events, more global character, no simple geometry)

NOAA AR 0696: sunspots



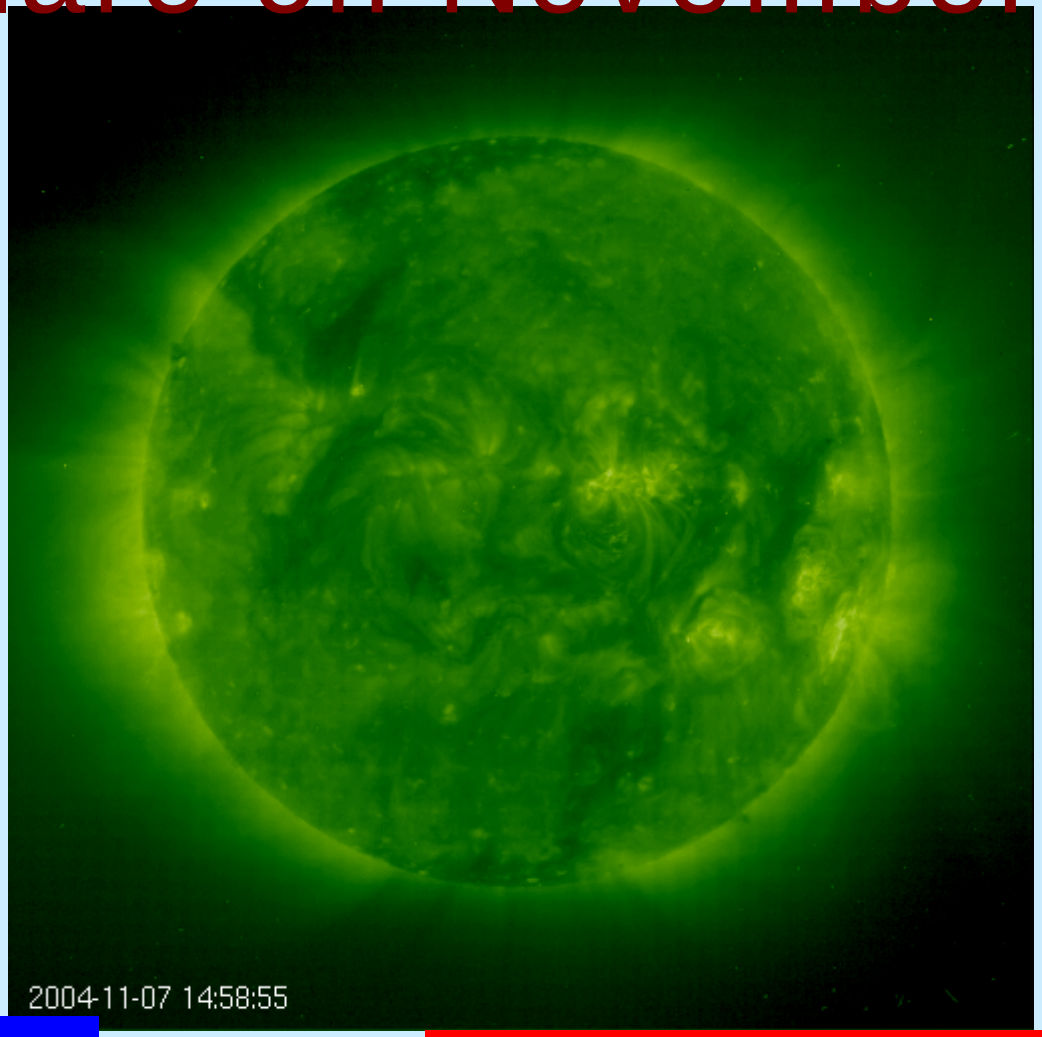
(Zhukov et al. 2004)

Calculated HCS position

- 

X2.0 flare on November 7

SOHO/EIT
Fe XII (195 Å)

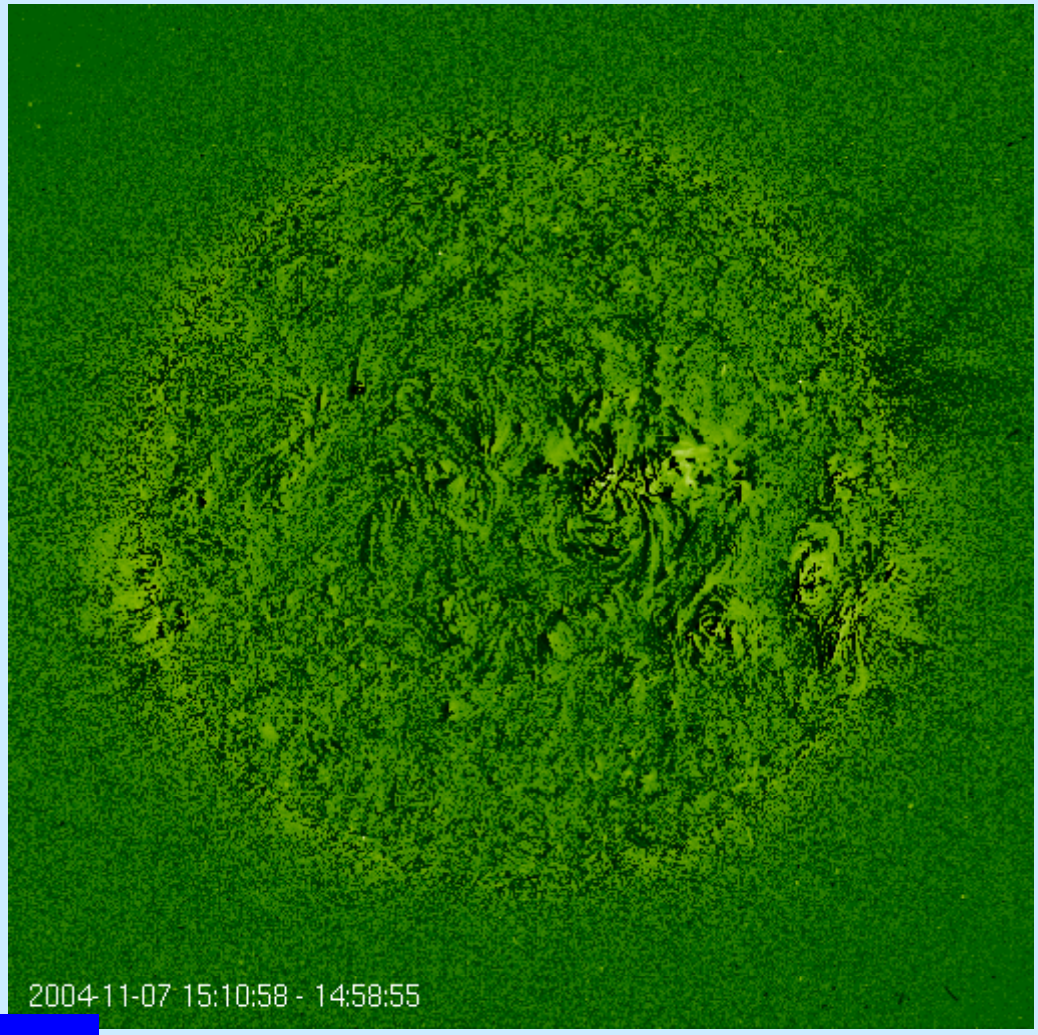


(Zhukov et al. 2004)

“October Revolution flare”

Coronal dimmings and an EIT wave on November 7

SOHO/EIT
Fe XII (195 Å)
running
difference



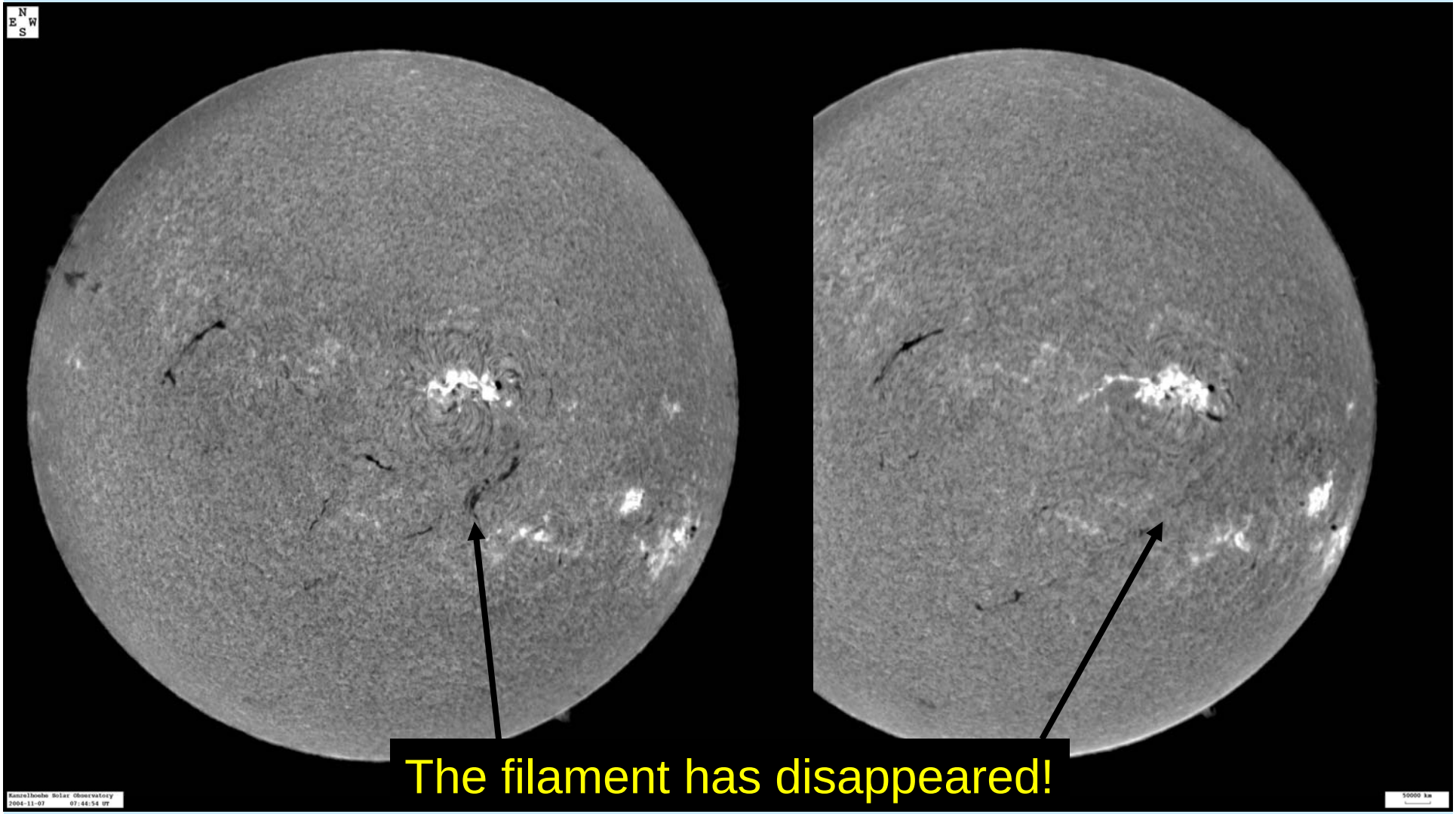
(Zhukov et al. 2004)

Full halo CME on November 7

SOHO/LASCO C3
running difference

(Zhukov et al. 2004)

Eruptive filament on November 7



Hα images, Kanzelhöhe Solar Observatory

(Zhukov et al. 2004)

Predictability of Bz<0 is low. It is partially because of the big free energy available for the self-organization of new unstable structures on the Sun and on the way to the Earth

- **Rotations:** steepened Alfven waves + vortexes in the corona and in the heliosphere
- **Mixing:** non-laminar and multi-scale geometry on the way in the heliosphere
- **Mutual nonlinear interactions:** compound ejecta and complicated background

- Nevertheless, sometimes one or only few scales dominate. Predictions are possible in such simpler situations (it is **not the case** for events like November 2004)

- NOAA Space Weather Outlook: a new global activity complex was **not expected** on the Sun (http://www.sec.noaa.gov/weekly/prf2004/prf1522.ps)

Can the orientation of interplanetary flux ropes be visually determined from solar observations?

Not always

Why so?

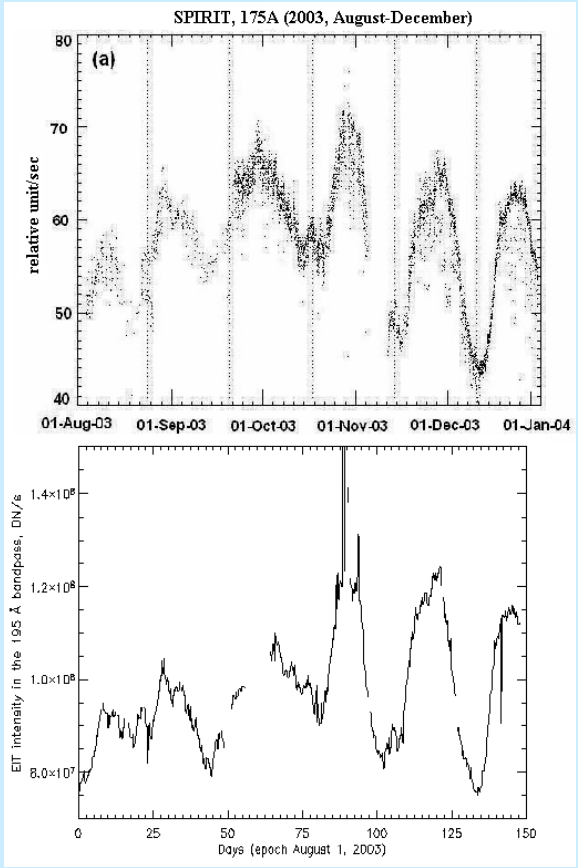
The answer is here

Acrobat Document

Lessons of October-November 2003 about the asymmetry on the Sun

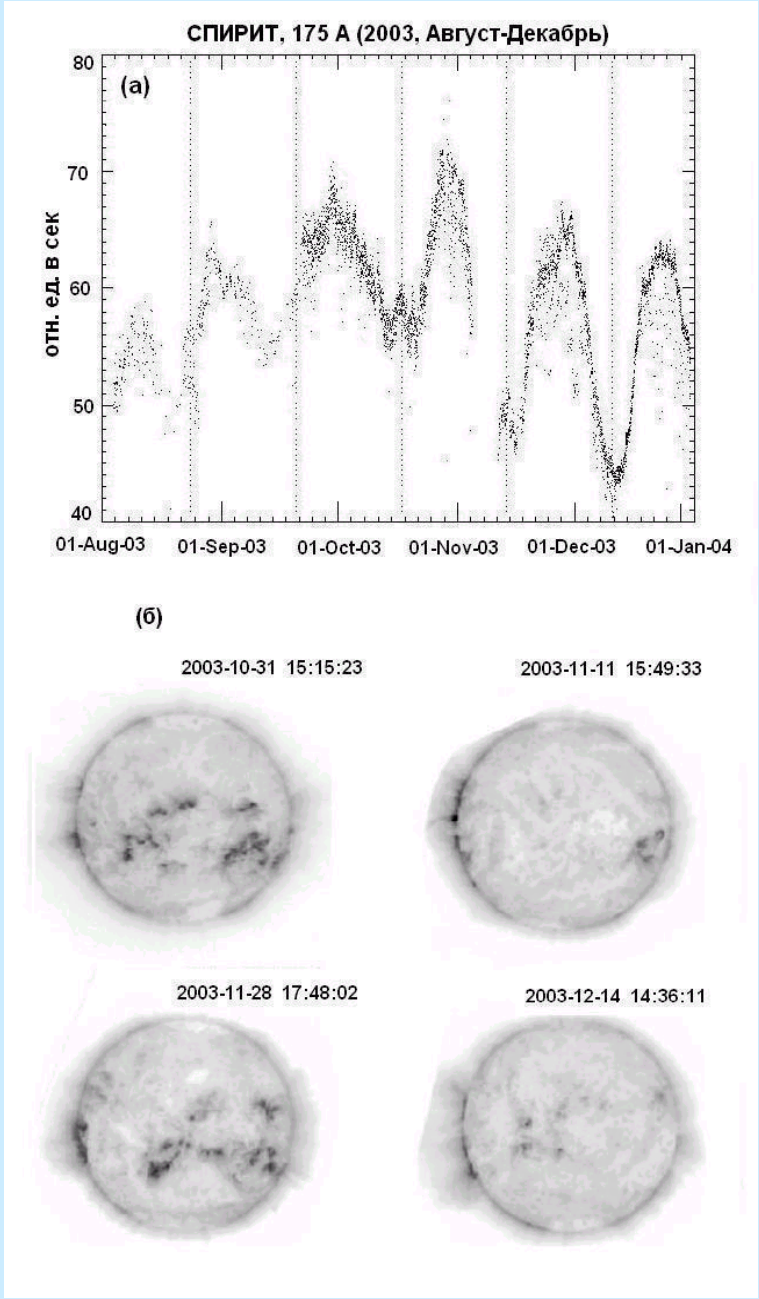
- **Asymmetry of the Sun** in the visible light: photosphere
- **Asymmetry** of the Sun in EUV: chromosphere and corona
- **Asymmetry** of the Sun in the emitted solar wind and IMF parameters: heliosphere
- **Global asymmetry** and couplings of the solar activity manifestations in different scales

«Bright» and «dark» sides of the Sun : 2003

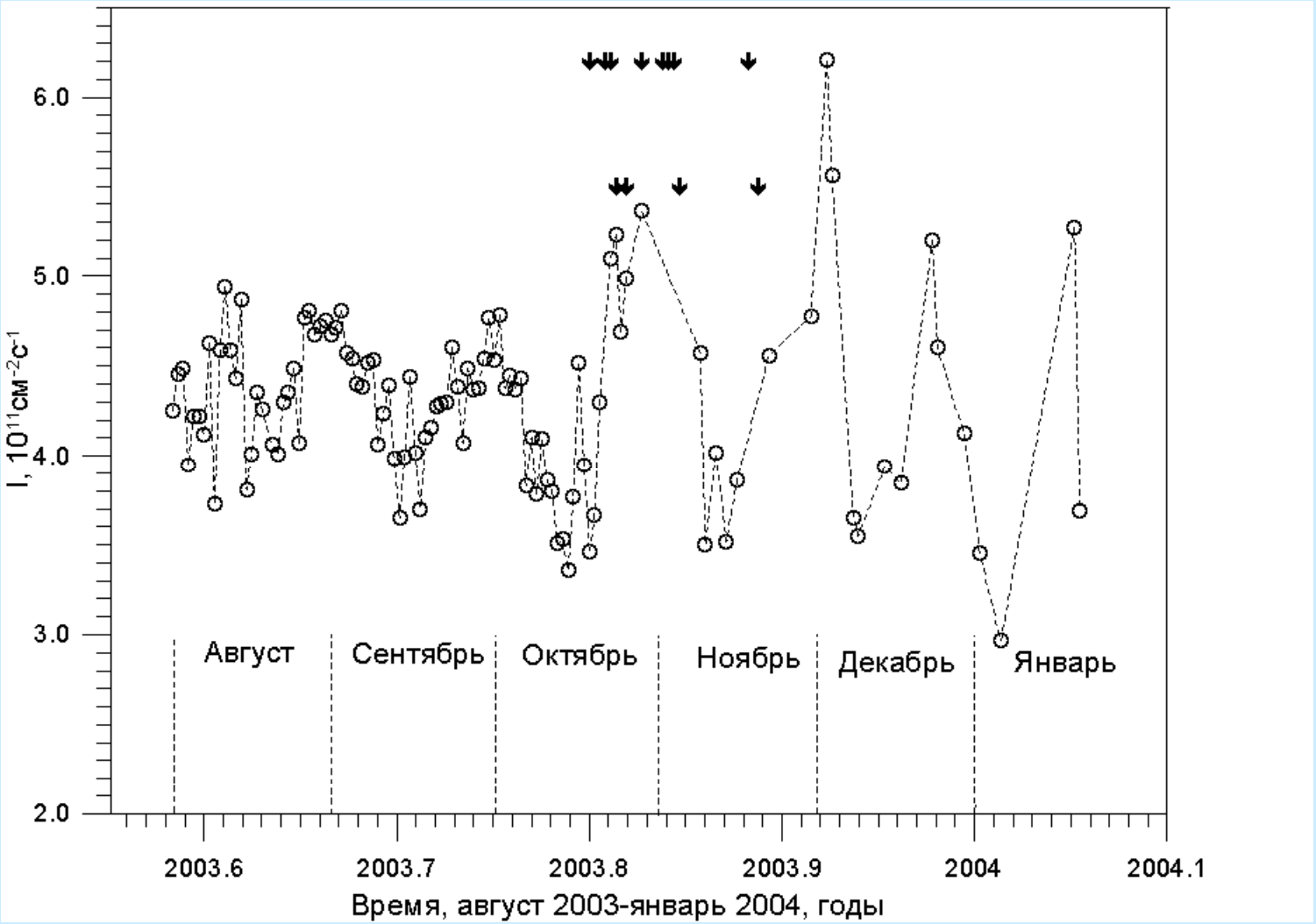


- CORONAS / SPIRIT: 27-day EUV rotational modulation observed
- SOHO / EIT data show the same pattern: «bright» and «dark» sides of the Sun
- **Time scales: impulsive (minutes), long-duration (hours- days) and superlong duration (many days) events**

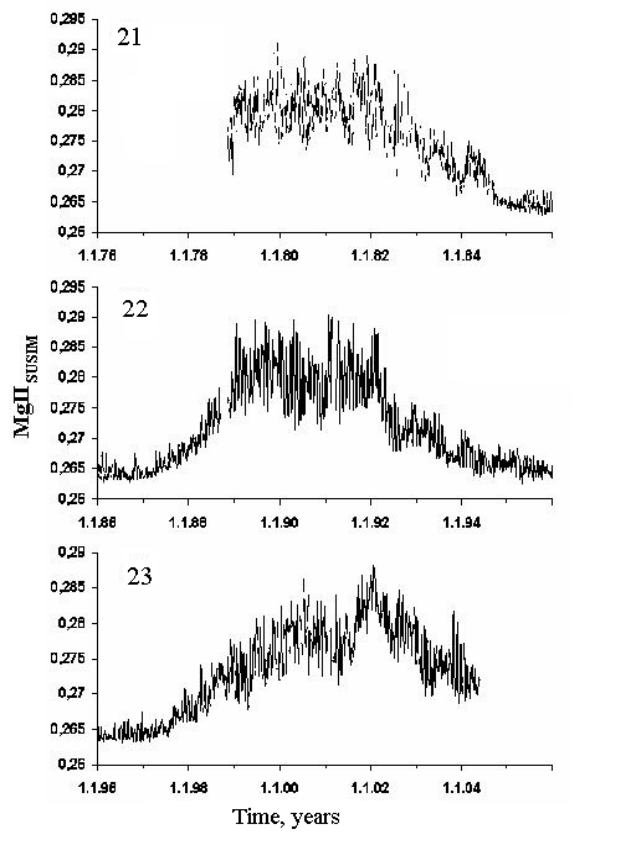
Next slide shows bright and dark hemispheres of the Sun:
The most important active regions and coronal holes reside as coupled clusters on the “bright” side of the Sun. The opposite side of the Sun is “dark”. It is «empty» of big active regions and coronal holes.


СПИРИТ, 175 А (2003, Август-Декабрь)
(а)
80
70
60
50
40
отн. ед. в сек
01-Aug-03
01-Sep-03
01-Oct-03
01-Nov-03
01-Dec-03
01-Jan-04
(б)
2003-10-31 15:15:23
2003-11-11 15:49:33
2003-11-28 17:48:02
2003-12-14 14:36:11

Ly-alpha - observed and calculated in 2003 -2004: rotational modulation is seen with the same phase

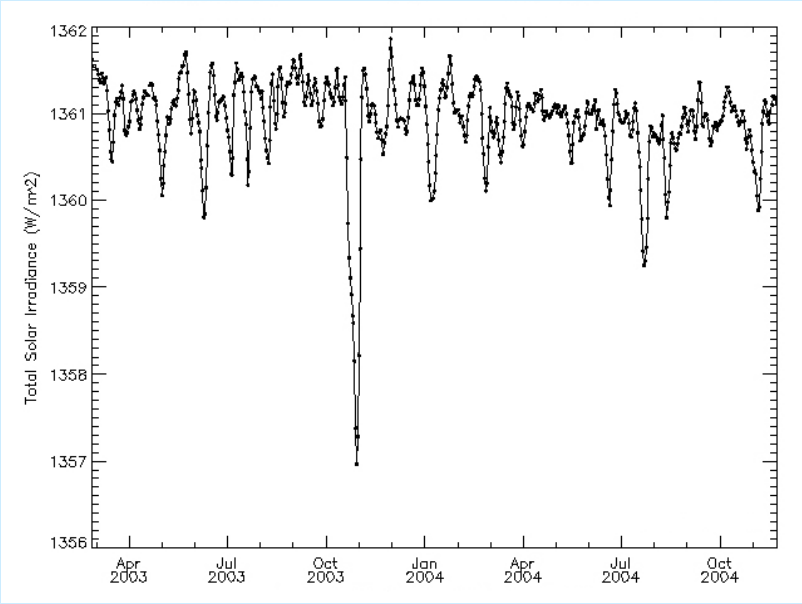


White light: three solar cycles and the rotational modulation



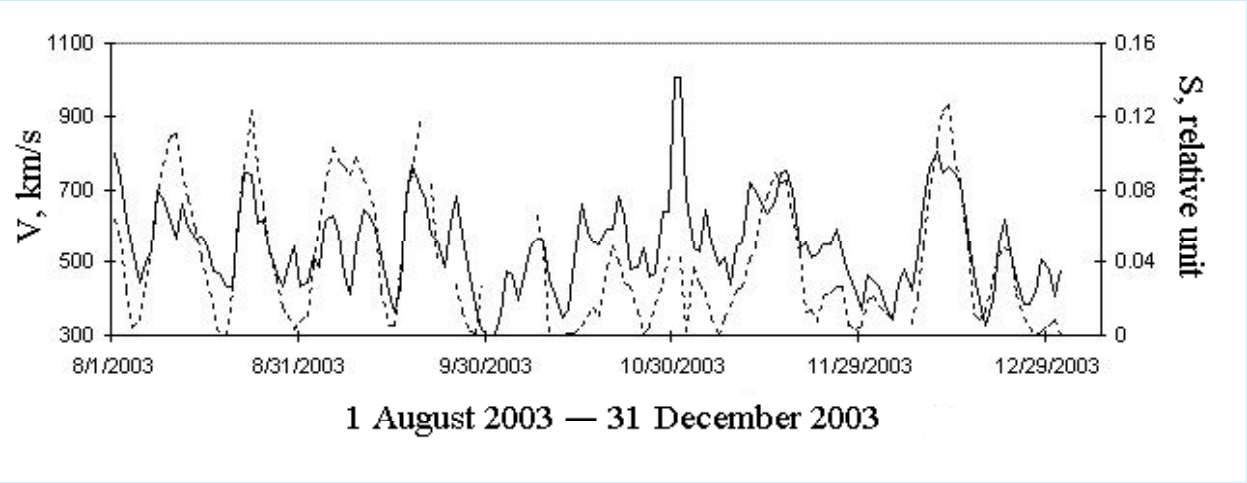
- (http://www-iup.physik.uni-bremen.de/gome/).
- MgII index (Wierek R.A. & Puga L.C., JGR,1999, 104, 9995)
- The same «bright» and «dark» sides of the Sun

The same rotational modulation in the Total Solar Irradiance (TSI)



- (http://lasp.colorado.edu/source/)
- next slides show correspondence with the solar wind streams from coronal holes

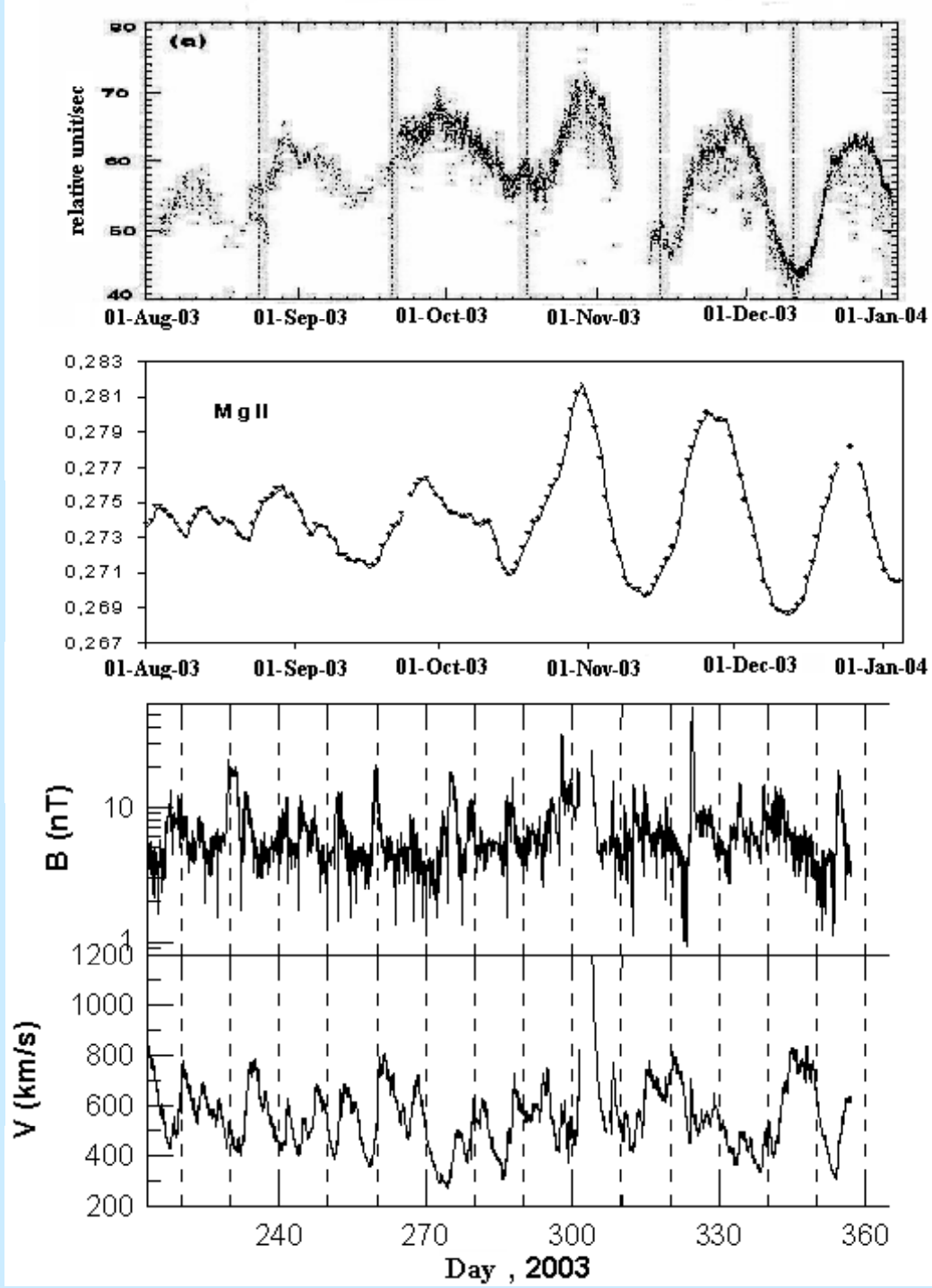
Calculated areas of coronal holes compared with the measured solar wind velocity (dots)



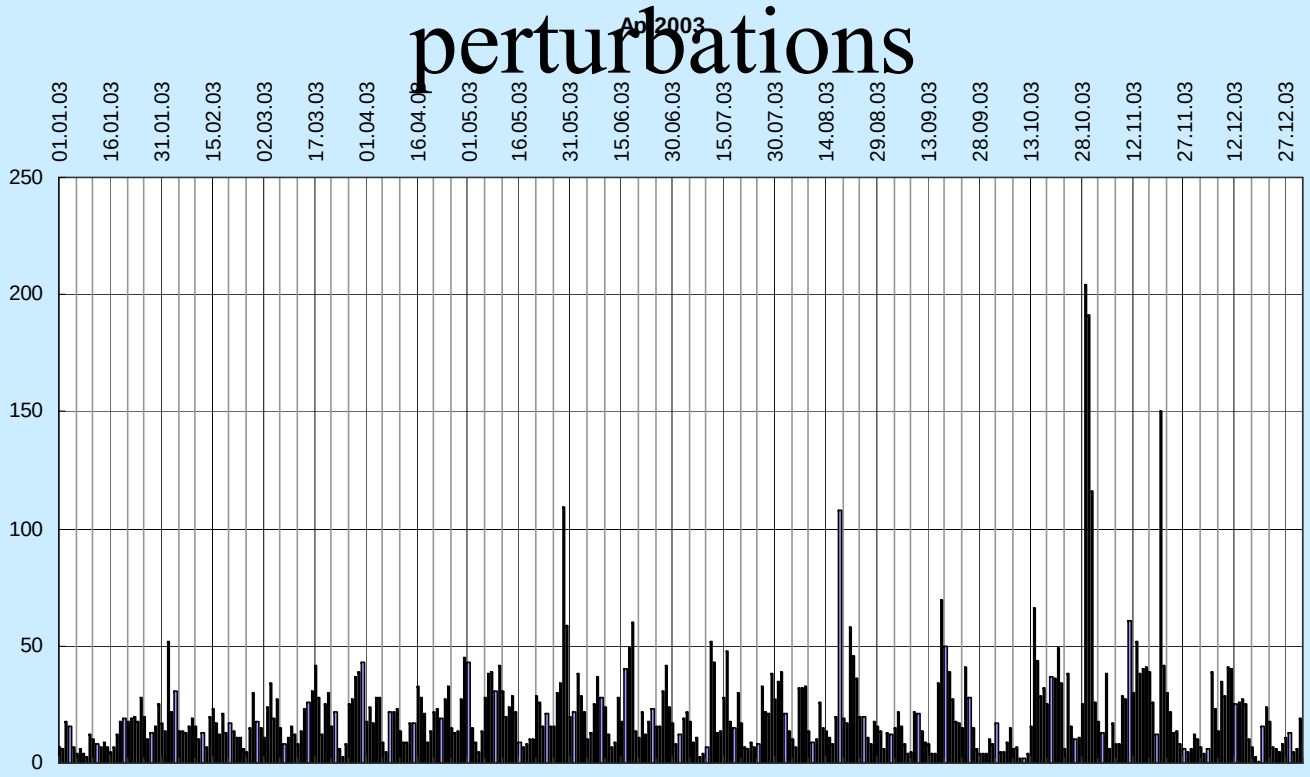
Next slide shows the comparison of observd electromagnetic radiation of the Sun with the solar wind parameters.

From top to bottom:
partial correspondence between

EUV radiaton (Coronas-F data)
MgII index
IMF magnetic field strength
Solar wind velocity at the Earth's orbit


(a)
relative unit/sec
80
70
60
50
40
01-Aug-03
01-Sep-03
01-Oct-03
01-Nov-03
01-Dec-03
01-Jan-04
Mg II
0,283
0,281
0,279
0,277
0,275
0,273
0,271
0,269
0,267
B (nT)
10
1
V (km/s)
1200
1000
800
600
400
200
240
270
300
330
360
Day , 2003

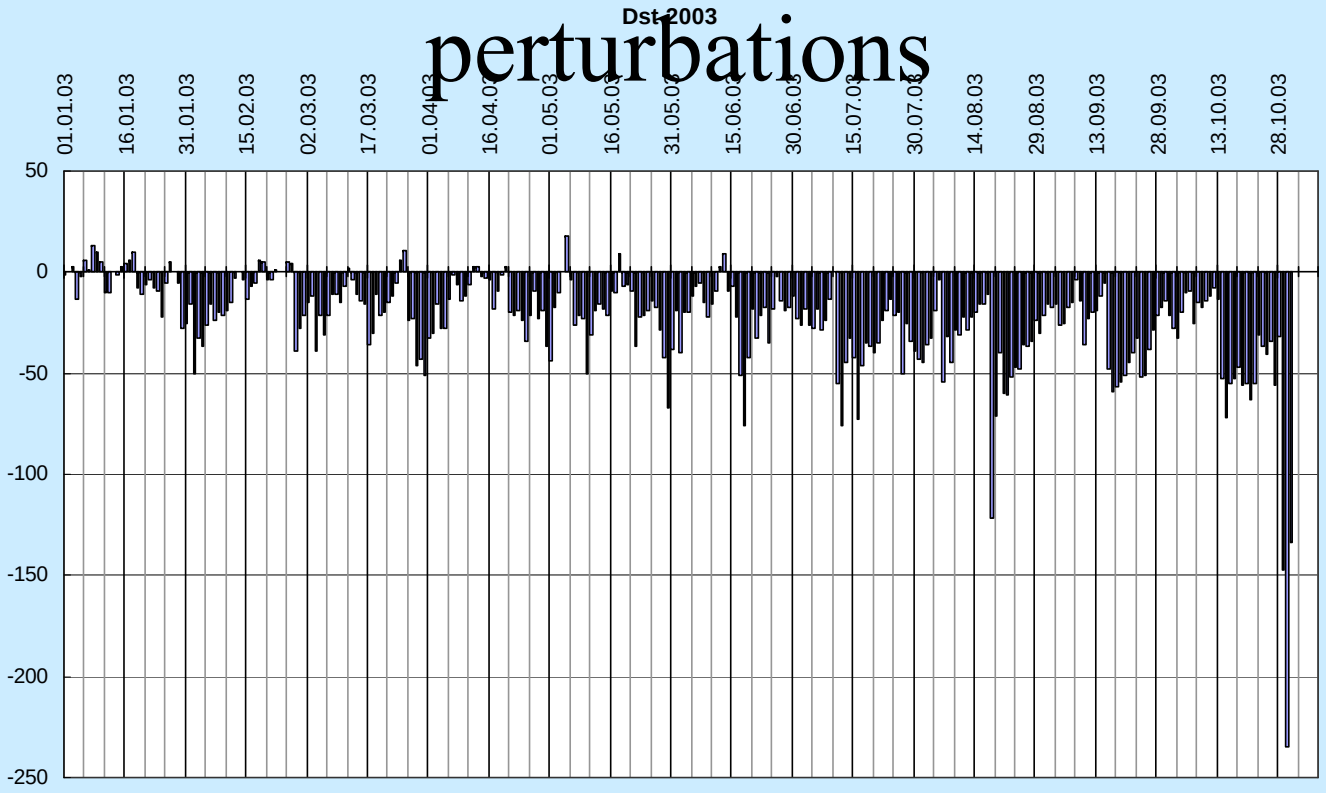
Daily average geomagnetic Ap index in 2003: corotating and sporadic perturbations



The leading edges of corotating clusters are more geoeffective: see next slide in the Dst index

(Veselovsky et al., Solar and Heliospheric Phenomena in October-November 2003: Causes and Consequences, Cosmic Research 42(5), 435-488)

Daily average geomagnetic Dst index in 2003: corotating and sporadic perturbations



Why such an asymmetry inside clusters?

1) generated on the Sun (leading sunspots are more compact that trailing ones). **Solar cause**.
2) generated in the heliosphere (corotating streams steepening). **Heliospheric cause.**

Both causes seem to be involved, but the quantiitative side is not clear

CONCLUSIONS (1)

- ✓ The **global asymmetry** of the Sun is permanently seen at all levels of its atmosphere: photosphere, chromosphere, corona and the heliosphere.
- ✓ This asymmetry is coupled in some way to **sub-photospheric** structures and processes regulating the available free energy releases in the solar atmosphere.
- ✓ Strongest solar activity manifestations including the most powerful flares and CMEs occur at the **"bright side" of the Sun**
- ✓ "Bright side" of the Sun contains **clusters of active regions and coronal holes**, which are connected in their dynamics (seen in eruptions of long and high transequatorial loops, global dimmings and coronal mass ejections, etc.).
- ✓ **Corotating and sporadic** perturbations can be superimposed and produce multiple and super-long duration energy releases lasting many days (October-November 2003 case).

CONCLUSIONS (2)

- Non-local and non-linear responses to **strong photospheric drivers** with global multi-scale manifestations.

- A better knowledge of (**sub-) photospheric** energy, momentum and mass transport processes is inevitably needed for successful predictions of geoeffective interplanetary situations in a scale of many or several days.

- More accurate magnetic field and velocity vectors as well as density and temperature distributions at some boundary level around the Sun are necessary as **inputs for realistic models.**

- Existing MHD models are not always sufficient for predictions because of the partial **loss of memory** about these conditions on the way from the Sun: not unique solutions, unstable, bi-stable and multi-stable situations.

CONCLUSIONS (3)

- ✓ Solar and heliospheric extreme events (SEEs) are relatively **rare** and sporadic dissipative phenomena.
- ✓ Extremely weak or strong activity periods on the Sun **can be not predicted** well in advance with a sufficiently good accuracy because we do not know in details their physical origins nor the chain of governing forces.
- ✓ **Subphotospheric** energy sources: heat flows, bulk mass motions, electric currents play the role in different proportions.
- ✓ These events can look as similar or different manifestations in the solar atmosphere from case to case depending on the situations controlled by many independent MHD and kinetic **dimensionless parameters**.

CONCLUSIONS (4)

- ✓ Spurious topological changes are often seen because of the projection effects in the images of the solar corona and false 2D-3D deconvolutions. STEREO movies are needed
- ✓ Coronal mass ejections, flares and eruptive prominences are **strongly non-local** phenomena with many space-time scales
- ✓ The formation of new zero points of the large scale magnetic fields is not always necessary for eruptions seen as prominences and CMEs
- ✓ Electric drifts of the plasma in time dependent inductive fields play the **key role** in the loop-like eruptions on the Sun

Thank you!