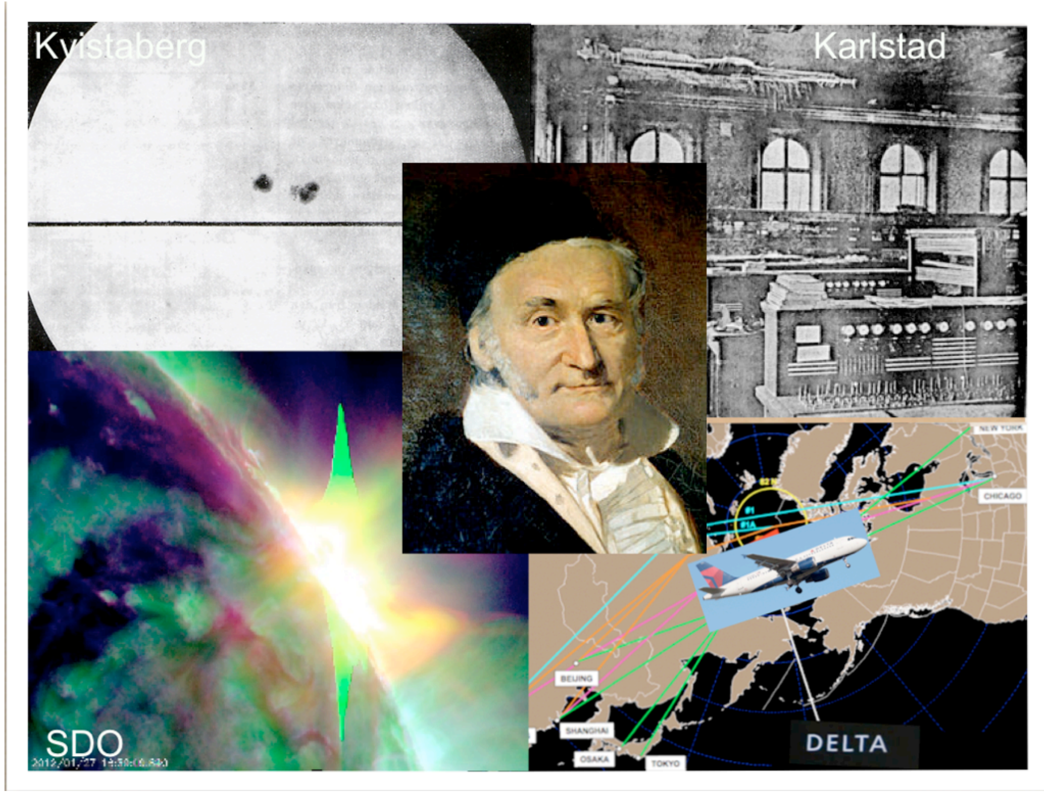
Solar Storms and Topology: Observed with SDO



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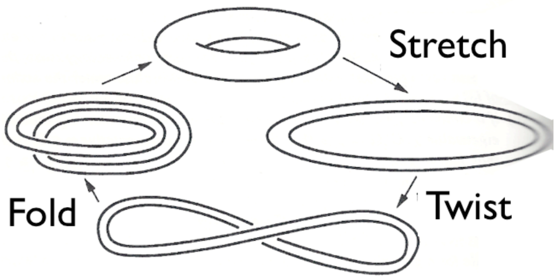
General Ideas and Assumptions Behind my Talk About Solar Storms

- Solar storms in the corona reduce the magnetic field complexity in the corona by transporting it away (CMEs) or untangle it (solar flares).Topology bounds the free energy to be released. The topological structure of the magnetic field also explains connected widely separated solar storms.

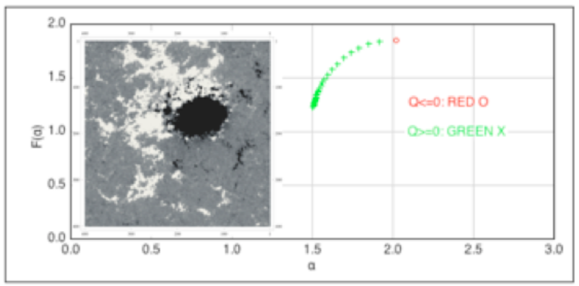
- The complexity is produced from interior (dynamo, coriolis forces), rotational motions at photosphere to the corona. We must therefore follow the evolution from interior to the corona. Solar Dynamics Observatory (SDO) can do that, and is therefore giving the most complete topological picture today.

- The observations of minor solar storms by SDO will represent today's most complete observations. The May 1921 and October 2003 events will represent severe solar storms and be discussed out from today's knowledge.

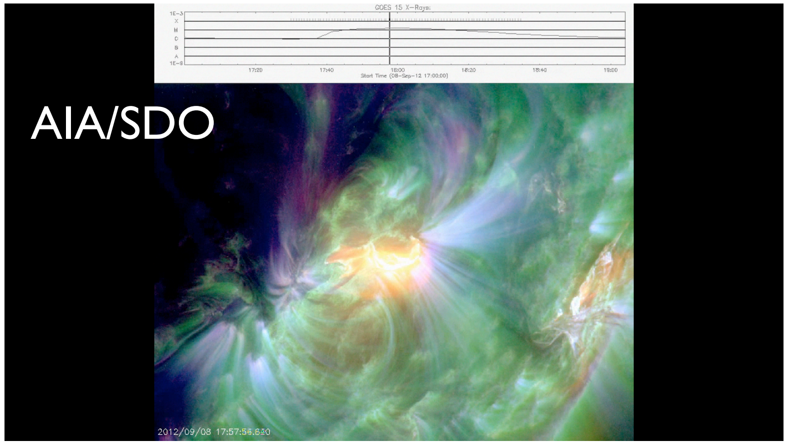


Stretch-Twist-Fold dynamo produces flux ropes and mean field.

HMI/SDO



Observed complex fractal flux ropes emerge through the photosphere.



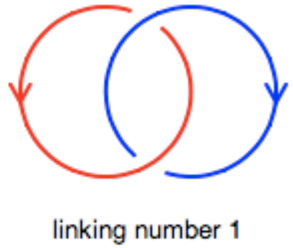
Connected solar flares observed with AIA/SDO.

Topological Measure of Solar Magnetic Field Complexity

Carl Friedrich Gauss
1777-1855

Gauss Linking number

$$\mathcal{L}_{i,j} = \frac{1}{4\pi} \oint_{C_i} \oint_{C_j} \frac{(\bar{x}_i - \bar{x}_j)\cdot(d\bar{x}_i \times d\bar{x}_j)}{|\bar{x}_i - \bar{x}_j|^3}$$



Hopf link

Total helicity (Hopf integral) - a measure of complexity

$$H = \int_V \bar{A}\cdot\bar{B}\, d^3x$$

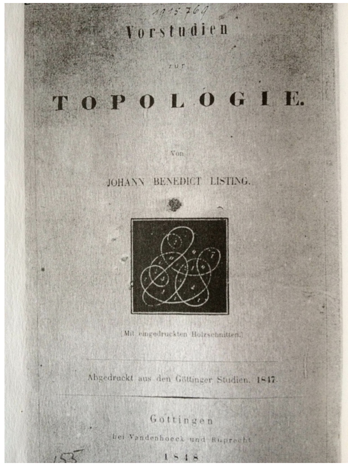
$$\bar{B} = \nabla\times\bar{A}$$
$$\nabla\cdot\bar{B} = 0$$

$$E(B) = \int_V \frac{B^2}{8\pi} d^3x \geq C|H(B)|$$

Gauge-invariant and topologically *well-defined* when integrated *over a volume V bounded by magnetic surfaces* ($\bar{B}\cdot\hat{n}|_S$) ***H* is also almost *conserved* on a time scale smaller than the global difussion time-scale.**

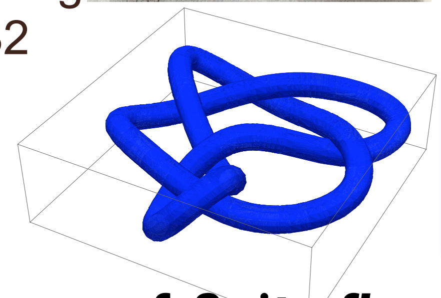
Using Biot-Savarts formula $\bar{A}(\bar{x}) = -\frac{1}{4\pi}\iint \frac{\bar{x}-\bar{x}'}{|\bar{x}-\bar{x}'|^3}\bar{B}(\bar{x}')d^3x'$

Johann
Benedict Listing
1808-1882


Vorstudien
TOPOLOGIE.
JOHANN BENEDICT LISTING.
Göttingen

$$H = -\frac{1}{4\pi}\iint \bar{B}(\bar{x})\cdot\frac{(\bar{x}-\bar{x}')}{|\bar{x}-\bar{x}'|^3}\times\bar{B}(\bar{x}')d^3x\,d^3x'$$

Helicity *H* measures the double sum of linking numbers <u>*over all pairs*</u> of <u>*magnetic field lines*</u>

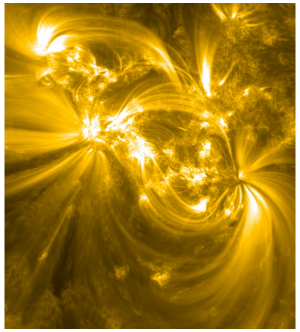


$$H_m = \sum_{i=1}^{N} T_i\,\Phi_i^2 + \sum_{i=1}^{N}\sum_{j=1,j\neq i}^{N} \mathcal{L}_{i,j}\,\Phi_i\Phi_j$$

Self helicity (T_i =Twist + Writhe) **Mutual helicity**

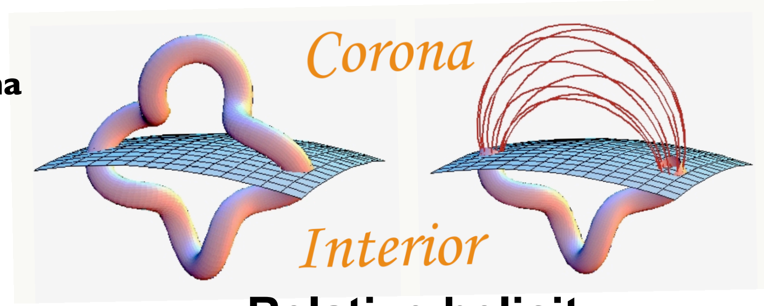
In the case of *finite flux tubes*, limited to *each flux tube i* and *flux tubes i, j*

Helicity Flow Through the Photosphere, and Accumulated to Produce a CME.



Coronal loops (AIA /SDO)

H_{corona}



Relative helicity

Sigmoid (AIA/SDO)

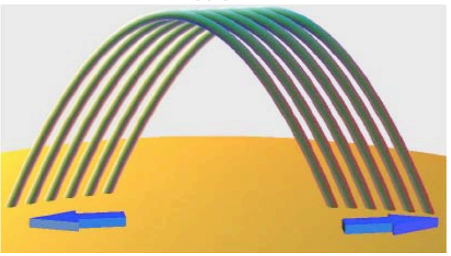
$$H_{corona} = H(\text{True field}) - H(\text{Reference field})$$

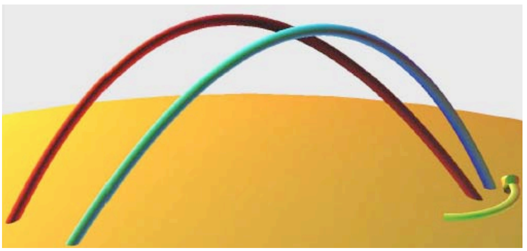
$$\frac{dH_{corona}}{dt} = \sum_{i=1}^{N}\sum_{j=1}^{N}\frac{d\theta_{ij}}{dt}\,\phi_i\phi_j$$

So how can we measure it for magnetic flux regions?

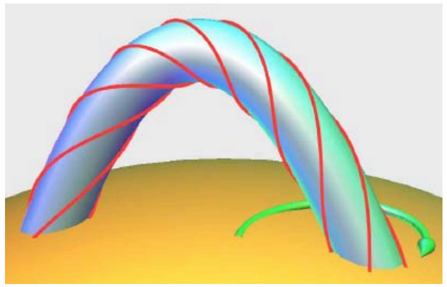
For a set of N small foot points,

where $\frac{d\theta_{ij}}{dt}$ is the angular velocity of *foot i about j,*



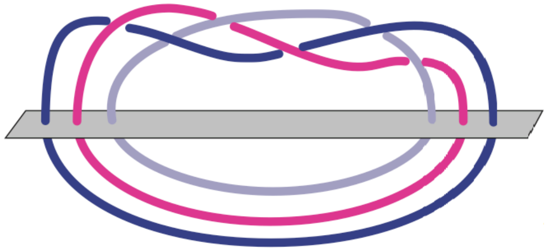


and $\frac{d\theta_{ii}}{dt}$ *is the rotational velocity of foot i*

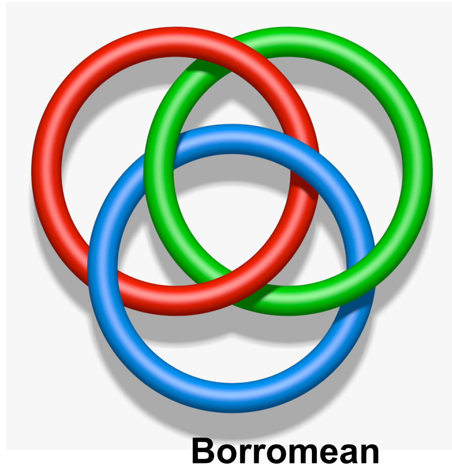


Higher Order Invariant Measure Needed to Model Coronal Loop Solar Flares

AIA/SDO (94,335,193 Å) Oct. 17, 2012



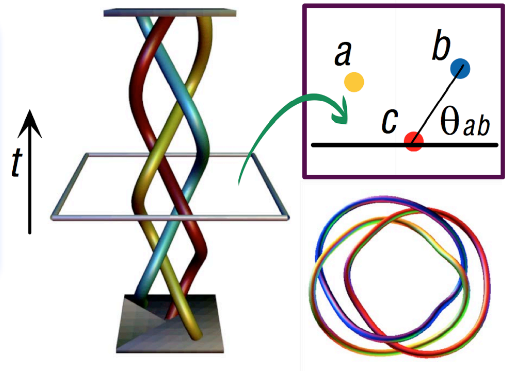
Topological equivalent configuration in form of braided flux tubes.



Borromean
No two linked (H_m=0), all are linked!

Based on Winding number and Riemann surfaces

$$\lambda_{ab}(\gamma(t)) = \frac{1}{2\pi i}\int_{\gamma(0)}^{\gamma(t)} \frac{db - da}{b-a}$$
$$\psi_{ab}(t) = Re\ \lambda_{ab}\ (\gamma(t))$$
$$W(t) = \psi_{ab}(t) + \psi_{bc}(t) + \psi_{ca}(t)$$



Coronal loops: Free energy related to the crossing number

$$E_m \geq 9.06 \times 10^{-2}\ (C_{min})^2\ \frac{\Phi^2}{N^2 L}$$

M. Berger and M.A.-Asgari-Targhi (Astrophys. J, 2009))

Global Connectivity of Solar Storm Activity

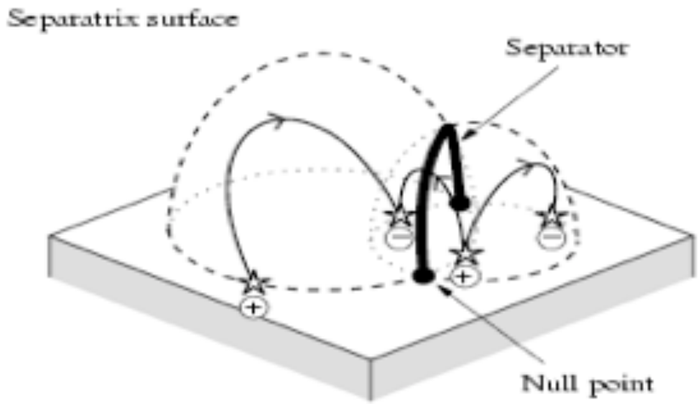
Henri Poincaré
1854- 1912

Heinz Hopf
1894- 1971

The **structure** of a vector field such as **the magnetic field** is **described by the critical points.** Poincaré and Hopf found that the **sum of the indices of a point** (given by the winding number) is **equal to the Euler characteristic** (M = 2,sphere).

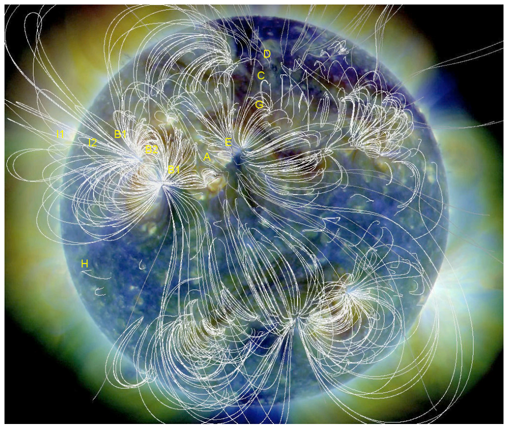
$$\sum_i index_v(x_i) = \chi(M)$$

Poincaré-Hopf Theorem

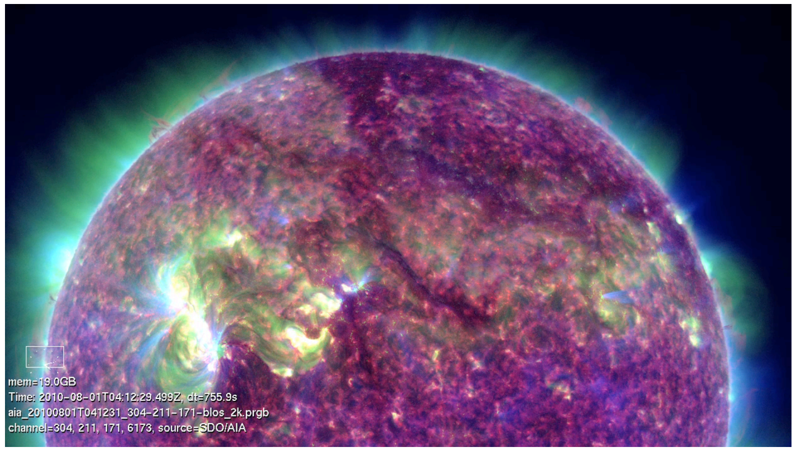


If the Sun is devided into magnetic flux domains, then the theorem gives that D = X-n-S
(Number of flux domains (D), separators (X), null point (n), sources (S)) and how activity could be connected and take place.

Connected (global) solar storm activity



Courtesy Schrijver and Title, JGR, 2011



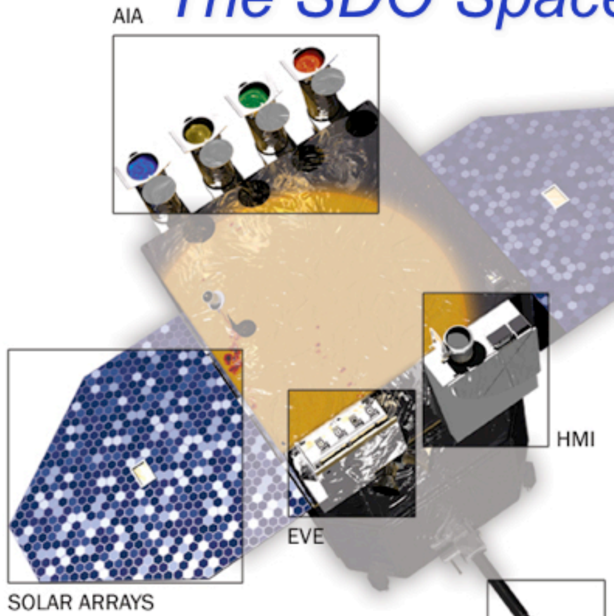
SDO/AIA, 2 August, 2010

SDO gives us a possibility to better understand solar storms topologically

To understand *how the* sun's interior *is* *coupled to solar surface* *and* *up to the outmost atmosphere where solar storms* take place. We must also understand how different areas are globally connected *thru the magnetic field.*

By observing the whole Sun all the time.

The SDO Spacecraft



The total mass of the spacecraft at launch was 3000 kg (payload 300 kg; propellant 1400 kg).

Its overall length along the sun-pointing axis is 4.7 m, and each side is 2.2 m.

The span of the extended solar panels is 6.25 m.

Total available power is 1500 W from 6.6 m^2 of solar arrays (efficiency of 16%).

The high-gain antennas rotate once each orbit to follow the Earth.

Launched on February 11, 2010 aboard an Atlas V EELV with Centaur second stage

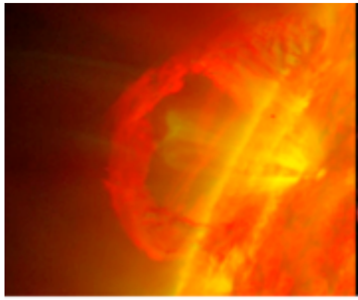
SDO is now in an inclined geosynchronous orbit ~36,000 km (21,000 mi) at the longitude of New Mexico for a 5-year mission

Launch of SDO
11 February 2010

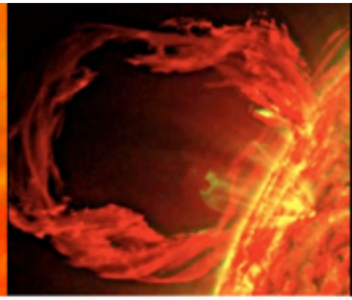
A.Title (AIA/Lockheed) | P. Scherrer (HMI/Stanford) | T. Woods (EVE/CU)

P.I.s of SDO

Moderate Solar Storm March 30, 2010

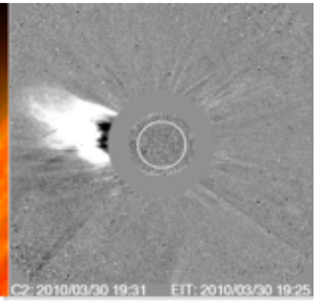


Erupting prominence,
30 March, 18.08 UT,
SODO, AIA.

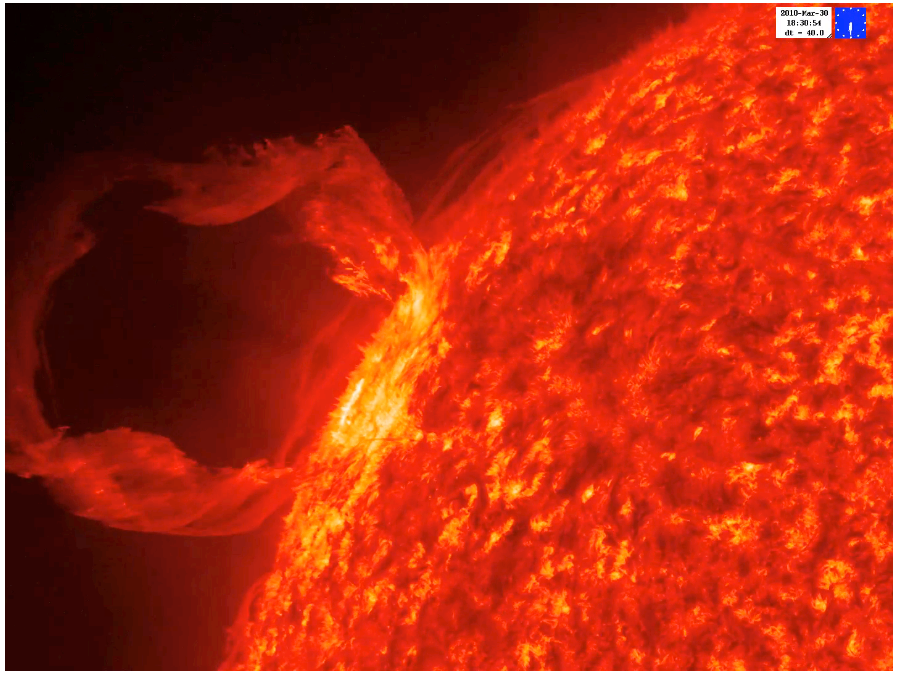


Erupting prominence,
30 March, 18.32 UT,
SODO, AIA.

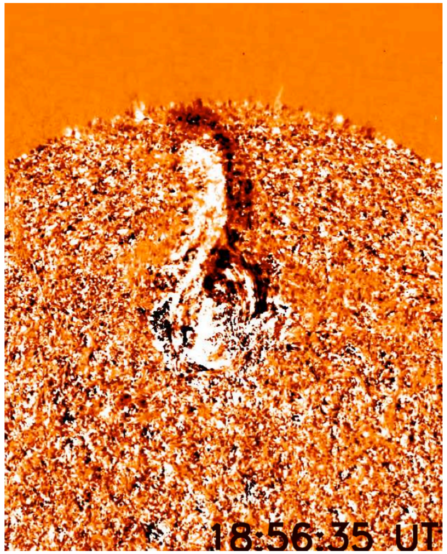
Erupting prominence,
30 March, 18.48 UT,
SODO, AIA.



CME, 30 March, 19.25 UT,
SOHO, C2.



Twist
AIA, SDO
Courtesy C. Schrijver.



Writhe
EUIV B, STEREO

Magnetic flux rope (torus)

Left-handed **twisted** around main prominence axis.

When the **twist of the magnetic field (*T_w*) > 2π** then the flux rope becomes **Kink unstable** and drives the eruption.

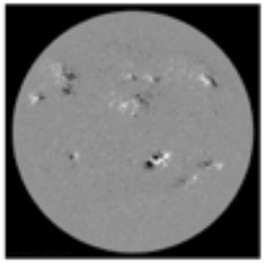
$$\mathcal{H}_m = \Phi^2(\mathcal{T}_w + \mathcal{W}_r)$$

Self helicity

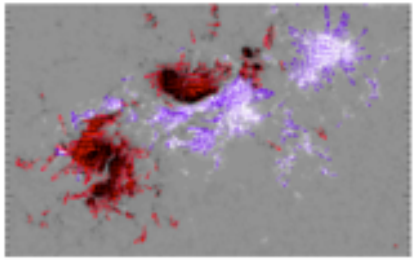
Since *H_m* is conserved the twist is converted into writhe (*W_r*).

At **eruption the twist was estimated to 6π** (3 turns).

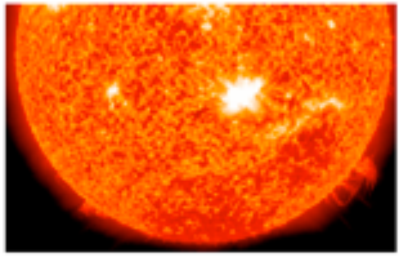
Moderate Solar Storm February 15, 2011



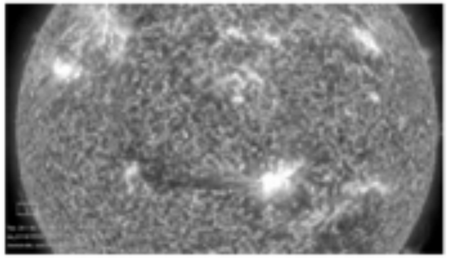
LOS magnetogram
HMI, SDO,
15 Feb 01UT



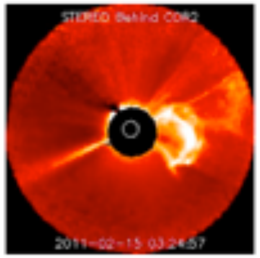
AR 1158, Twisted, winded
vector field, HMI, SDO



X2 solar flare, 15 Feb.
01.53 UT, SDO, AIA

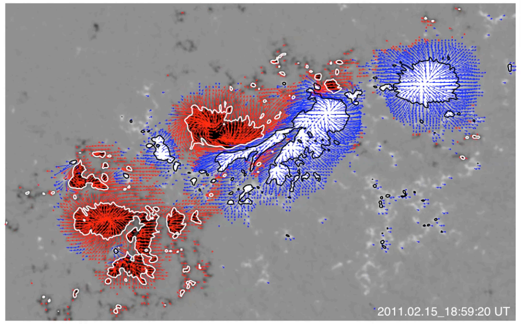


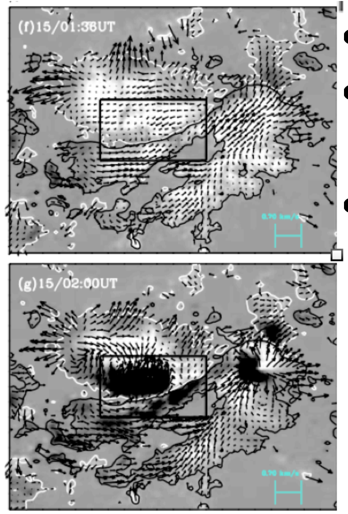
Connective storms

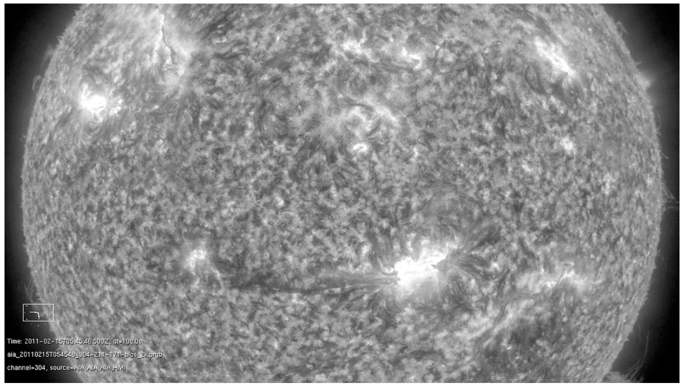


CME, 15 Feb.
03.25 UT,STEREO

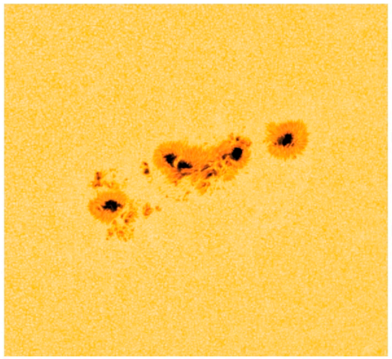
- Magnetic beta-gamma-delta complexity.
- Vector field shows stretching and rotation.
- Jing et al. (Astrophys. J. Lett., 2012) found a **reduction of the helicity at times of the X2 solar flare.**
- Vemareddy et al.,(Astrophys, 2012) **negative helicity injection into positive at flare site. A sigmoid structure.**

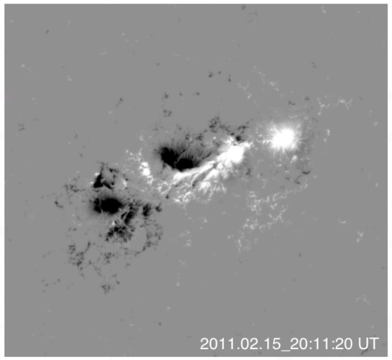






Courtesy AIA, SDO.

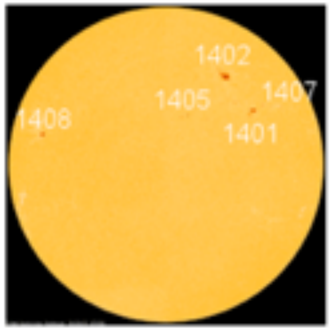




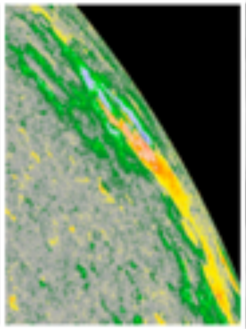
Courtesy T. Hoeksema, HMI, SDO.

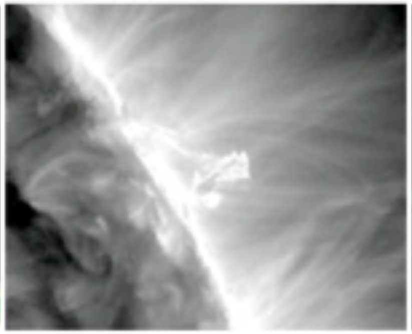
Schrijver and Title (JGR, 116, 2011) show that **regions up to 100° away are involved in defining the large-scale coronal field topology for flares and CMEs.**

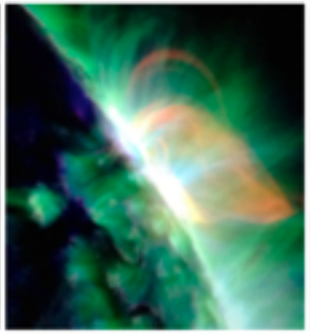
Moderate Solar Storms January 23-27, 2012



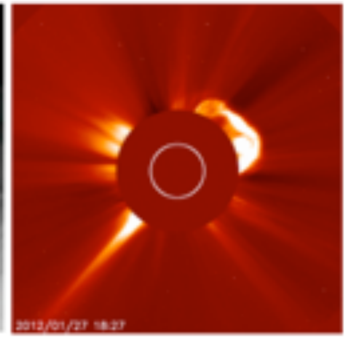
Jan. 23
SDO/HMI

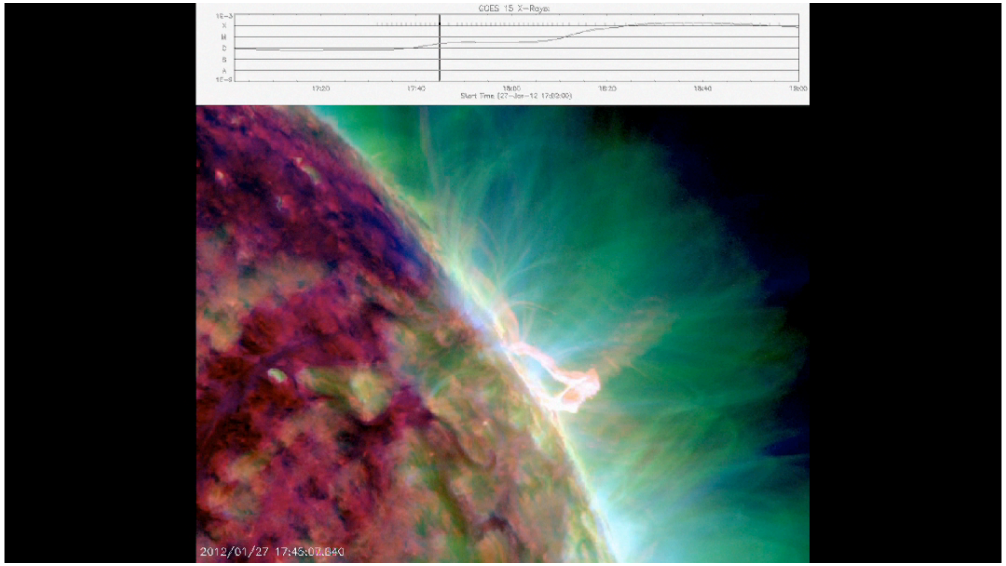

Jan. 27, 00.00 UT
SDO/HMI


Twist, Jan. 27, 17.47 UT
SDO/AIA 193 Å


Eruption Jan. 27, 18.07 UT, SDO/AIA 131, 171, 193 Å


X1.7 solar flare, Jan. 27, 18.25, SDO/AIA 193 Å


CME, Jan. 27,18.27 UT
SOHO/LASCO C2

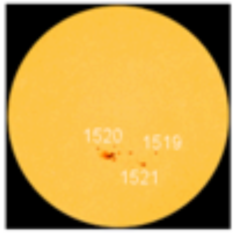


Courtesy. AIA, SDO.

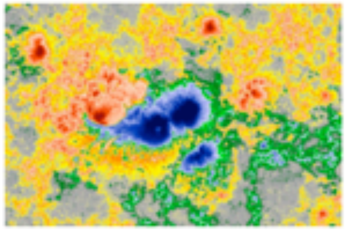
- AR 1402 reached a size of 500 millions.
- Magnetic beta-gamma complexity.
- Produced a halo CME on 23 and a Proton event of 6310 pfu.
- On 27 a halo CME, 796 pfu proton event and an X1.7 solar flare.

A **kink instability (N sigmoid)** is again associated with the eruption.

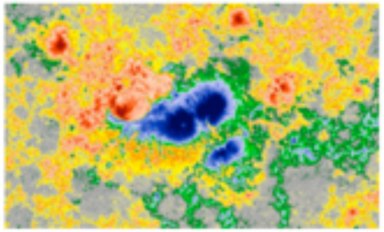
Moderate Solar Storm July 12, 2012



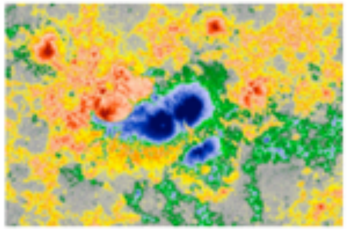
July 12,
SDO/HMI



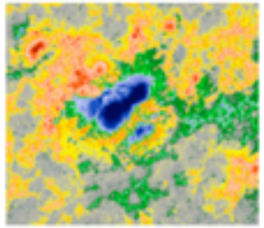
July 12, 13.07 UT
SDO/HMI



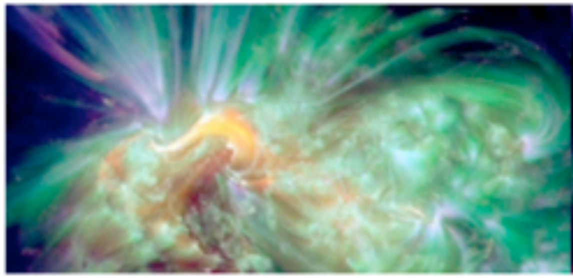
July 12, 16.00 UT
SDO/HMI



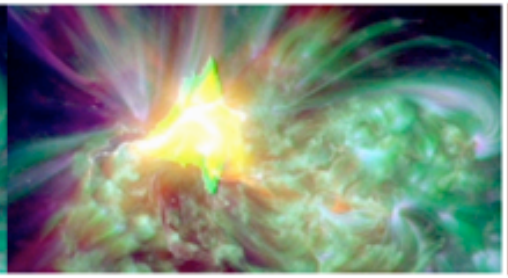
July 12, 17.00 UT
SDO/HMI



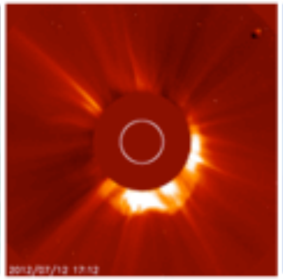
July 14 09.00 UT
SDO/HMI



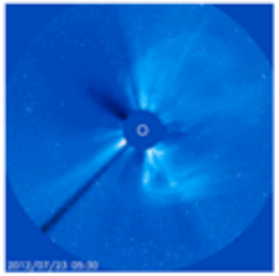
Sigmoid, July 12,16.14 UT
SDO/HMI



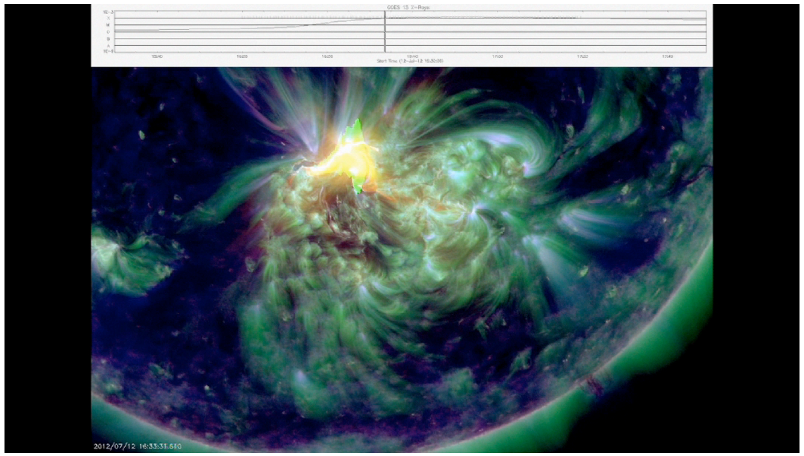
X1.4 solar flare, July 12, 16.43 UT
SDO/HMI



CME, July 12, 17.12 UT
SOHO/LASCO C2



CME, July 23, 05.30 UT
SOHO/LASCO C3



Courtesy. AIA, SDO.

- AR 1520 had a size of 1460 millions.
- Magnetic beta-gamma-delta complex.
- A **coronal S-shaped sigmoid** structure (**kink instability**) **just before onset of X solar flare.**
- Produced a halo CME.
- Minor proton event ≈100pfu.

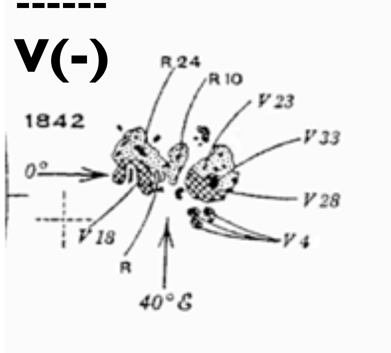
Severe Solar Storms May 12-16, 1921

(close to solar cycle minimum)

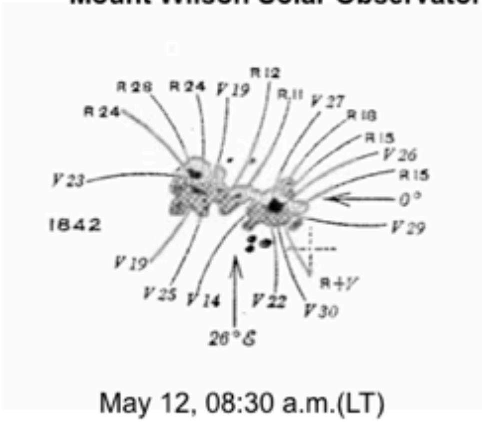
R (+)

V(-)

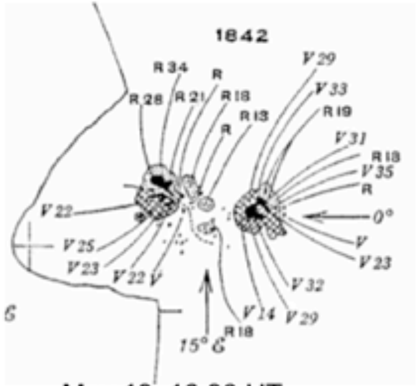
Mount Wilson Solar Observatory



May 11, 09:10 a.m.(LT)
17:10 UT, Seeing 2-4, E.P.

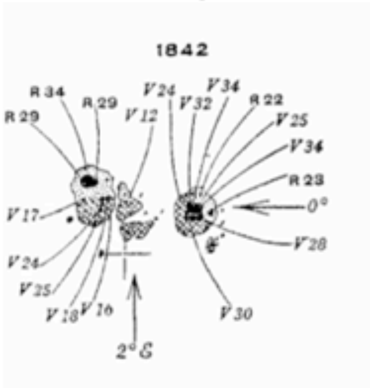


May 12, 08:30 a.m.(LT)
16:30 UT, Seeing 4, E.P.

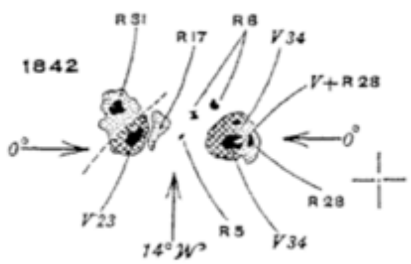


May 13, 16:30 UT,
Seeing 2-6, E.P.

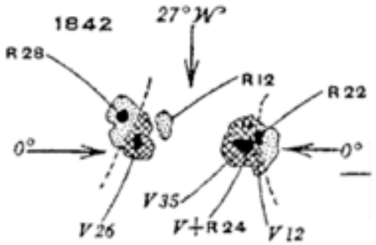
12-inch (30,48cm) aperture refractor,
150-foot (45,72m) focal length.
Observation method:
direct objective projection,
17-inch (43.18cm) image.



May 14, 14.00 UT,
Seeing 4, E.P.



May 15, 18:30 UT,
Seeing 3, S.B.N.



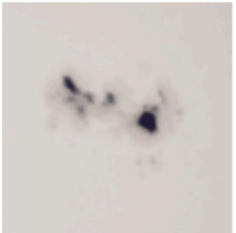
R/V and V/R(Hale)

May 16, 17:00 UT,
Seeing 3, S.B.N.

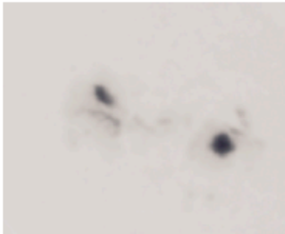
What would SDO have observed for similar event?

- AR 1842 reached an average size of 1324 millions.
- Showed a beta-gamma (delta?) complexity.
- **Rotation, emerging, dissapearing flux. Right group follows Hale rule, left not.** Only right survives next rotation (June 10 center).
- **Very strong magnetic flux density between +3.4 kG and - 3.5 kG (MW).**
- Three to four (halo) CMEs since four sudden commencements were observed. First reported at 13 GMT on 13 May (RGO).

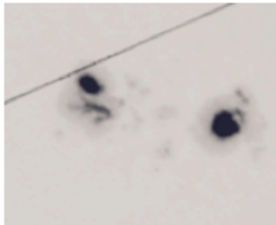
Severe Solar Storms and Effects May 11-16, 1921



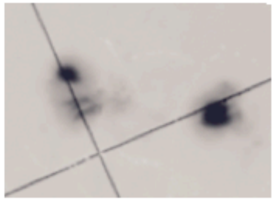
May 11, 08.15 UT
(RGO)



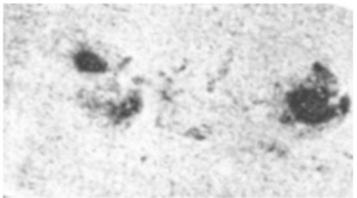
May 12, 08.41UT
(RGO, CAPE)



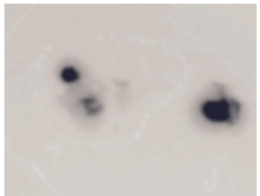
May 13, 08.55 UT
(RGO)



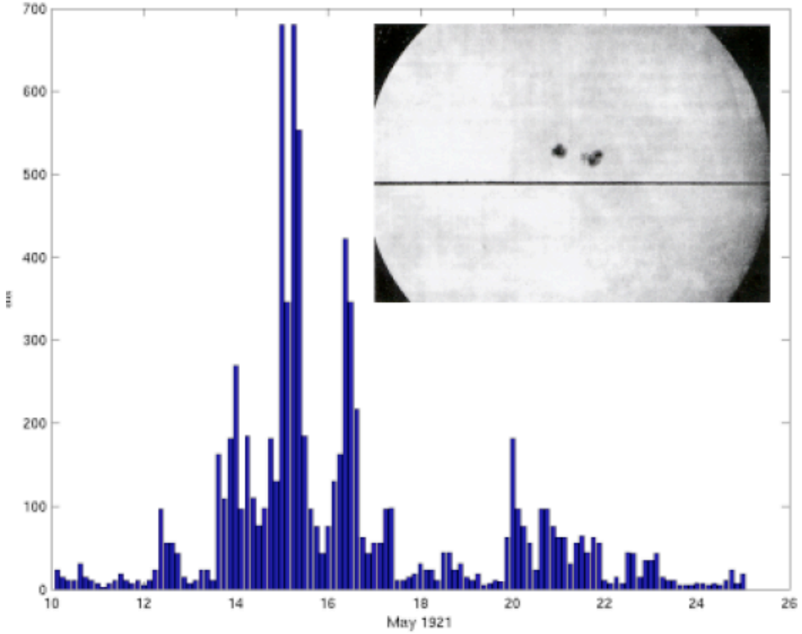
May 14, 10.26 UT
(RGO)

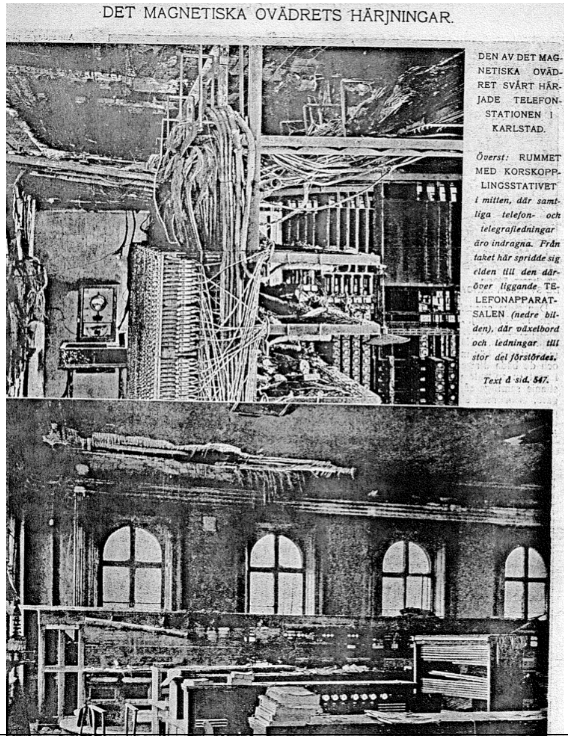


May 15, 14:25 UT,
(Kvistaberg, Sweden)



May 16, 07.59 UT
(RGO)





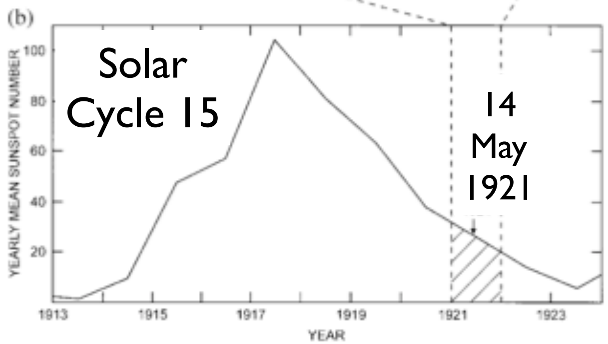
DET MAGNETISKA OVÄDRETS HÄRJNINGAR.

DEN AV DET MAGNETISKA OVÄDRET SVÅRT HÄRJADE TELEFONSTATIONEN I KARLSTAD.

Överst: RUMMET MED KORSKOPPLINGSSTATIVET *i mitten, där samtliga telefon- och telegrafledningar äro indragna. Från taket här spridde sig elden till den därunder liggande* TELEFONAPPARATSALEN *(nedre bilden), där växelbord och ledningar till stor del förstördes.*

Text å sid. 547.

aa_{max} = 680nT
May 15, 03-06



E=20V/km => a dB/dt of ~5000nT/min

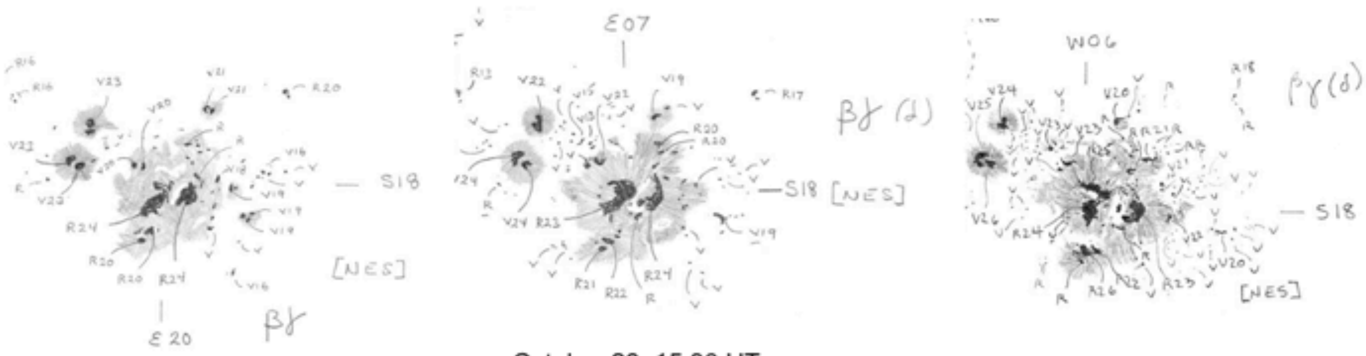
(Kappenman, Adv.Space Res. 2006:
Elovaara et al.,CIGRE 1992)

Telegraph fire
on the morning of May 15.

Severe Solar Storms 27-29 October, 2003

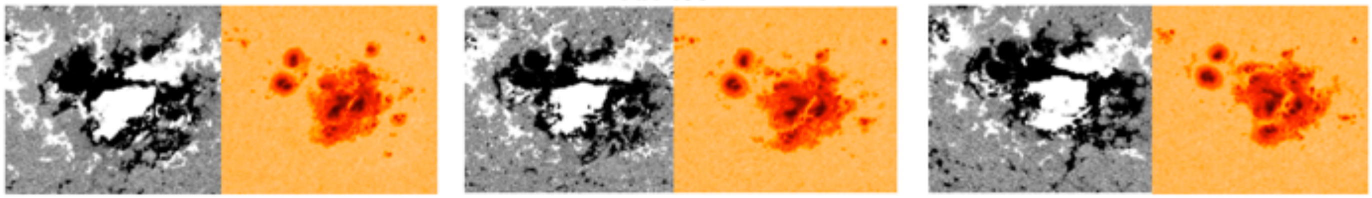
(three years after solar cycle maximum)

Mount Wilson Solar Data

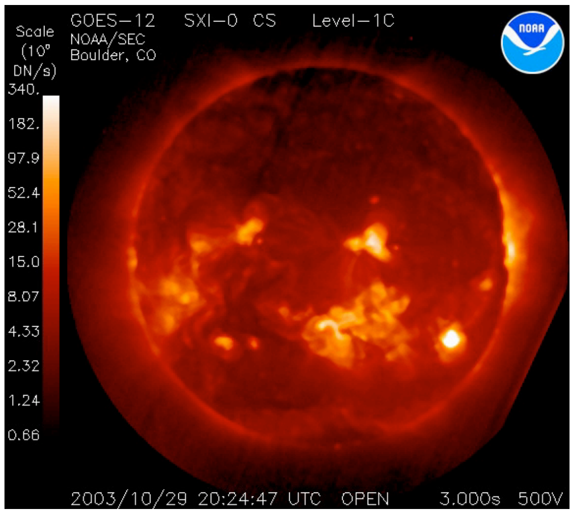


October 27, 15:30 UT. October 28, 15:30 UT. October 29, 15:30 UT.

SOHO MDI Solar Data
AR 486

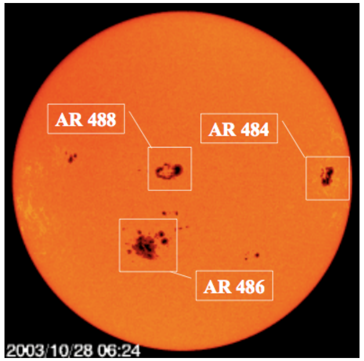


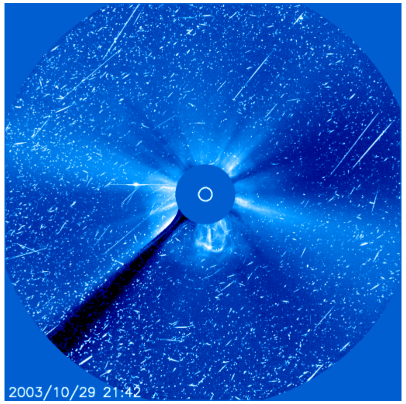
October 27, 15:59 and 17:36 UT. October 28, 15:59 and 17:36 UT. October 29, 15:59 and 17:36 UT.

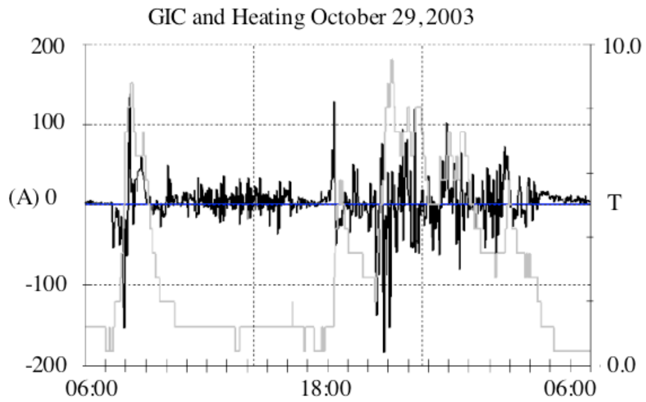


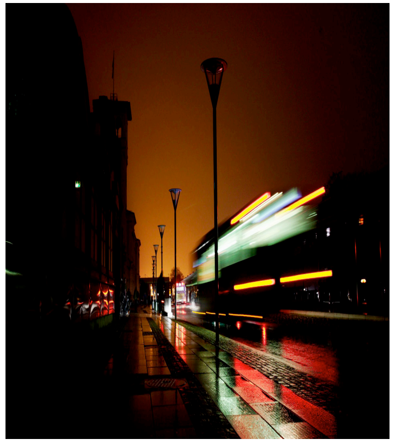
- AR 486 reached a sized of 2600 millions.
- Magnetic beta-gamma-delta complex.
- Magnetic flux density between +2.6 and -2.6 kG (MW).
- Rotation (123°/46hrs), raised total AR helicity.
- **Braided helicity related to solar flare**.
- **Sigmoid, connected solar flares.**
- On 28 October an X17, on 29 October X10 flare.
- The halo CME of 28 (2125km/s) produced a proton event of 29 500 pfu.
- The halo CME of 29 had a velocity of 1948 km/s.

Severe Solar Storms and Effects October 27-29, 2003





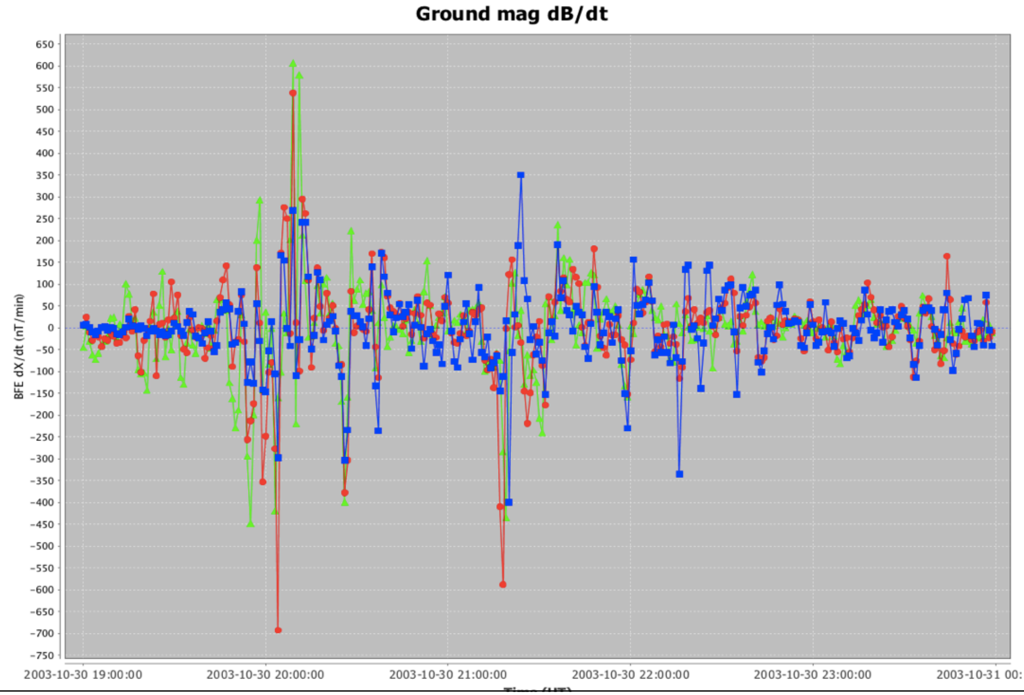




dB/dt ≈ 700nT/min (Uppsala) - 20 UT, Oct. 30

aa_{max} = 570nT, October 30, 21-24 UT

Power blackout in Malmö October 30



THE END

Thank You!