Solar terrestrial relations, space weather, solar variability and climate

Chris Davis
September 2011

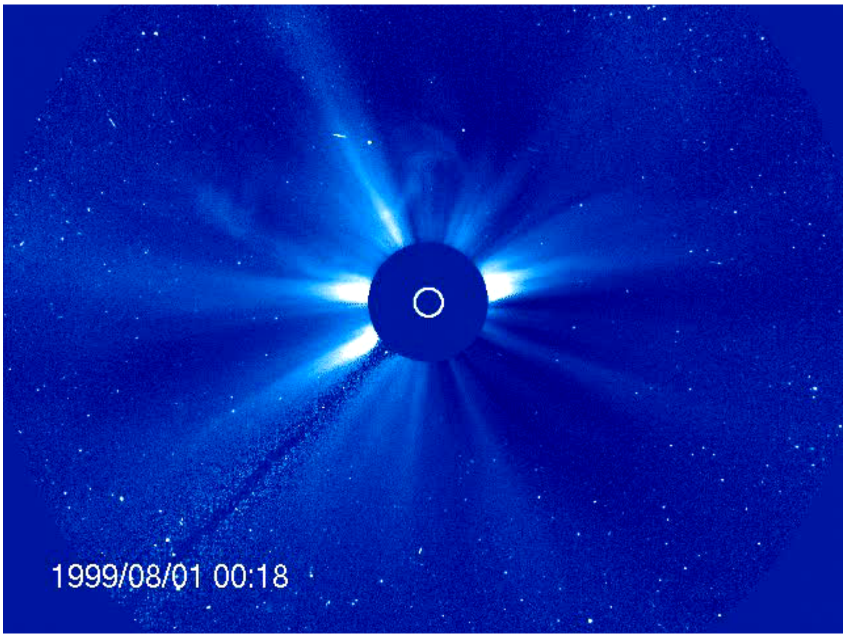
With thanks to Richard Harrison, Jackie Davies, Curt de Koning, Dusan Osdrcil, Mathew Owens and Mike Lockwood

RAL Space

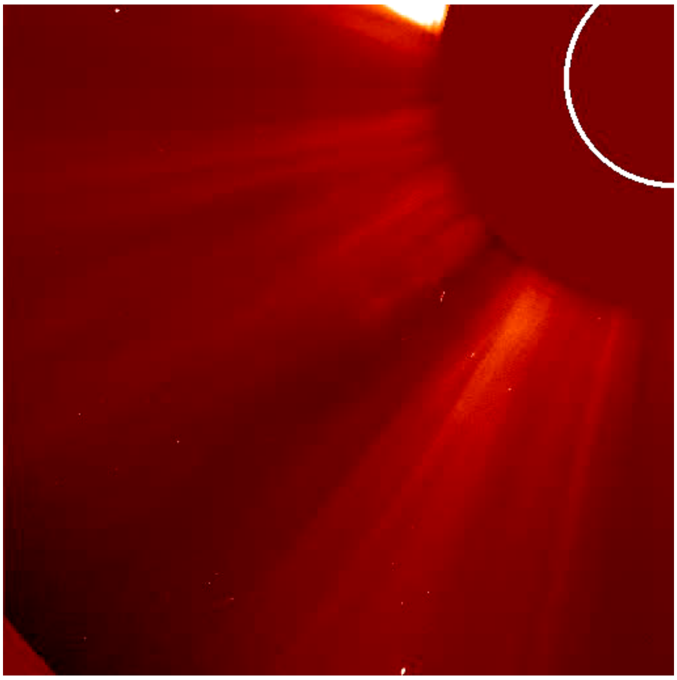
University of Reading

RAL Space

Solar wind and Coronal Mass Ejections (CMEs)



A Coronal Mass Ejection (CME)



An eruption/ejection of material into interplanetary space.

~ 10^{12} kg ejected at typical speeds of 350 km/s.

Up to a few per day.

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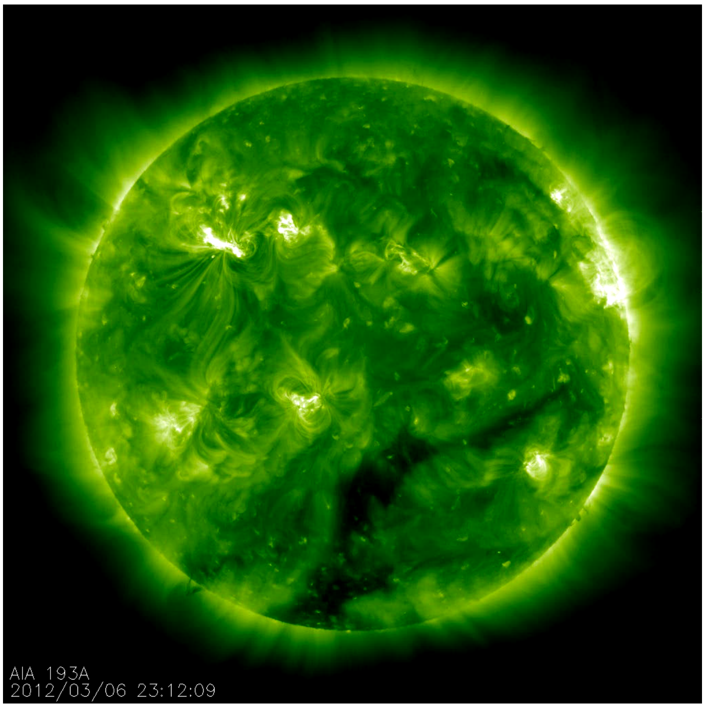
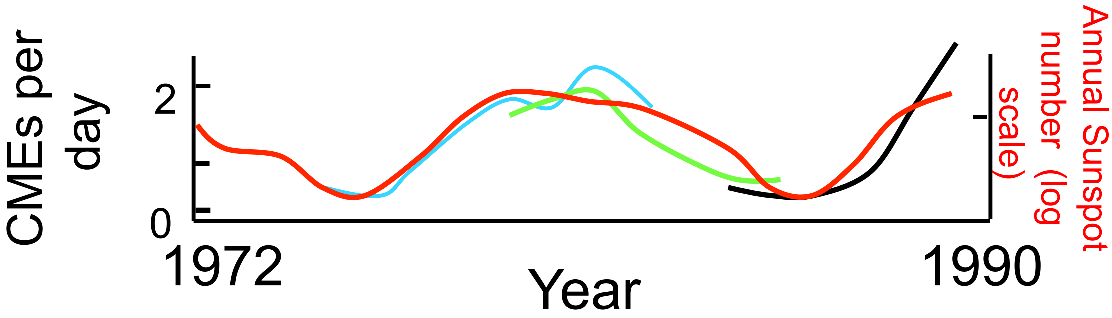
A solar flare



An explosive release of energy in an active region.

~ 10^{25} J released in tens of minutes (100 million 1 megaton bombs! Or 100 million million tonnes of TNT)

CME occurrence changes with the solar cycle



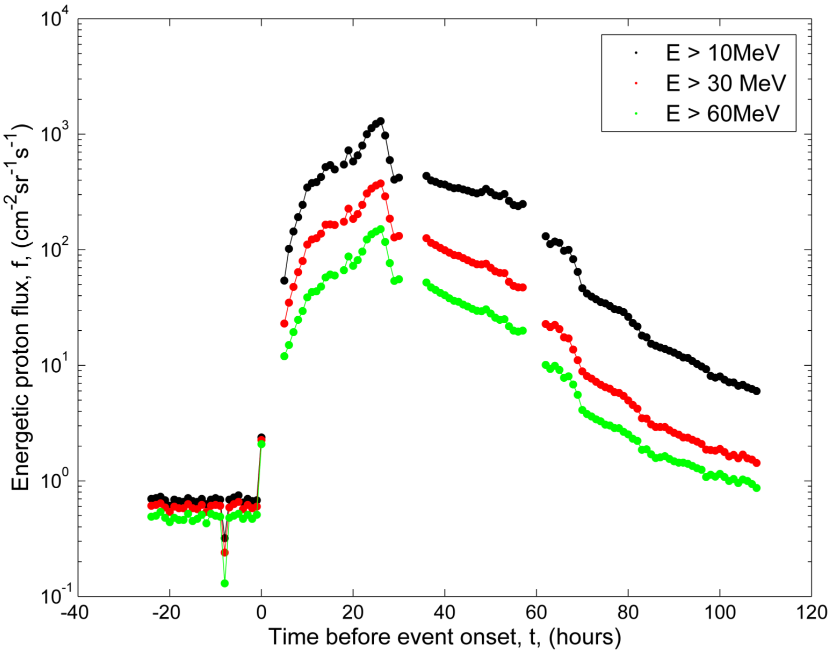
When the Sun is active, around two CMEs occur every day

As a CME expands into interplanetary space, the enhanced magnetic field sweeps up and concentrates plasma ahead of it. This is accelerated in a process known as Fermi acceleration, generating solar energetic particles (SEPs).

Though flares generate much faster SEPs than CMEs, those associated with CMEs represent a much greater radiation risk because they contain much heavier elements and occur for much longer (so-called 'gradual' events).

Monitoring these vast eruptions in the solar wind and studying their effects on Earth's technology has become known as 'Space Weather'

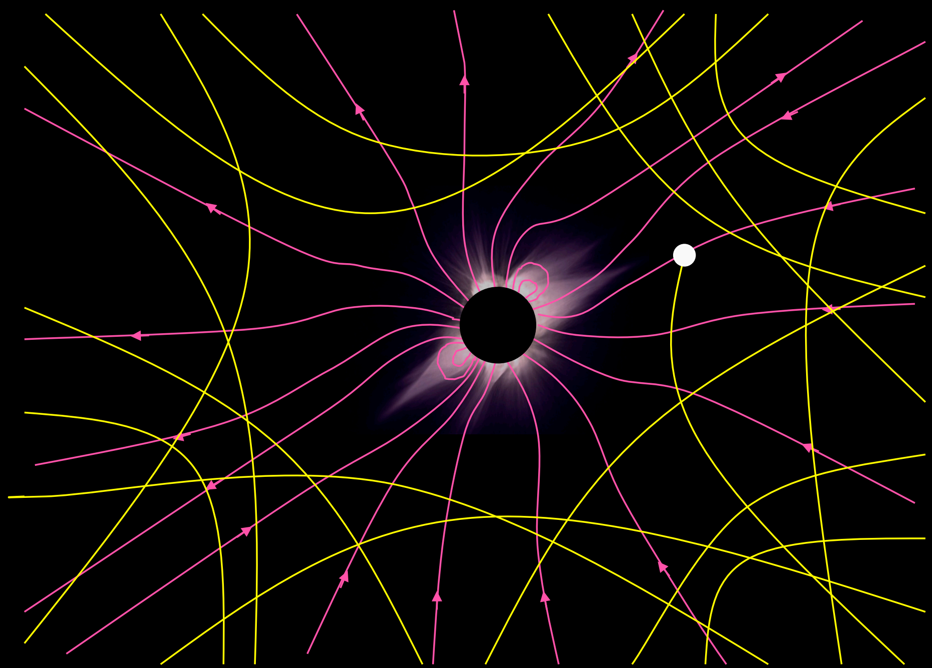
Satellite observations of a typical event...



07/09/2012

Thanks to Luke Barnard.

Galactic Cosmic Rays – energetic particles from outside our solar system

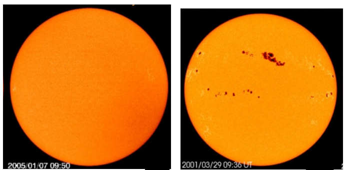


The coronal magnetic field is dragged out by the solar wind flow to give the interplanetary magnetic field which shields Earth from galactic cosmic rays

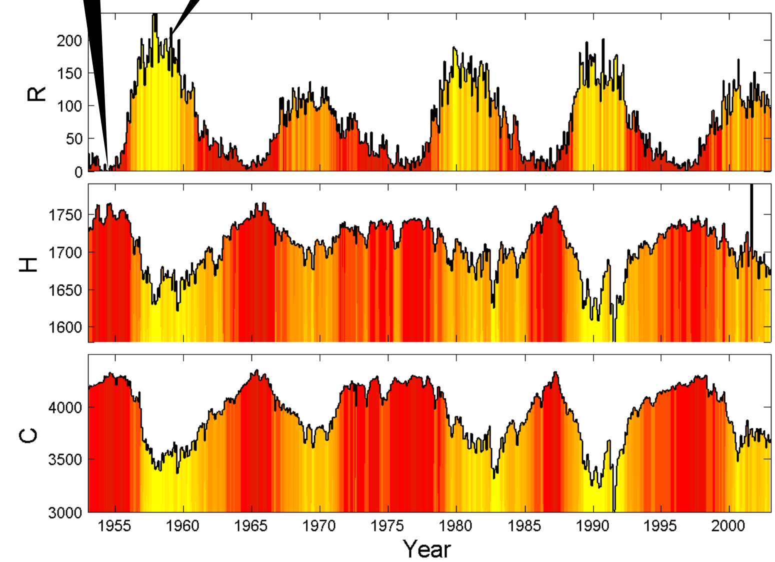
When the Sun is active, with many CMEs occurring, the IMF at Earth is relatively strong, protecting our planet from cosmic rays

When the Sun is inactive, as it has been recently, the IMF is weaker, more cosmic rays reach the Earth and its space environment.

There isn't a 'good' time to be in space!



Cosmic Rays
Anticorrelation with sunspot numbers



Sunspot Number

Huancauyo – Hawaii neutron monitor counts (>13GV)

Climax neutron monitor counts (>3GV)

SEP Radiation Effects

On Equipment

On Humans

RAL Space

SEP Radiation Effects

On Equipment

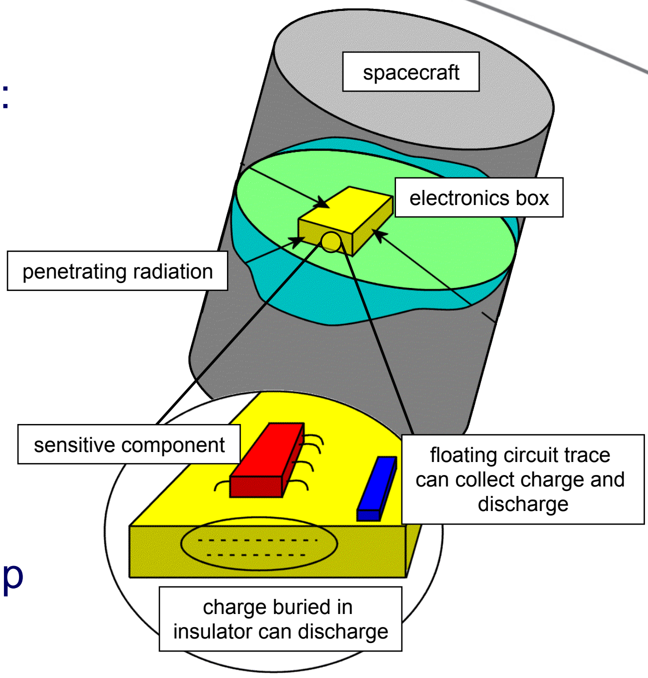
On Humans

RAL Space

Spacecraft Damage

radiation environment damage:

- Surface charging
  - 0.1 – 100 keV electrons
- Single event upsets
  - MeV ions
- Cumulative radiation dose
  - Limits spacecraft lifetime
- Internal charging ("deep dielectric charging")
  - MeV electrons



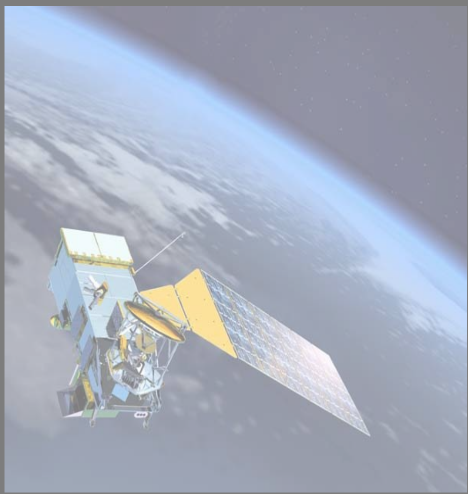
SEP Radiation Effects

On Equipment

On Humans

SEP Radiation Effects

On Equipment



On Humans

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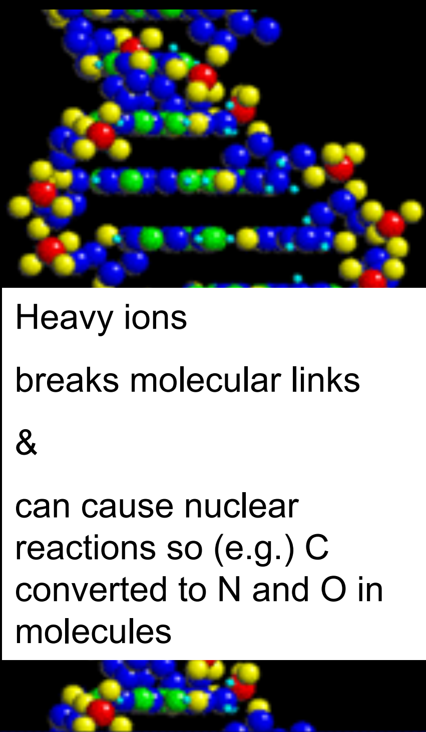
Biological Effects

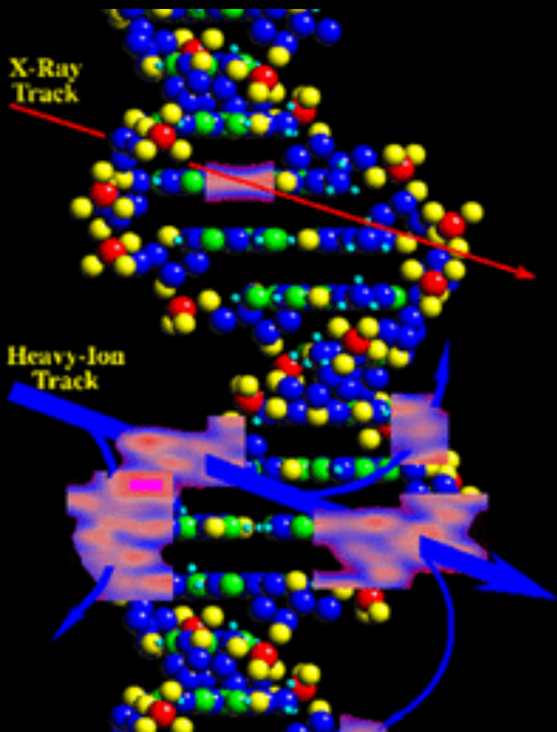


Heavy ions

breaks molecular links

&

can cause nuclear reactions so (e.g.) C converted to N and O in molecules



RAL Space

Exposure in space

RAL Space

Radiation doses from GCRs (at 1977 solar minimum) and/or SPE

Given in REM behind a shield of 10 $g.cm^{-2}$

GCR dose	Open Space	59	REM yr^{-1}
	Moon	29	REM yr^{-1}
	Mars	12	REM yr^{-1}
Total GCR dose	Trip to & stay on Moon (190 Days)	18	REM
	Trip to Mars (947 days)	92	REM
Total dose in a solar particle event*	Open Space	130	REM
	On Lunar Surface	60	REM
	On Martian Surface	25	REM
Lifetime dose limit for a male aged 55	anywhere	30	REM
Lifetime dose limit for a female aged 55	anywhere	15	REM

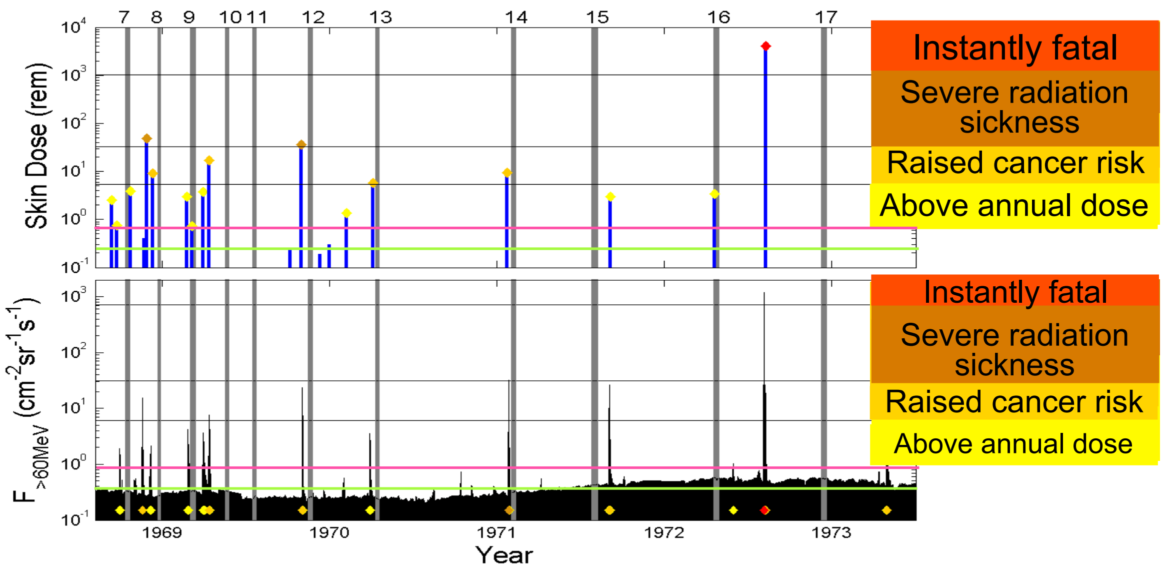
UNITS: Röntgen Equivalent Man, 1 REM = 10 mSv ≡ 0.01 J kg^{-1}

* For a severe event

The Apollo Missions


SEPs: just how lucky were the lunar astronauts?

- SEPs during the era of the Apollo Missions

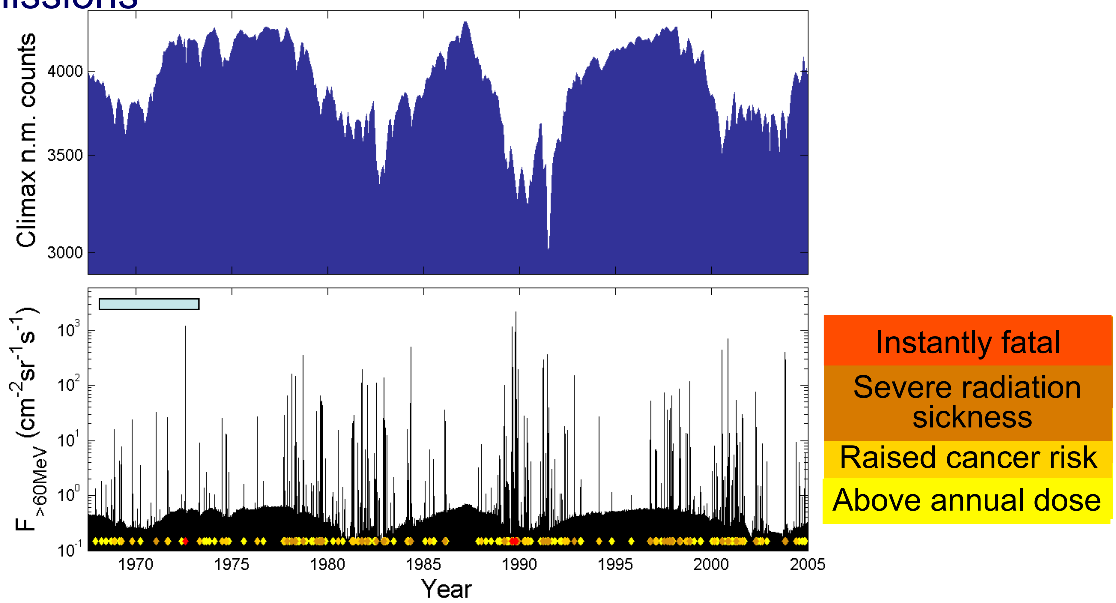


Max. annual dose for a radiation worker

Average annual dose at Earth's surface


SEPs: what's the space weather been like?

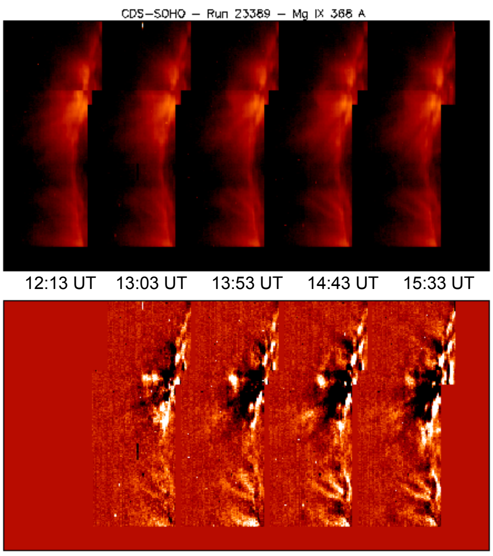
- SEPs and Galactic cosmic rays since the Apollo Missions



Forecasting Space Weather events at Earth

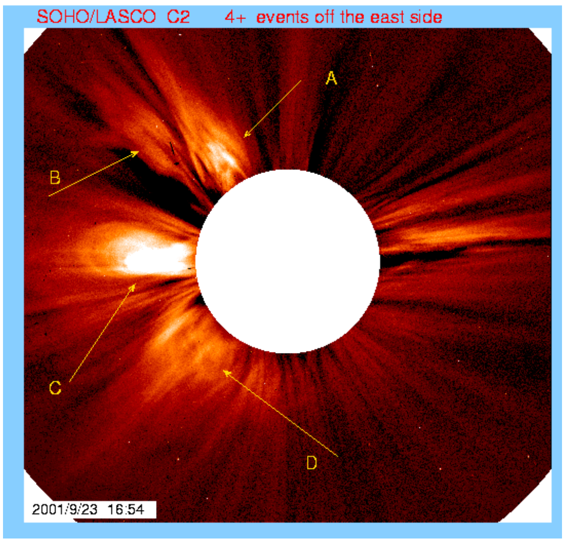
Earth's aurora as seen from the International Space Station

'Coronal dimming' can be used to predict the source of potential CME sites

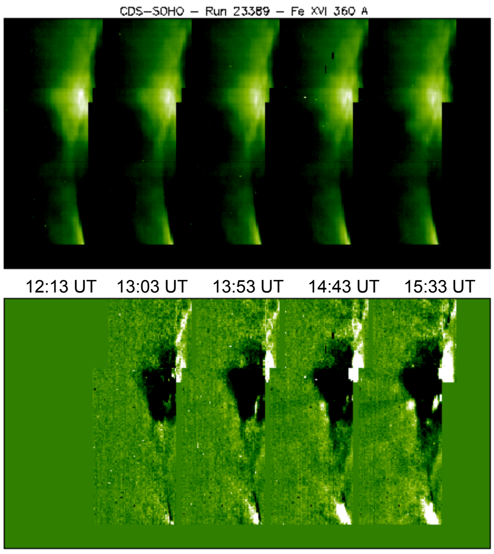


1 million K Mg IX 368 Å line

The Events of September 23, 2001

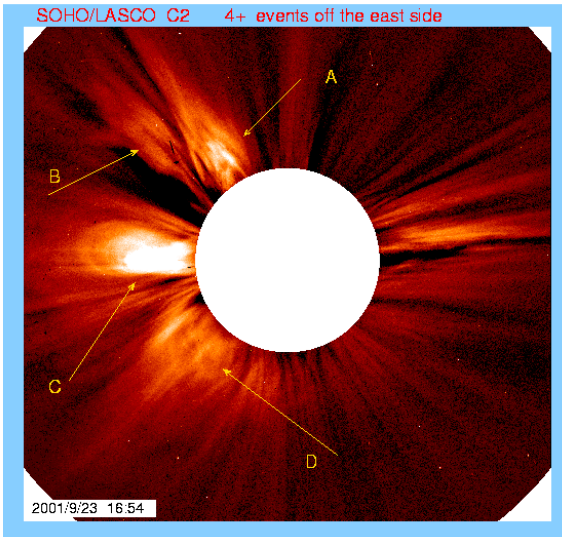


Dimming is an indication that material being lost from the corona

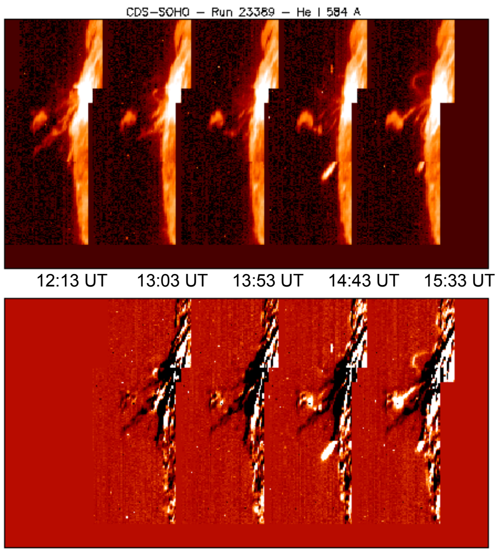


2 million K Fe XVI 360 Å line

The Events of September 23, 2001

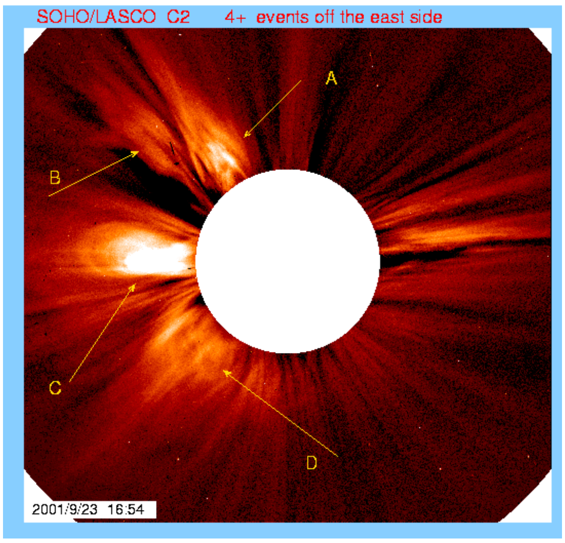


Spectroscopic observations such as these from SOHO's CDS reveal thermal profile



20,000 K He I 584 Å line

The Events of September 23, 2001



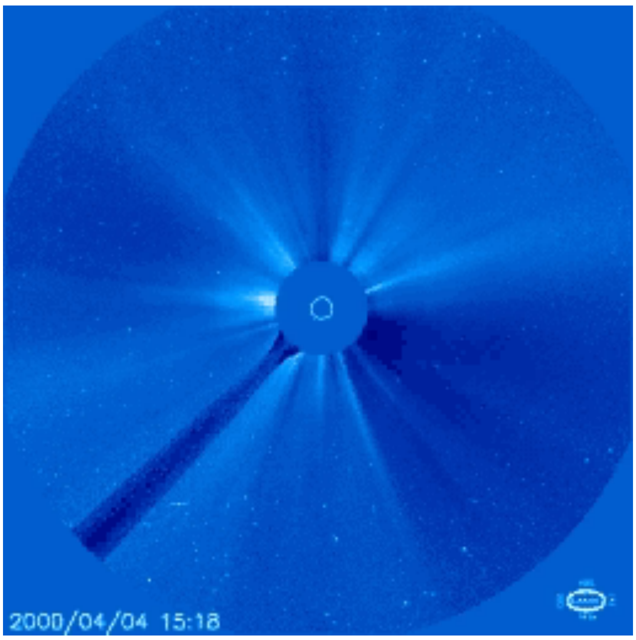
Onset of dimming and CME ‘coincident’.
Location of dimming under ascending CME.
Dimming mass and CME mass consistent

Date	Dimming mass (DEM/Si X) [kg]	CME Mass [kg]
Jul 16 1997	$4.3x10^{10}/1.3x10^{11}$	$5x10^{10}$
May 8 1999	$1.1x10^{12}/4.2x10^{12}$	$3x10^{11}$
Jul 25 1999	$7.4x10^{11}/3.4x10^{12}$	$3.5x10^{12}$
Feb 19 2000	$1.1x10^{14}/2.7x10^{14}$	$1.1x10^{12}$
Aug 19 2000	$6.4x10^{11}/1.8x10^{12}$	$4.7x10^{11}$

(from Harrison, Bryans, Simnett and Lyons, 2003, A&A 400)

Dimming under CMEs (EUV & X-rays) has been reported using SOHO (CDS & EIT) and Yohkoh (SXT) since 1997 (Sterling & Hudson, 1997; Harrison, 1997; Golapswamy & Hanaoka, 1998; Zarro et al., 1999).

Tracking CMEs



CMEs are observed by Thomson scatter of sunlight by electrons in plasma. This process is far more efficient for CMEs travelling perpendicular to the observer since the plasma cloud is at its densest along the line-of-sight at this point (as it is closest to the Sun).

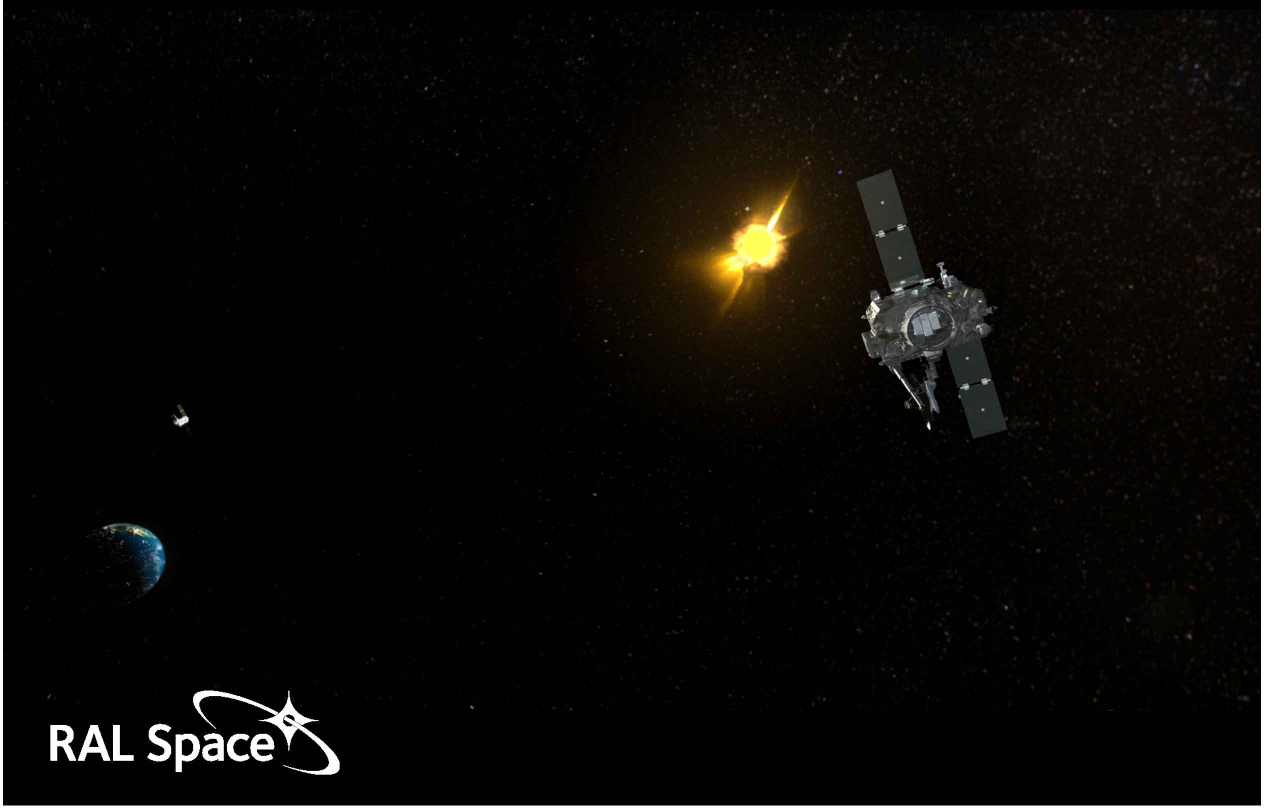
Earth-directed CMEs observed from spacecraft near the Sun-Earth line appear as diffuse ‘halos’

It is difficult to estimate the speed of Earth-directed CMEs observed by SOHO since it is the expansion rate of the CME that is being measured, not the velocity.

While there is a statistical relationship between the CME expansion rate and its speed, this is not sufficiently accurate for forecasting purposes.

Better to observe CMEs from outside the Sun-Earth line. This was the justification for the Solar TErestrial RElations Observatory (STEREO).

Introducing the STEREO mission



Space Weather forecasting

Accurate prediction of a CME at Earth requires estimates of;

- CME direction
- CME initial speed
- Acceleration/deceleration of CME by ambient solar wind
- Deflection of the CME by ambient solar wind (?)

and/or

- Observations of the CME once it has reached its final 'cruise speed'

Method 1: The Forward Modelling Method

Forward Modeling of CMEs Using STEREO-SECCHI Data 121

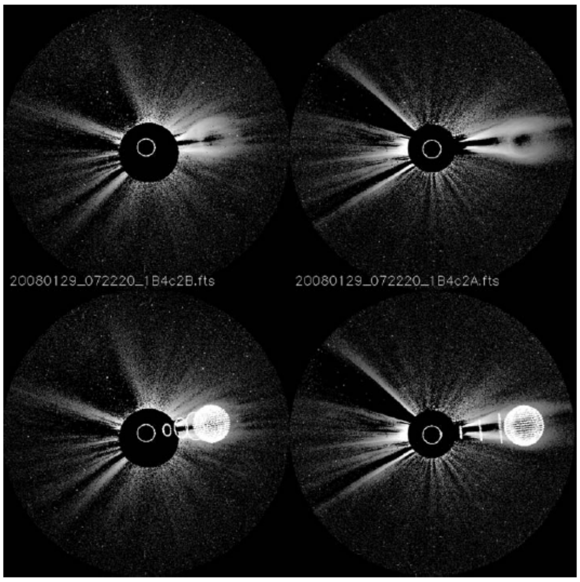


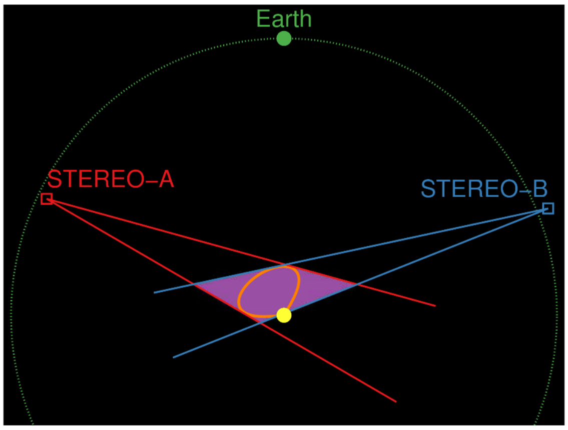
Figure 5 Example of model fit for the event of 29 January 2008 observed at 7:20 UT in COR2 B and A (top row). The second row shows the same images with the wireframe fit overlaid. It is not possible to determine accurately the flux-rope length in this case.

The forward modelling method (FMM) uses STEREO coronagraph data.

An interface allows you to estimate the size and position of a 3D structure seen from one spacecraft and iterate until it matches that seen in the other – then the initial speed and direction (and acceleration) of the CME can be estimated.

Methods 2 and 3: Geometric and polarimetric localization

Both use STEREO coronagraph data to return estimates of CME initial speed and direction



Geometric localization:

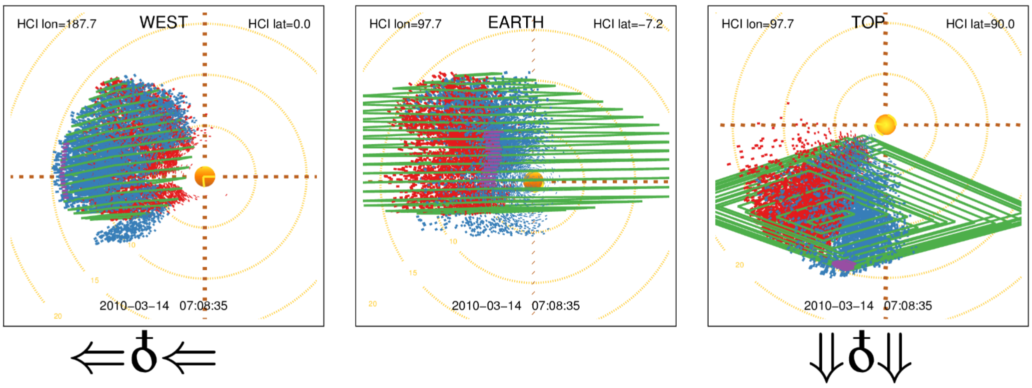
- uses a series of lines of sight from two spaced-based coronagraphs
- works on the CME boundary

Polarimetric localization:

- measured polarization fraction within CME can be related to source location relative to plane of sky

Curt A de Koning

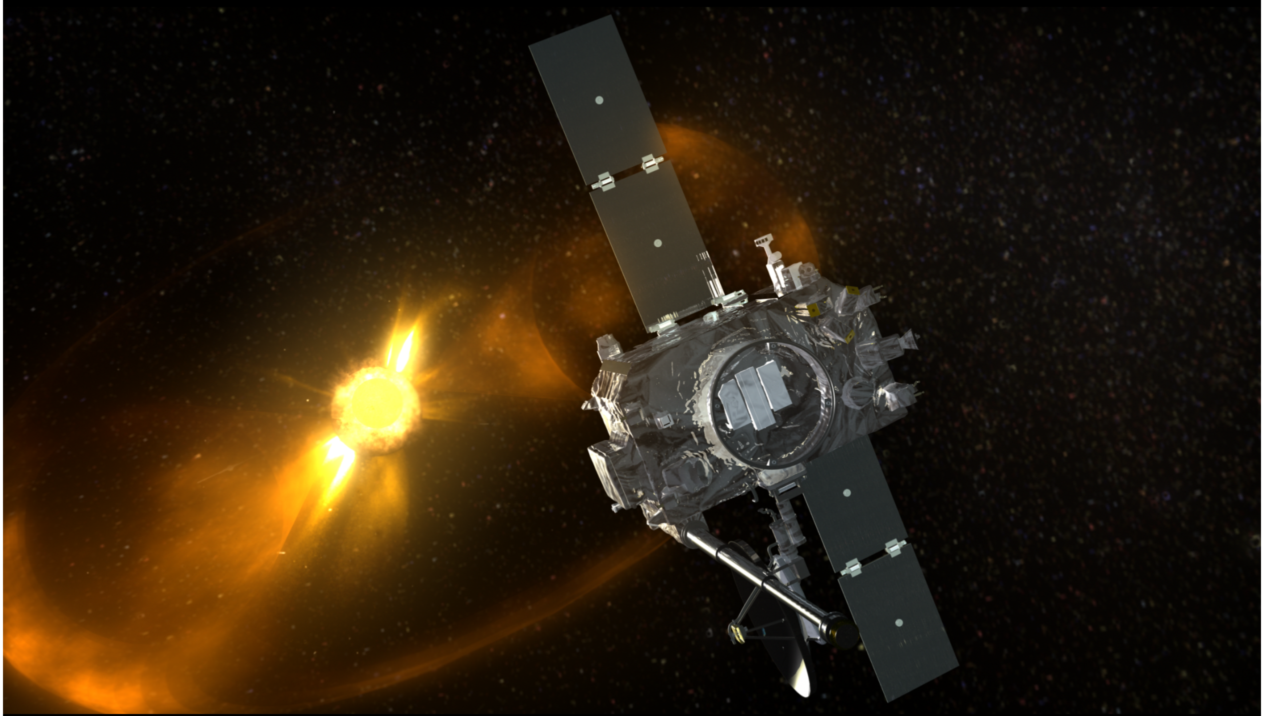
CME location within 3D space on 2010 March 14 at 07:08 UT



- CME speed = 252 km/s
- CME longitude = -52° W
- CME latitude = 21° N

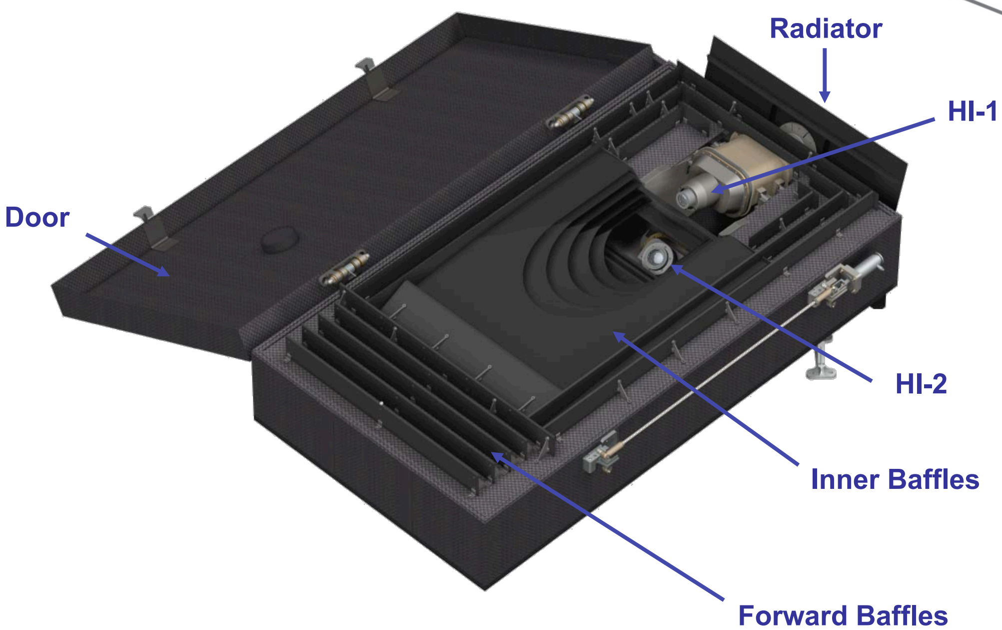
Curt A de Koning

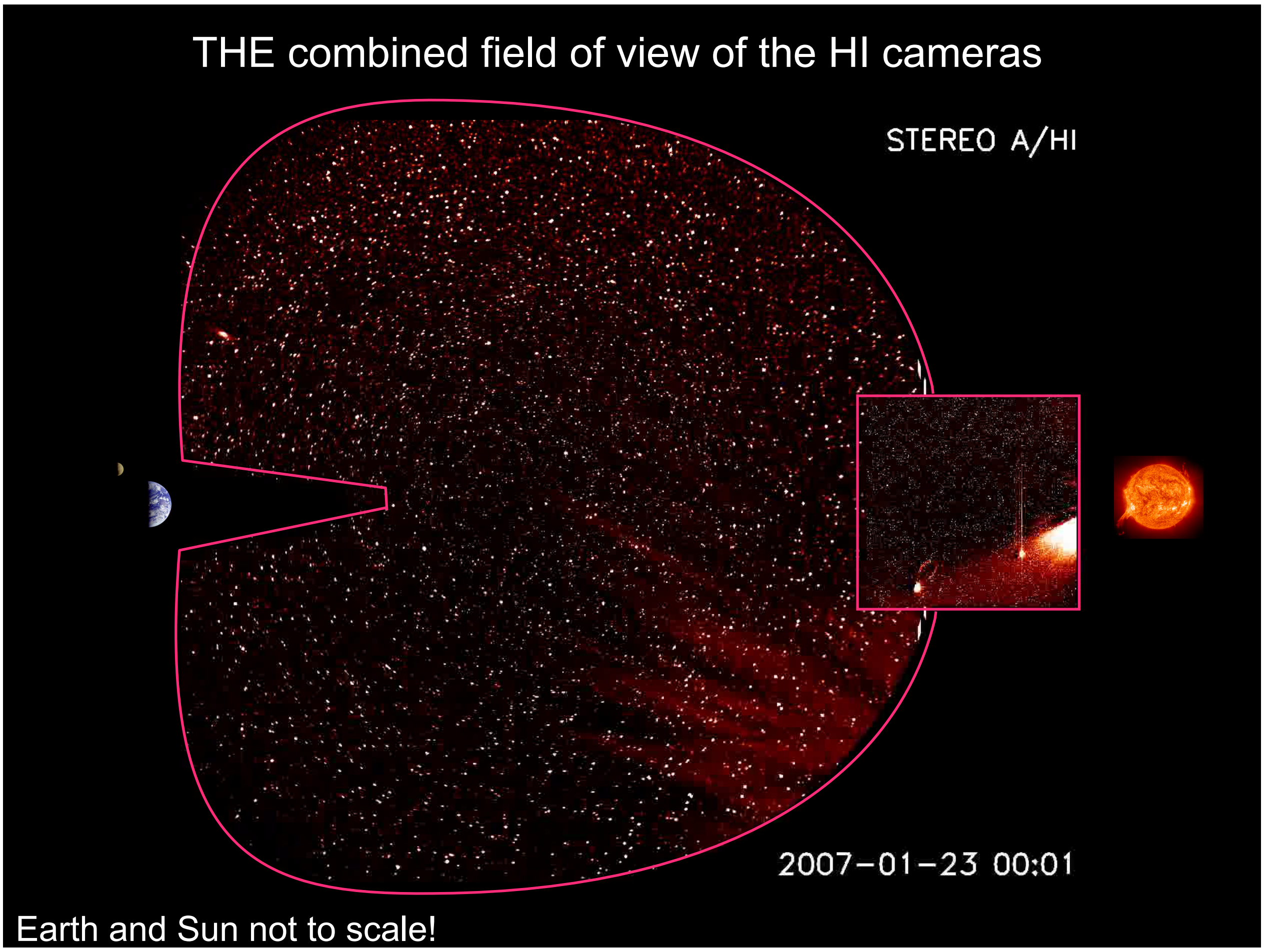
Method 4: Tracking CMEs using the Heliospheric Imagers (HI)

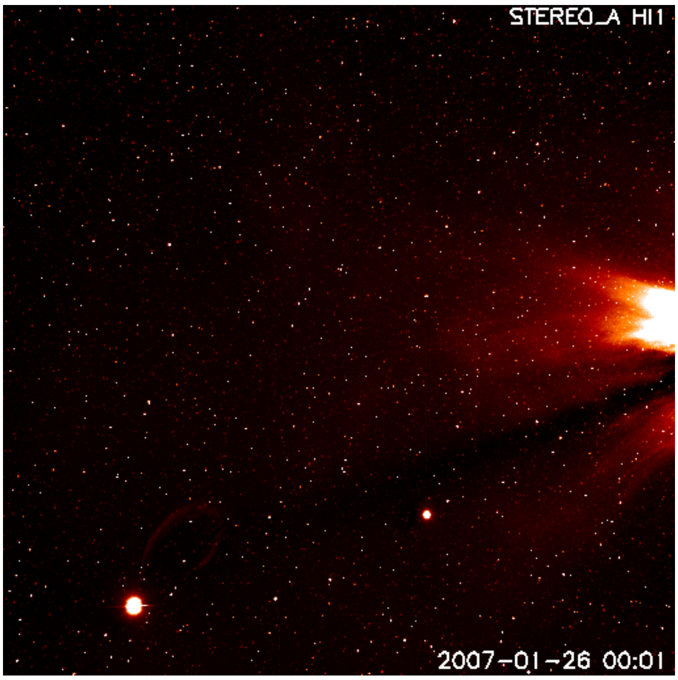


Estimates the average speed and direction of a CME in interplanetary space

HI Assembly Overview

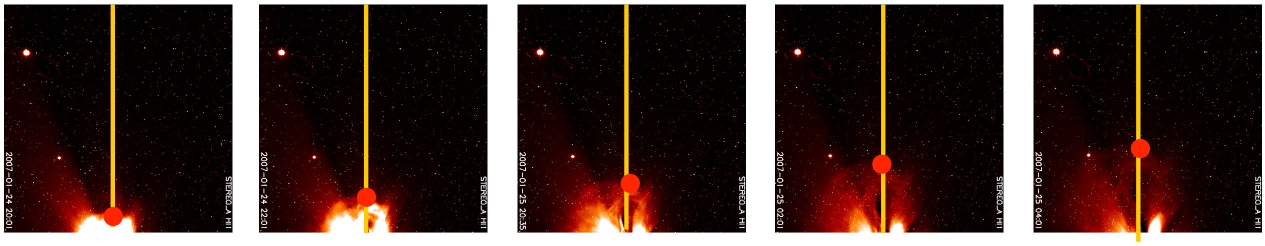


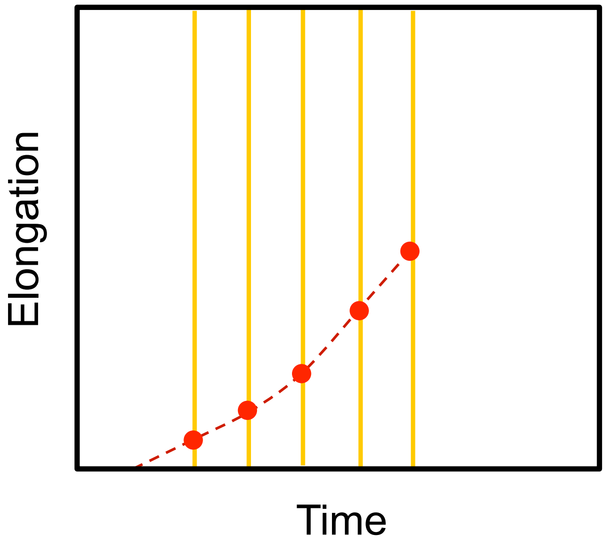




As a CME moves across the field of view, it will have an apparent acceleration due to the wide field of view of the cameras.

This can be used to estimate the speed and direction of a CME.



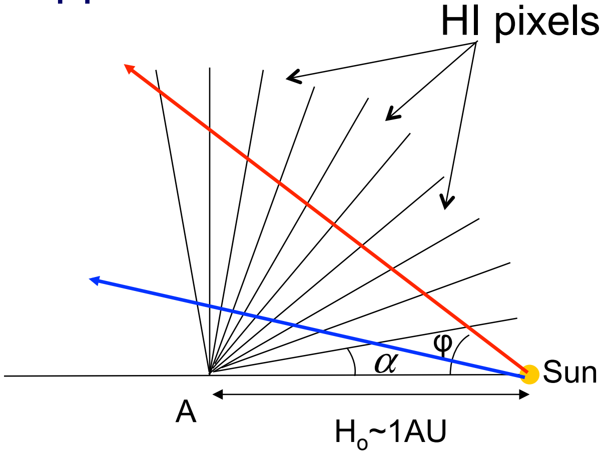


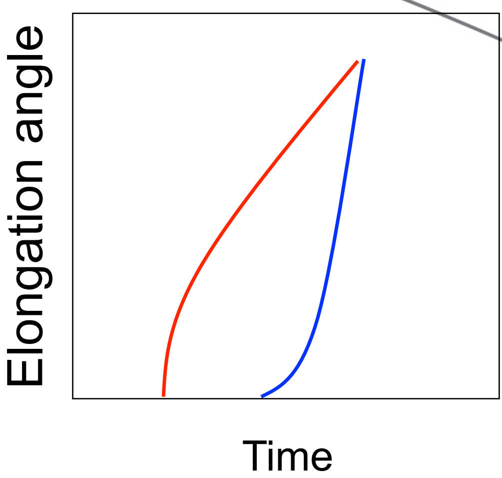
The ecliptic lies approximately along the central line of the HI images.

Tracking the rate at which the CME expands along this line generates a 'J-map'.

The gradient is a function of speed and direction of the CME

Apparent acceleration at large elongations – the 'Fixed Phi' approximation

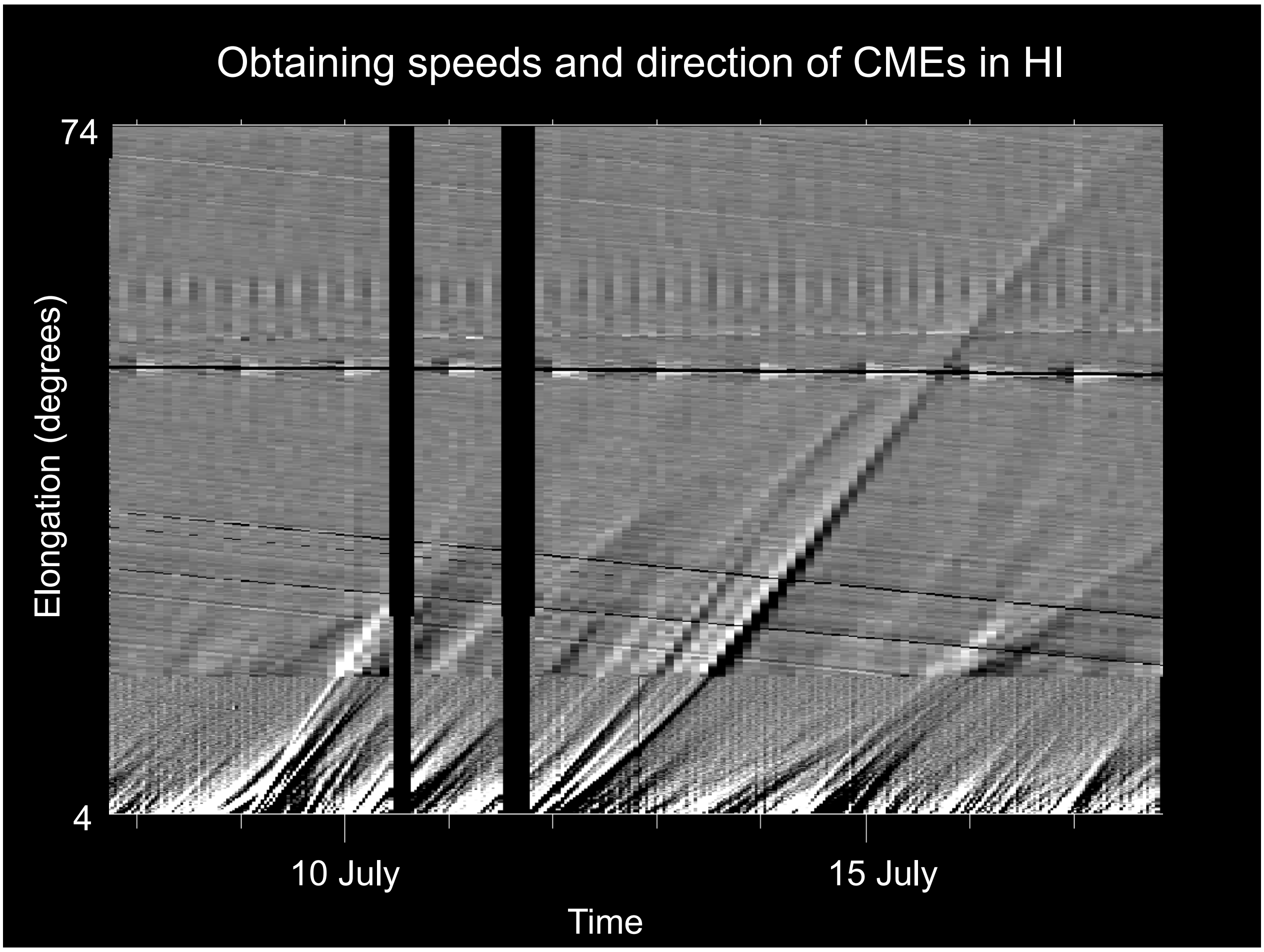


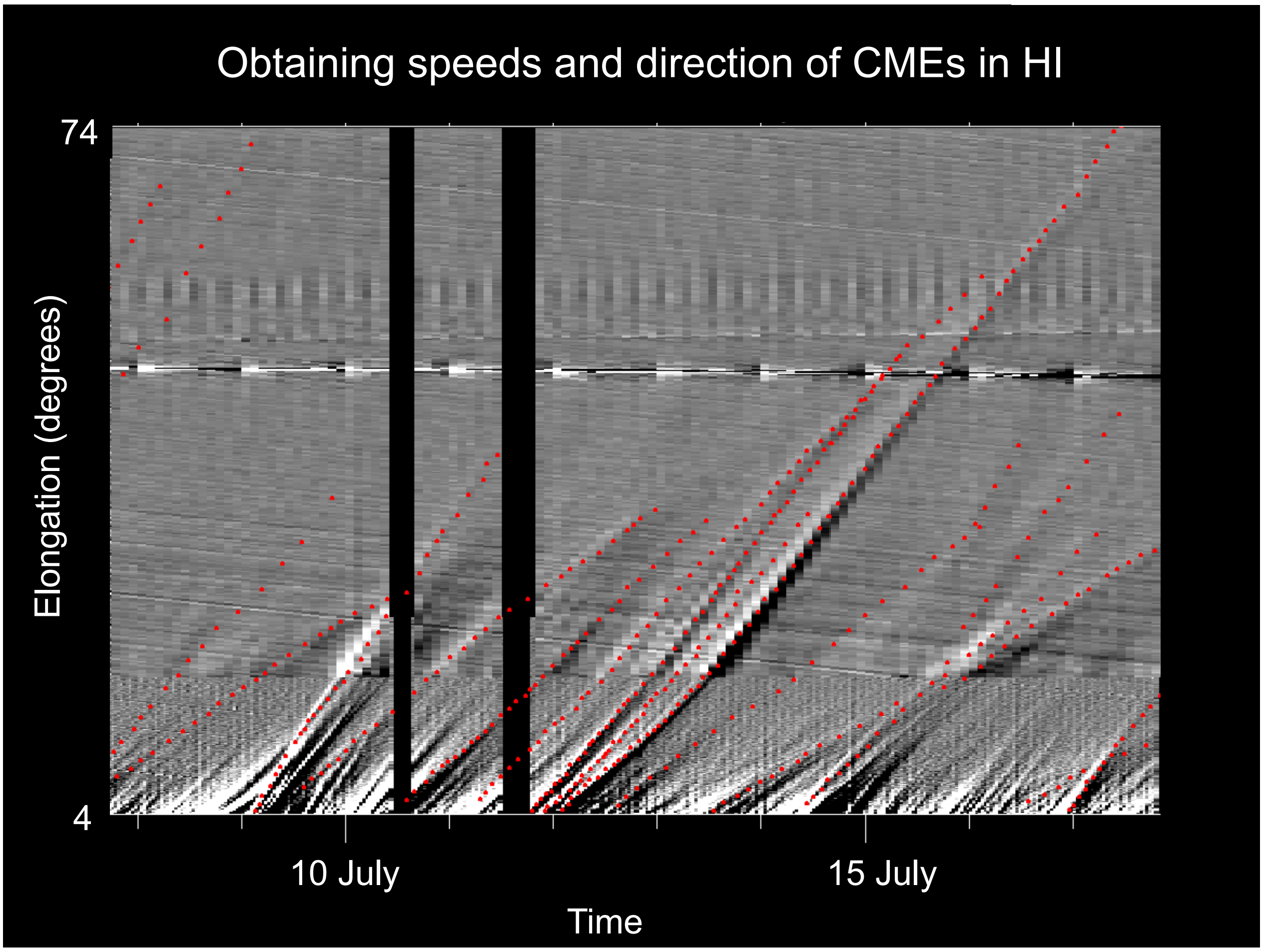


Assuming the CME propagates radially (φ constant) and at a constant speed;

$$\alpha(t) = \arctan\left[\frac{vt\sin(\varphi)}{H_o - vt\cos(\varphi)}\right]$$

(Sheeley et al., JGR,1999)


Obtaining speeds and direction of CMEs in HI
74
4
Elongation (degrees)
10 July
15 July
Time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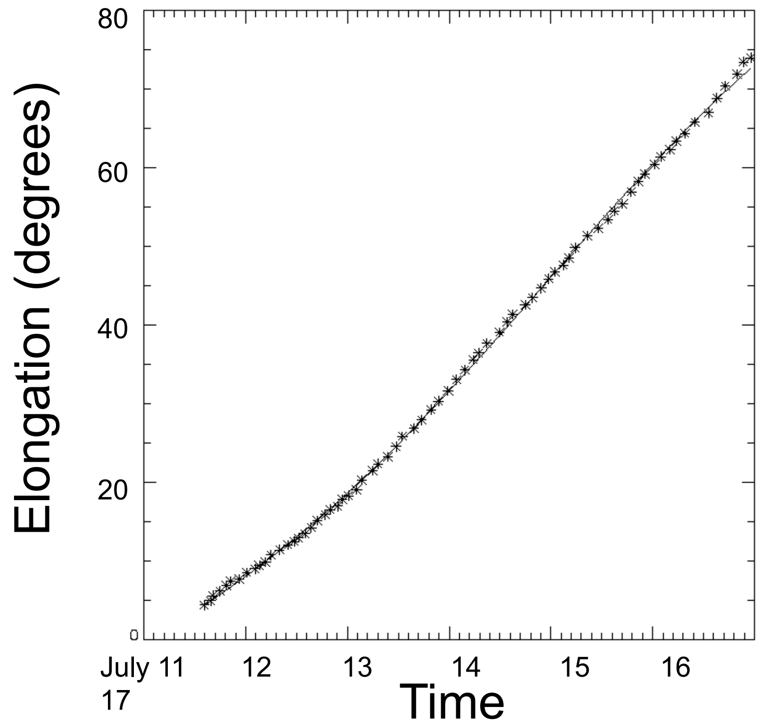
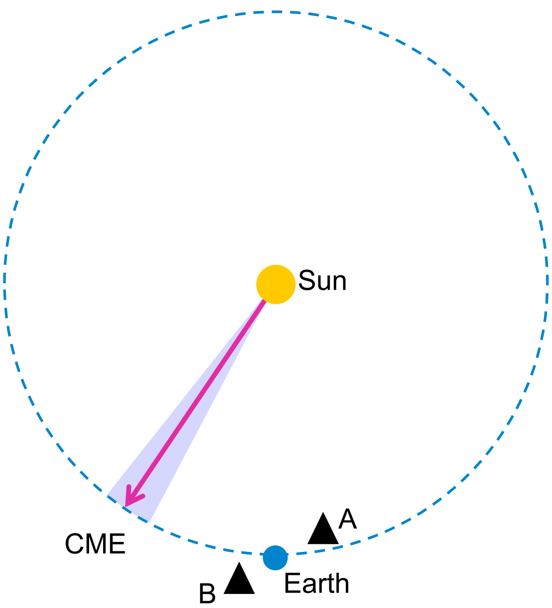


Event 123

Launch date 2007-07-11
Launch time 12:47 UT

Speed: 301 kms^{-1}
Angle from Earth -34^{o}

Predicted arrival at 1 AU
2007-07-17 at 09:09 UT



2008-02-04	HI 1 movie HI 2 movie	-	Ahead : vel 504.0 km/s; angle -19.3±24.0°; est launch 2008-02-03T19:55:32.440; est arrival 2008-02-07T05:11:43.138 Ahead : vel 484.0 km/s; angle -54.3±17.5°; est launch 2008-02-04T09:31:31.010; est arrival 2008-02-07T22:09:11.406 Ahead : vel 439.0 km/s; angle -21.3±15.0°; est launch 2008-02-04T08:35:36.564; est arrival 2008-02-08T05:53:46.387
2008-02-05	HI 1 movie HI 2 movie	-	Ahead : vel 360.0 km/s; angle -7.3± 3.5°; est launch 2008-02-05T00:42:16.049; est arrival 2008-02-09T18:29:59.827
2008-02-07	HI 1 movie HI 2 movie	-	Ahead : vel 383.0 km/s; angle -4.8±30.5°; est launch 2008-02-05T08:26:45.036; est arrival 2008-02-09T19:26:32.921
2008-02-09	HI 1 movie HI 2 movie	-	Ahead : vel 227.0 km/s; angle -21.2±10.5°; est launch 2008-02-08T09:26:38.351; est arrival 2008-02-15T22:01:55.779
2008-02-11	HI 1 movie HI 2 movie	-	Ahead : vel 313.0 km/s; angle -57.1±17.5°; est launch 2008-02-10T20:17:02.447; est arrival 2008-02-16T07:17:57.450 Ahead : vel 210.0 km/s; angle -68.1±10.5°; est launch 2008-02-10T16:58:39.347; est arrival 2008-02-18T20:15:09.899
2008-02-14	HI 1 movie HI 2 movie	-	Ahead : vel 302.0 km/s; angle -68.1± 8.5°; est launch 2008-02-12T14:45:19.394; est arrival 2008-02-18T06:37:00.374 Ahead : vel 297.0 km/s; angle -40.1±13.0°; est launch 2008-02-13T13:18:17.483; est arrival 2008-02-19T07:27:12.486 Ahead : vel 244.0 km/s; angle -27.1±12.5°; est launch 2008-02-13T13:55:58.539; est arrival 2008-02-20T14:05:21.228 Ahead : vel 246.0 km/s; angle -54.1±17.0°; est launch 2008-02-14T04:35:56.782; est arrival 2008-02-21T03:23:17.822
2008-02-16	HI 1 movie HI 2 movie	-	Ahead : vel 311.0 km/s; angle -57.0±16.5°; est launch 2008-02-15T08:08:18.902; est arrival 2008-02-20T20:07:07.184 Ahead : vel 332.0 km/s; angle -68.0±18.0°; est launch 2008-02-15T18:45:07.783; est arrival 2008-02-20T22:23:02.771 Ahead : vel 239.0 km/s; angle -50.0±17.5°; est launch 2008-02-15T12:05:51.493; est arrival 2008-02-22T15:50:14.657
2008-02-17	HI 1 movie HI 2 movie	-	Ahead : vel 271.0 km/s; angle -68.0±12.5°; est launch 2008-02-15T20:48:37.916; est arrival 2008-02-22T04:18:03.348 Ahead : vel 141.0 km/s; angle -26.0± 6.0°; est launch 2008-02-14T14:47:19.432; est arrival 2008-02-26T17:57:04.056
2008-02-18	HI 1 movie HI 2 movie	-	Ahead : vel 263.0 km/s; angle -36.0±44.5°; est launch 2008-02-16T12:29:22.411; est arrival 2008-02-23T00:37:10.305
2008-02-21	-	HI 1 movie HI 2 movie	Behind: vel 350.0 km/s; angle 6.3±10.0°; est launch 2008-02-21T00:16:38.047; est arrival 2008-02-25T21:40:19.578
2008-02-22	HI 1 movie HI 2 movie	-	Ahead : vel 507.0 km/s; angle -43.9± 4.5°; est launch 2008-02-22T01:00:48.738; est arrival 2008-02-25T10:04:23.744
2008-02-24	HI 1 movie HI 2 movie	-	Ahead : vel 148.0 km/s; angle -19.8±37.5°; est launch 2008-02-21T21:16:22.138; est arrival 2008-03-04T11:05:00.732
2008-02-25	HI 1 movie HI 2 movie	-	Ahead : vel 438.0 km/s; angle -12.8±19.5°; est launch 2008-02-23T21:41:50.882; est arrival 2008-02-27T19:35:29.622 Ahead : vel 287.0 km/s; angle -67.8±12.0°; est launch 2008-02-24T07:05:08.196; est arrival 2008-03-01T06:22:49.548
2008-02-28	HI 1 movie HI 2 movie	HI 1 movie HI 2 movie	Ahead : vel 263.0 km/s; angle -48.7±13.0°; est launch 2008-02-26T09:18:57.280; est arrival 2008-03-03T21:48:01.402 Behind: vel 183.0 km/s; angle 46.3±20.0°; est launch 2008-02-27T12:52:28.953; est arrival 2008-03-07T21:46:03.729 Behind: vel 176.0 km/s; angle 58.3±20.0°; est launch 2008-02-27T17:33:55.946; est arrival 2008-03-08T11:24:11.309
2008-03-01	HI 1 movie HI 2 movie	-	Ahead : vel 268.0 km/s; angle -21.6± 7.0°; est launch 2008-02-28T13:01:44.730; est arrival 2008-03-05T22:40:14.580
2008-03-02	HI 1 movie HI 2 movie	HI 1 movie HI 2 movie	Ahead : vel 343.0 km/s; angle -29.6±10.5°; est launch 2008-02-29T16:53:18.081; est arrival 2008-03-05T16:57:54.979 Behind: vel 410.0 km/s; angle 25.3±25.0°; est launch 2008-03-01T13:39:40.717; est arrival 2008-03-05T18:06:57.244
2008-03-04	-	HI 1 movie HI 2 movie	Behind: vel 302.0 km/s; angle 4.3±29.0°; est launch 2008-03-03T09:21:42.432; est arrival 2008-03-09T01:48:37.638 Behind: vel 300.0 km/s; angle 0.3± 6.5°; est launch 2008-03-03T14:21:16.280; est arrival 2008-03-09T07:42:46.253
2008-03-06	HI 1 movie HI 2 movie	HI 1 movie HI 2 movie	Ahead : vel 495.0 km/s; angle -11.4±12.0°; est launch 2008-03-04T23:51:57.880; est arrival 2008-03-08T11:09:24.183 Ahead : vel 196.0 km/s; angle -39.4±25.0°; est launch 2008-03-05T02:05:27.858; est arrival 2008-03-13T20:26:32.756 Behind: vel 402.0 km/s; angle 19.3±10.5°; est launch 2008-03-05T11:15:15.616; est arrival 2008-03-09T17:48:49.348
2008-03-15	HI 1 movie HI 2 movie	-	Ahead : vel 309.0 km/s; angle -67.0±21.0°; est launch 2008-03-15T01:06:53.518; est arrival 2008-03-20T14:51:30.489

RAL STEREO HI Support Group

2008-03-27 10:13 GMT Chris Davis

The STEREO HI group at RAL use this technique to produce an event list (www.stereo.rl.ac.uk)

How accurate are our estimates? We need to compare with other techniques and in-situ data

The 'Fixed phi' method assumes a point feature. Other techniques make different assumptions about the CME shape;

Fixed Phi and Harmonic Mean Models

Two models of solar transient geometry are extensively used in the analysis of time-elongation profiles.

- The Fixed Phi (FP) model: radially-propagating point source

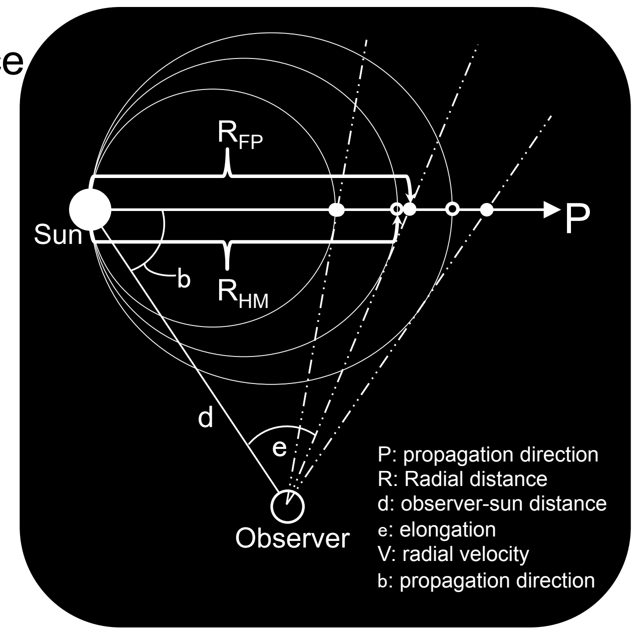
Sheeley, Kahler and Webb, Rouillard

R_{FP}=dsine/sin(e+b)
e=atan(Vtsinb/(d-Vtcosb))

- The Harmonic Mean (HM): radially-expanding circle, anchored at Sun-centre.

Lugaz, Möstl

R_{HM}=2dsine/(1+sin(e+b))
e=acos((-b+a $(a^2+b^2-1)^{1/2}$)/(a^2+b^2))
where: a=2d/Vt-cosb and b=sinb



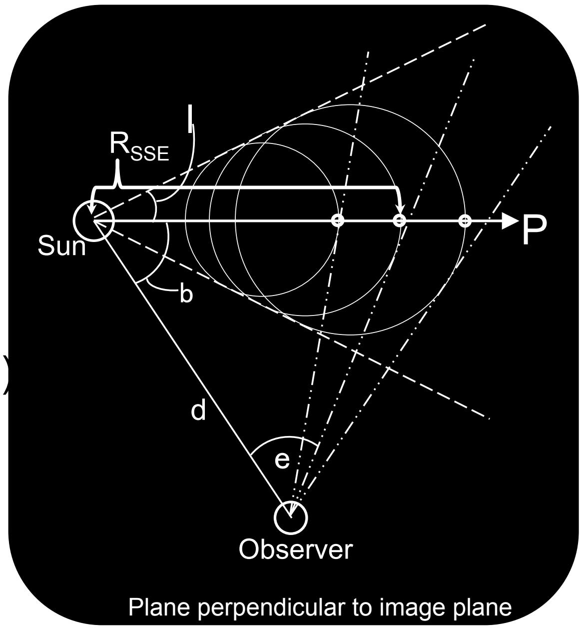
The Self-Similar Expansion Model

radially-expanding circle, defined by half-width l
(Equivalent geometry to Lugaz model 2).

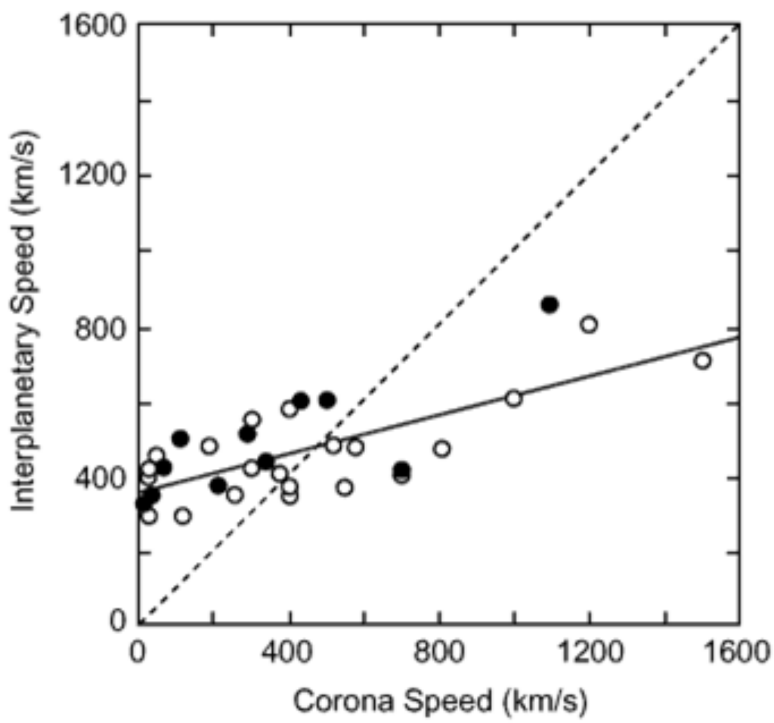
R_{SSE}=dsine (1+sinl)/(sinl+sin(e+b))

e=acos((-bc+a $(a^2+b^2-c^2)^{1/2}$)/(a^2+b^2))

where: a=2d(1+sinl)/Vt-cosb
b=sinb,
c=sinl

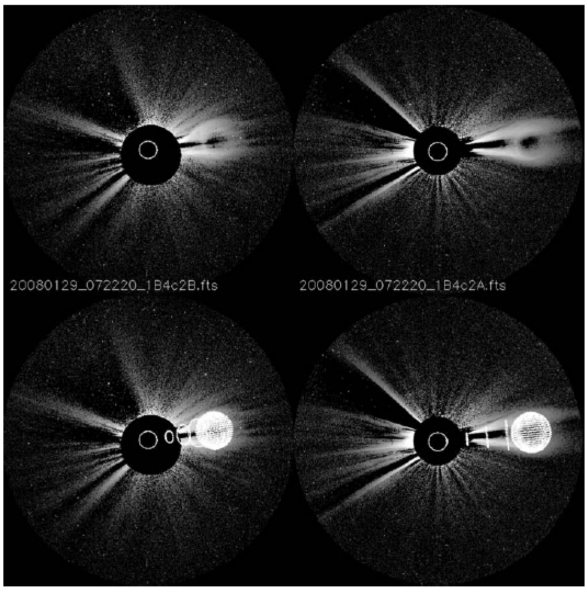


Evidence of CME interaction with the ambient solar wind



Lindsay et al (1999) compared CME speeds estimated from Solwind and SMM coronagraph data with speeds measured in situ by Helios-1 and Pioneer Venus Orbiter between 1979 and 1982.

Davis et al (2009) repeated this analysis for STEREO, comparing estimates from coronagraphs with those from the HIs



Thernisien et al, 2009 used STEREO COR2 data to estimate speeds and directions for 26 CMEs between November 2007 and August 2008

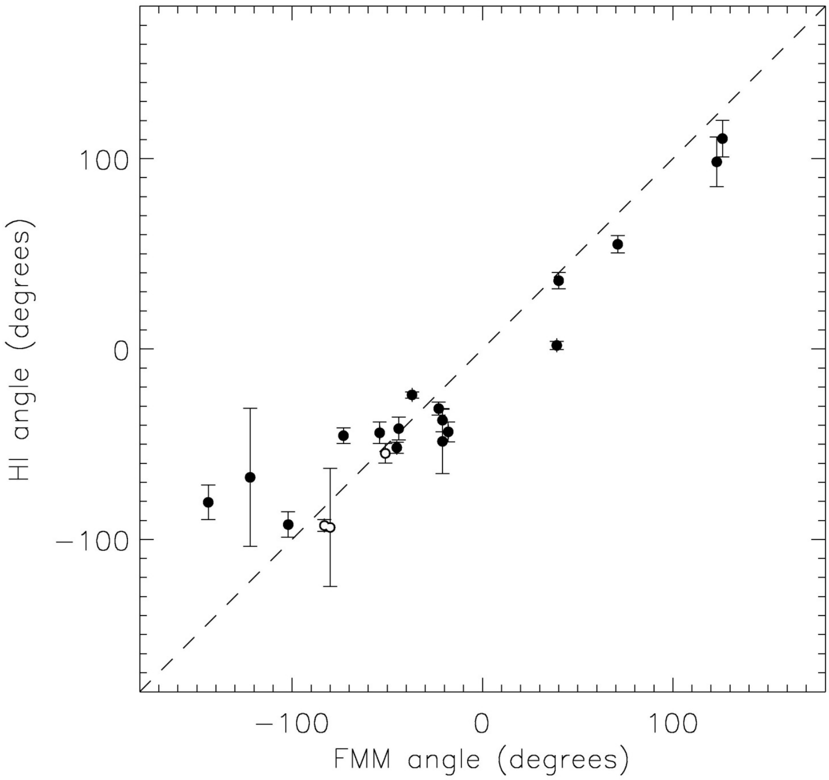
They then compared their values with those published by CDAW (coordinated data analysis workshop).

Both these sets of values were estimated from coronagraph data. How do they compare with measurements in HI?

Table 3 Velocity and acceleration of the 26 events. ϕ is the Stonyhurst longitude from Table 1, V is the 3D velocity of the apex of the model, V_{CDAW} is the projected velocity given by the CDAW catalog, V_p is the projected speed, and a is the 3D acceleration calculated using a second-order fit.

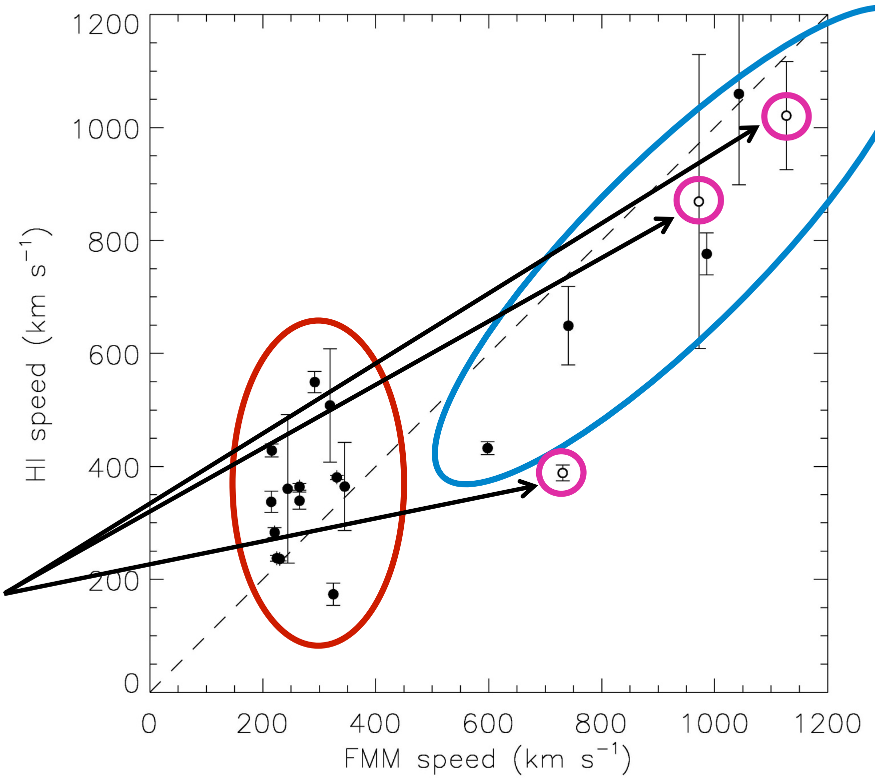
Date	ϕ (degrees)	V	V_{CDAW} (km s^{-1})	V_p	a (m s^{-2})
04-Nov-2007	−44	216	179	150	9.0
16-Nov-2007	123	345	326	289	11.8
04-Dec-2007	71	265	210	251	7.0
16-Dec-2007	−144	325	184	191	4.8
31-Dec-2007	−80	972	1013	957	−5.0
31-Dec-2007 up	−91	846	1013	845	−16.0
31-Dec-2007 low	−91	967	1013	967	−57.0
02-Jan-2008	−51	731	676	568	−6.3
23-Jan-2008	−160	442	362	151	10.4
29-Jan-2008	107	246	166	235	5.0
04-Feb-2008	−21	598	306	214	7.0
12-Feb-2008	93	249	266	249	12.1
13-Feb-2008	−18	225	157	70	2.9
15-Feb-2008	−73	230	163	220	8.2
24-Feb-2008	−122	244	246	207	8.8
17-Mar-2008	40	221	211	142	6.9
18-Mar-2008	−83	340	–	337	8.5
25-Mar-2008	−83	1127	980	1119	−30.6
05-Apr-2008	126	1043	962	843	4.0
26-Apr-2008	−21	741	515	266	1.4
17-May-2008	−45	986	630	697	13.1
24-May-2008	39	331	225	208	6.1
02-Jun-2008	−37	265	–	159	5.0
12-Jun-2008	−102	319	274	312	5.2
26-Jun-2008	−147	389	204	212	0.9
07-Jul-2008	−23	292	–	114	15.0
31-Jul-2008	141	288	–	181	1.8
07-Aug-2008	−54	215	–	174	0.6

Davis et al (2009) found good agreement when comparing the angle of propagation from both COR2 and HI (except for some events where this angle is large and the CMEs fade in HI images)

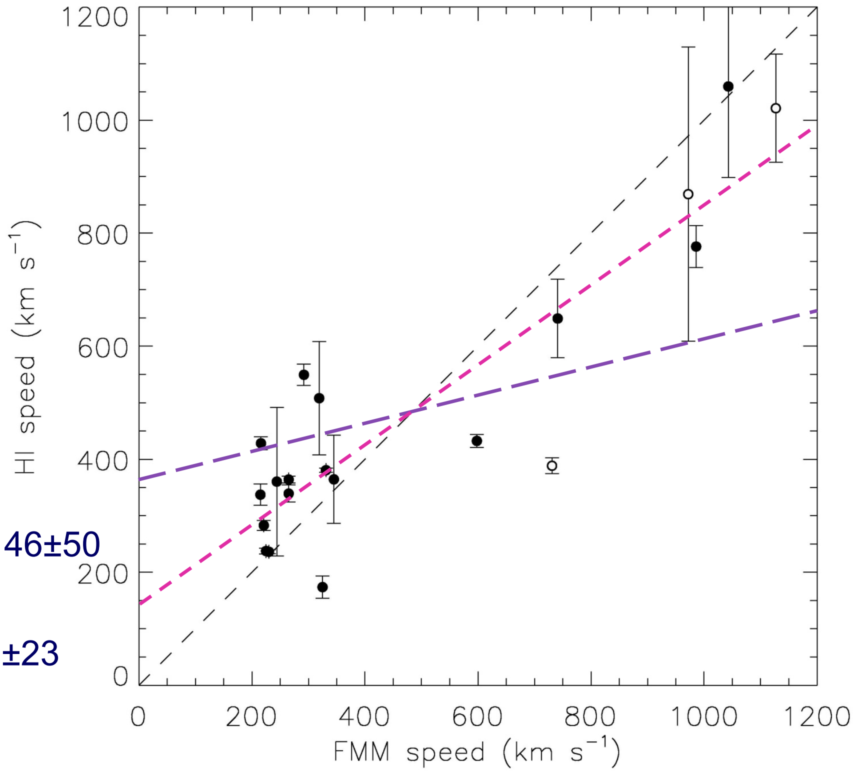


Less clear agreement with velocities, with some evidence that the speed of a CME is modified by the ambient solar wind speed.

Decelerating in COR2



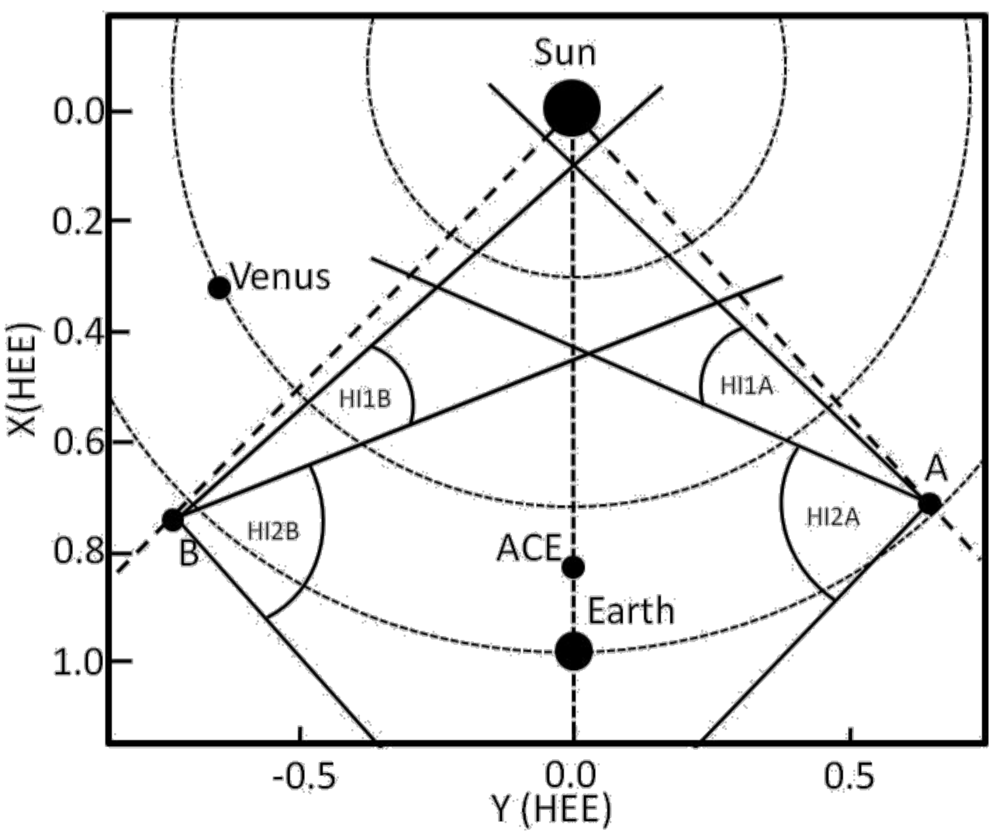
While the STEREO results also point to an interaction with the solar wind, the acceleration is smaller for the modern data. This could be due to differences in the techniques used or to a change in the solar wind between the two studies

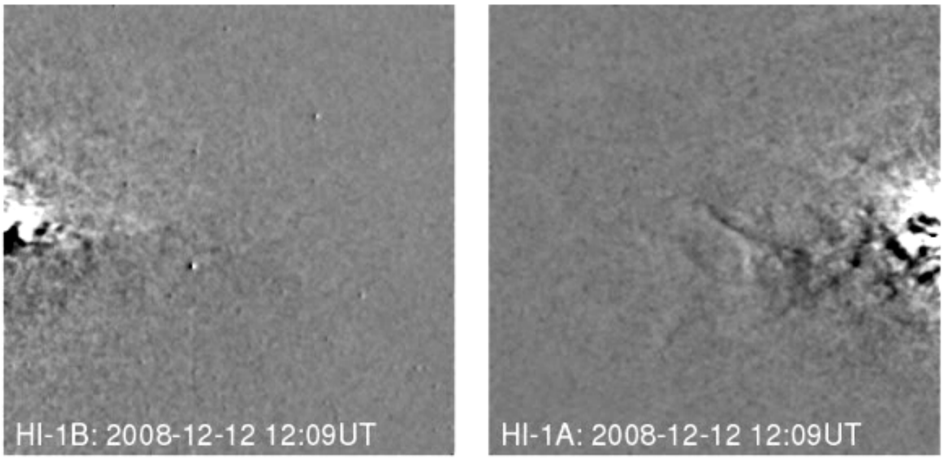


$V_{HI}=(0.71\pm0.08)V_{COR}+146\pm50$

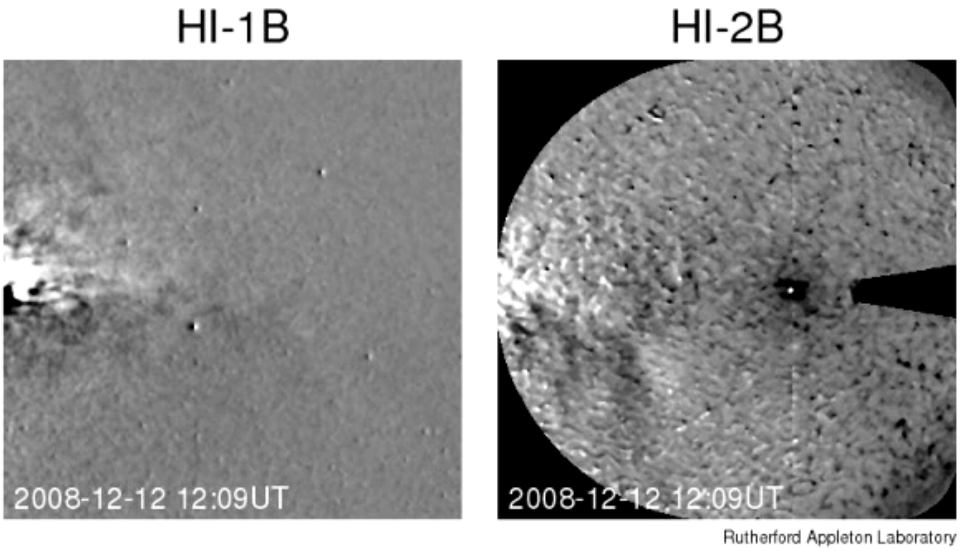
$V_{IP}=(0.25\pm0.04)V_c+360\pm23$

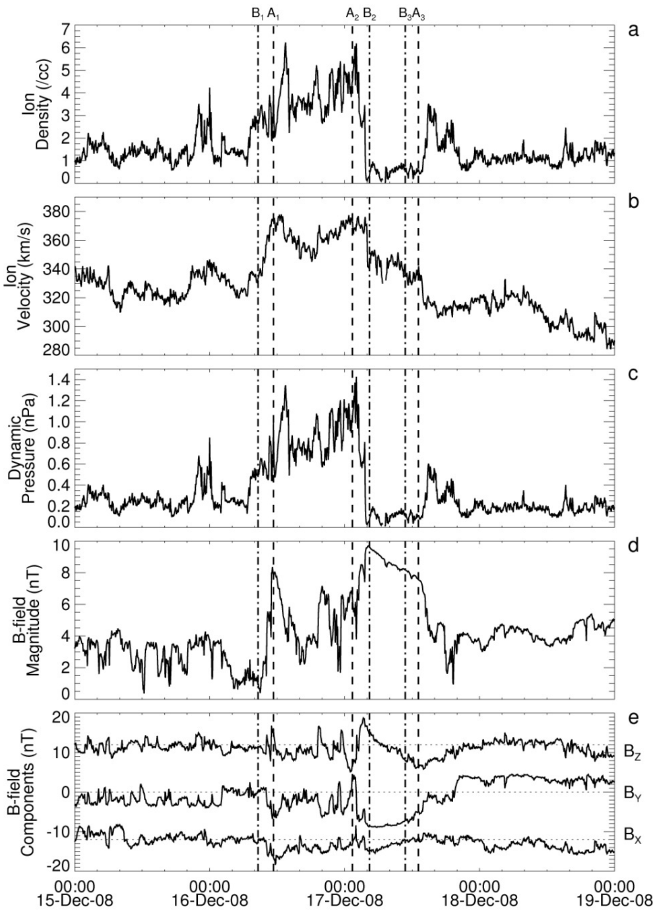
Tracking a CME with STEREO: The CME of December 12 2008




HI-1B: 2008-12-12 12:09UT
HI-1A: 2008-12-12 12:09UT

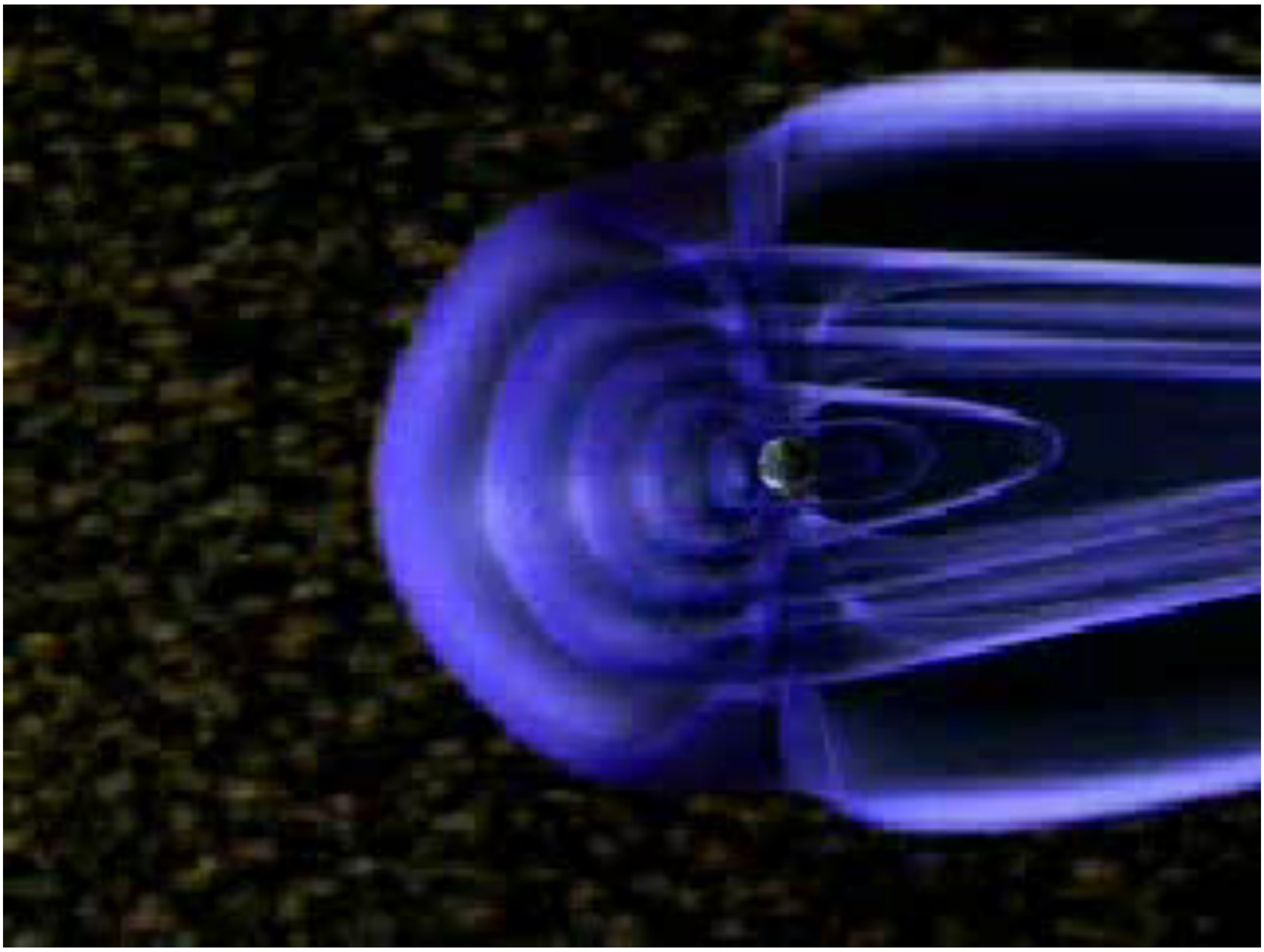
Similar observations were made with HI-B

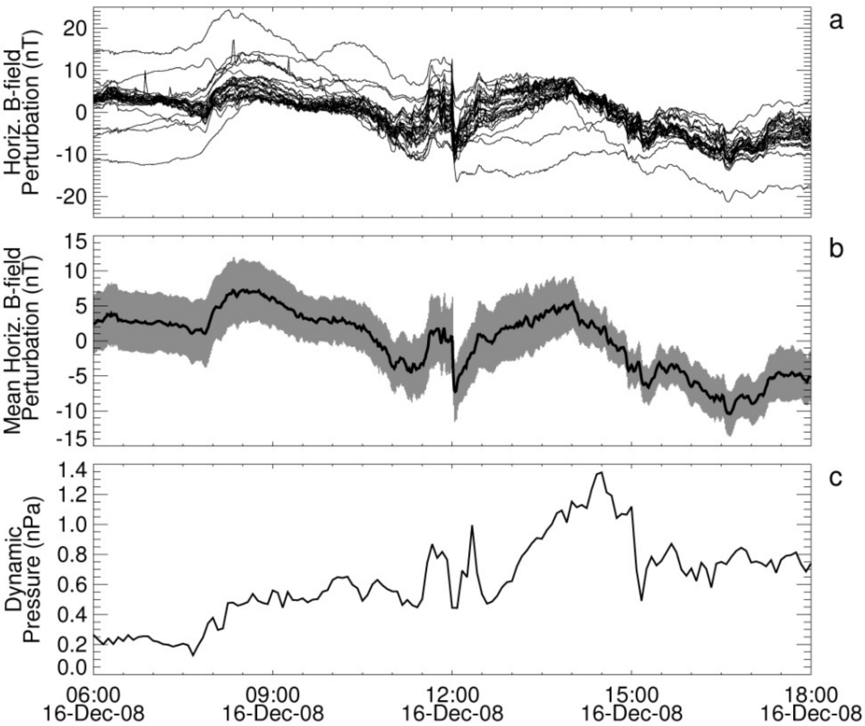




The ‘Fixed Phi’ method was applied to the HI data. The direction indicated that it was Earth-directed and the speeds of several distinct CME features were used to estimate their arrival time at the ACE spacecraft (0.1 AU upstream of the Earth in the solar wind). These times (dotted lines) closely matched the arrival of a high speed, dense plasma with an enhanced magnetic field.

The orientation of the magnetic field was northward, so geomagnetic activity was low but the solar wind dynamic pressure still compressed the Earth’s magnetosphere





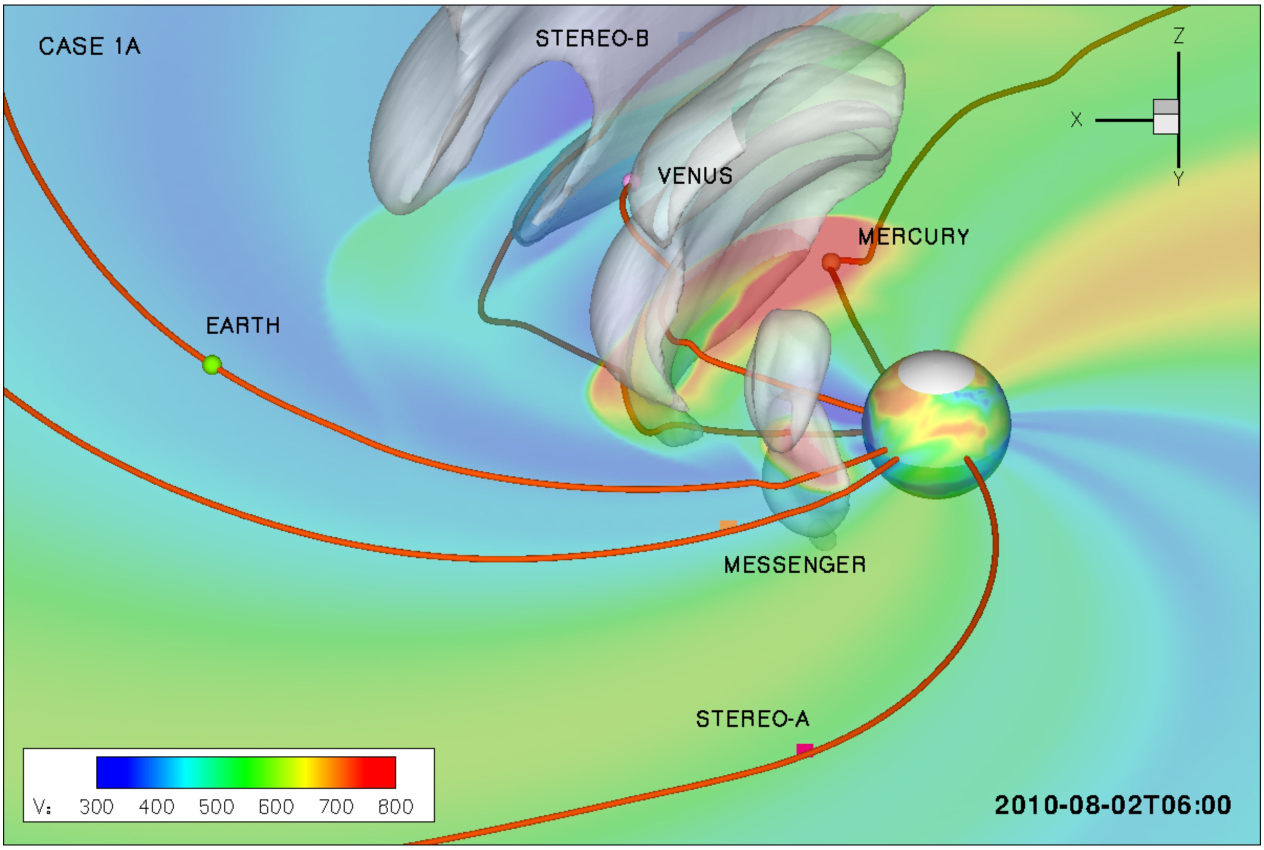
This was shown by comparing the dynamic pressure pulse seen at ACE (bottom) with the mean variation in dayside magnetometers on Earth (middle panel)

Predicting space-weather events at Earth

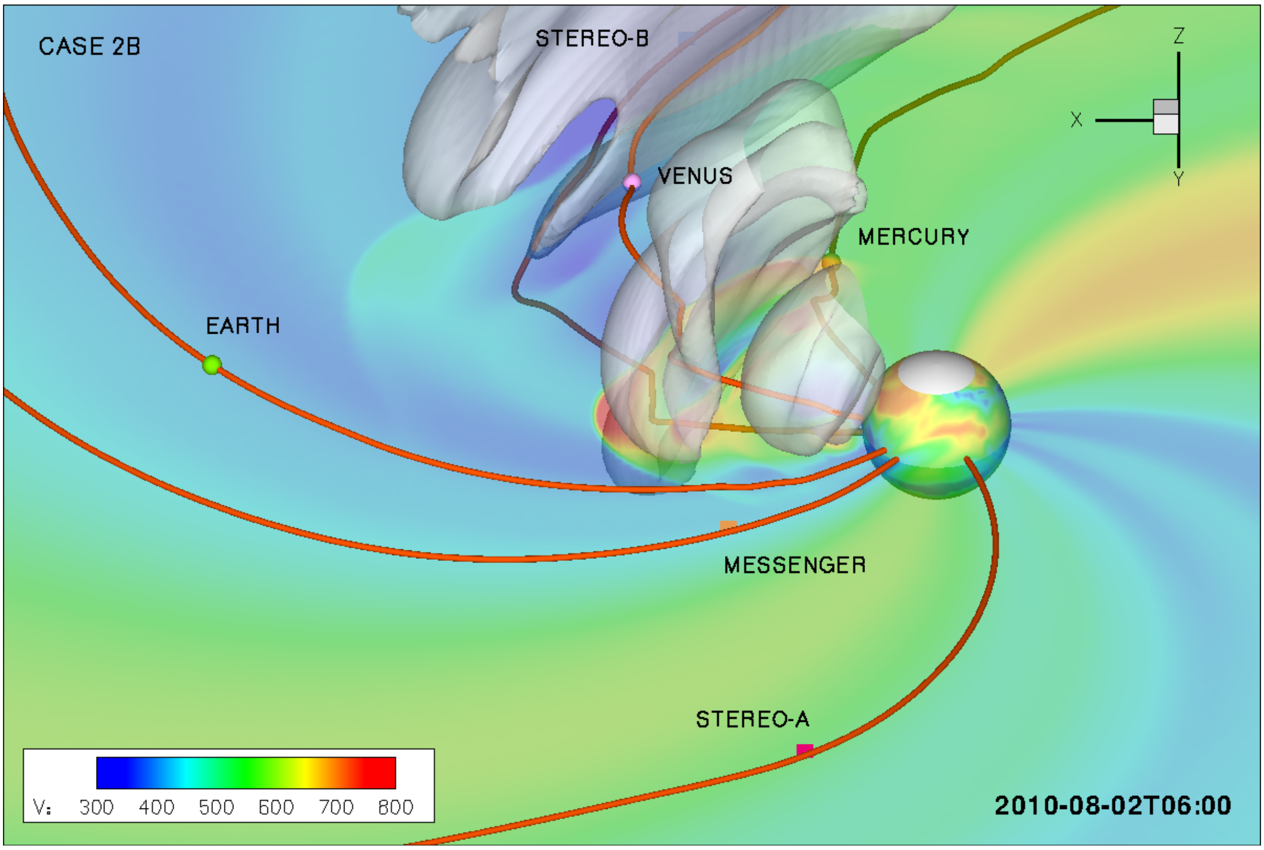
- Observations of precursors such as coronal dimming
- An initial estimate CME propagation direction – from STEREO coronagraph data
- An estimate of ambient solar wind conditions – Enlil

Turning these into a forecast requires repeated runs of the model with a range of initial conditions that reflect the uncertainties in the measurements (what the Met Office call 'ensemble forecasts')

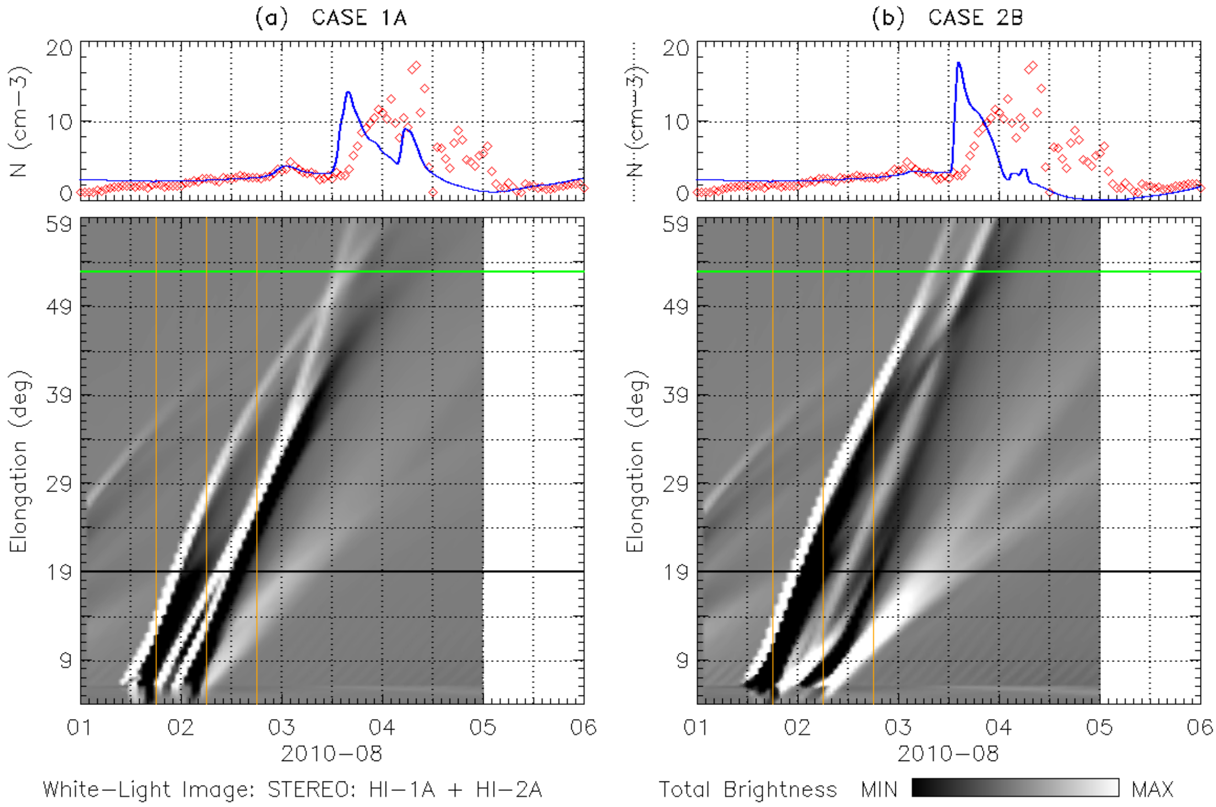
Enlil - Numerical Heliospheric Solution (Case 1a)

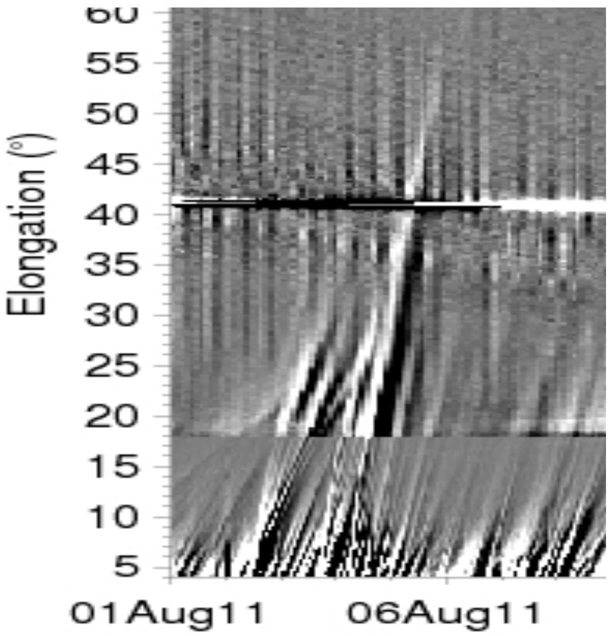


Enlil - Numerical Heliospheric Solution (Case 2b)



Enlil can produce synthetic J-Maps (Case 1a vs Case





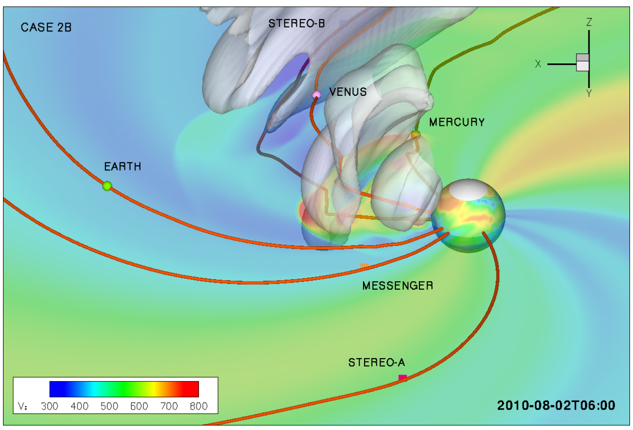
Which can then be compared with the observations from HI to see which modelling scenario best represents reality.

'Real-time' data from STEREO is lower resolution and has many data gaps due to telemetry constraints. This adds to the challenge of making real-time space-weather predictions

The Enlil model is now being used operationally by the Space Weather Prediction Center, Boulder Colorado

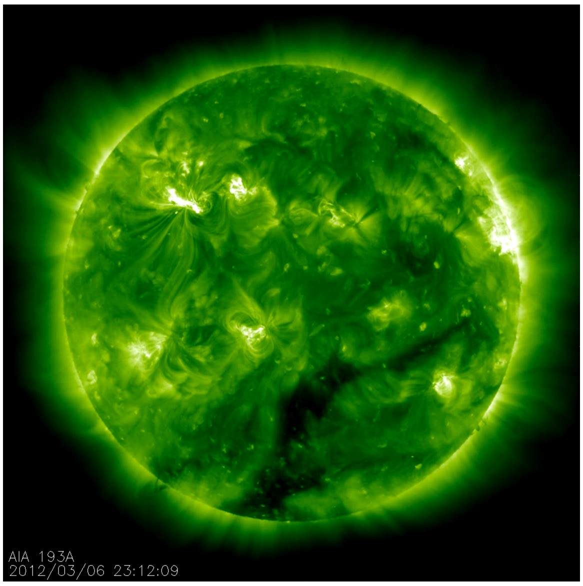
An agreement has been signed recently between the UK and USA governments for the UK Met Office to run Enlil as an Ensemble model.

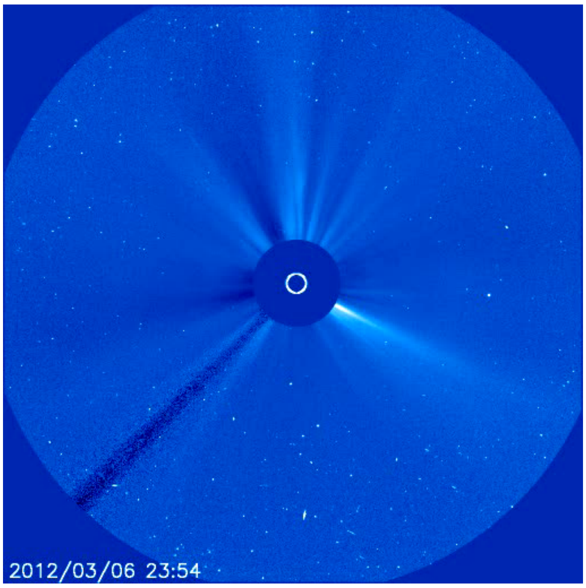
Future space weather forecasts should be able to give likelihoods of a storm at Earth (e.g. 60% chance of aurora over the UK tonight)



Impact of the solar events of 7 March 2012: Recorded by RAL instrumentation aboard the SDO and STEREO spacecraft and the RAL ionosonde

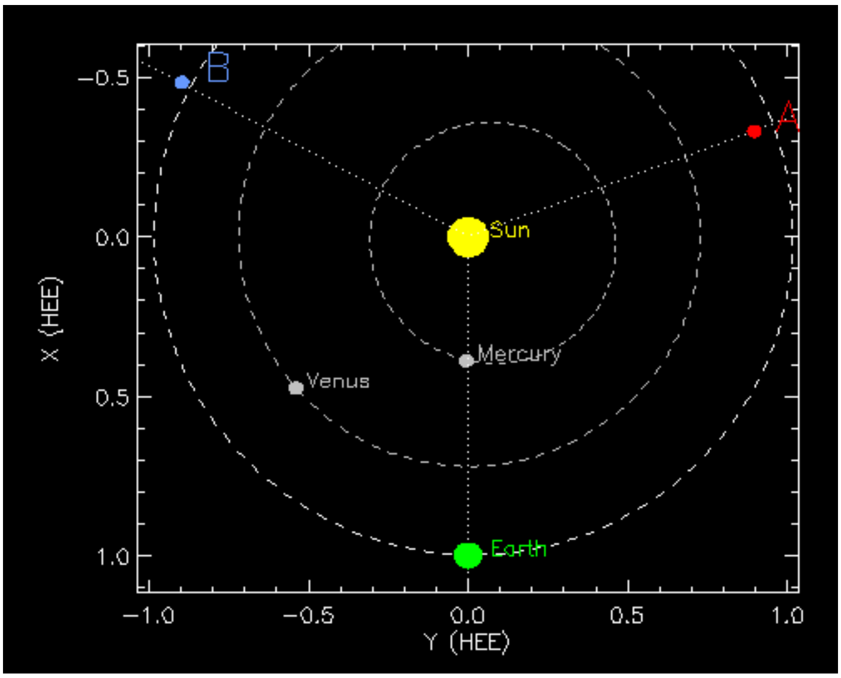
• (left) Bright solar flare and coronal activity detected using RAL cameras on NASA's SDO
• (right) Associated solar mass ejection detected heading straight for Earth from SOHO coronagraph



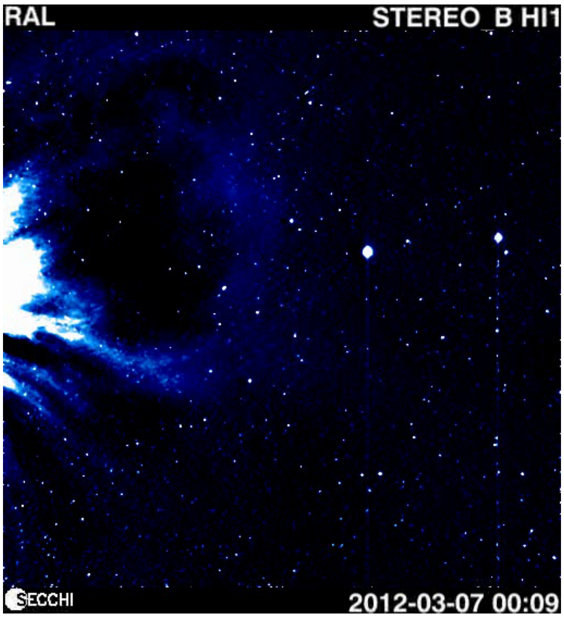


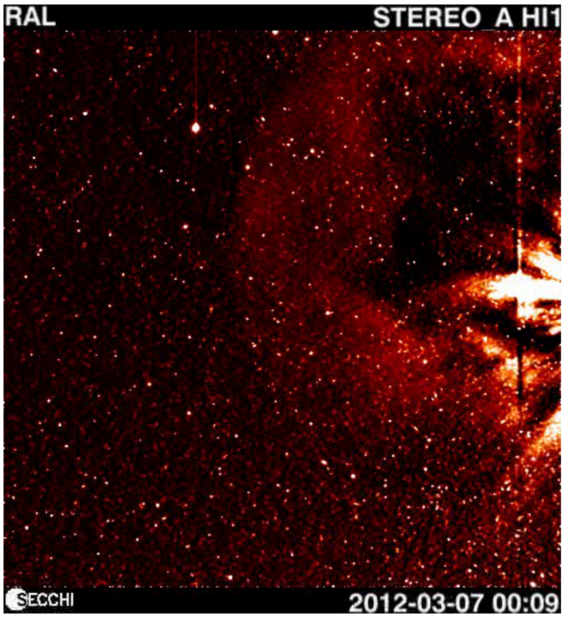
RAL Space

Location of STEREO spacecraft, March 2012

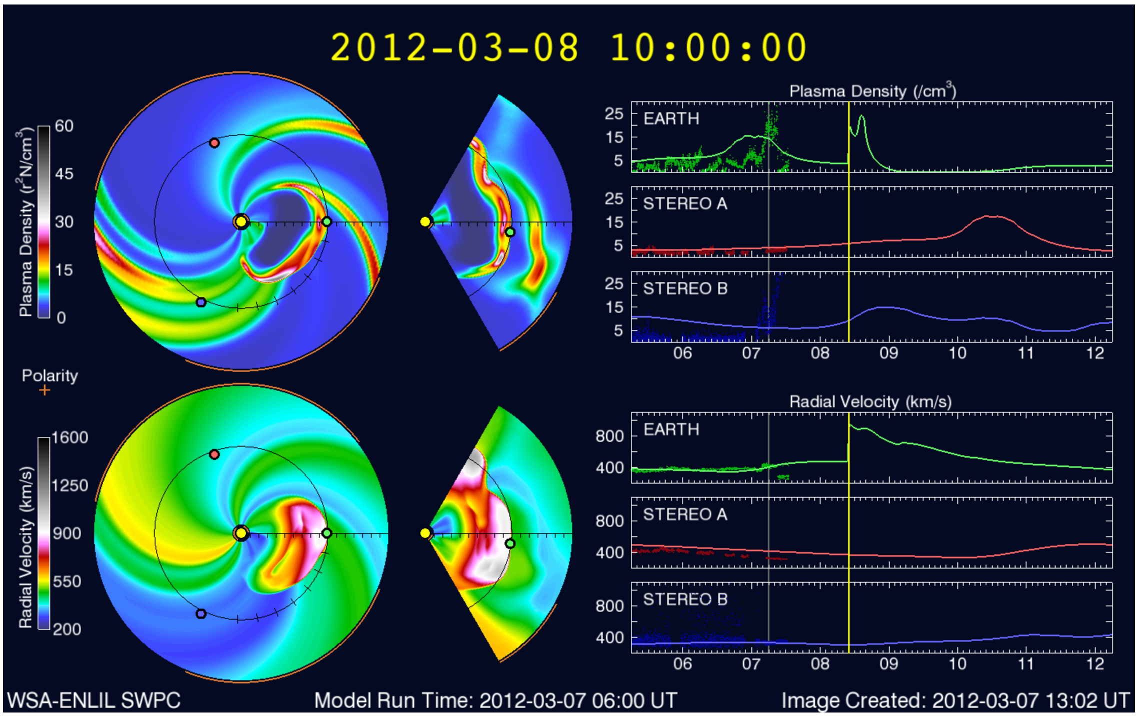


HI view of 7 March 2012 CME

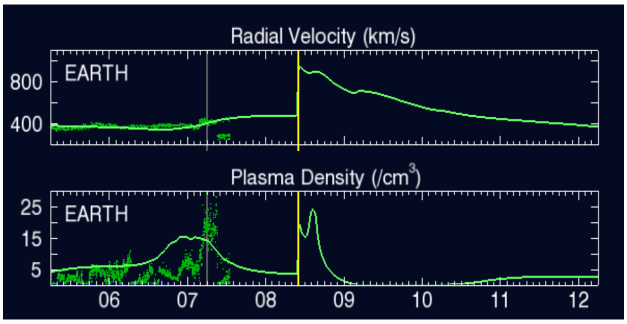




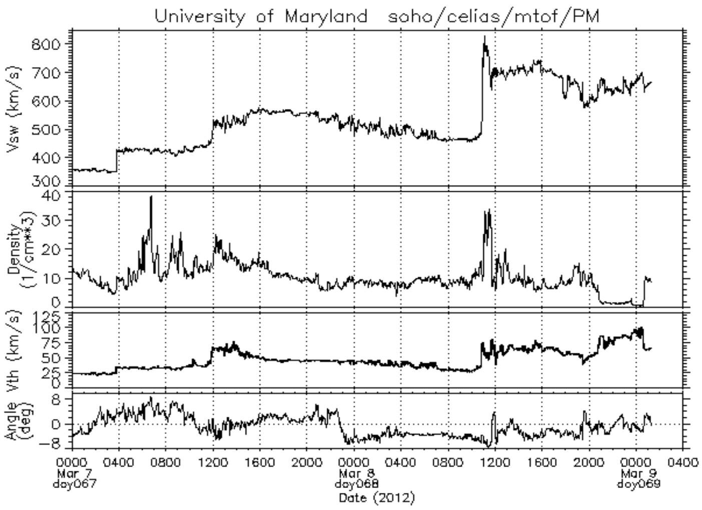
The Enlil MHD model of the heliosphere for this event – run using data from SOHO & STEREO - Earth is the green dot; the STEREO spacecraft are red and blue; the Sun is yellow



Model Prediction



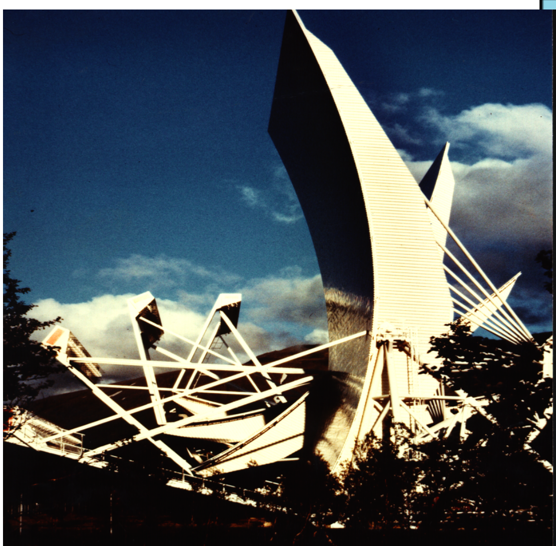
Observation

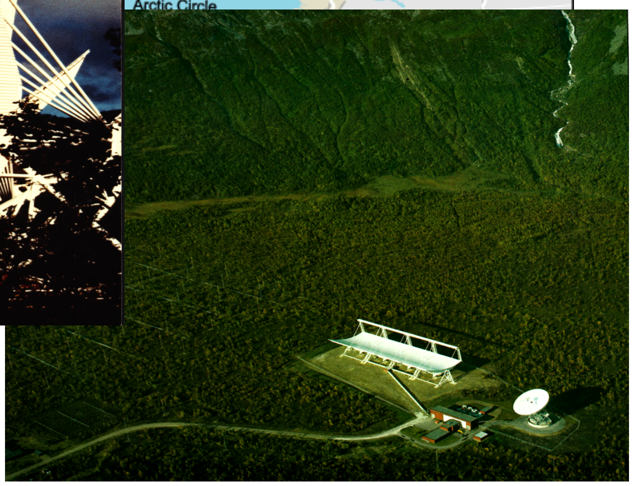


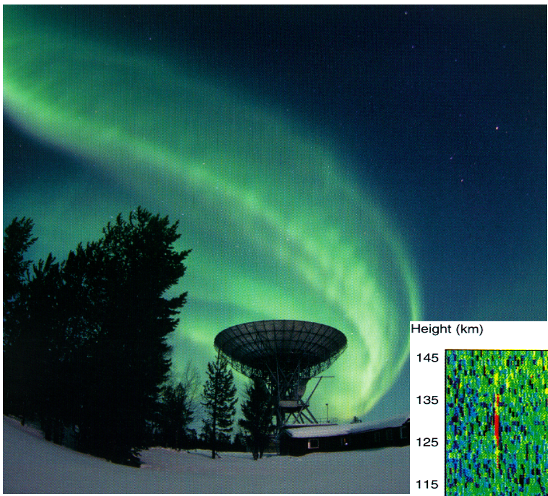
Aurora imaged in Iceland on March 8

The European Incoherent SCATter RADAR - EISCAT

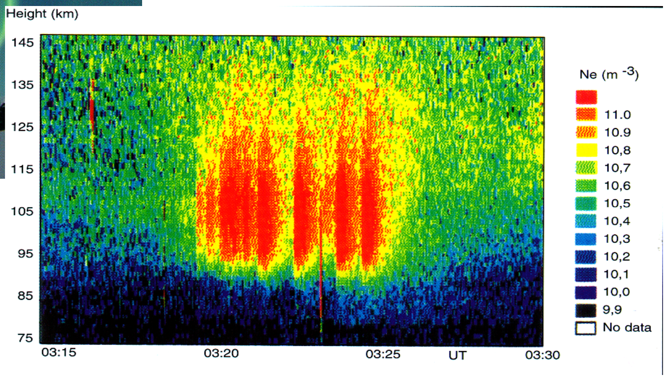
The EISCAT radars



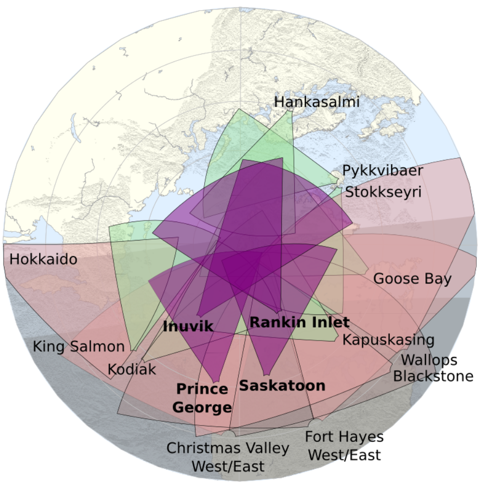


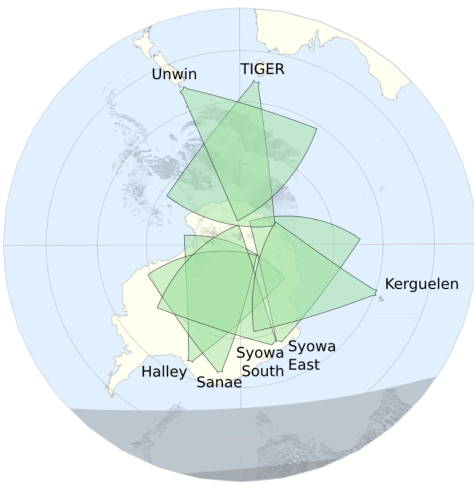


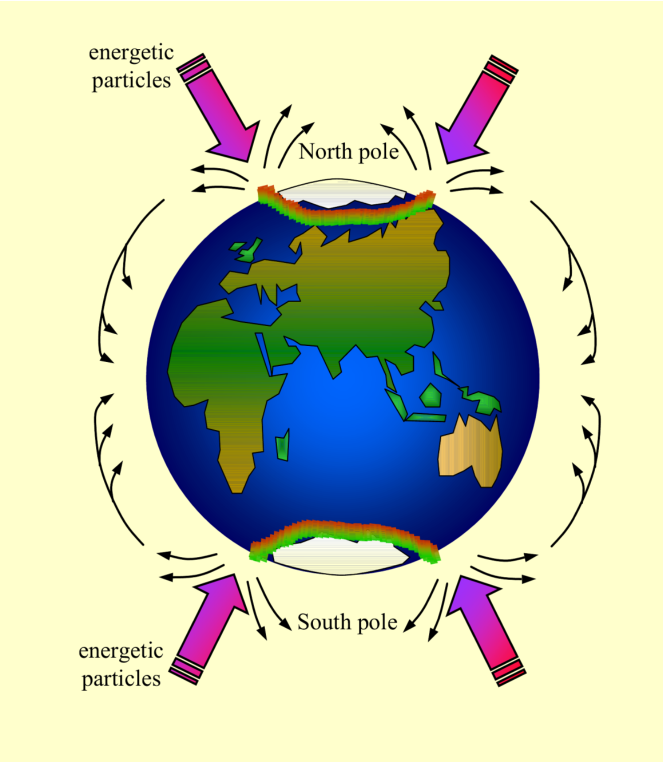
The EISCAT radars situated in northern Scandinavia can measure the energetic particles as they reach Earth.



SuperDARN radars



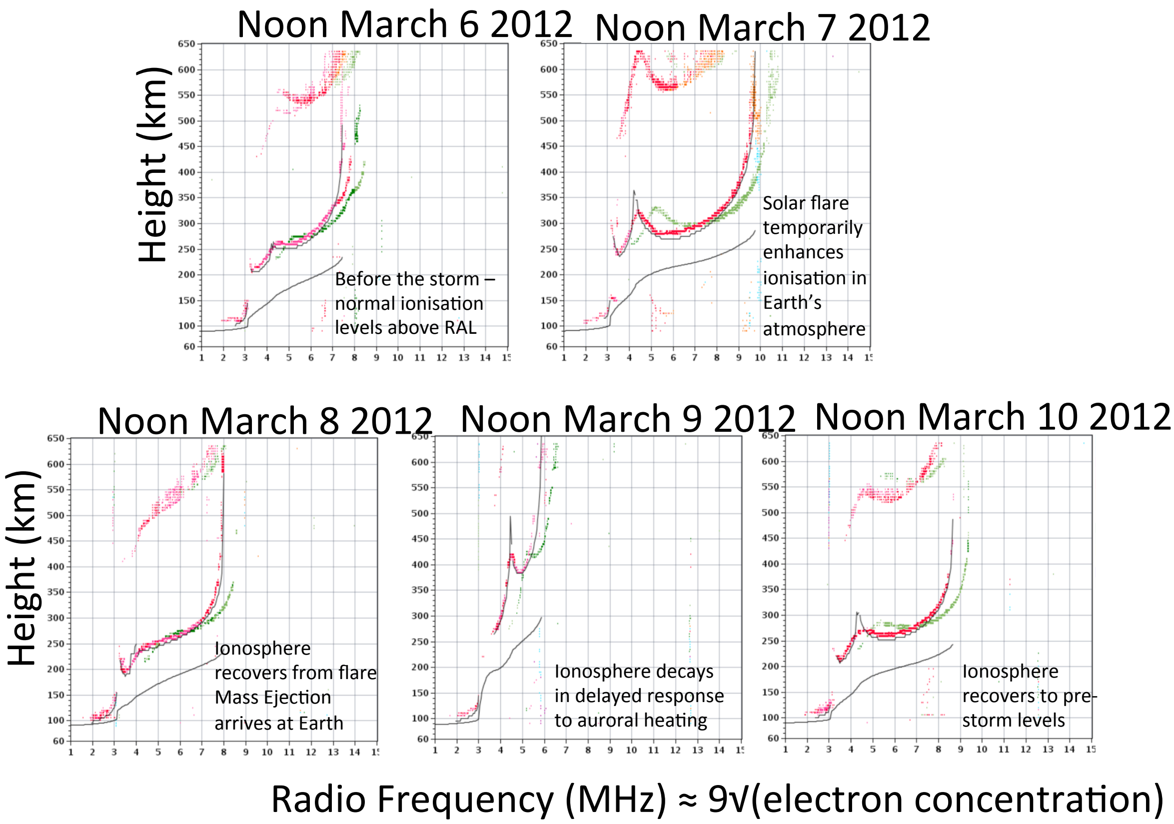




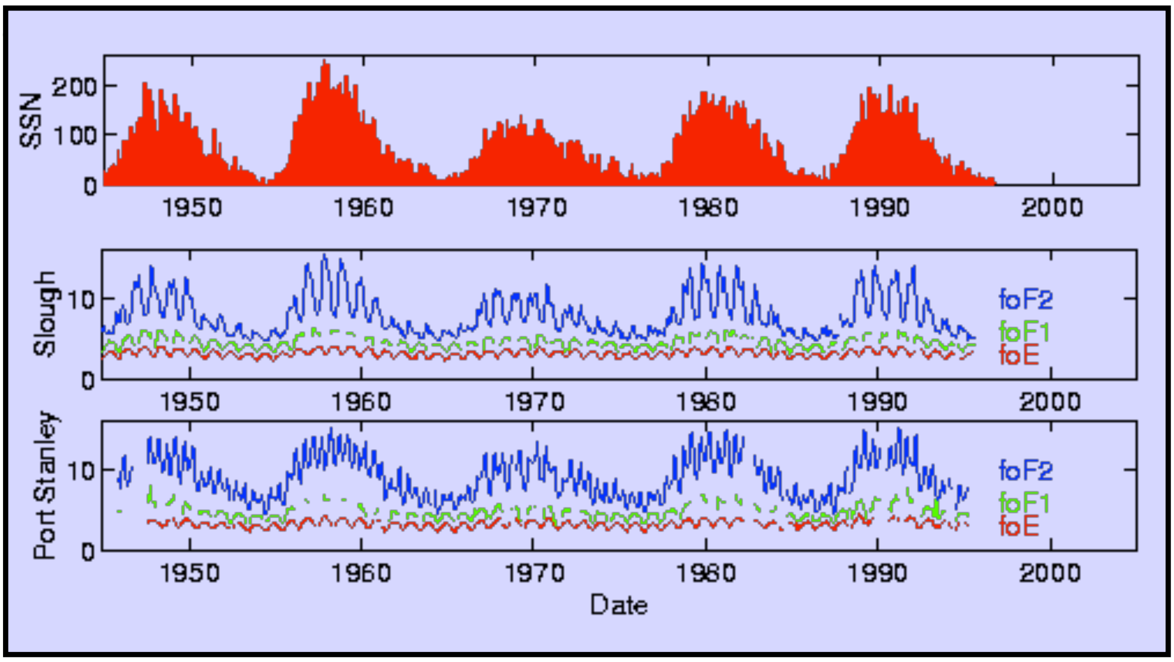
Auroral heating causes the atmosphere to expand, changing the atmospheric chemistry

The Chilton ionospheric monitoring station at RAL, Oxfordshire.

Ionosphere above RAL 6-12 March 2012: Shows disturbed ionosphere on March 7 & 9



The Earth's ionosphere is sensitive to changes in solar activity.



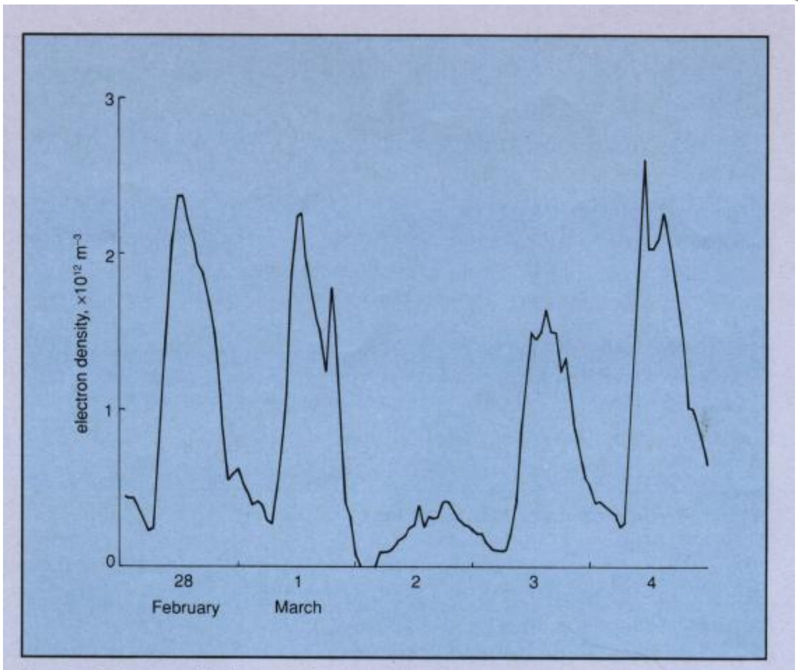
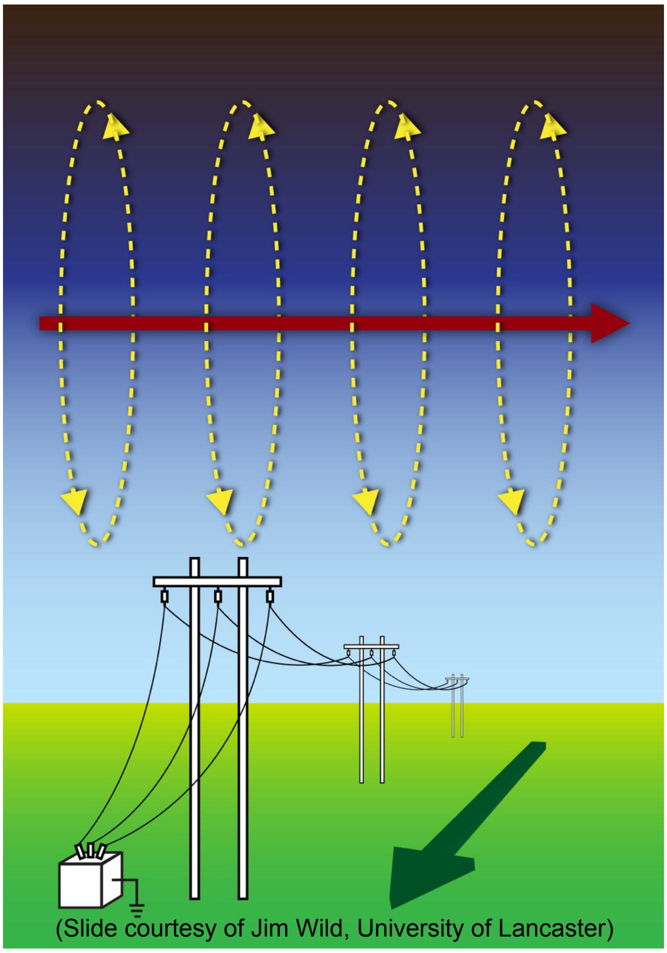


Fig. 2 F2 layer peak electron density at Slough (52°N, 1°W) during the severe magnetic storm which started around midday on 1st March 1982

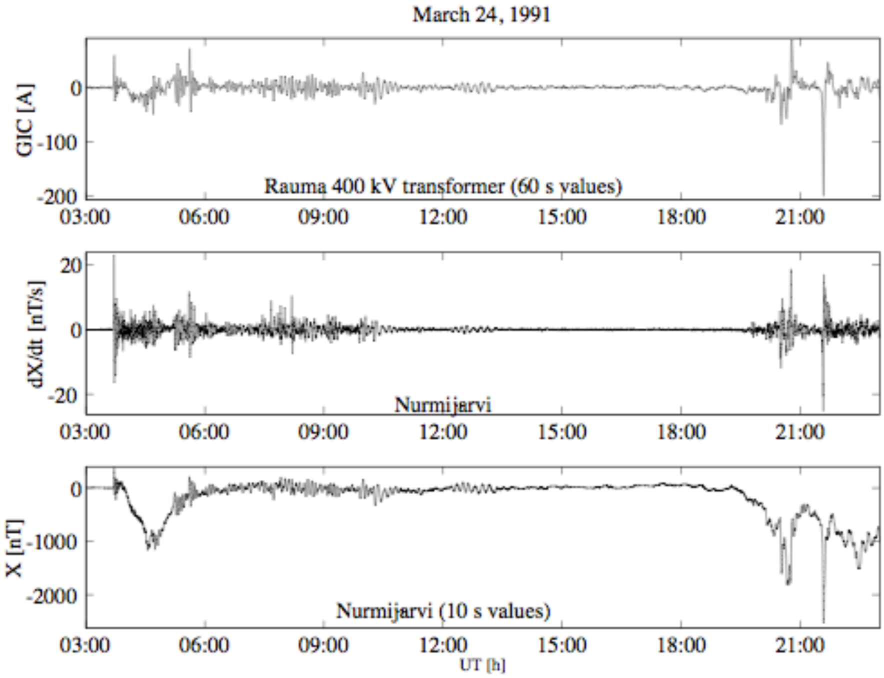


Fluctuating electrojet (~10^6 A)

Time-varying magnetic field at ground level

Electric field induced in the Earth's crust (~several V/km) ➜ potential difference over continental scales)

Large GIC measured in Finland

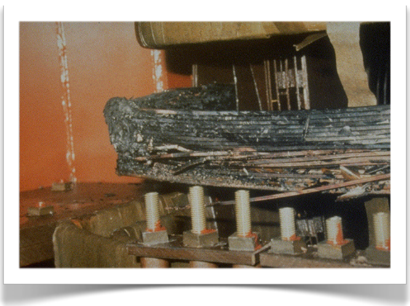


From Pirjola & Boteler [2006]

(Slide courtesy of Jim Wild, University of Lancaster)

What is the effect of GICs in transformers?

- Half wave saturation with DC offset current of magnitude similar to magnetising current (well below transformer rated current).
- Harmonics, eddy currents, reactive power variation.
- Intense heating ➜ catastrophic melting
- Stray heating initiates paper and oil degradation; possibly bubble formation if moisture content ‘high’; possibly sulphur deposition
- Unclear what sustains degradation when GIC subsides
- Unclear effect of transformer designation and design



(Slide courtesy of Jim Wild, University of Lancaster)

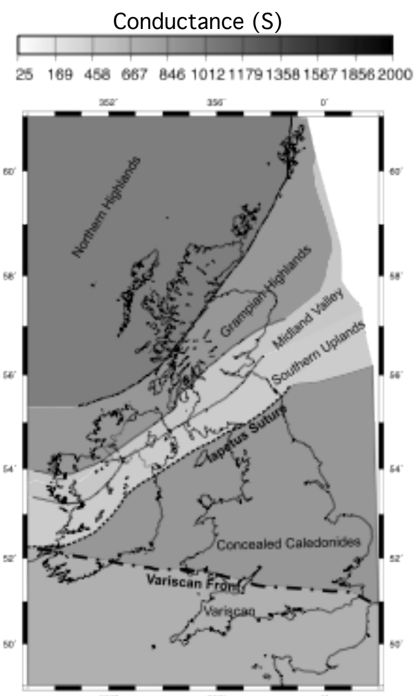
(Slide courtesy of Jim Wild, University of Lancaster)

Modelling GIC

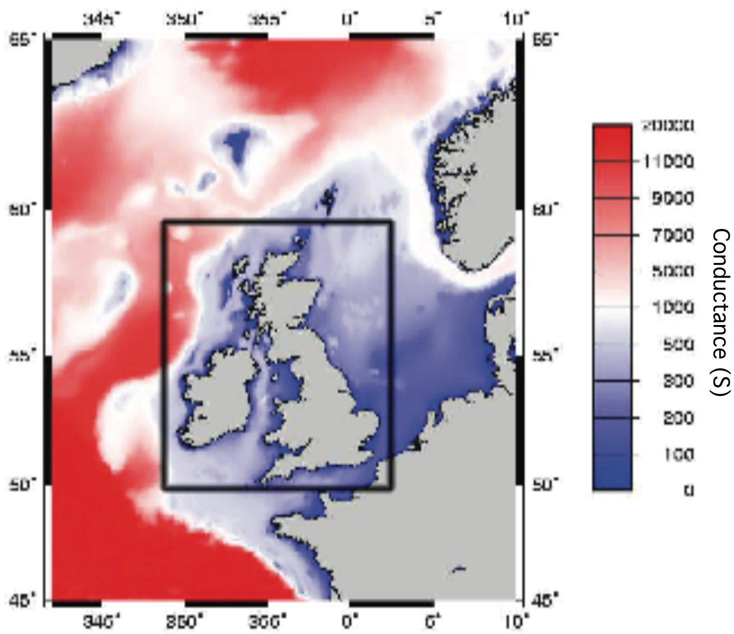
- GIC model require three key inputs, specifically:-

1. A realistic description of the power transmission system, including the location of nodes and connections, as well as line resistances, earthing and transformer resistances
2. A realistic description of the Earth's surface conductivity in the region of the power transmission system
3. Knowledge of the electric field imposed upon the surface of the Earth over the grid

Surface Conductivity



From Thomson *et al.* [2005]



From McKay [2003]

(Slide courtesy of Jim Wild, University of Lancaster)

Other space weather effects include;

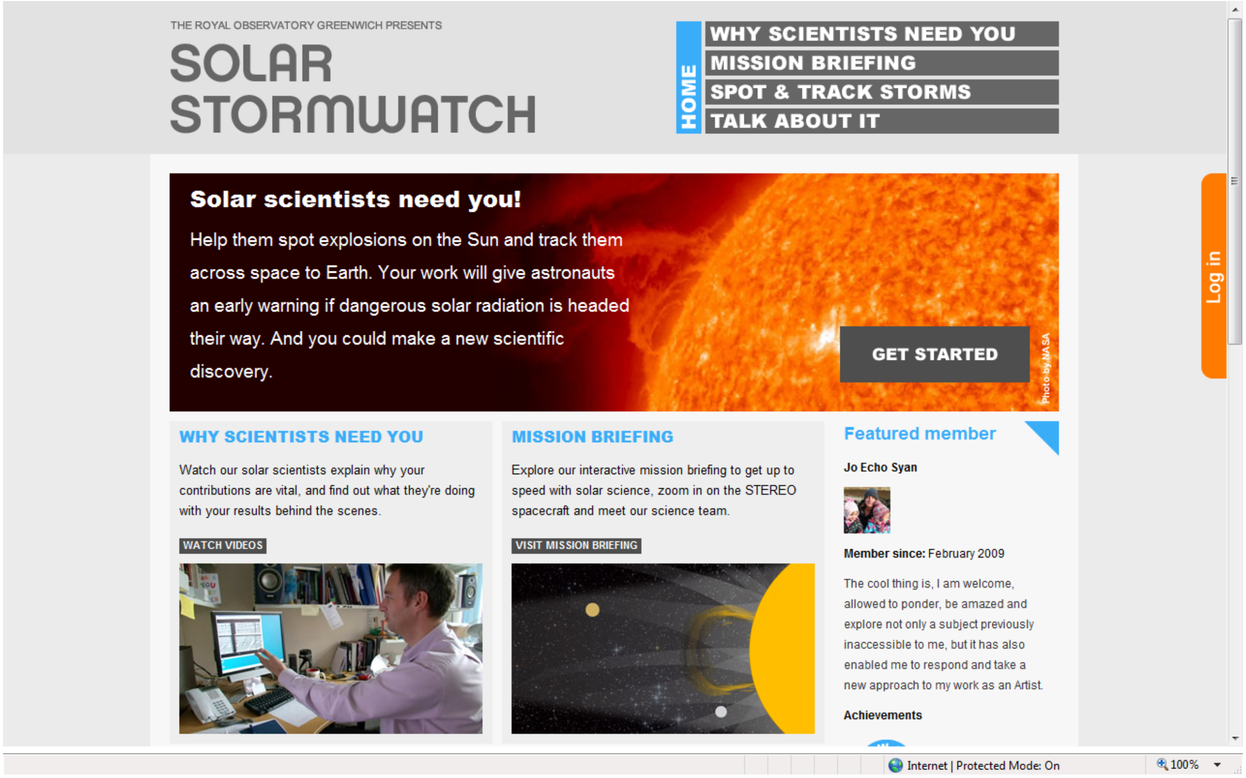
•Loss of HF communication (particularly important to trans-Atlantic aircraft)

•Increased radiation exposure for trans-Atlantic passengers overflying the poplar regions

•Increased susceptibility of modern ‘fly-by-wire’ aircraft to cosmic rays

STEREO is a science project, not an operational space-weather mission. Nevertheless, efforts are being made to use STEREO data in real-time space-weather forecasting.

The UK HI team, in collaboration with the Royal Greenwich Observatory and the Galaxy Zoo team have created the citizen science project Solar Stormwatch (www.solarstormwatch.com) in which interested members of the public apply these techniques to the real-time HI data in order to provide estimates of CME speeds and directions.
Their predicitons are made via the website and twitter.


THE ROYAL OBSERVATORY GREENWICH PRESENTS
SOLAR STORMWATCH
HOME
WHY SCIENTISTS NEED YOU
MISSION BRIEFING
SPOT & TRACK STORMS
TALK ABOUT IT
Solar scientists need you!
Help them spot explosions on the Sun and track them across space to Earth. Your work will give astronauts an early warning if dangerous solar radiation is headed their way. And you could make a new scientific discovery.
GET STARTED
Photo by NASA
Log in
WHY SCIENTISTS NEED YOU
Watch our solar scientists explain why your contributions are vital, and find out what they're doing with your results behind the scenes.
WATCH VIDEOS
MISSION BRIEFING
Explore our interactive mission briefing to get up to speed with solar science, zoom in on the STEREO spacecraft and meet our science team.
VISIT MISSION BRIEFING
Featured member
Jo Echo Syan
Member since: February 2009
The cool thing is, I am welcome, allowed to ponder, be amazed and explore not only a subject previously inaccessible to me, but it has also enabled me to respond and take a new approach to my work as an Artist.
Achievements
Internet | Protected Mode: On
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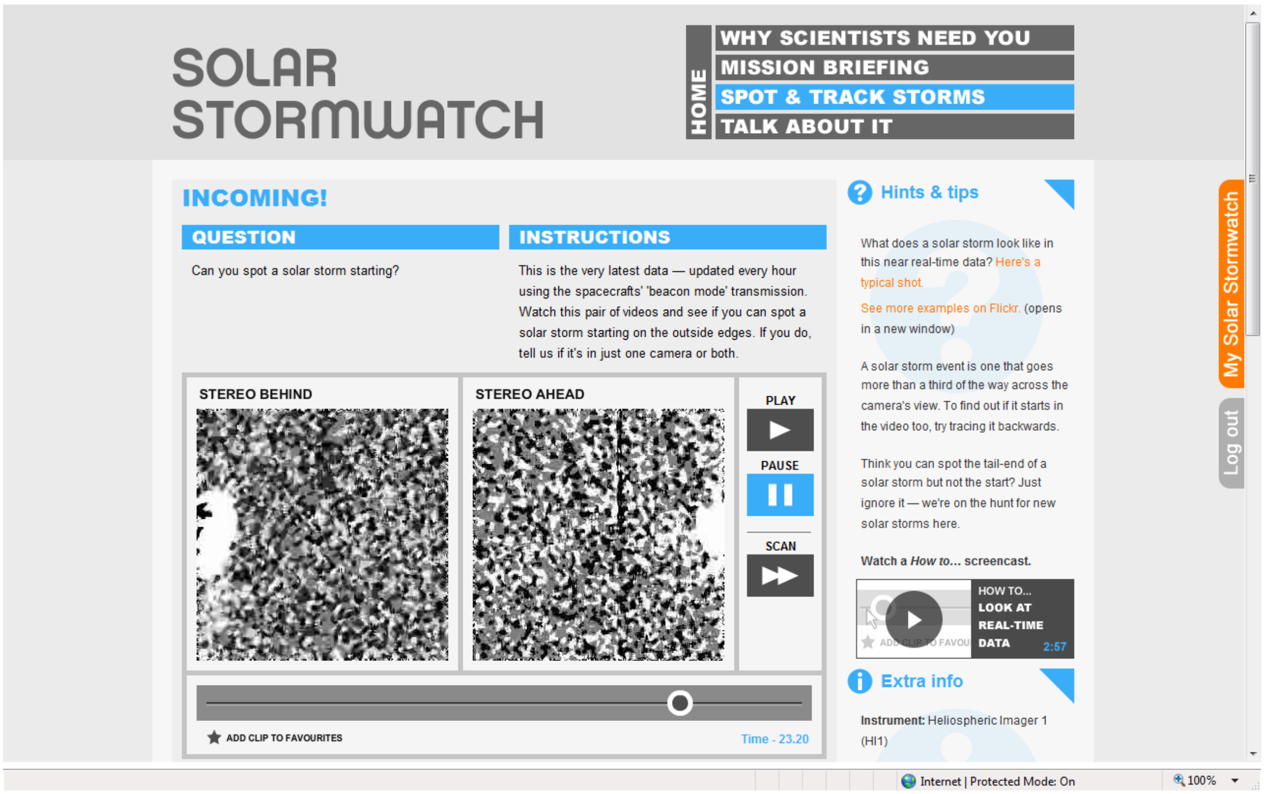
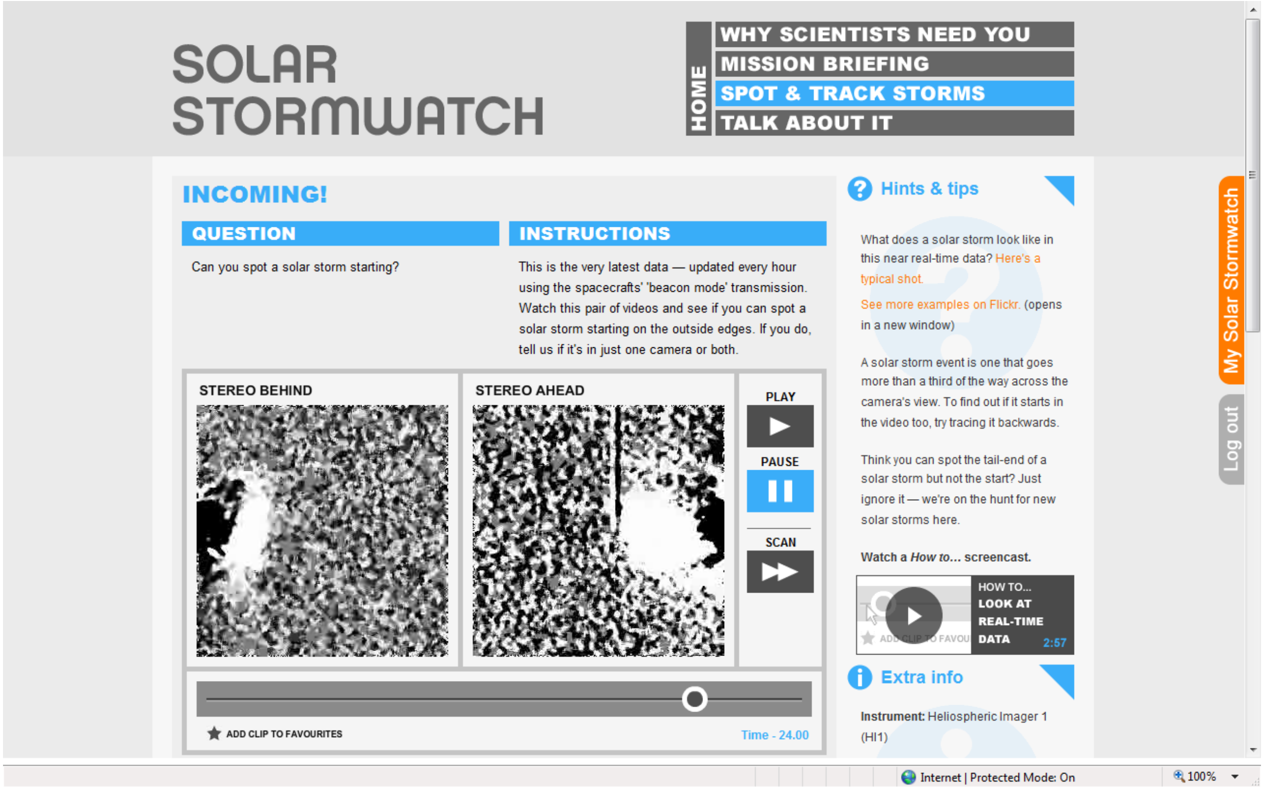
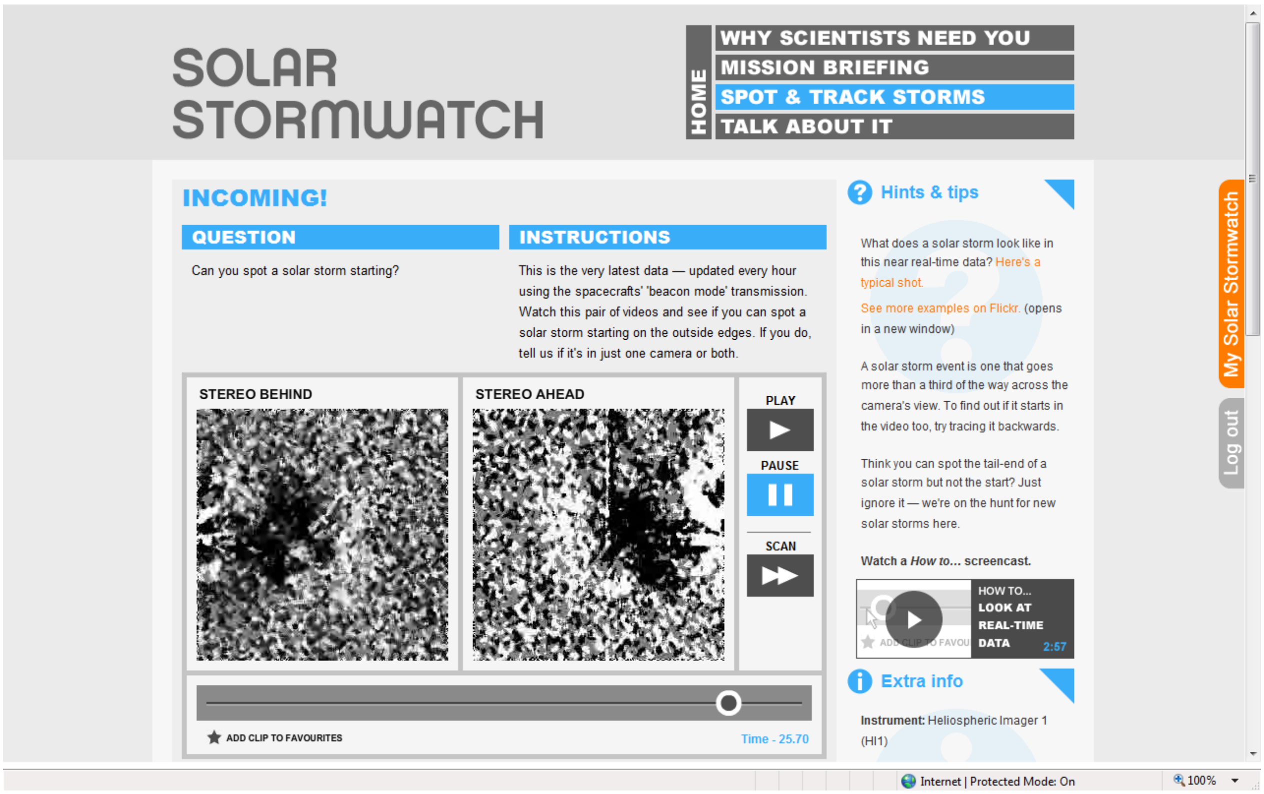

SOLAR STORMWATCH
HOME
WHY SCIENTISTS NEED YOU
MISSION BRIEFING
SPOT & TRACK STORMS
TALK ABOUT IT
INCOMING!
QUESTION
Can you spot a solar storm starting?
INSTRUCTIONS
This is the very latest data — updated every hour using the spacecrafts' 'beacon mode' transmission. Watch this pair of videos and see if you can spot a solar storm starting on the outside edges. If you do, tell us if it's in just one camera or both.
STEREO BEHIND
STEREO AHEAD
PLAY
PAUSE
SCAN
ADD CLIP TO FAVOURITES
Time - 23.20
Hints & tips
What does a solar storm look like in this near real-time data? Here's a typical shot.
See more examples on Flickr. (opens in a new window)
A solar storm event is one that goes more than a third of the way across the camera's view. To find out if it starts in the video too, try tracing it backwards.
Think you can spot the tail-end of a solar storm but not the start? Just ignore it — we're on the hunt for new solar storms here.
Watch a How to... screencast.
HOW TO... LOOK AT REAL-TIME DATA 2:57
Extra info
Instrument: Heliospheric Imager 1 (HI1)
My Solar Stormwatch
Log out
Internet | Protected Mode: On
100%





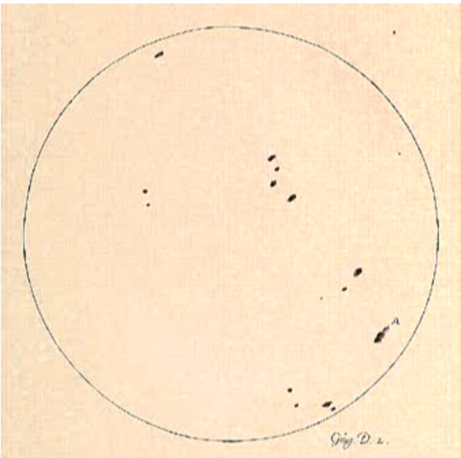
www.solarstormwatch.com

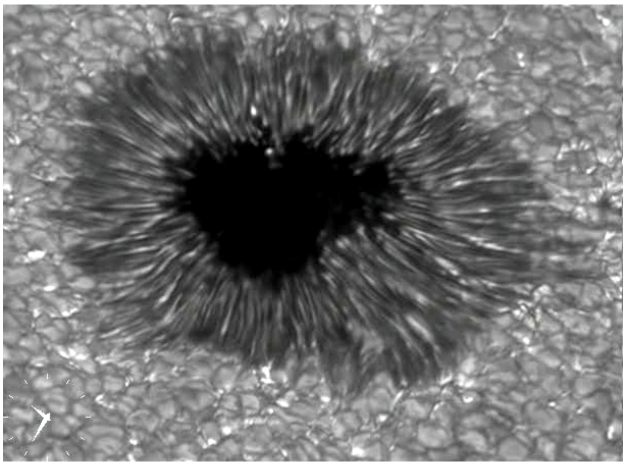
Space Climate

With many thanks to Mathew Owens and
Mike Lockwood

September 7, 2012

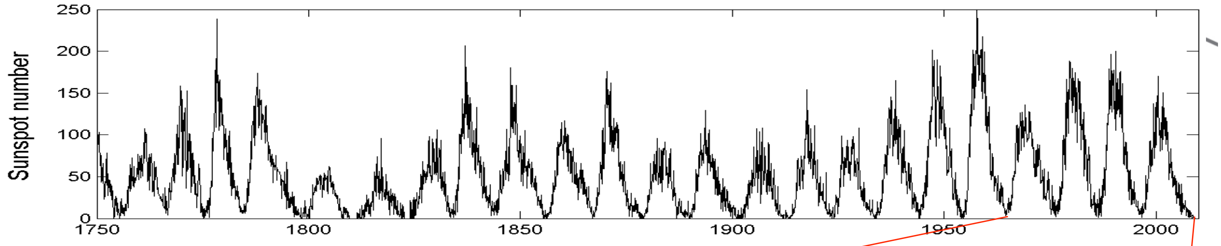
Sunspots – evidence of photospheric structure

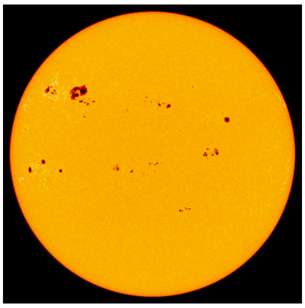


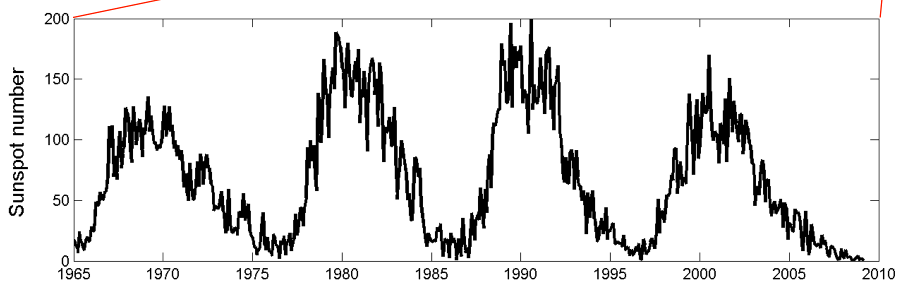


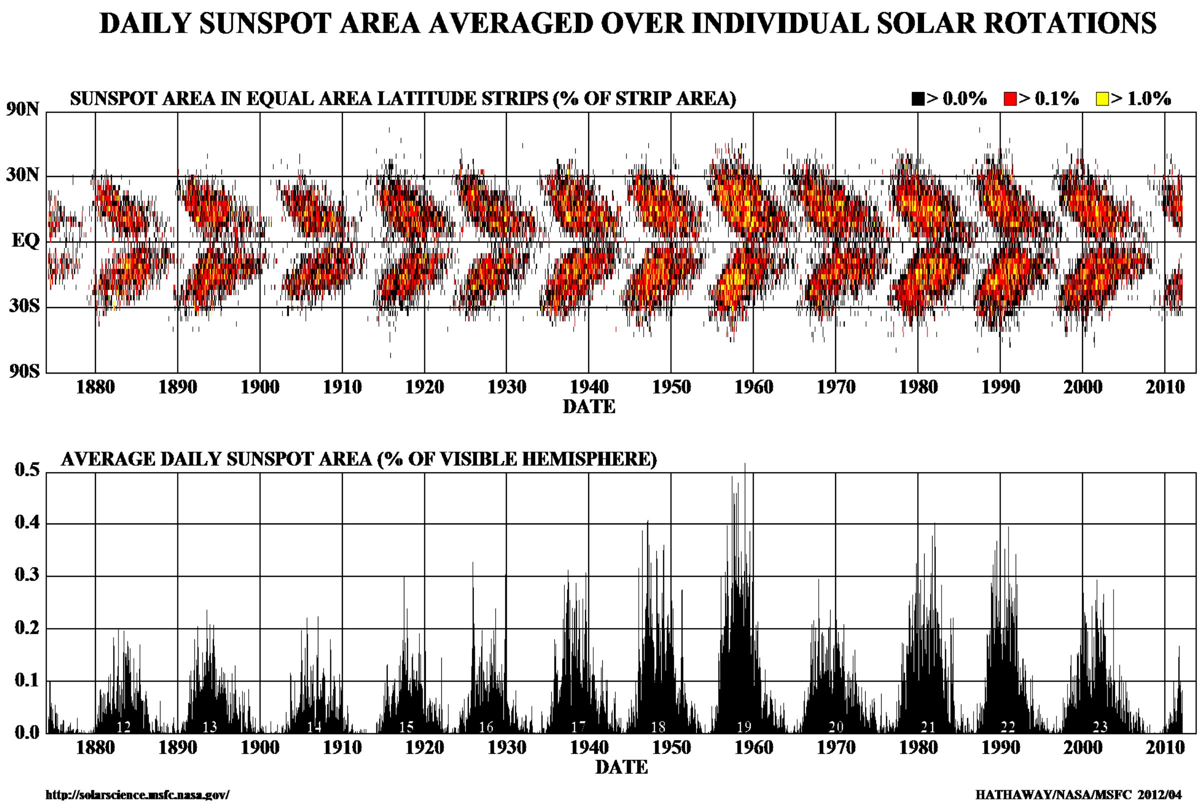
Sunspot number records

Royal Greenwich Observatory data



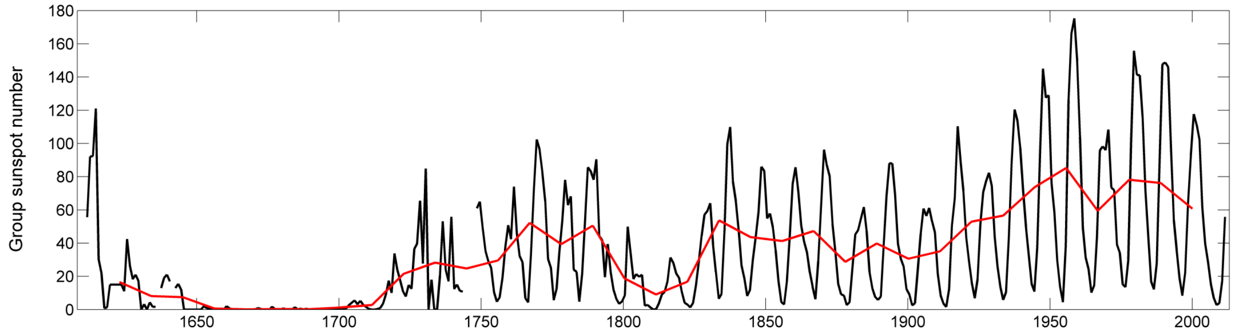






Group sunspot number

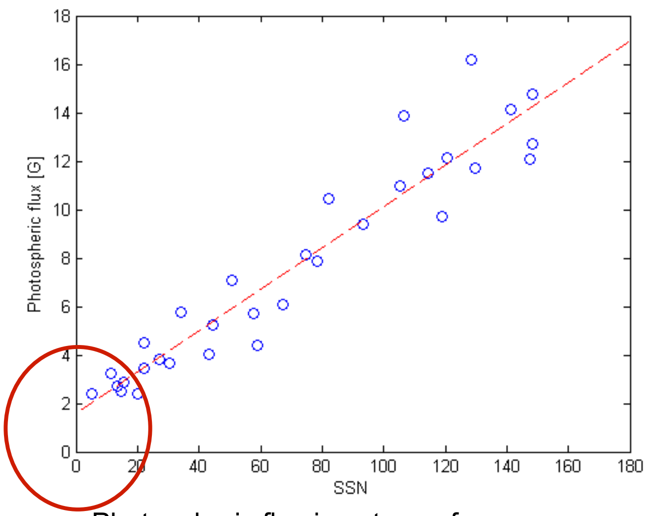
Hoyt & Schatten, Sol. Phys, 1998



What does sunspot number actually measure?

No, really.

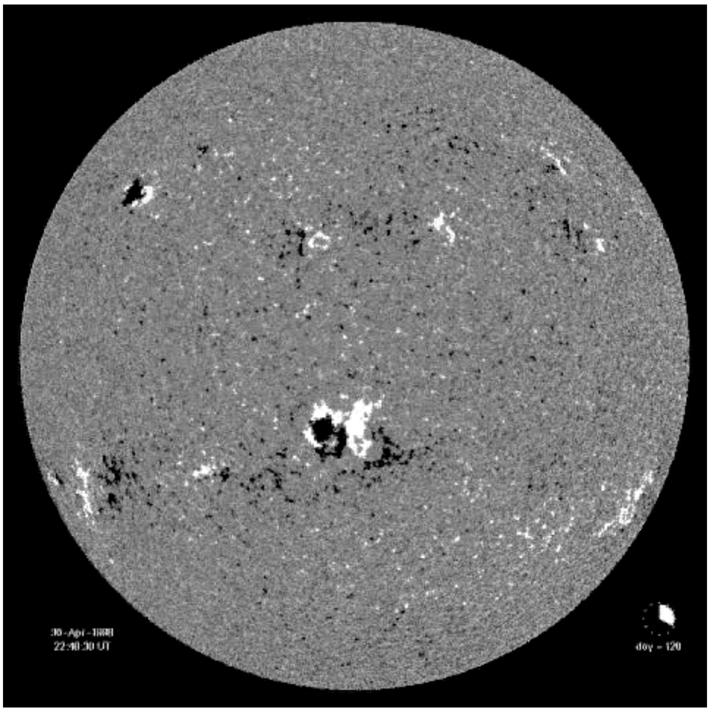
- Changing observers, changing eyesight, changing telescopes, even changing methods of counting!
- At best, sunspot number is a threshold concept
  - – Flux still emerges at R=0



Photospheric flux is not zero for zero sunspot number!

Photospheric flux

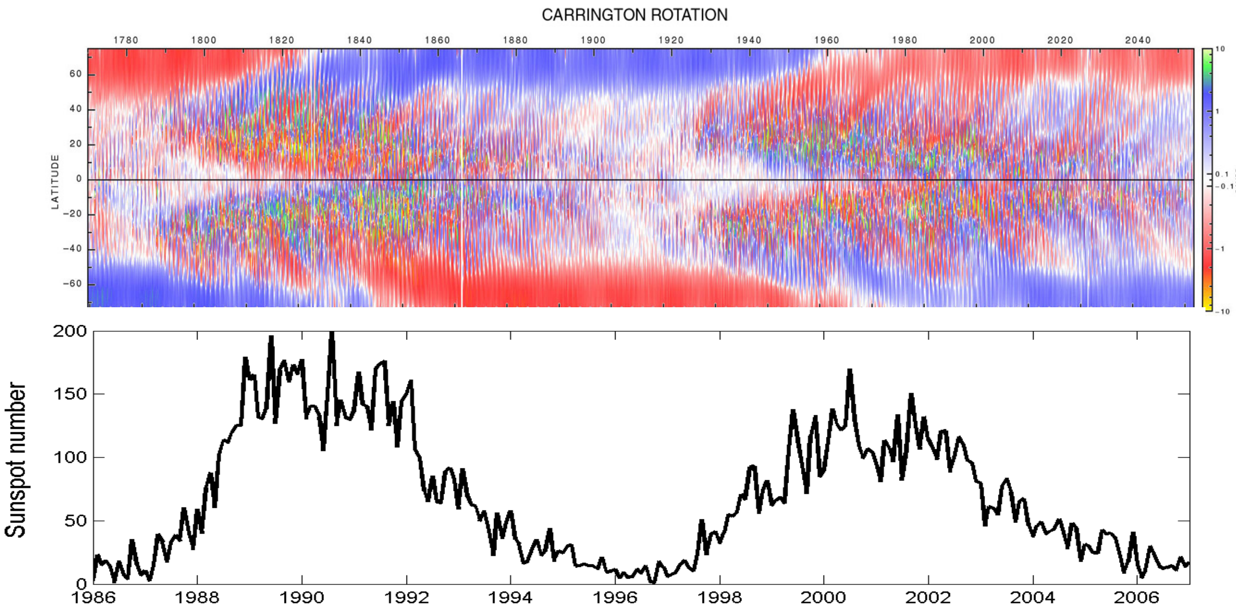
SOHO MDI magnetogram



- Zeeman splitting to measure line-of-sight B
- Magnetograms back to 1970s
- Hard to observe polar regions

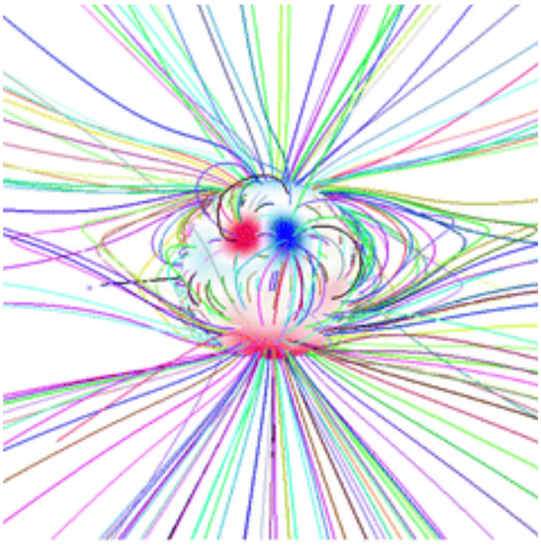
Photospheric flux

Top: David Hathaway, MSFC



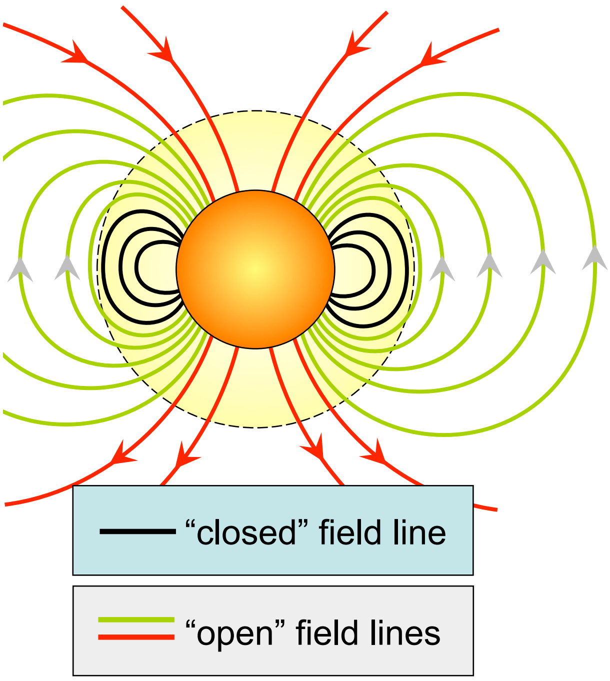
Modelling the corona

Left: Riley et al., 2006; Owens et al., 2008a
Right: Eclipse photograph, Carlos & Espenak, 1995.



Open Solar Flux

Flux threading the coronal source surface

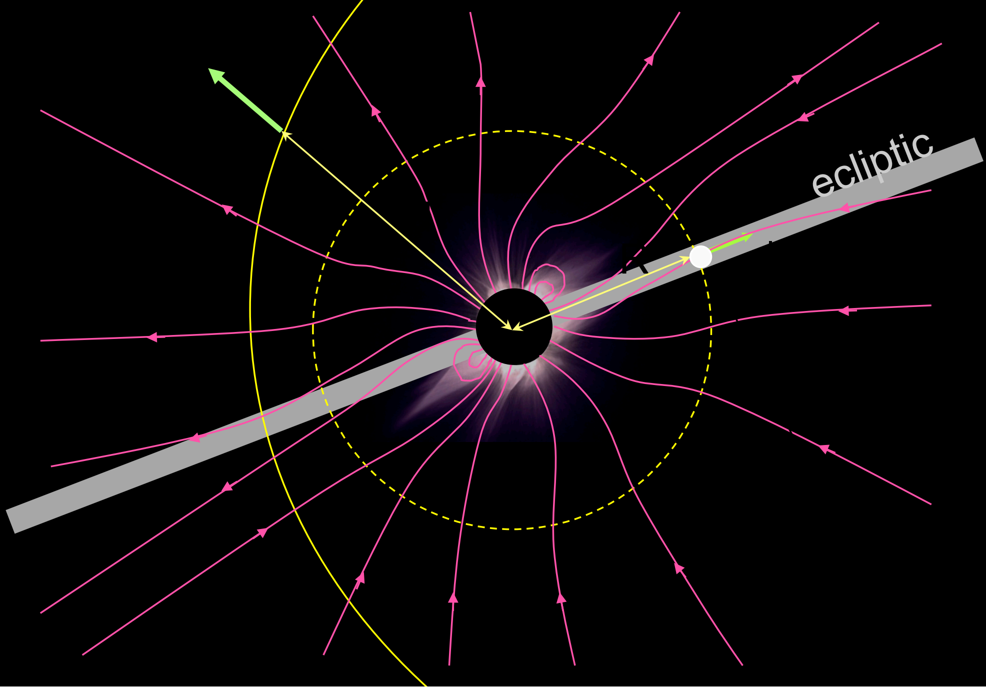


Unsigned Flux,

$$F_U = \int_{-\pi/2}^{+\pi/2} \int_{0}^{2\pi} |B_R|\, r^2 \cos(\theta)\, d\theta\, d\phi$$

r = heliocentric distance
B_R = radial field
θ = solar latitude
ϕ = solar longitude

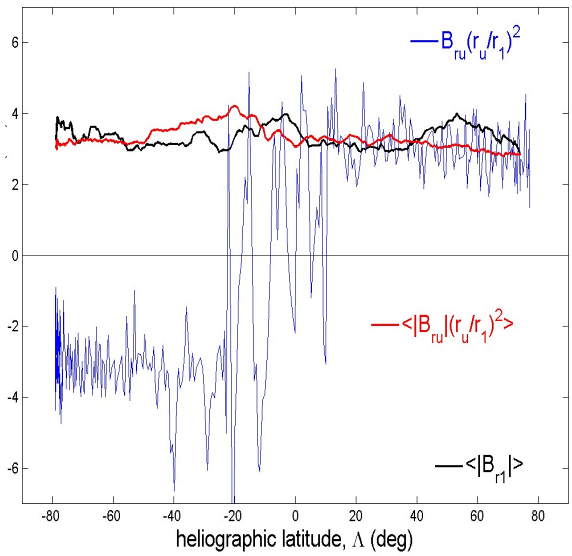
Ulysses

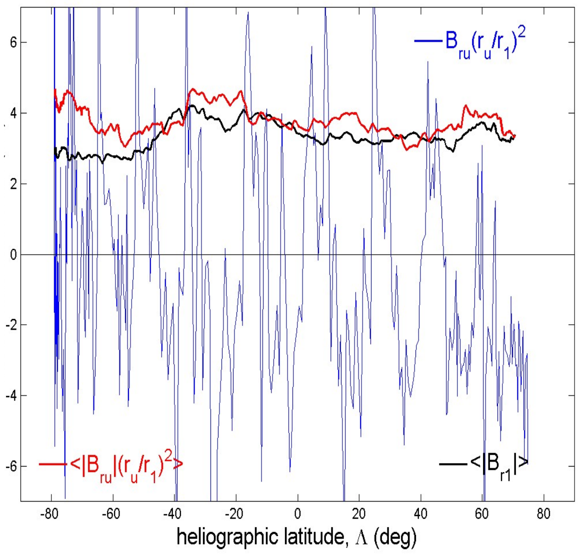


Ulysses Perihelion passes

(Fast Latitude Scans)

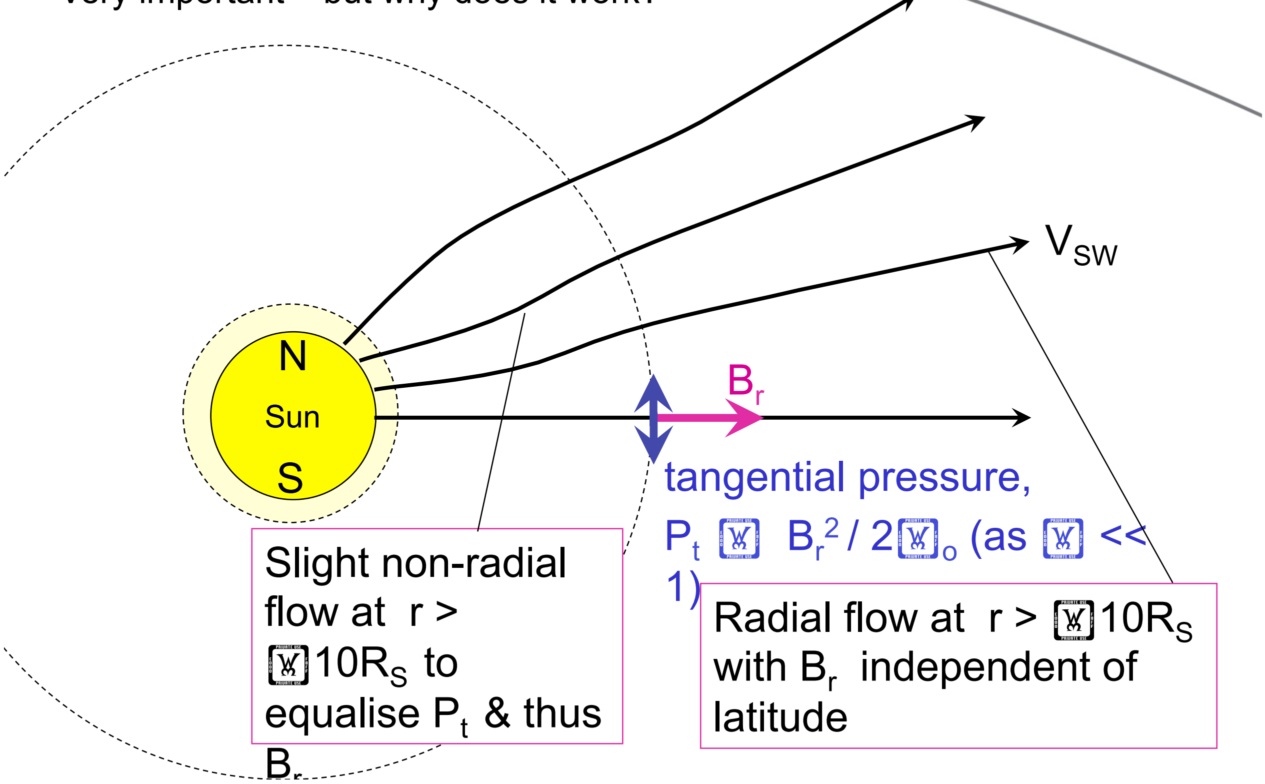
- 1st - near sunspot min
- 2nd - near sunspot





The “Ulysses Result”

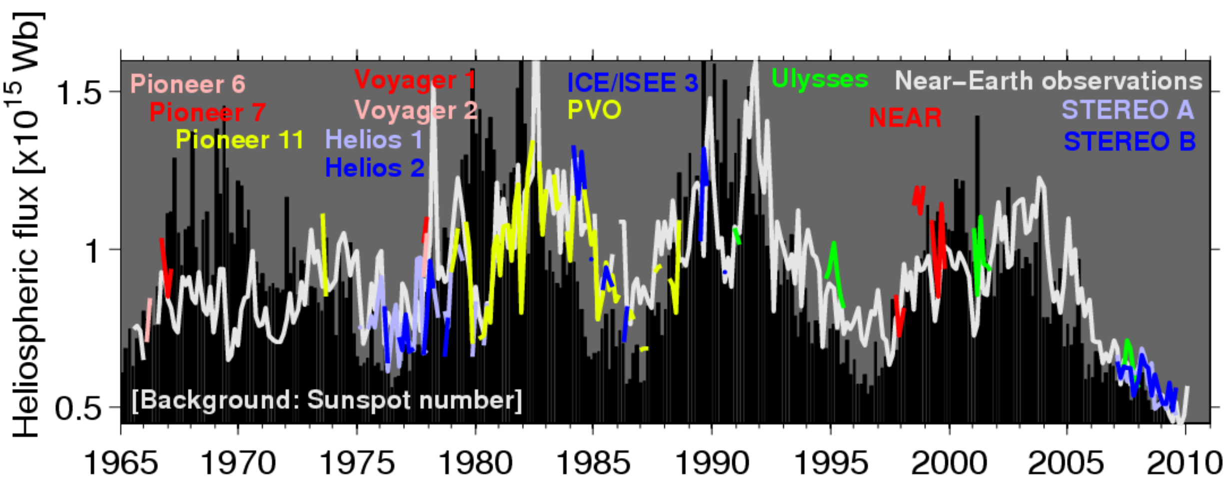
Very important – but why does it work?



University of Reading
RAL Space

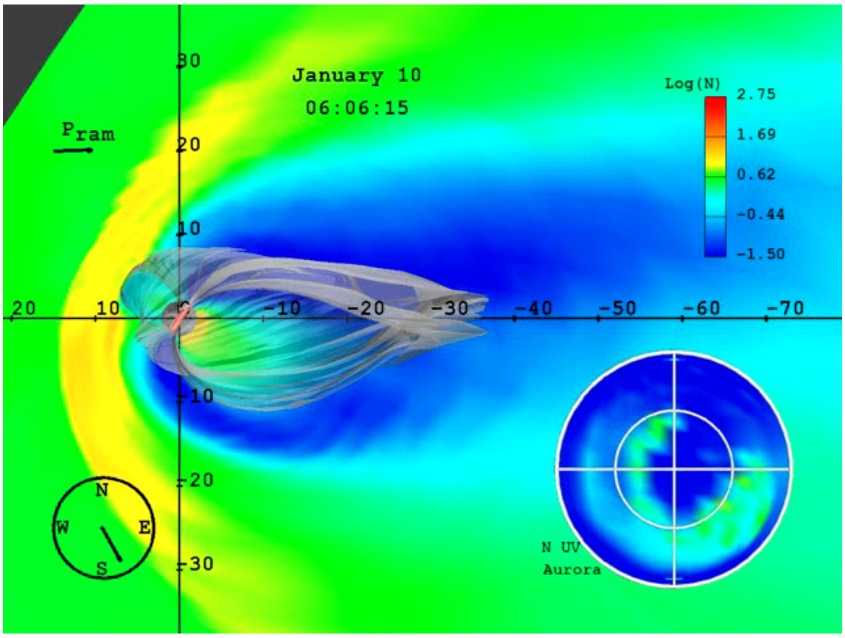
Heliospheric magnetic flux

Owens et al., JGR, 2008



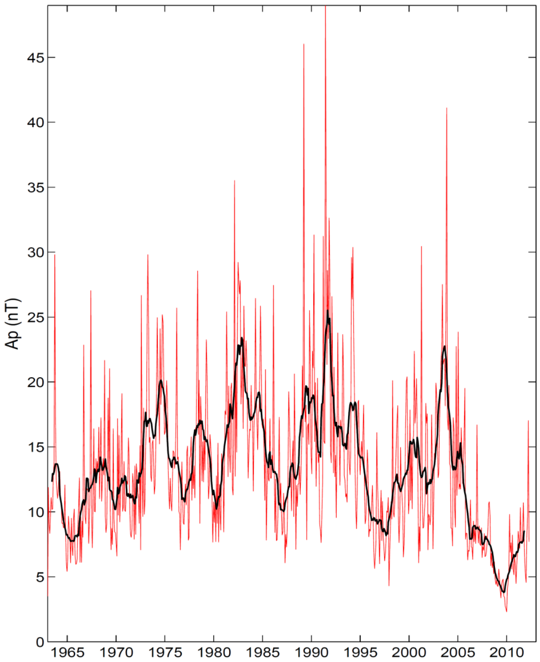
Geomagnetic disturbances

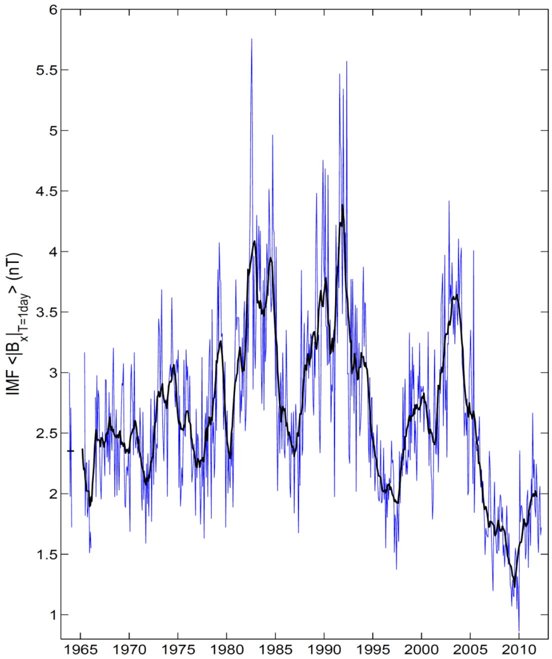
Movie courtesy John Lyon of the CISM group



Geomagnetic Ap Index

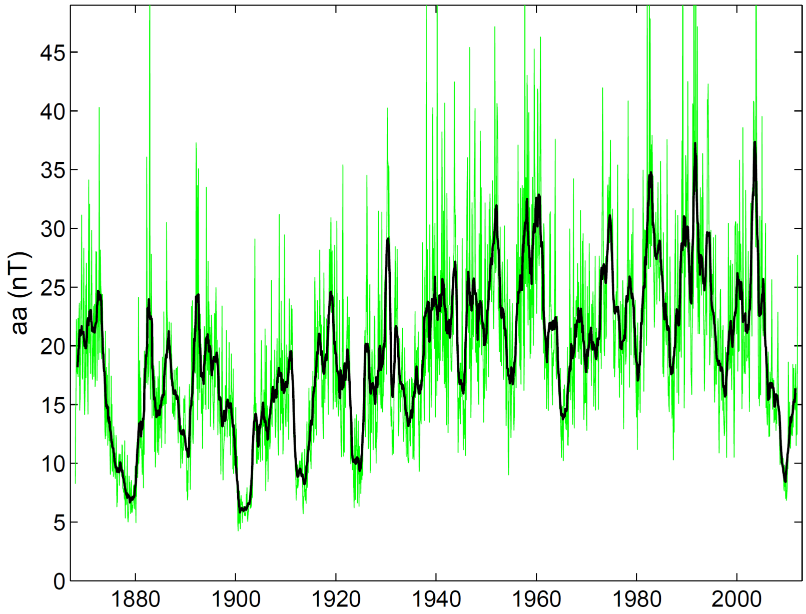
(from 13 stations around the globe)





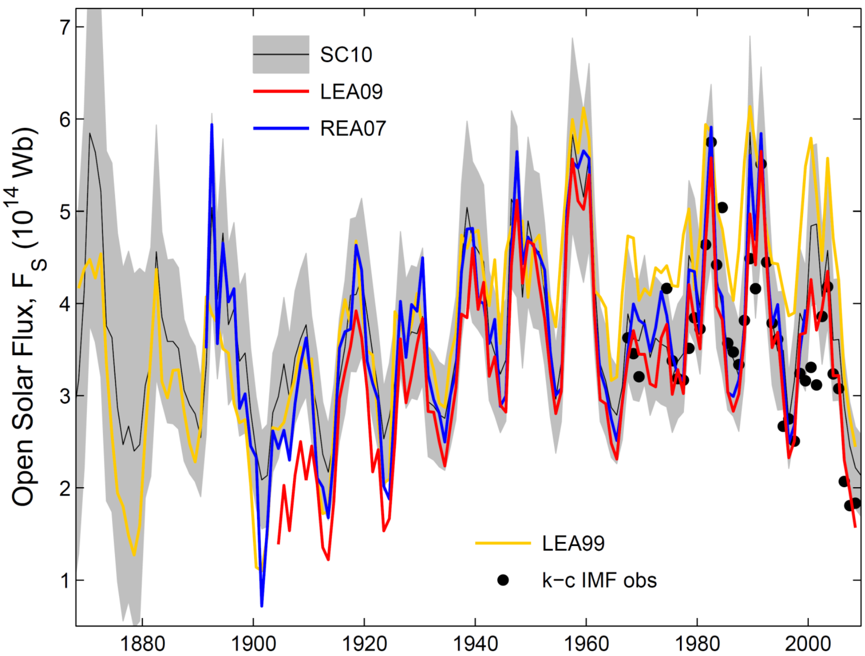
aa Geomagnetic index

(from 2 stations. Mayaud, 1972)

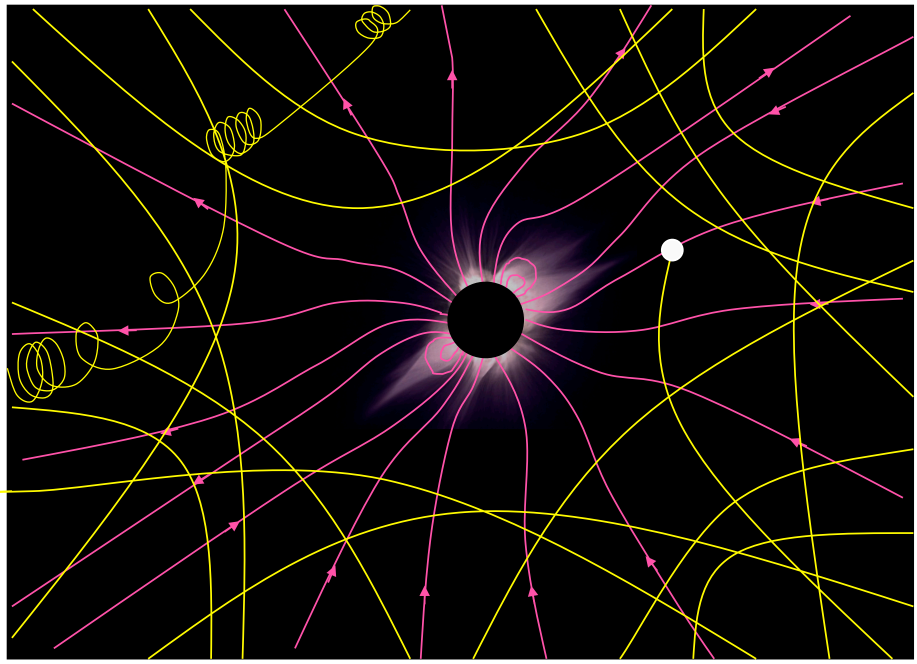


Open solar flux reconstructions

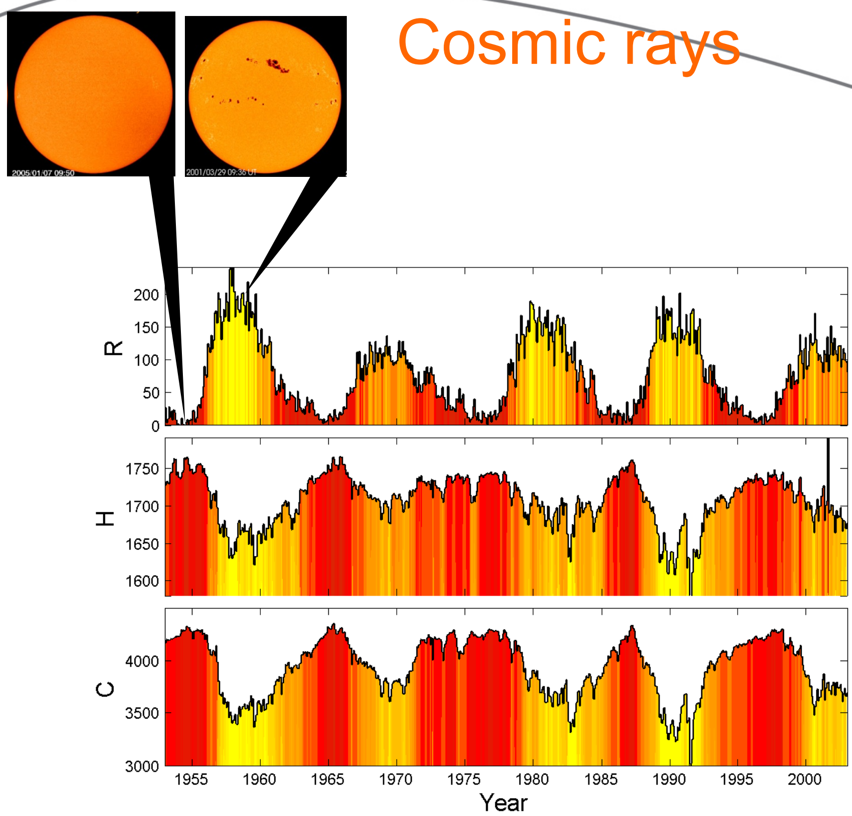
- LEA99 –Lockwood et al 1999. No kinematic correction
- REA07 – Rouillard et al. (2007). Uses modulus on averages over T = 1 day
- LEA09 – Lockwood et al. (2009). Uses kinematic correction
- based on SC10 – Svalgaard and Cliver (2010) fit of OSF and B (±1σ)

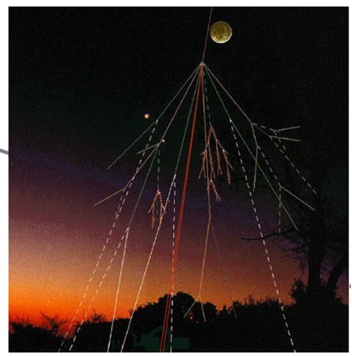


Galactic cosmic rays



Cosmic rays





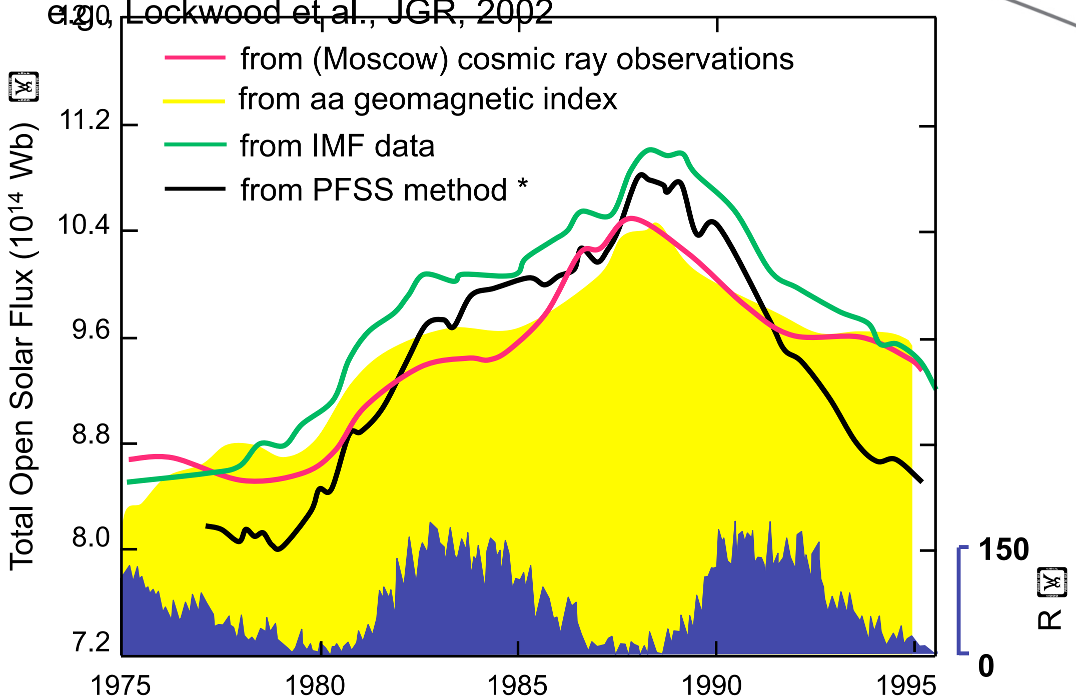
Sunspot Number

Huancauyo – Hawaii neutron monitor counts (>13GV)

Climax neutron monitor counts (>3GV)

Rise and fall of open solar flux

e.g., Lockwood et al., JGR, 2002



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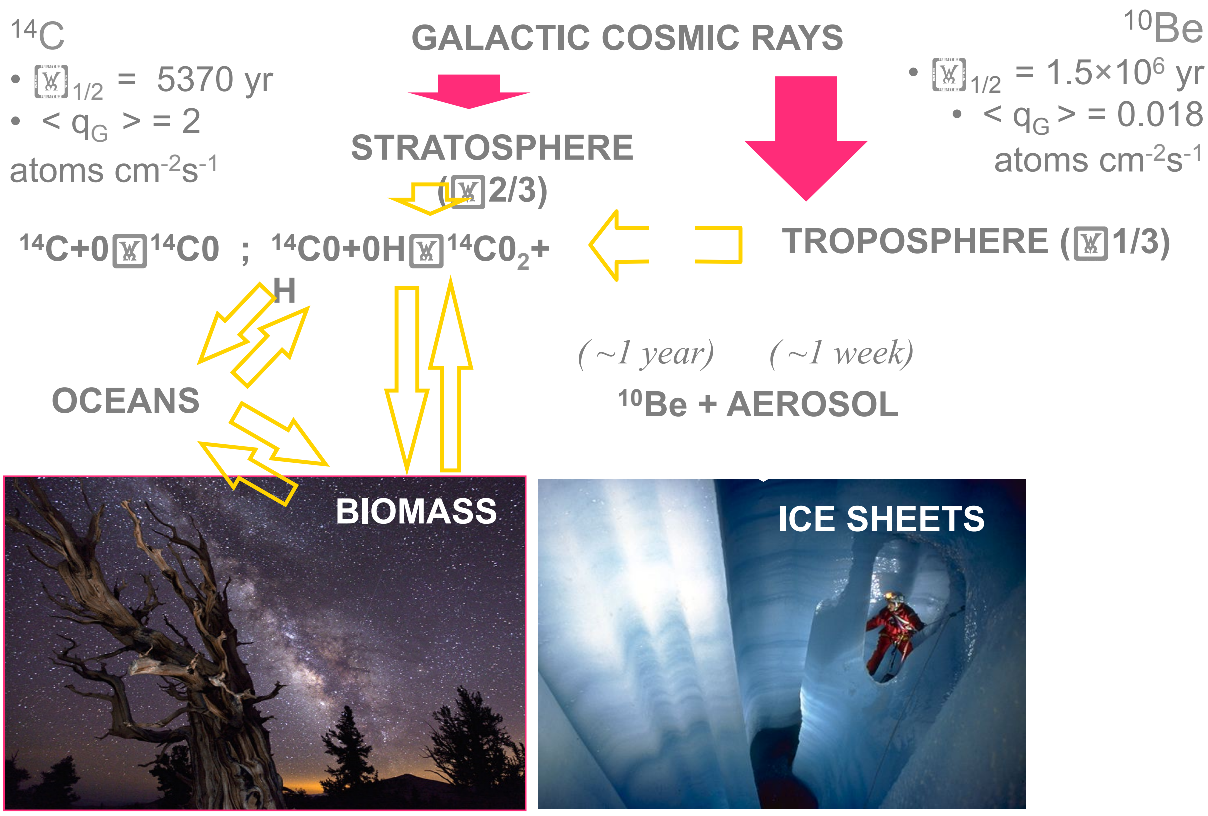
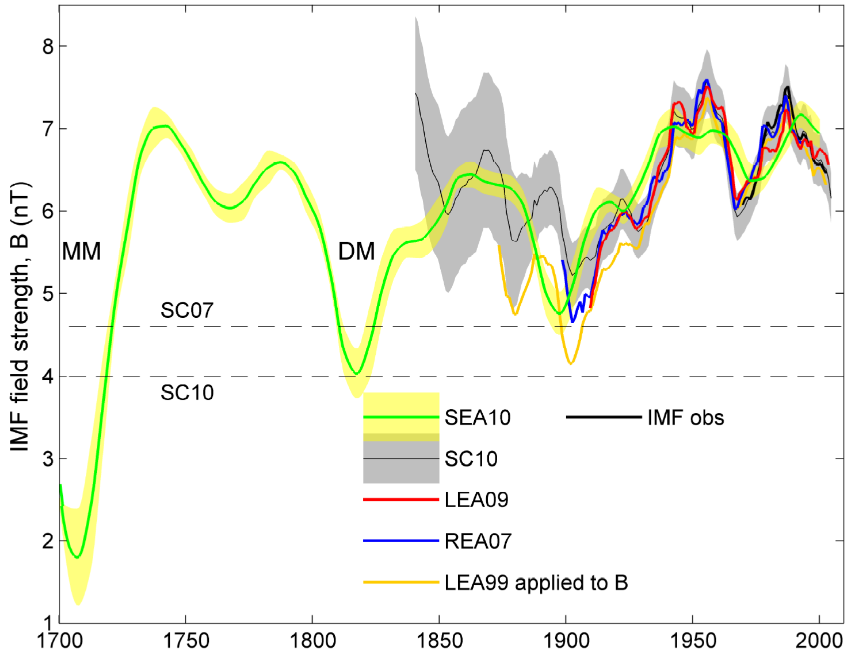
^{14}C & ^{10}Be: spallation products from O, N & Ar



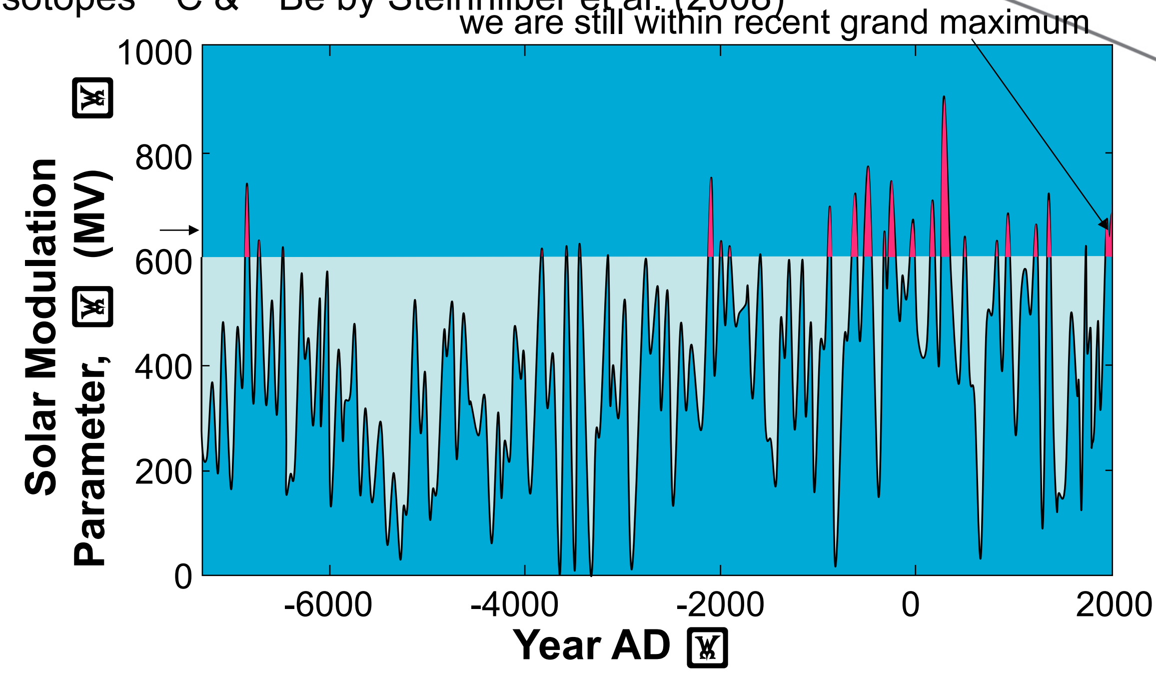
Ice core reconstructions

Steinhilber et al., JGR, 2010



Millennial Variation

composite (40-year means) from cosmogenic isotopes ^{14}C & ^{10}Be by Steinhilber et al. (2008)



Solanki et al., 2004; Vonmoos et al., 2006 & Muscheler et al., 2007

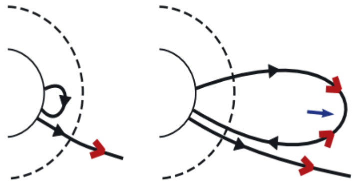
Modelling open solar flux

Solanki et al., Nature, 2000

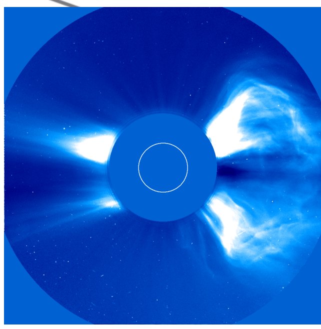
- OSF can be modelled as a continuity equation

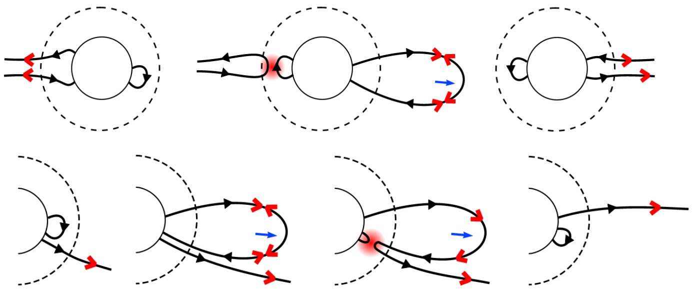
$$\frac{d(\mathrm{OSF})}{dt} = S - L$$

- Source: New closed loops. Sunspots or CMEs
- Loss: Disconnection of magnetic flux. ???



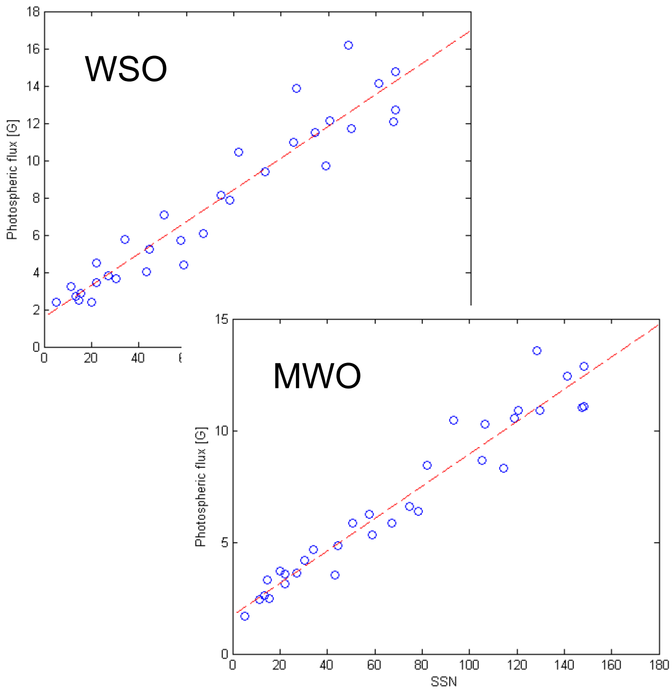
Owens and Crooker, JGR, 2006

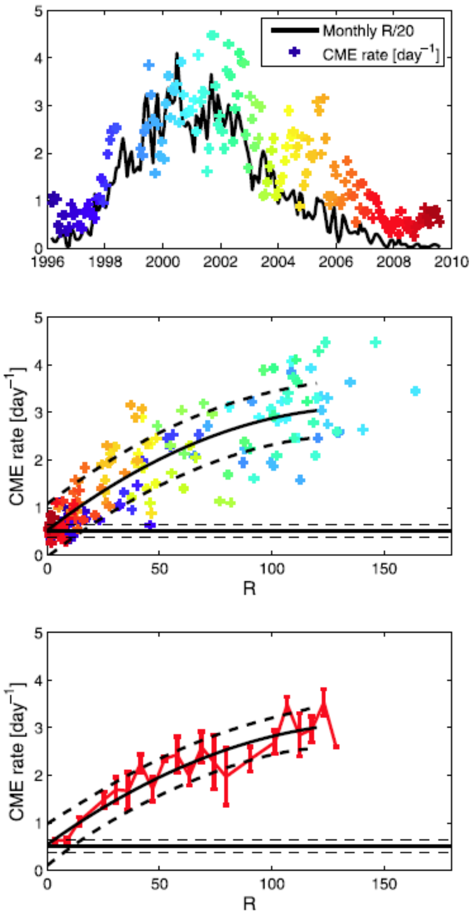




Owens and Crooker, JGR, 2007

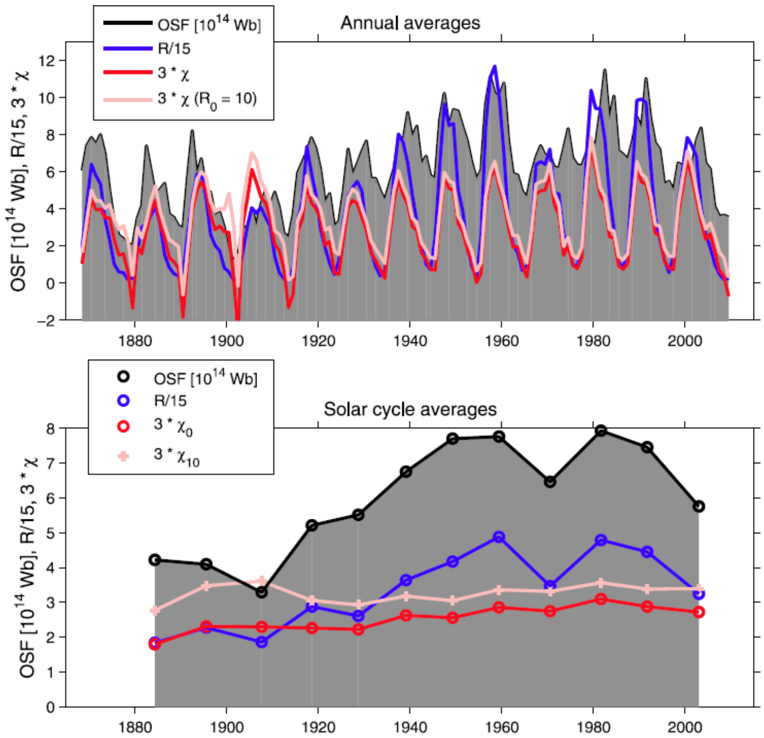
Coronal mass ejections and sunspot number



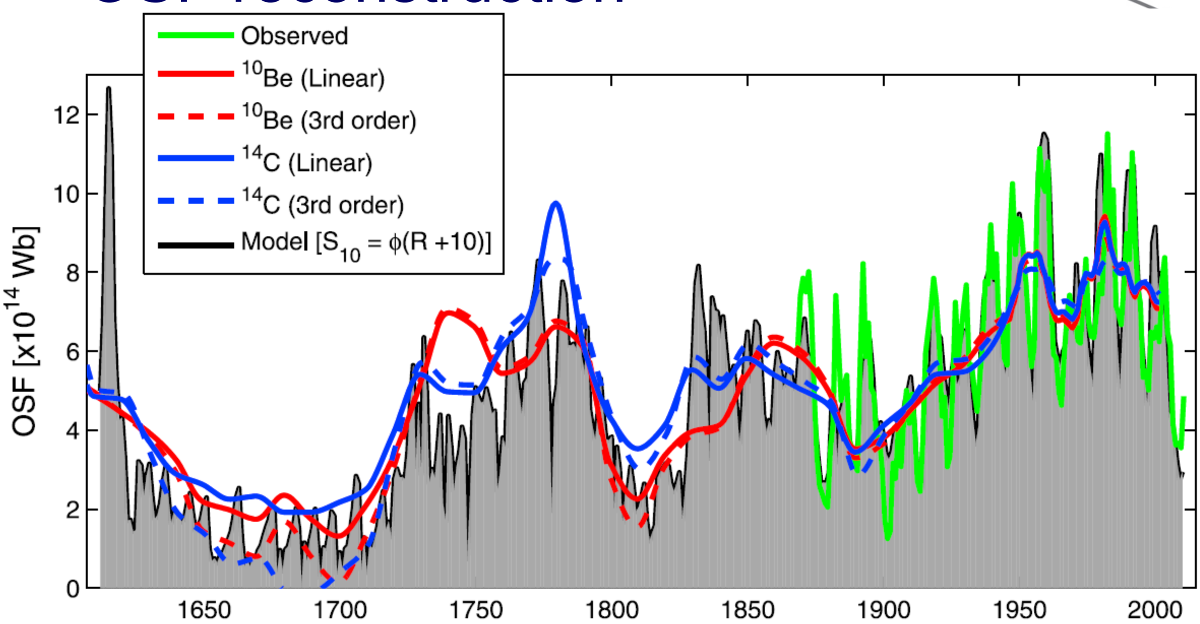


Computing the OSF loss rate

Owens and Lockwood, JGR, 2012

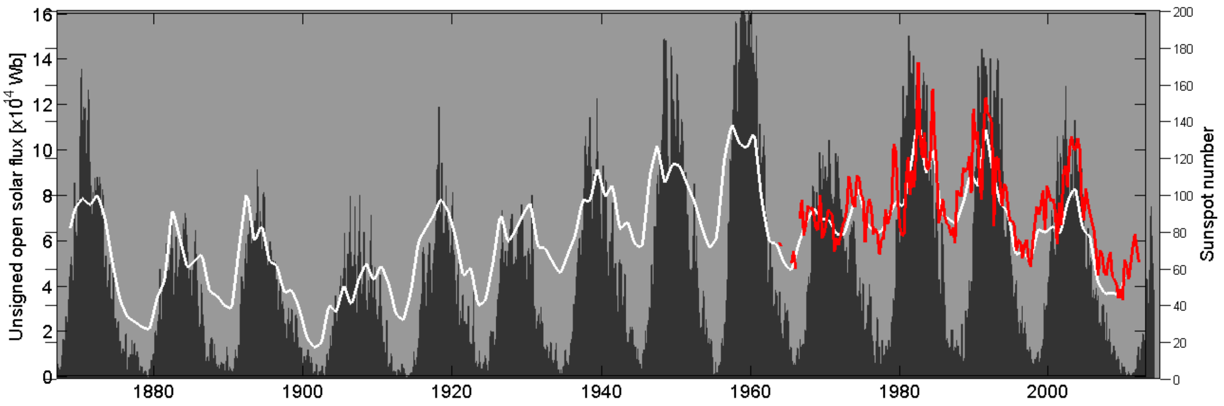


OSF reconstruction

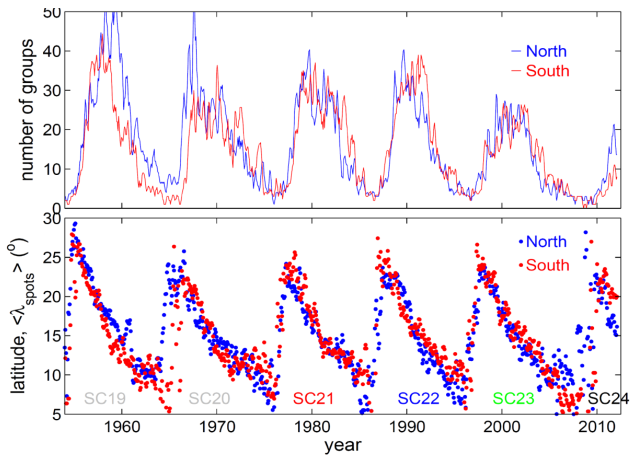


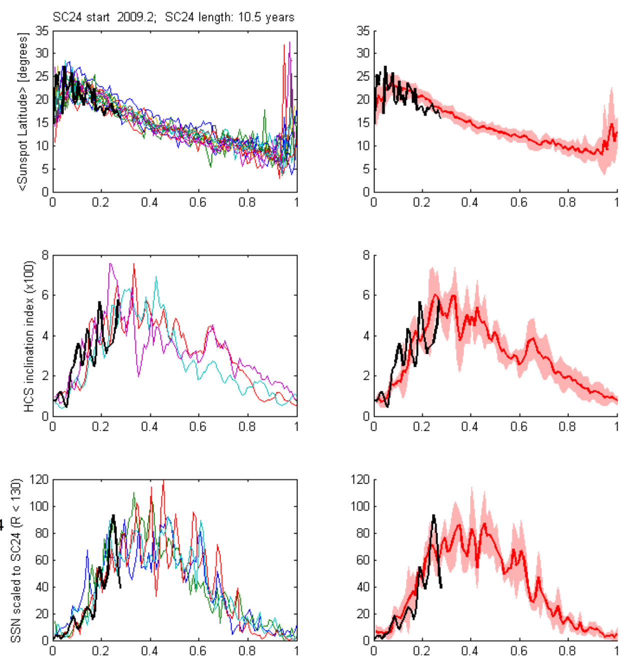
Cycle 24 – where are we now?

Unsigned open solar flux



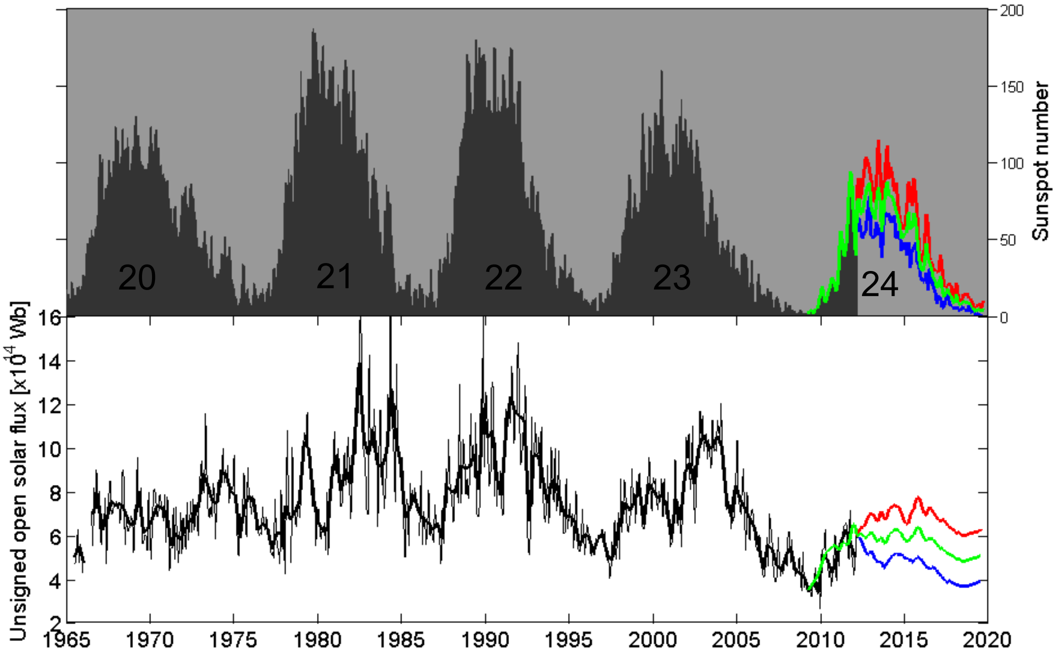
Cycle 24 – where are we now?





Where are we going?

The next solar cycle



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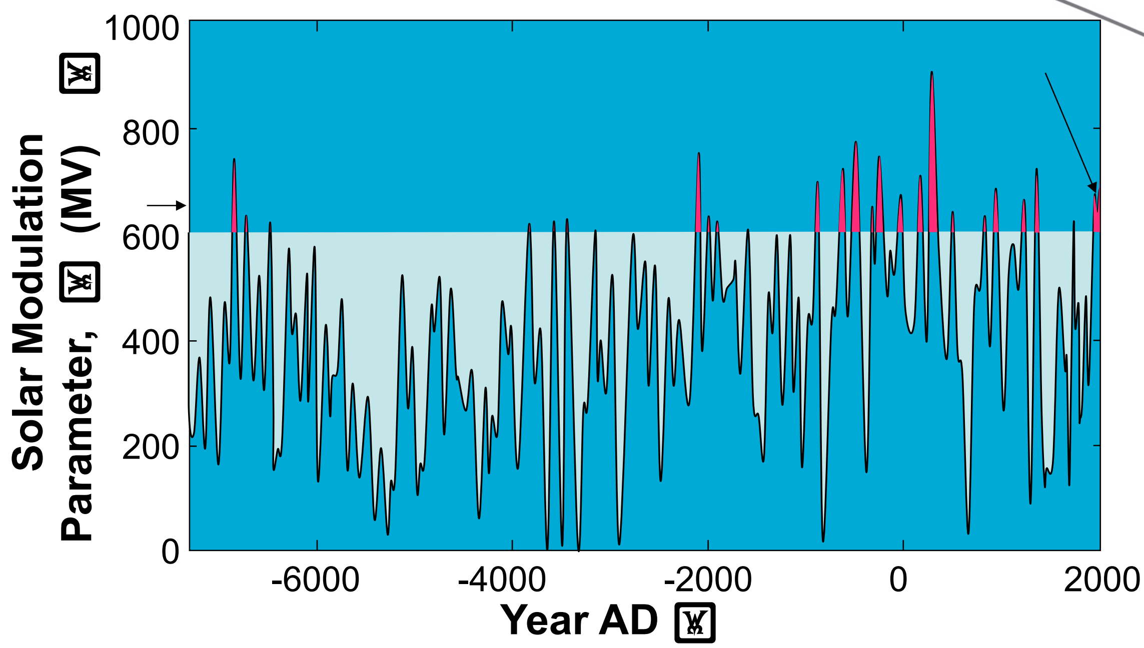
End of the Grand Solar Maximum

Abreu et al. JGR, 2008

we are still within recent grand maximum



Solanki et al., 2004; Vonmoos et al., 2006 & Muscheler et al., 2007

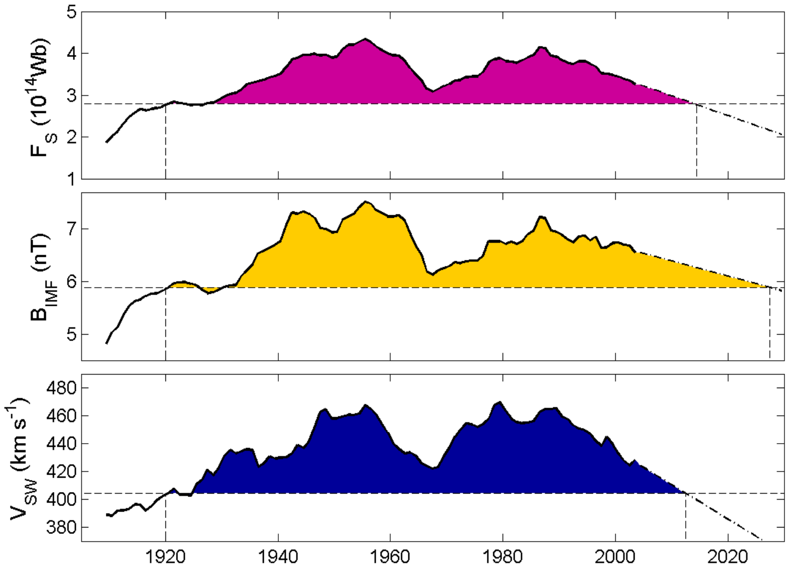
End of a Grand Solar Maximum

Abreu et al., JGR, 2008

Solar cycle running means

Defining GSM by [?] > 600 MV, it began in 1920

Linear extrapolation gives end dates consistent with GSM durations



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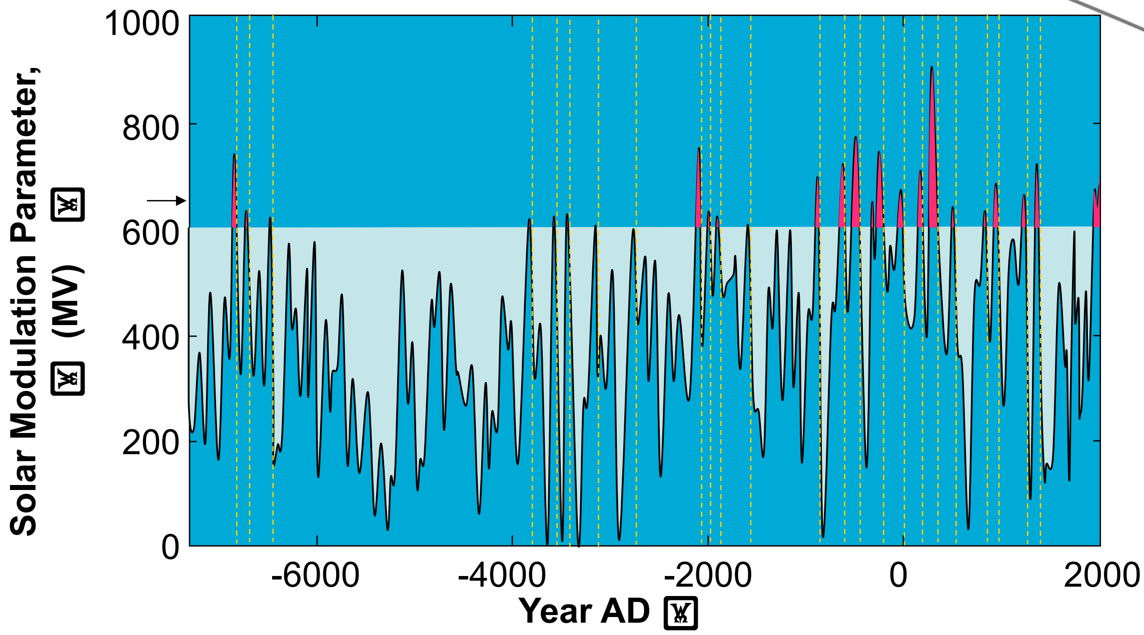
End of previous GSMs

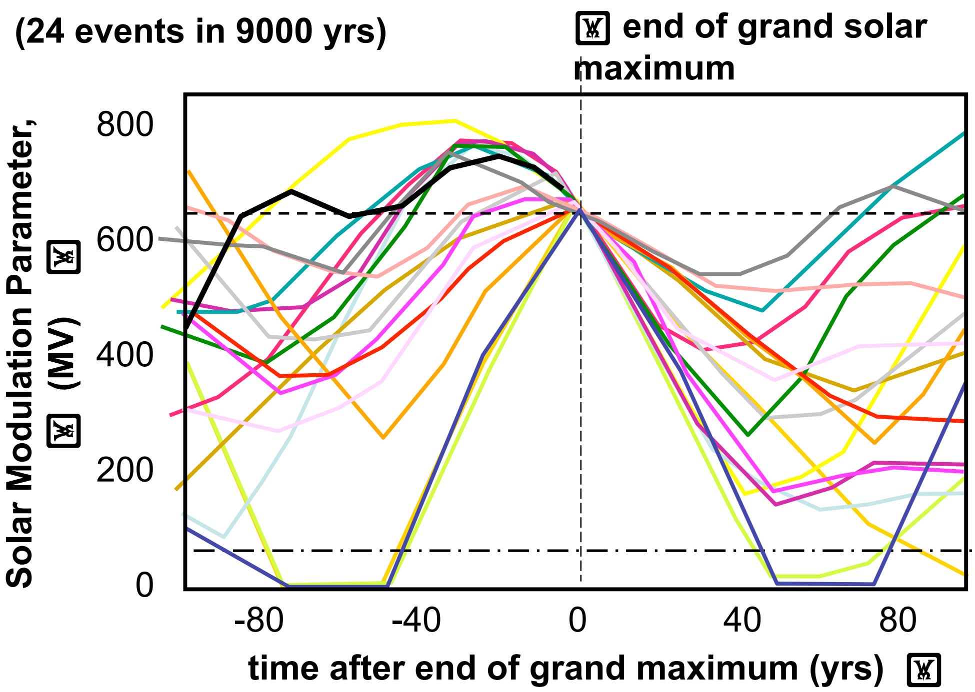
Steinhilber et al. (2008)



Previous GSMs

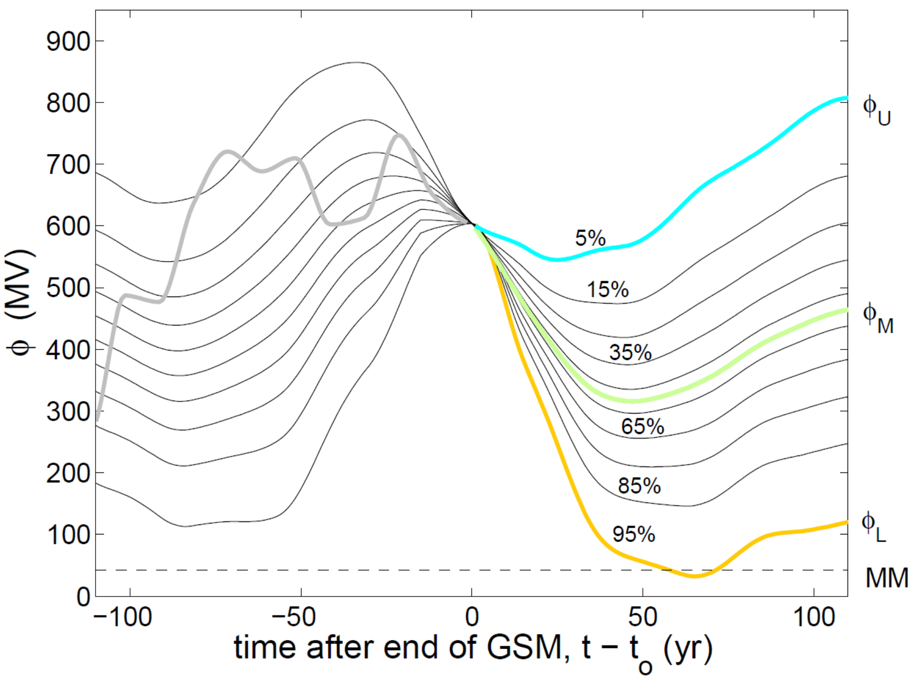
Barnard et al., GRL, 2011

(24 events in 9000 yrs)



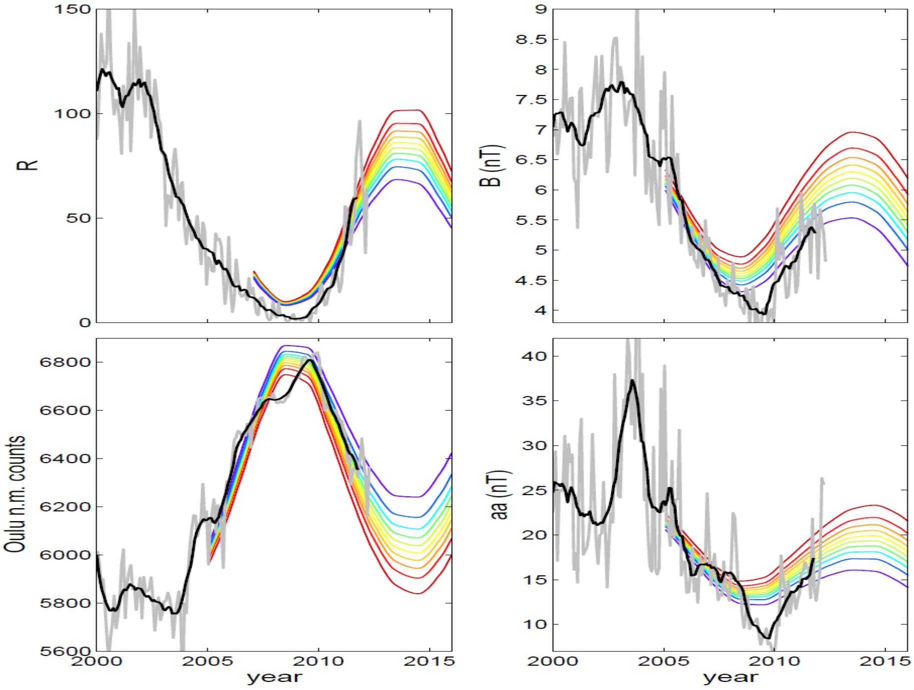
"Analogue" forecast

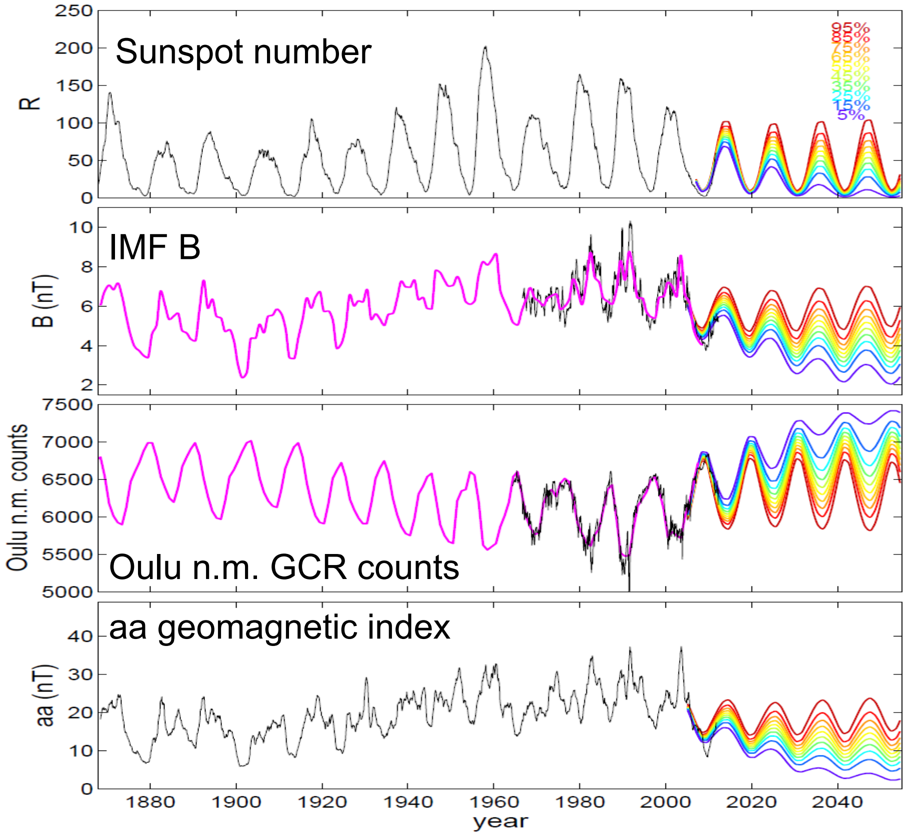
Barnard et al., GRL, 2011



“Analogue” forecasts

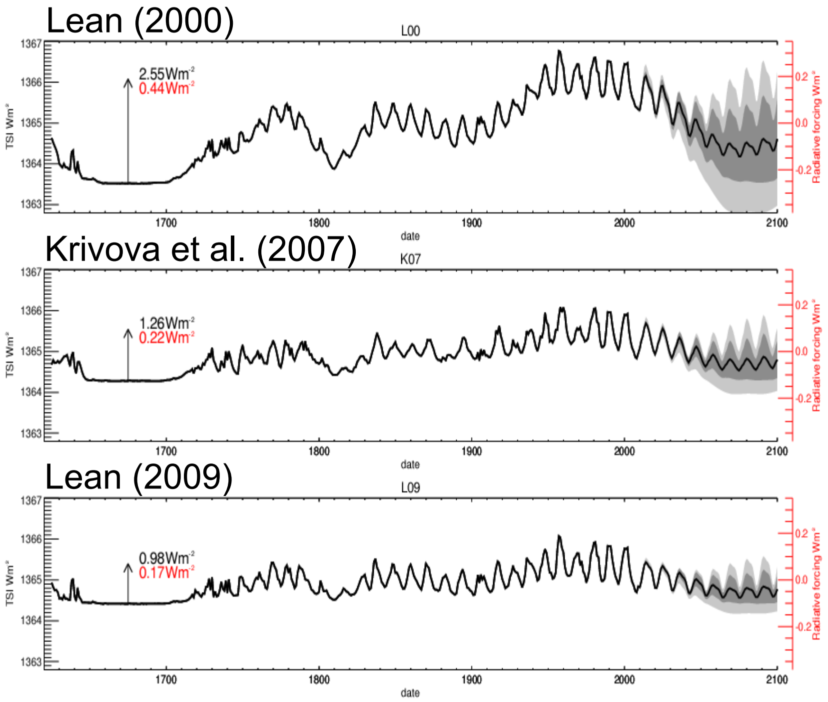
Lockwood et al., Astron&Geophys, 2012





Total solar irradiance

Jones et al., JGR, 2012

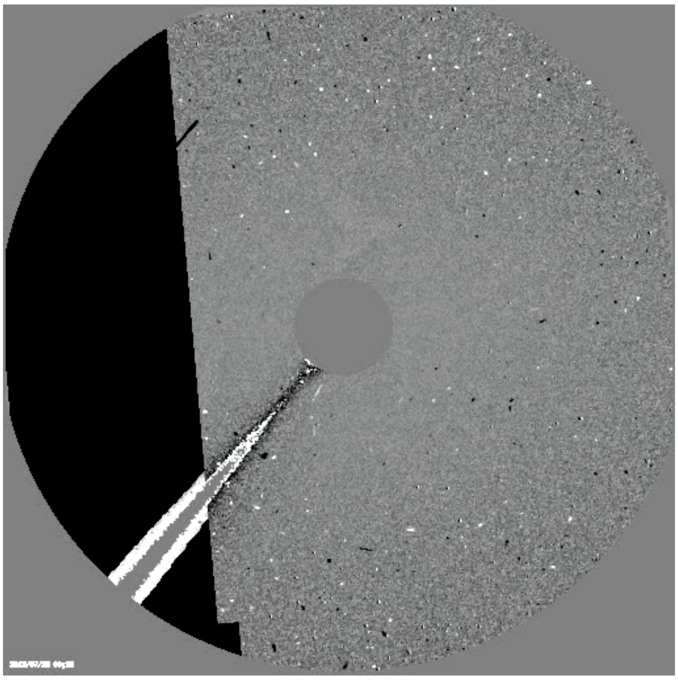


Conclusions

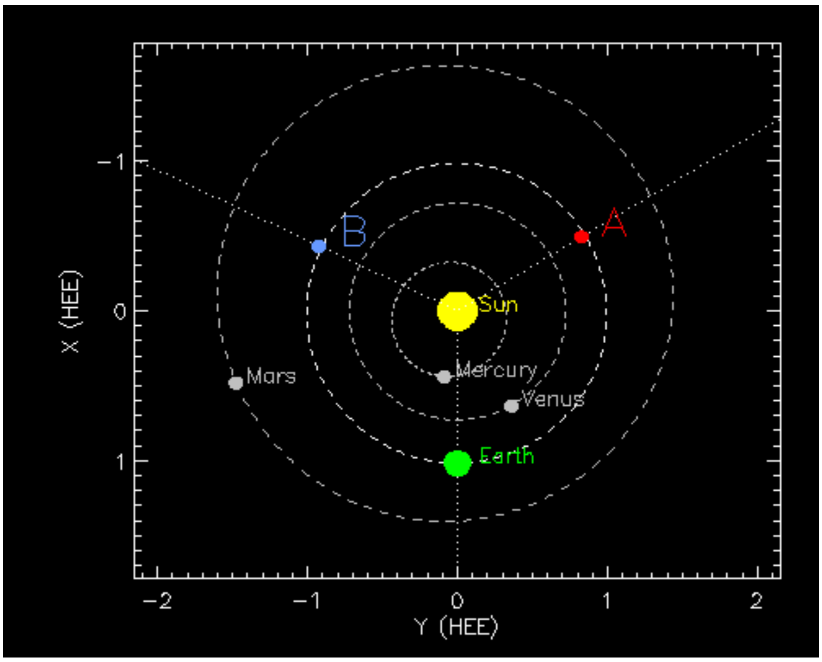
- The Sun varies on many timescales, from seconds to millennia.
- The space-age has been a period of high activity
- We're currently very close to solar maximum, likely the smallest for ~100 years.
- This could well be the start of a long-term decline.

- We live in interesting times!

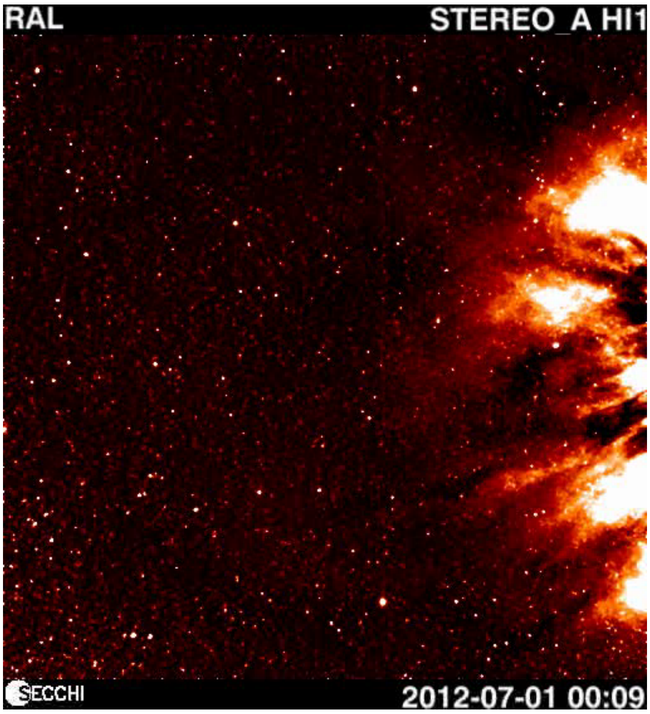
Extremely fast CME, 23rd July 2012 as seen from SOHO

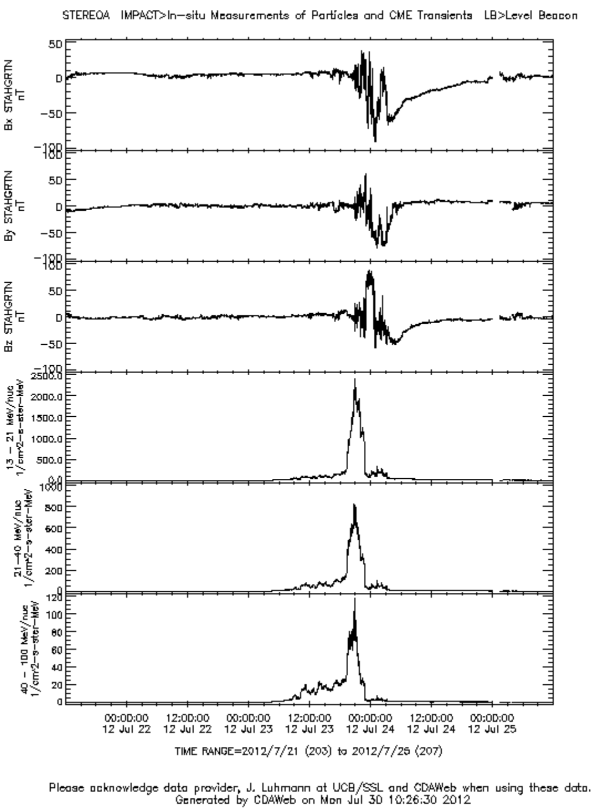


Location of STEREO spacecraft during 23rd July 2012 CME



Extremely fast CME, 23rd July 2012 as seen from STEREO/HI





In-situ magnetic field and particle data from STEREO-A