Living With the Sun

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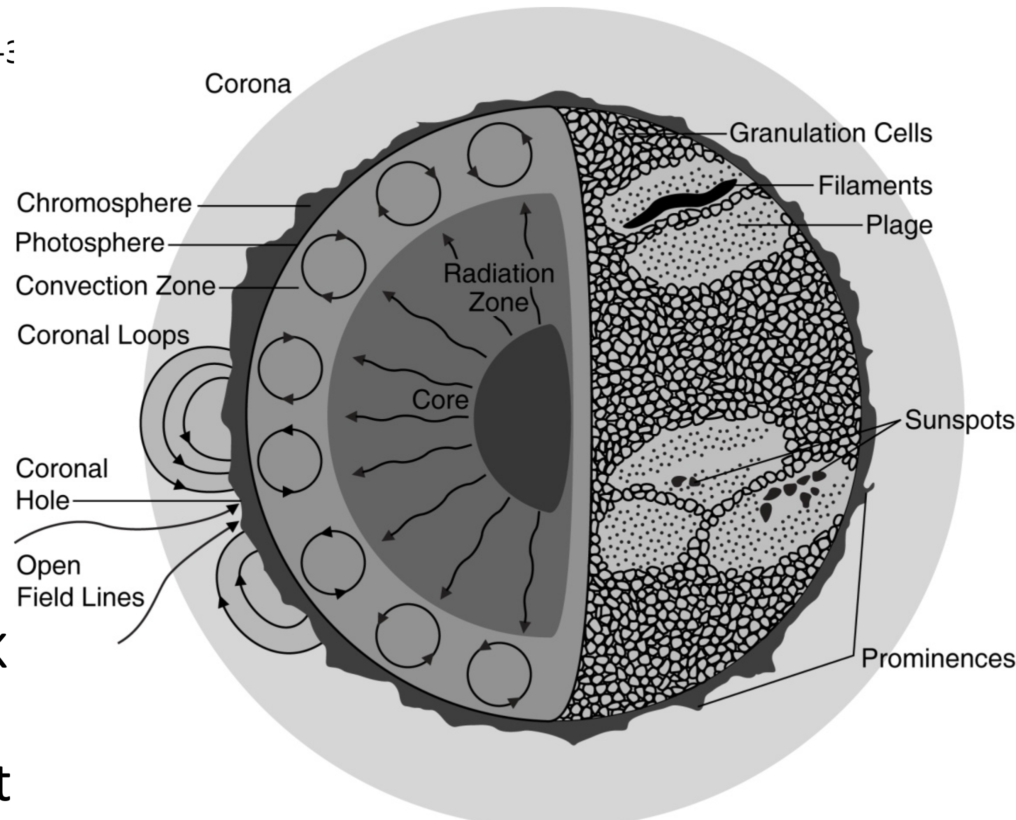
Highlighting the work of many, including those who sponsor missions, ground-based programs, data systems, and modeling projects

52nd ESLAB Symposium, ESTEC, May 2018

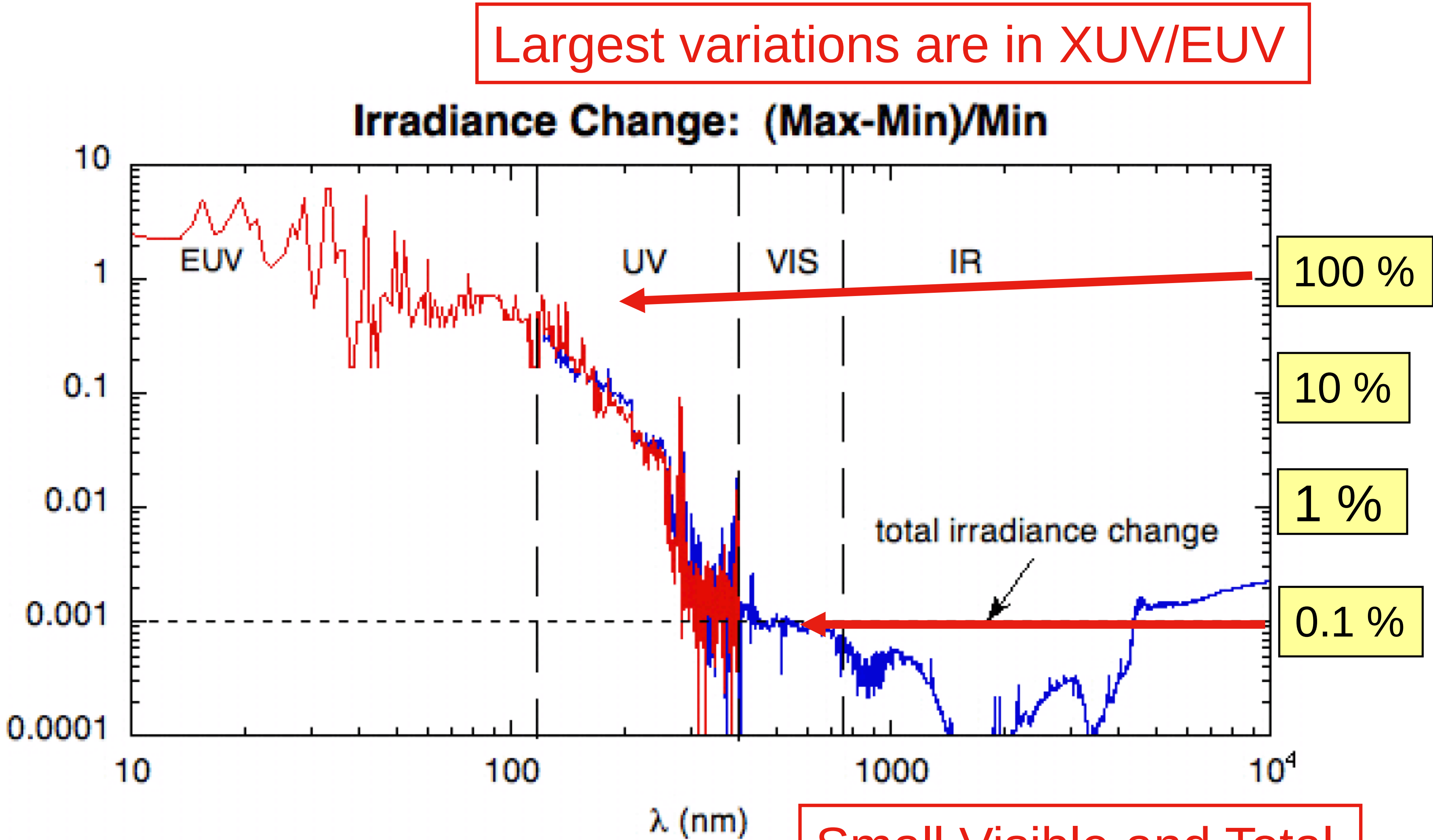
Solar Interior Structure: A Nuclear Furnace

- Core
  - Contains nuclear reactions
  - T ~ 1.5×10^7K; P = 1.6×10^5 kg · m^{-3}
  - Out to 0.25 R_S
- Radiative Zone
  - Energy transfer by photons
  - Out to 0.75 R_S
  - Top is the tachocline; T = 5×10^5K
- Convection Zone
  - Heat transfer by fluid motions
  - Region of solar dynamo
  - Top is the photosphere; T – 5785K
  - Number density about $10^{23} m^{-3}$
- Surface of Sun defined by radius at which photons can escape



Cut-away diagram illustrating solar interior, and atmospheric regions and features.

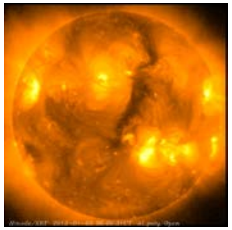
The more variable ionizing emissions play the major role in defining the planetary obstacles to the solar wind, and allow ionized constituents to be affected by electric and magnetic fields



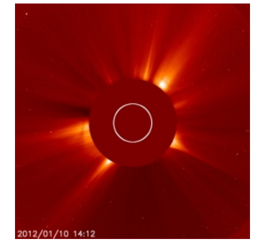
(slide from C. Amman, HAO/NCAR)

The available image wavelengths allow investigations of the emission processes and related solar features

corona

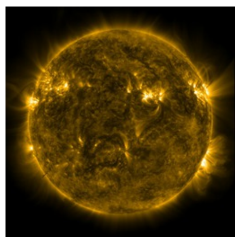


Soft x-rays (<10nm)

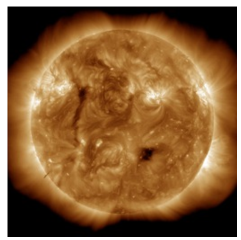


white light

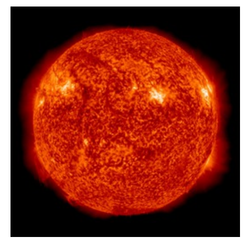
chromosphere-transition region



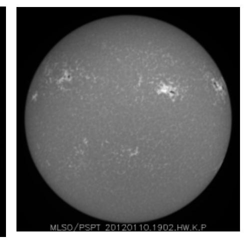
FeXX171nm



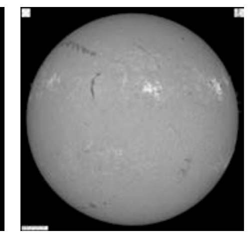
FeX193nm



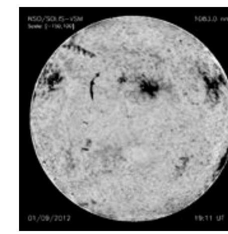
HeII304nm



CaII393.4nm

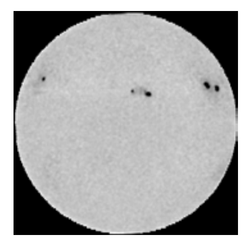


Ha656.3nm

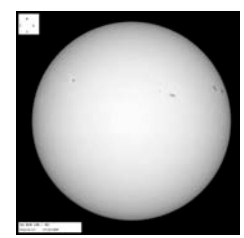


HeII10830

Photosphere



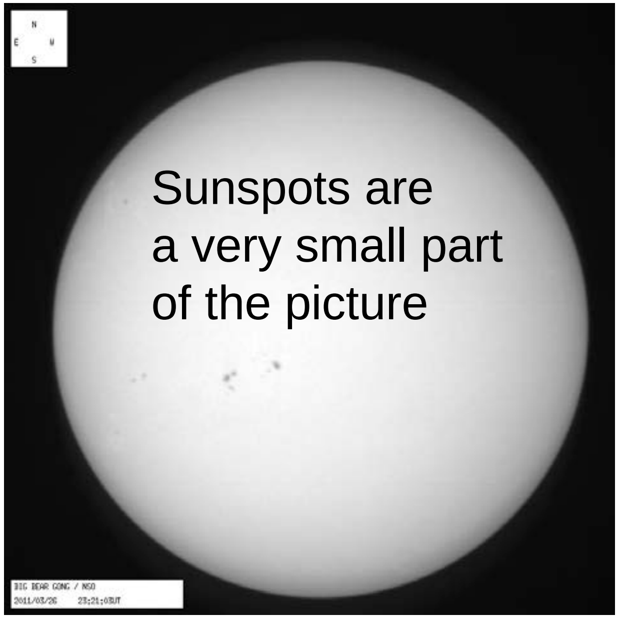
NaI589.6nm

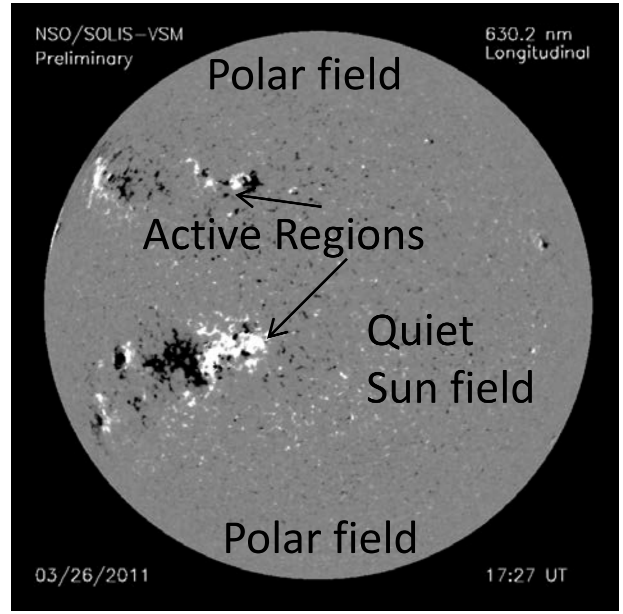


white light

Wavelength: **X-ray** **EUV** **UV** **VIS** **IR**

But what influences all these and other outputs?:



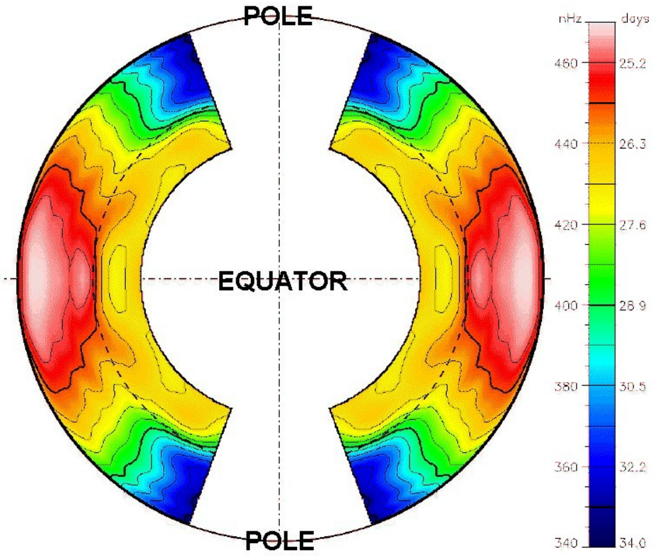


Magnetographs making regular observations, some at high spatial and time resolution, transformed much thinking

SOLAR MAGNETIC FIELDS DETERMINE MUCH OF WHAT WE EXPERIENCE IN THE HELIOSPHERE.

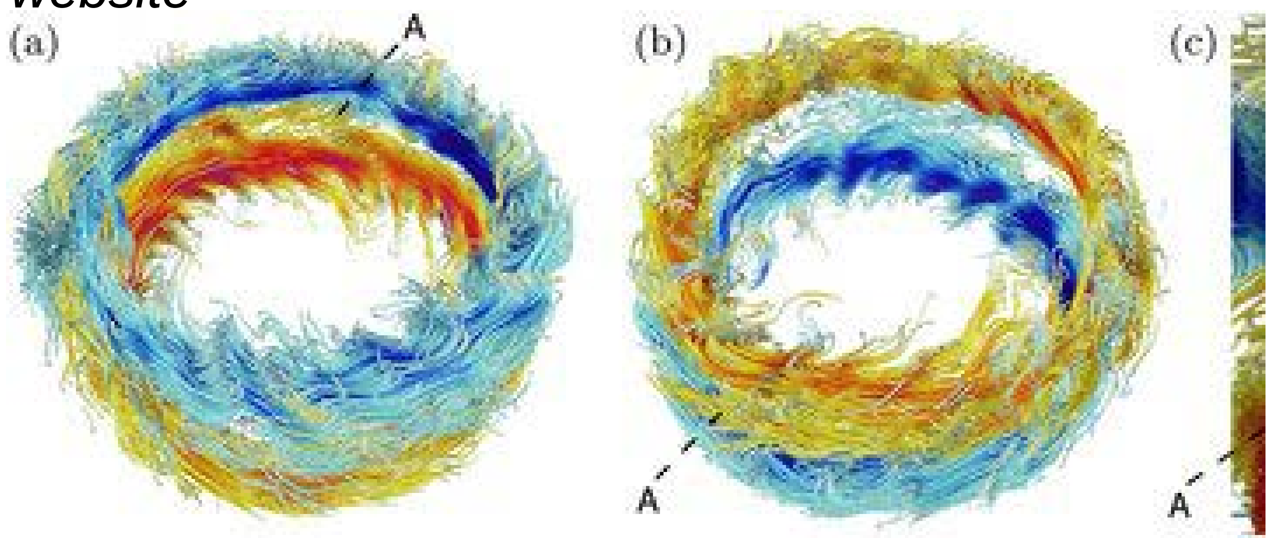
(NSO SOLIS magnetogram (right) and matching visible light image)

What lies beneath(?)

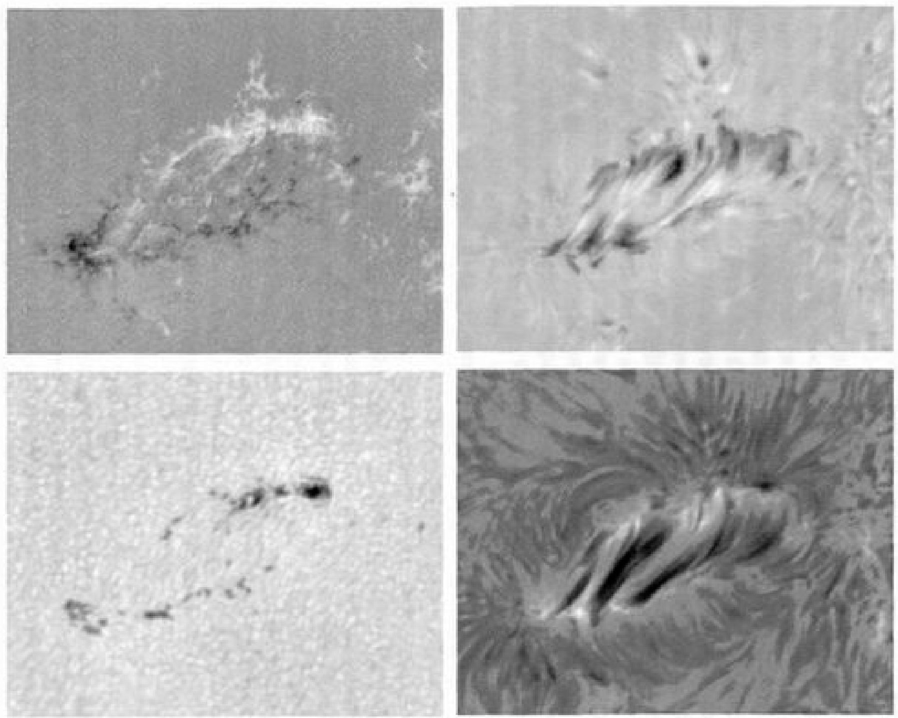


Helioseismology results from MSFC website

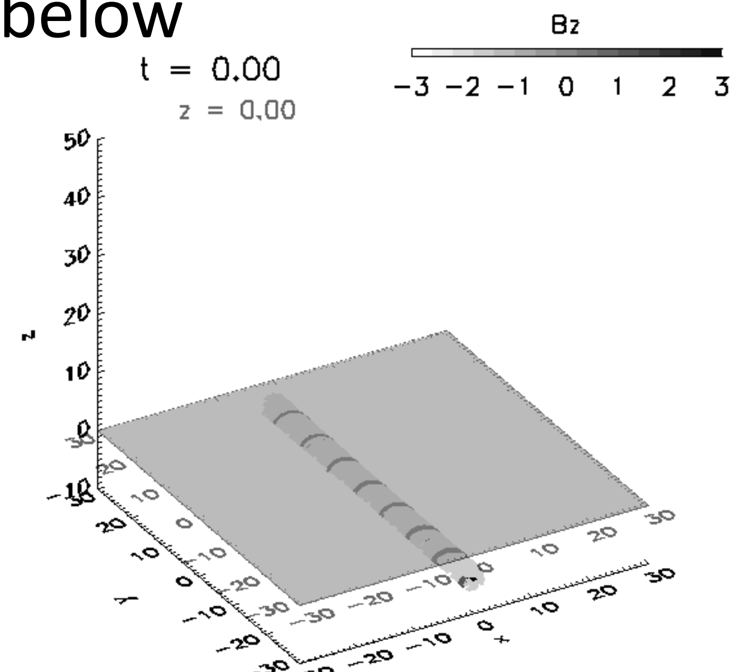
Helioseismology revealed a lot of this information. Now, simulations of field generation in the solar convection zone make ‘wreaths’ of twisted toroidal fields that go through Sun-like magnetic polarity cycles (colors below indicates handedness of twist).



One new picture: Brown et al., ApJ 2011



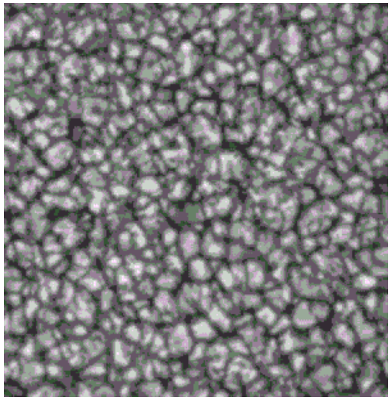
The appearances of active region fields and associated features on the Sun can be reproduced by numerical simulations of emergence of strong flux tubes from below

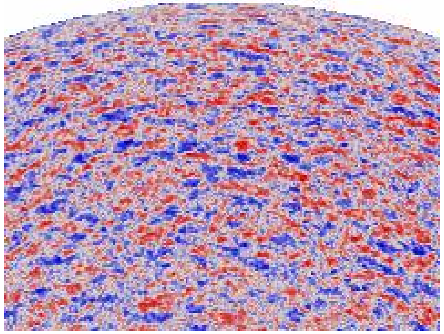


(Observed emerging flux from B. Schmieder, in Scholarpedia, and Strous 1997 PhD thesis (above), Magara et al., ApJ 2004 simulation (right))

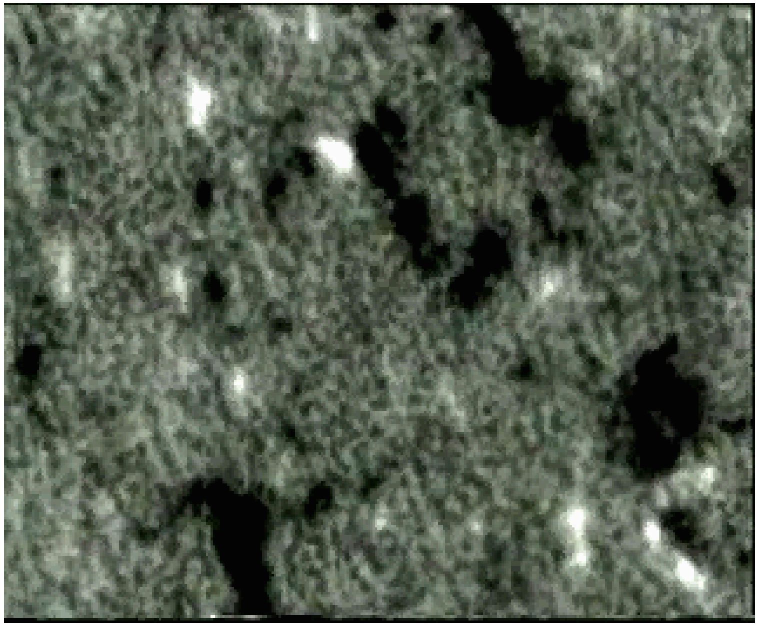
In the 'gray' background: additional "Quiet Sun" or "Magnetic Carpet" Fields are seen

High resolution images, magnetograms, and dopplergrams suggest small scale fluxes of both sign are convected to and collect in the supergranule boundaries.



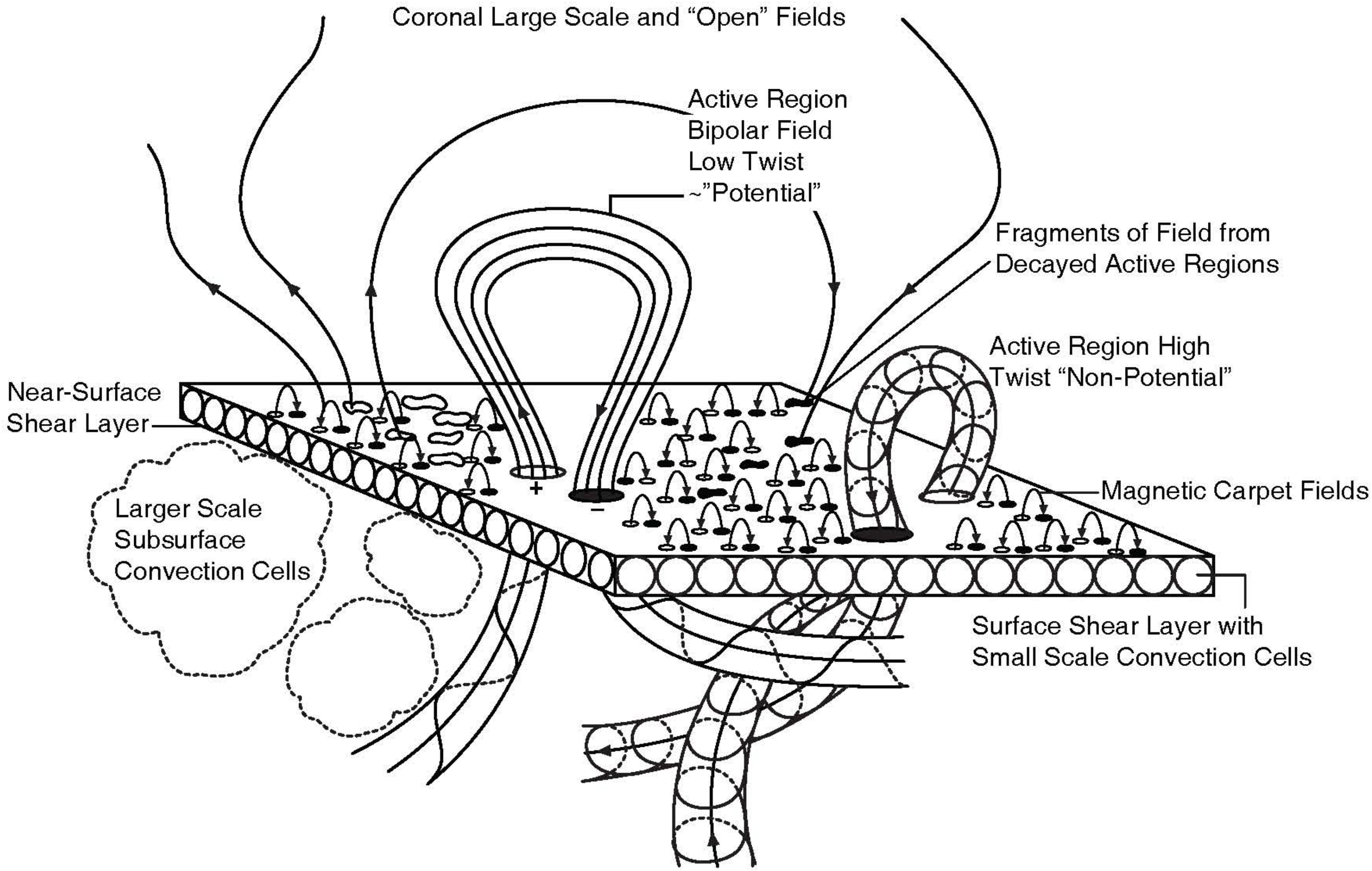


Supergranules and their associated Vertical motions seen as Doppler shifts (Scales are ~35Mm)



Black-inward fields, white-outward fields in SOHO MDI magnetograms

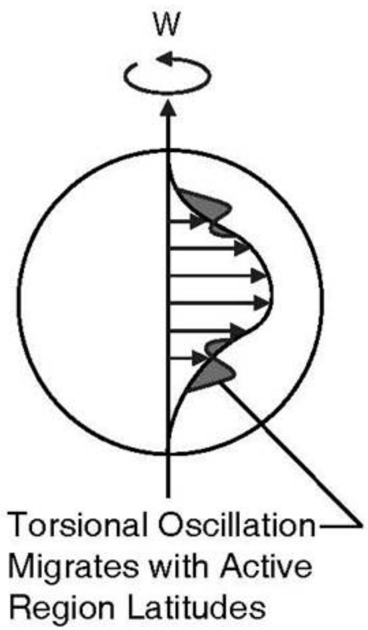
The active region and smaller scale fields interact

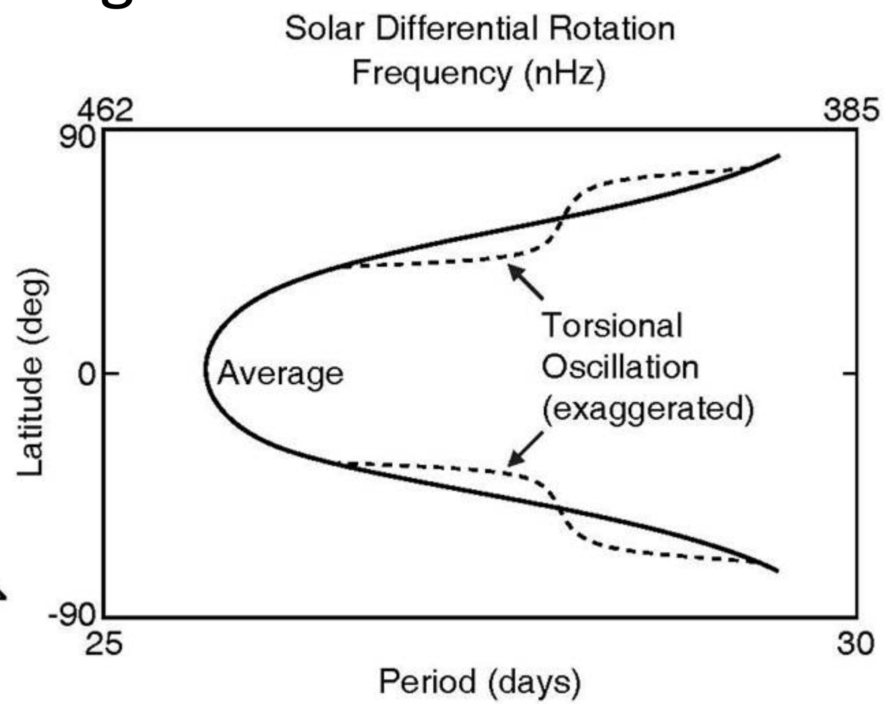


Resulting in a diffusion-like spreading and decay of emerged fields

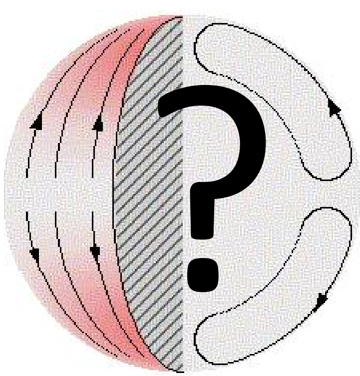
In addition, the emerged fields behave as if advected by the observed large-scale surface flows

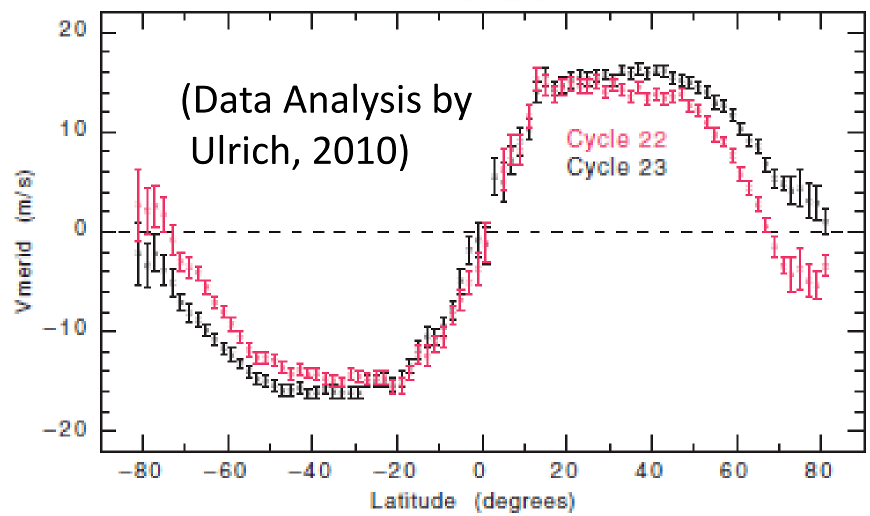
Differential rotation



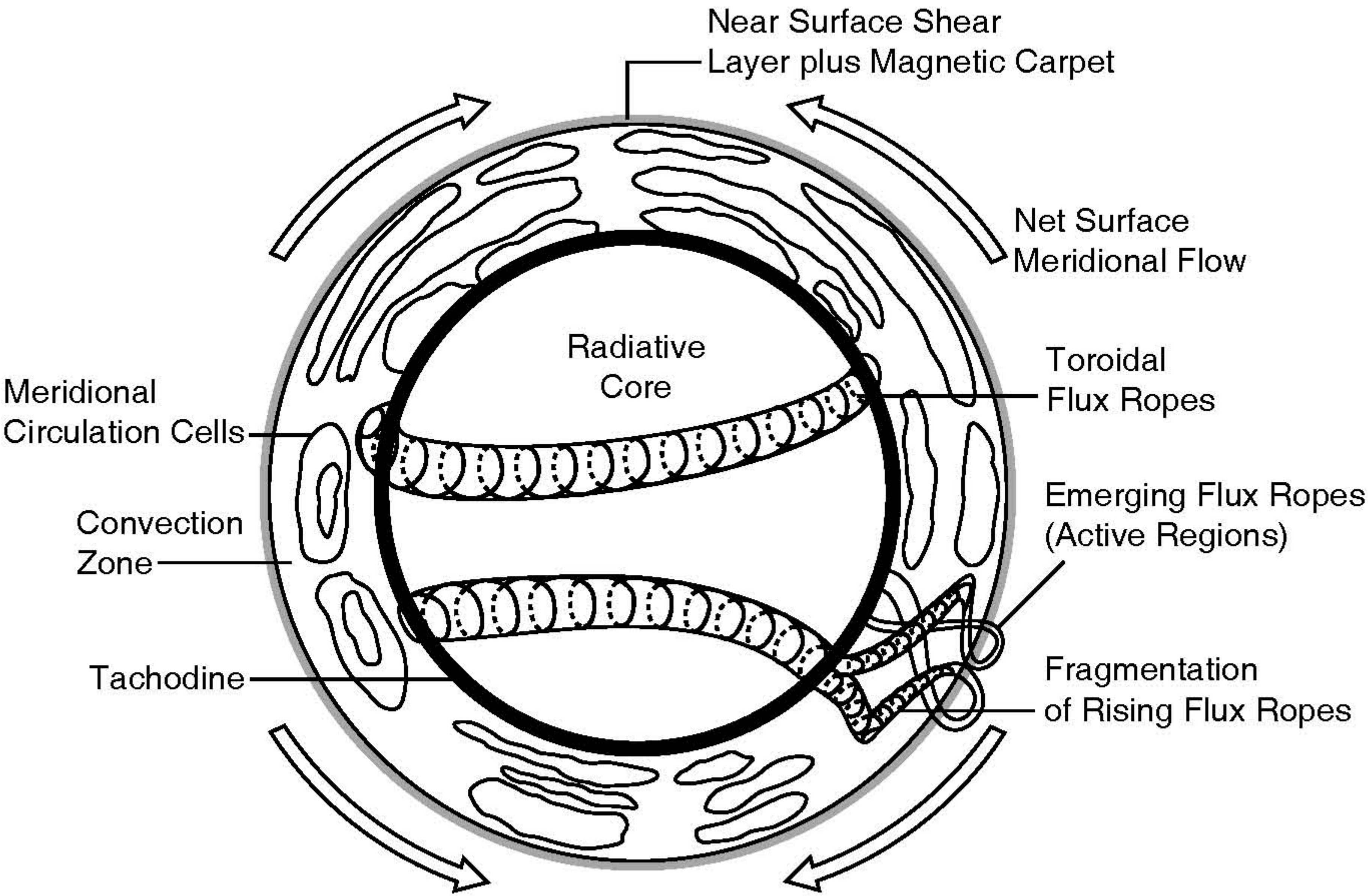


Meridional flow

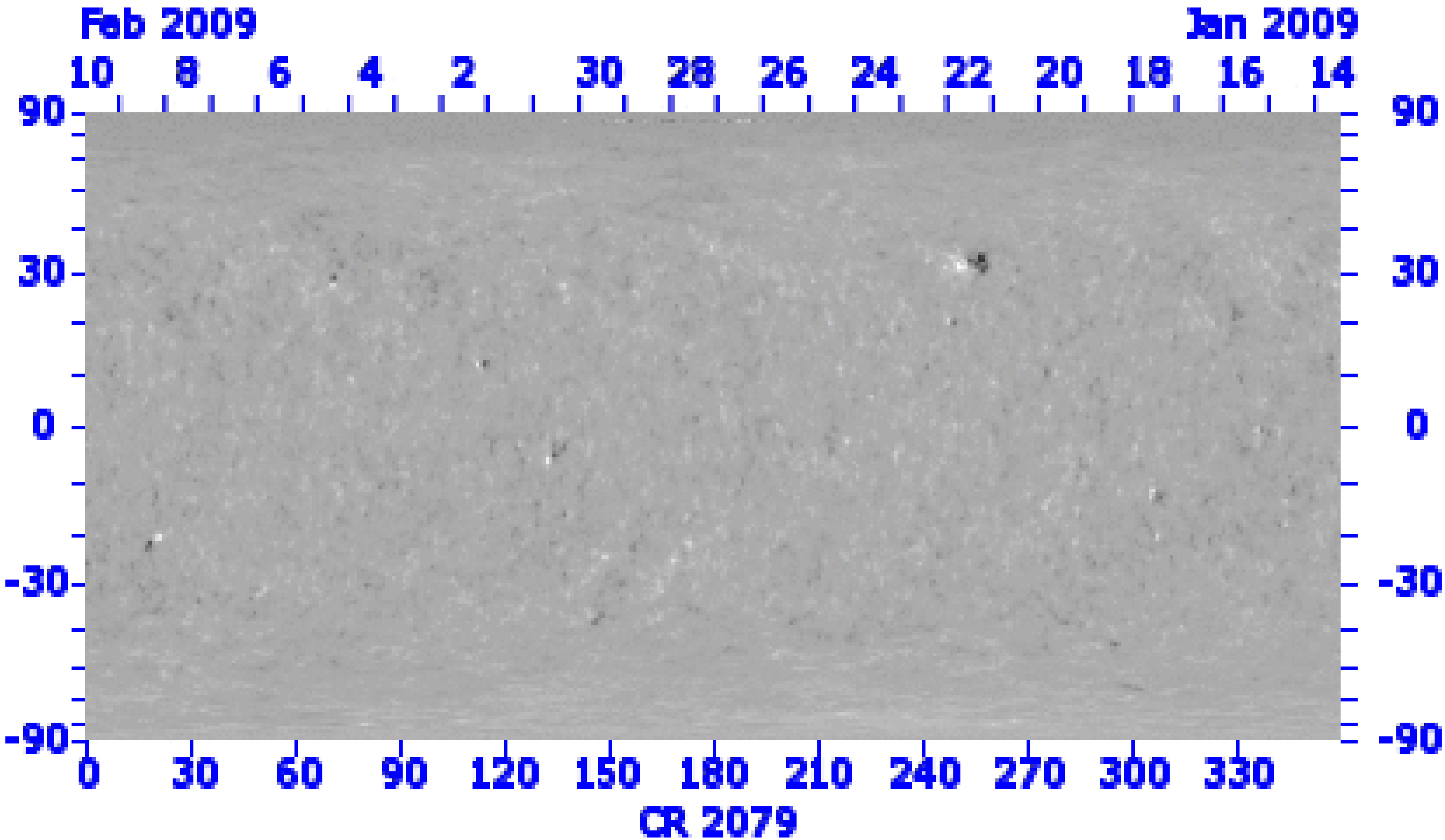


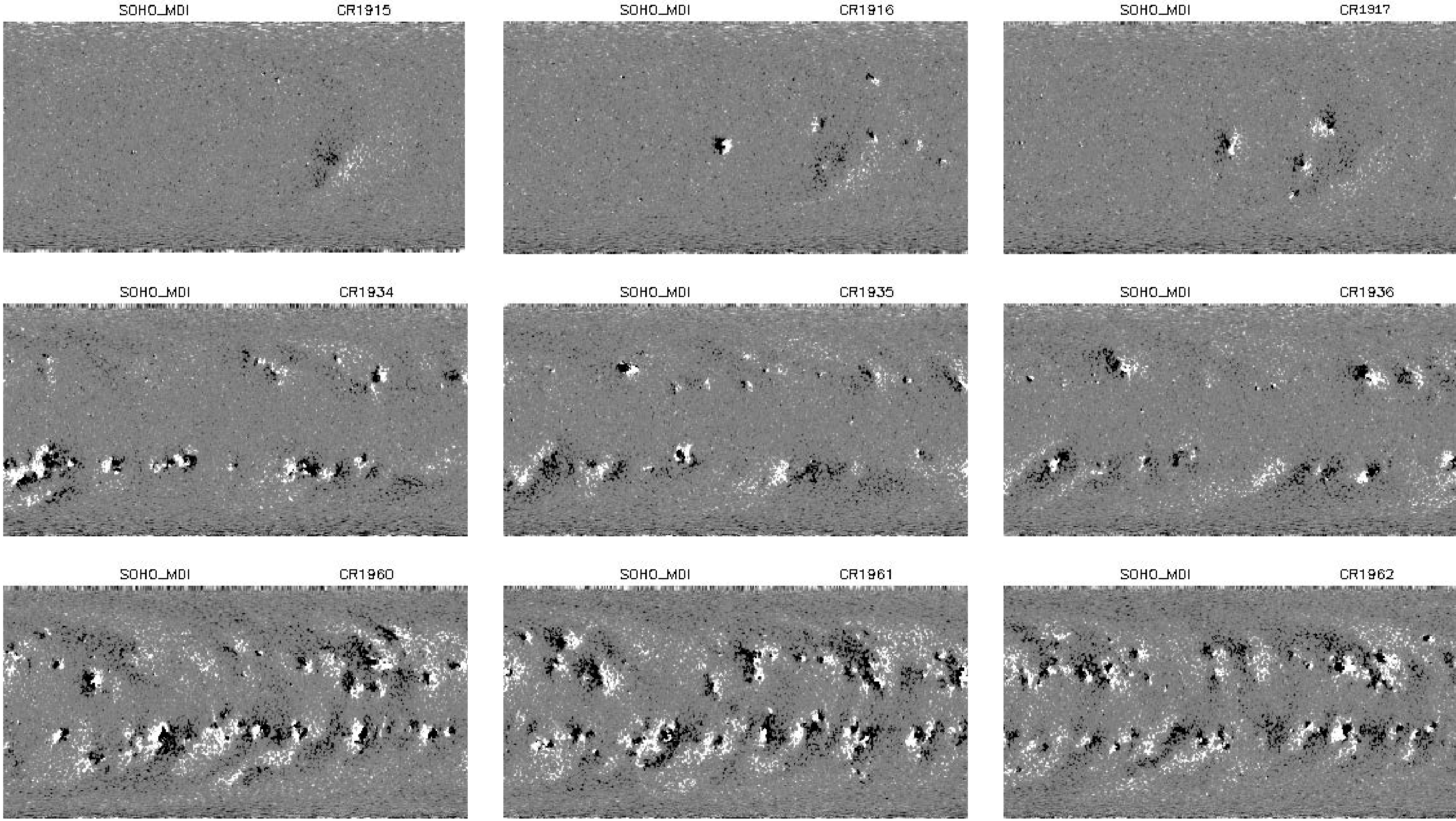


The global picture?



The resulting global solar field's evolution with activity is seen in sequences of solar surface field maps (here from GONG) showing active region emergence and redistribution in action (2009-2012)



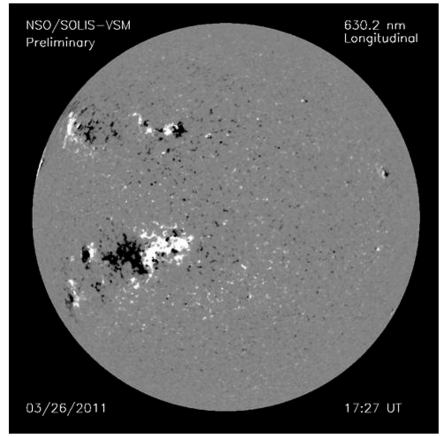


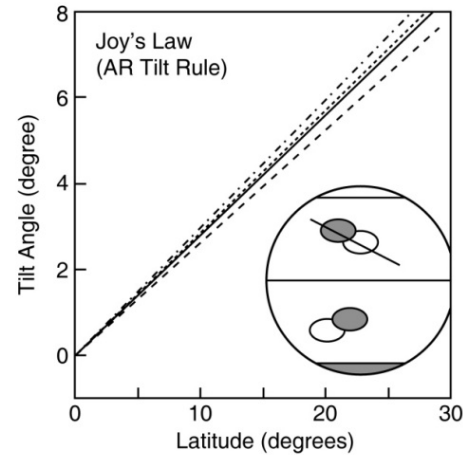
Sample synoptic maps of the photospheric field illustrate the solar cycle changes in the global solar surface field and hence the heliosphere's cycling inner boundary condition

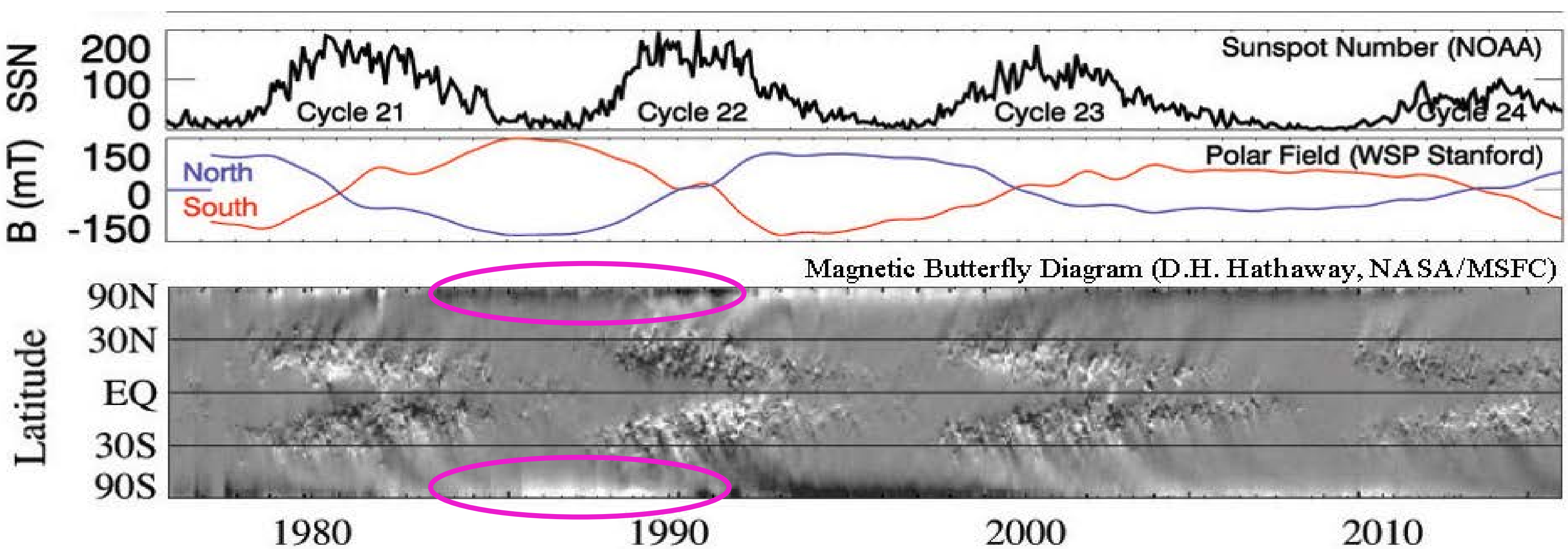
(synoptic maps from SOHOMDI of CR 1915-1917, 1934-1936, and 1960-1962)

In this picture the polar fields are simply ‘survivors’ of a cycle’s emerged flux

Active region ‘tilt’ is also a key factor in what survives

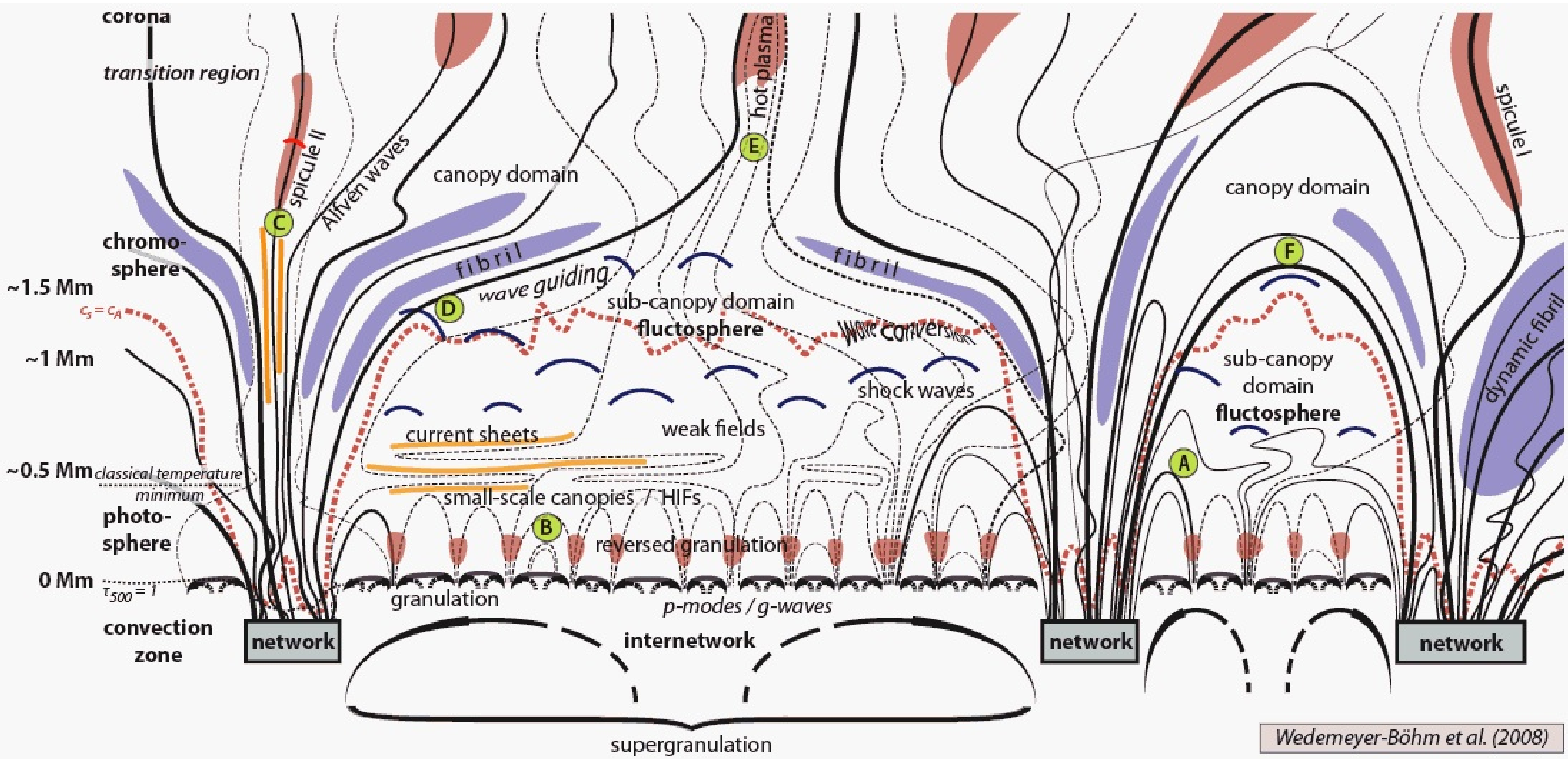




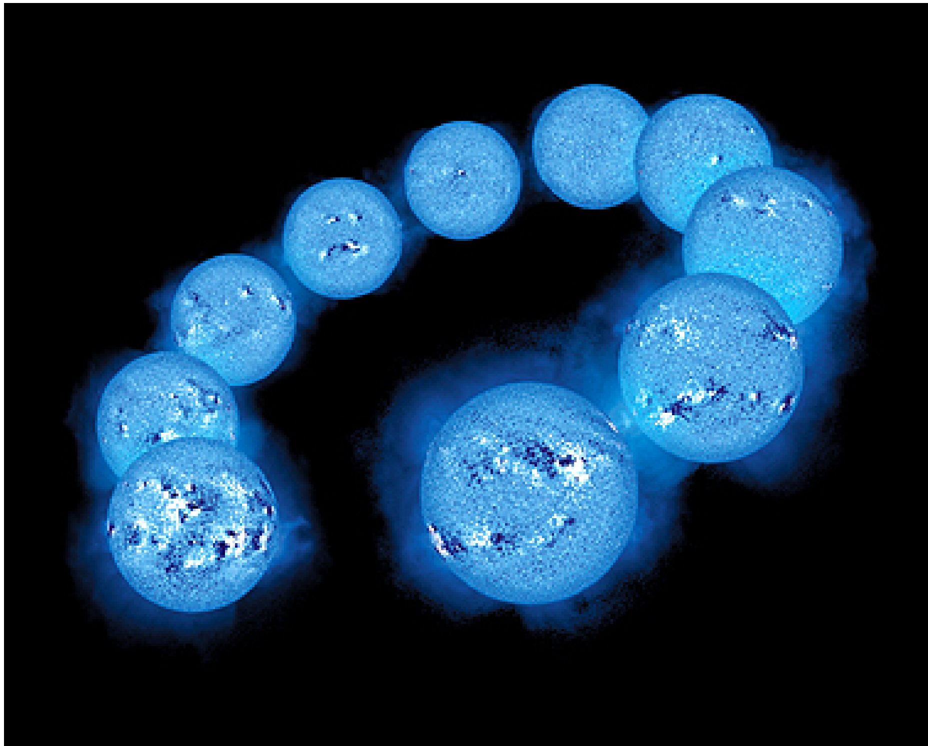


updated from Li et al. Solar Phys 2011

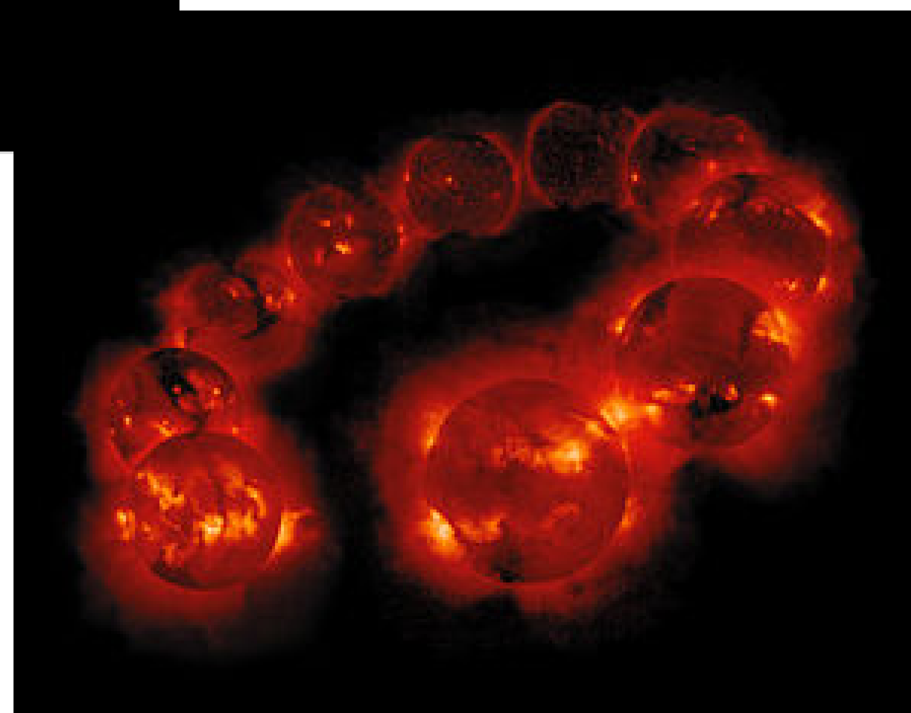
Meanwhile related coronal heating leads to emissions



It’s complicated and probably involves multiple processes. Observations suggest waves, currents, reconnection, and shocks may all be involved

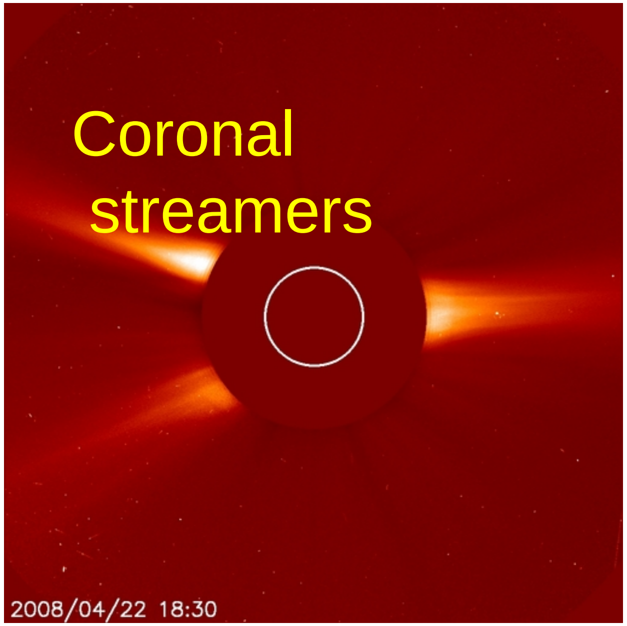


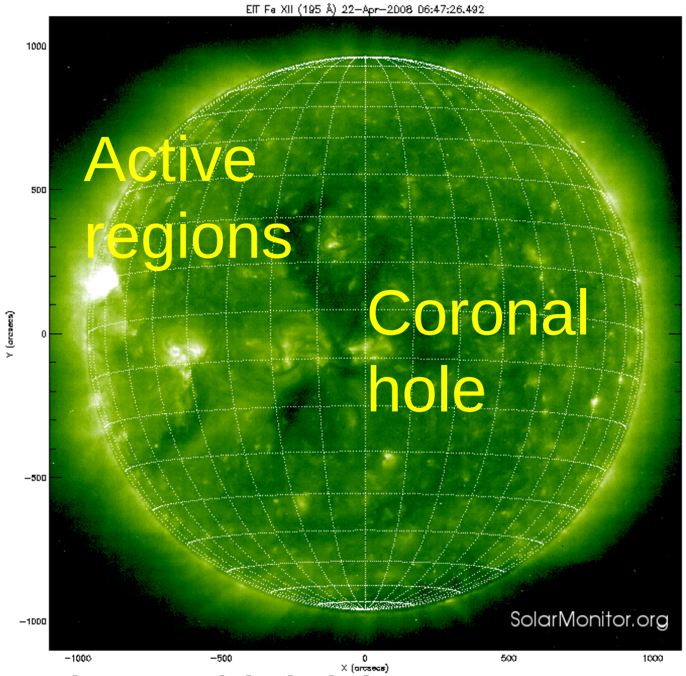
Note it is the hot coronal loops forming over changing active regions (here seen in Soft X-rays and fields (images from NSO and Yohkoh SXT)) that cause the solar cycle variations in atmospheres.



Coronal heating and brightness depend on the field strength and geometry (Solar minimum is at center. LMSAL figures.)

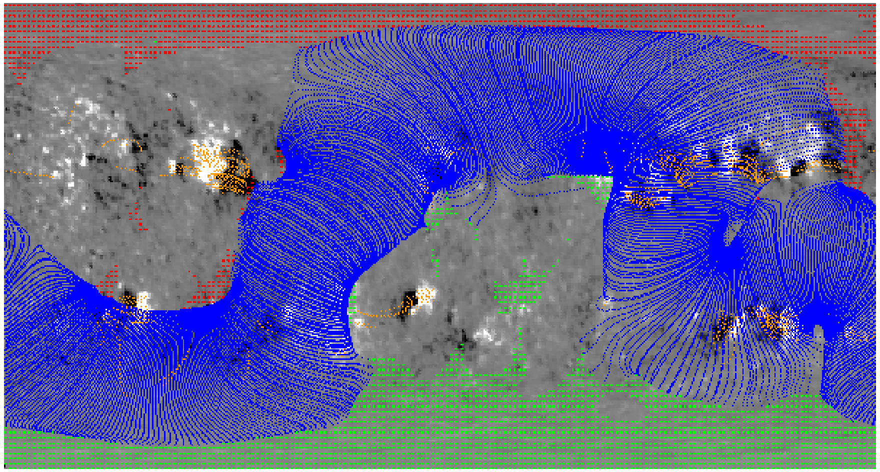
A consequence of the hot coronal plasma pressure is the opening of some coronal fields and related escape of coronal plasma as solar wind-



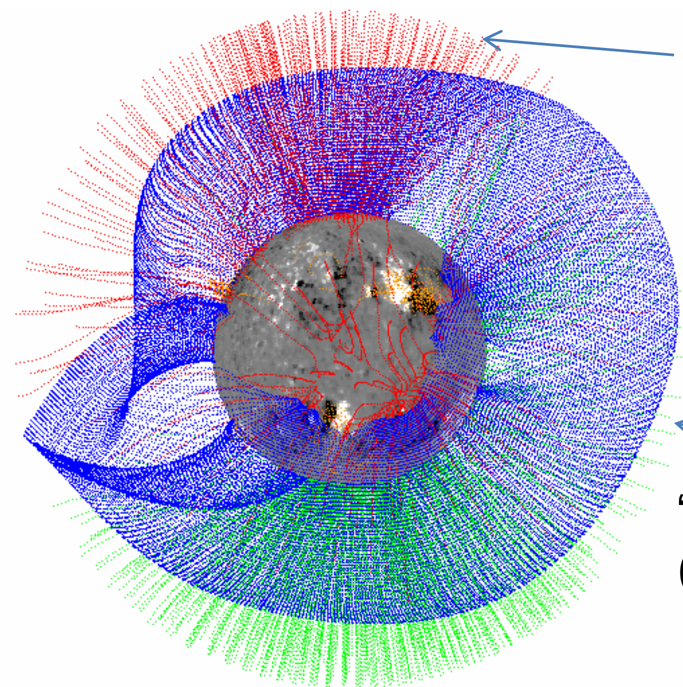


*SOHO L*ASCO C2 coronagraph (left) and EIT (right) images

Interpretation of these images –including the “coronal holes”, requires knowledge of the solar field



e.g. One cannot simply look at a photospheric field map and tell what the corona's structure is like.

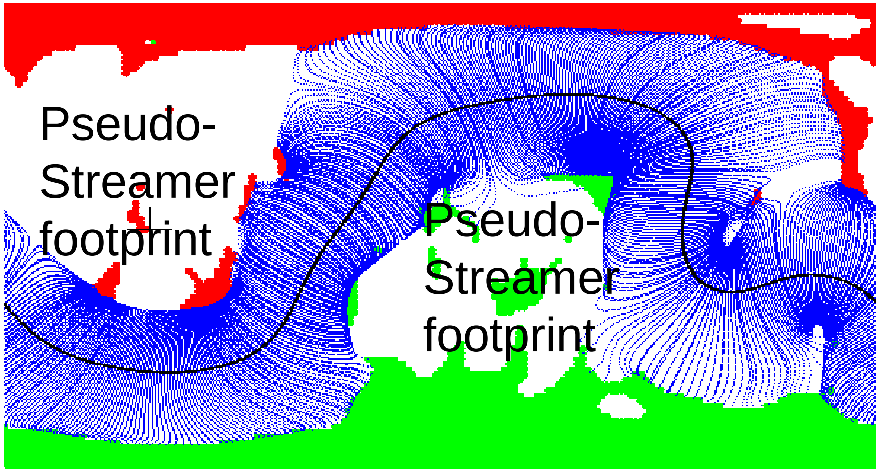


'open' Fields color coded by field polarity

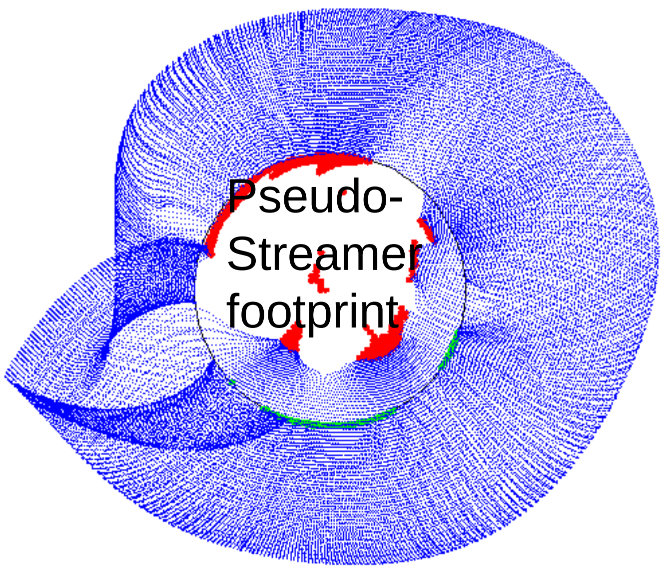
"helmet streamer" belt (outermost closed fields encircling the Sun)

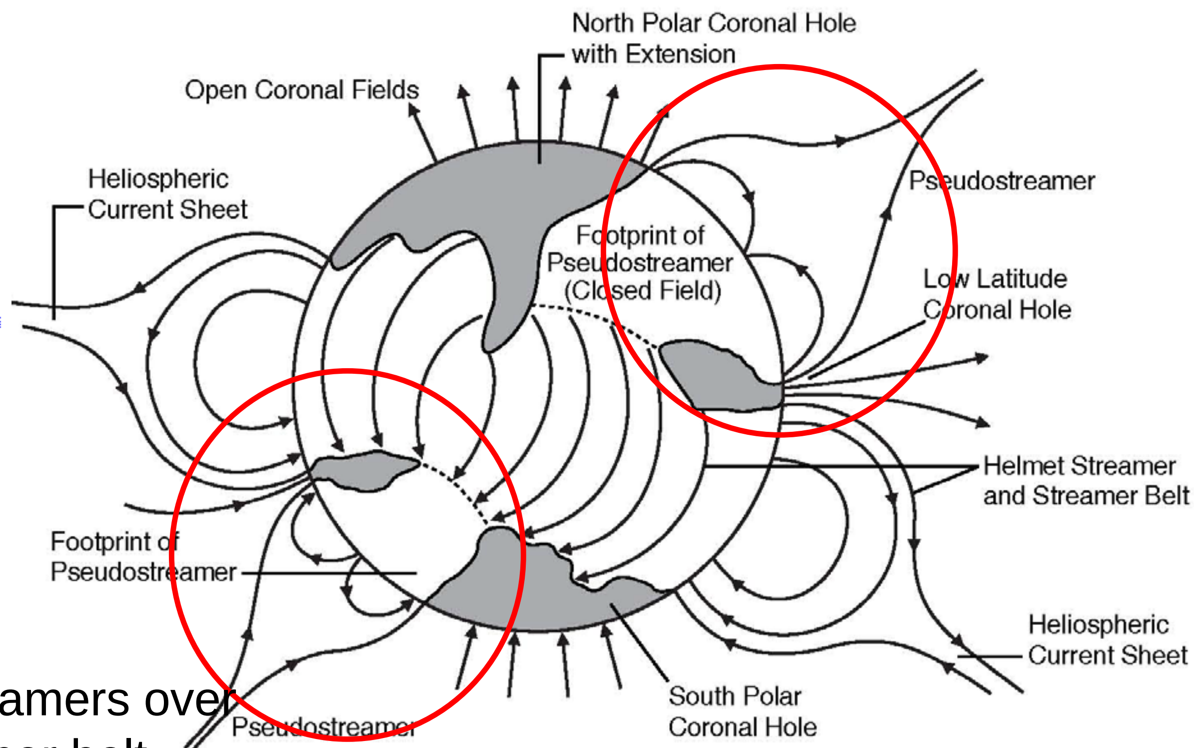
But the synoptic maps can be used to construct various coronal field models, e.g. the Potential Field Source surface (PFSS) models, developed in the late 60s and since widely used.

gong.nso.edu/data/magmap/pfss.html provides models and archives (G. Petrie website)

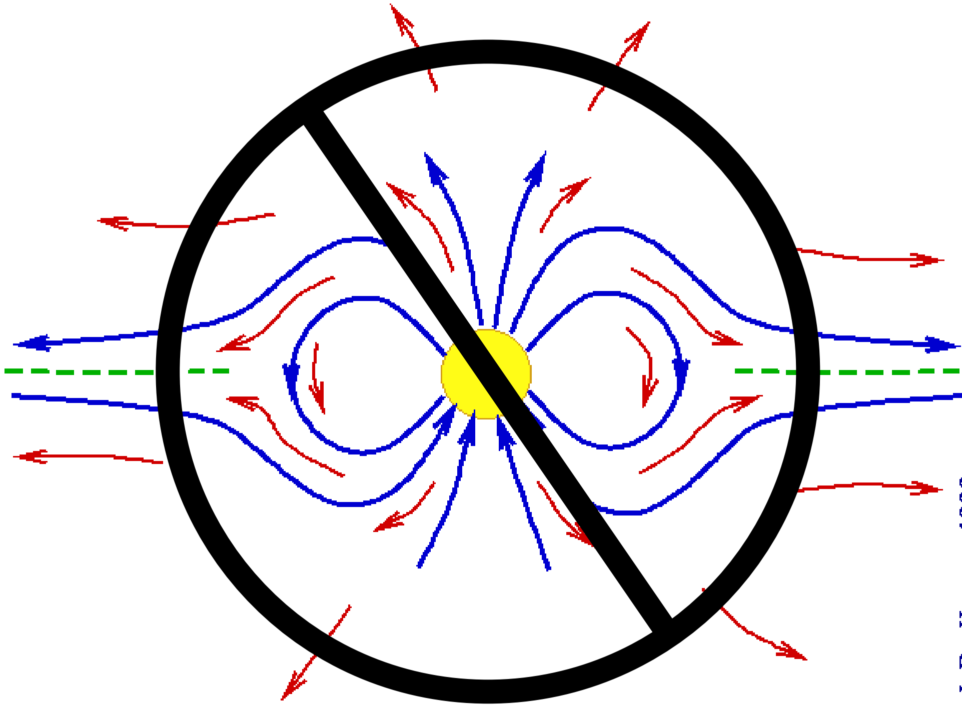


This information has changed the way we see the corona and interpret related heliospheric observations. Taking into account its non-dipolar nature has been especially important.



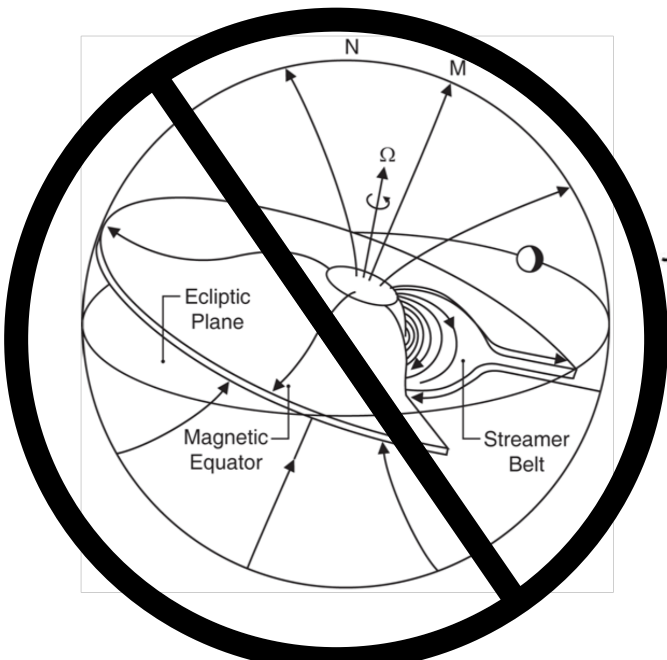


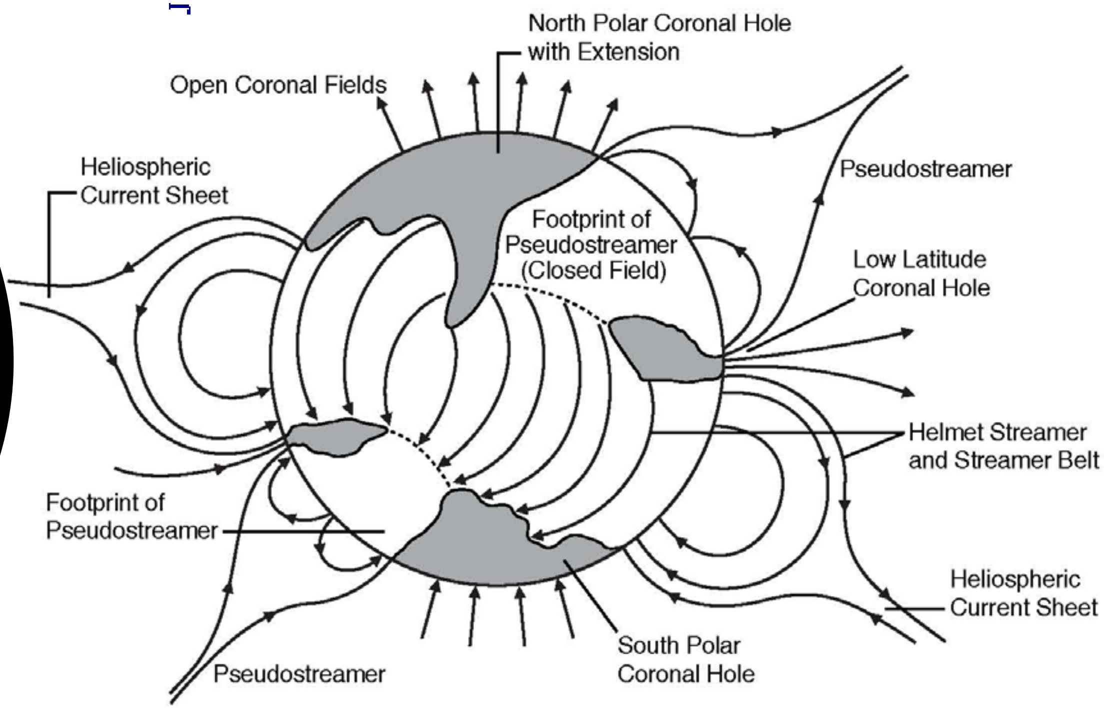
Pseudostreamers=coronal streamers over closed fields outside the streamer belt



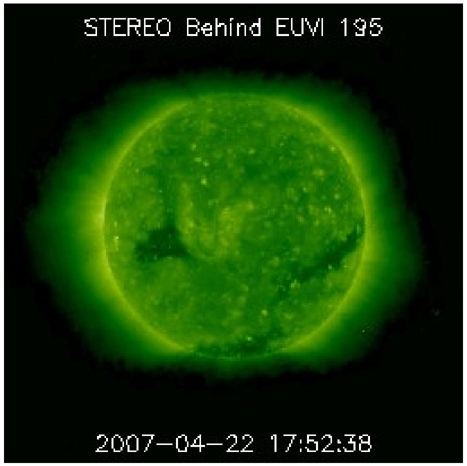
J. De Keyser, 1999

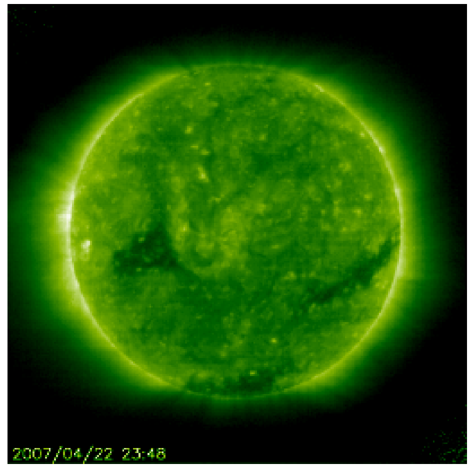
This shift in coronal structure view has been particularly important in moving beyond the dipolar concepts of the corona and solar wind

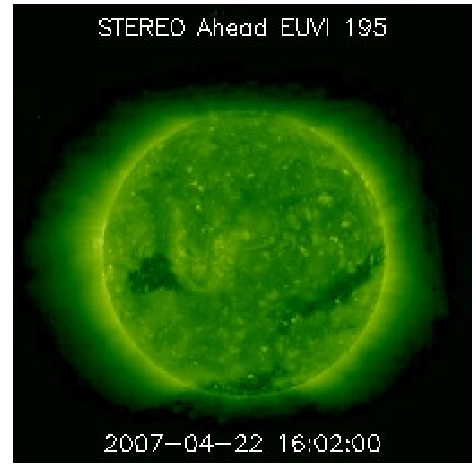


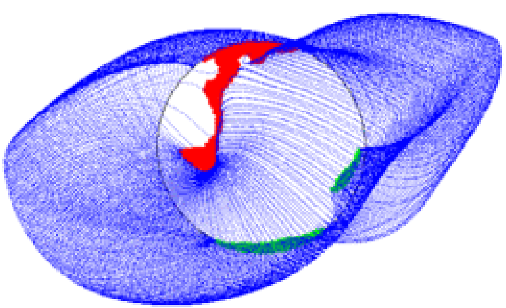
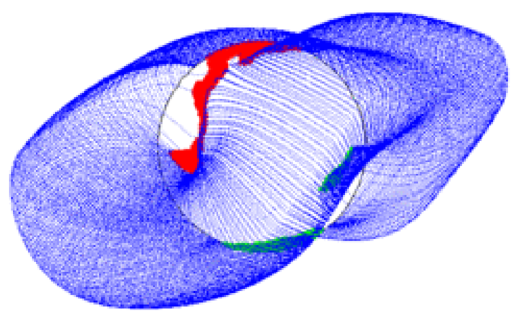
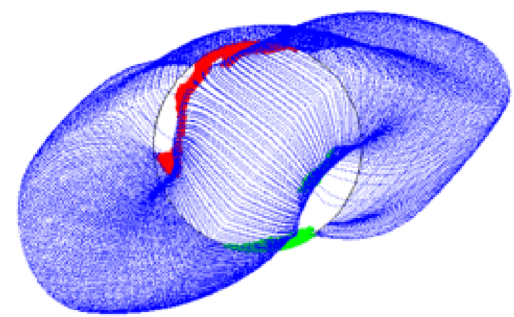


With it we can describe the observed coronal holes. e.g. The open field footprints seen here at the start of the STEREO mission in early 2007, when the large scale coronal field looked like a gently warped dipole



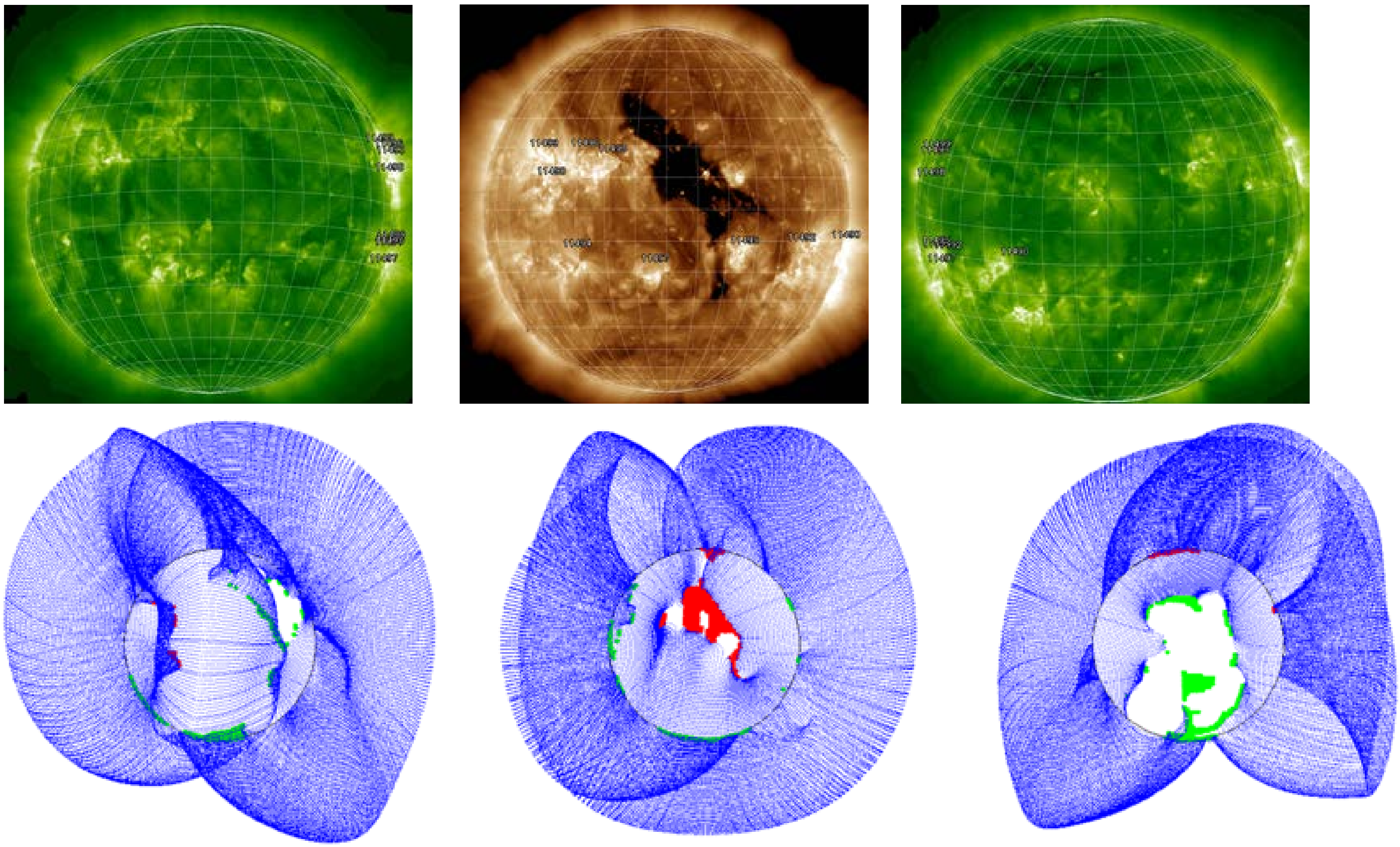




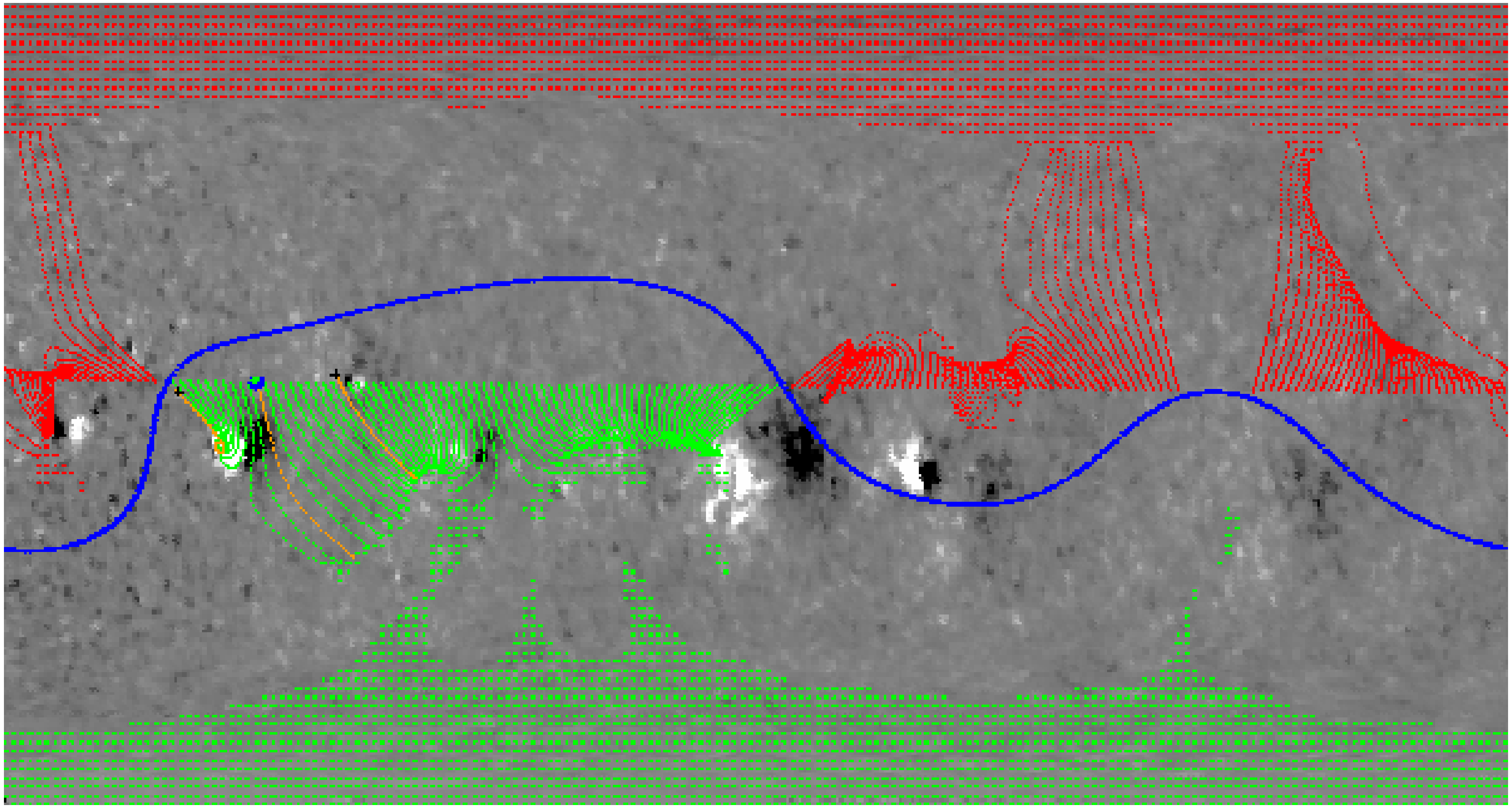
(SECCHI and SOHO EIT EUV Images from STEREO Science Center and PFSS models from the GONG website)

-and later when the streamer belt became extremely warped with large pseudostreamers, and low latitude coronal holes prevailed



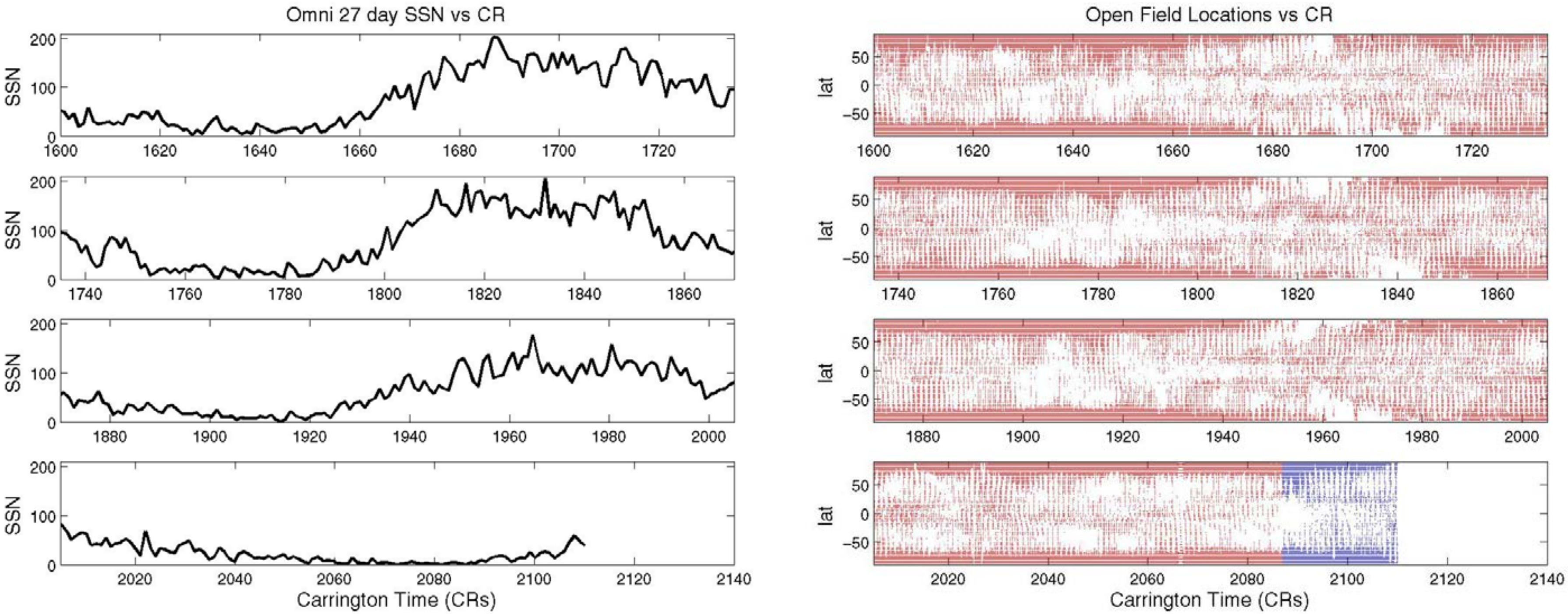
SECCHI EUV and SDO AIA Images from STEREO Science Center and PFSS models from the GONG website

Such models illustrate how ecliptic solar wind source regions change with time



PFSS field lines mapping to the ecliptic, showing Earth and STEREO connections for 2007-2012. Open fields are color coded by open field polarity (sign of radial component) (from the GONG website)

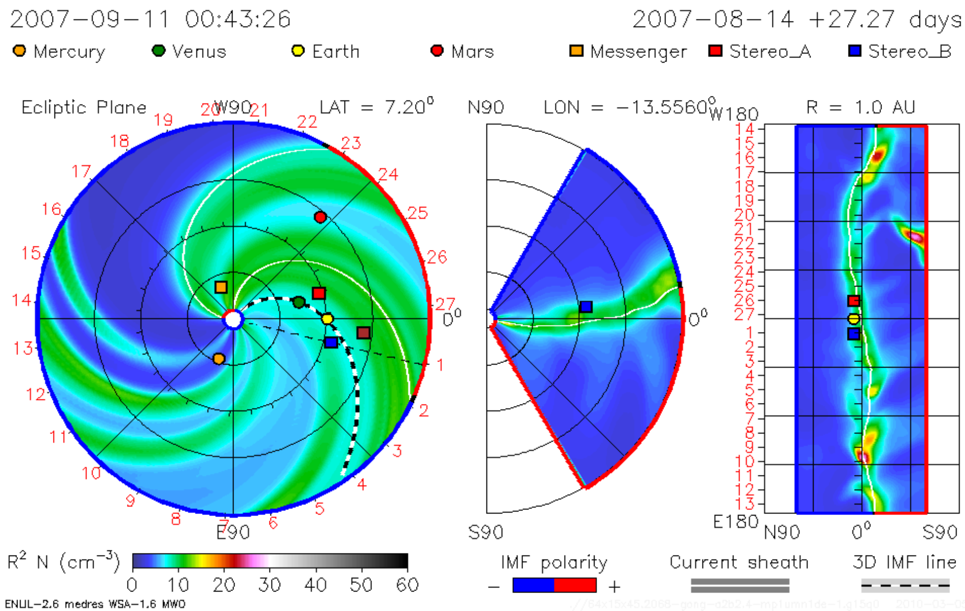
-and how the global distributions of solar wind sources evolve over the solar cycle

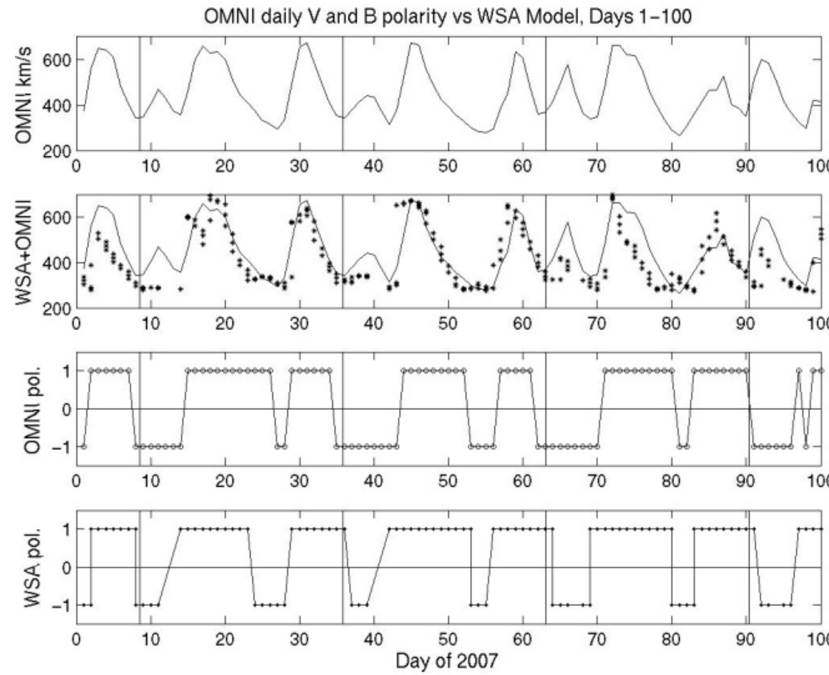


Note that Polar Coronal Holes do not migrate between hemispheres, but vanish at max and then return anew

Updated from Luhmann et al., JGR 2002

Modeling Solar Wind Structure

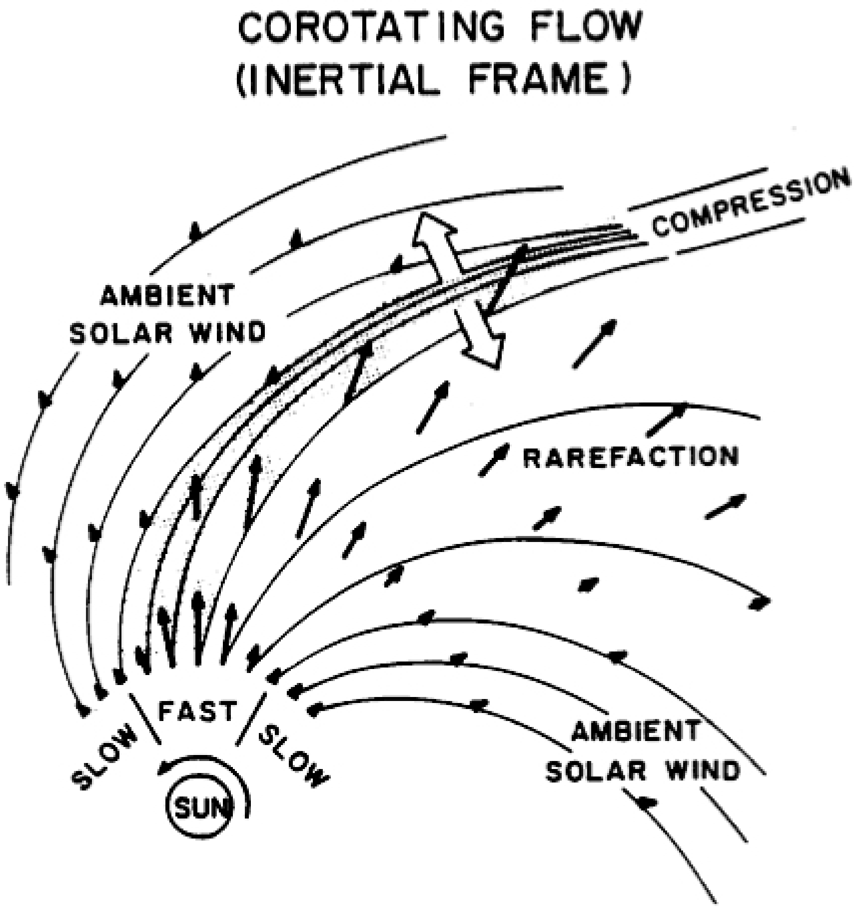


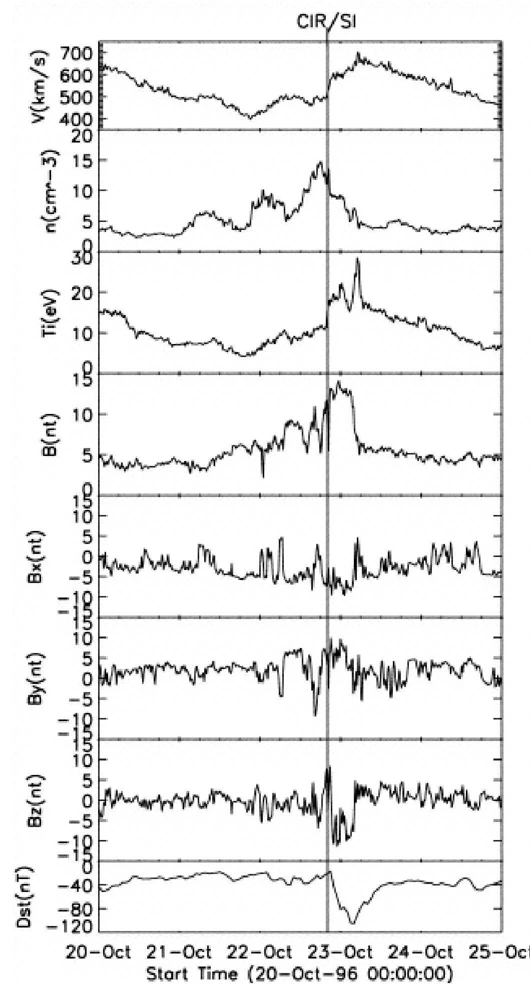


Models now exist that propagate accurate coronal hole streams outward and produce the observed solar wind structure

(Here the WSA-ENLIL model (Odstrcil et al., 2004 JASTP) and STEREO measurements (right) fitted to model

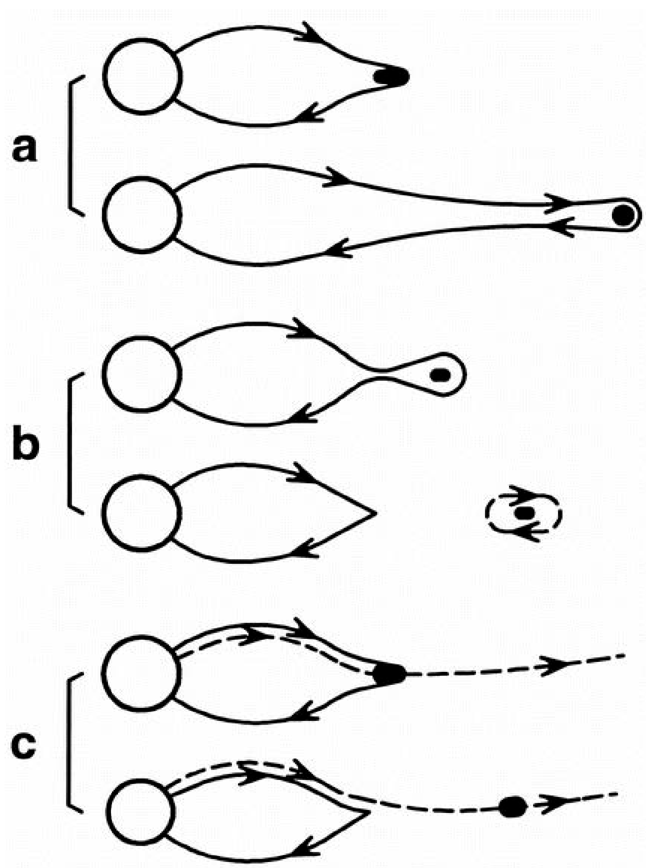
Interactions of the Solar Wind streams from the different coronal hole source regions (SIRs-or CIRs) can also make significant interplanetary field and plasma disturbances

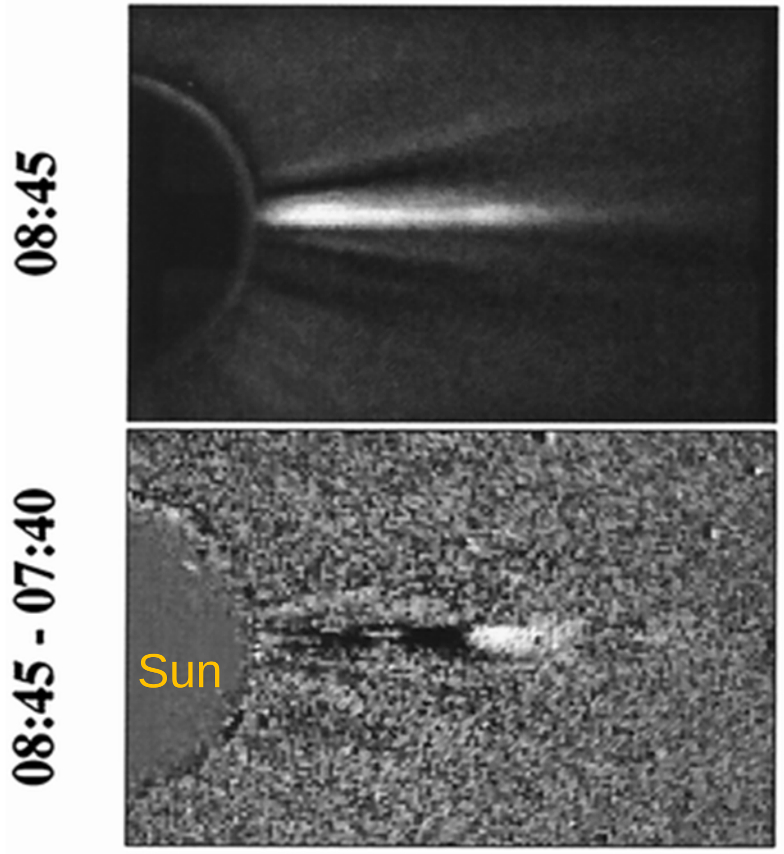




(figures from V. Pizzo, JGR 1991 (left), and J. Zhang, ApJ, 2006 (right))

Coronagraph and Heliospheric Imager movies also show the constant shedding of small structures from the streamer belt that affects the stream boundaries

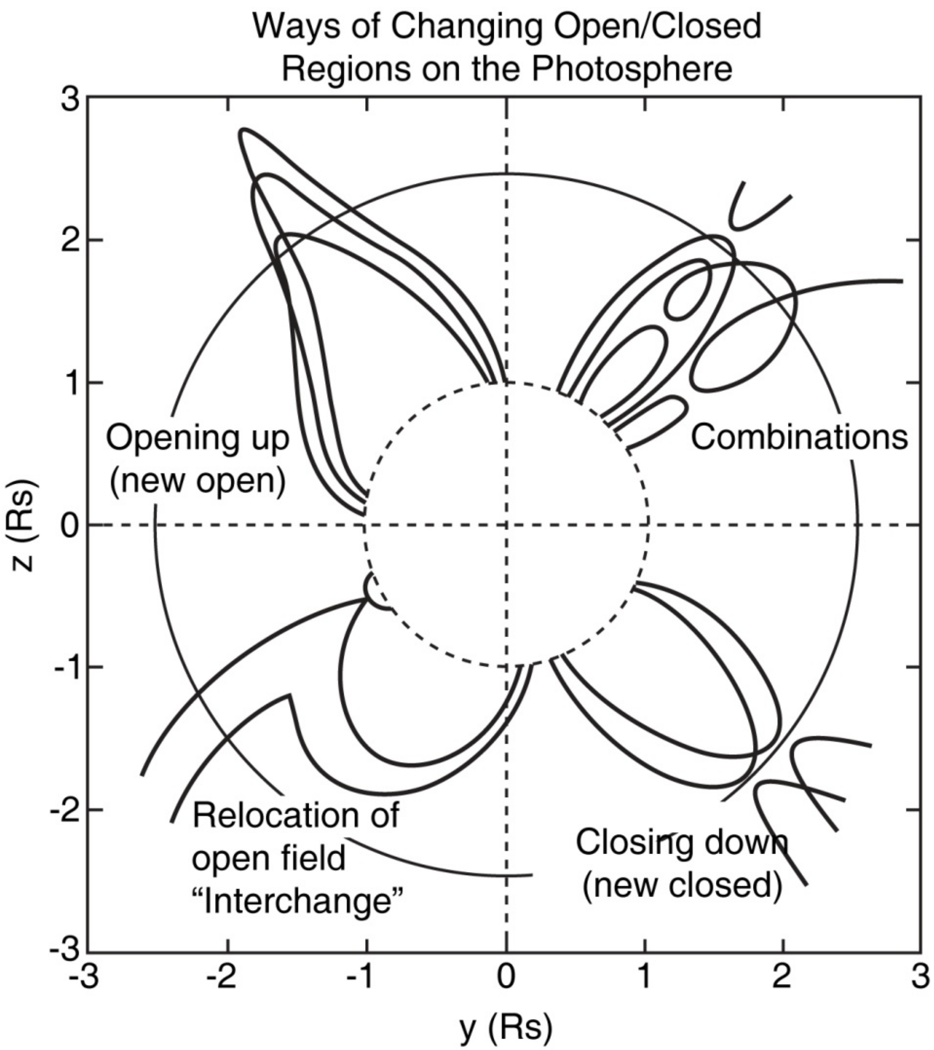


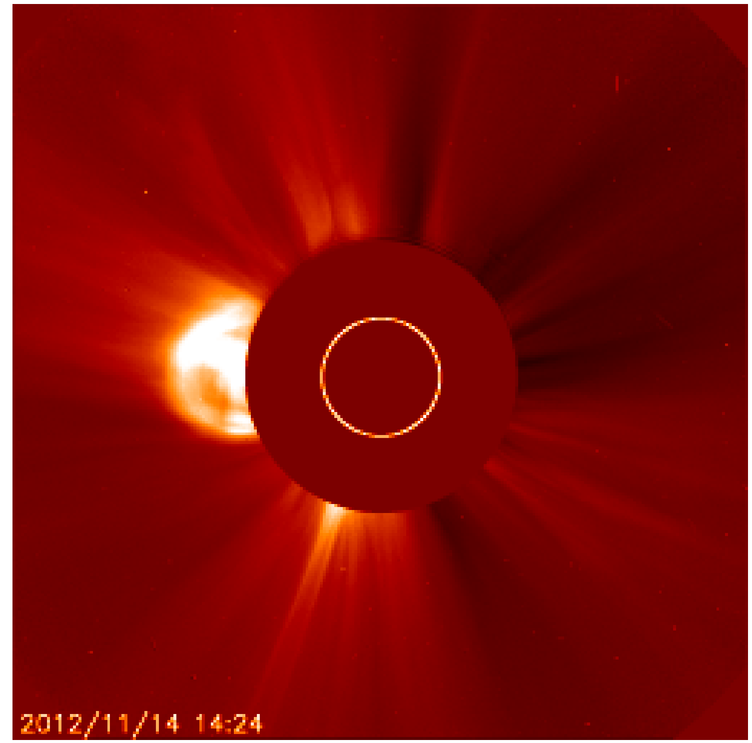


(Figures from Wang et al., ApJ)

Various streamer boundary reconnection styles are invoked to explain them. These'blobs move at low solar wind speeds

But coronal transients have a spectrum of sizes and speeds: At the ‘extreme’ end are the CMEs

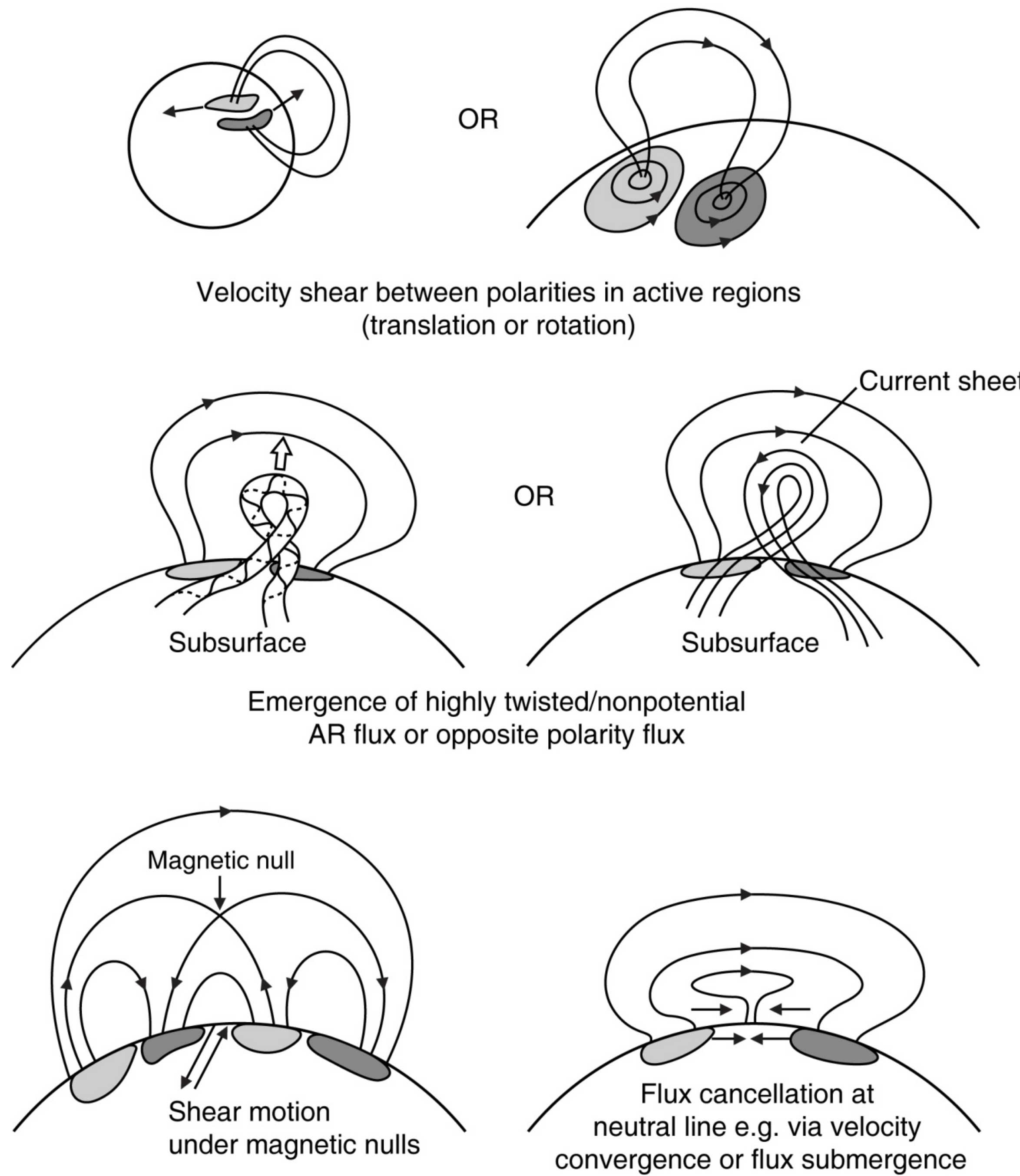




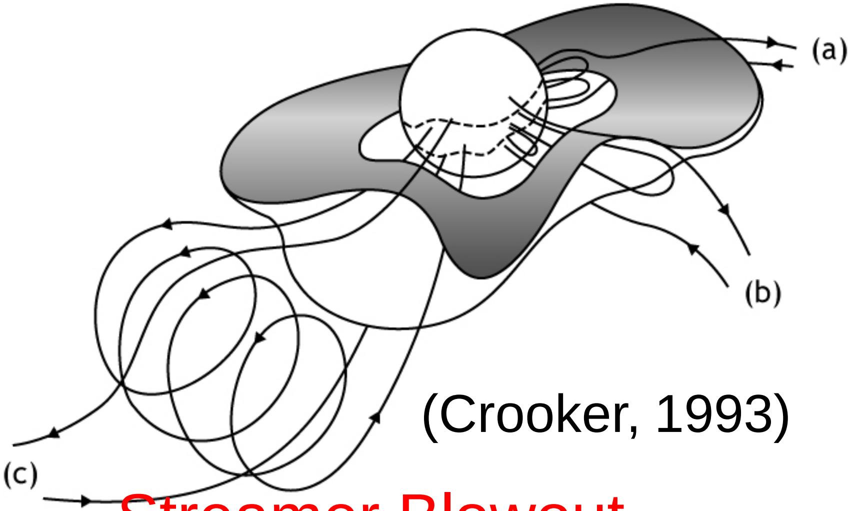
Coronal Mass Ejections- CMEs with speeds up to 1000s of km/s can occur

(SOHO LASCO images)

Ideas on where these get their extra energy involve active regions and coronal settings with magnetic nulls, sheared or twisted field, sites of rapid field evolution including field reconnection



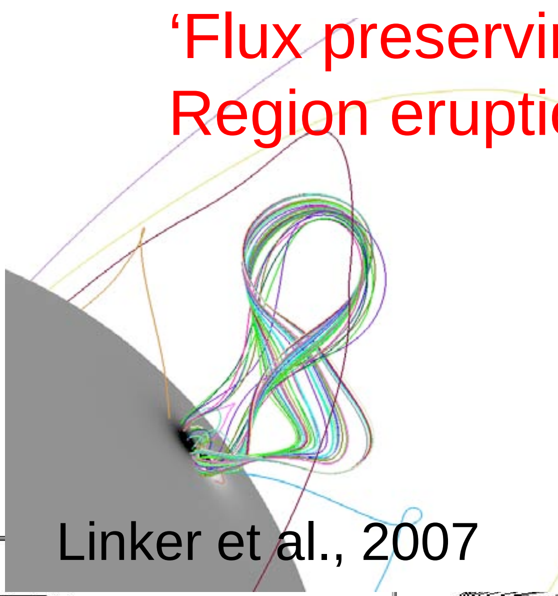
The associated CMEs can take many forms



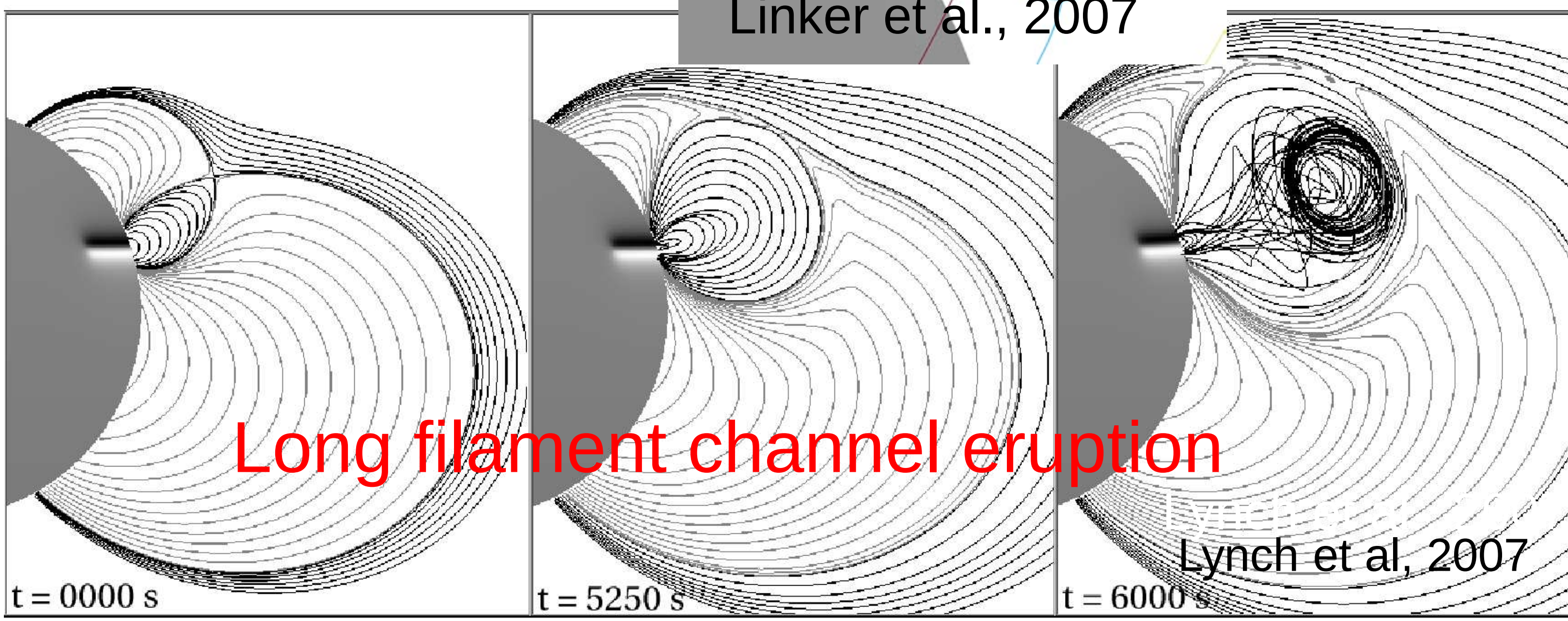
(Crooker, 1993)

Streamer Blowout

'Flux preserving' Active Region eruptions-



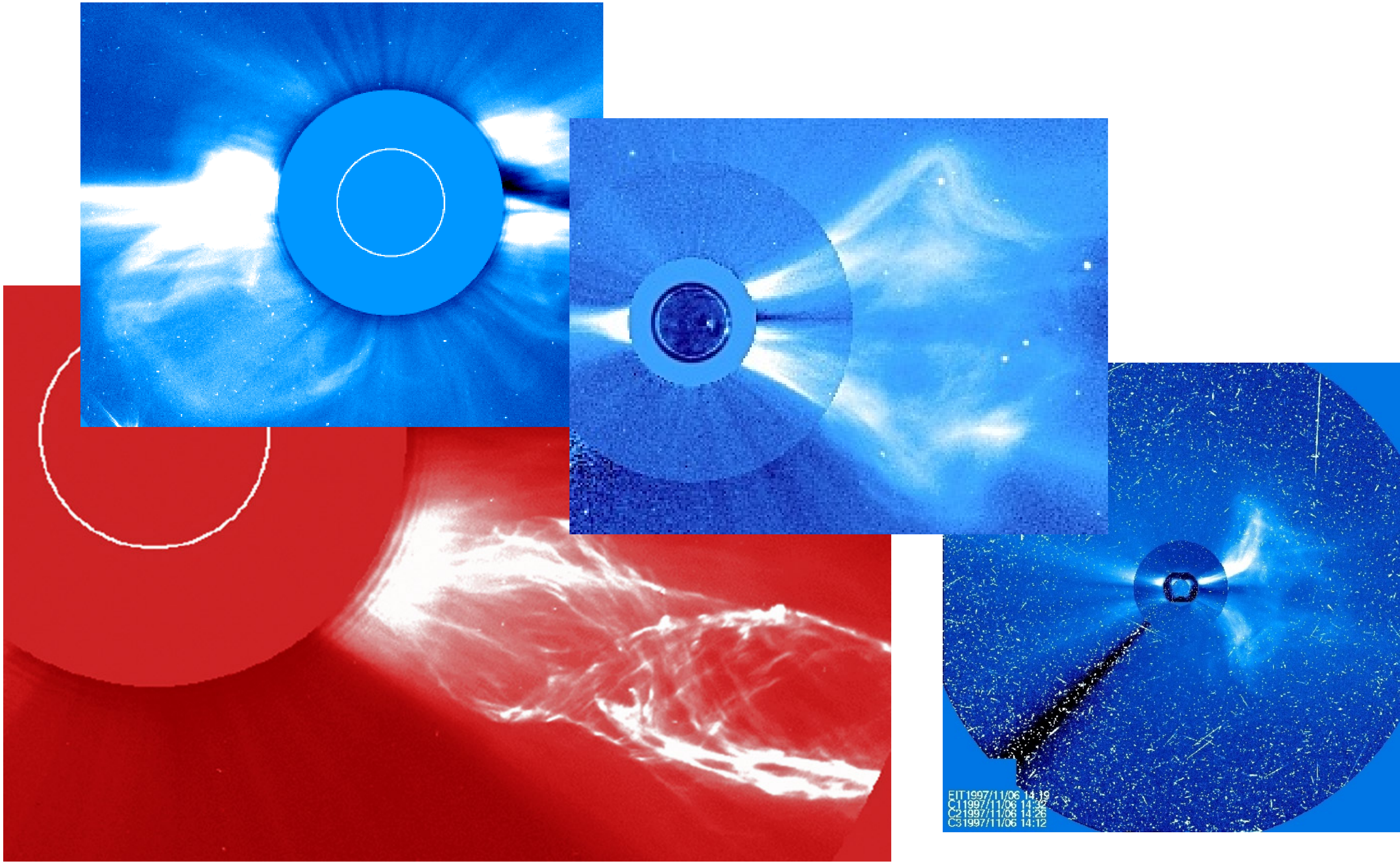
Linker et al., 2007



Long filament channel eruption

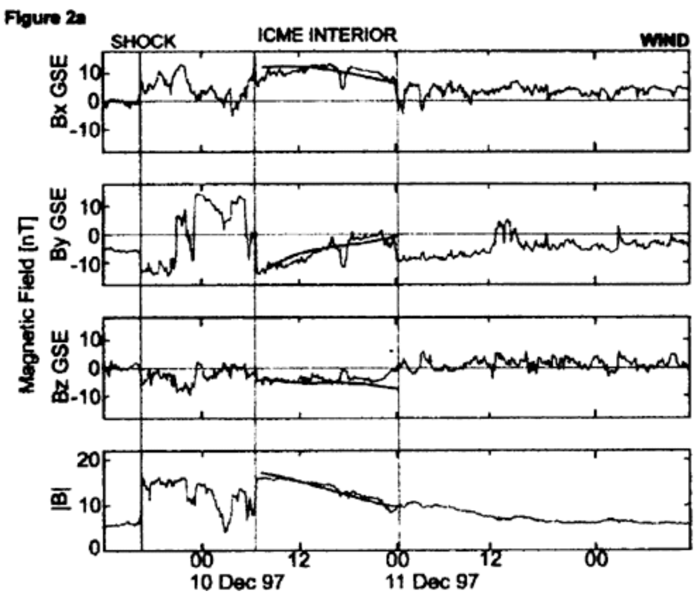
Lynch et al, 2007

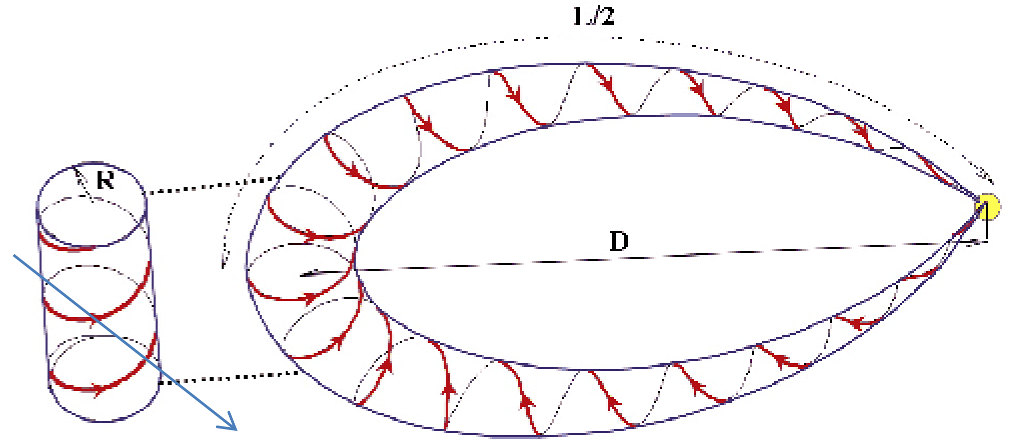
Departing CMEs undergo rotations, distortions, deflections



Some are from internal or source-related forces (e.g. rotation, expansion), some from interaction with the surrounding structure.

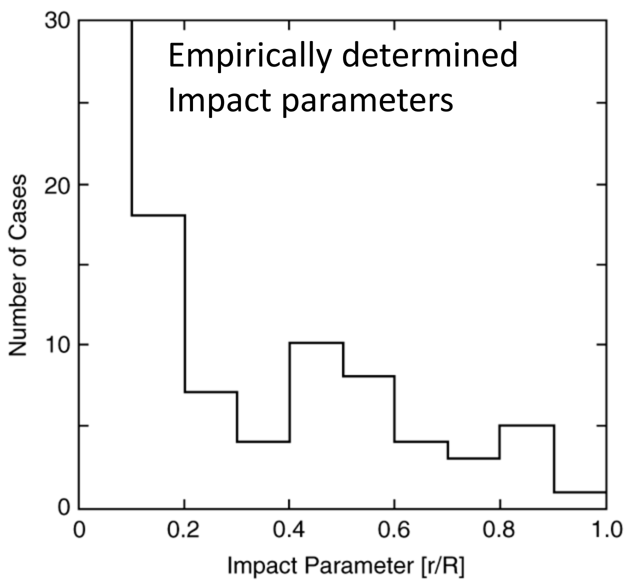
Some ICME ejecta can be fitted with flux rope models





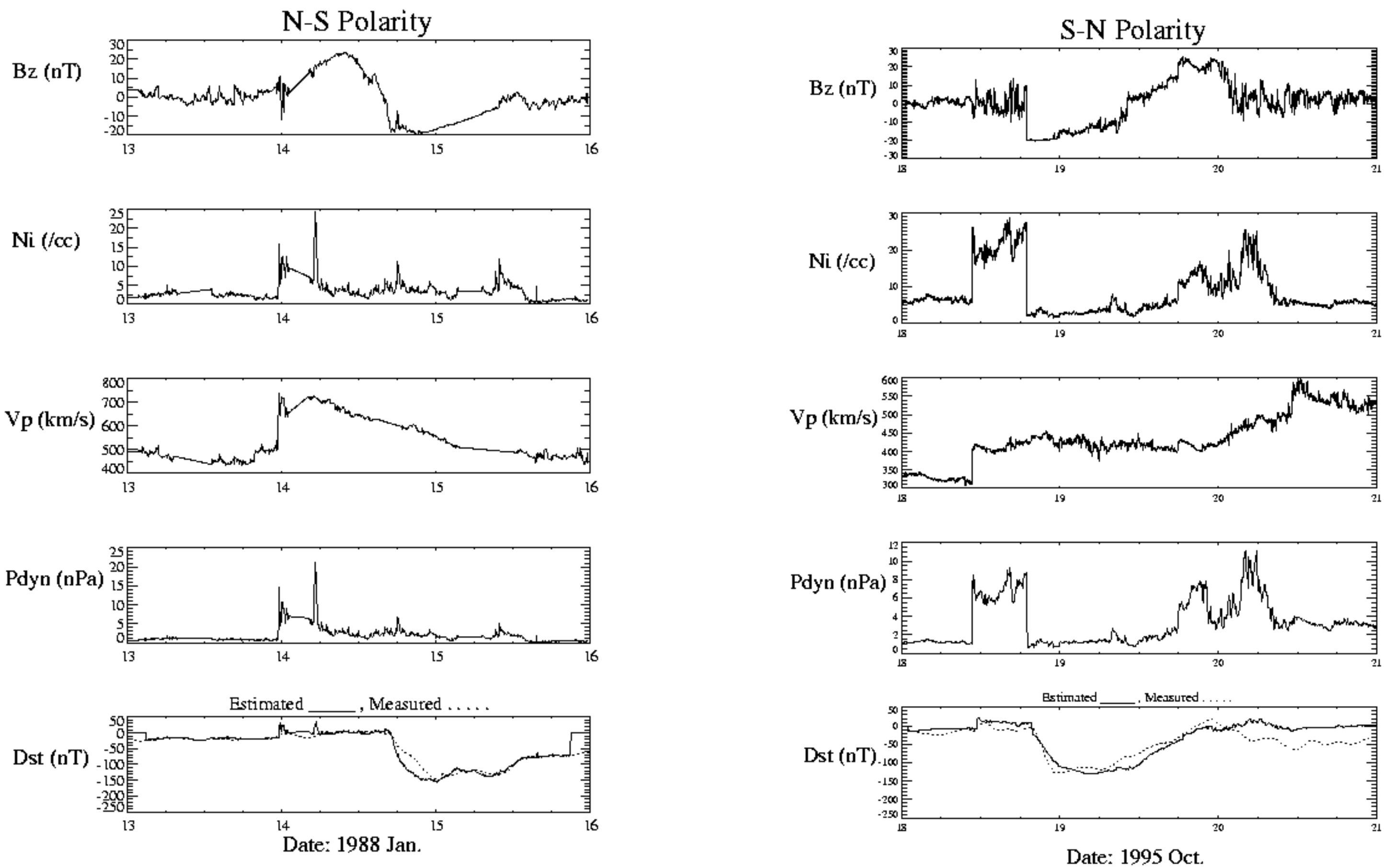
Spacecraft effectively cuts through the structure at a distance from the axis called the impact parameter

How they appear depends on how the spacecraft intersects them >>>>>>



Mulligan and Russell, JGR

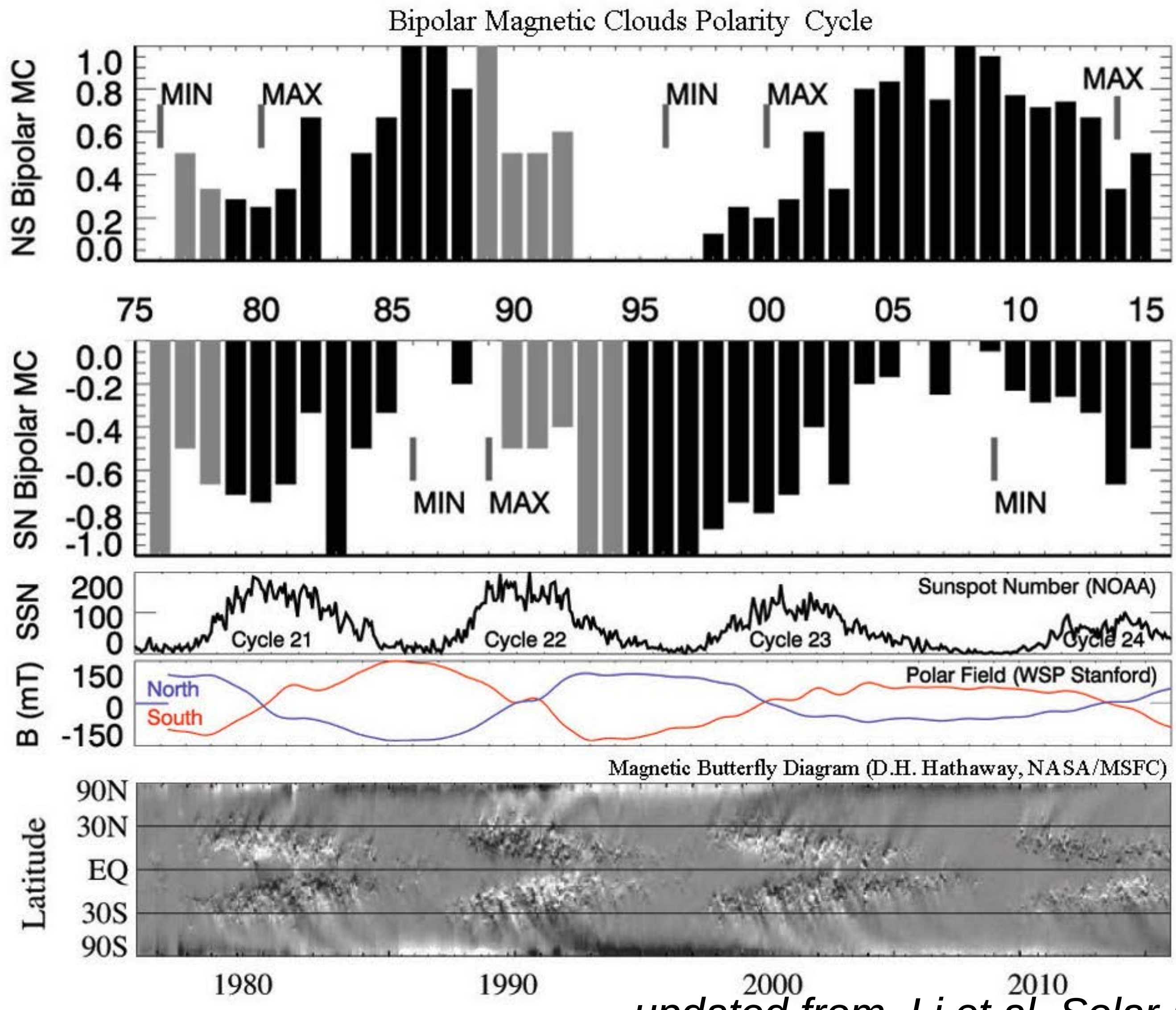
The resulting interplanetary disturbances have "polarities" related to their solar sources and evolution



Figs from Fenrich and Luhmann (GRL, 1995)

Magnetized planets have much different responses to ICMEs depending on their magnetic field orientations and strengths

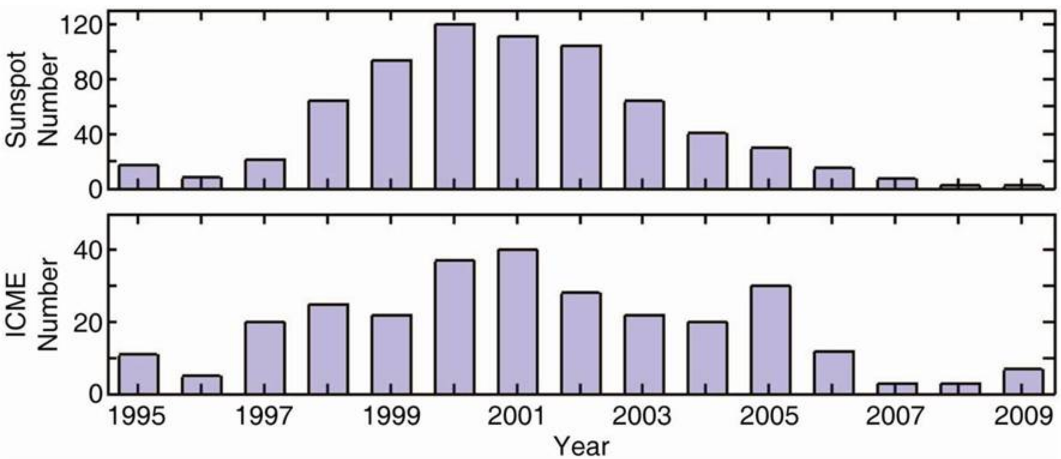
The Flux-rope type ICMEs show ‘polarity’ preferences that vary with the solar polar field cycle



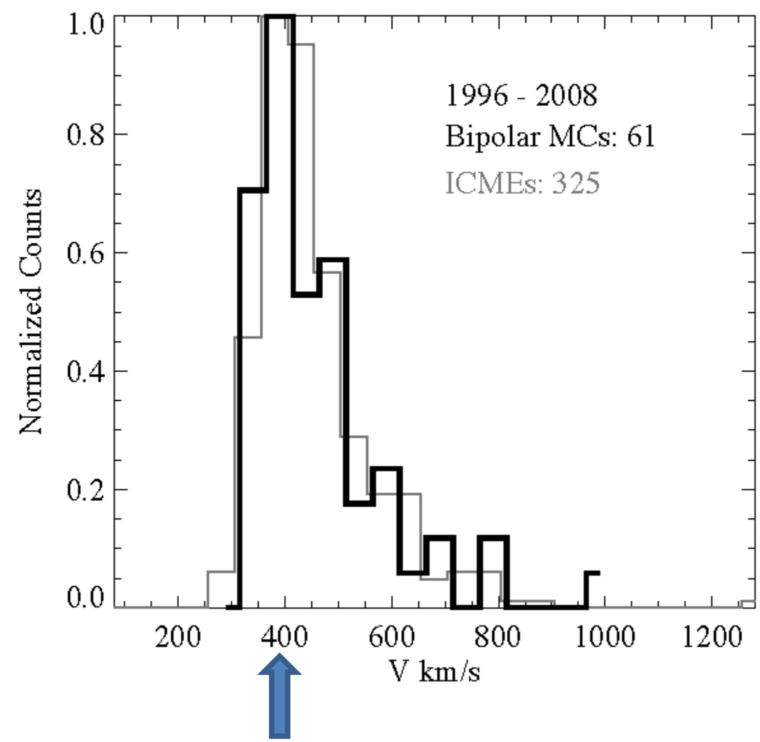
updated from Li et al. Solar Phys 2011

Statistically, CME/ICME occurrence varies with the solar cycle and ICME speeds look like solar wind speeds. Only a few are very fast (>1000 km/s)

MIN MAX MIN



Speed distribution of ICMEs

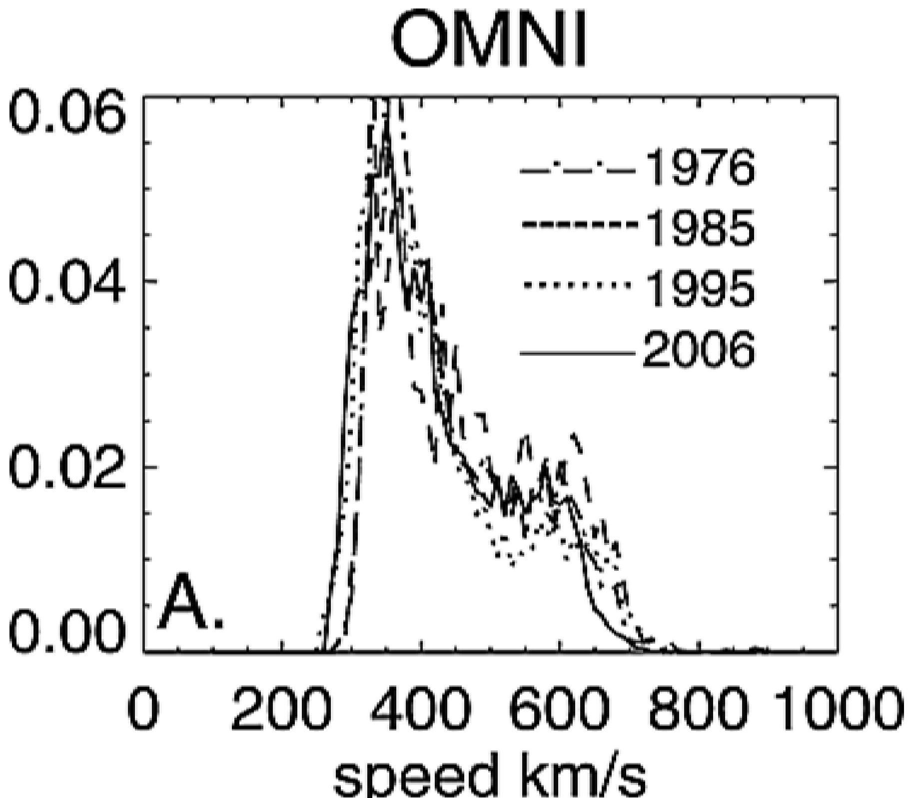


Typical solar wind speed

ICME rates are known to roughly follow the sunspot number cycle trend, with maximum rates around solar maximum like CMEs *(plot from Lan Jian, GSFC))*

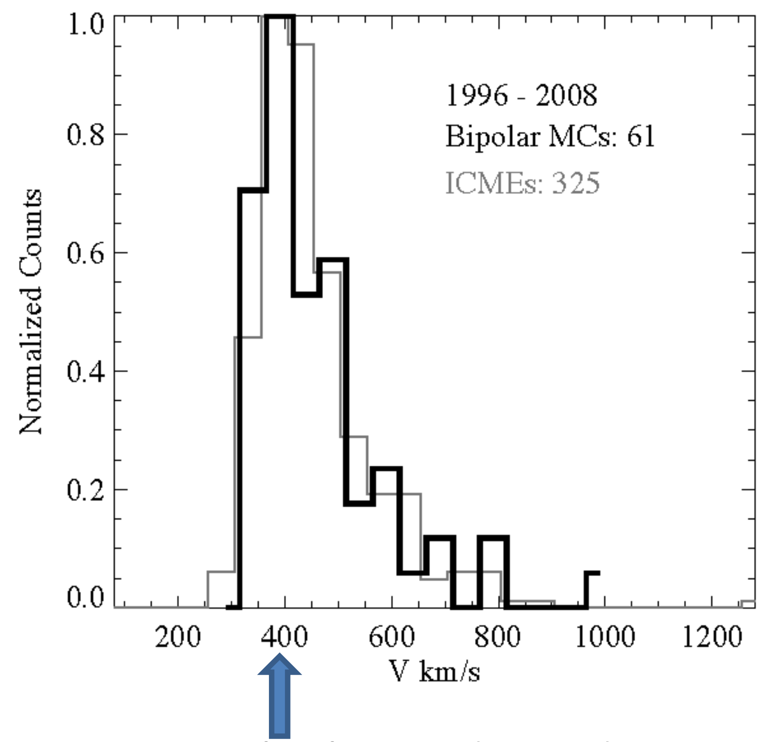
Plot: Y. Li SSL/UCB

While they produce enhanced solar wind parameters, in part from their ambient flow interaction, most ICMEs have little more than typical solar wind speeds at 1 AU



Solar wind speed statistics@1 AU
(S. MacGregor et al. JGR 2011)

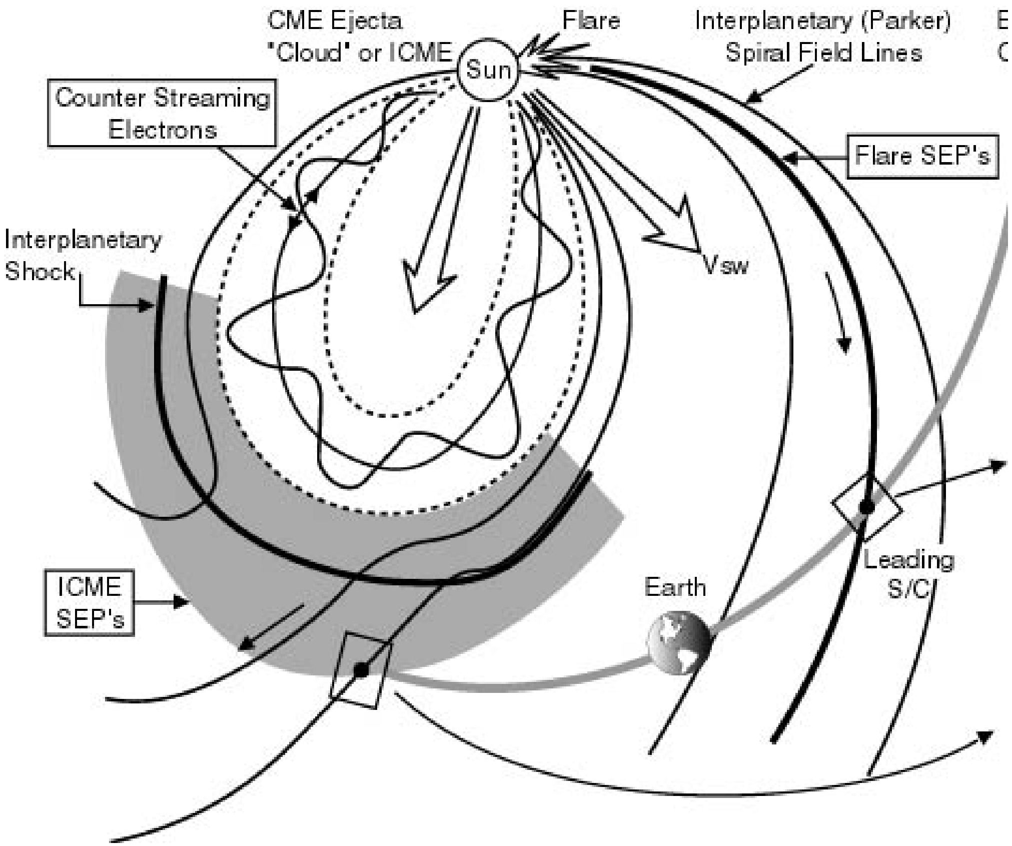
Speed distribution of ICMEs

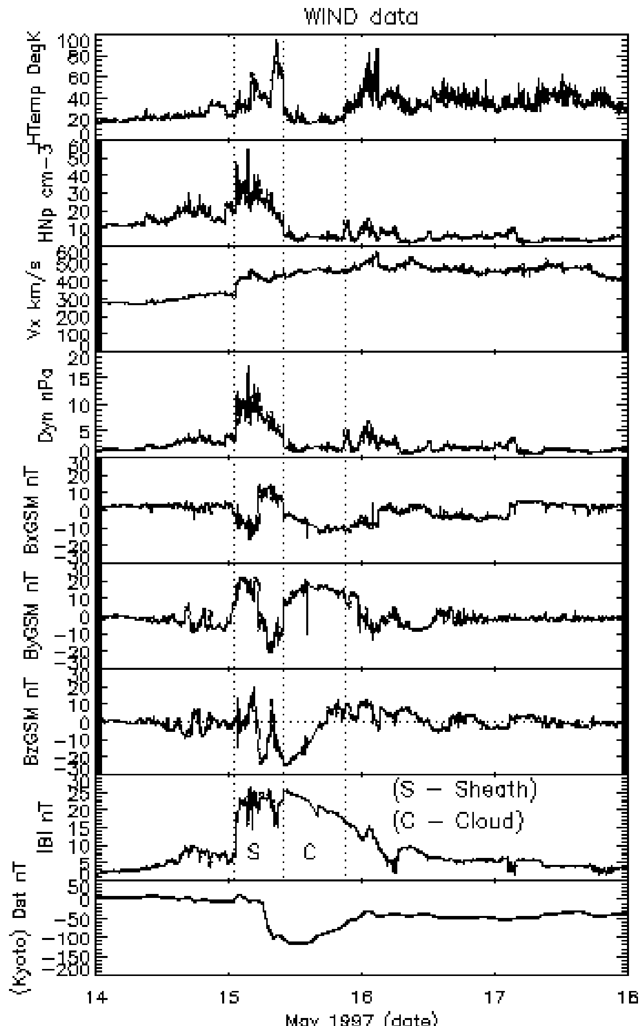


Typical solar wind speed

Plot from Y. Li SSL/UCB

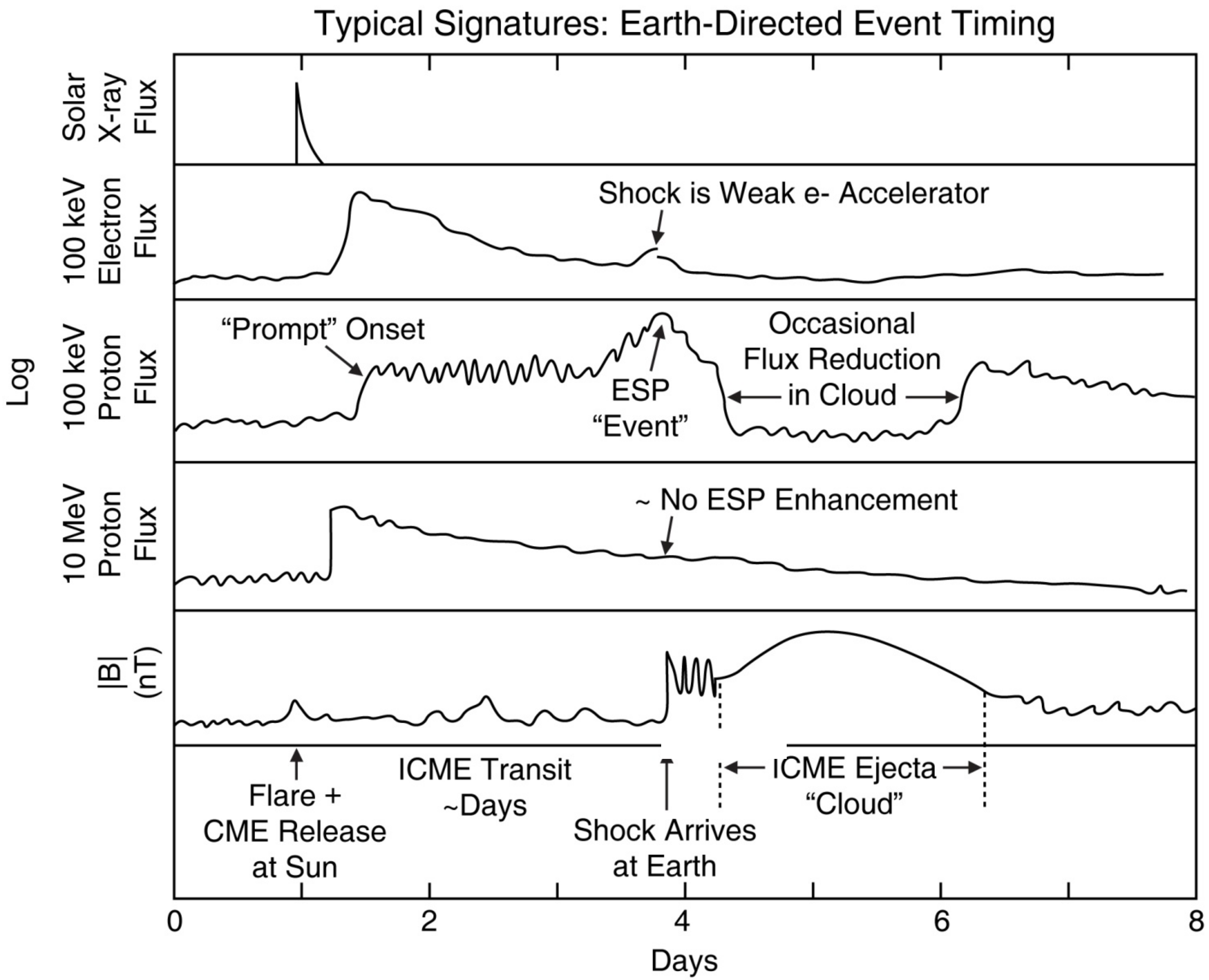
What other consequences do interplanetary counterparts of CMEs, ICMEs, add to the picture?



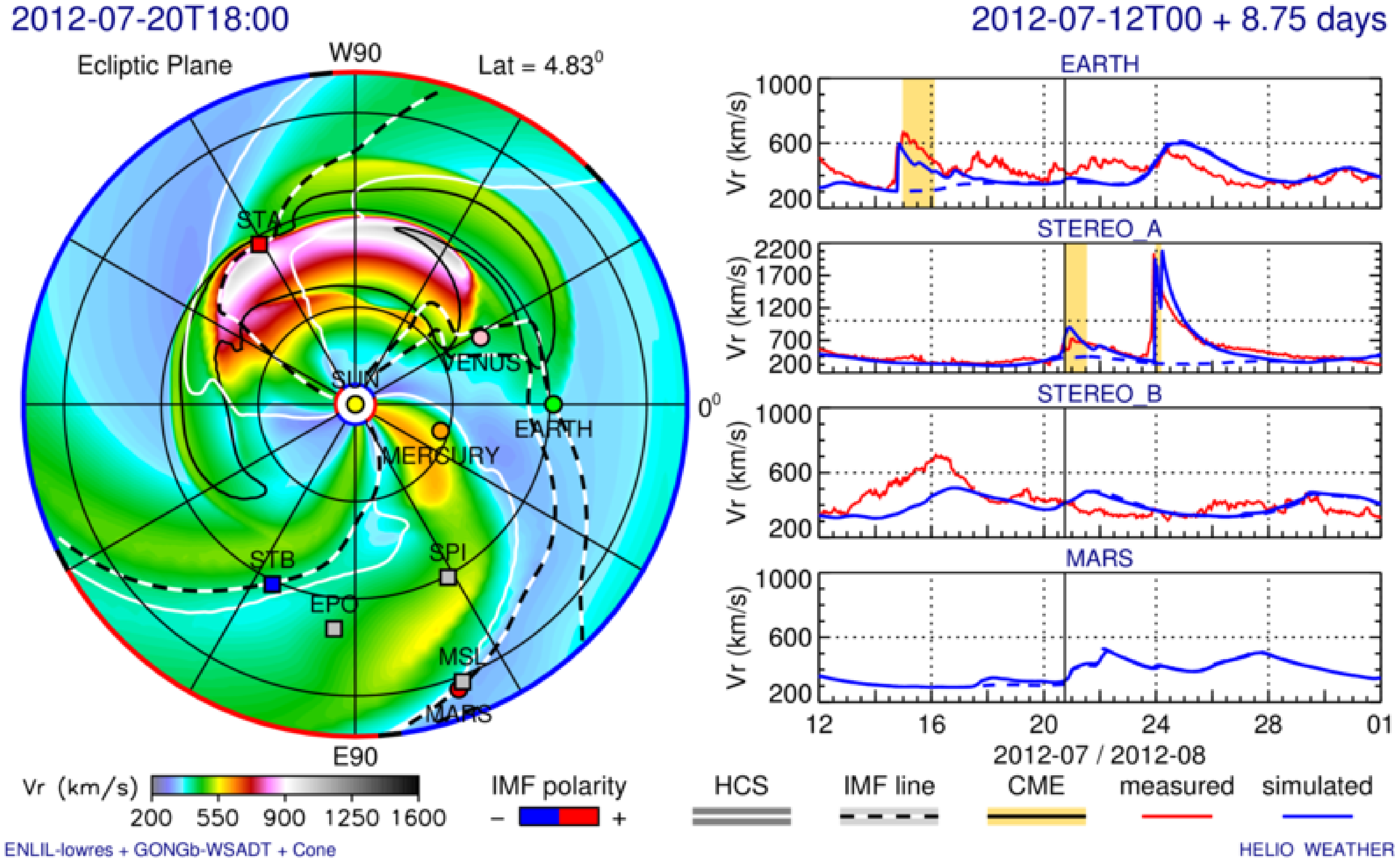


Fast ICMEs may have leading shocks, and generally have compressed solar wind sheaths leading the arrival of the coronal ejecta. The shocks are important sources of **SEPs**

SEPS, Solar Energetic Particles, are typically the first sign of a major ICME to arrive at an observer

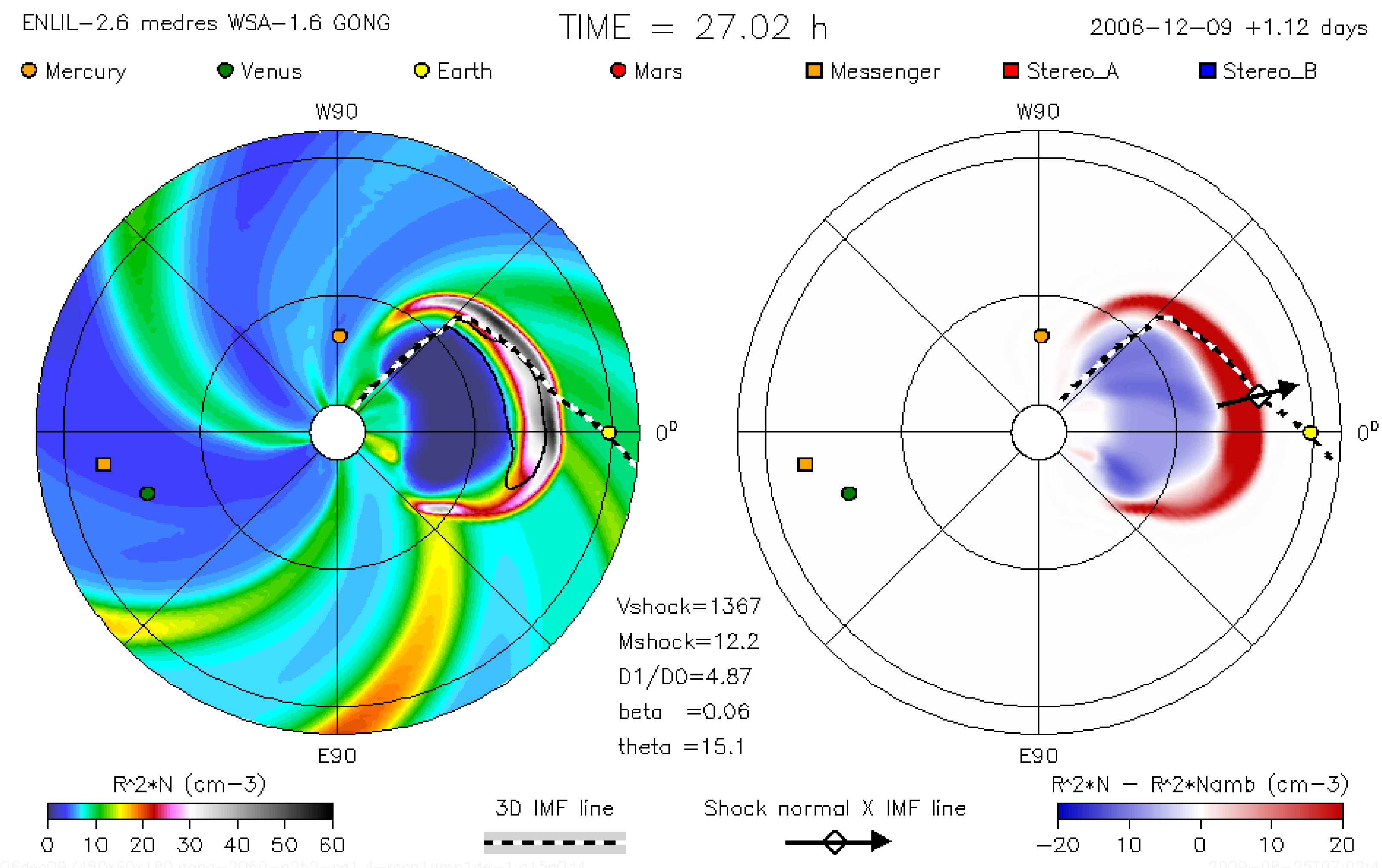


One can use simplified ejecta launched into solar wind models to model the shock arrival, but also the shock transit



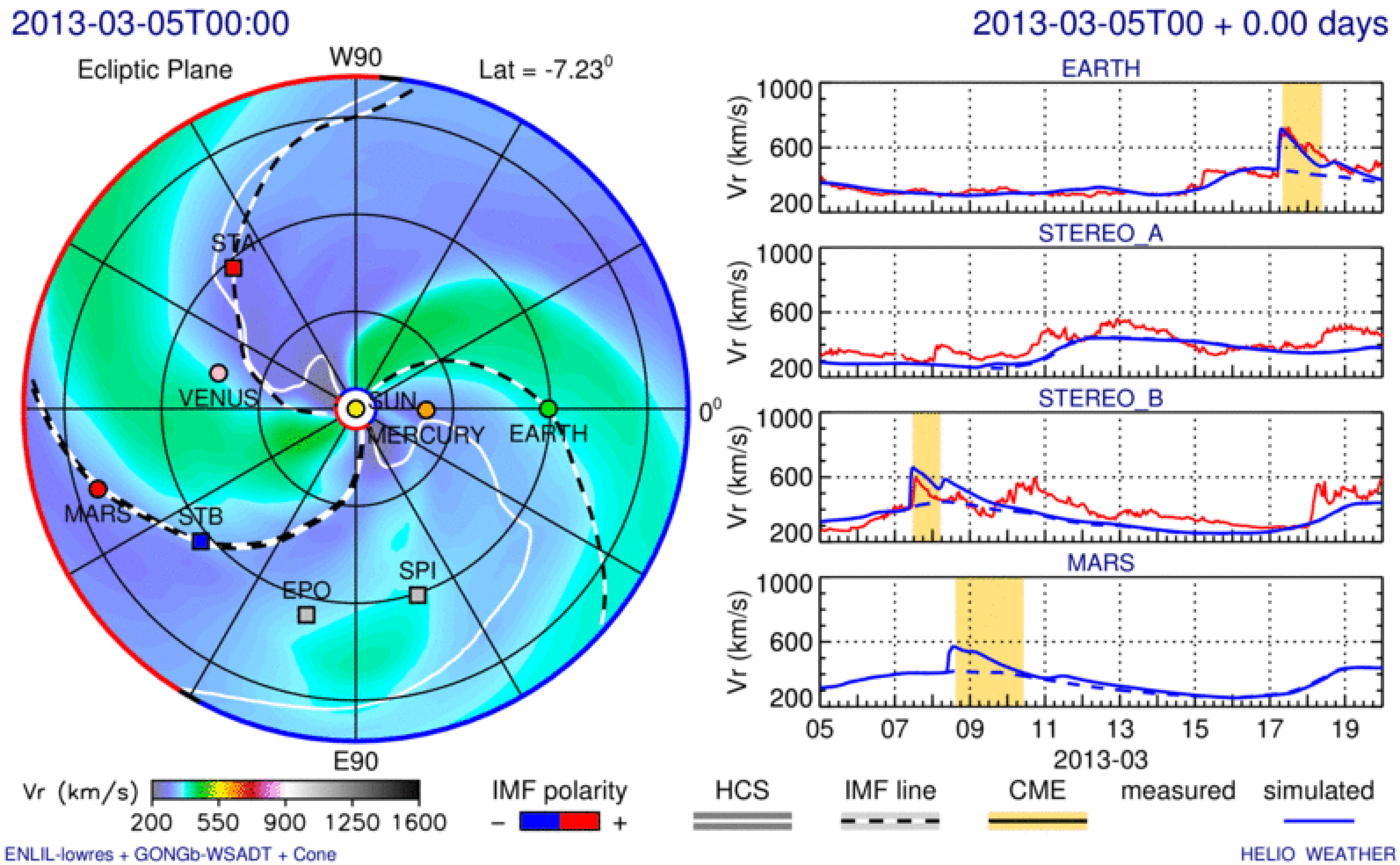
(WSA-ENLIL simulation of July 2012 events with simplfied 'cone model' CMEs (from Odstrcil and Mays, NASA GSFC CCMC run)

One can then take a model shock and observer-connected Interplanetary field lines and approximate what SEPs from that source any observer will experience

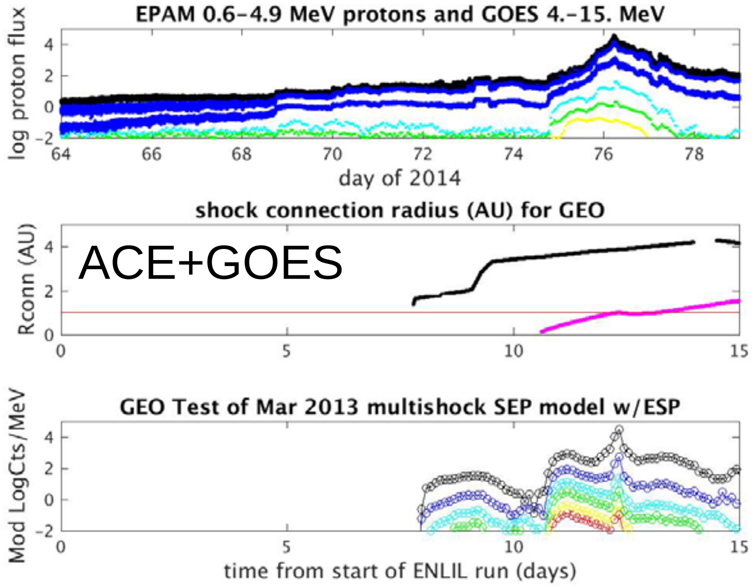


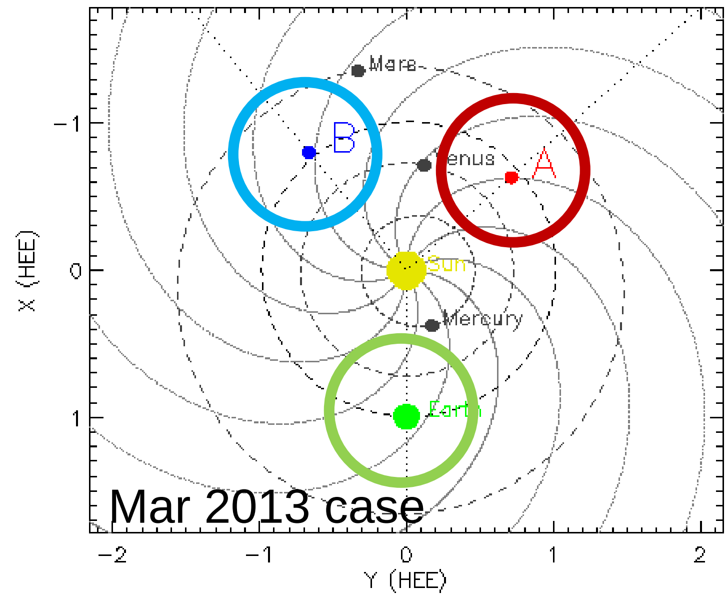
e.g. model shocks detected in WSA-ENLIL simulations (D. Odstrcil Figure)

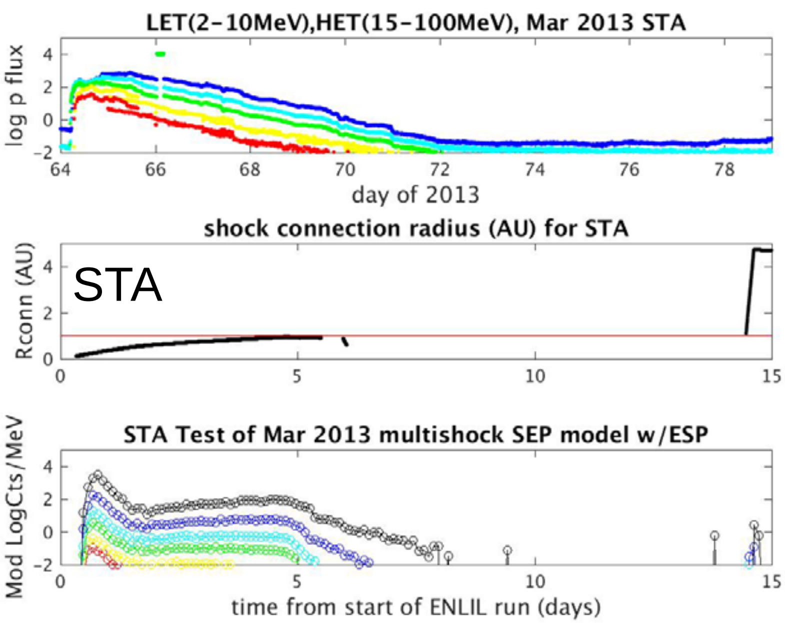
This relatively simple example (e.g. with isolated, spread out CMEs) illustrates such results: e.g. March 2013

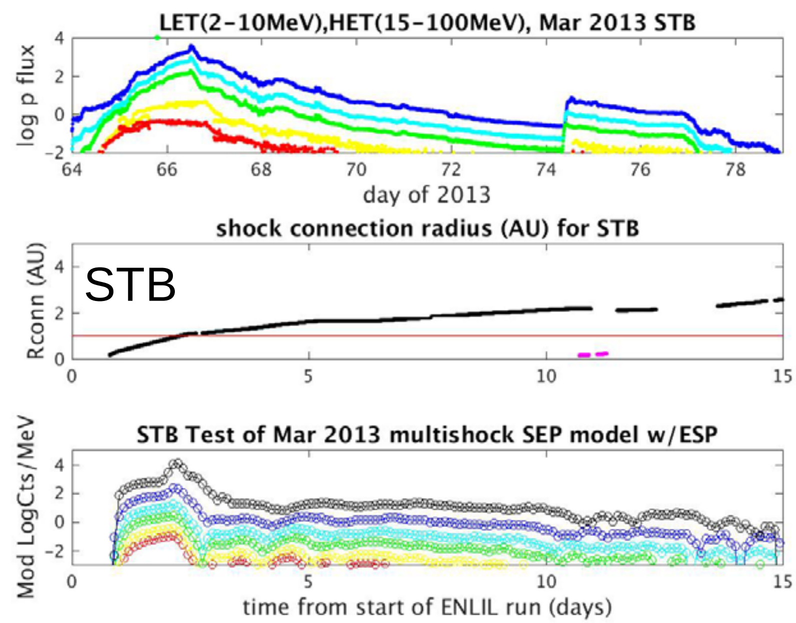


Observer ‘layout’ (from SSC)



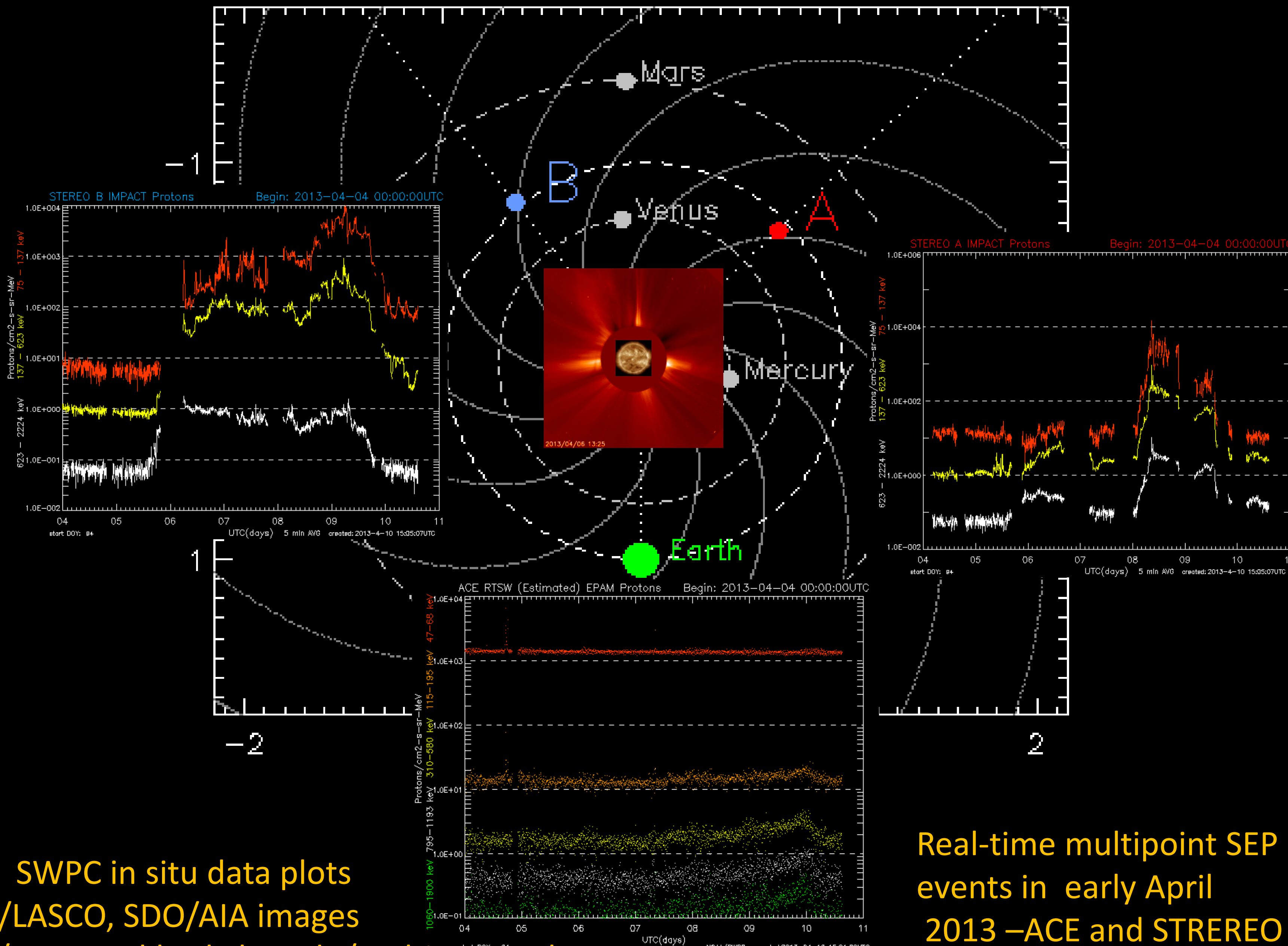






Note each ‘observer’ connects to the ENLIL shocks differently

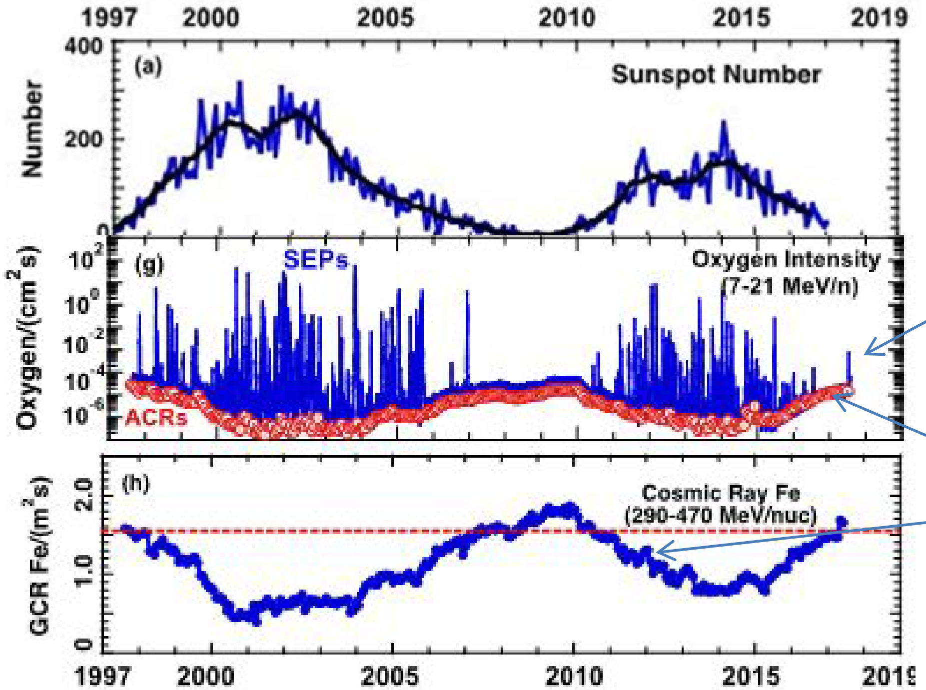
This allows us to connect SEP observations at multiple sites created by any shock(s)



NOAA SWPC in situ data plots
SOHO/LASCO, SDO/AIA images
http://stereo.ssl.berkeley.edu/multistatus.php

Real-time multipoint SEP events in early April 2013 –ACE and STREREO

Like ICMEs, SEP fluxes vary with the phase and strength of solar activity. At the same time, the Galactic Cosmic Ray (GCR) flux varies in antiphase with solar activity, being excluded or swept from the heliosphere by the solar wind disturbances

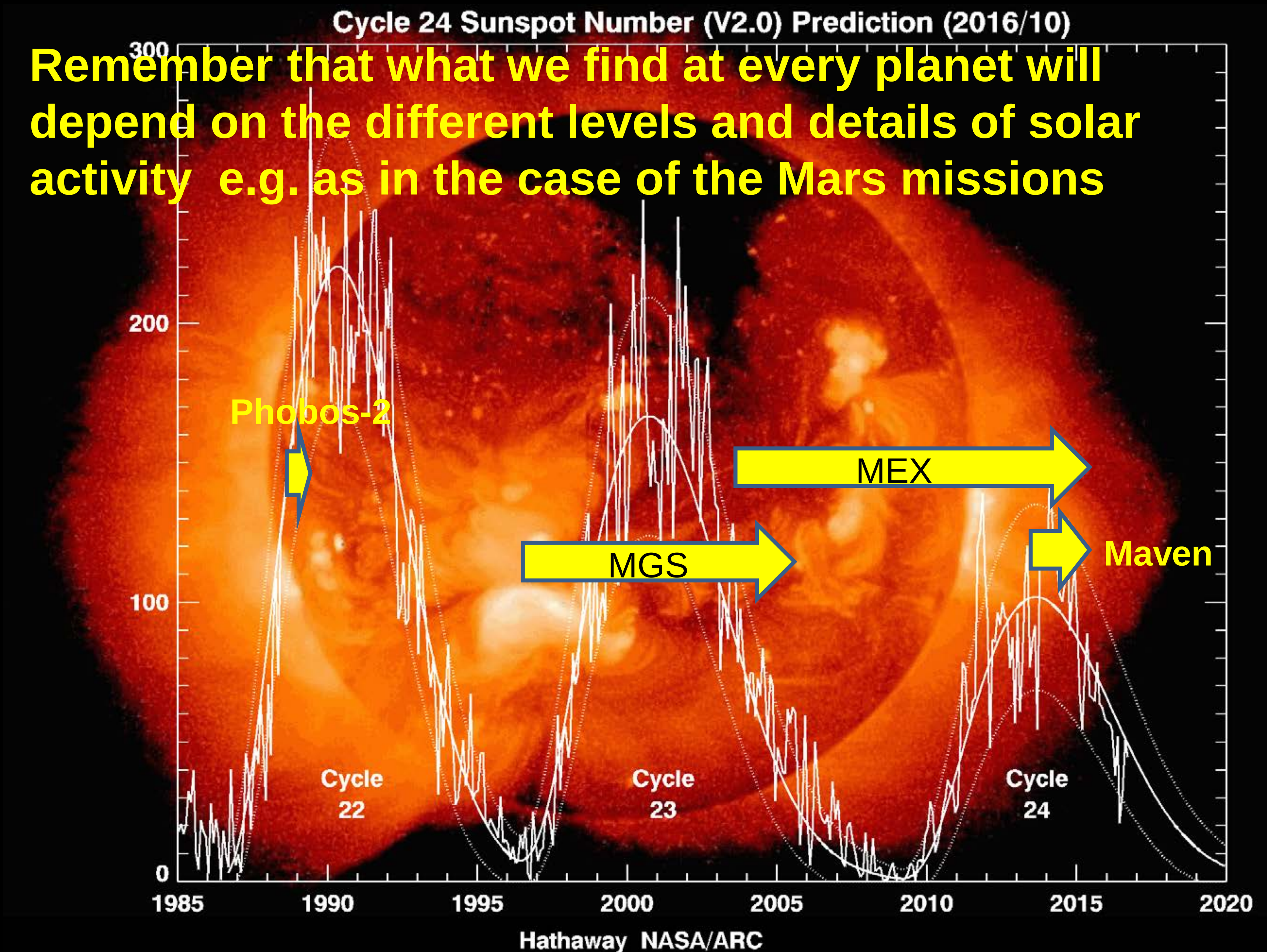


Expect fewer Solar energetic Particle (SEP) Events

Expect higher Anomalous and Galactic Cosmic Ray fluxes

From 'ACE NEWS' 2017

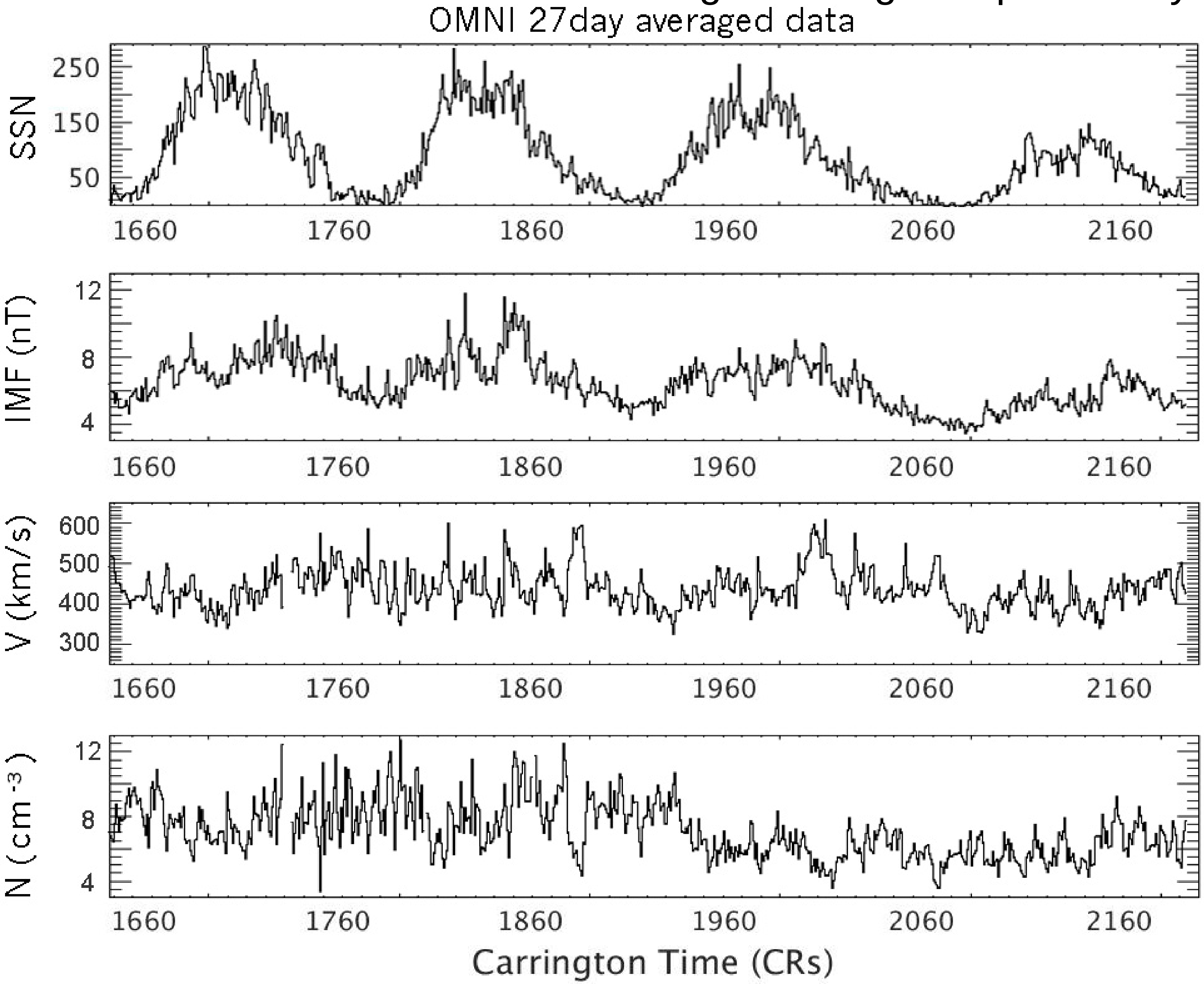
Remember that what we find at every planet will depend on the different levels and details of solar activity e.g. as in the case of the Mars missions



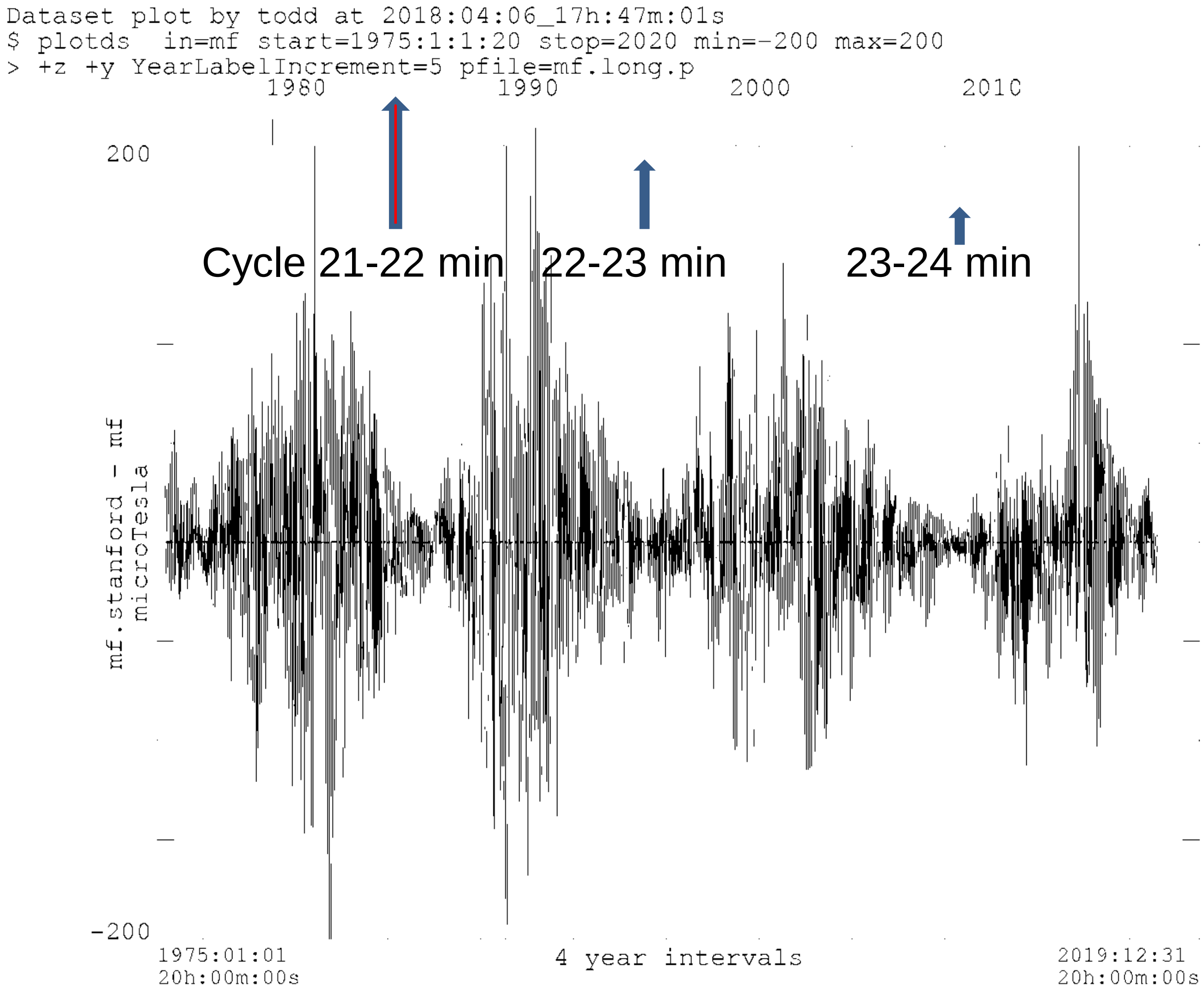
We cannot study the planets without knowing the Sun…

An update

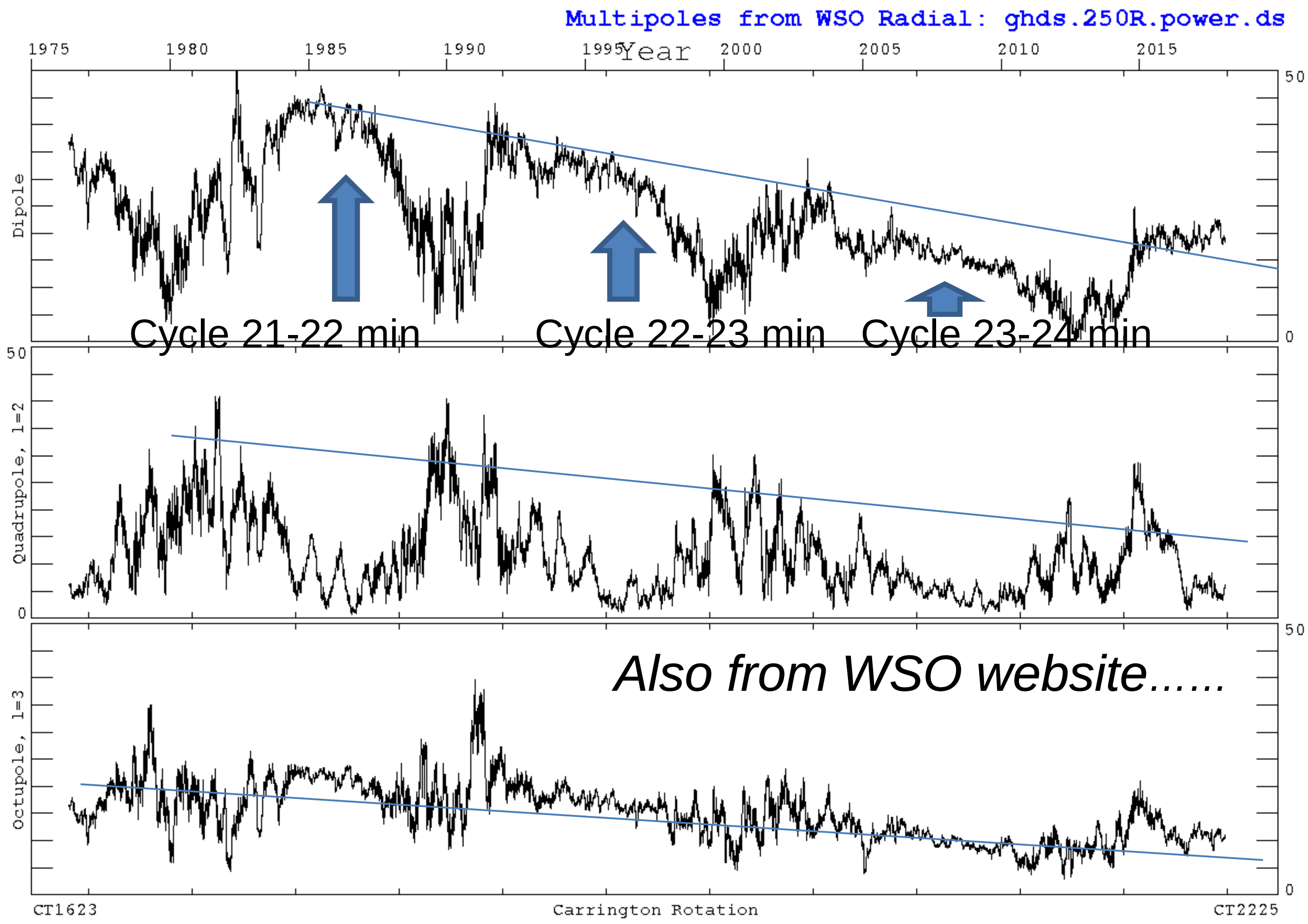
The Sun and its effects have been changing since the space age began, with numerous downward trends following declining sunspot activity



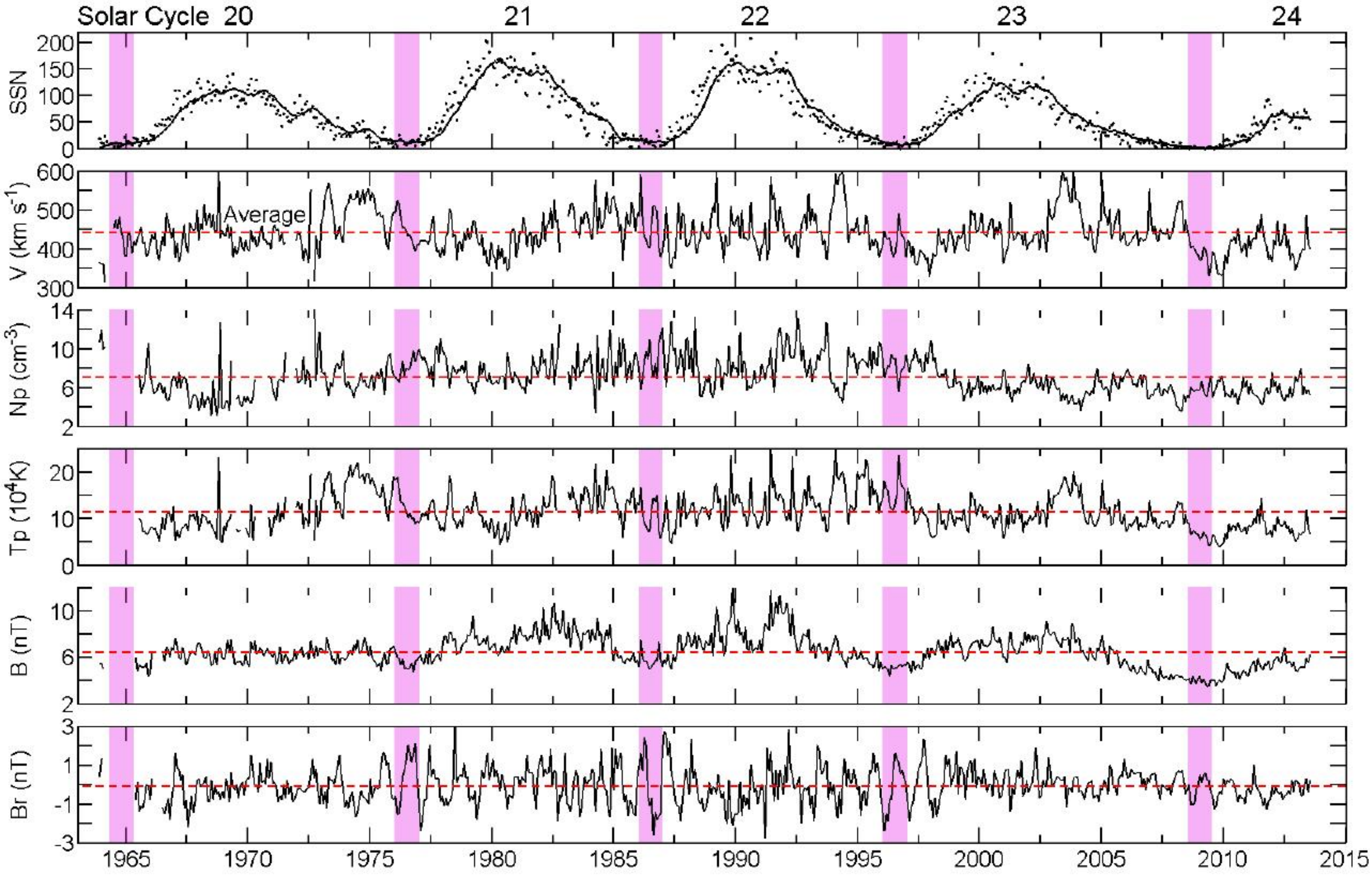
The solar magnetic field state has been characterized not only by weakening magnitudes…. (Mean Field-WSO magnetograph)



e.g. but the effective dipolar field component of the surface field at solar minima has declined more rapidly than higher order harmonics

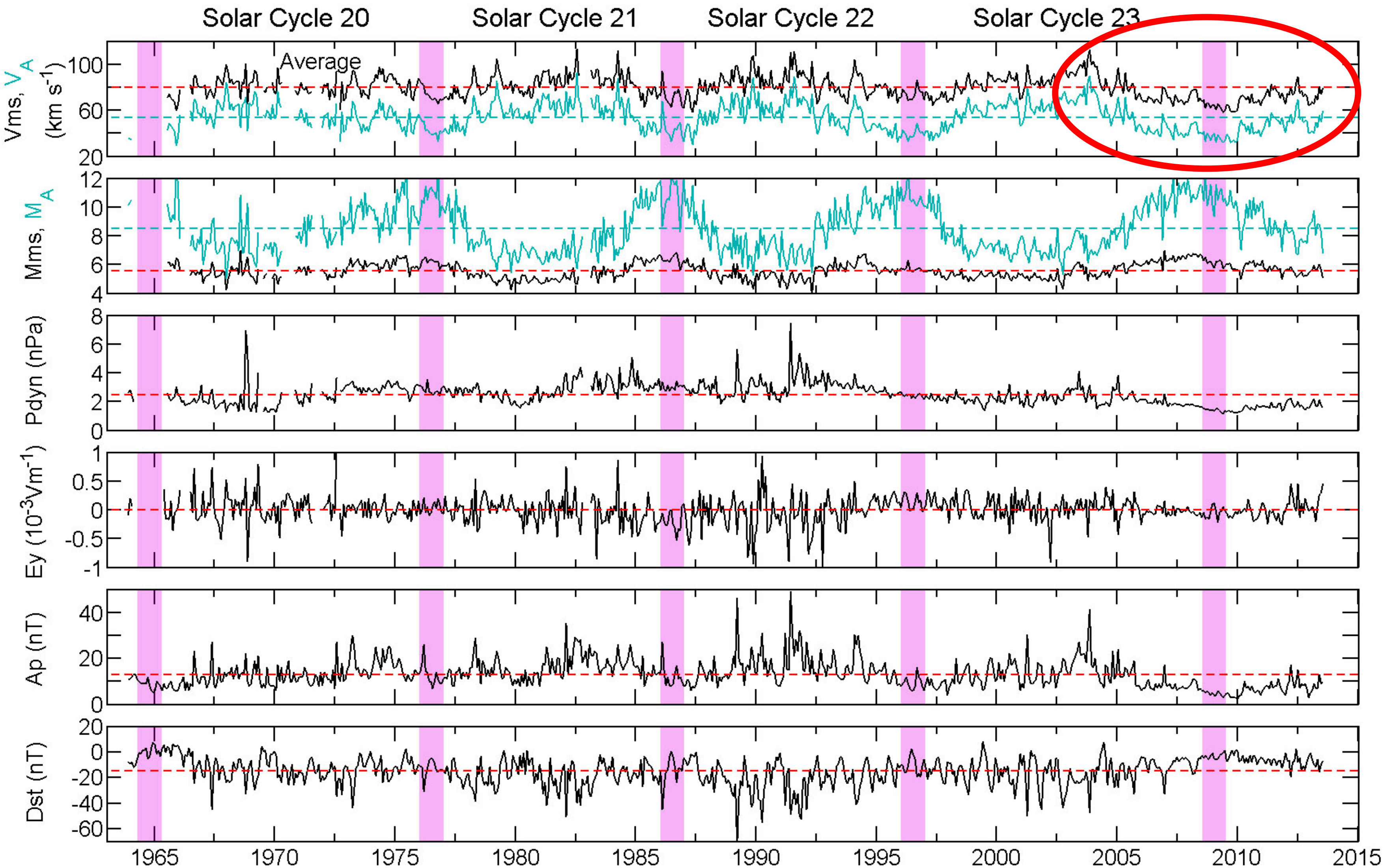


This has meant more coronal structure at low solar activity, more low latitude coronal holes, more pseudostreamers etc.



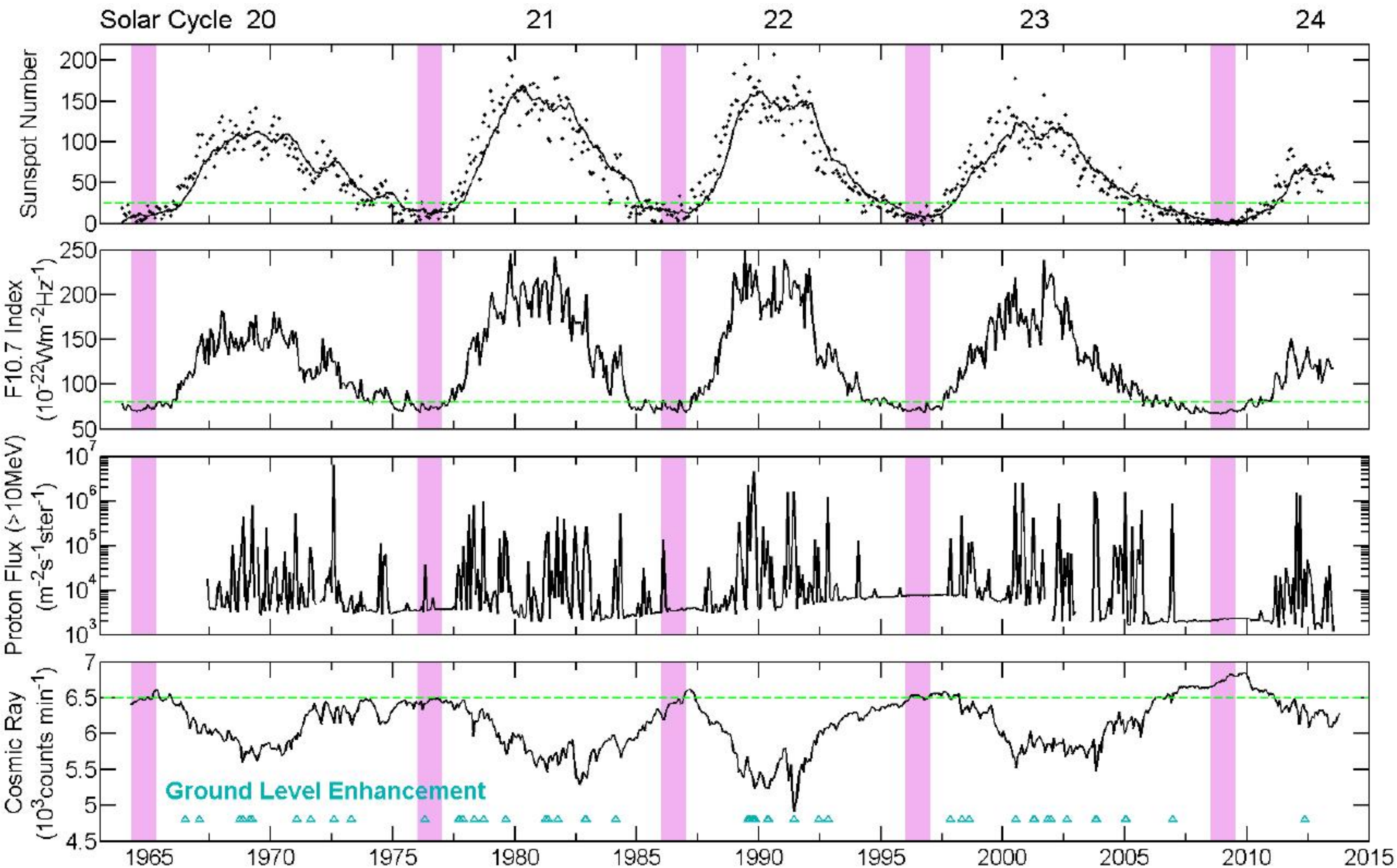
Solar cycle 24 has had low solar wind fields and densities

Lan Jian- series of plots from OMNI data



Lan Jian-from OMNI data

One result has been lower ambient Alfven and magnetosonic speeds that have been easier to exceed. eg. by CMEs



Lan Jian-from OMNI data

Perhaps in part because of this, the weak cycle has still had significant SEP events. GCR Fluxes have been higher.