Space Climate 6: Levi, Finland
Introduction to Solar Dynamics & Observations

A Norton, Stanford University

I The Solar Cycle, Dynamo, Abundances, Solar Wind

II Hemispheric Asymmetry, Flux Emergence into Atmosphere

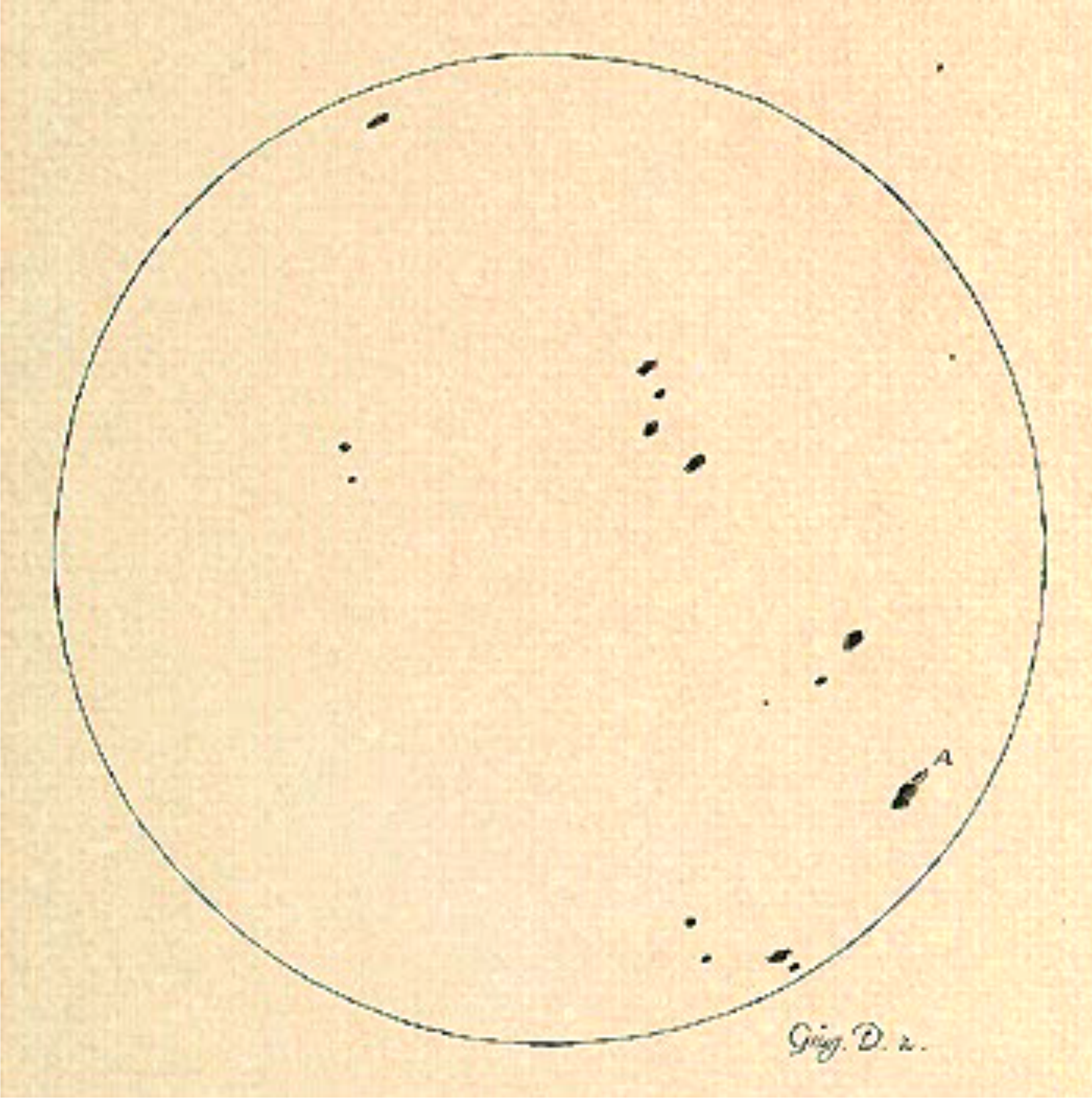
III Terminology (MOVIES), Open Flux, Predicting the Next Solar Cycle

2013.01.07 Continuum Intensity / Helioseismic Magnetic Imager
Solar Dynamics Observatory

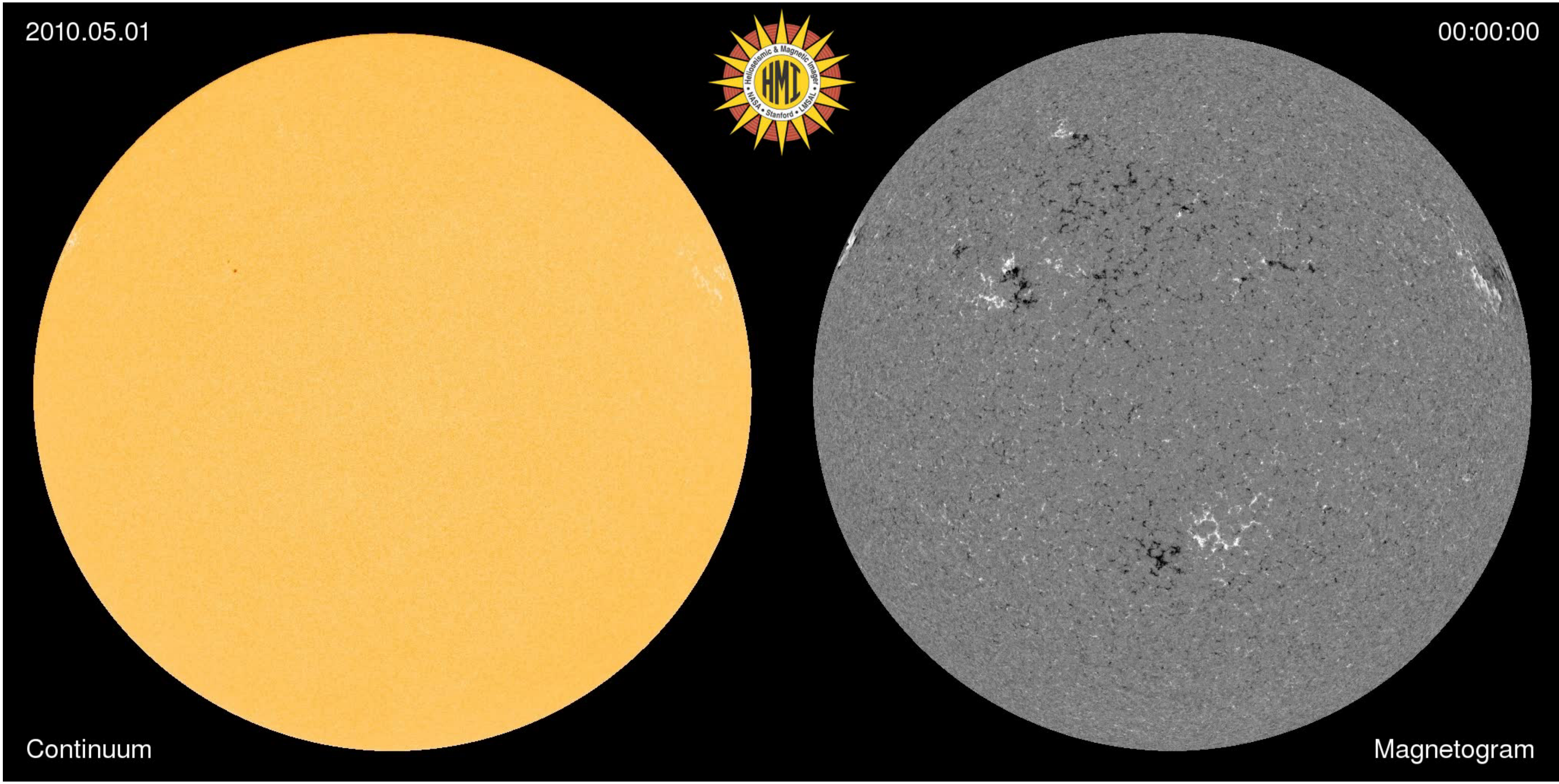
Original Sunspot Observations…

800 BC "A dou (or mei) is seen in the Sun” – oldest record of sunspot found in China’s Book of Changes.

1663 Galileo => heresy for heliocentric beliefs. But his observations of sunspots were also offensive to the church since they showed the Sun as imperfect and changing.



400 years later…



Solar Dynamics Observatory: HMI, AIA, EVE keep an eye on the Sun 24/7 as do many other instruments in space & on the ground.

Space Weather is Dominated by the Sun

The Sun is the architect of the solar system.

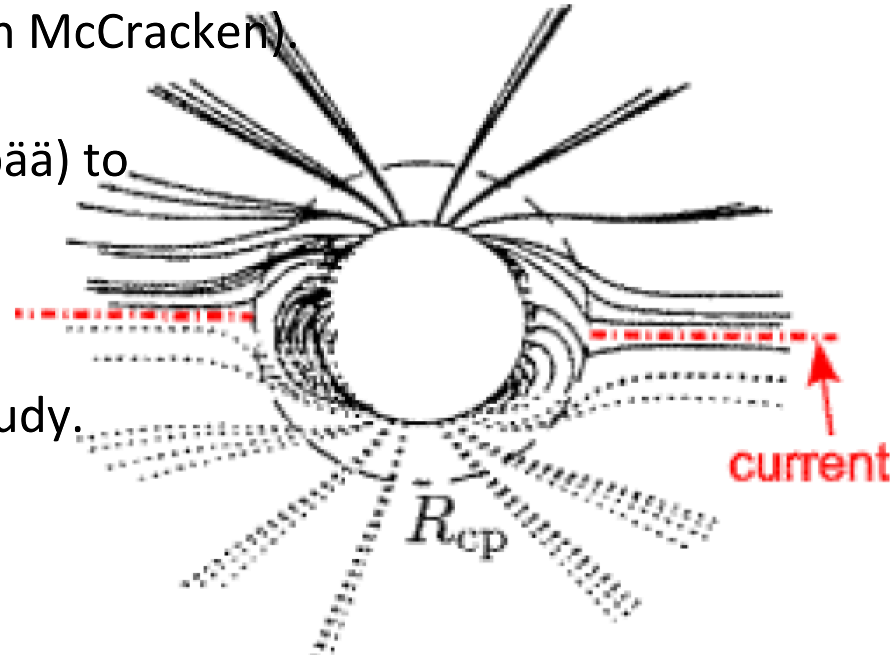
Its large-scale magnetic structure determines the location of the current sheet, high- and low-speed solar wind, sector structures.

Short-term energetic events, i.e., coronal mass ejections cause storms with consequences at Earth.

Long-terms solar cycle (Rainier Arlt) modulation affects total solar irradiance (Greg Kopp and Natalie Krivova) and cosmic rays (Ken McCracken).

Short-term geomagnetic response (Kari Pajunpää) to solar events varies.

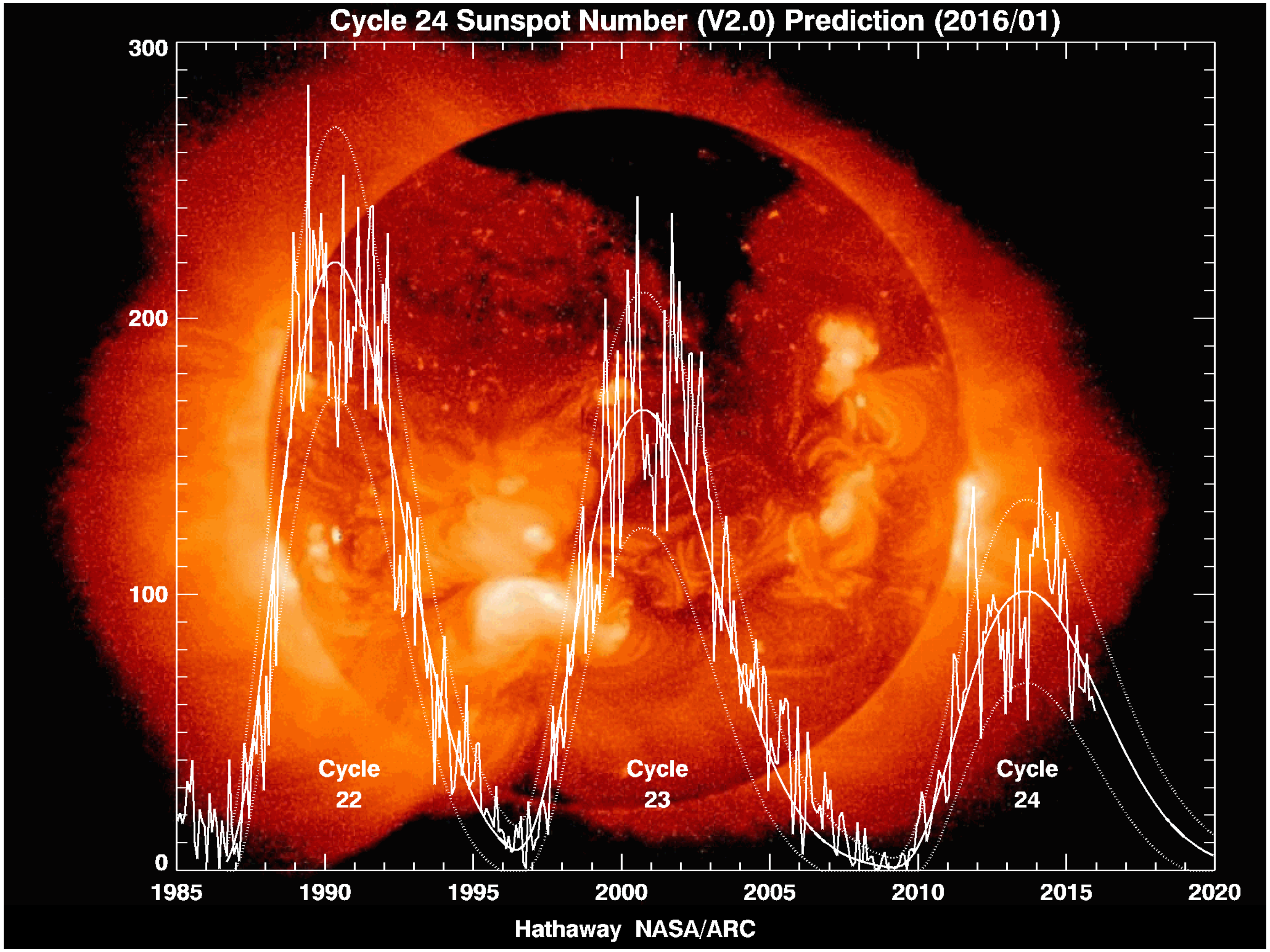
Long-term climate (Achim Drebs) influences have more uncertainty but are important to study.



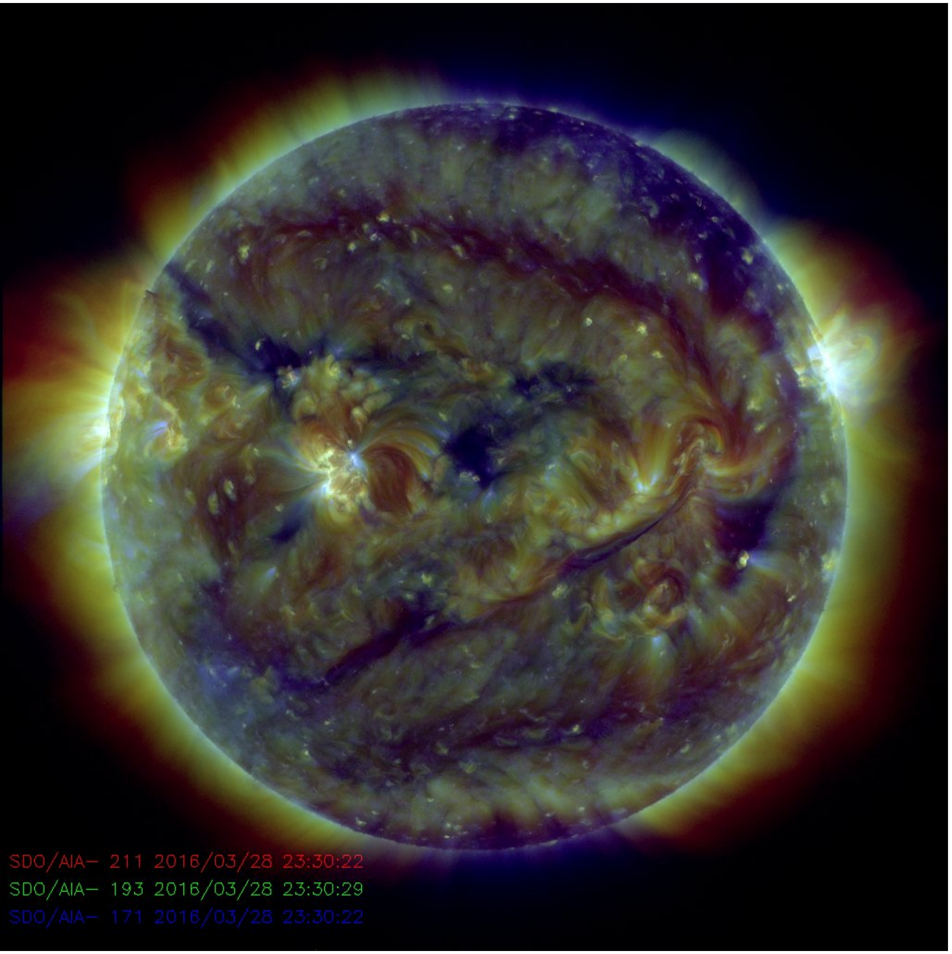
The Solar Cycle

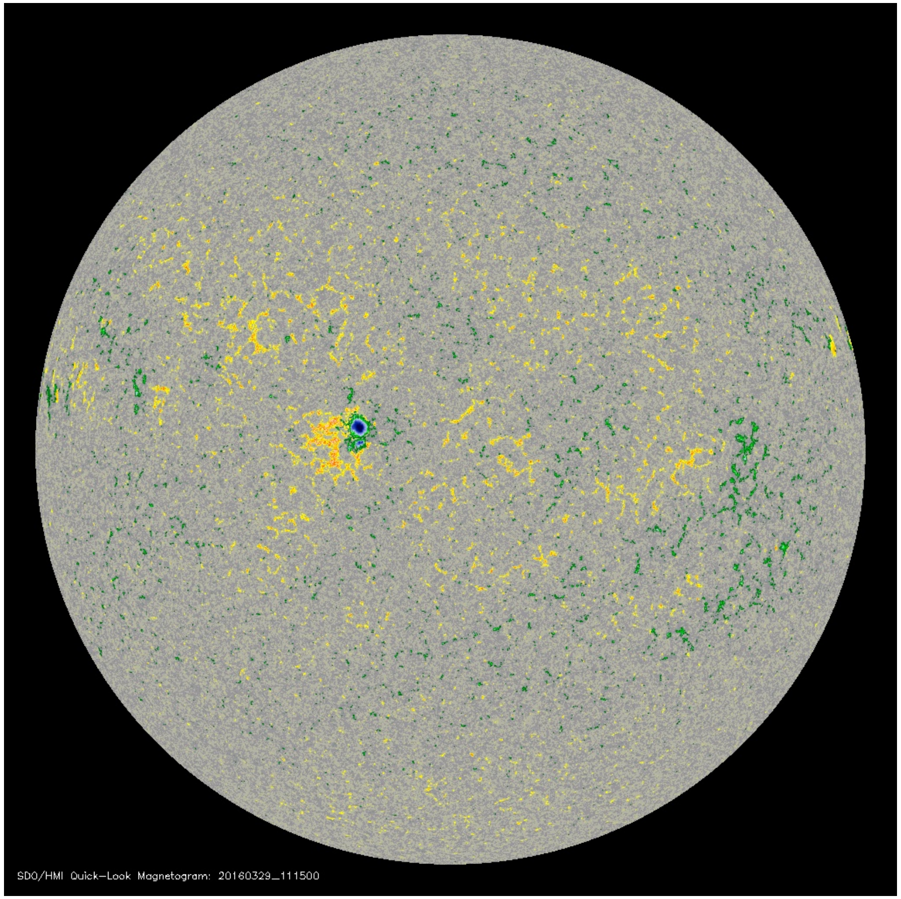
~11 year period where number of sunspots rises and falls.
Currently in Cycle 24 which is weaker than recent cycles.

You've probably lived through 2 + a bit solar cycles, yes?



What mechanisms generate the sunspot cycle?

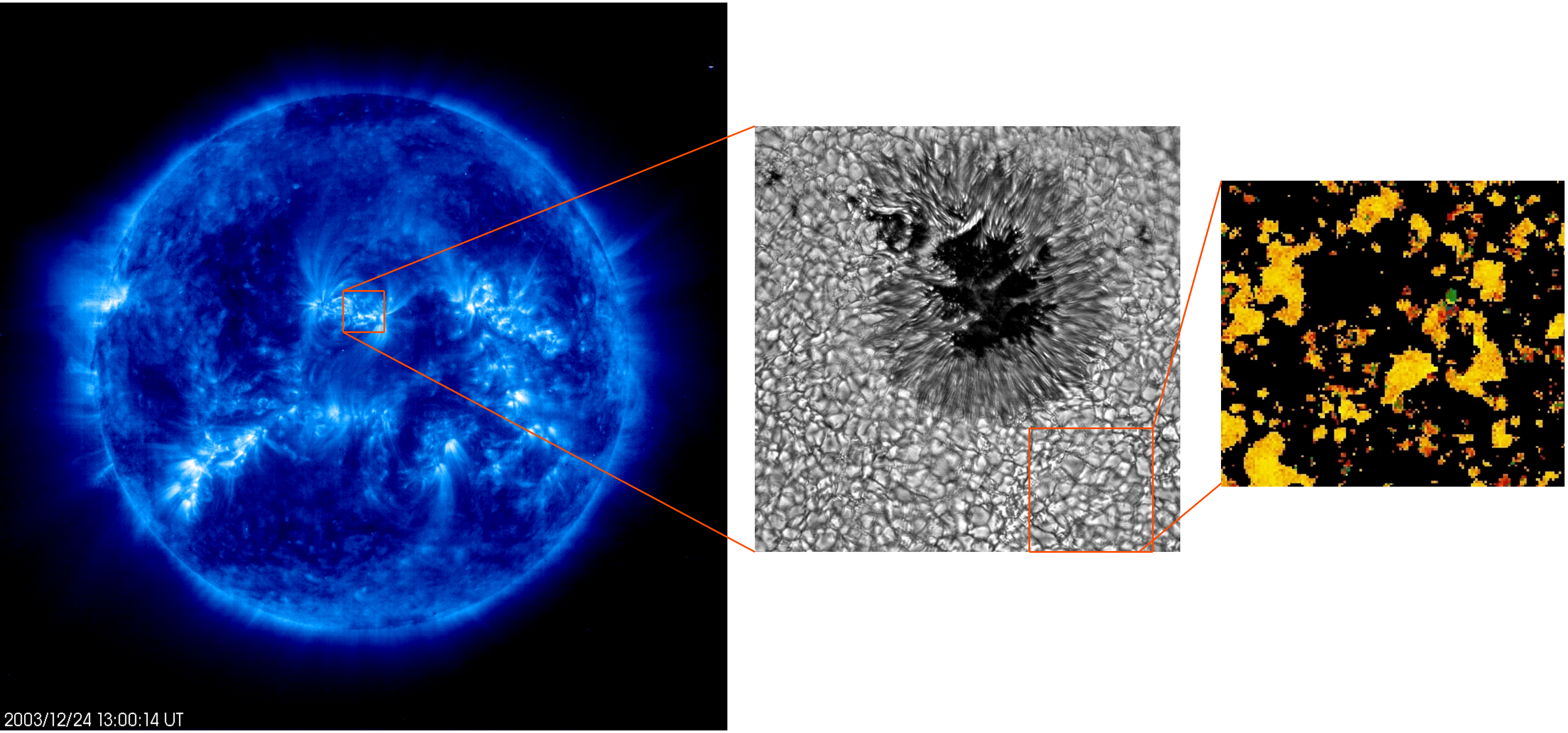




HMII (right) – photospheric magnetic flux
AIA (left) – composite 171 183 211 Angstroms
29/3/2016

The Answers? May be found in the Study of Solar Magnetism

(May be found elsewhere but magnetic fields are my obsession.)



Magnetic fields and their dynamics structure the Sun and modulate energy transport on many scales: global (years/decades), local (weeks/months) and elemental flux tube (minutes).

SOHO EIT 171 A (left) T. Rimmele/NSO/AURA/NSF (middle) Socas-Navarro /HAO (right)

My Interests: Dynamics of Magnetized Plasma

...in the Interior SOLAR DYNAMO: Observations to constrain global MHD theory

- Search for a DIAGNOSTICS OF THE INTERIOR FIELD FROM SUNSPOT STATISTICS.

...link Interior to Atmosphere FLUX EMERGENCE: How magnetic flux rises from interior through convection zone to surface?

...in the Atmosphere MHD WAVES: Types and observational signatures. OBSERVED OSCILLATIONS confirm and characterize waves. OBSERVING WITH HINODE THIS WEEK IN A PORE! Hinode Obs Proposal #302 with IRIS*

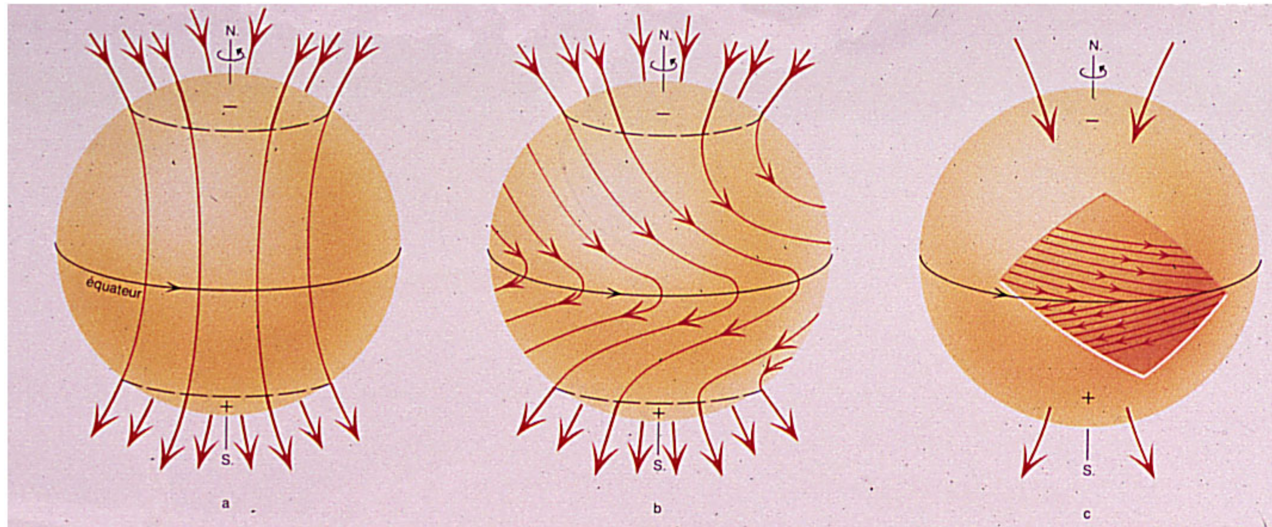
...Instrument Development

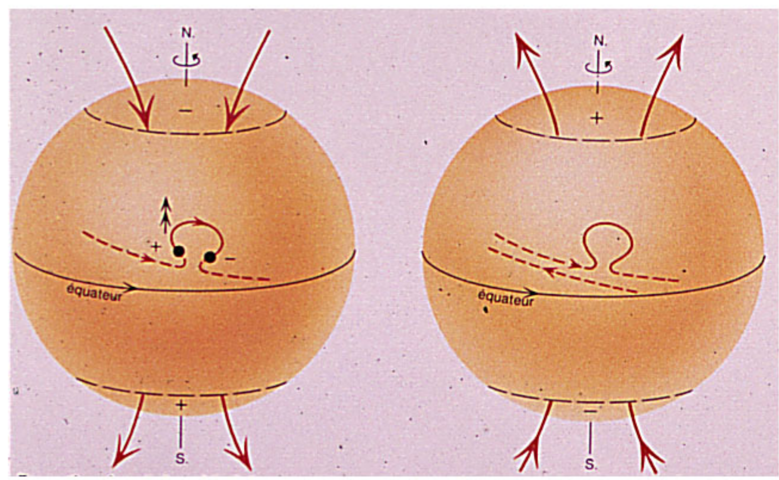
The Solar Dynamo – α Ω

Differential rotation can convert poloidal into toroidal field. (Ω effect)

Cyclonic & convective motions regenerate poloidal field of opposite polarity. (α effect)

Galactic disks host a dynamo. Galactic dynamo theory has same problems as solar – differential rotation is thought to amplify field, problems with respect to diffusion, quenching, etc.





http://webast.ast.obs-mip.fr/people.donati/dynamo.html

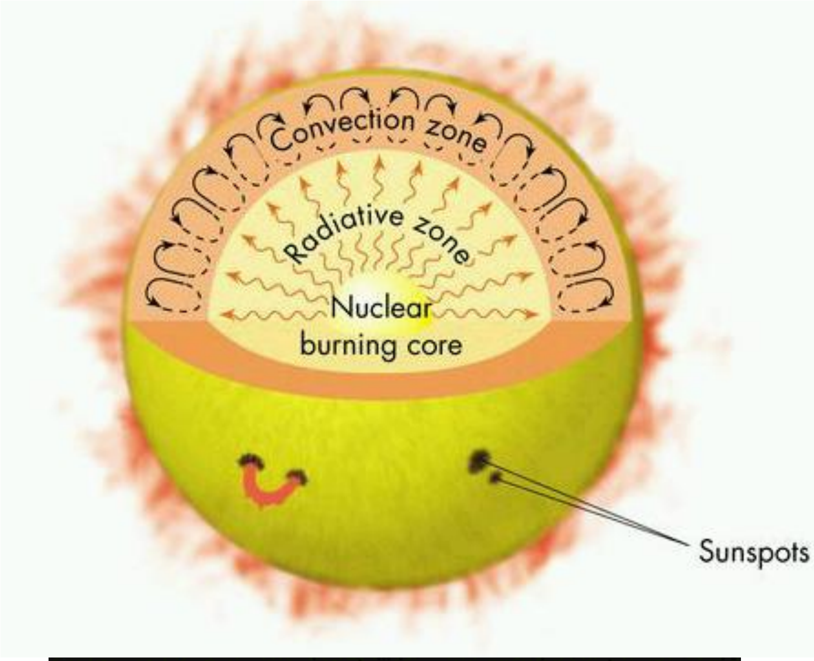
The Solar Dynamo

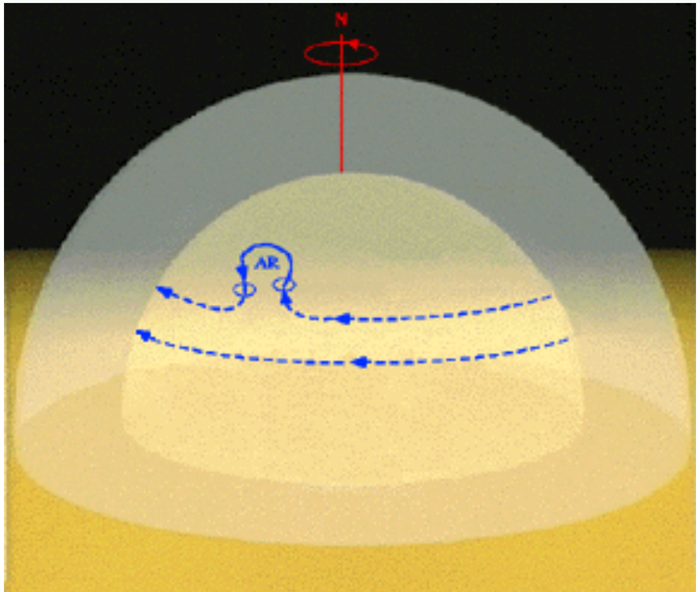
Shear layer in the ‘tachocline’ at the base of the convection zone converts mechanical energy into magnetic energy by stretching and amplifying field.

Magnetic field is stored in very strong ‘toroidal flux rings’ that serve as a reservoir of magnetic field.

Buoyancy instabilities cause flux to rise and emerge on the solar surface.

However, recent work argues that a near(er)-surface dynamo (also sometimes called distributed dynamo) operating through out the convection zone can amplify fields to create sunspot size surface magnetic flux.

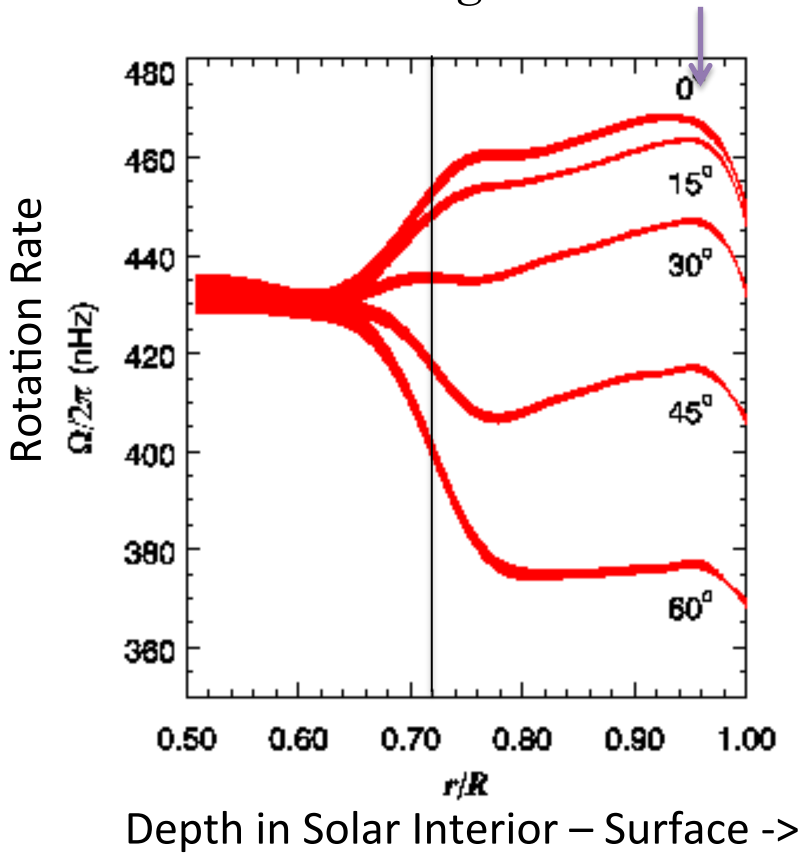




Where is the Tachocline?

- *Below convection zone, solar rotation is no longer differential, but uniform. Shear layer ~ 0.7 where this transition occurs.*

- *Surface shear layer (0.95 – 1.0 R) is seen though its profile is uncertain at high latitudes*

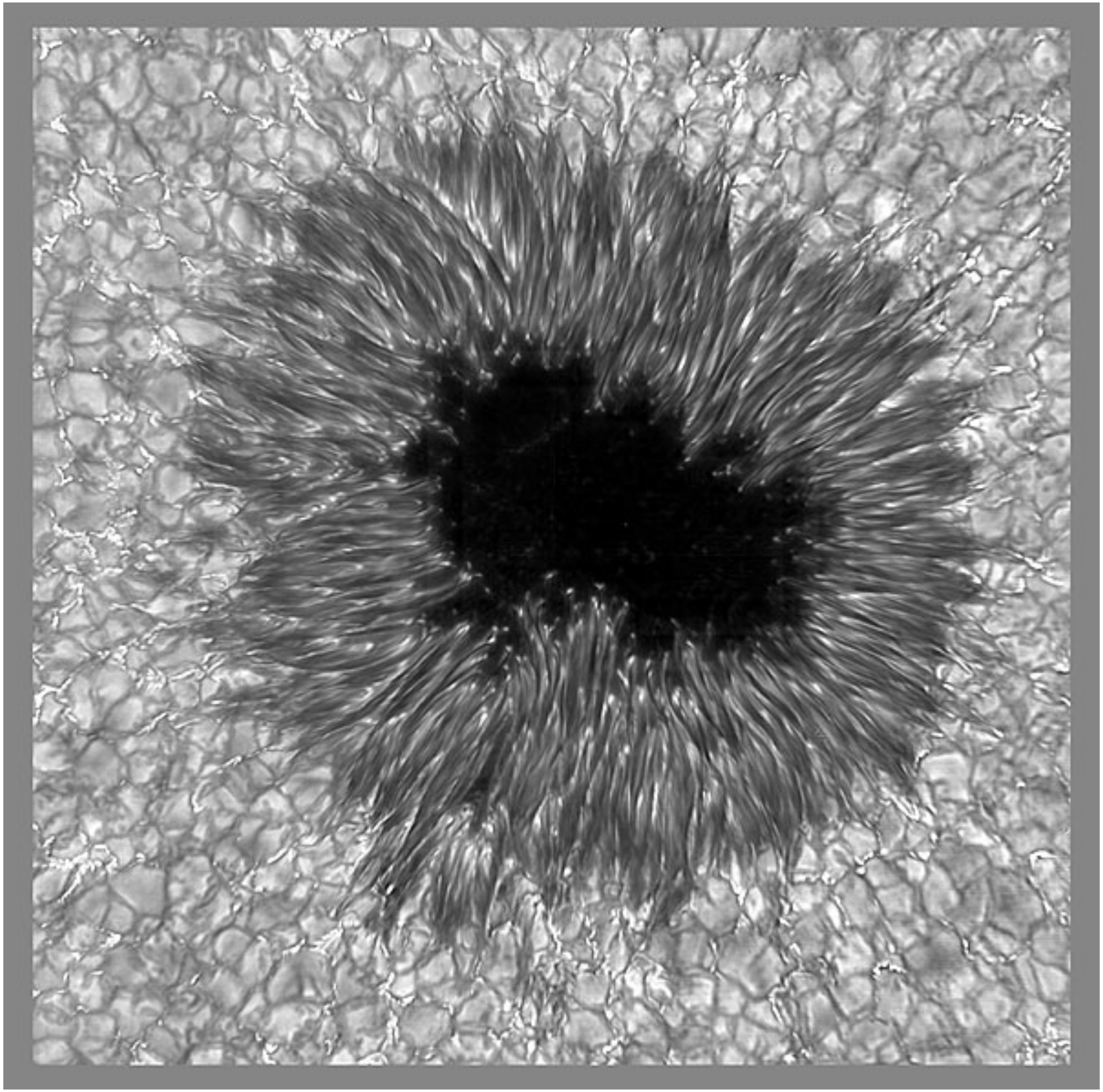


NSF National Solar Observatory
1995-2009 GONG-MDI Data

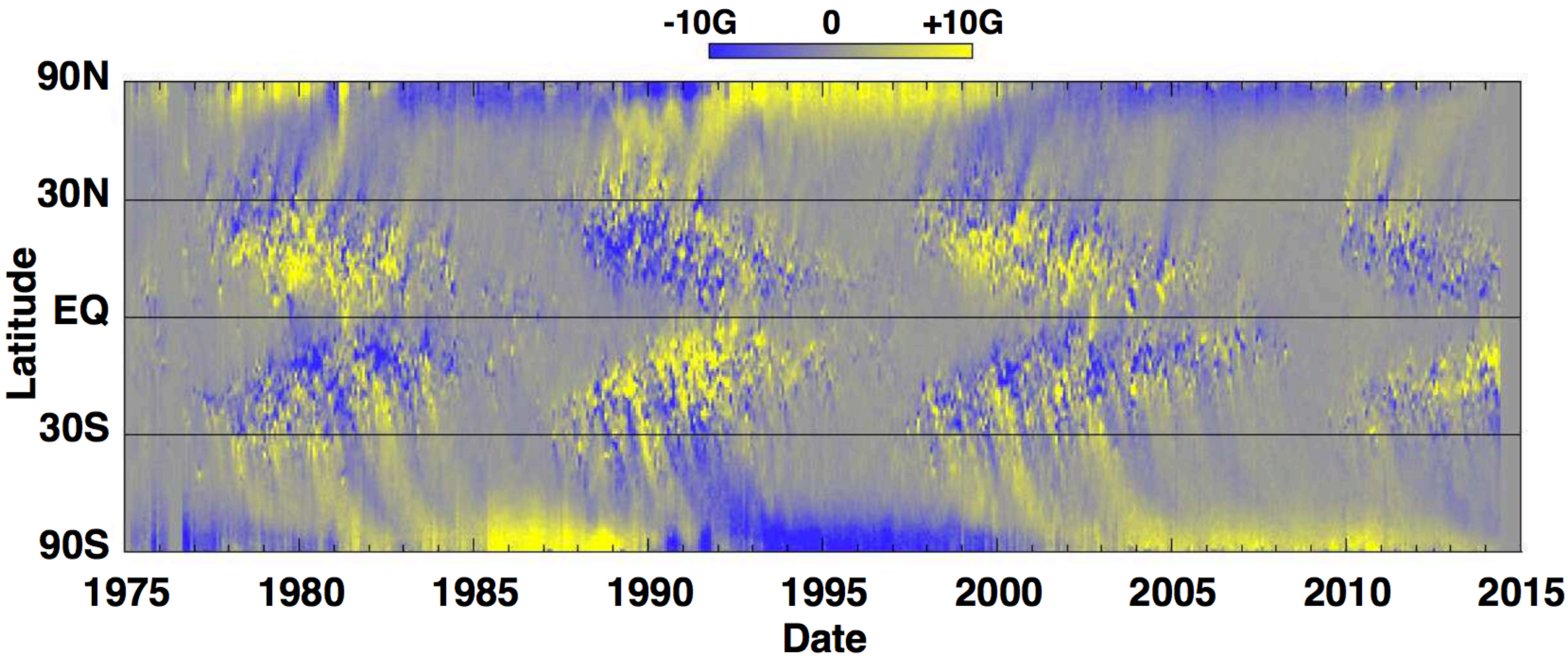
Sunspot Umbra: the dark core of a sunspot, cooler than the surrounding photosphere because is suppresses convection. Average size is ~10000 km, but can be as large as 60000 km.

Sunspot Penumbra: the lighter areas, marked by a radial filamentary structure. Typical size is ~5000 km. Waves are observed to move across the penumbral structures. Structure is thought to be 'uncombed'.

Image credit: Friedrich Woeger, KIS, and Chris Berst and Mark Komsa - taken here at the Dunn Tower.

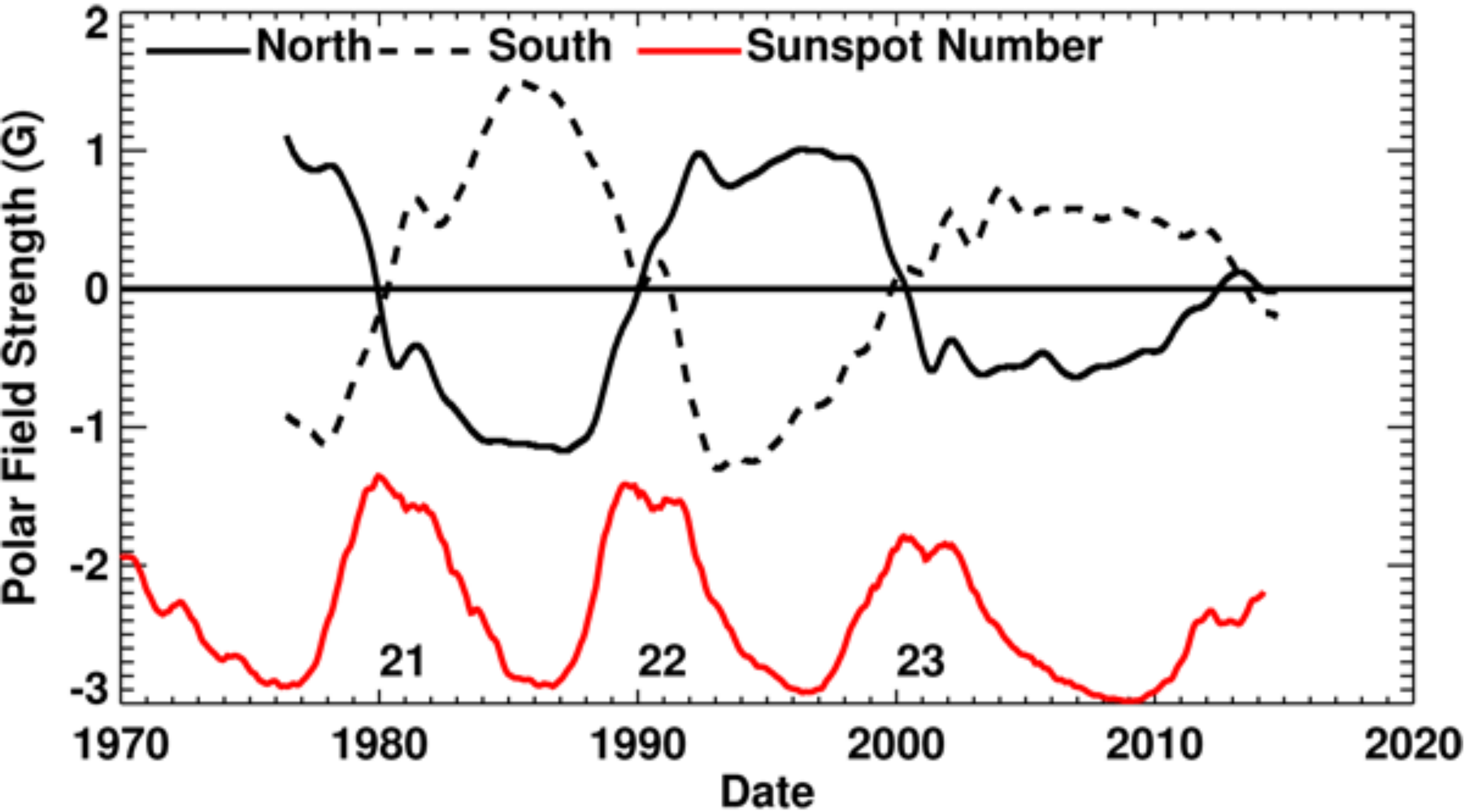


Hale's Law & Polar Reversals



Dynamo models must: produce oscillatory behavior.
have leading sunspots with opposite polarities in the N/S hemisphere.
produce sunspots within +/- 35° of equator and appear closer to equator later in cycle.
recreate polar behavior: decay of follower sunspot diffuses and it carried to poles.

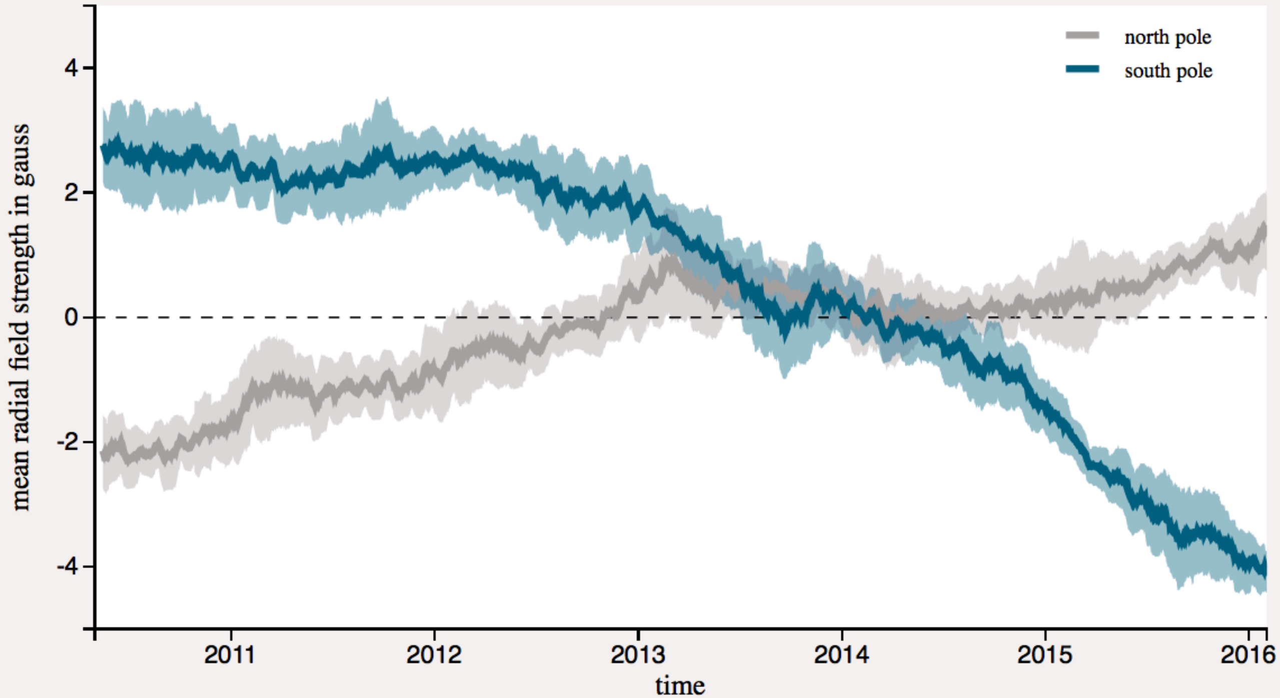
Polar Field Strengths



The Sun's polar field (black lines) reported by Wilcox Solar Observatory (Stanford) since the 1970s. The polar field strength out of phase with sunspot cycle (in red).

Current Polar Field Strengths

http://jsoc.stanford.edu/data/hmi/polarfield/.



Mean Br above 60 degrees in latitude N (gray) and S (blue) determined from HMI magnetic field data X Sun, M Bobra). Note polarity reversals took place in Nov 2012 (N) and Mar 2014 (S) Southern polar field stronger now than it was in Cycle 23. As polar field strength is used to predict next solar cycle – this suggests Cycle 25 will be no weaker than 24.

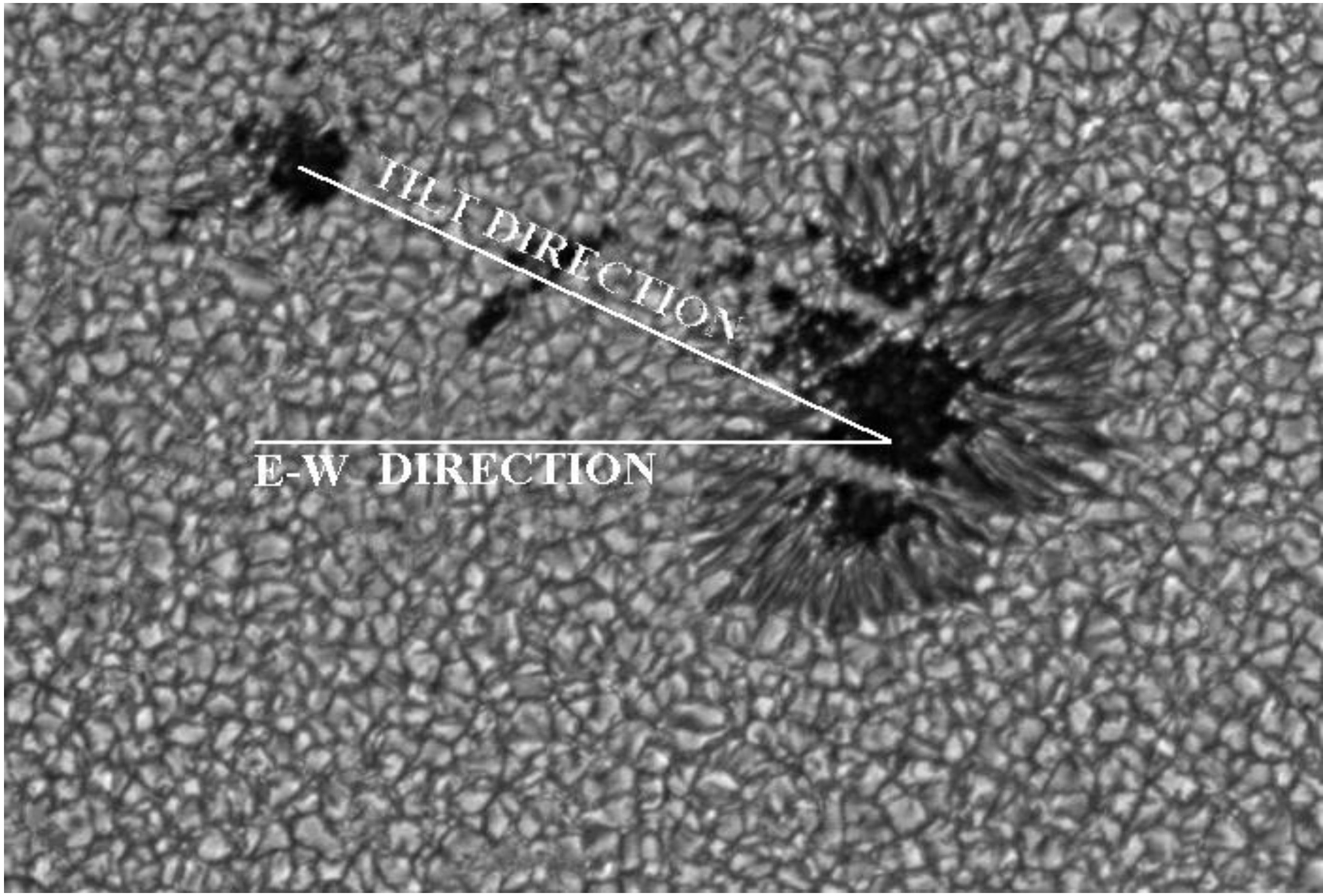
Joy's Law – Axis Tilt of Bipolar Active Region

- Tilt angle increased with increasing latitude.

- Caused by Coriolis force acting on the flow within rising flux tubes

- Note: the follower spot is less coherent and decays before the leader sunspot.

- Very noisy – lots of groups break the law.



Swedish tower – La Palma, Canary Islands
http://science.nasa.gov/ssl/pad/solar

Outstanding questions in Solar Physics?

A:* *Gene Parker: "The Sunspot is without explanation. Why is the Sun obliged to create them? We understand a lot about them, excepting why the Sun is compelled by the basic laws of physics to create cool, magnetic spots."

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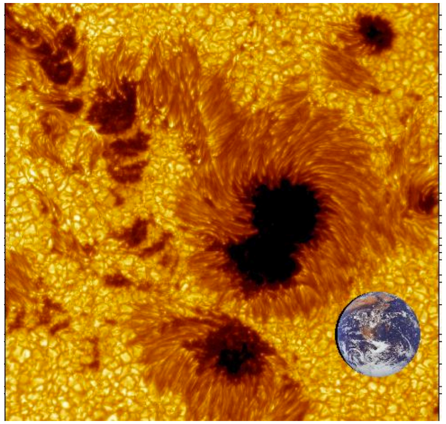
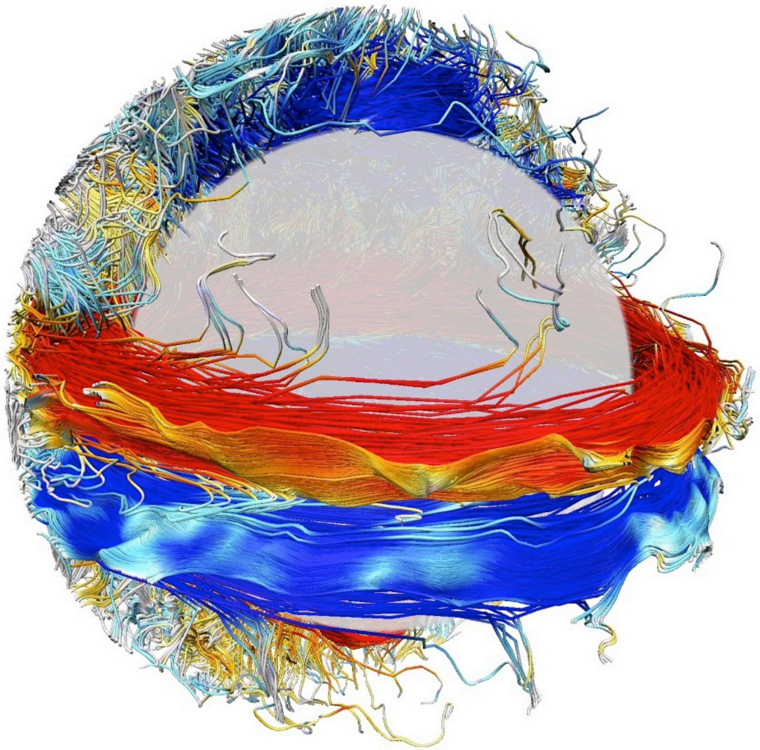




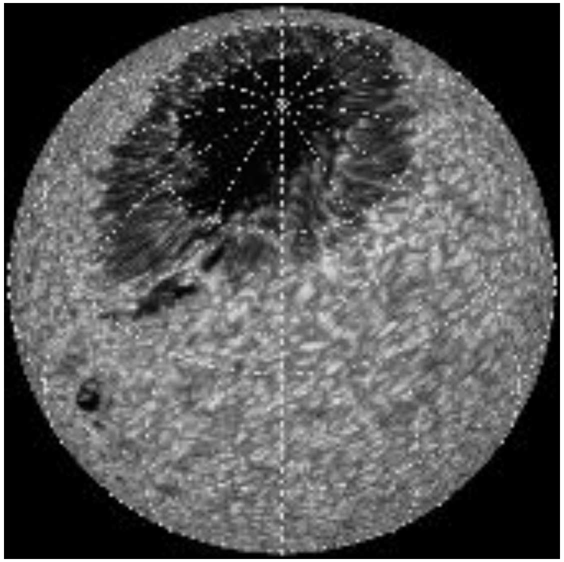
⇒ Other main sequence stars show evidence of 'starspots' and cyclical magnetic activity. Image at left is numerical modeling of magnetic wreaths in "Grand Minima and Equatorward Propagation in a Cycling Stellar Convective Dynamo" Augustson et al 2015 ApJ.

Stellar Dynamos Studies

⇒ Other main sequence stars show evidence of 'starspots' and cyclical magnetic activity.

⇒ The types of magnetic fields hosted by solar-type stars change when a tachocline develops, ie, fully convective stars have more poloidal field whereas more toroidal field develops when a tachocline is present. (Moira Jardine St. Andrews)

⇒ The star's period of rotation, the presence of differential rotation and a tachocline appear to be important ingredients in the generation of stellar magnetic fields. (Moira Jardine St. Andrews)



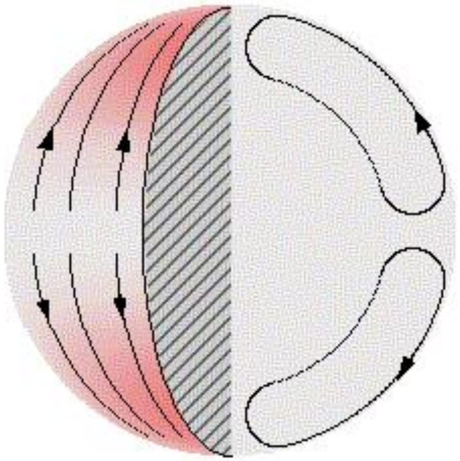
Popular Dynamo Models at Odds With Each Other

1. Flux Transport Dynamo has had best success recreating butterfly diagram, solar cycle period, polar field reversals. (Dikpati, Charbonneau, Gilman) Toroidal fields generated in tachocline, poloidal fields generated near surface, meridional circulation transports toroidal flux equatorward and sets cycle length

   Meridional circulation cell in N & S

   surface - poleward flow~ 10 - 20 m/s

   amplitude sets solar cycle period



2. Near Surface Shear Dynamo (or Distributed Dynamo) – both toroidal and poloidal fields generated in convection zone, near surface shear layer conditions allow equator-ward flow of flux.

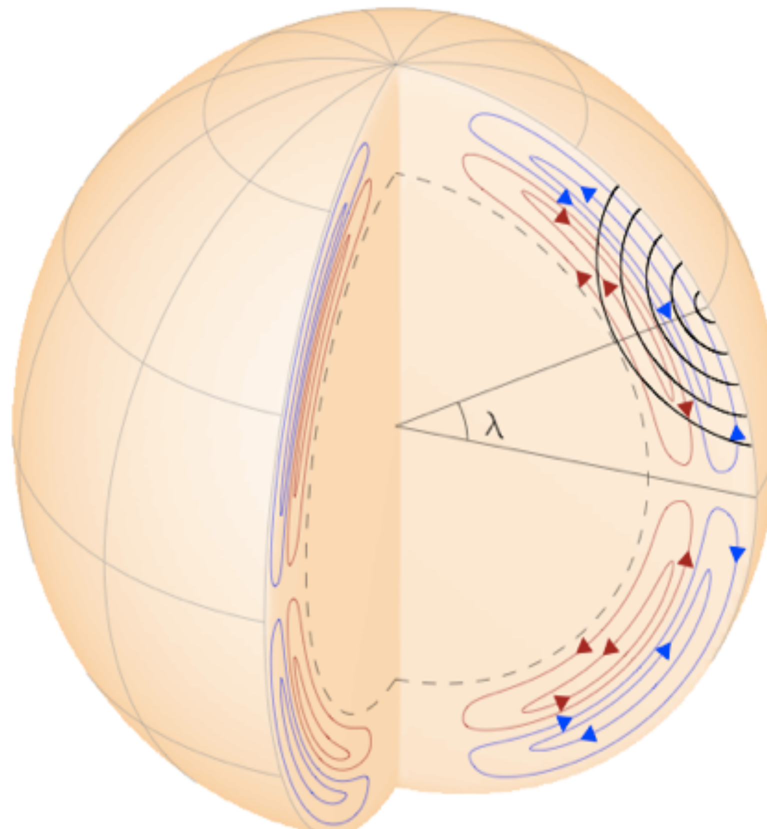
3. As observer / data analyst, I'm asking "How can the analysis of surface magnetism advance dynamo science?" Seeking signatures to distinguish between proposed dynamo mechanisms.

However Meridional Flow Measurements Recently Showed 2 Subsurface Cells

Multiple cells have been detected (Zhao et al 2013)using 2 years of HMI data + time-distance helioseismology techniques.

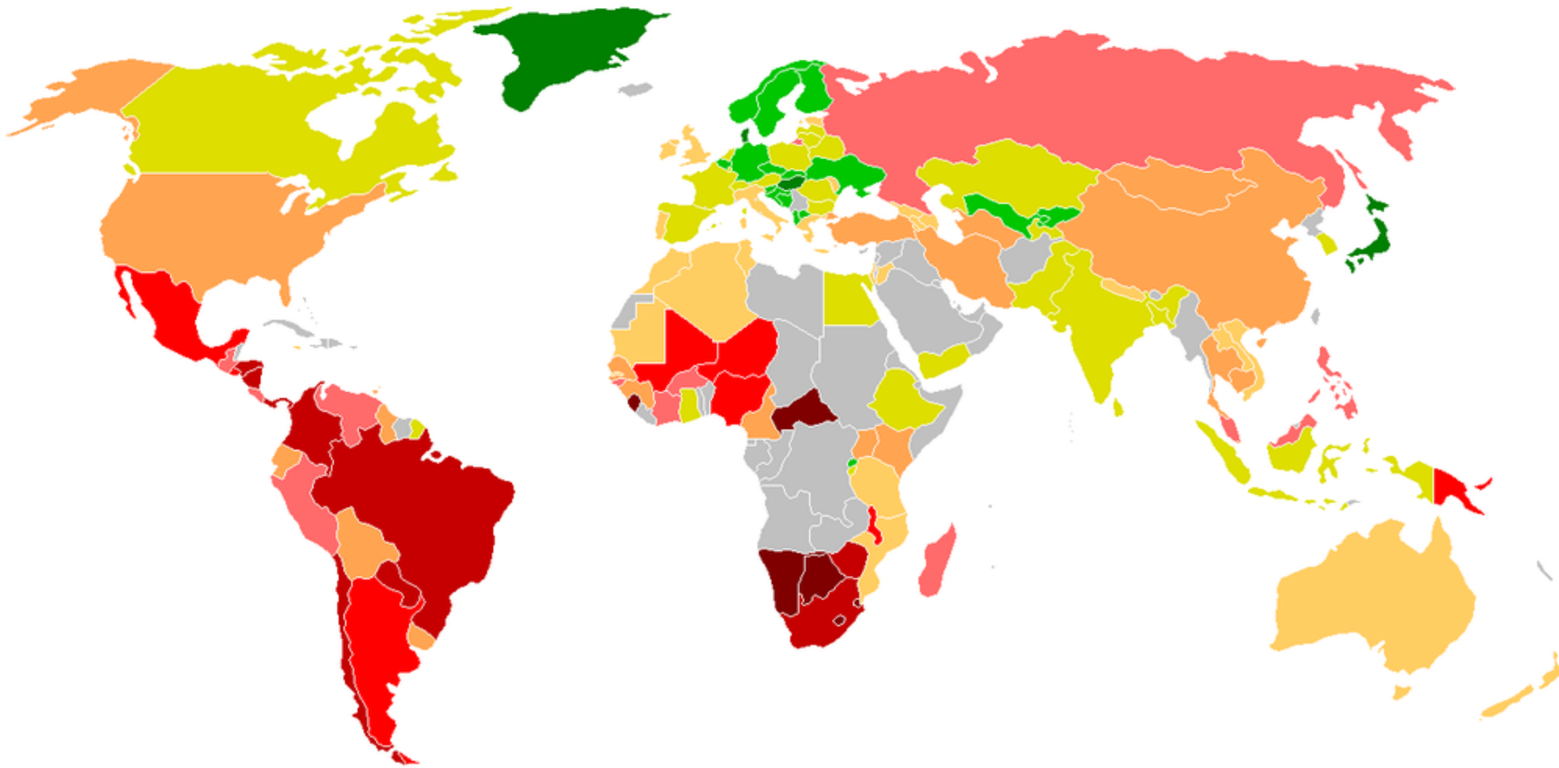
The flows in a range of latitudes show significant hemispheric asymmetry.

Below 0.82 R, the flow again becomes poleward, also with a substantial hemispheric asymmetry.
South is known to lag N in Cycle 24.



The plot thickens!

Dynamo Models Have Geographically Biased Support



Color	Dynamo Model	Color	Dynamo Model	Color	Dynamo Model
dark green	*αΩ Mean Field(-MC)*	light orange	*Fossil Field Decay*	dark red	*Interface Layer*
green	*Near Surface/Dist*	orange	*Flux Transport BL*	maroon	*Gerbils provide shear*
yellow	*$\alpha^2\Omega$ Dynamo*	pink	*Mean Field + MC*	grey	*Who Cares? (NA)*
		red	*Truncated*		

Observed Signatures that Support/Refute the Most Popular Types of Dynamos

1) Flux Transport Babcock Leighton

-/+flux tubes could not stay in tact during rise (but we observe them as tortured)

+meridional circulation return flow produces equatorward sunspot belt motion

+Sunspots produced as pairs indicated strong toroidal field in solar interior

3) Near Surface Shear Dynamo (or Distributed Dynamo)

-Why do sunspots appear +/- 35 degrees of equator? Negative shear at surface?

-The shear is negative from 0.95 R – 1.0 R at all latitudes so field should be distributed evenly across the latitudes!

-Can't reproduce how the follower spot is observed to be incoherent / Joy's Law.

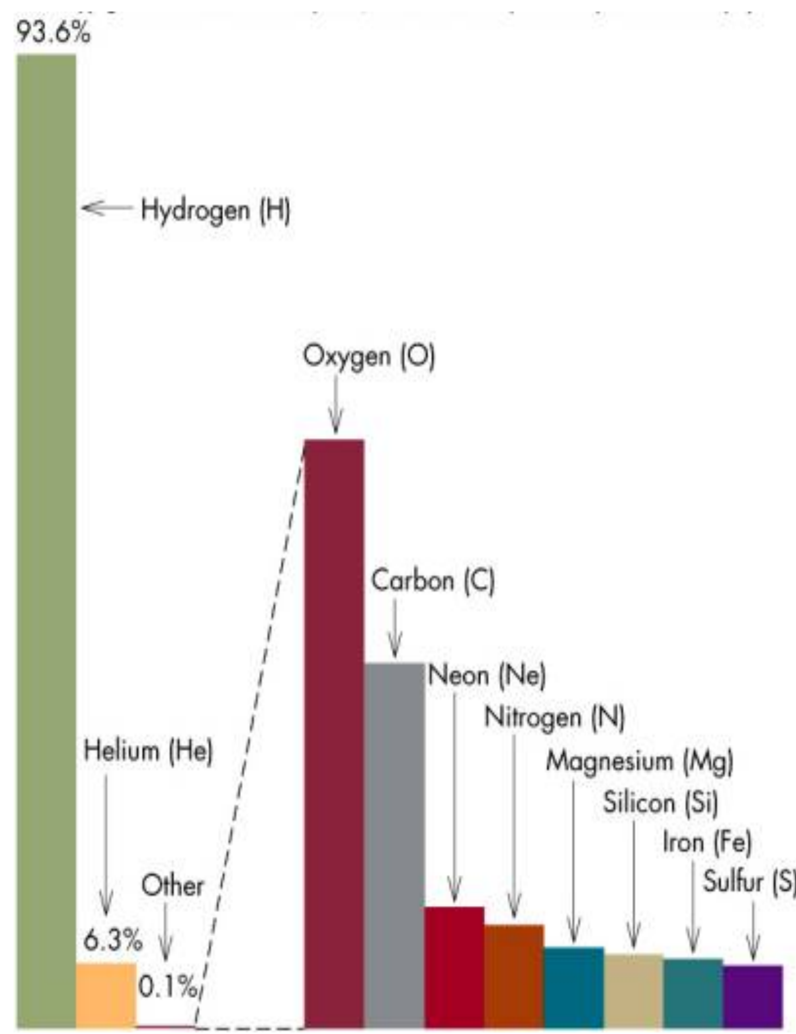
+Flux moves at correct speed for expected anchor depth

Assumed Solar Elemental Abundances Affect Solar Dynamo Models

Composition of the Sun and meteorites serves as a ***standard reference*** for all other solar system, galactic and cosmic chemical/abundance research.

Small changes in certain elemental abundances change our standard models and their outputs. I.e, oxygen provides a lot of opacity around the base of the convection zone.

Processes that create elements & determine their abundances: Big Bang, Stellar Nucleosynthesis, Supernova and Cosmic Ray Spallation (Ken McCracken's talk on Friday!)



D. Dooling NSO Outreach materials

Elemental abundances: Solar Photosphere vs Meteorites

Plot from Holweger 1996 review paper.

Meteorites are the oldest solar system objects studied in the lab.

Explanations (with caveats):
Li and Be are fragile nuclei that are depleted in the solar convection zone.

C, N and O may have only partially condensed in the solar nebula (they form volatile gases).

Difference between solar atmospheric conditions and the laboratory:
strong temperature and pressure gradients, plasma is in a strong, anisotropic radiation field and is turbulent, just to name a few.

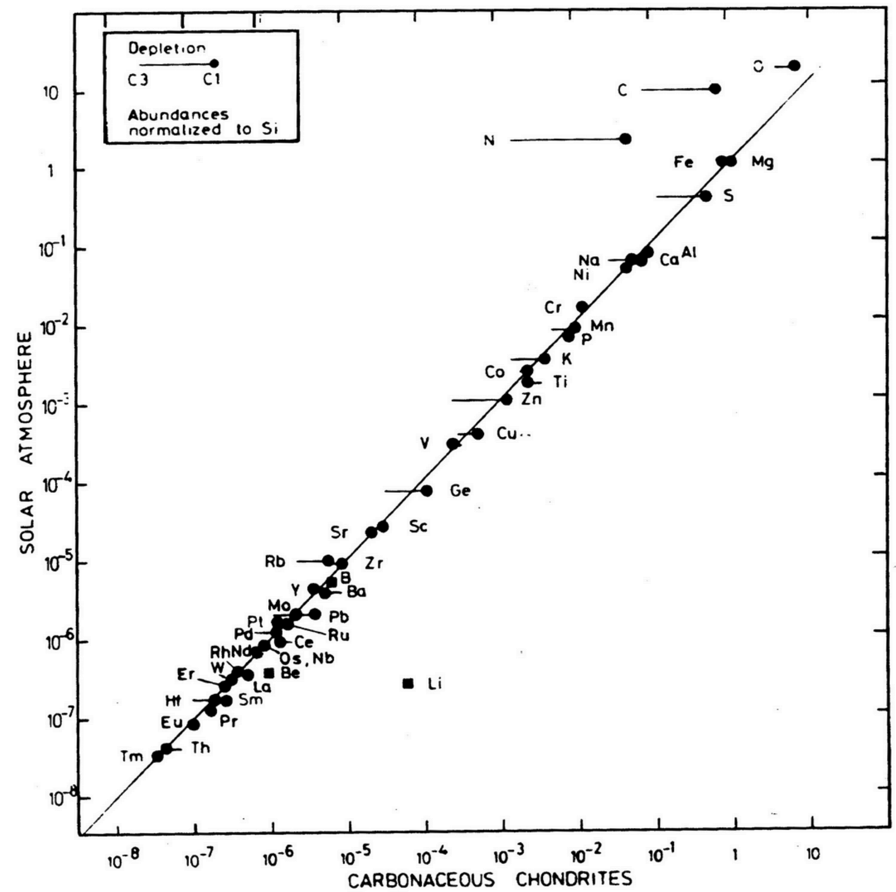


Figure 7.7. Abundances in the Solar Atmosphere Compared with those in C1 and C3 Carbonaceous Chondrites. Courtesy H. Holweger and International Astronomical Union.

What are the current dilemmas in solar abundance research?

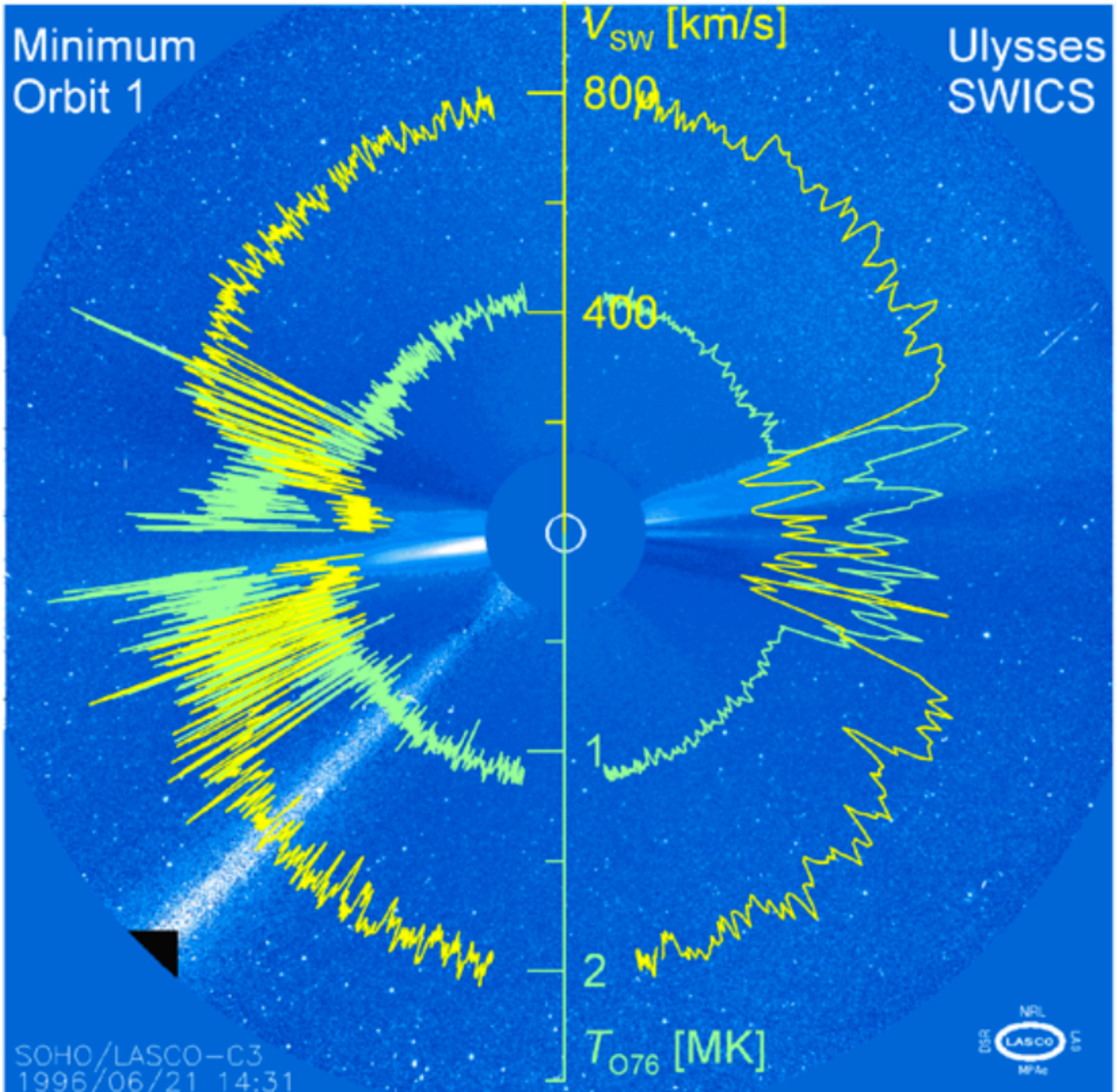
Helium: Not present in photospheric spectrum and is largely lost by meteorites. Values must be inferred from the corona or the solar wind, but these have large uncertainties (lines formed in non-LTE). Best to use models to get He abundance.

Lithium, Beryllium & Boron: Can all be burned by nuclear processes. Li at ~2.5×10^6 K. Be at 3×10^6 K. Li is depleted by 160 whereas Be and B are not depleted. Evidence of the depth of the convection zone! It appears the the solar convection cell has reached deep enough to burn Li, but not Be and B.

Neon, Argon: Not present in photospheric spectrum and lost by meteorites so there is uncertainty in the values.

Carbon, Nitrogen, Oxygen: These elements are lost by meteorites but are found in the photosphere. Their abundances are dependent upon the treatment of the atmospheric conditions - LTE or non-LTE. Oxygen is also a reference line for Ne and Ar, so if its abundance is changed then the abundances of Ne and Ar also scale up or down.

Solar Wind Composition Sampled by Ulysses – Lepri et al 2012



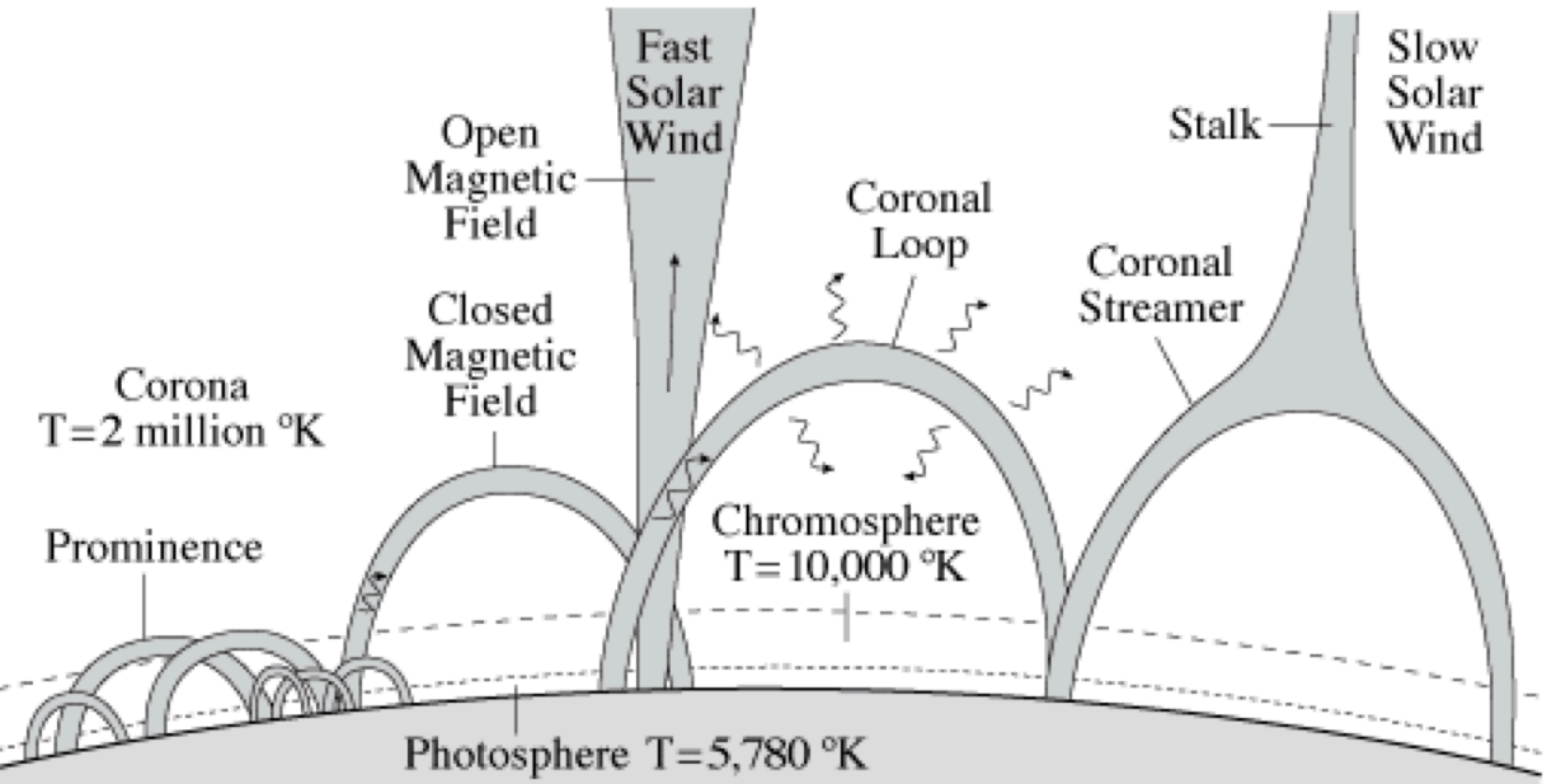
At solar minimum, wind is bi-model with the cool, slow wind from the poles expanding into a greater solid angle. The fast wind near the current sheet has a width of about ~20 degrees and based on its composition, originates from a hot source around 1 million K

Ionic composition different in fast vs slow solar wind. Composition found in closed coronal loops matches that found in slow solar wind.

Q: How does plasma from magnetically closed corona escape to form magnetically open heliosphere?

Coronal loops

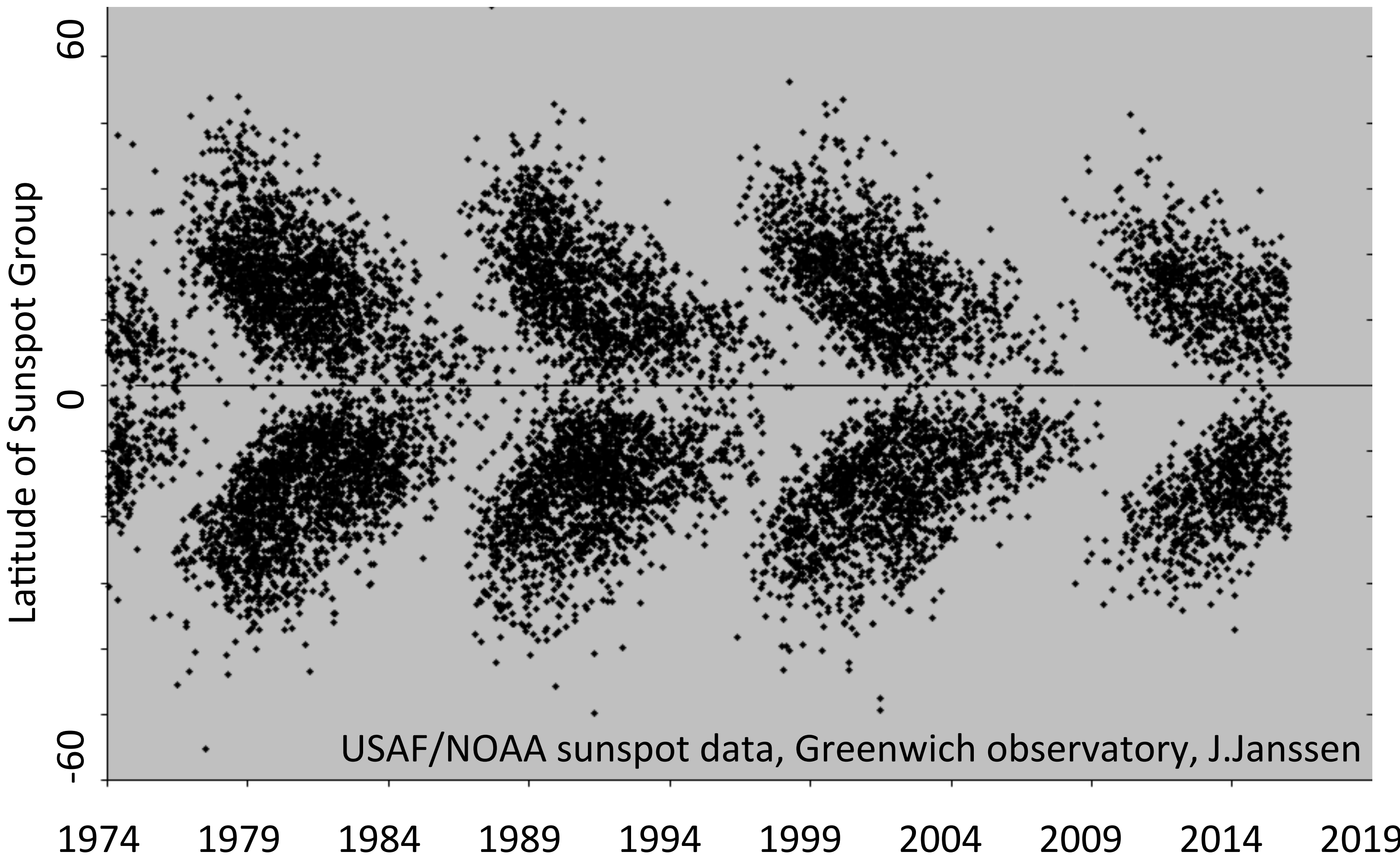
Cartoon Illustrating Connection to Fast & Slow Wind (LPL, U of A)



Atmosphere stitched throughout by loops in chromosphere and corona. Footpoints of the loops connect to photosphere and are moved by flows. They host MHD waves, can experience magnetic reconnection if geometry becomes unstable, and dissipate energy in this way. Note sources of solar wind.

Space Weather Interview – Holly Gilbert & Cali Cofield

SDO/HMI Quick-Look Continuum: 20131022_050000



Clearly, the Northern hemisphere knows something about the Southern hemisphere. The strong symmetry of the butterfly diagram indicates the hemispheres are coupled somehow. Is diffusion enough?

If the Flux-Transport dynamo theory is correct, and the meridional flow is a strong determinant for how the magnetic flux migrates, how is hemispheric coupling achieved?

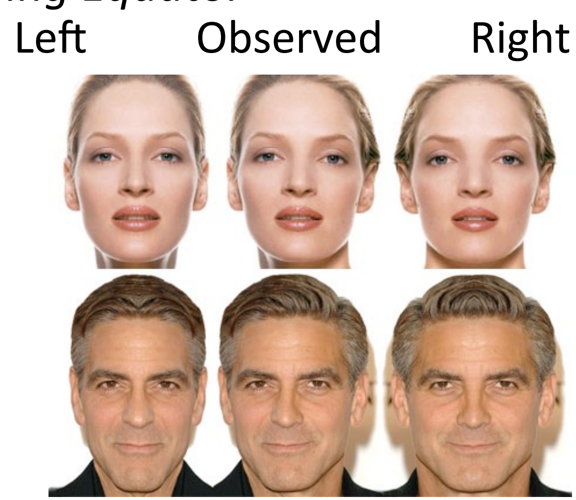
What should be different in the hemispheres?

Everything, except stochastic variation
Nothing, except stochastic variation

Observed N-S hemispheric asymmetry from:

Flows	*E-W Zonal flows, N-S Meridional flows*
Sunspot Cycle	*Sunspot statistics, Joy's law, Timing of Max*
Polar Fields	*Timing of Reversal*

Hemispheric Coupling Mechanisms: *Diffusion and Flux Crossing Equator*



Mirror/Reflection Symmetry
with Equator as Plane of Reflection:
Asymmetries are not surprising. Deviations from bilateral symmetry ...
Right/left sides of us are not symmetric across midline though formed by fluid flows in considerably closer quarters than Sun's hemispheres.

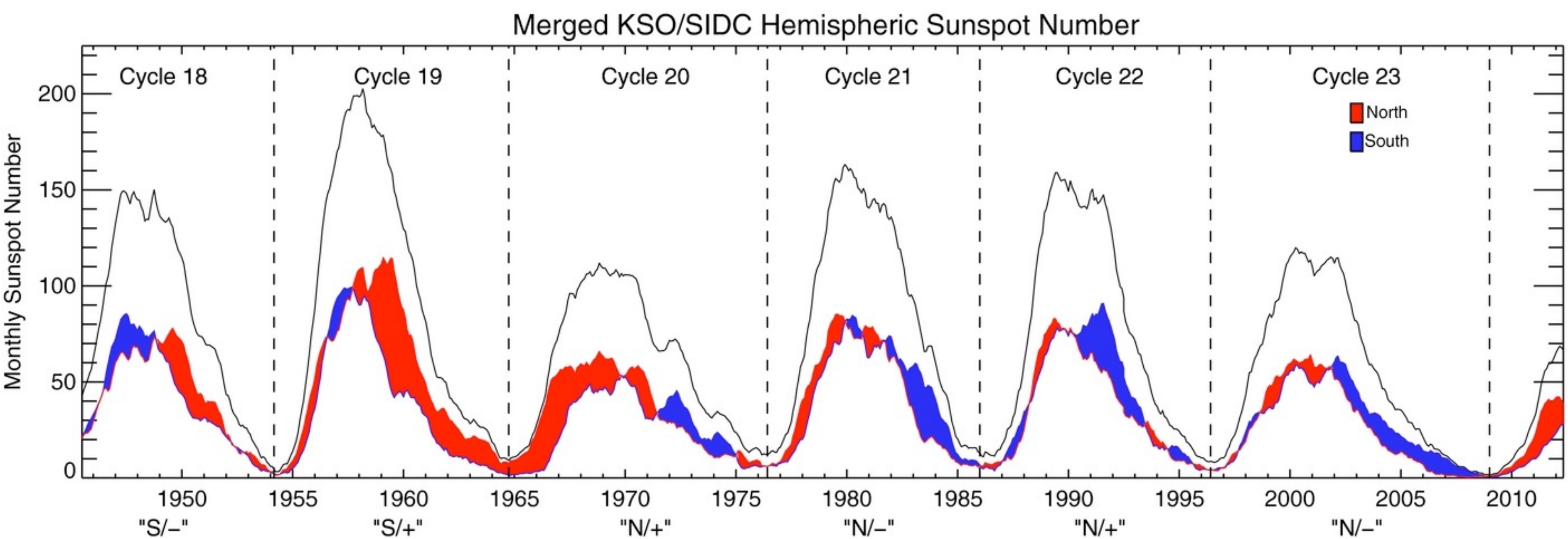
N-S Asymmetries in Sunspot Number or Area

Asymmetry Measure = N - S   *Normalized Asymmetry = (N - S) / (N + S)*

Temmer et al 2006 data Kanzelhöhe Solar Observatory (KSO) and Skaltnaté Pleso Observatory for 1945-2004 (cycles 18-23). Solar Influences Data Center has hemispheric sunspot numbers from Royal Observatory Belgium from 1950 –on.

Sunspot numbers N (red) and S (blue), Total (black)
Smoothed over 12 months, Dashed lines indicate solar minimum, McIntosh et al. 2013

Average hemispheric cycle amplitudes differences are within 16% of each other.
Time lags in hemispheres appears randomly distributed ~ 20% of cycle length.

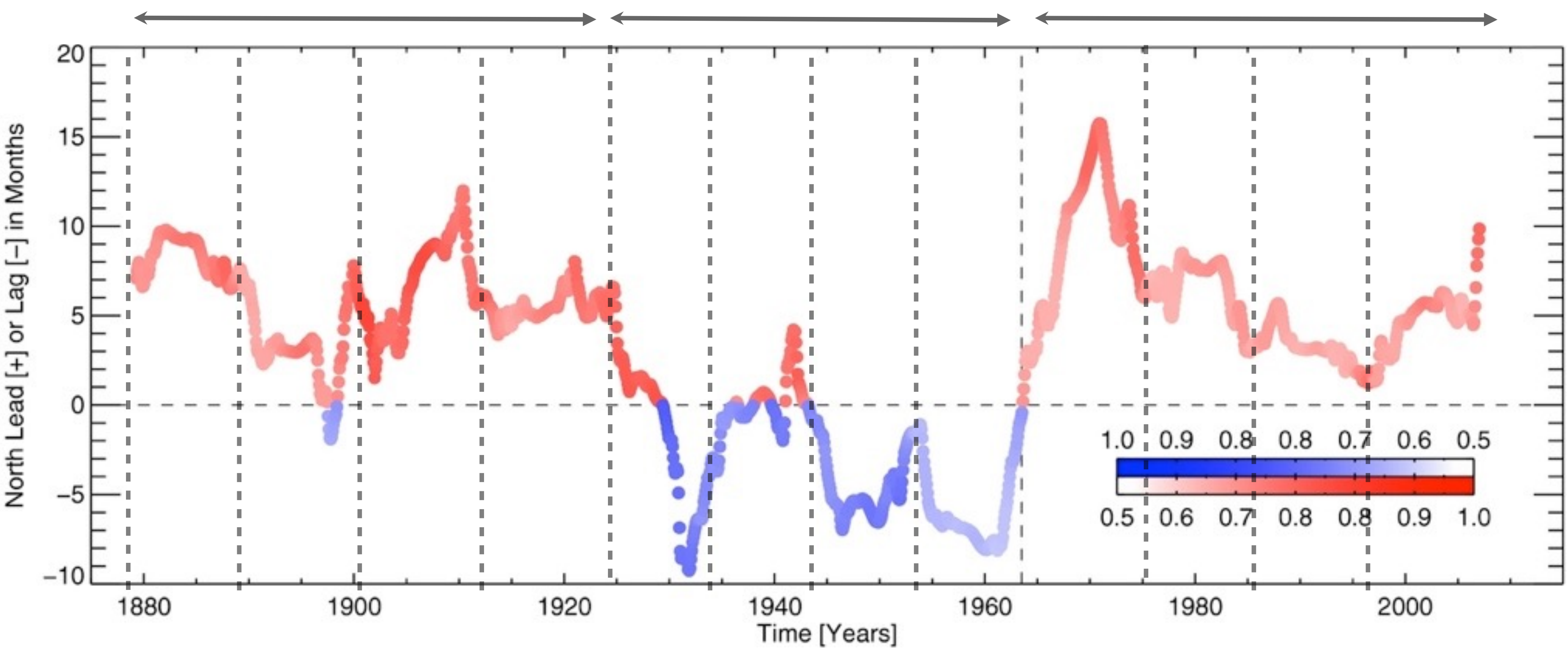


Long-term Hemispheric Trends for Sunspot Area

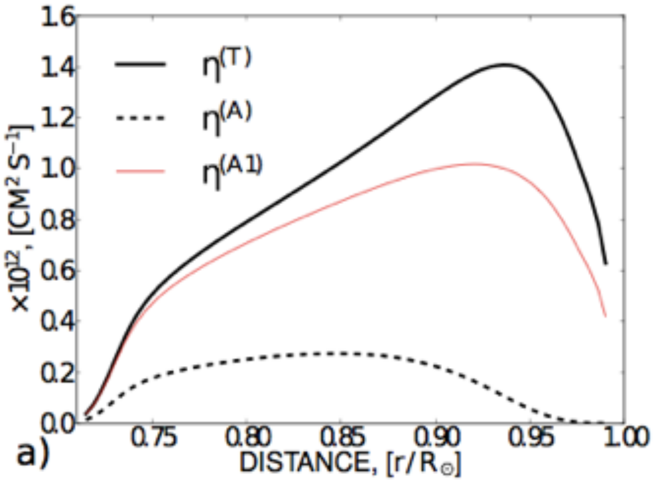
Greenwich Observatory sunspot area separated by hemisphere are cross correlated to show average of the N/S lag times in months. Cross correlation values relate to the average value of 120 months.

North (Red) leads by roughly 5 months until ~1930 when the South (blue) begins to lead until 1964. The color saturation indicates the magnitude of the cross correlation coefficient. Fig 12 from McIntosh et al. 2013 ApJ 765.

Persistant phase between hemispheres for ~ 4 sunspot cycles.



Magnetic diffusion is doing all the coupling



__ *total turbulent diffusion*

--- *anisotropic part due to rotation*

__ *A1 anisotropic for a=3*

Since organized flows are not, in general, cross-hemispheric, diffusion is doing the coupling. It's turbulent. It's anisotropic (greater meridional than radial diffusion) caused by rotational influence on convection.

Good news that we know exactly what η_T values are...

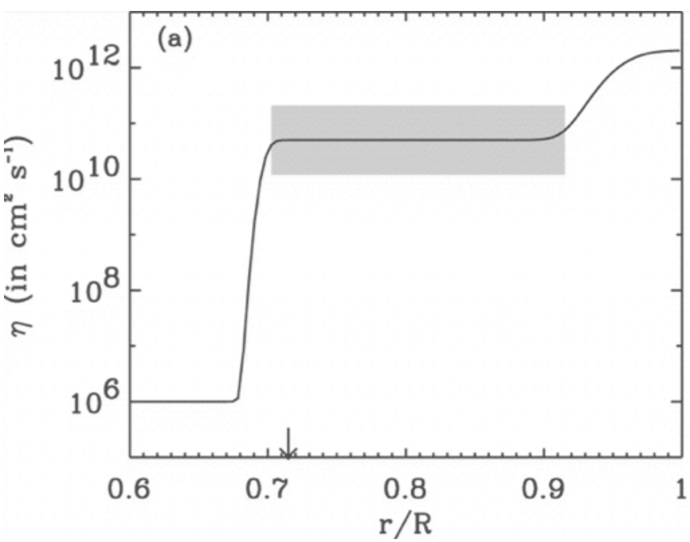
600 km^2 s^{-1} (Simon et al '95, Sheeley '92, supergranules)

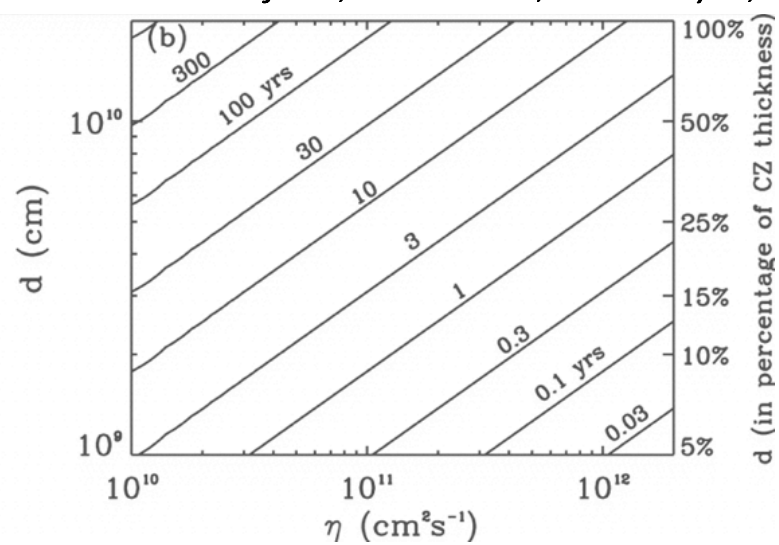
200 km^2 s^{-1} (Schrijver '90, Komm et al '95, cross corr. mag elements)

60 km^2 s^{-1} (Berger '98, Hagenaar '99 granule flows)

1-5 km^2 s^{-1} (Chae et al '08 high-res plage flows)

0.7 x 10^{12} cm^2 s^{-1} Pipin & Kosovichev 2013 ((above) used for mean field dynamo with turb. pumping, double celled meridional flow, tachocline, shear layer, helicity





0.3-2 x10^{11} cm^2 s^{-1} Dikpati & Gilman BL Flux Transport 2 × 10^{11} cm^2 s^{-1} means magnetic field can diffuse the depth of the convection zone in 50 yr (4 cycles) but diffuses to mid-depth in 10 yr, or one cycle.

Outstanding questions in Solar Physics

Q: From our observed and calculated values, diffusion should not be effective enough to keep hemispheric cycles in sync. Either our understanding of the dynamo process is wrong or diffusion is somehow much more effective.

What role does turbulent diffusion play in both the coupling of the hemispheres and the creation of kGauss magnetic fields at depth in the convection zone?

Turbulent diffusion is based on scalar quantity but we need a vector field which has its own internal stresses. (Same problem exists with the galaxy - need 10^25 cm^2/s .)

Magnetic Flux– How does it rise through the Convection Zone and emerge into the atmosphere?

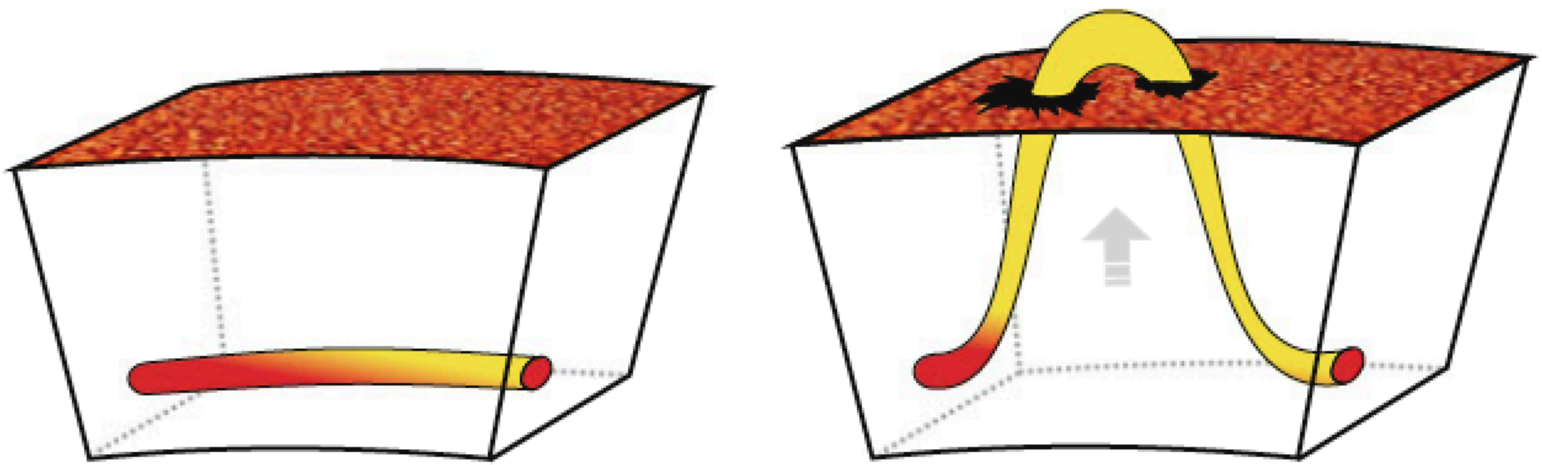


Fig. 3.3 Schematic representation of a sunspot pair as the manifestation of an underlying toroidal flux rope having risen through the photosphere as an "Ω-loop". At *left*, the flux tube lies in the azimuthal direction, before destabilisation and buoyant rise through the photosphere (at *right*). The magnetic fields impedes convective energy transport, so that cooling leads to a collapse of the magnetic field into two sunspots of opposite polarities. Diagram kindly provided by D. Passos.

D. Passos, Charbonneau 2013

Flux Rope / Filament Eruption – they can stay coherent out to 1 AU, magnetic clouds! We think twist allows them to stay in tact.

Outstanding questions in Solar Physics?

Q: **Han Uitenbroek:** *"How does the magnetic flux stay coherent as it rises through the convection zone to the solar surface? The forces it experiences en route should shred it -- only a strong twist could keep it together. Do we observe this twist?"*

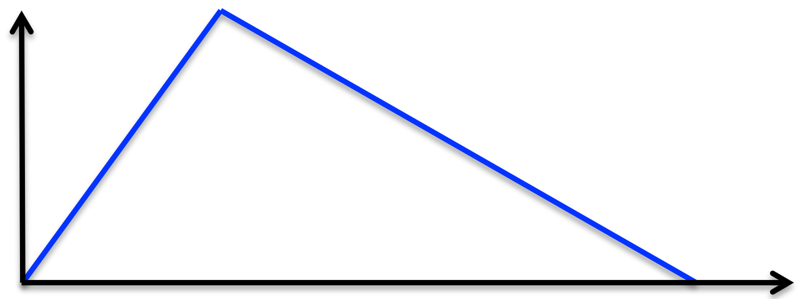
Time it takes flux to rise through convection zone

Fan 2009 simulations for a rising flux tube. Toriumi et al 2013 helioseismology observations of 1.5 km/s at 10–5 Mm 0.5 km/s at 5–2 Mm

5 Mm	5 hr	Rempel & Cheung (2014) simulations
50 Mm	40 hr	15 – 30 hrs for flux to rise last 15 Mm
100 Mm	145 hrs	Note: Takes ~1week to traverse top half of CZ
120 Mm	200 hrs (~8 days)	
150 Mm	425 hrs (~18 days)	
200 Mm	1900 hrs (~80 days)	Takes 2.5 months to traverse entire CZ

After rise through CZ, flux gets stuck at surface, needs MBI/MRT instability to emerge.

Sunspot Emergence & Decay Rates



- There are many observational studies on sunspot emergence and decay.

- Majority of studies are photometric (I_c) data and report values in μHem/day (msh or MSH). More studies on decay than emergence.

- We use HMI Sharp data to study both photometric and magnetic emergence rates for 10 small to mid-size active regions. (+ 3 regions)

Spaceweather HMI Active Region Patches (SHARP data)

Vector Magnetic Field data
Azimuth is disambiguated

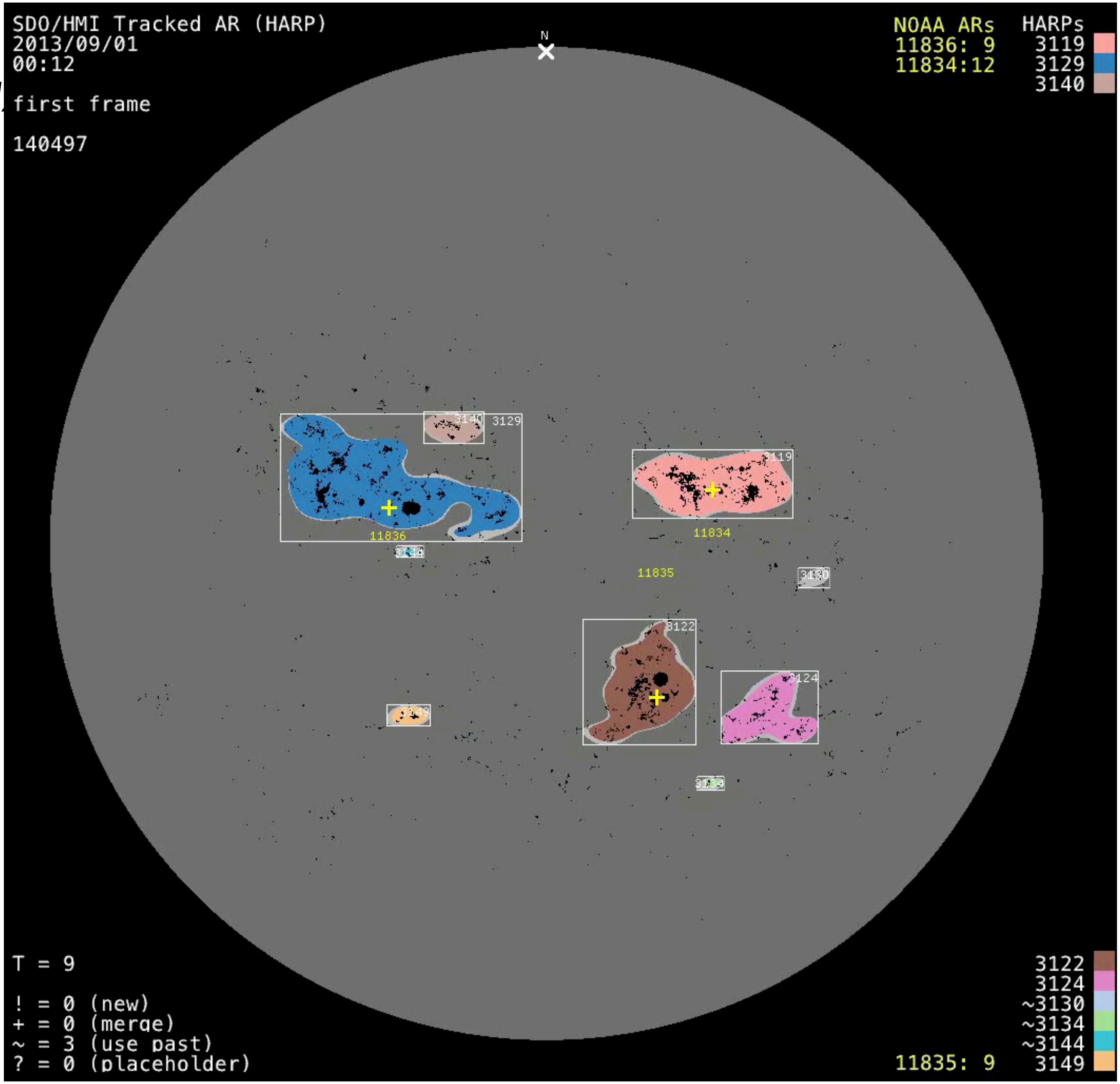
Every active region for entire mission is available

Disk crossing data
720 second data cadence

Dataproducts are:
hmi.sharp_720s or
hmi.sharp_cea_720s for cylindrical equal area
projection

September 2013 data at right. Monthly movies found: jsoc.stanford.edu/data/hmi/HARPS_movies/definitive-tracker/

Bobra et al 2014, Sun 2014, Hoeksema et al 2014.



Joint Science Operations Center (Stanford)
Example of accessing Sharp Data

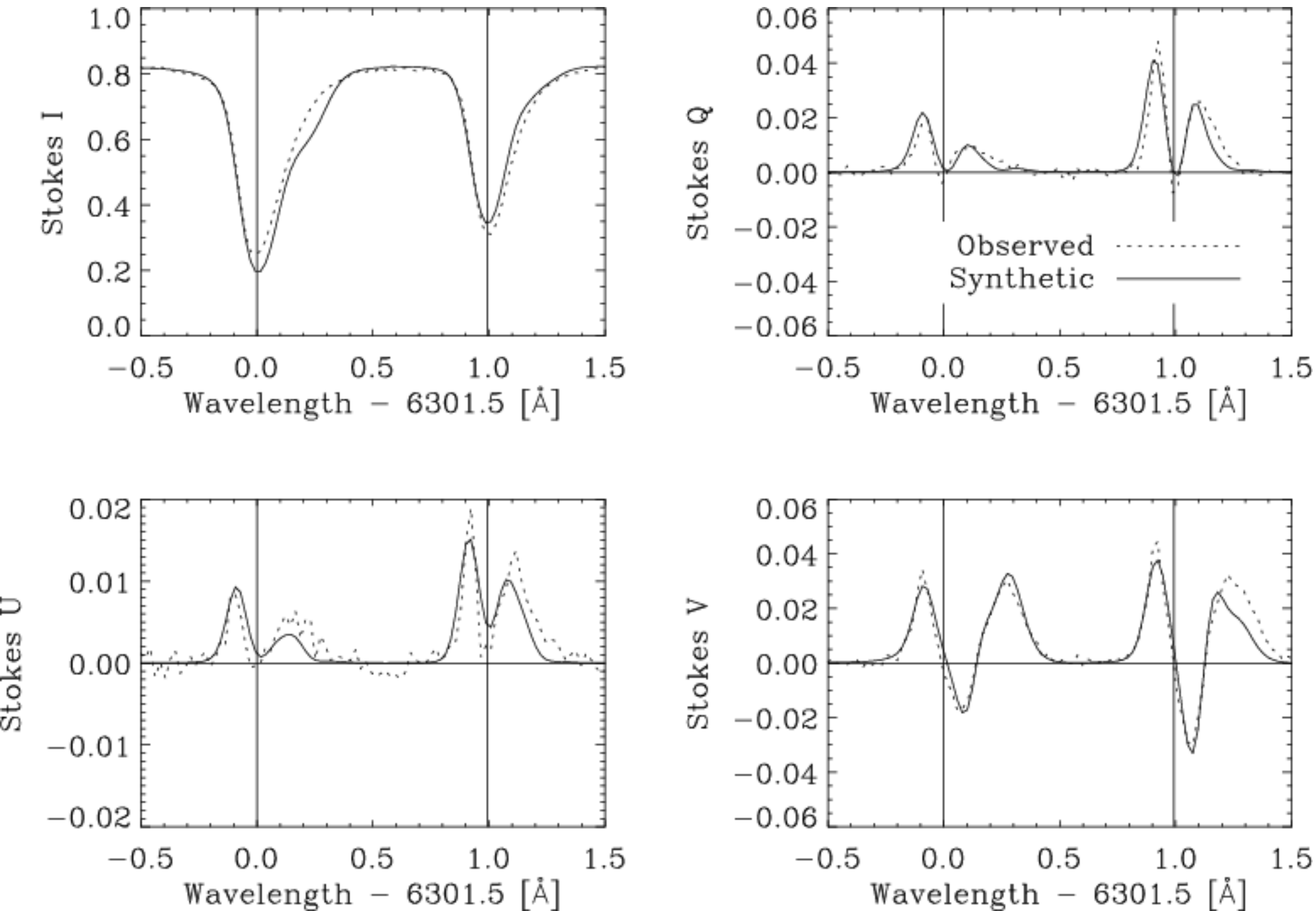
http://jsoc.stanford.edu/ajax/lookdata.html
harp # 3119 or #401 (#4946 today nrt)
2013.09.01 or 2011.02.09

Sharps description – Bobra et al, Solar Physics, 2014

If you have questions about HMI data, please come see me, I'll try to help you get what you need.

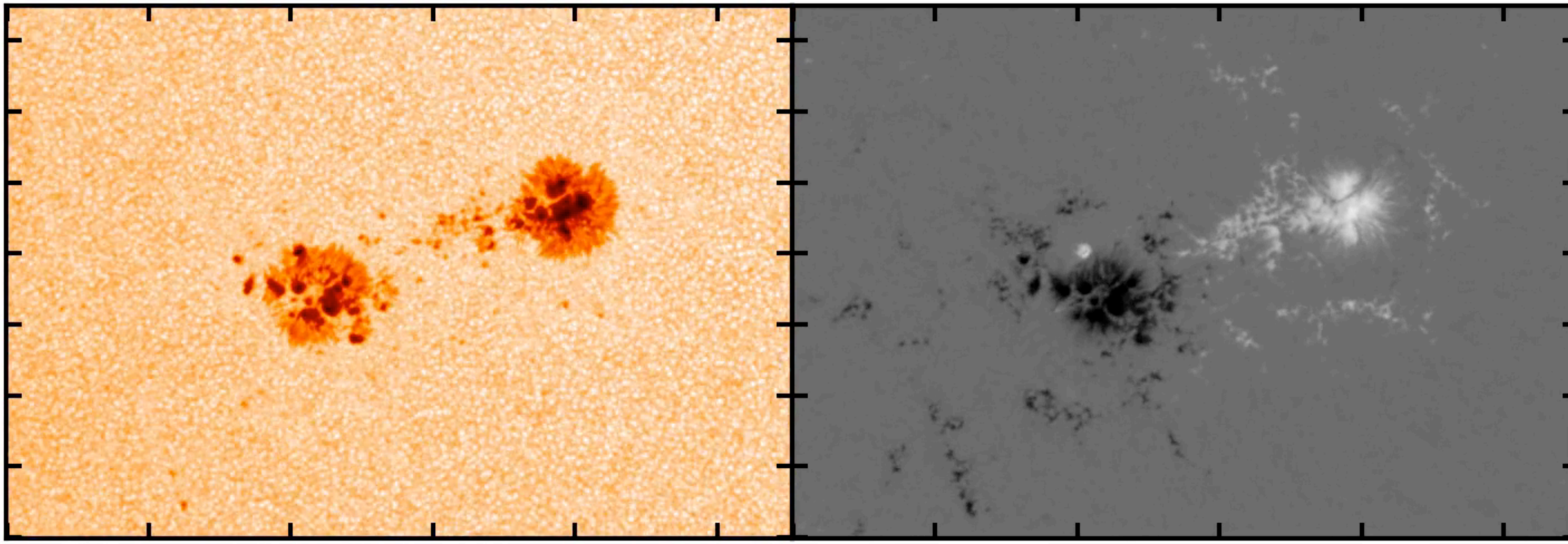
USFLUX	Total unsigned flux	Mx
MEANGAM	Mean angle of field from radial	Degree
MEANGBT	Horizontal gradient of total field	$\mathrm{G\,Mm^{-1}}$
MEANGBZ	Horizontal gradient of vertical field	$\mathrm{G\,Mm^{-1}}$
MEANGBH	Horizontal gradient of horizontal field	$\mathrm{G\,Mm^{-1}}$
MEANJZD	Vertical current density	$\mathrm{mA\,m^{-2}}$
TOTUSJZ	Total unsigned vertical current	A
MEANALP	Characteristic twist parameter, α	$\mathrm{Mm^{-1}}$
MEANJZH	Current helicity (B_z contribution)	$\mathrm{G^2\,m^{-1}}$
TOTUSJH	Total unsigned current helicity	$\mathrm{G^2\,m^{-1}}$
ABSNJZH	Absolute value of the net current helicity	$\mathrm{G^2\,m^{-1}}$
SAVNCPP	Sum of the modulus of the	A

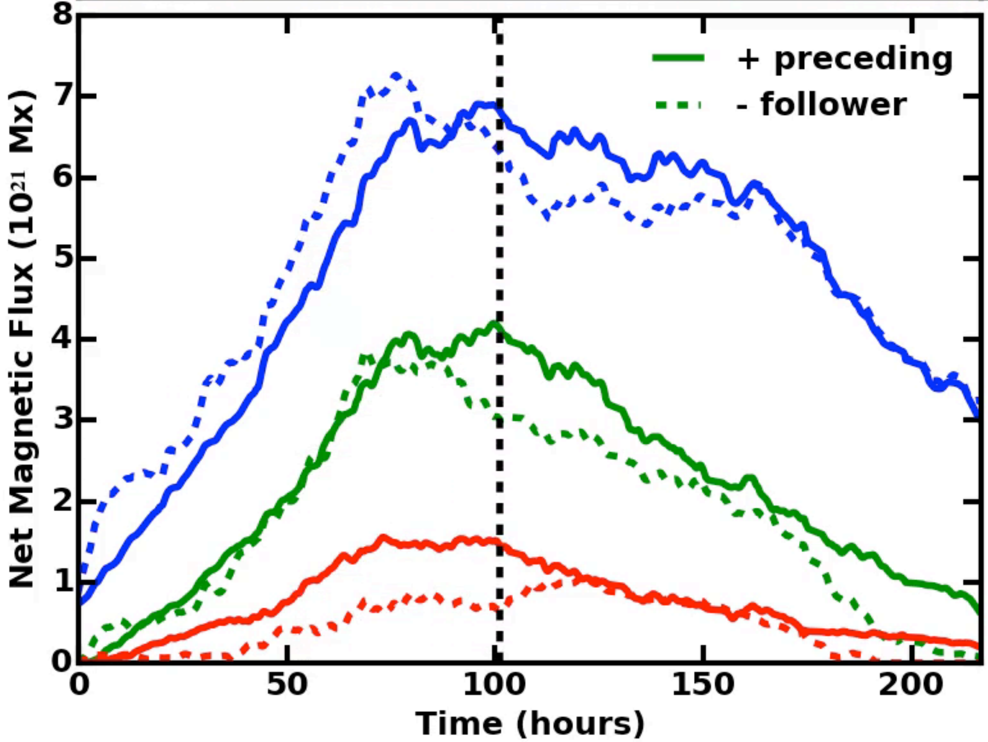
Spectropolarimeters use a slit to sample light and send it to a diffraction grating. A combination of circular polarization (Stokes V) and linear (Stokes Q, U) and regular intensity using a magnetically sensitive spectral line allow observers to utilize the Zeeman effect to determine magnitude and direction of the magnetic field.



Trade-off: Filtergram gives you large FOV but less spectral information.

Vector magnetic field information allows a much richer study of solar dynamics because we have the directional orientation of the field instead of magnitude alone.
Movie by K. Hayashi using HMI data from 2011.02.12





Back to Flux Emergence
HMI Sharp Data
NOAA 11428, 2 Mar 2012
−17° Lat, 550 × 375 sharp_cea_720s
Emergence & Decay Rates in 10^{20} Mx/hr

(p) spot .52, -.31
(f) spot .51, -.24

I_c [10000, 65000], Br [2700 G, -1500]
Flux ($\times 10^{21}$ Mx) vs Time (hours) Gaussian
Smoothed FWHM 20 h

Rates for Preceding Spot Flux Emergence

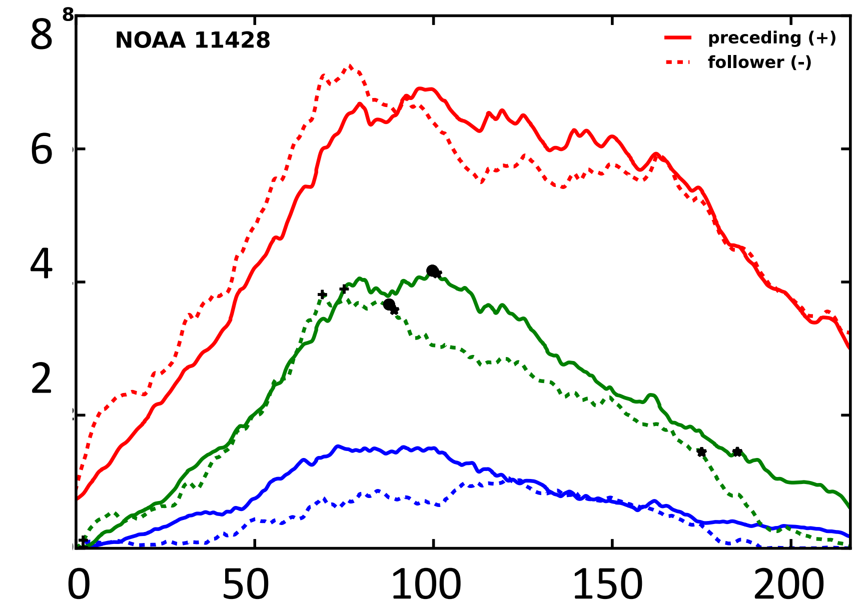
- Mean emergence rates were 0.61 x 10^{20} Mx /hr
- Decay rates were half that, 0.32 x 10^{20} Mx/hr.

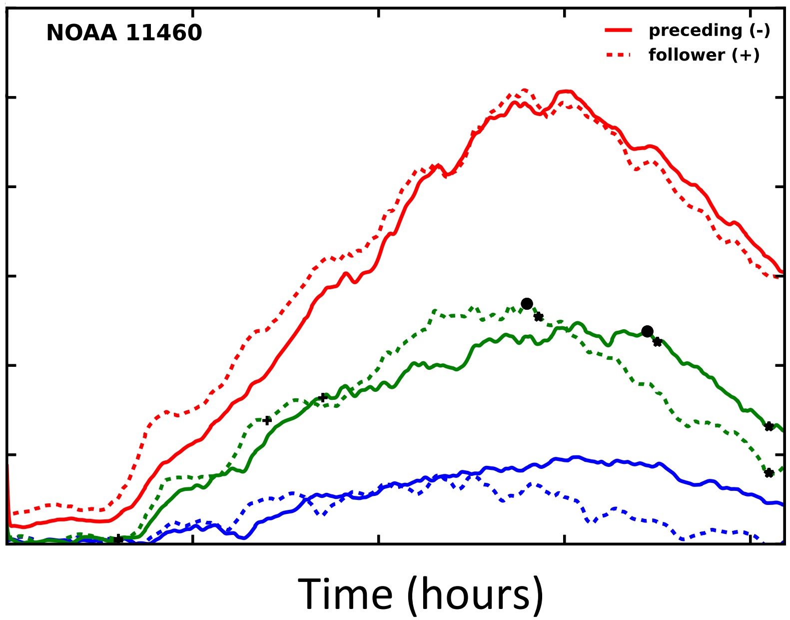
and Following Spots

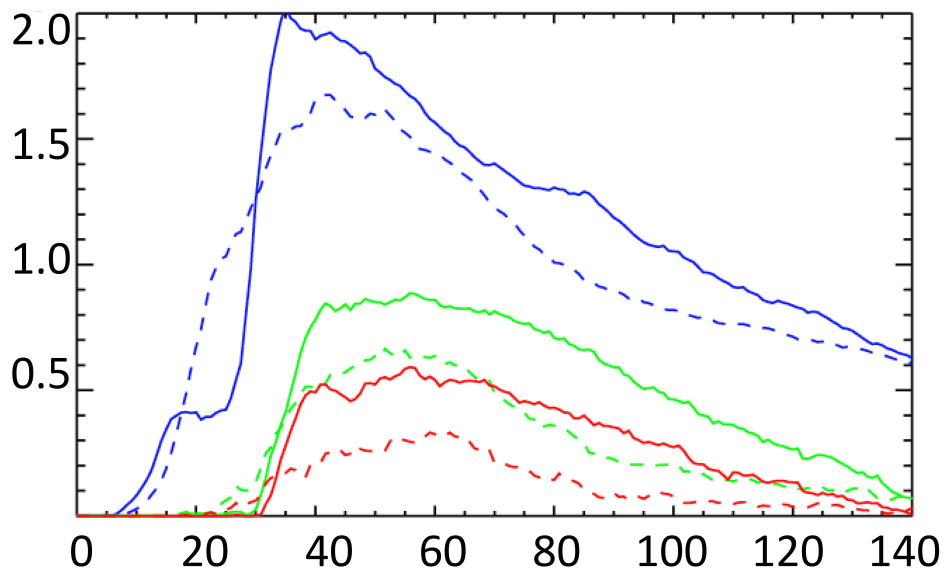
- Emergence rates 0.6 x 10^{20} Mx /hr
- Decay rates were half that, 0.33 x 10^{20} Mx/h.

- *However, follower spots begin their decay ~19 hr earlier than leaders.*

Compare with Simulations (Mag Flux 10^{21} Mx vs Time







HMI observations, 2 AR in top panels.

Rempel & Cheung 2014 left
MURaM MHD code, domain size 147x74x16 Mm. Total flux of emerging loop is 1.7 x 10^{22} Mx. Includes convection. Rate is ~6.6 x 10^{20} Mx/hr.

Note different range of x-axis values.

Outstanding questions in Solar Physics?

***Q:* What role does the magnetic field play in the solar interior / CZ?**

We treat the magnetic field as a tedious consequence in the interior, and as king in the atmosphere. However, we are probably misunderstanding a crucial role it plays in the interior – angular momentum transport, helicity transport, enhanced diffusion at the small scales.

We assume that B assists in efficient energy transport, but the energy of B in the interior is so much smaller than that of flows anywhere mid-photosphere and below that

.

Section III

Variety of Atmospheric Phenomenon:
(an excuse for beautiful movies)

Open Flux, Prediction of Solar Cycle Amplitude from geomagnetic precursor

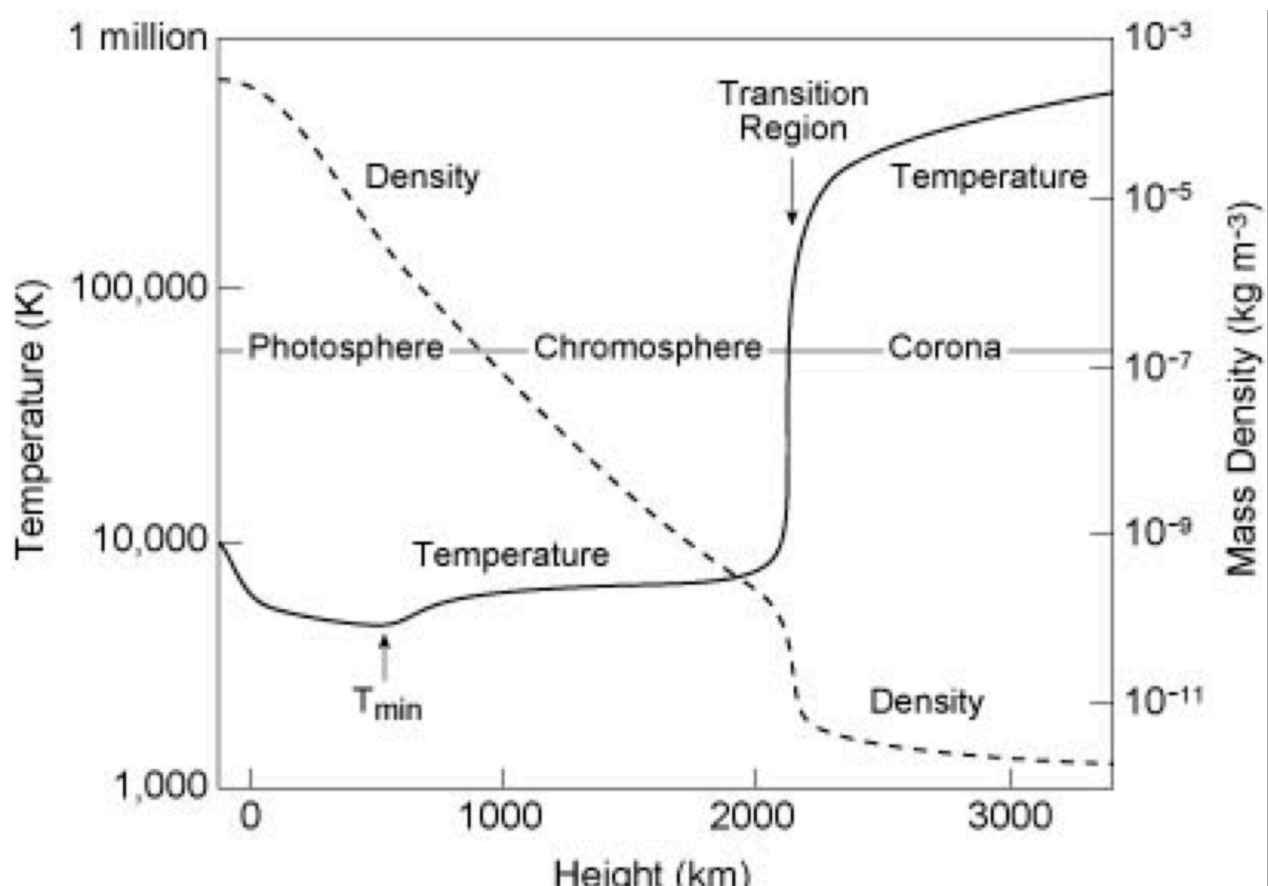
Outstanding questions in Solar Physics? (Moving into the Atmosphere)

Q:* *What mechanisms transport heat into the corona so effectively as to make the temperature rise from 6000 K in the photosphere to millions of degrees in the corona?

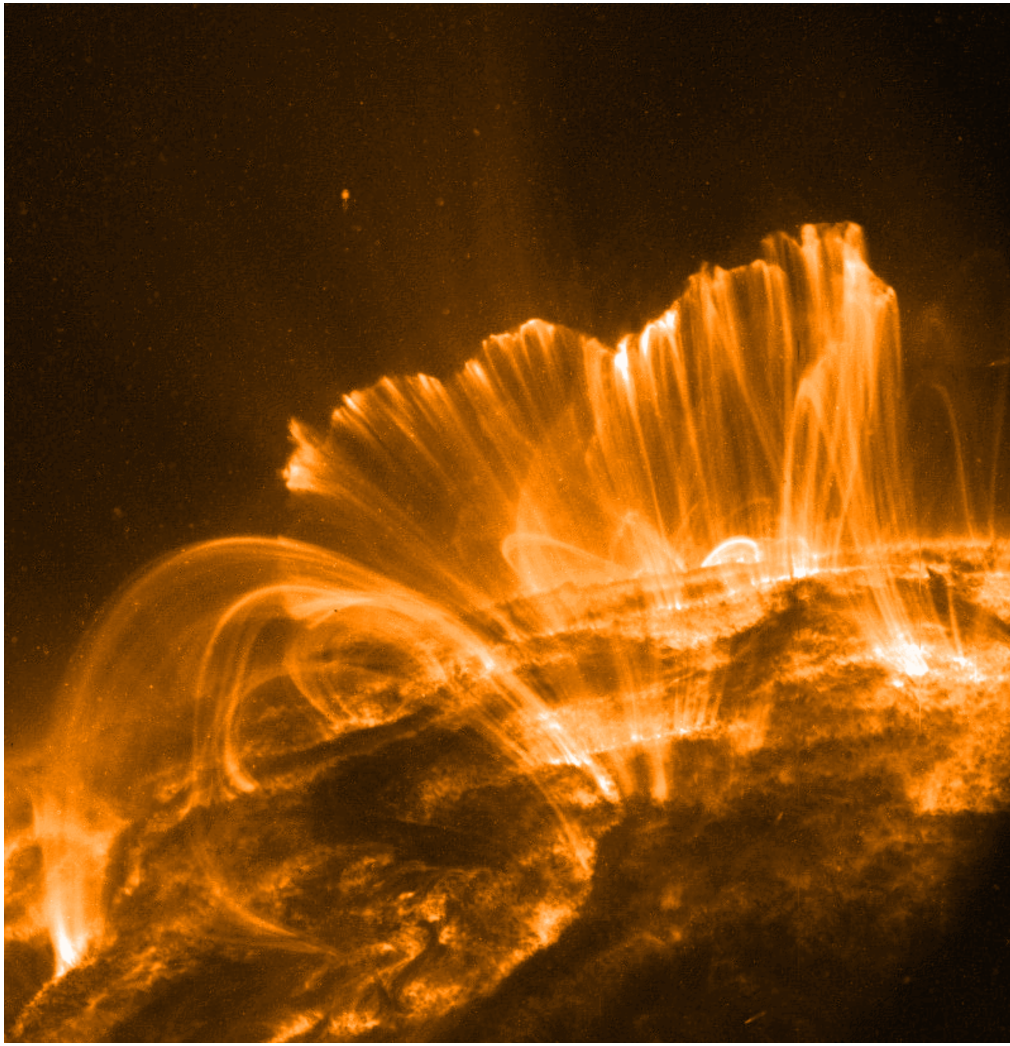
⇒ Other stars show evidence of an atmospheric temperature inversion which means that coronal heating and corona formation is a universal process for cool stars.

Main Heating Mechanisms

MHD Waves (steady state)
Magnetic Reconnection (impulsive)



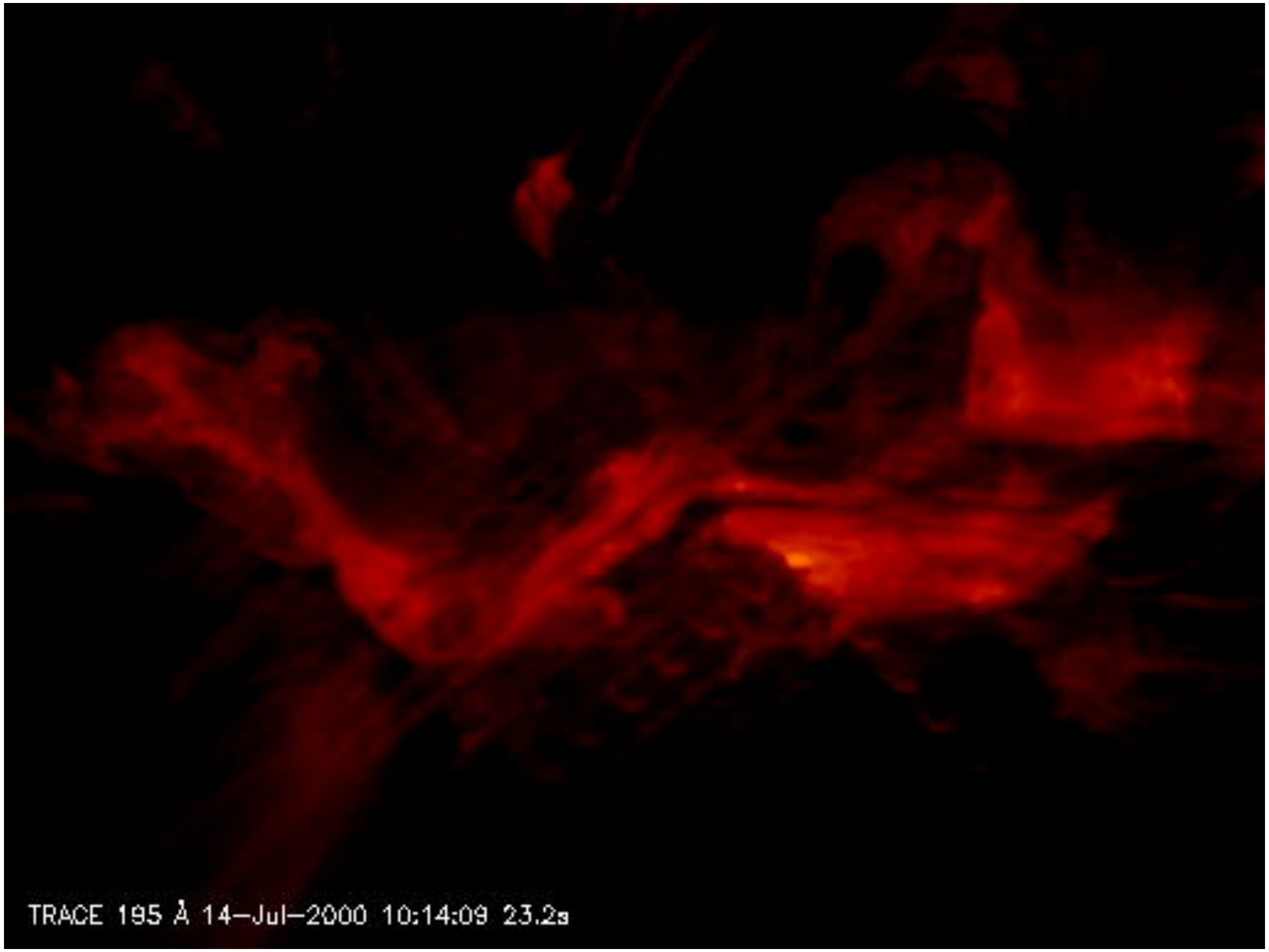
Outstanding questions in Solar Physics?



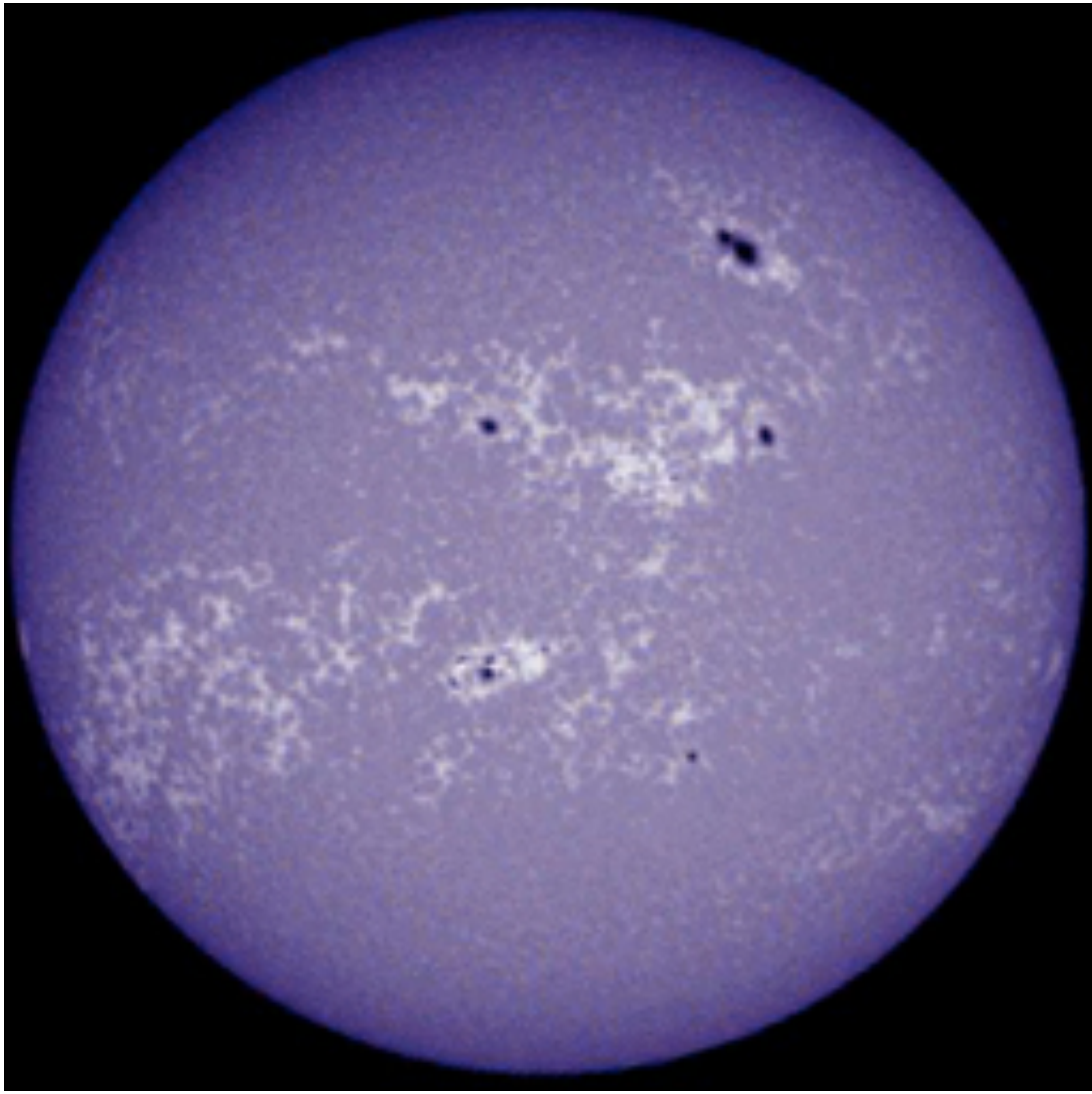
***Q:* Spiro Antiochos:** *"Why do the loops in the corona look so smooth if they are supposed to be tangled and mangled by the photospheric motions? There is thought to be a tangling that produces complex geometries that, in turn, lead to nanoflares releasing energy through magnetic reconnection. However, in the TRACE images, the loops look smooth and parallel, i.e., combed."*

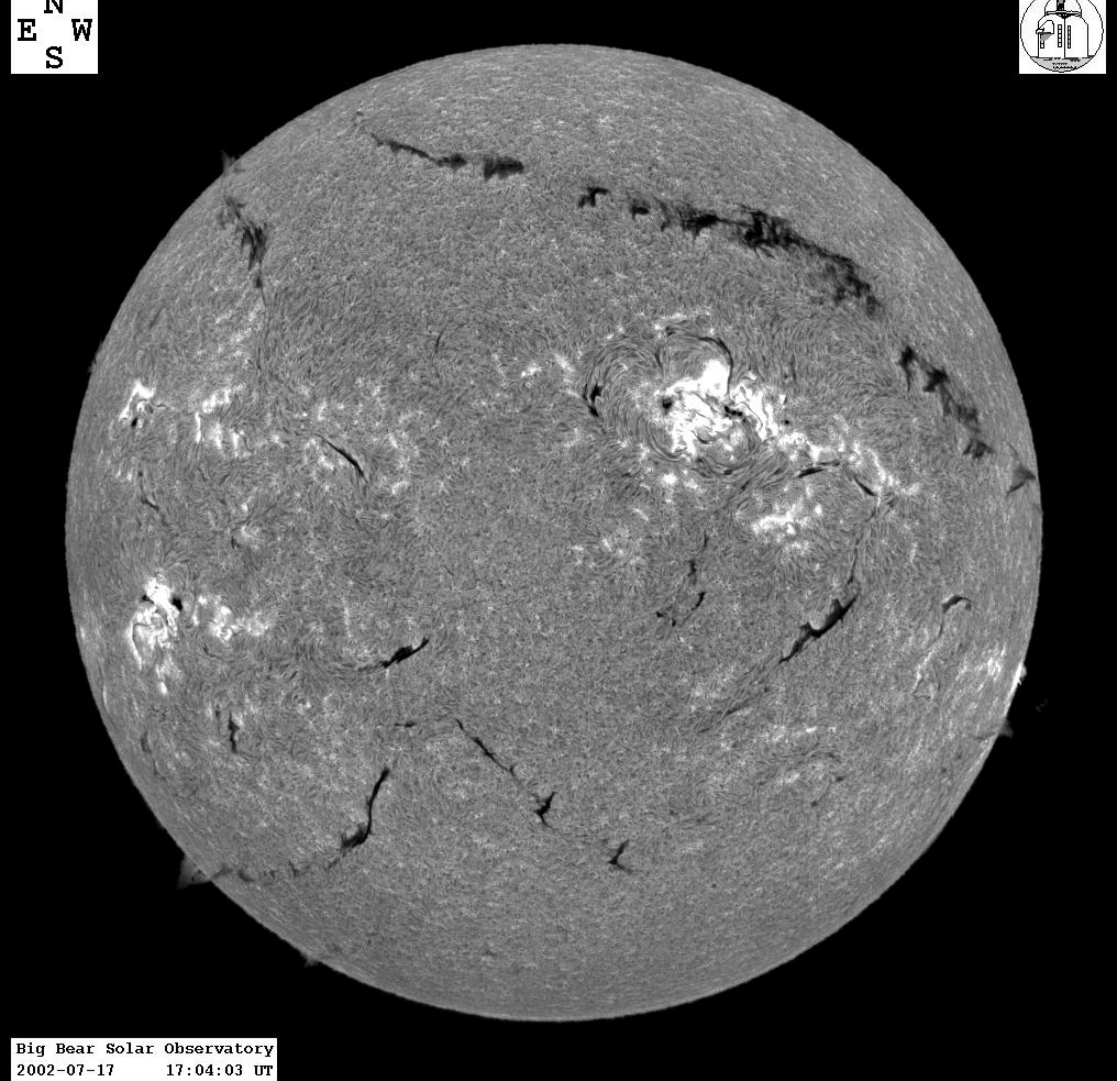
Two ribbon flare: Two ribbons lie at the feet of the flare loops, often occurs in a decaying active region. Neutral line runs parallel to and in between the ribbons - 195 Angstroms Trace. The backbone is the ***Cusp*** , it would be the apex of the loops if viewed edge-on.

NEXT MOVIE: Post-flare loops: Transverse structures located between the two ribbons after a flare, seen in H-alpha, transition zone and coronal lines. Trace 171 Angstroms.

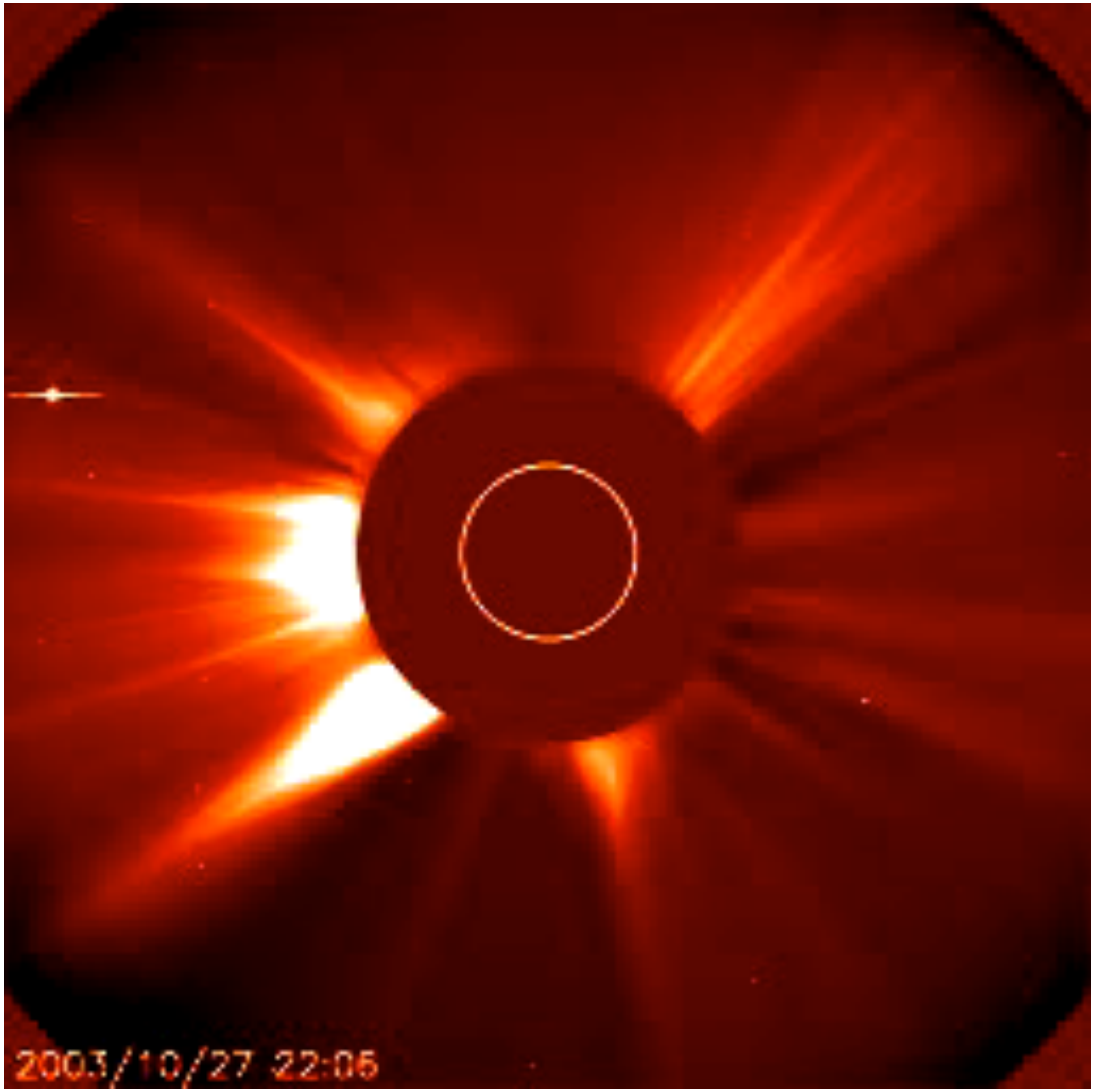


Plage: observed as bright features in chromospheric emission and are found surrounding sunspots (active regions). Plage are linked to the increased irradiance during solar maximum.



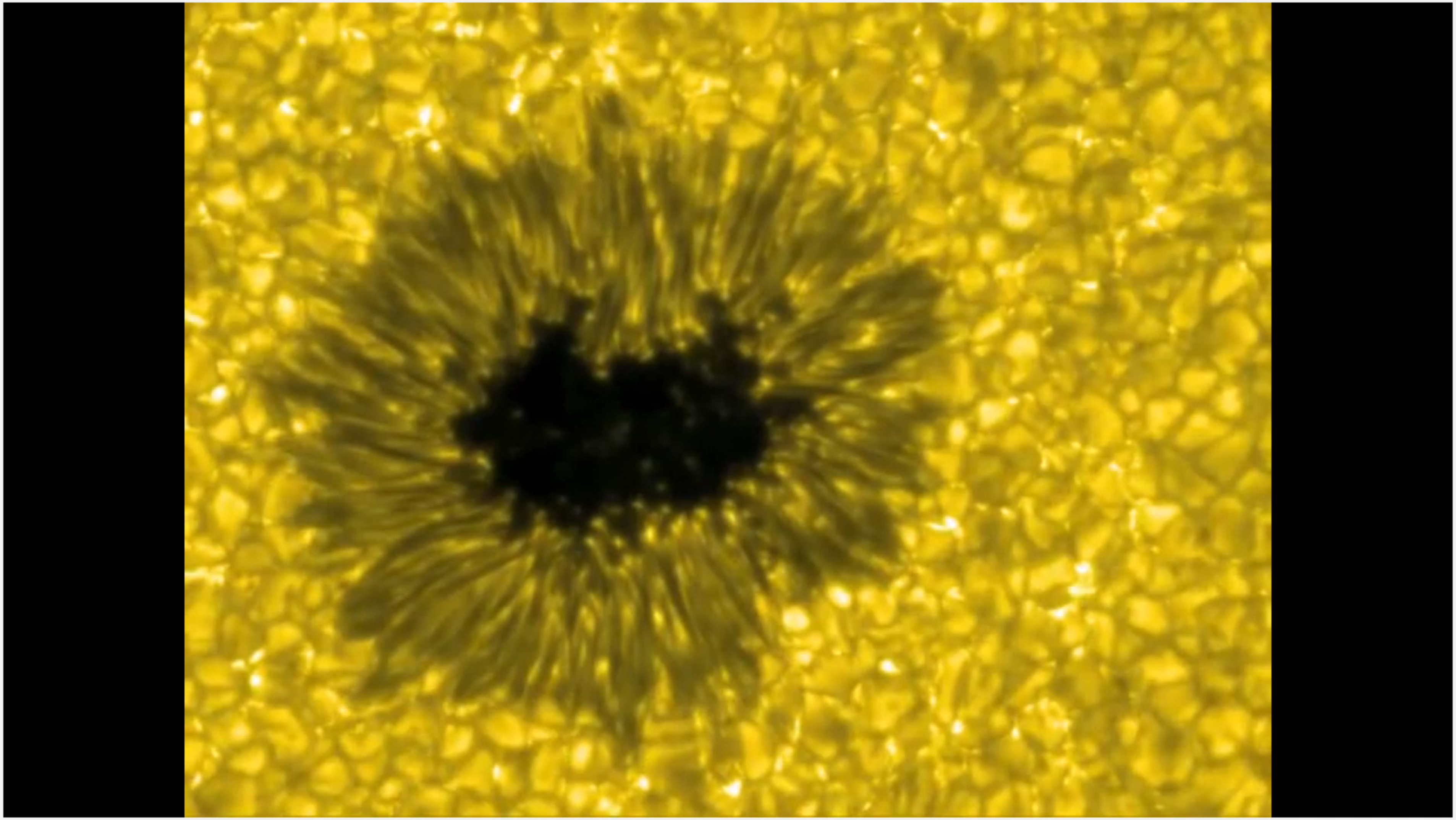


Filament: A strand of relatively cool gas suspended by magnetic fields over the solar photosphere so that it appears as a dark line over the Sun's disk. A filament on the limb of the Sun seen in emission against the dark sky is called a prominence. Filaments often mark areas of magnetic shearing and can be seen only in the centers of strong spectral line, such as H-alpha or the H and K lines of calcium.



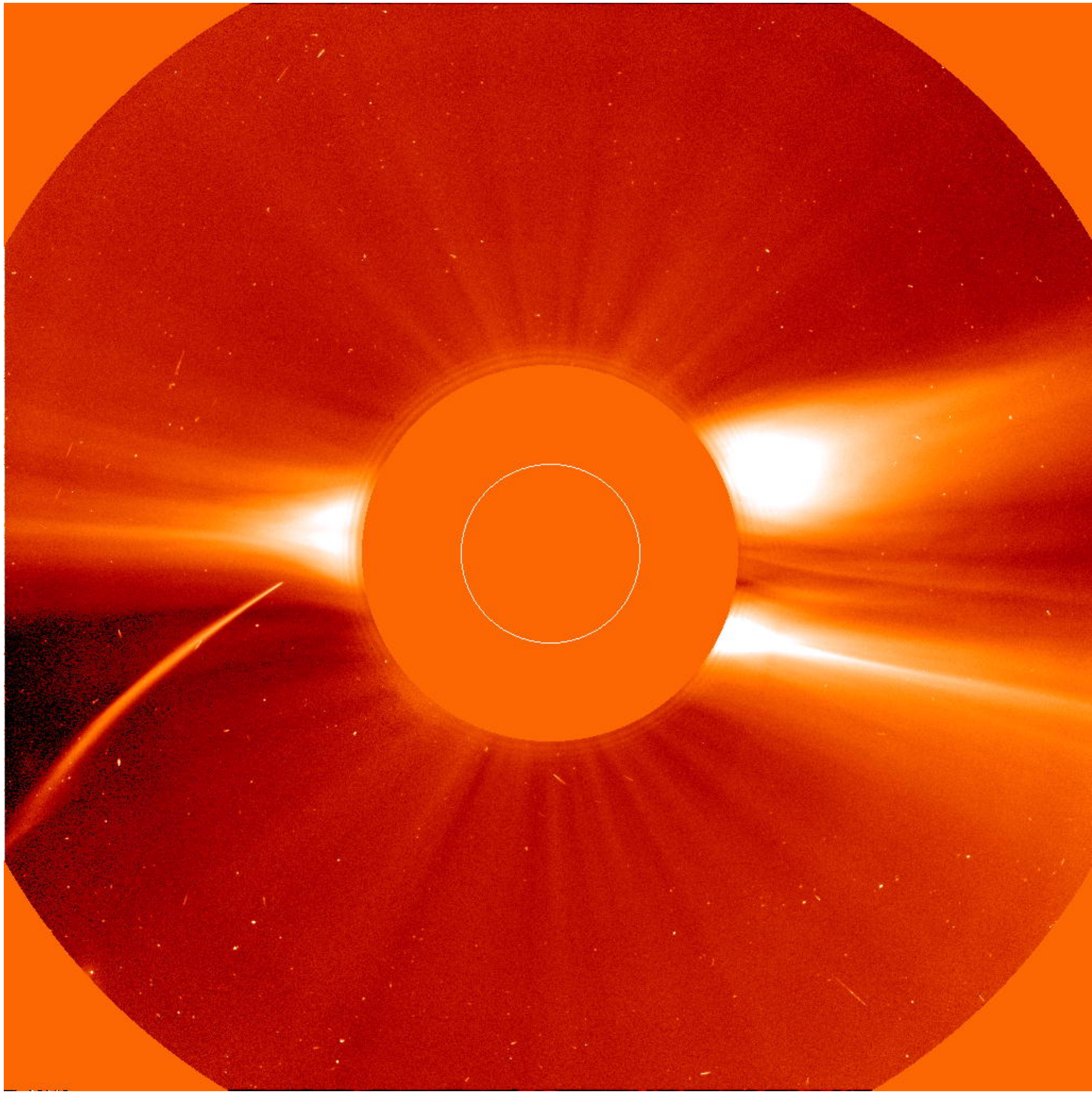
Coronal Mass Ejection: A huge eruption of material from the Sun's corona into interplanetary space. CMEs are the most energetic of solar explosions and eject up to100 billion kilograms of multi-million-degree plasma at speeds ranging from 10 to 2,000 km/s. They often look like bubbles. CMEs originate in regions where the magnetic field is closed. These storms can disrupt power grids, damage satellite systems, and threaten the safety of astronauts. (X17 and X10 flares and the two associated CME's, LASCO C2)

Evershed Flow: The horizontal flow of gas in the penumbrae of a sunspots; the effect is named after its discoverer, the English astronomer John Evershed (1864-1956). The maximum outflow velocity is about 2 km/s. Image from Tom Berger, Dutch Open Telescope. 28 Aug 2007 Hinode SOT



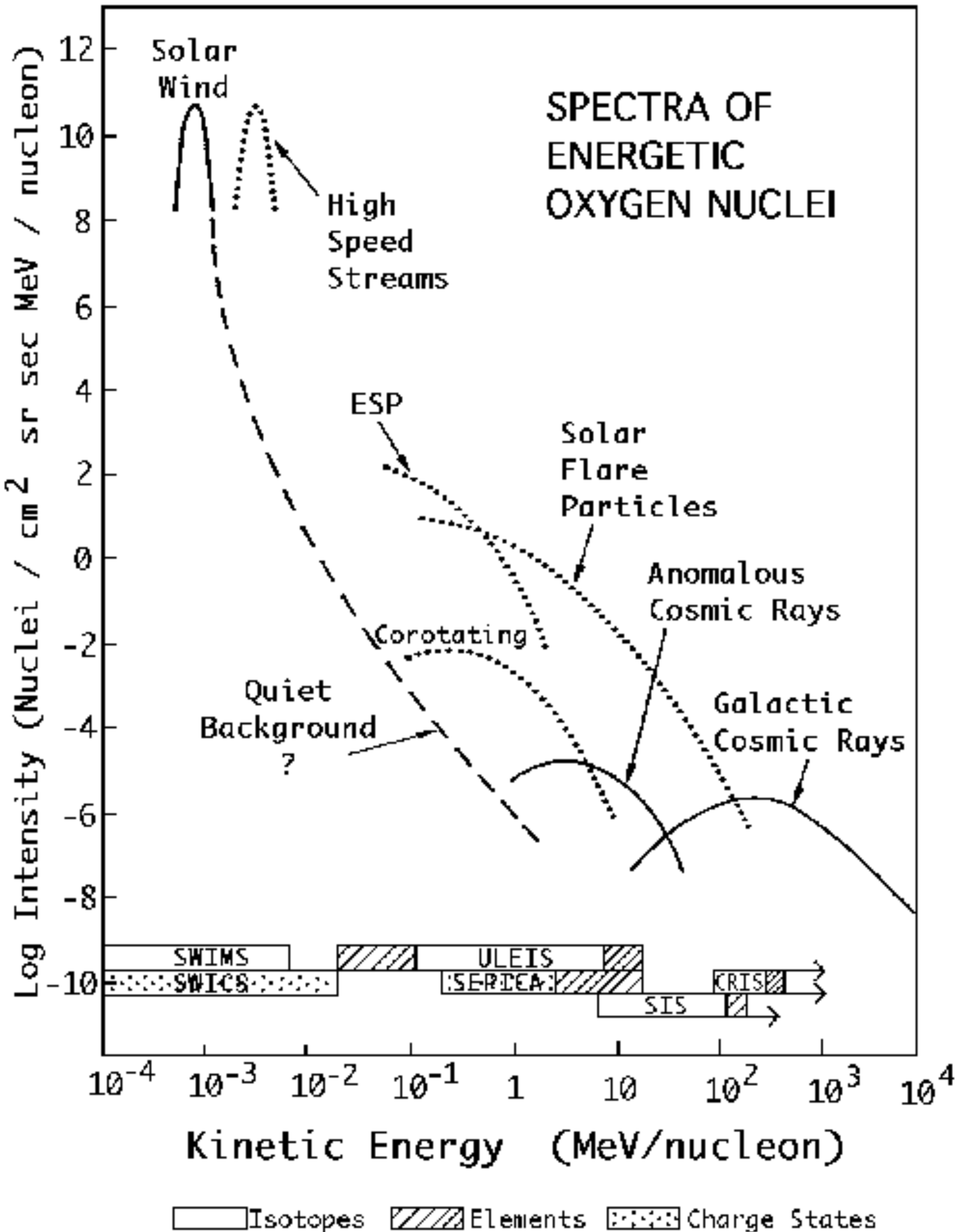
Polar Plumes: Polar plumes appear prominently in white light coronagraph observations of coronal holes as distinct, strongly collimated flow tubes. They might carry the bulk of the mass and energy of the solar wind emanating from polar regions. Electron density is greater in plumes (8x). Temperature is lower (20%). Density contrast between plume and inter-plume area disappears by 7 Rsun.

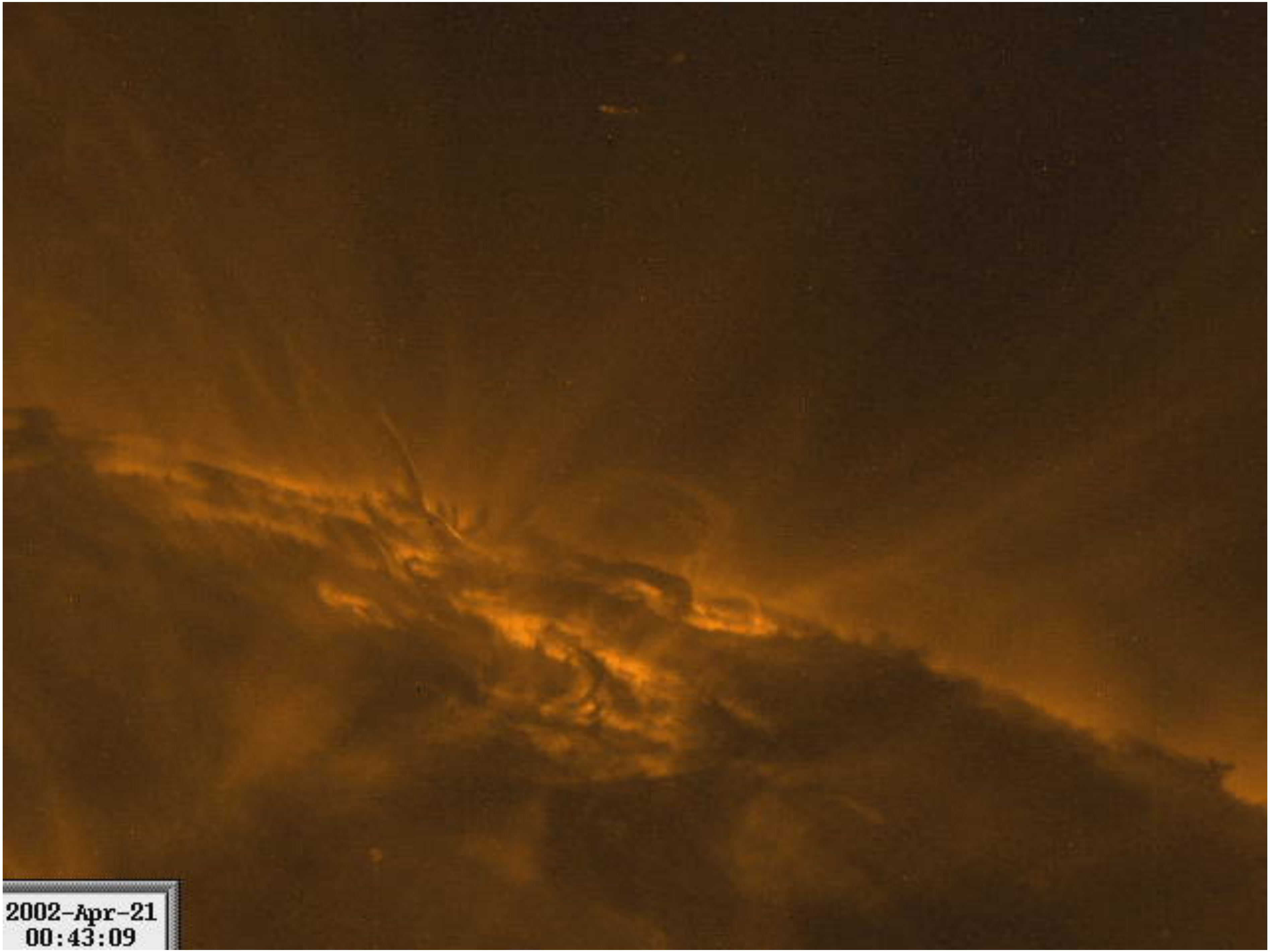
The image (Dec 23 1996) shows the ***Streamer Belt*** along the Sun's equator, where the slow, equatorial solar wind originates. Over the polar regions, one sees the polar plumes all the way out to the edge of the field of view. The frame was selected to show Comet SOHO-6, one of seven sungrazers discovered by LASCO, before it plunged into the Sun.



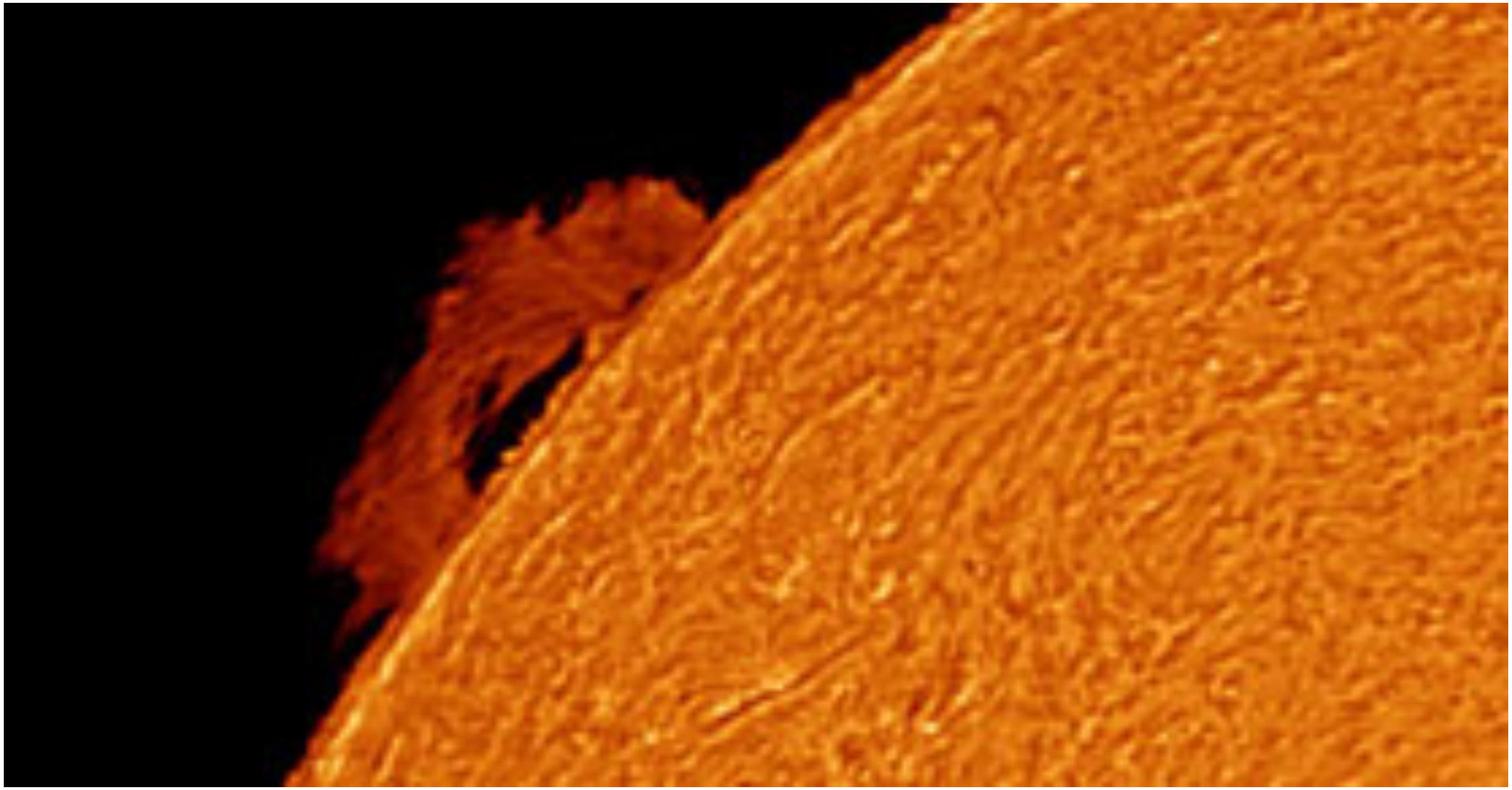
Outstanding questions in Solar Physics?

A: Joe Giacalone: "The Sun is an efficient particle accelerator. How? You've heard one theory - perpendicular shocks - but it remains an open-ended question."

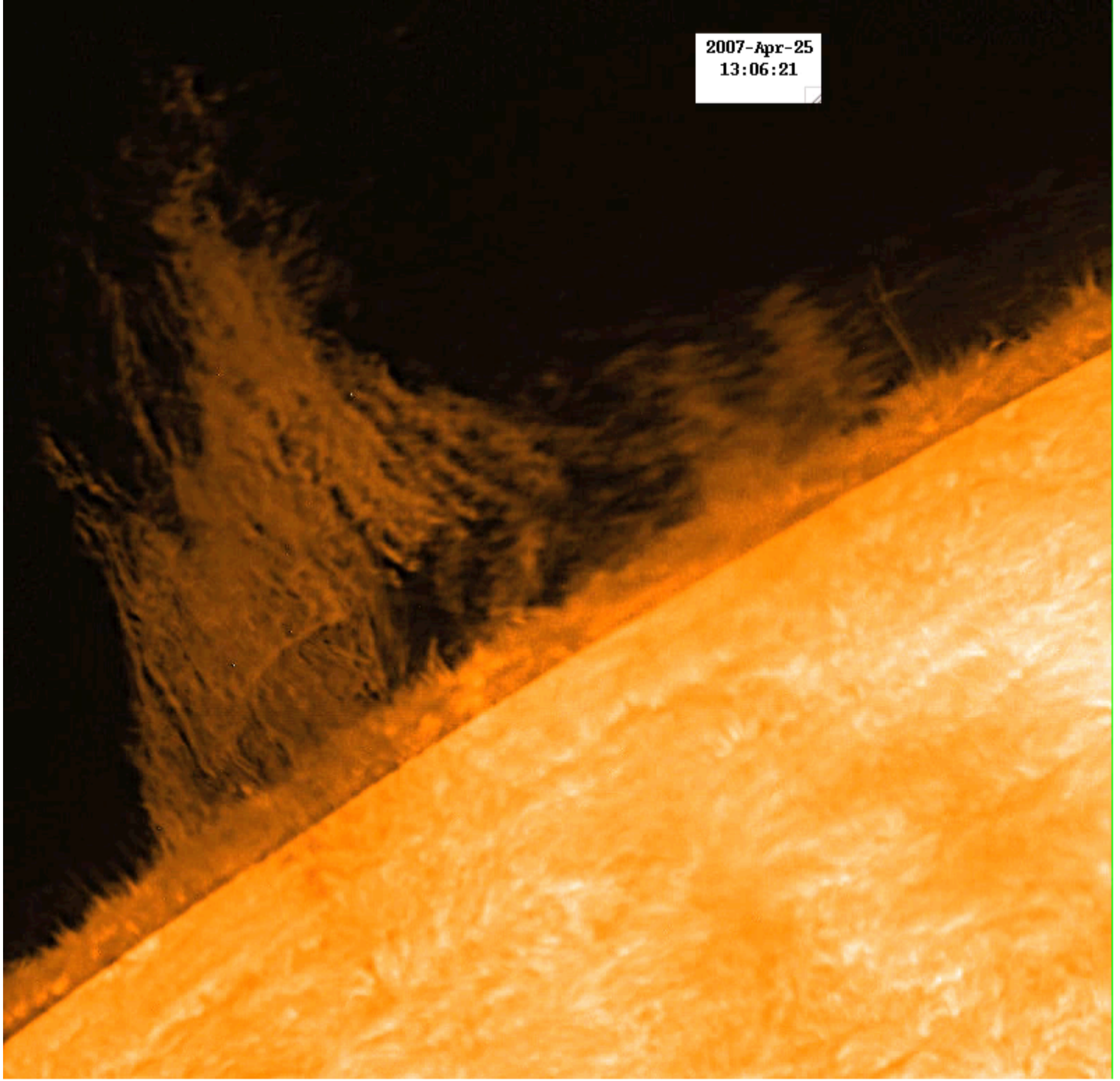



2002-Apr-21
00:43:09

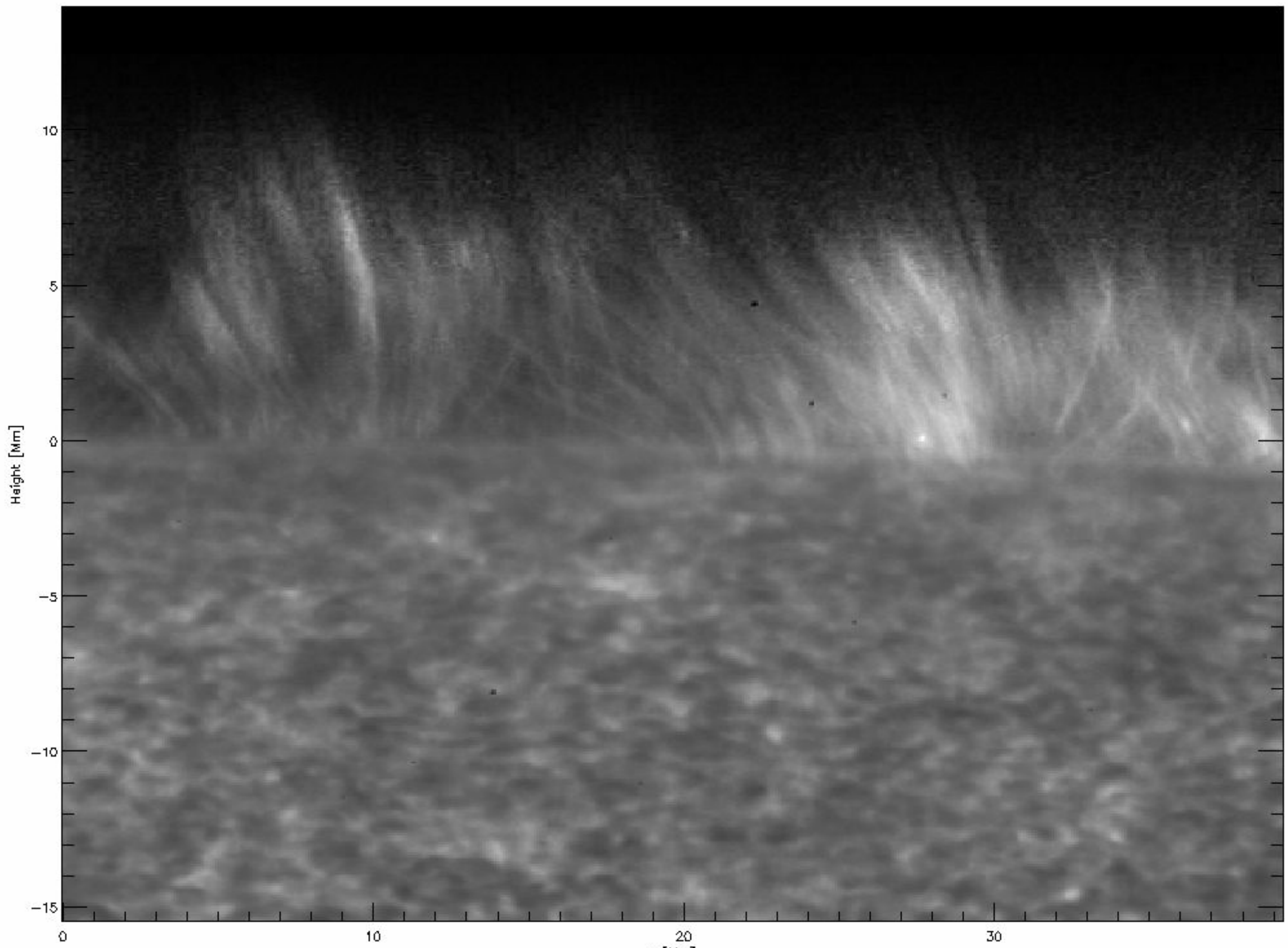
Prominence: an elongated structure full of material 100x cooler and denser than the corona (like cool clouds). Held up by magnetic structures, they can live for weeks/months, and are seen as bright against the black background of space. They can reach heights of several 100,000 km above the limb. They eventually become unstable and erupt. A prominence would be a filament if observed on the disk.

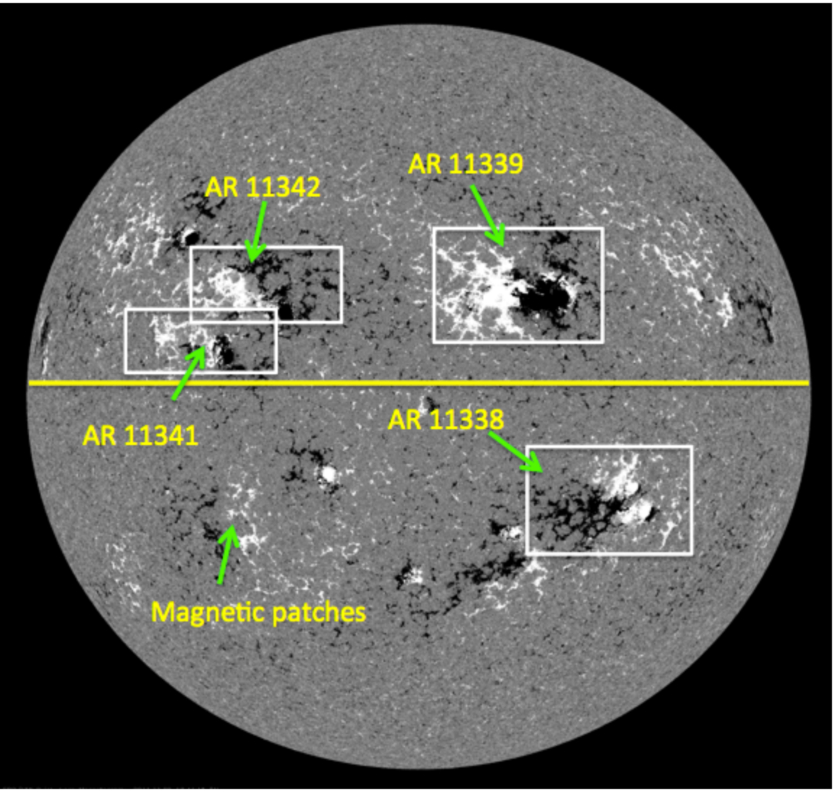


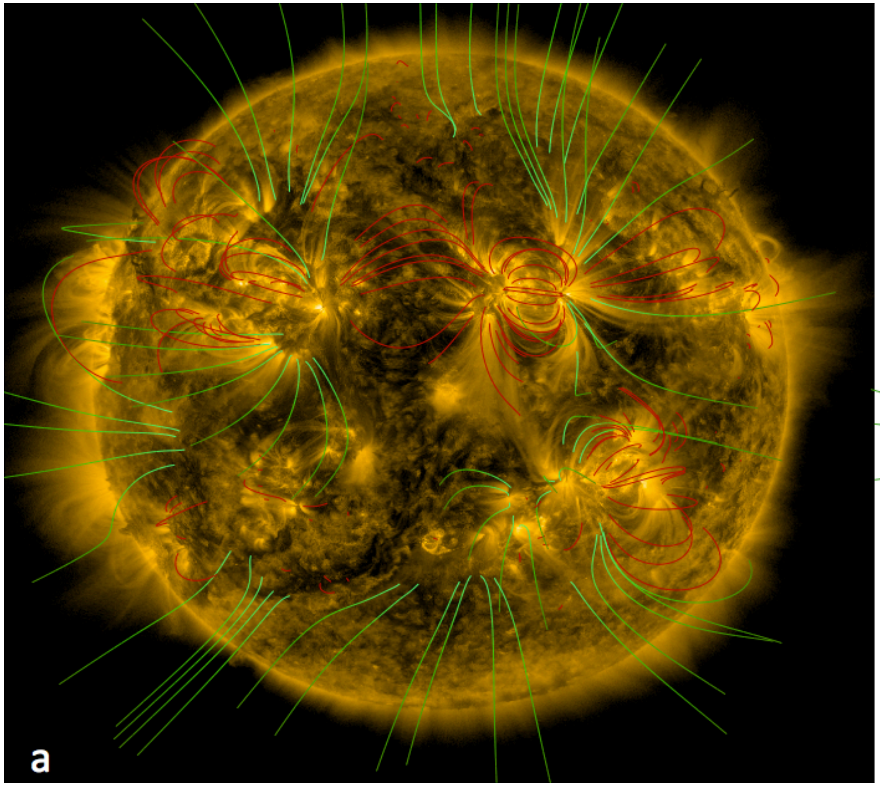
Prominence, spicule forest, Hinode SOT wing of H-alpha

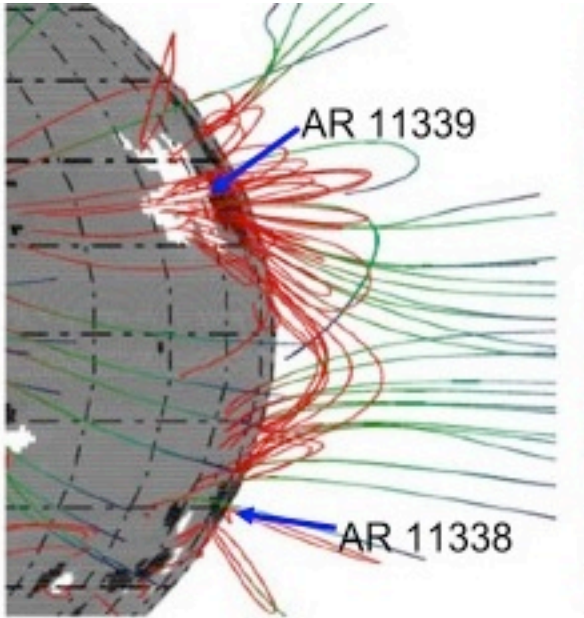


Spicule dynamics observed in Ca II H with *Hinode*/SOT . Spicules are likely the chromospheric signature of network fields. They are hot material seen in the chromosphere, flowing 20 km/sec from the photosphere, lasting about 5 minutes, structured by the magnetic field.





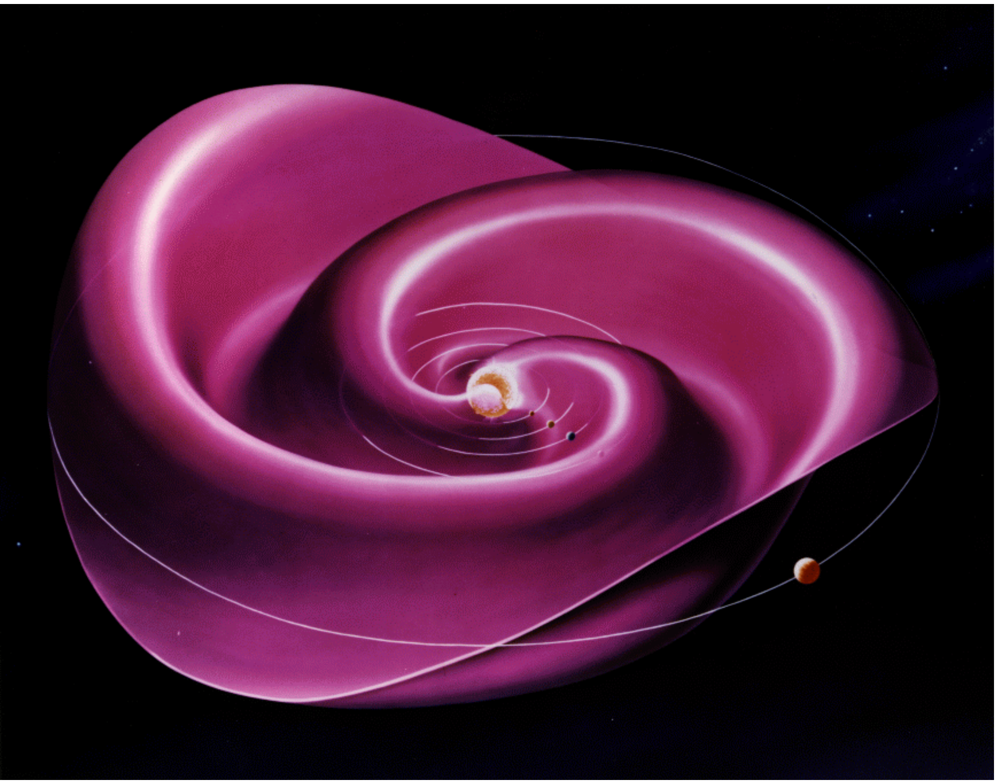




Observed magnetic field at the solar surface is used to extrapolate field lines higher in atmosphere (Tadesse et al http://hmi.stanford.edu/hminuggets/?p=1058) to examine the coronal field structure.

Certain models assume that at a given height, the field lines must be radial. Other models allow currents and assume the field to be open at a certain height but not radial.

These assumptions affect the modeling results of the outflow of the solar wind, the geometry of the current sheet, etc, as sampled by OMNI, etc.

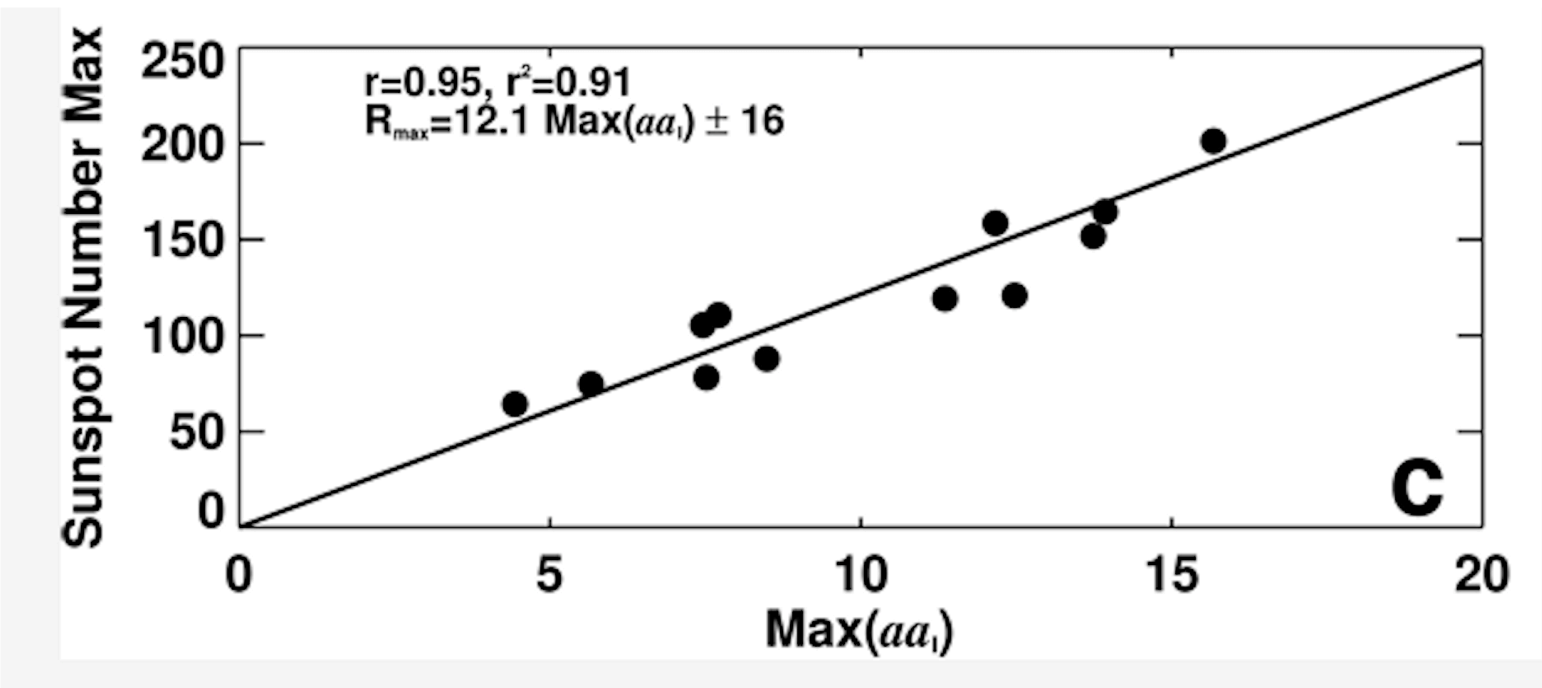


The **Heliospheric Current Sheet** is the surface within the Solar System where the polarity of the Sun's magnetic field changes from north to south. This field extends throughout the Sun's equatorial plane in the heliosphere. The shape of the current sheet results from the influence of the Sun's rotating magnetic field on the plasma in the interplanetary medium (Solar Wind).A small electrical current flows within the sheet, about 10^{-10} A/m². The thickness of the current sheet is about 10,000 km near the orbit of the Earth.

Predicting the Next Solar Cycle

Can use Earth's magnetic field changes at, and before, sunspot minimum. Feynman separated geomagnetic *aa* index into two components: one in phase with and proportional to the sunspot number, the other remaining component relating to high speed streamers.

The max of the geomagnetic aa index near sunspot min is proportional to the sunspot number during the following max. Puzzling why a geomagnetic index has the least error in predictive capability.



New Instruments = New Era of Solar &Heliospheric Research

1. DKIST – 4 m. telescope - IR and Vis spectropolarimeters, coronal magnetometers ground-based in Hawaii (2019)
2. Solar Orbiter – approach to 0.28 AU, polar observations, launch 2018/19
3. Solar Probe Plus – in situ measurement of E & B fields, shocks, launch 2018/19
4. Solar Sentinels – 6 spacecraft to study Sun at solar maximum, particle detectors

Important to have good, young scientists (you) working to answer all the open questions regarding the Sun-Earth connection and Space Weather.

Many open questions remain.

We hope you learn a lot this week, if not from people, from the data.