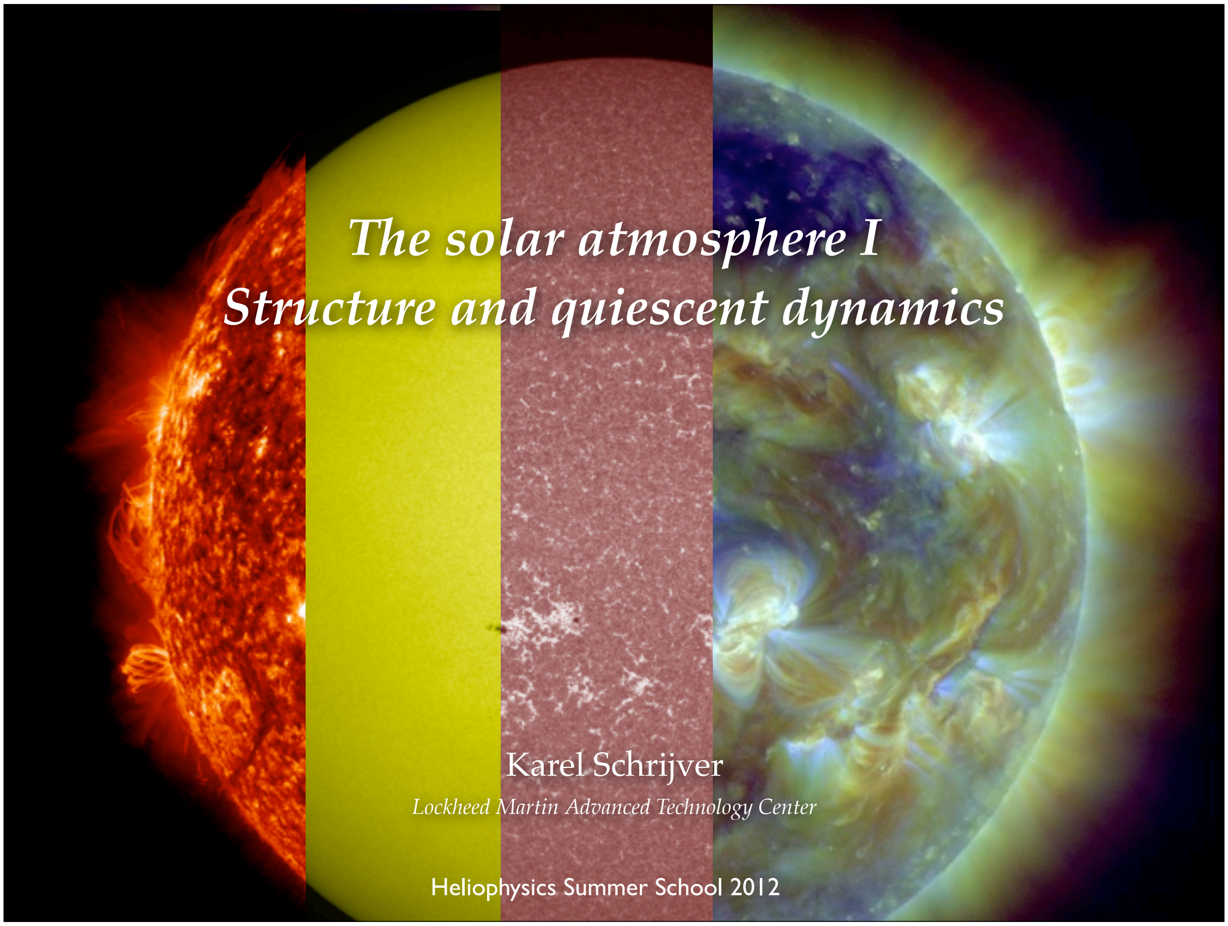
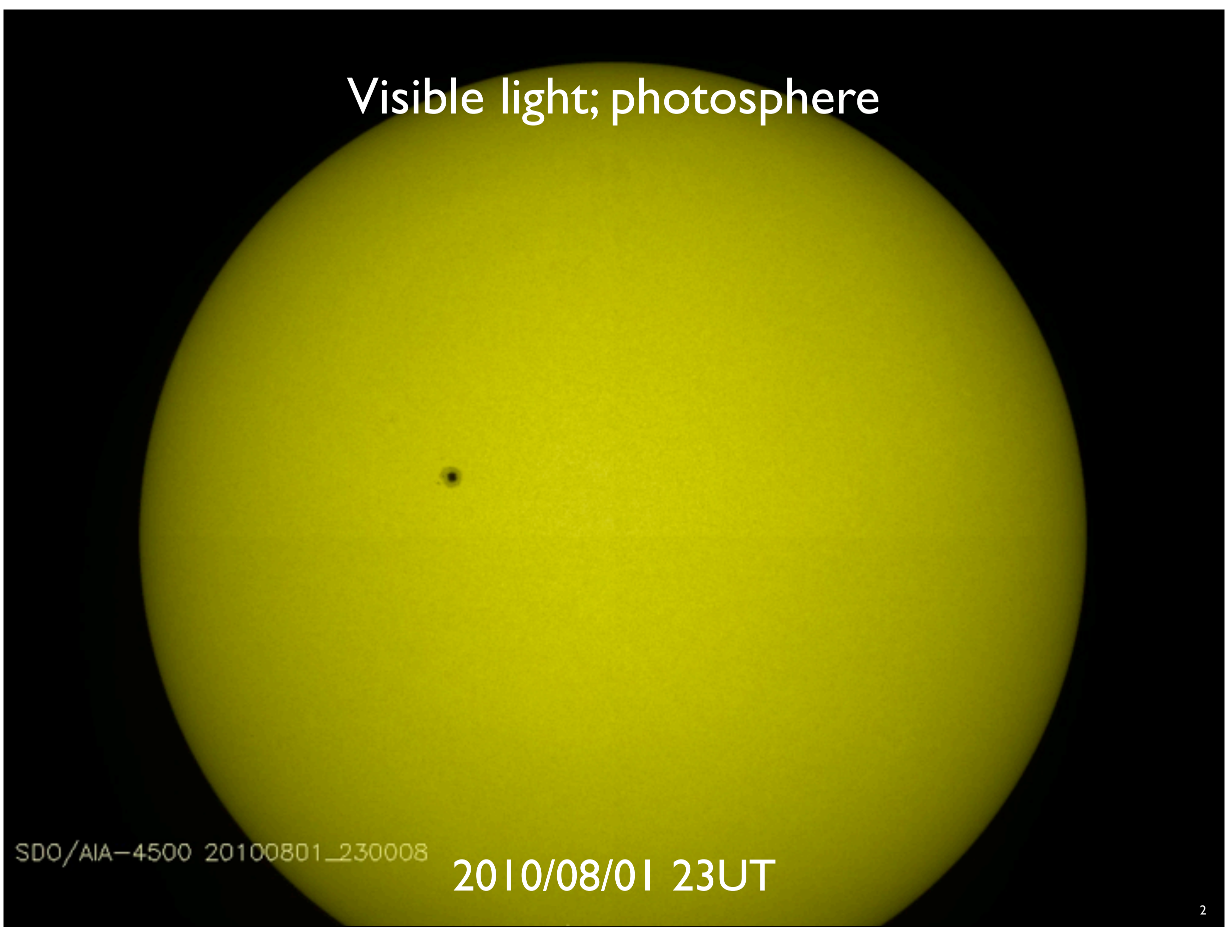
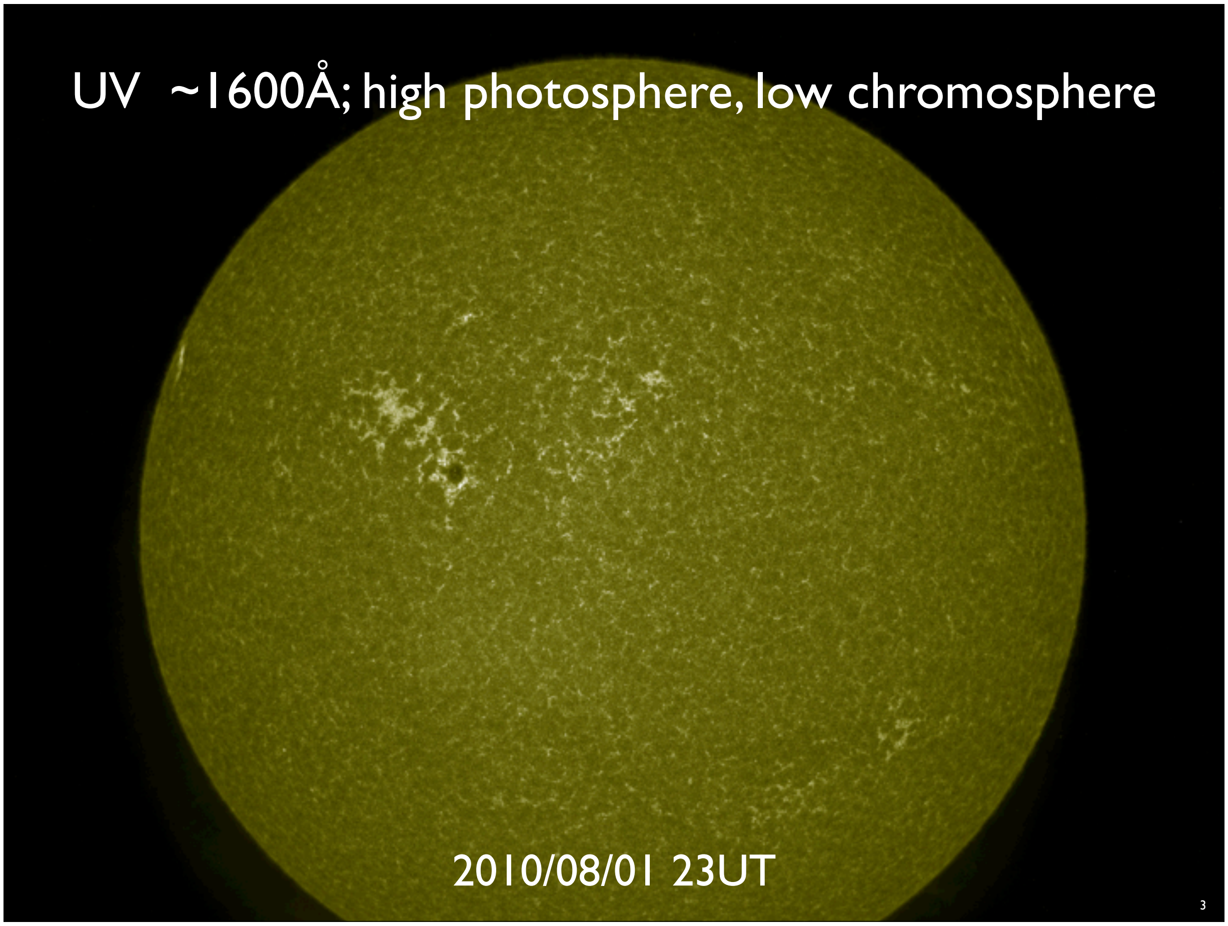
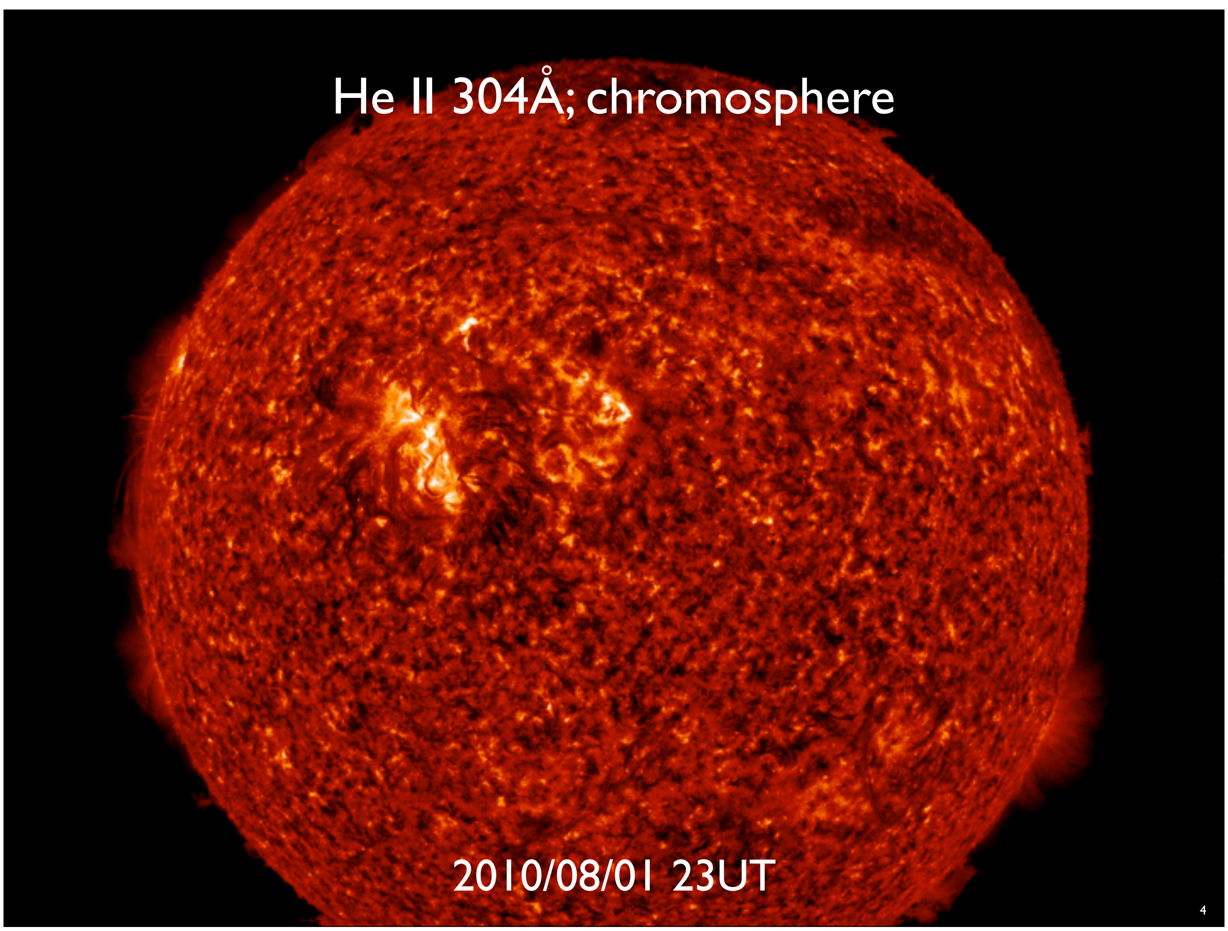
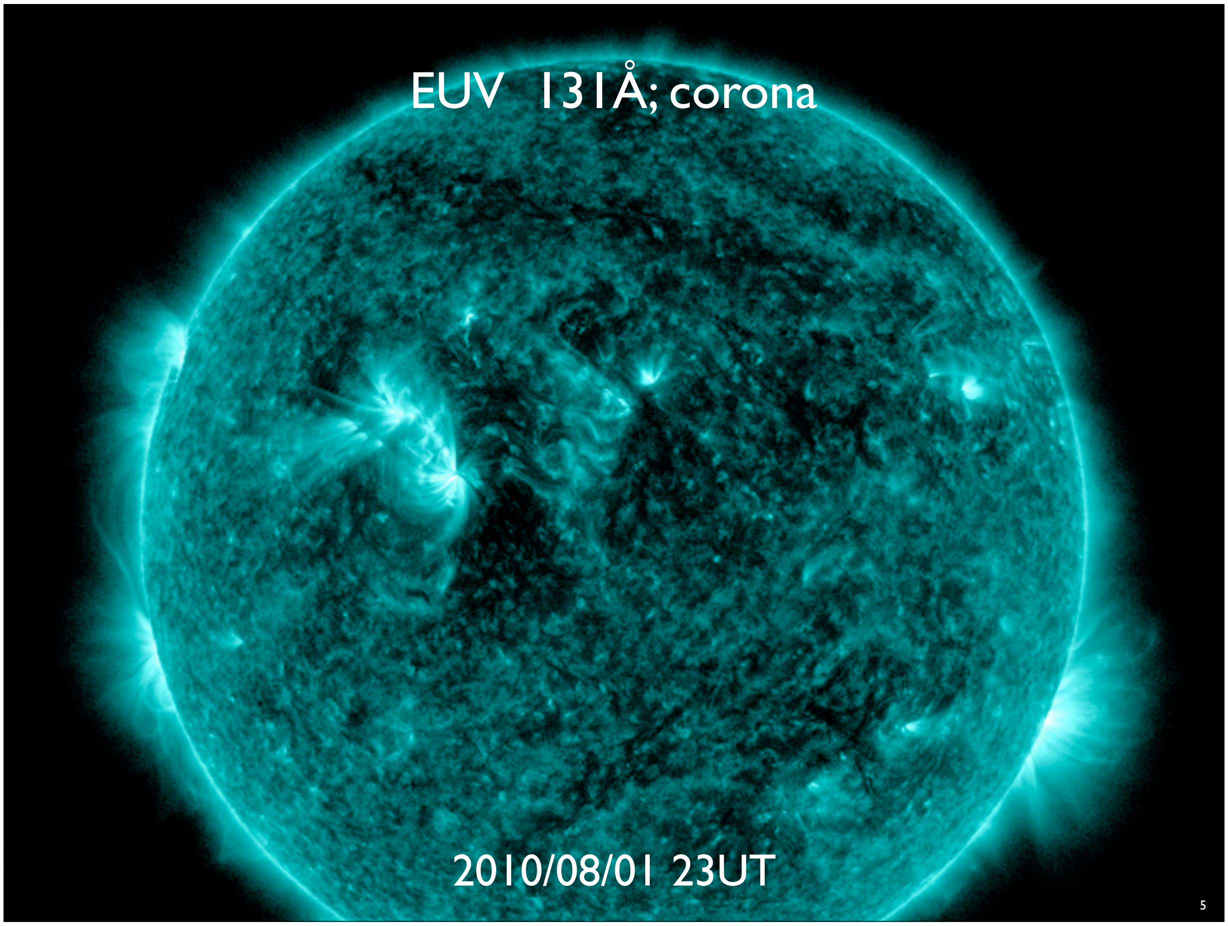
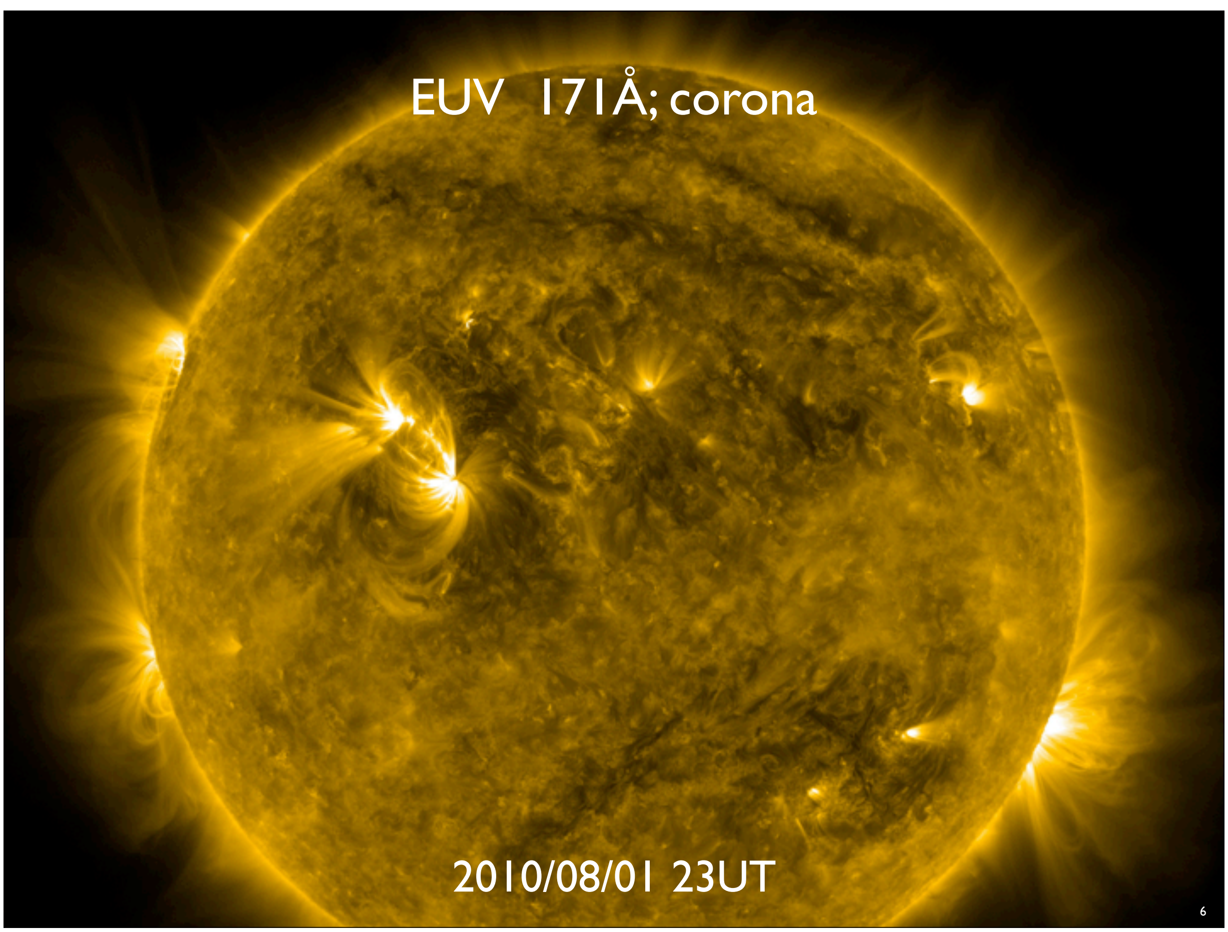

The solar atmosphere I
Structure and quiescent dynamics
Karel Schrijver
Lockheed Martin Advanced Technology Center
Heliophysics Summer School 2012

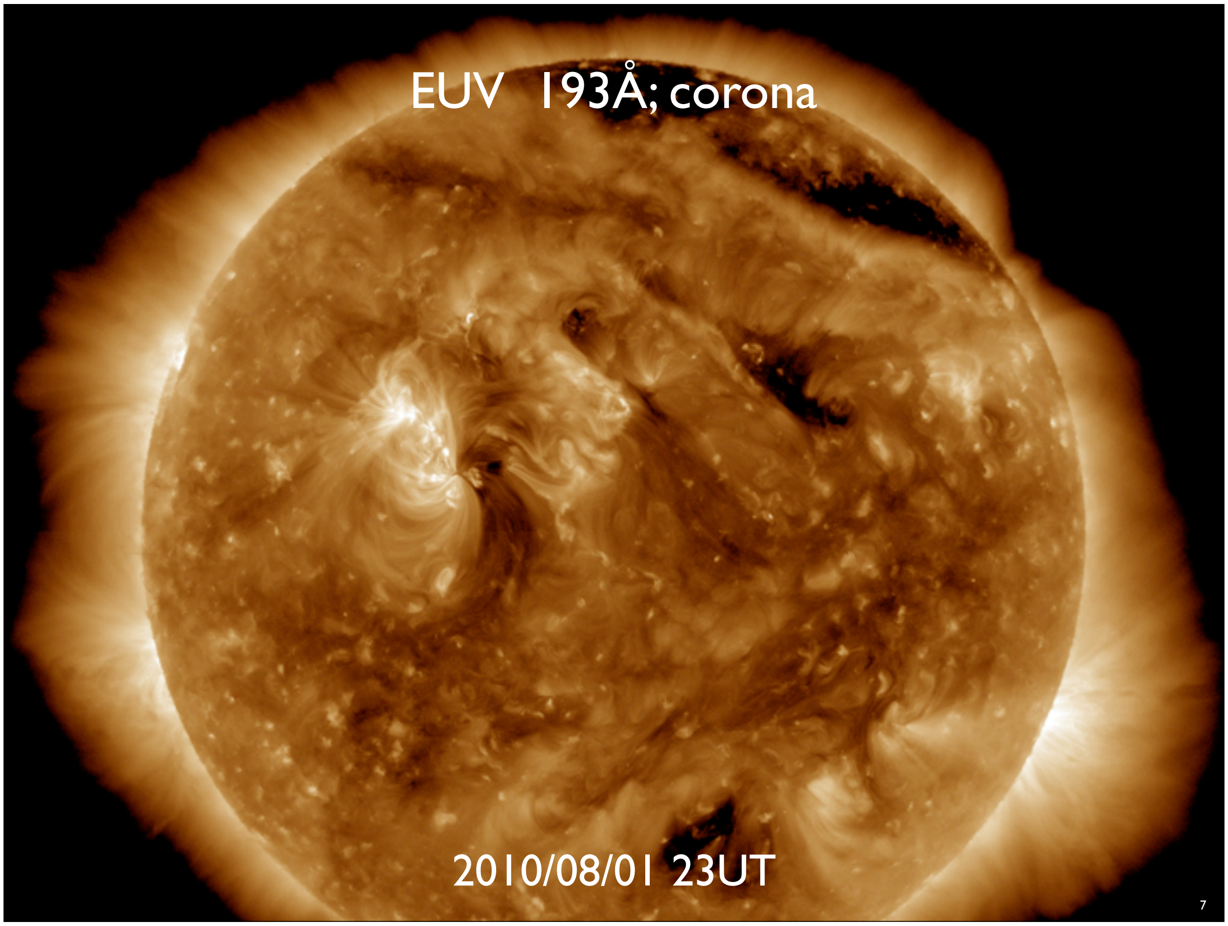

Visible light; photosphere
SDO/AIA-4500 20100801_230008
2010/08/01 23UT
2

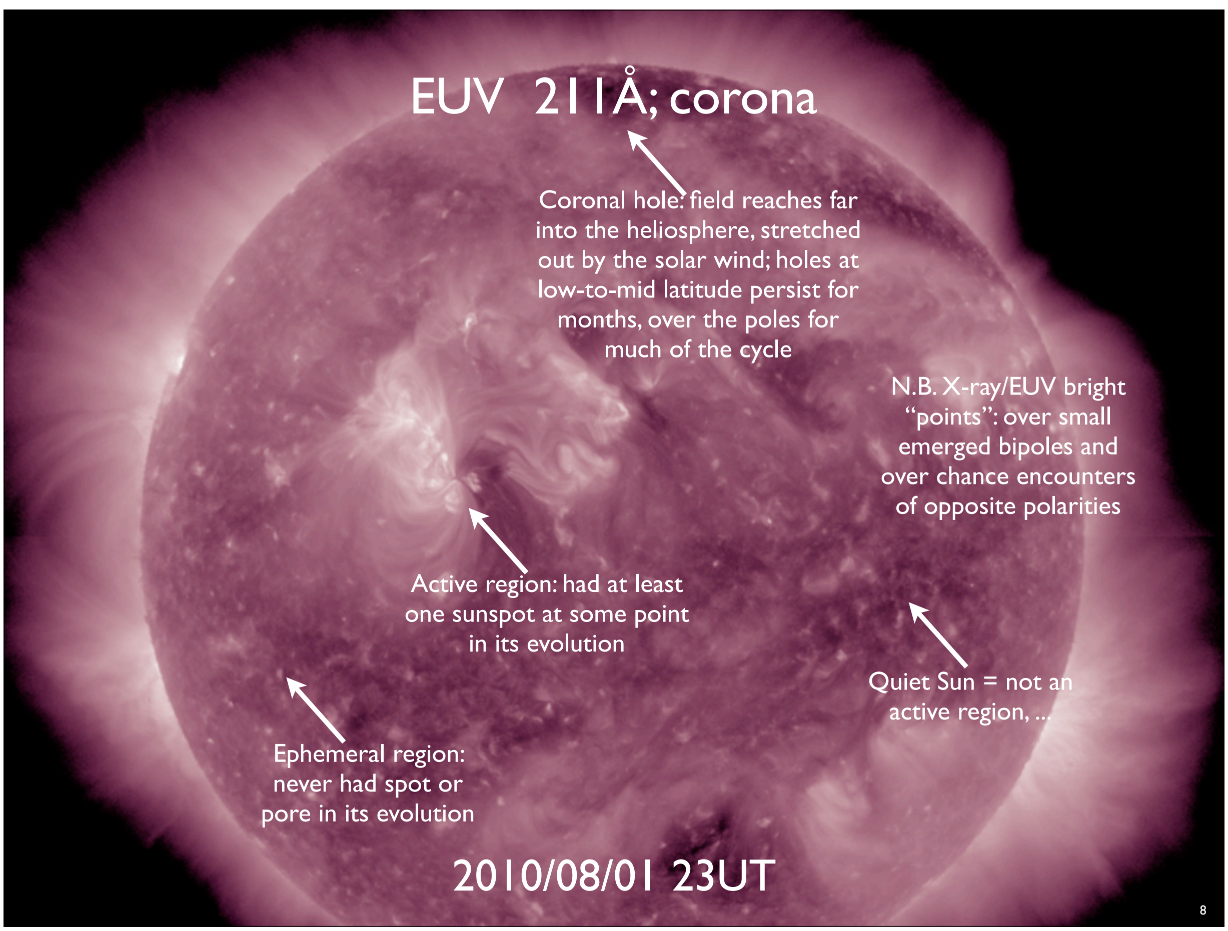

UV ~1600Å; high photosphere, low chromosphere
2010/08/01 23UT
3

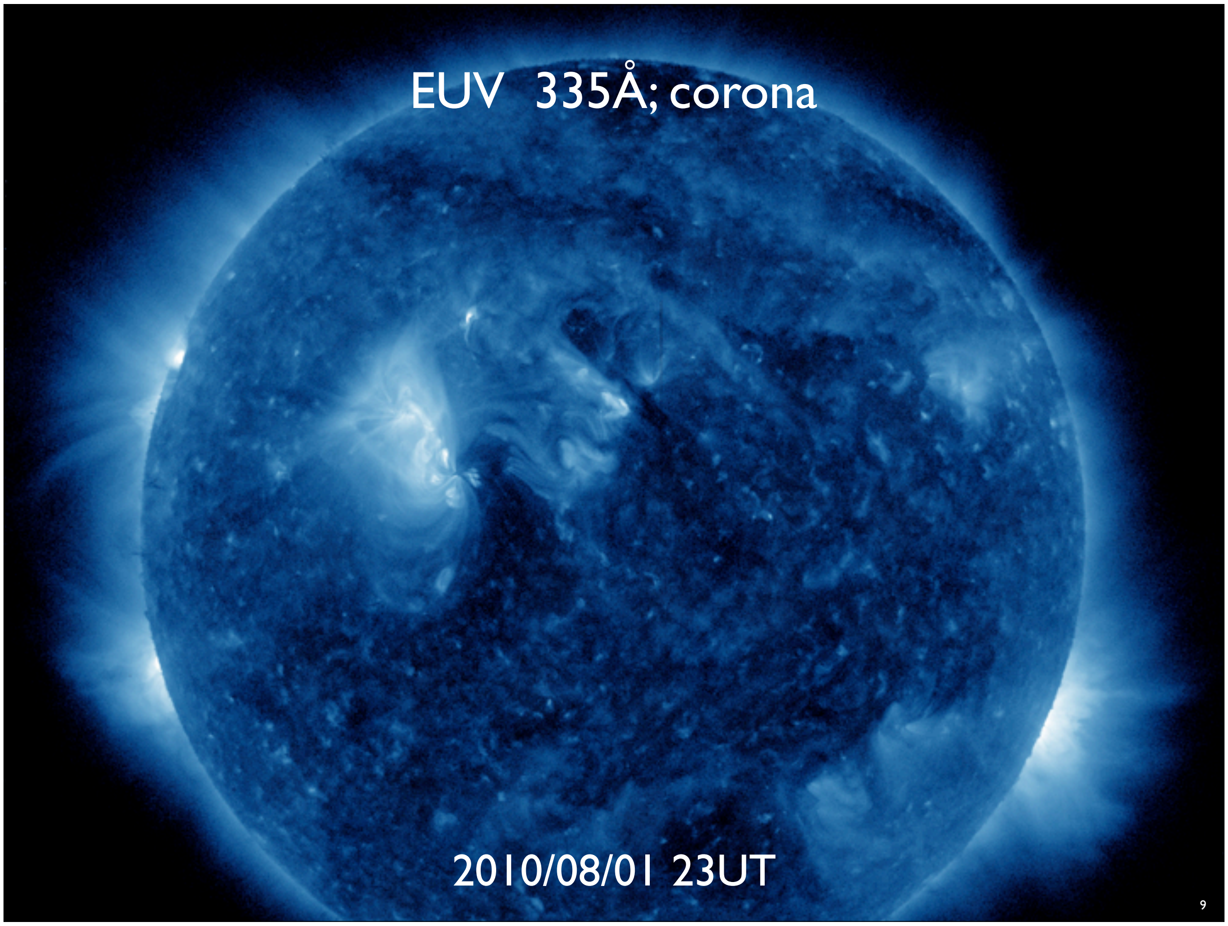

He II 304Å; chromosphere
2010/08/01 23UT
4

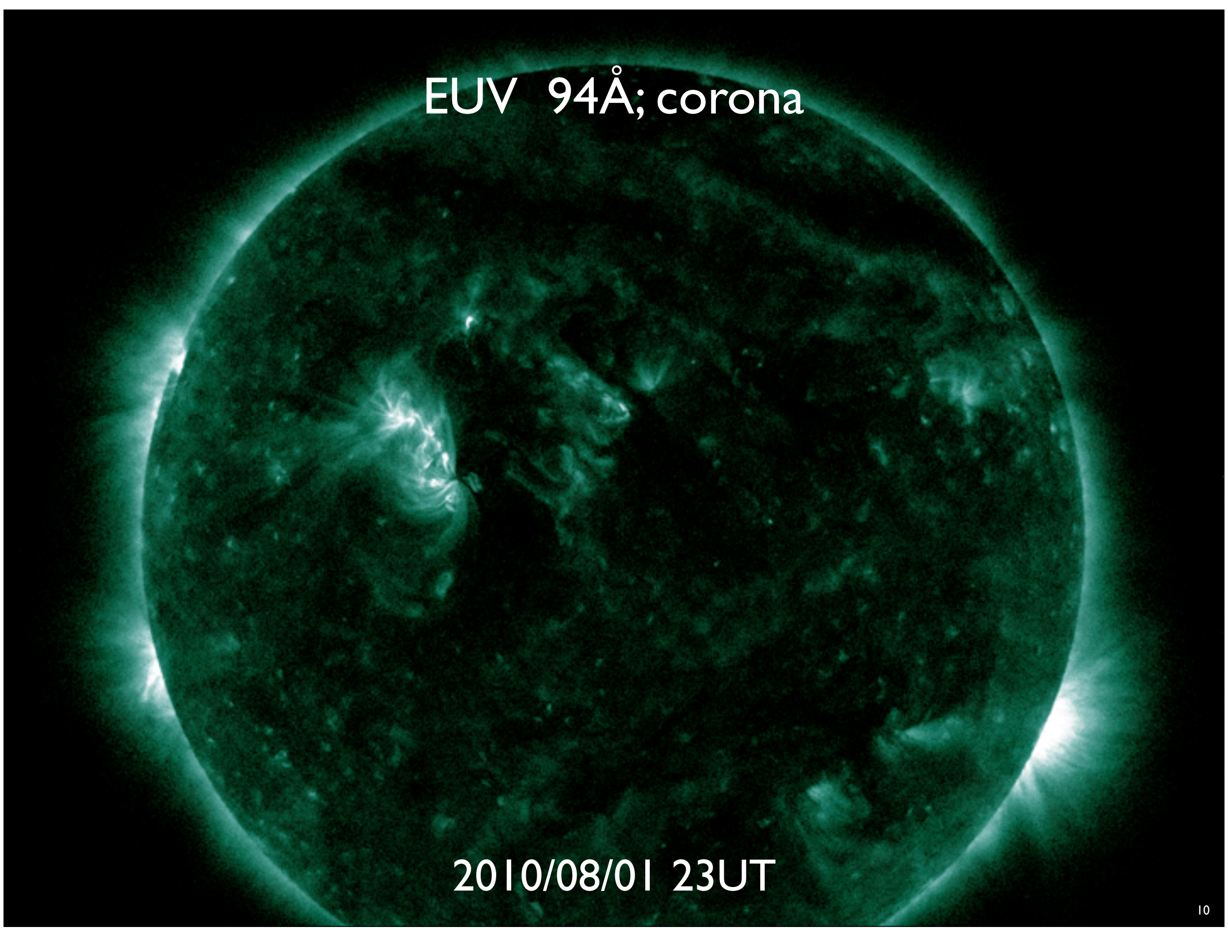

EUV 131Å; corona
2010/08/01 23UT
5

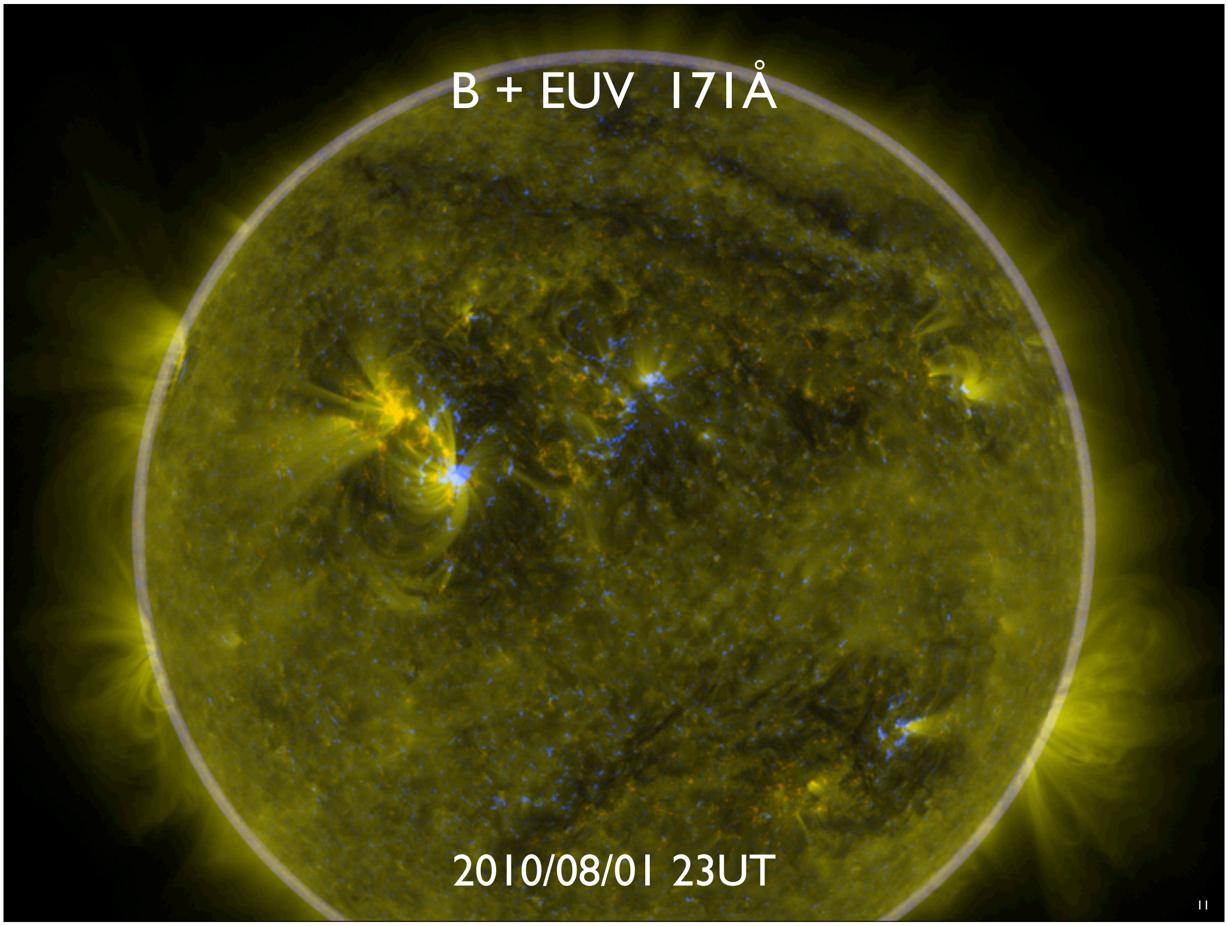

EUV 171Å; corona
2010/08/01 23UT
6

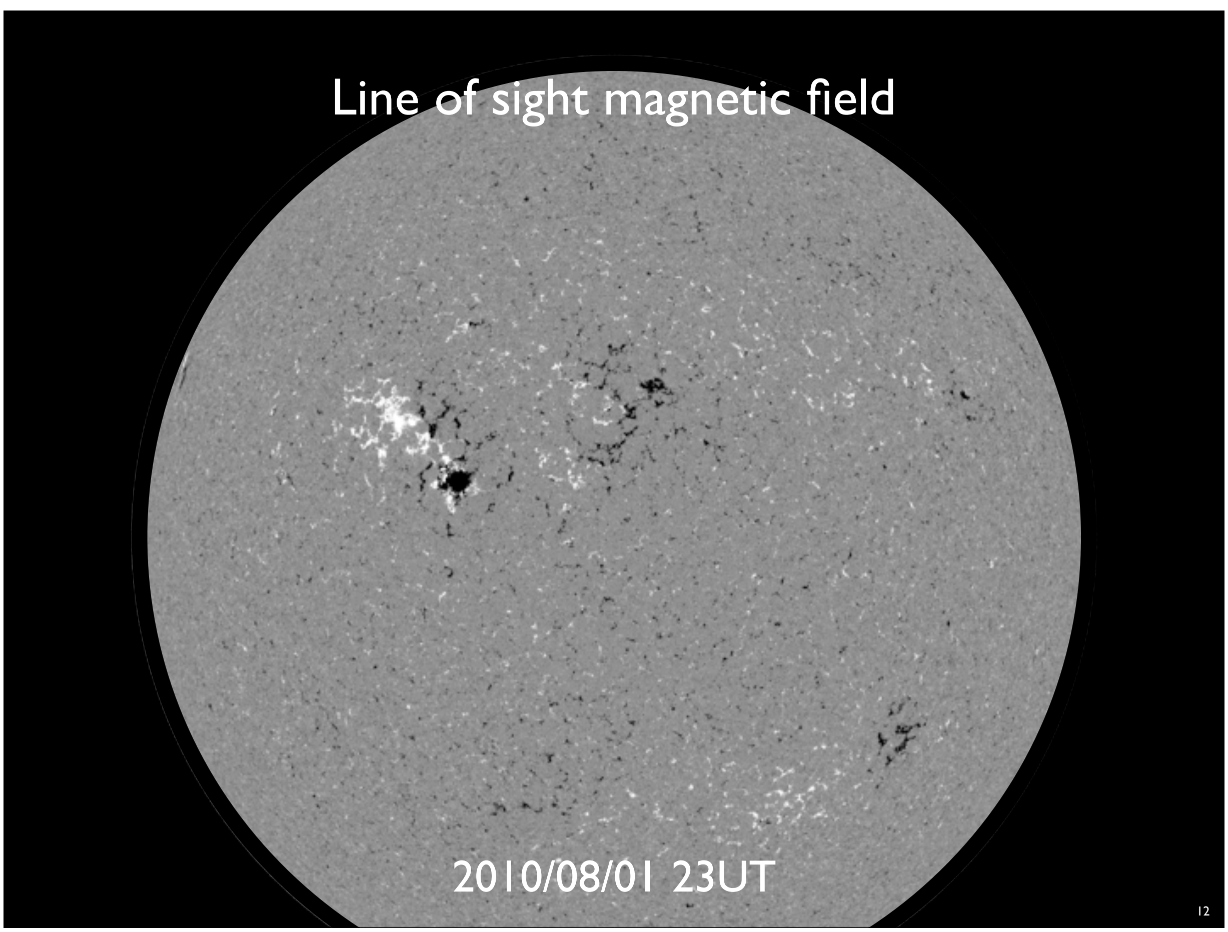

EUV 193Å; corona
2010/08/01 23UT
7


EUV 211Å; corona
Coronal hole: field reaches far into the heliosphere, stretched out by the solar wind; holes at low-to-mid latitude persist for months, over the poles for much of the cycle
N.B. X-ray/EUV bright "points": over small emerged bipoles and over chance encounters of opposite polarities
Active region: had at least one sunspot at some point in its evolution
Quiet Sun = not an active region, ...
Ephemeral region: never had spot or pore in its evolution
2010/08/01 23UT
8


EUV 335Å; corona
2010/08/01 23UT
9

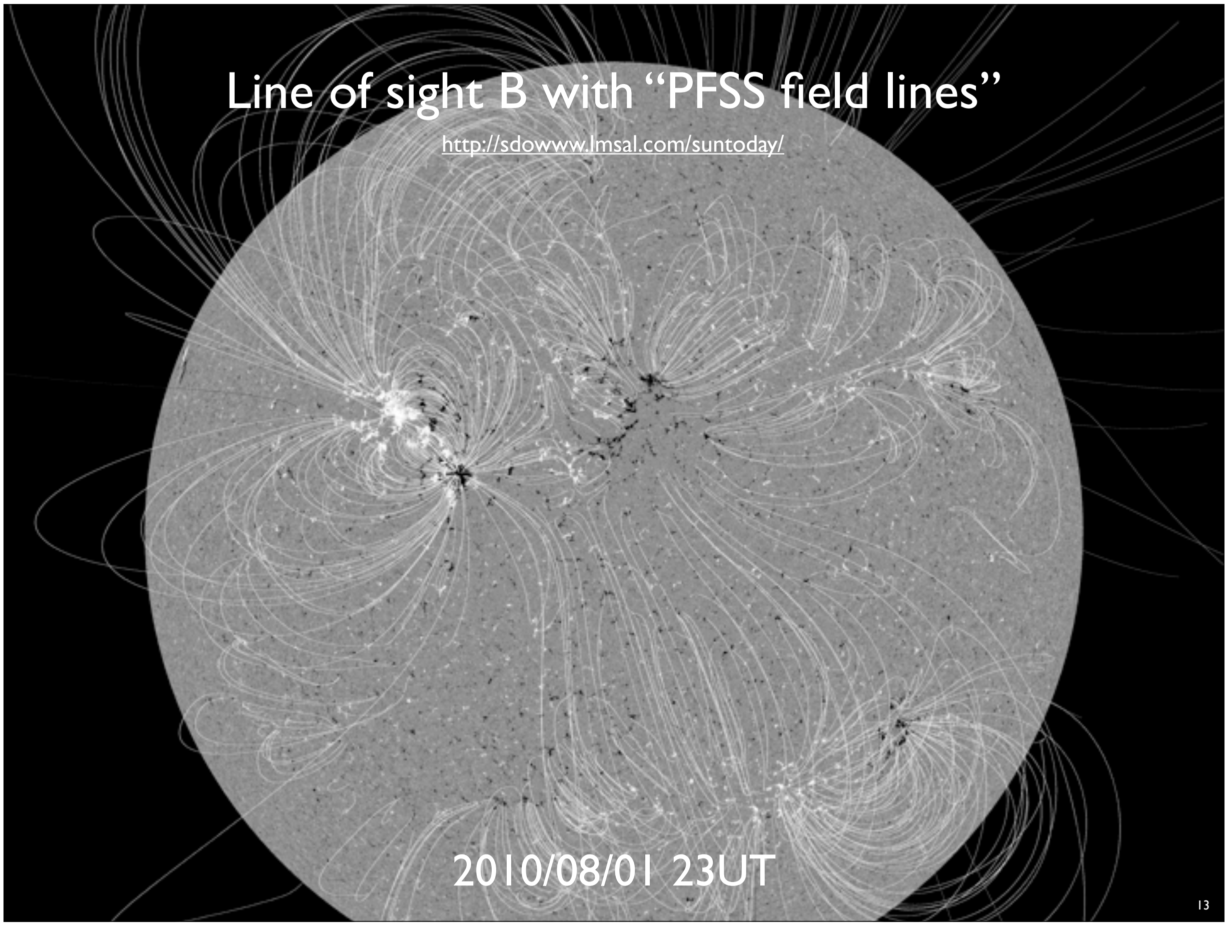

EUV 94Å; corona
2010/08/01 23UT
10


B + EUV 171Å
2010/08/01 23UT
11


Line of sight magnetic field
2010/08/01 23UT
12

Line of sight B with "PFSS field lines"

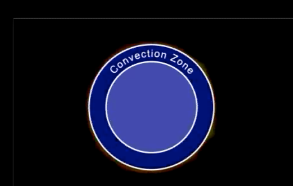
http://sdowww.lmsal.com/suntoday/



2010/08/01 23UT

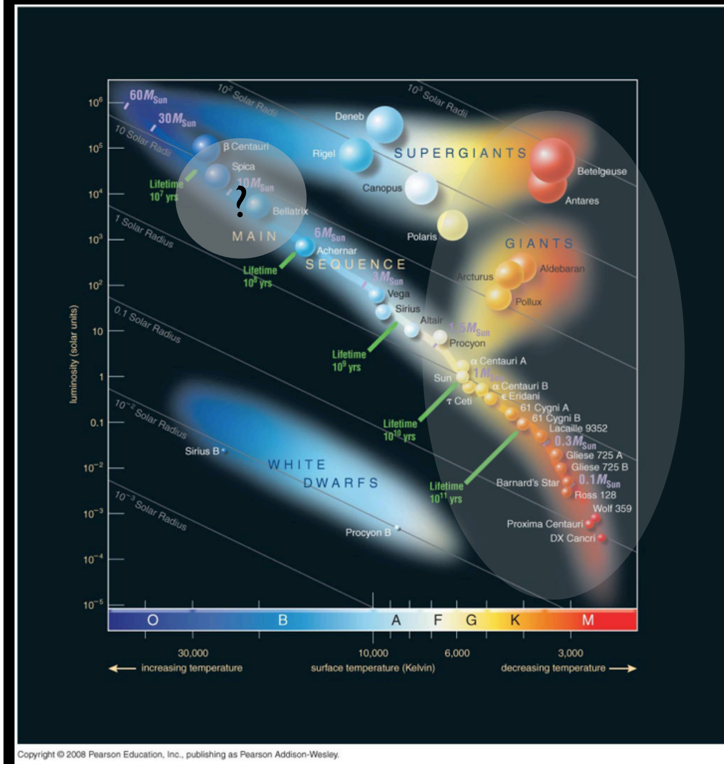
Basic structure of the nearest star

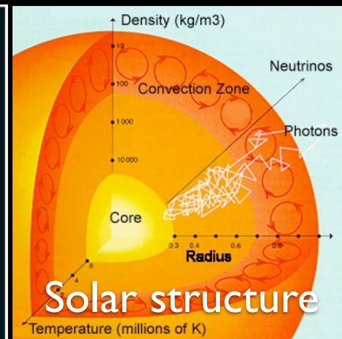
- Radiative core - 0 to 0.71 of the radius (R_s)
  - Inside 0.2 R_s hydrogen burns to helium
    Energy is transported by radiation
    Contains 98 % of the solar mass



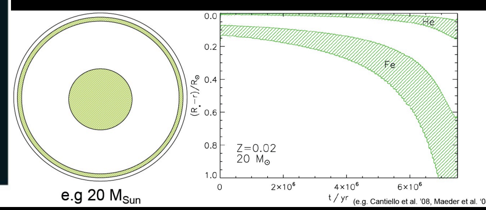
- Convective zone - 0.71R_s to the solar surface
  - Energy is transported largely by mass motion
  - Contains 2% of the solar mass and 64% of the solar volume
  - Virtually all energy leaves the Sun from the surface - *Photosphere*

“Sun-like” stars - from the perspective of activity



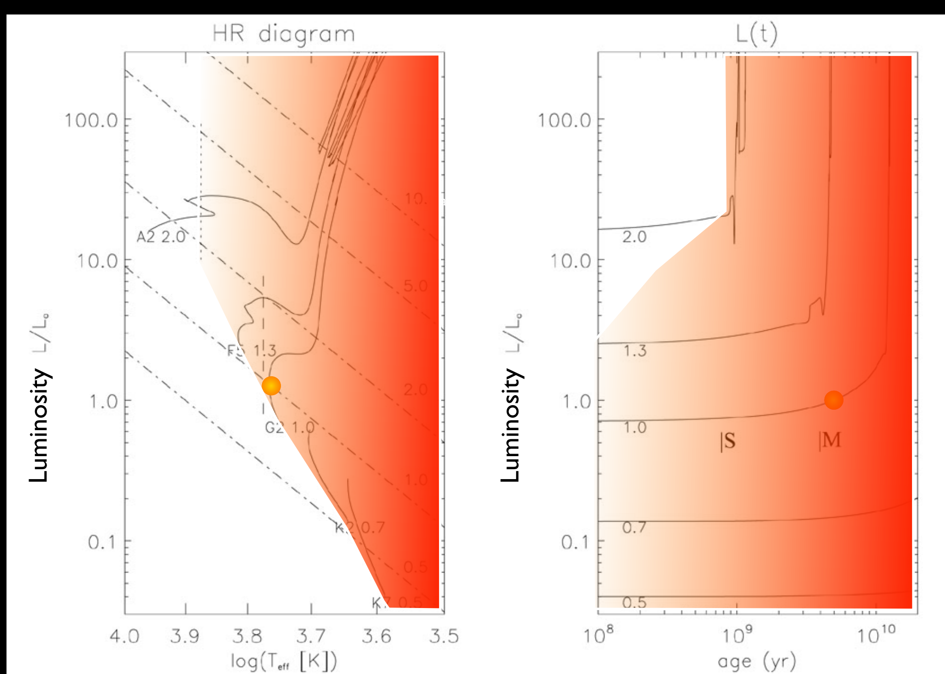


All rotating stars with convective envelopes exhibit atmospheric magnetic activity.



Stellar evolution and luminosity/radiance

Hertzsprung-Russell diagram luminosity-age diagram



Domains in the solar atmosphere

Domain:	"Definition"	"Conceptually"
Photosphere	Optically thick to thin	Scattering-free l.o.s. in continuum
Chromosphere	Optically thick in strong lines only	10-20 kKelvin
Transition Region	?	Transition in ionization and plasma β
Corona	Optically thin X-ray to IR	> 1MK
Heliosphere	?	Beyond "Alfvén" point

N.B. From photosphere to geospace: 5 g/cm^2
Earth atmosphere: 1,000 g/cm^2

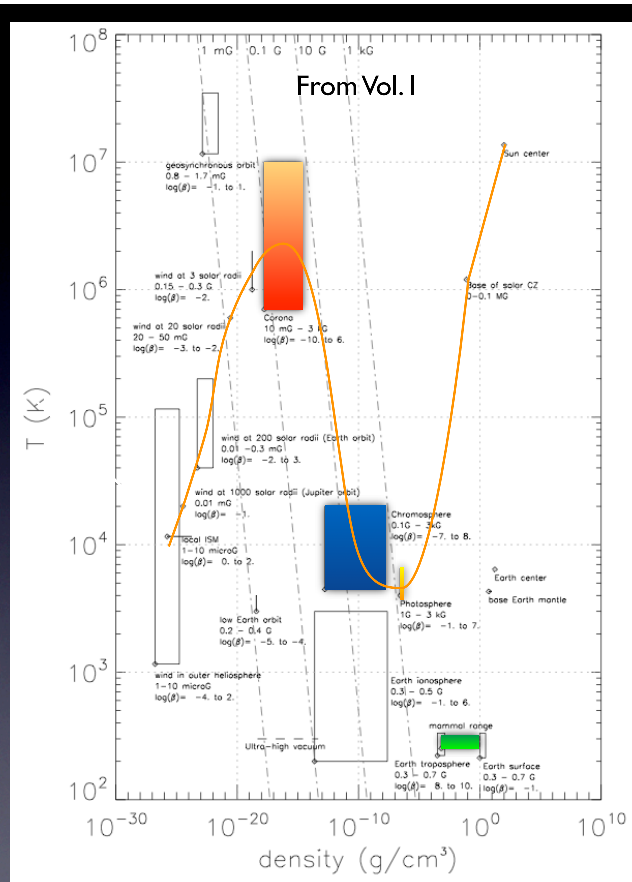
Domains in the solar atmosphere

Domain:	Energy balance	Plasma/field
Photosphere[b]	Hot upflows, radiative cooling	High plasma β except in strong field; frozen in field; single-fluid MHD
Chromosphere	Non-radiative EM heating, some acoustic heating; radiative cooling	Plasma β wide range around but mostly above unity; multi-fluid MHD
Transition Region	Conductive heating from above; radiative cooling	Low plasma β; MHD approximation
Corona[a]	Non-radiative EM heating, cooled by conduction and radiation	Low plasma β; MHD approximation
Heliosphere	Outflow of plasma, cooling by expansion, heated by waves	Plasma β ranges around unity

a: The closed-field domain is often in near-hydrostatic balance.
N.B. The open-field corona is cooled mostly by conduction and expansion

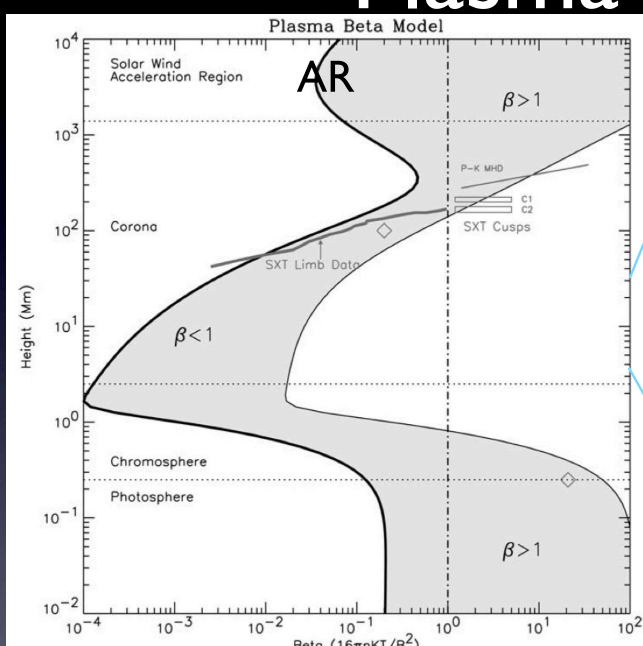
b: Mostly in near-hydrostatic stratification, except in strong downflows which can be supersonic.

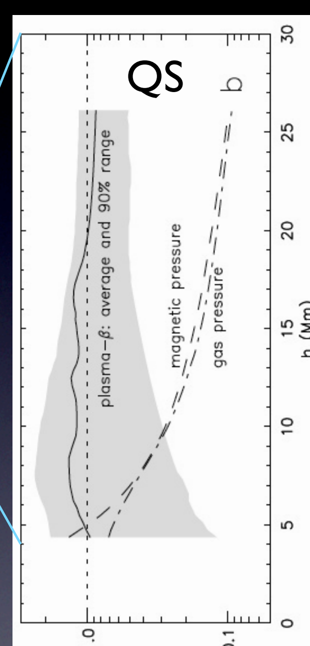
Comparison of properties



Our intuition (based on where we can live [green box] is of little use thinking about the solar atmosphere [yellow, blue, red boxes]

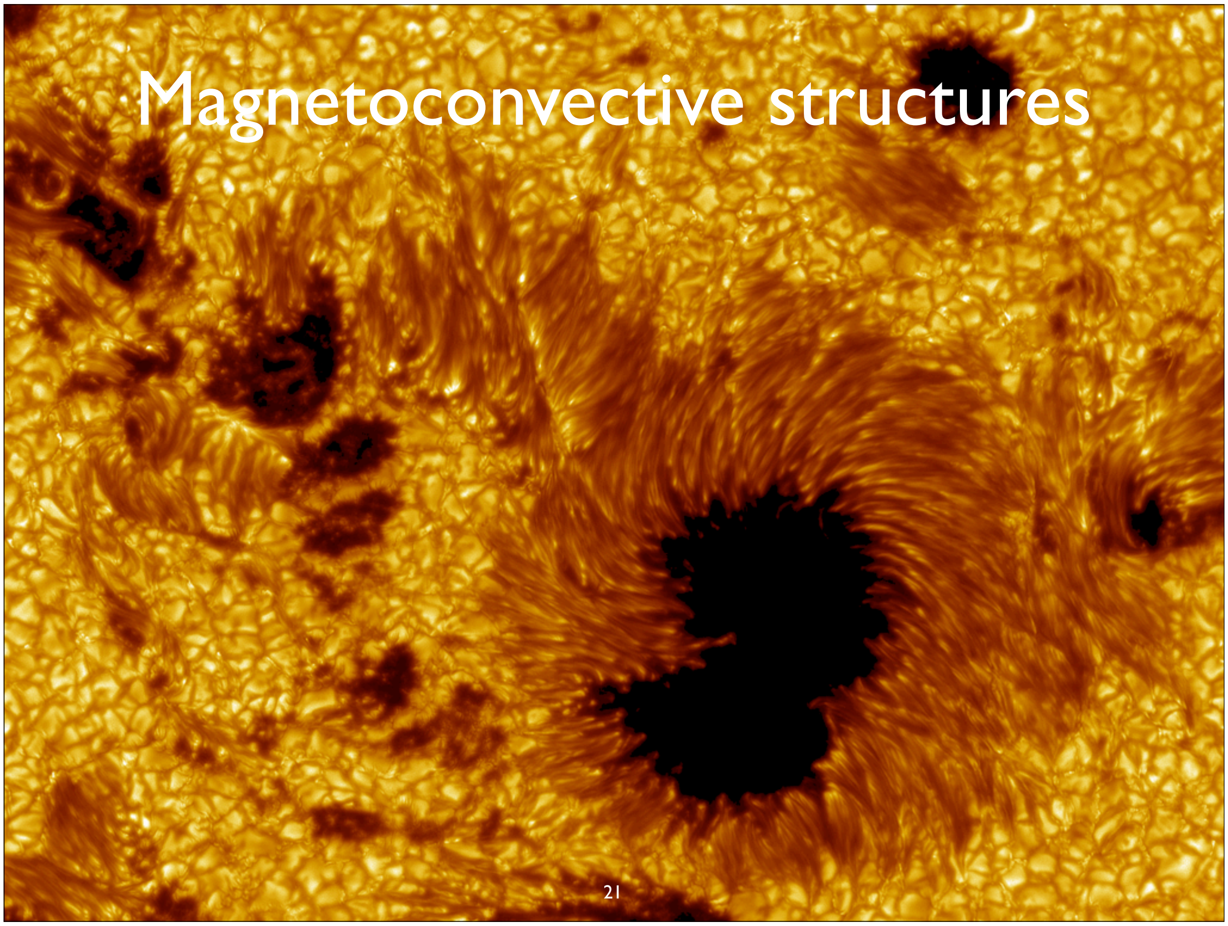
Plasma β





- Rough estimate for medium-sized active region (Gary, 2001SoPh..203...71G)
- Characteristic quiet-Sun region (Schrijver and Van Ballegooijen, 2005ApJ...630..552S)

Magnetoconvective structures

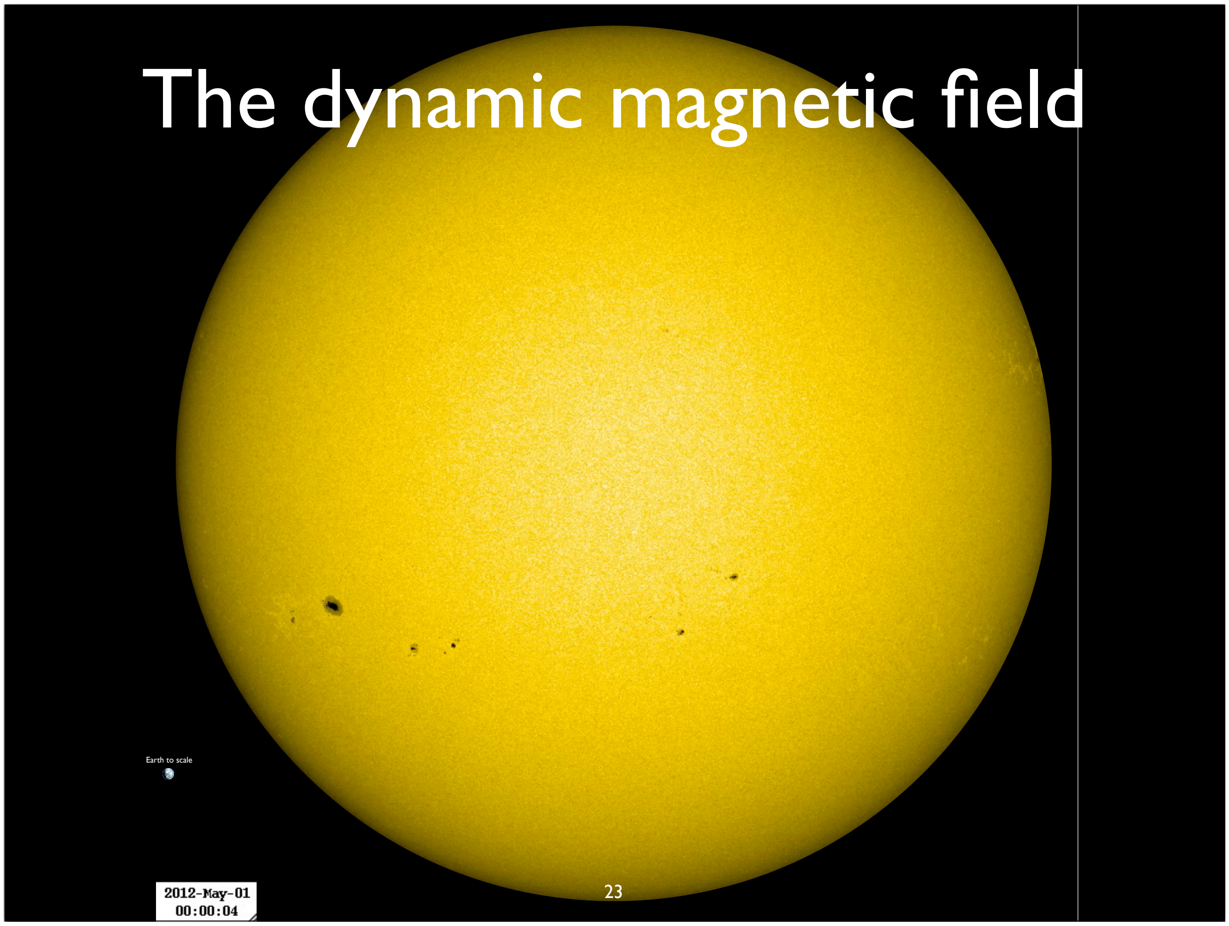


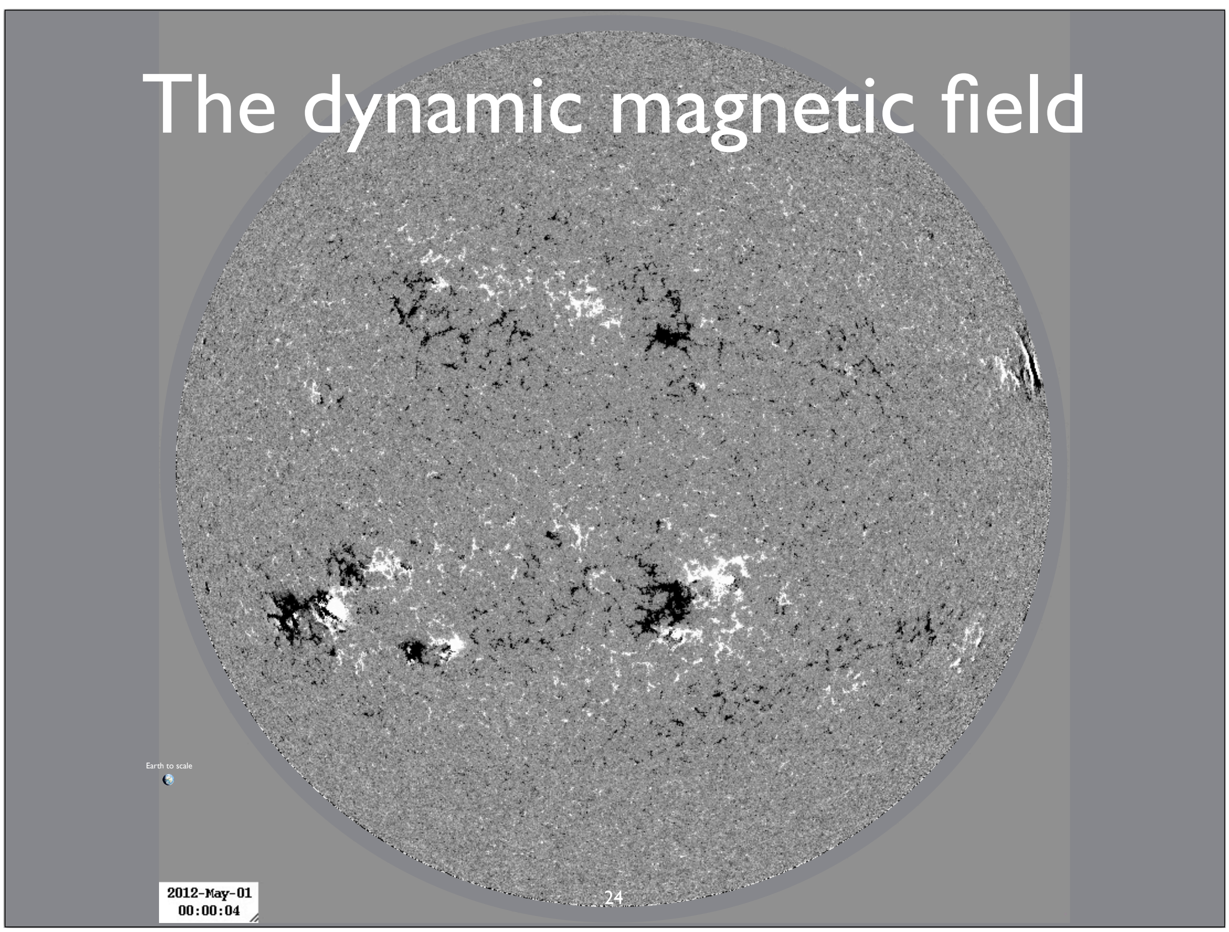
Magnetic 'elements'

Table 4.1. *The hierarchy of magnetic concentrations.*[a]

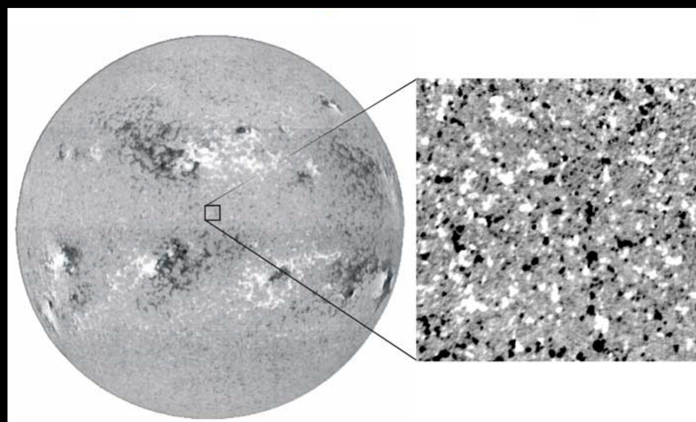
Property	Sunspot with Penumbra: Large	Sunspot with Penumbra: Small	Pore	Magnetic Knot (micropore)	Faculae, Network Clusters	Filigree Grain
Φ (10^{18}Mx=10^{10} Wb)	3×10^4	500	250 - 25	≈ 10	$\lesssim 20$	≈ 0.5
R (Mm)	28	4	-	-	-	-
R_u(Mm)	11.5	2.0	1.8 - 0.7	≈ 0.5	-	≈ 0.1
B (in G = 10^{-4}T)	2,900 $\pm$ 400	2,400 $\pm$ 200	2,200 $\pm$ 200	$\approx 1,500 - 2,000$	-	≈ 1500
Overall contrast in continuum	*dark*			-	*bright*	
Cohesion	*single, compact structure*				⇓ *cluster of*	↑
Behavior in time	*remain sharp while shrinking during decay*			?	-	*modulated by granulation*
Occurrence	*exclusively in active regions*				*both inside and outside active regions*	

[a] Φ is the magnetic flux, R is the radius of a sunspot, R_u is the radius of a sunspot umbra or of a smaller magnetic concentration, and B is the magnetic field strength at its center.

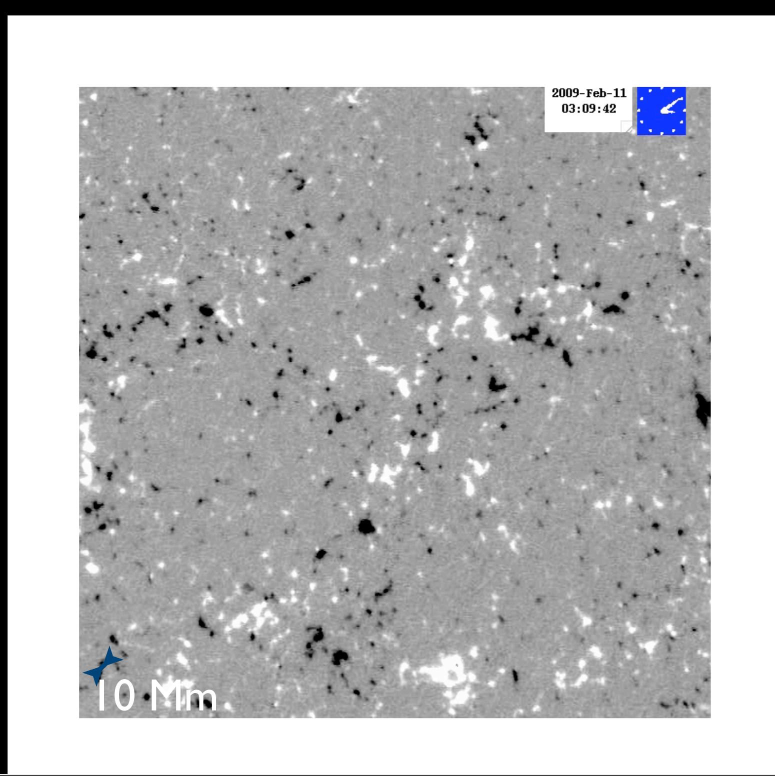

The dynamic magnetic field
Earth to scale
2012-May-01
00:00:04
23


The dynamic magnetic field
Earth to scale
2012-May-01
00:00:04
24

The dynamic magnetic carpet

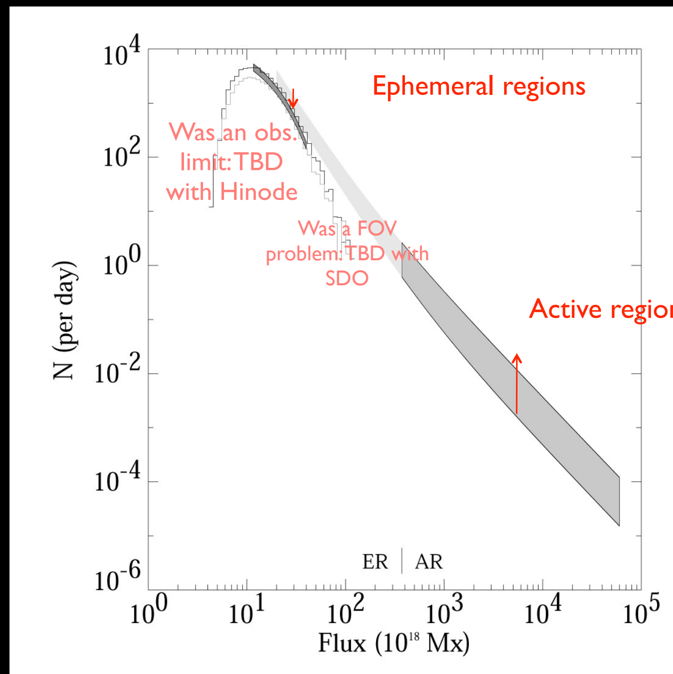


The dynamic magnetic carpet



Spectrum of emerging bipolar regions

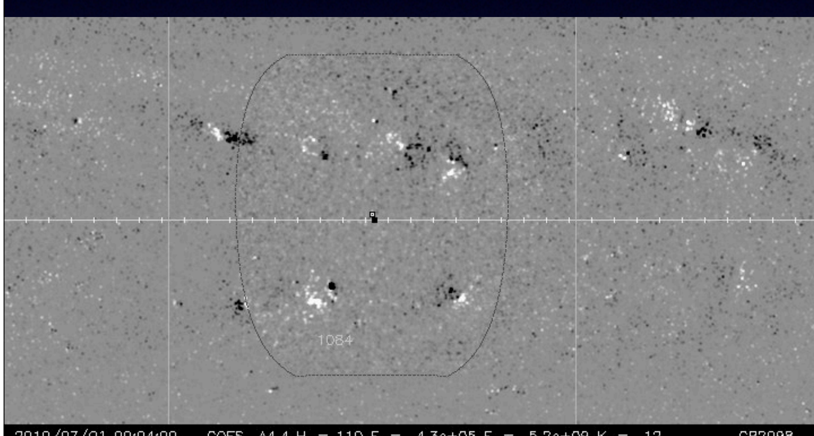
- Bipolar regions form a continuum from large active regions to small ephemeral regions, and perhaps even smaller “intranetwork field”:
- Regions with less flux
  - Increased spread in latitude and orientation;
  - Less cycle dependence, perhaps slight anticorrelation

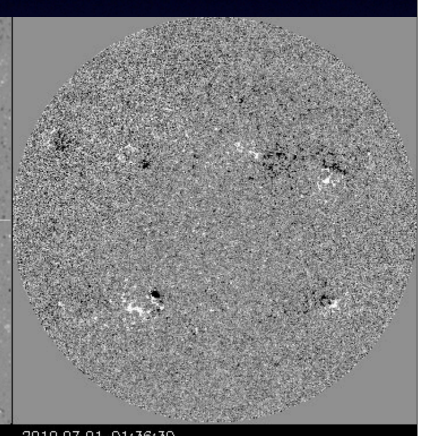


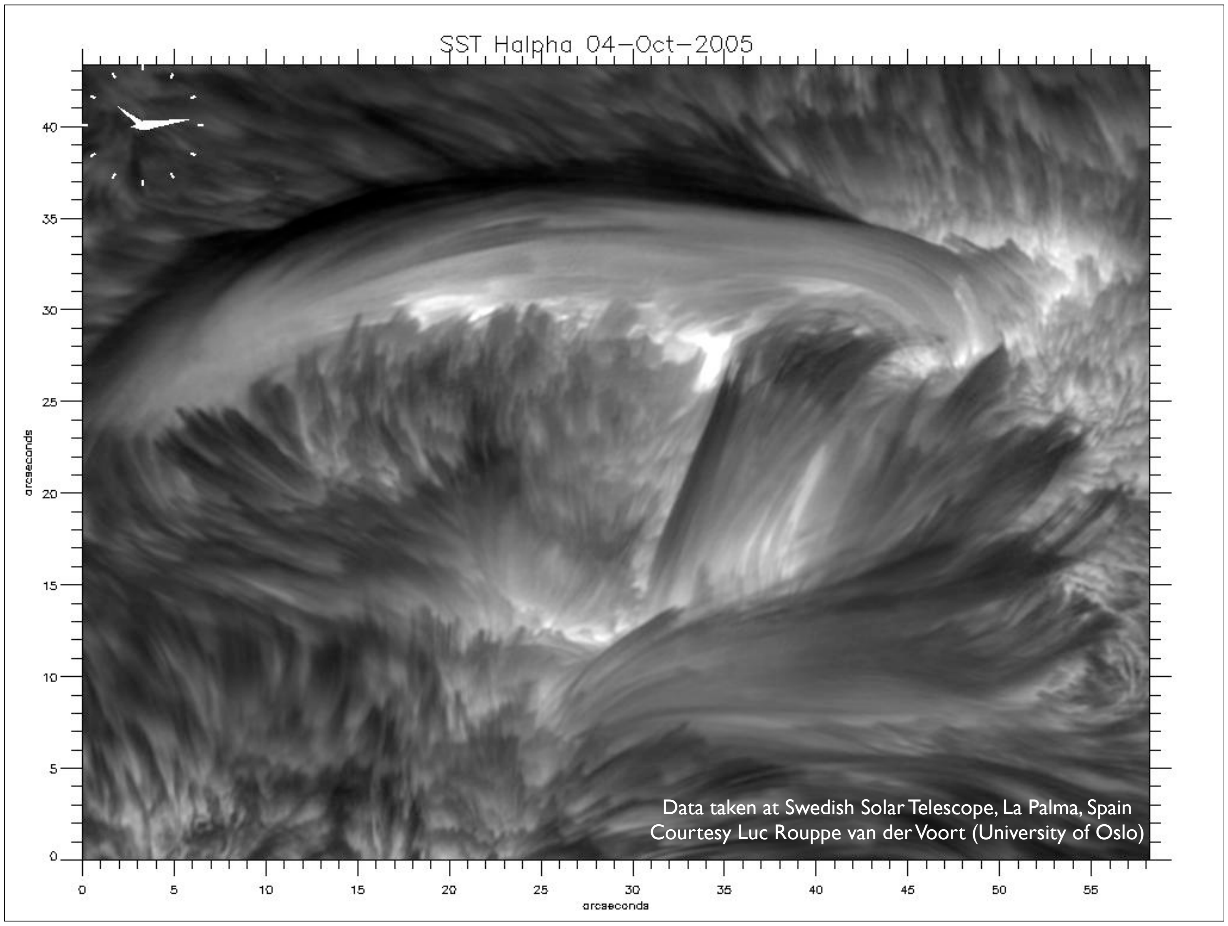
The dynamic magnetic field

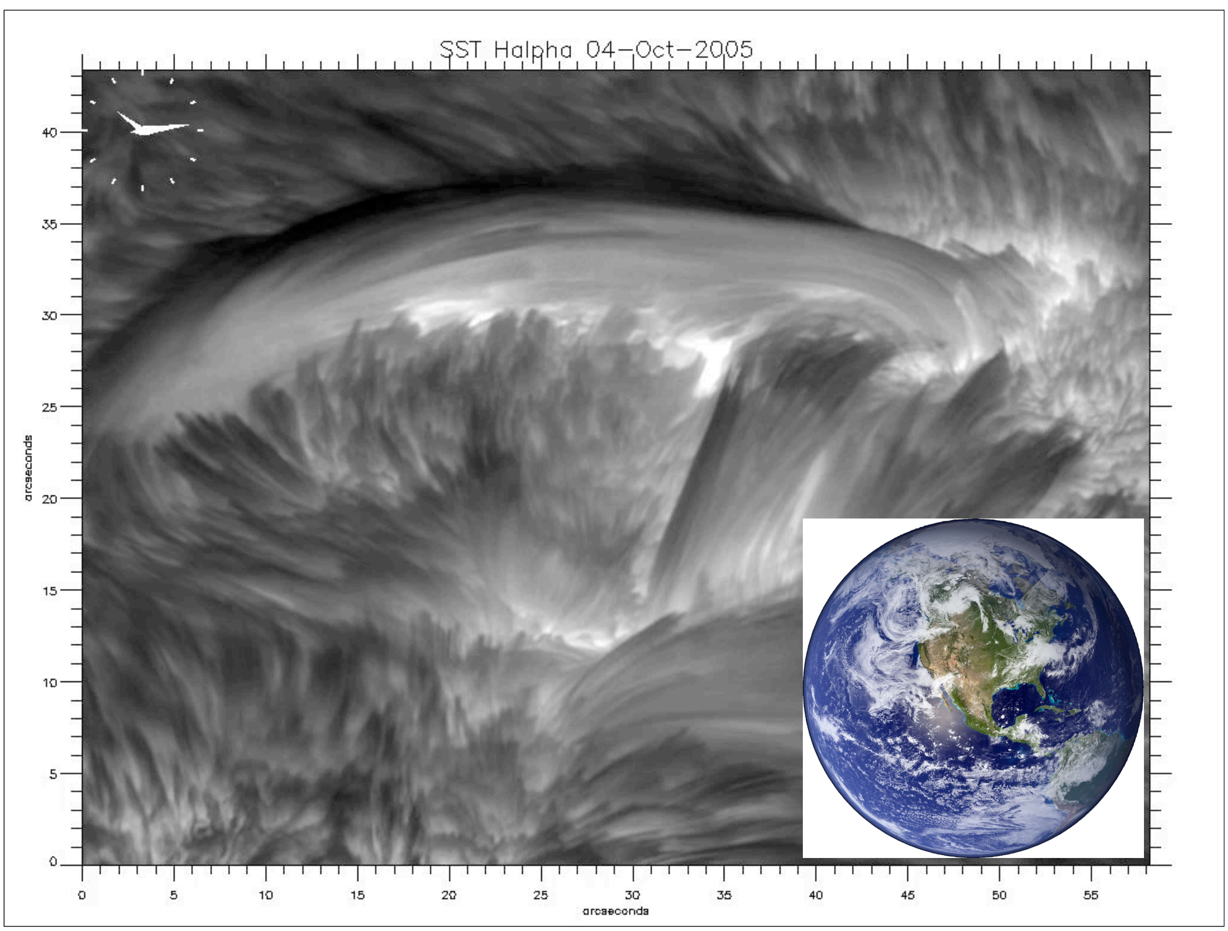
“Carrington map”

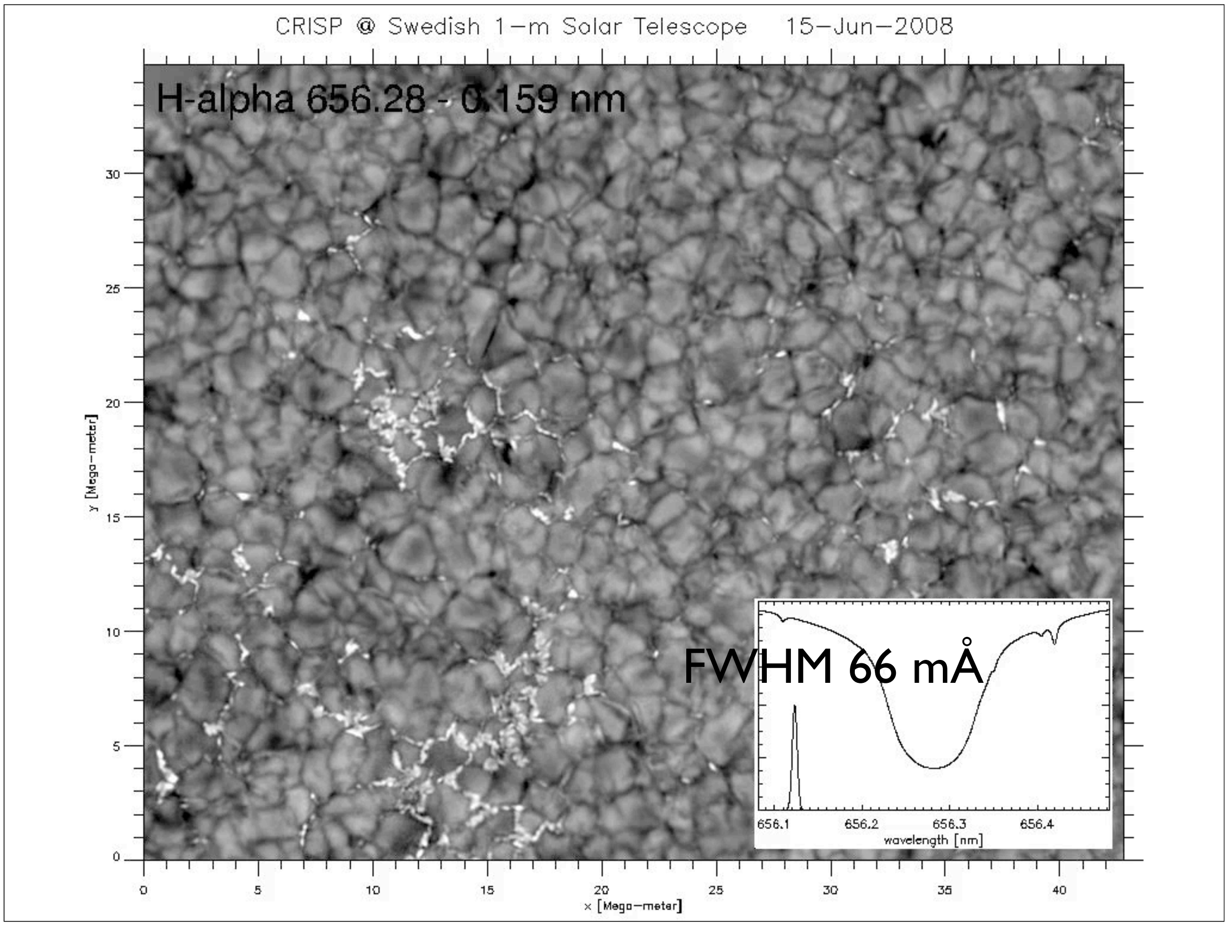
Obs. magnetogram

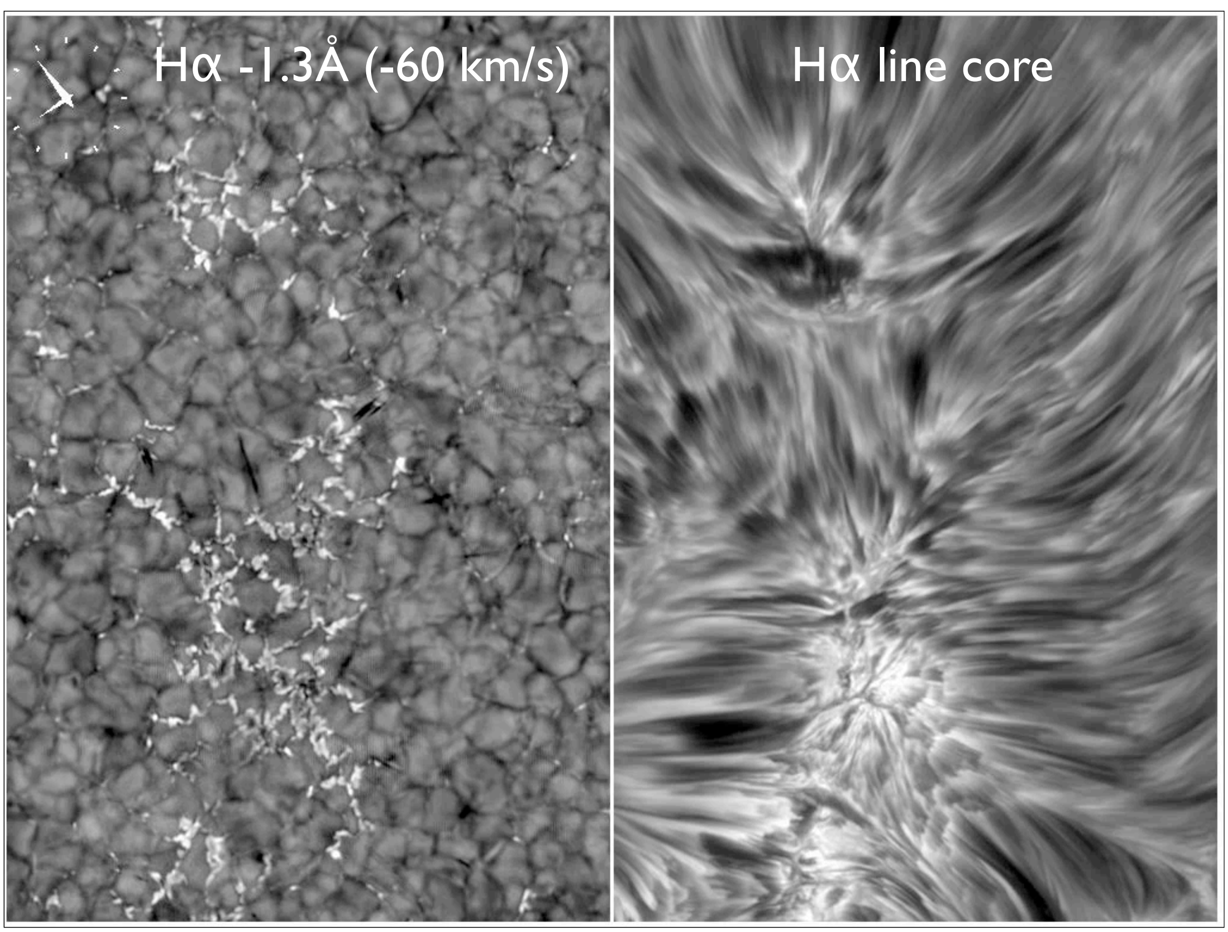





SST Halpha 04-Oct-2005
arcseconds
arcseconds
Data taken at Swedish Solar Telescope, La Palma, Spain
Courtesy Luc Rouppe van der Voort (University of Oslo)

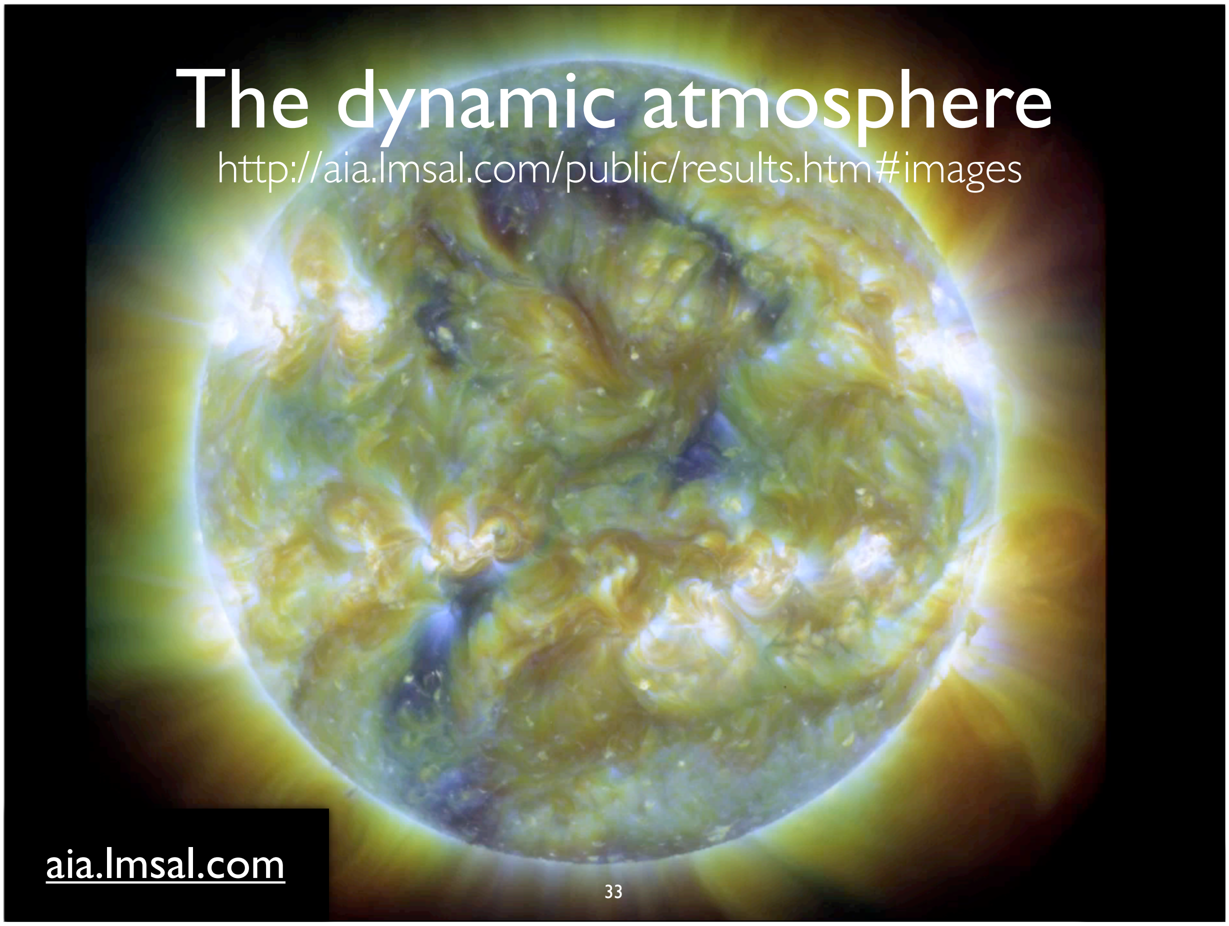

SST Halpha 04-Oct-2005
arcseconds
arcseconds


CRISP @ Swedish 1-m Solar Telescope 15-Jun-2008
H-alpha 656.28 - 0.159 nm
FWHM 66 mÅ
y [Mega-meter]
x [Mega-meter]
wavelength [nm]


Hα -1.3Å (-60 km/s)
Hα line core

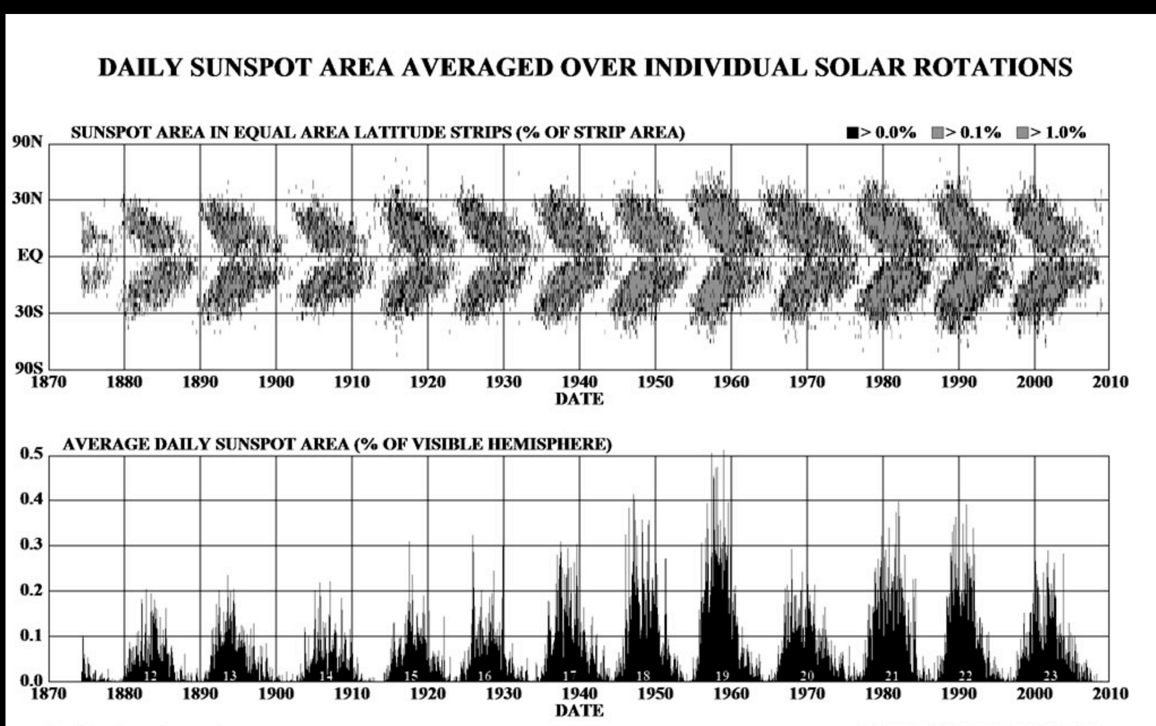
The dynamic atmosphere

http://aia.lmsal.com/public/results.htm#images



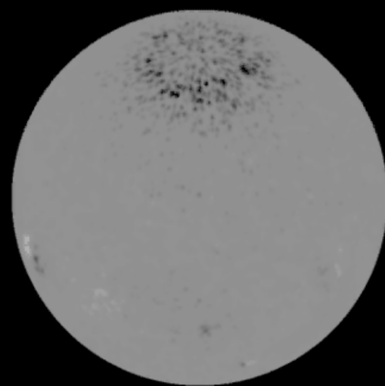
aia.lmsal.com

Sunspot cycle



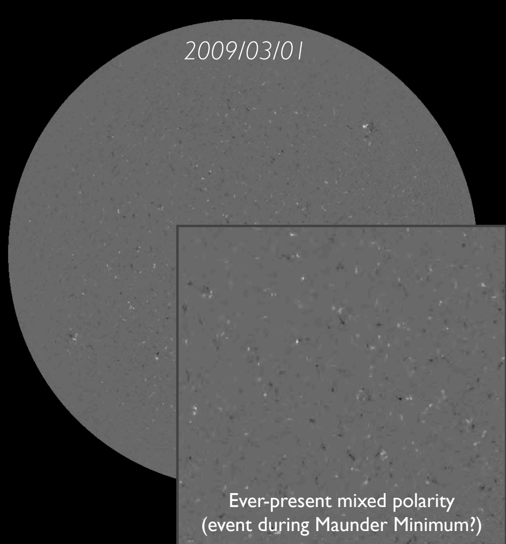
Simulations of activity

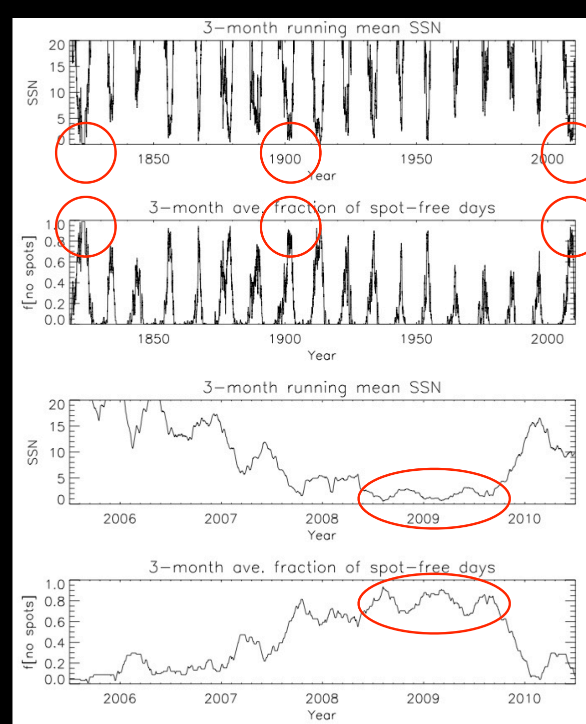
Simulated "Sun" from 40°N, "co-rotating":



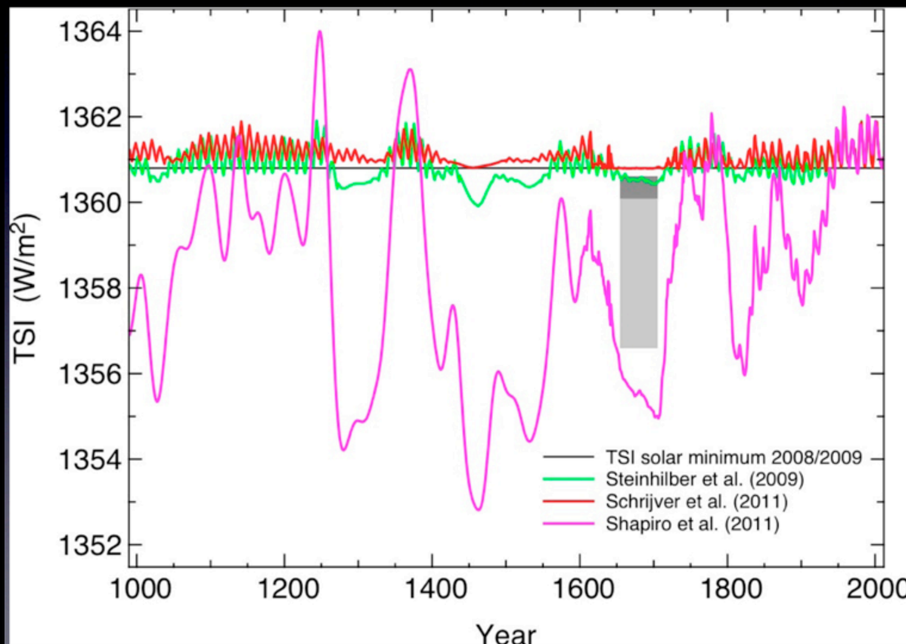
Small-scale field essentially constant

The 2008-2009 sunspot minimum has historical precedents, but is unrivaled in the era of modern instrumentation.





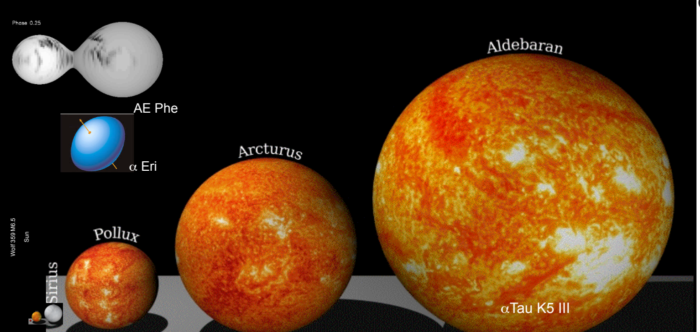
All magnetic elements contribute to total solar irradiance (TSI)

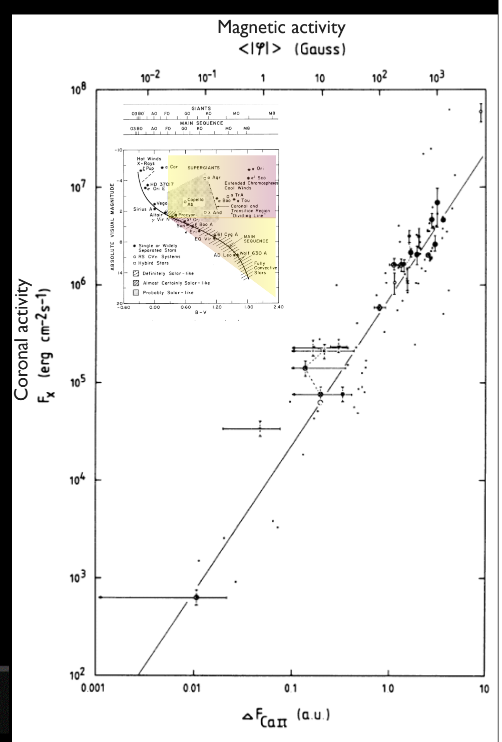


Feulner: http://adsabs.harvard.edu/abs/2011GeoRL..3816706F

Magnetic energy conversion in stellar atmospheres

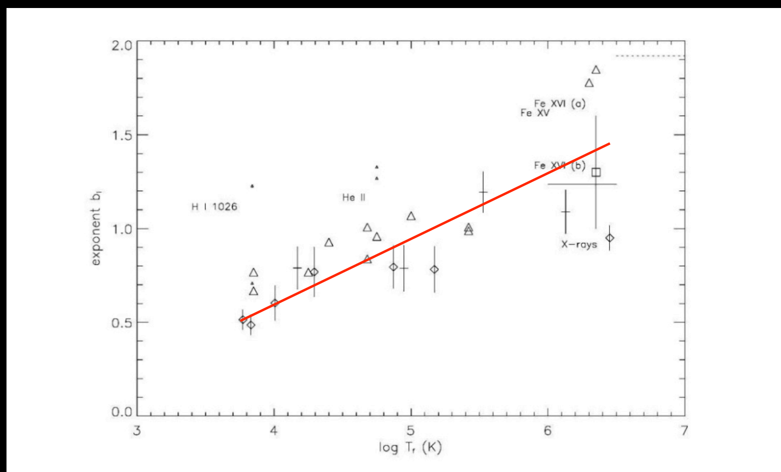
- Magnetized chromosphere and corona form an integrated system *($E_{chr./TR} \approx 30 E_{cor./hel.}$; $M_{chr./TR} \approx 50 M_{cor./hel.}$)*
  - power-laws; over 100,000x in flux density at Röntgen wavelengths.
- Basal "background" heating:
  - adequate wave power, acoustic tunneling, magnetic carpet, magneto-acoustic couplings, …?



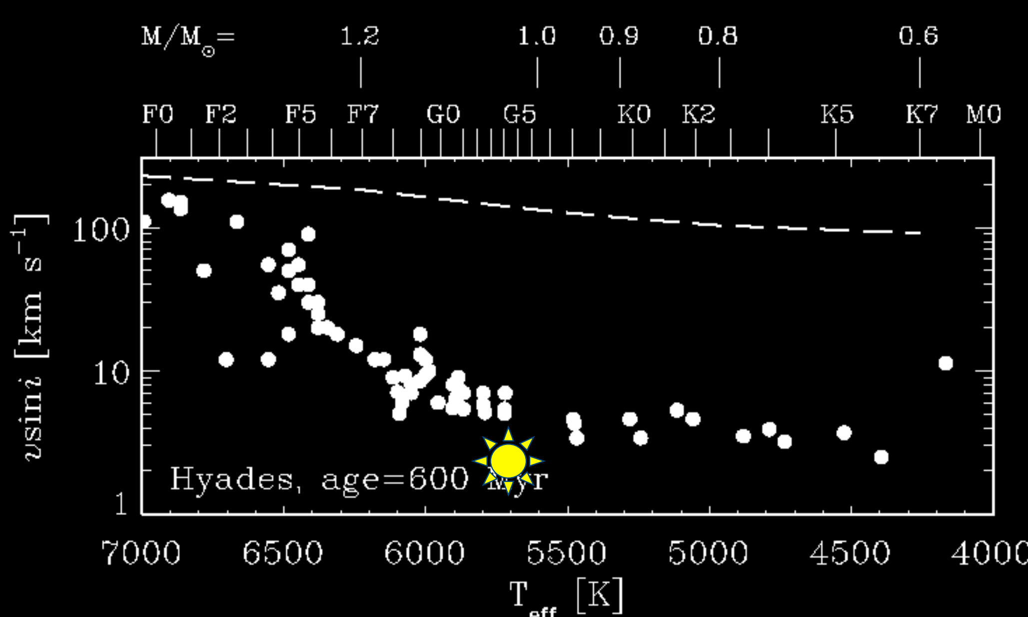


"Flux-flux relationships"

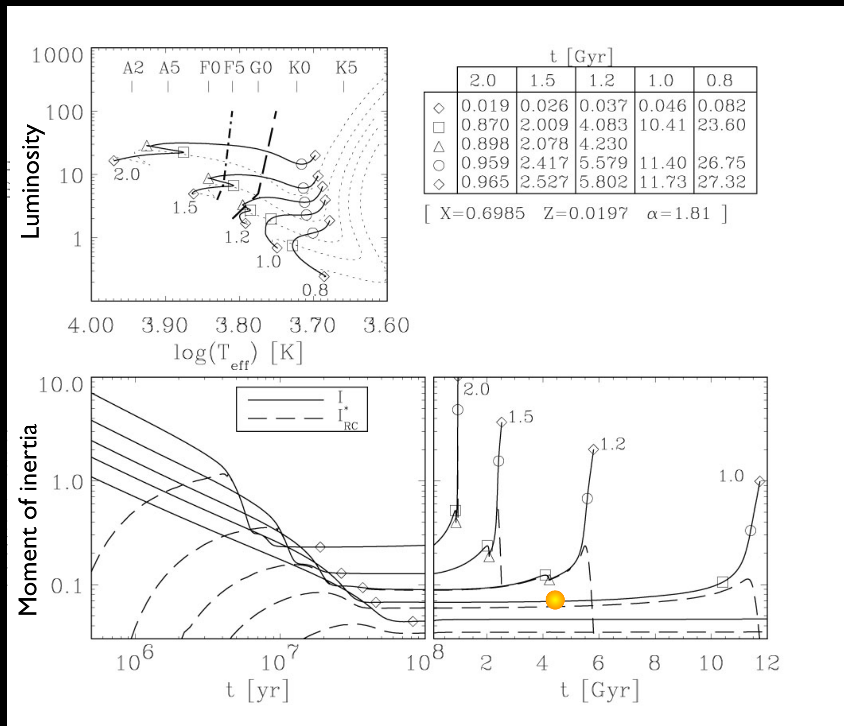
- At moderate spatial and temporal resolution, radiative losses from any thermal domain in a cool-star atmosphere scale with the (unsigned) magnetic flux density underneath:
  - $F_i = a <|fB|>^b$
- Coronal flux density depends nearly linearly on magnetic field, chromospheric flux density close to a square root.



Rotation and age: evolution and mass loss



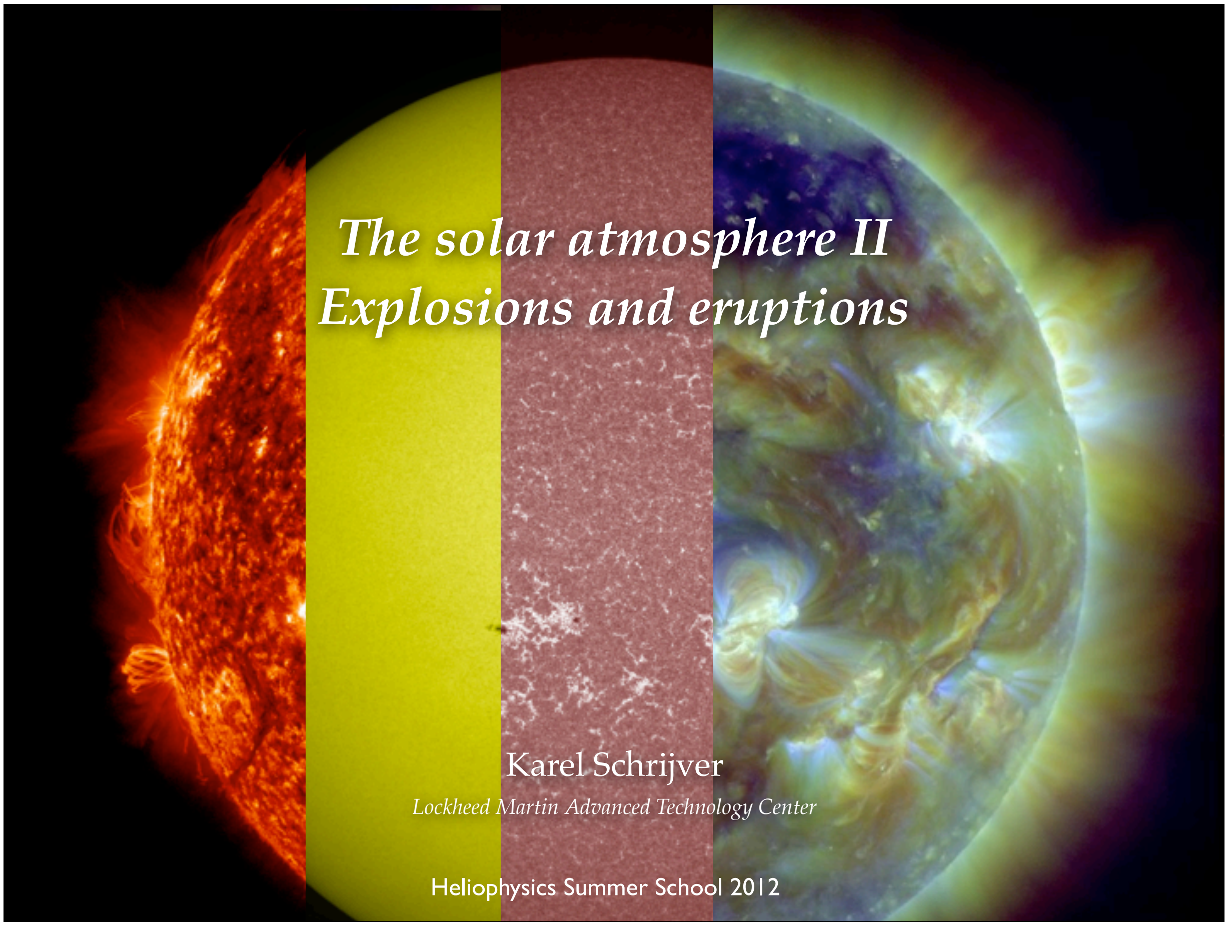
Evolution and angular momentum



The Sun in time

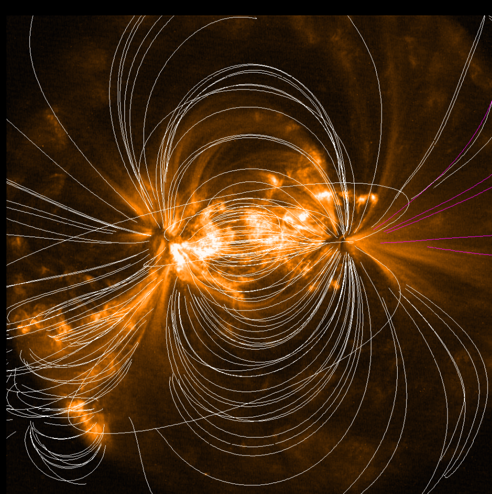
Evolving Sun & Earth

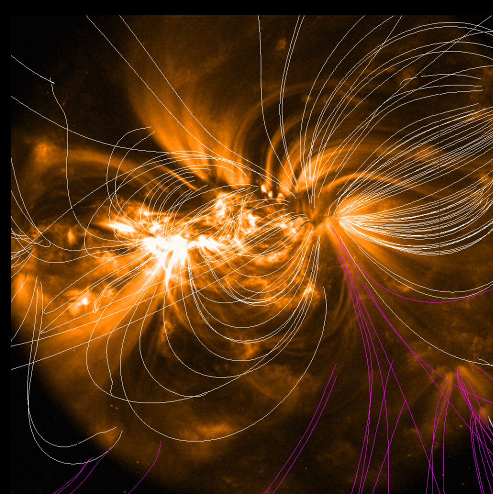
Time (y)	*Sun*	*Earth*
	T Tauri accretion	
10^6	Disk accretion	
	Disk clearing, planet formation	
10^7	Volume III *Chapter 3*	
	Sun begins main-sequence phase	Moon formation
10^8	Appr. end of dynamo saturation ~1000x present-day coronal activity	
	~100x present-day coronal activity	End of late heavy bombardment Oldest rocks surviving on present-day Earth form Oldest cyanobacterial microfossils
10^9	~10x present-day coronal activity	Initial atmospheric oxygen Transvaal chert microfossils
		Multicellular life develops Photosynthetic habitable zone beyond Earth orbit
10^{10}	Red giant Sun	Sun expands to Earth orbit
	Volume III *Chapter 2*	Volume III *Chapter 4*



Magnetic "free" energy in coronal field

- Significantly non-potential : ~10-30% of the regions on the surface.





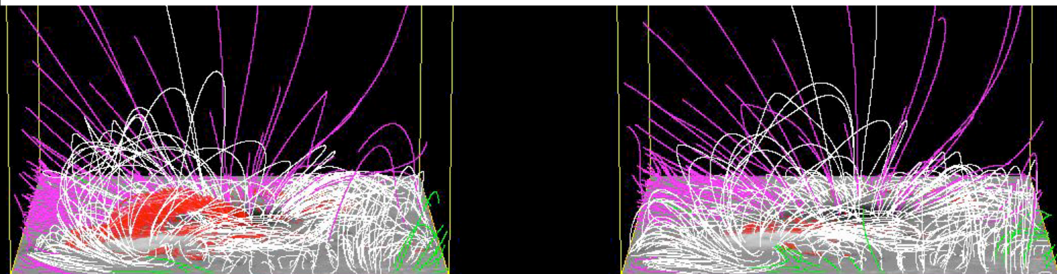
- ARs with *significantly** non-potential coronae are *~3x* more likely to produces CMX flares that on average are *~3x* more energetic.

** based on a subjective comparison of images and field extrapolations.*

Mapping "free" energy

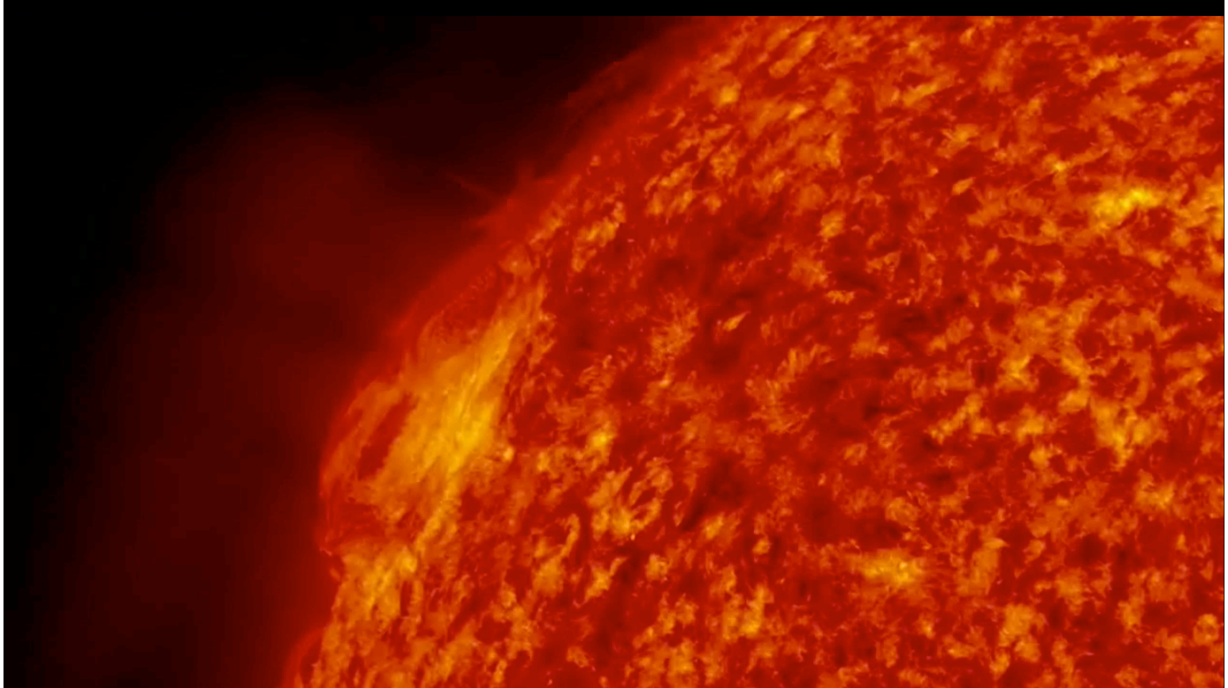
Table 6.1. *Characteristic coronal energy densities.*

Energy Type	Formula	Value (J/m^3)	Parameter Values
Magnetic	$B^2/2\mu$	40	$B = 100$ gauss
Thermal	nkT	0.01	$n = 10^{15}$ m^{-3}, $T = 10^6$ K
Bulk kinetic	$m_p n v^2/2$	10^{-6}	$n = 10^{15}$ m^{-3}, $v = 1$ km/s
Gravitational	$m_p n g h$	0.04	$n = 10^{15}$ m^{-3}, $h = 10^8$ m

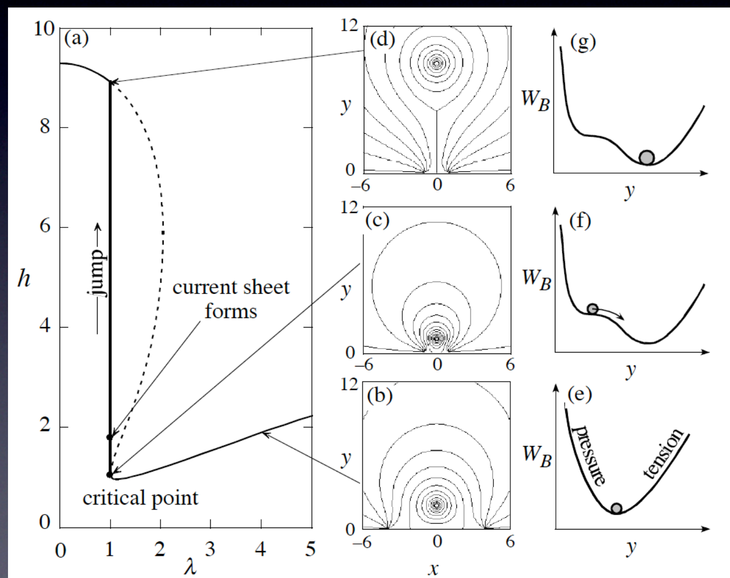


Nonlinear force-free field model: Schrijver et al., ApJ 675, 1637 (2008)

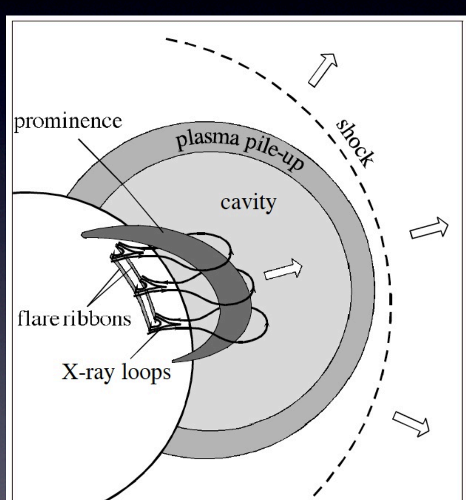
Explosions and eruptions

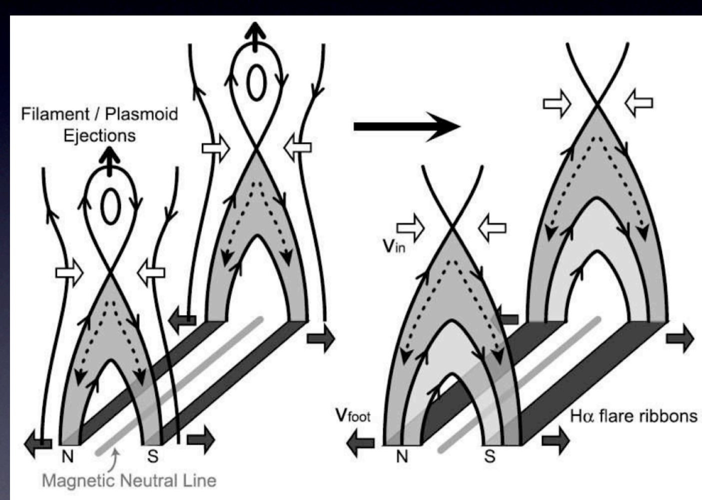


Magnetic instability



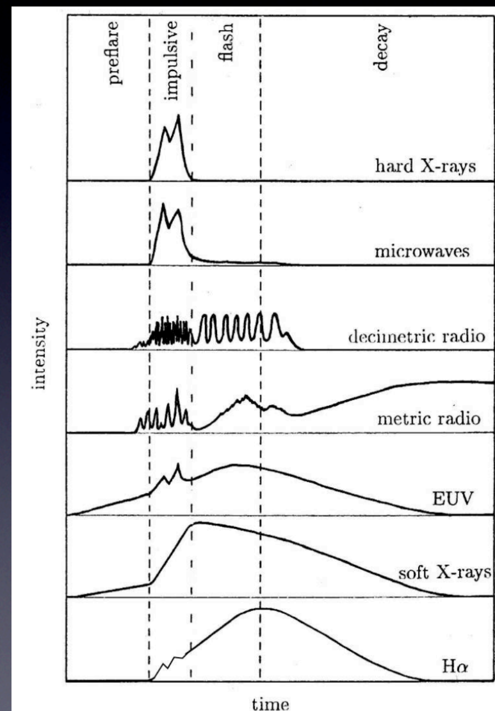
Dynamics of eruption





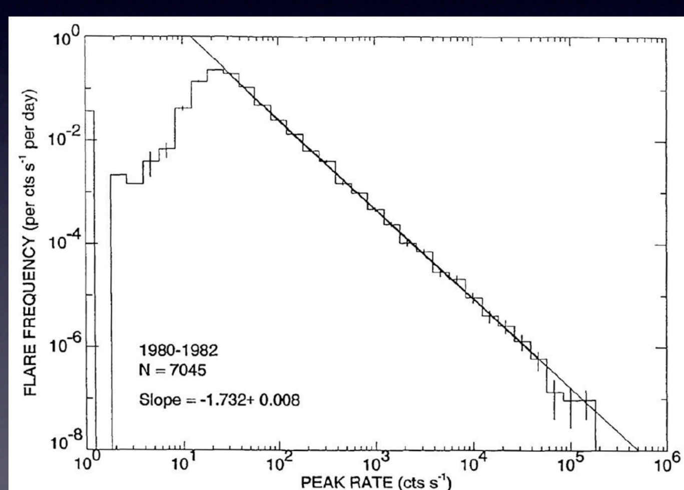
Appearance of flares

- "Neupert effect": soft X-rays behave as "capacitor" for hard X-rays
- Goes X-rays: ~½−1% of flare radiative energy
- (X)(E)UV: ~30% of flare radiative energy
- Visible light: bulk of radiative energy, but against bright photosphere
- Rough equipartition between "radiant" and bulk kinetic energy, with substantial spread.

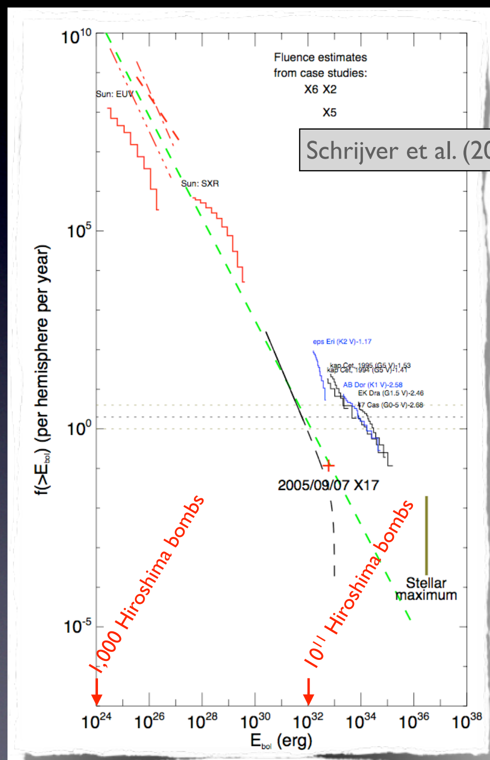


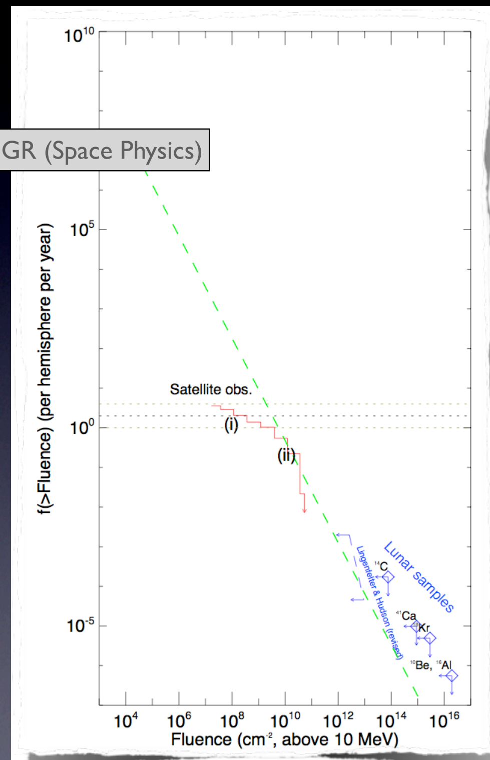
Power law for flare class

- Cause of power-law behavior: "self-similarity", "self-organized criticality", intrinsic coronal or intrinsic to dynamo?



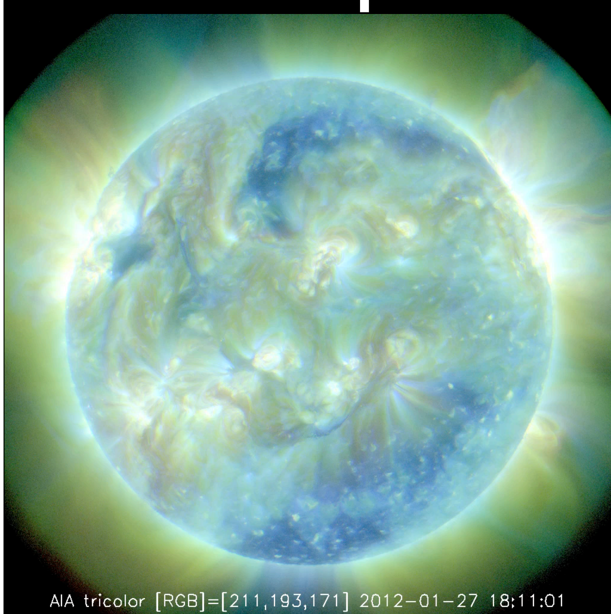
Energy & SEP fluences





Schrijver et al. (2012), JGR (Space Physics)

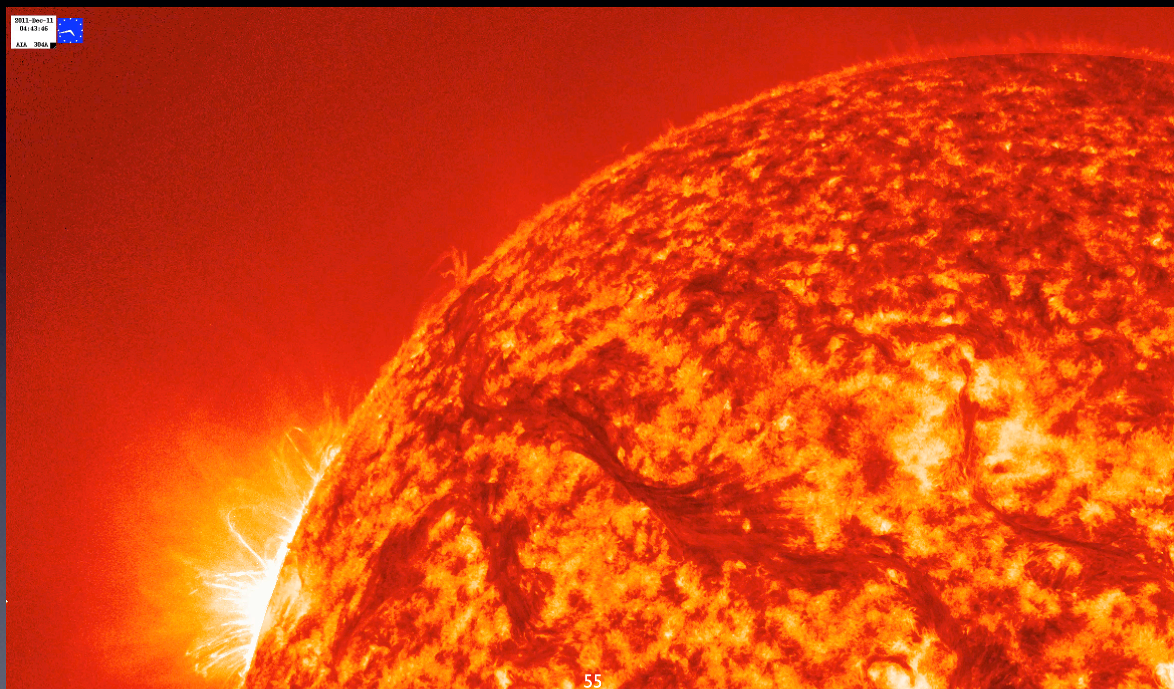
Coupled disturbances

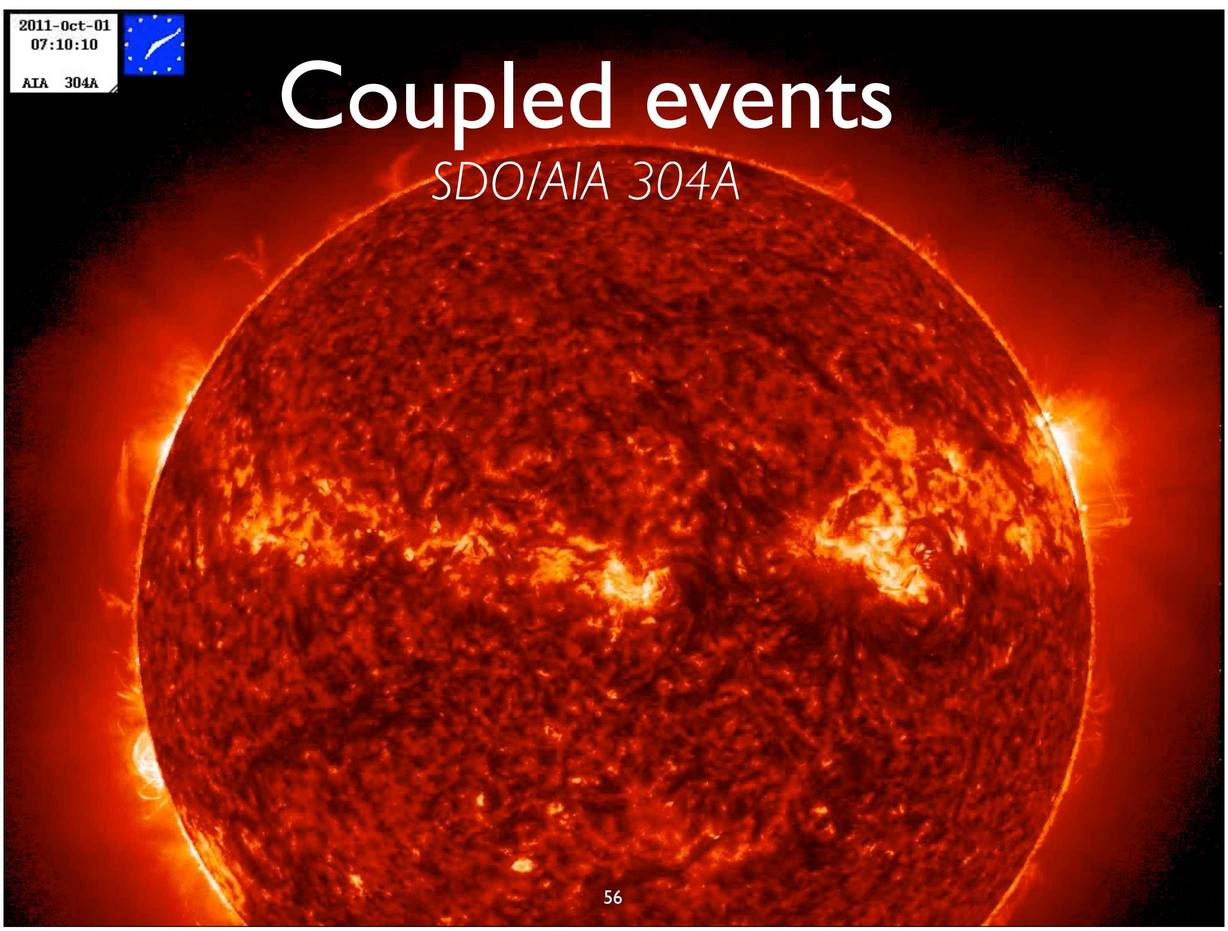


- Left: intensities Red/Green/Blue: ~2, 1.5, 1 million degrees
- Right: "running ratios", showing relative intensity changes

Coupled events

SDO/AIA 304A



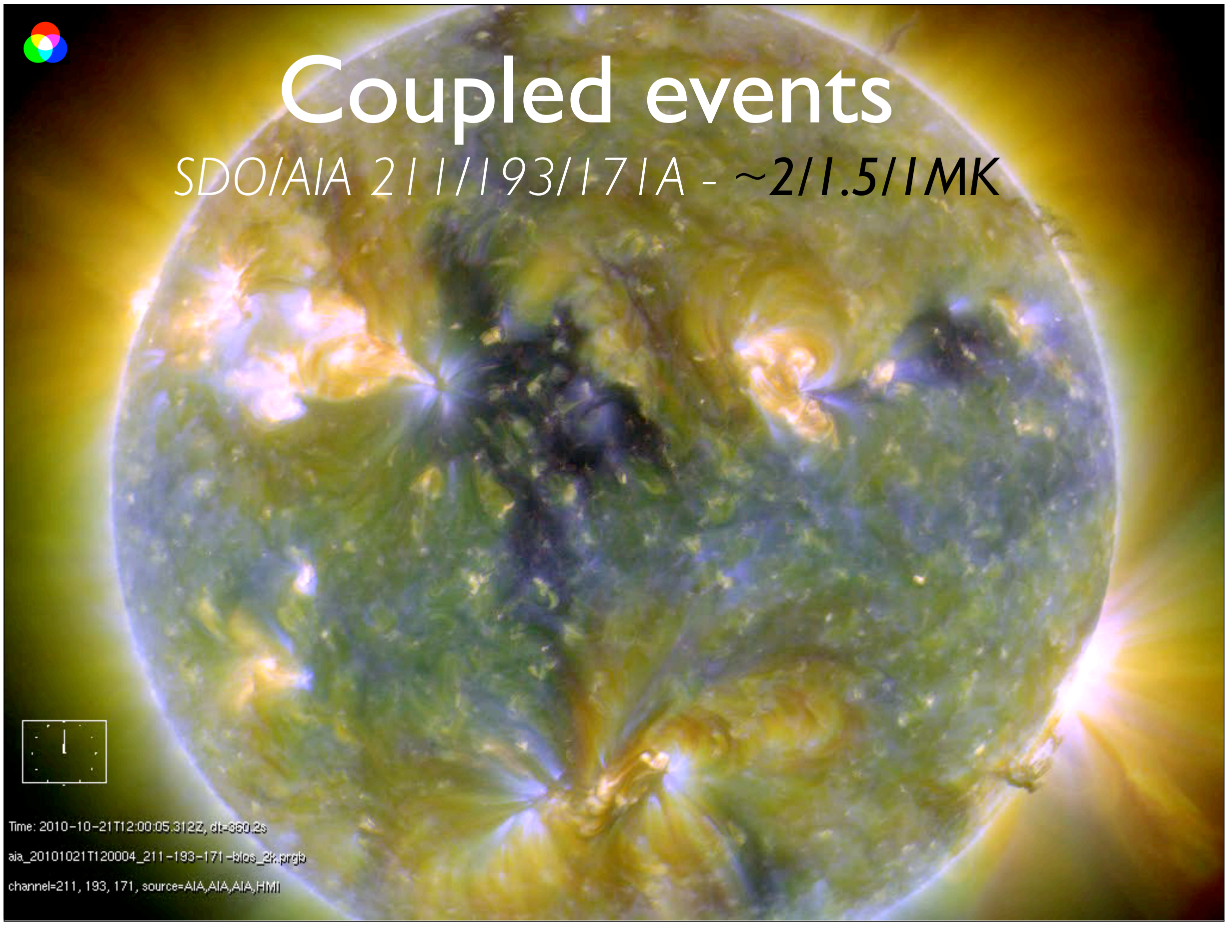


Coupled events

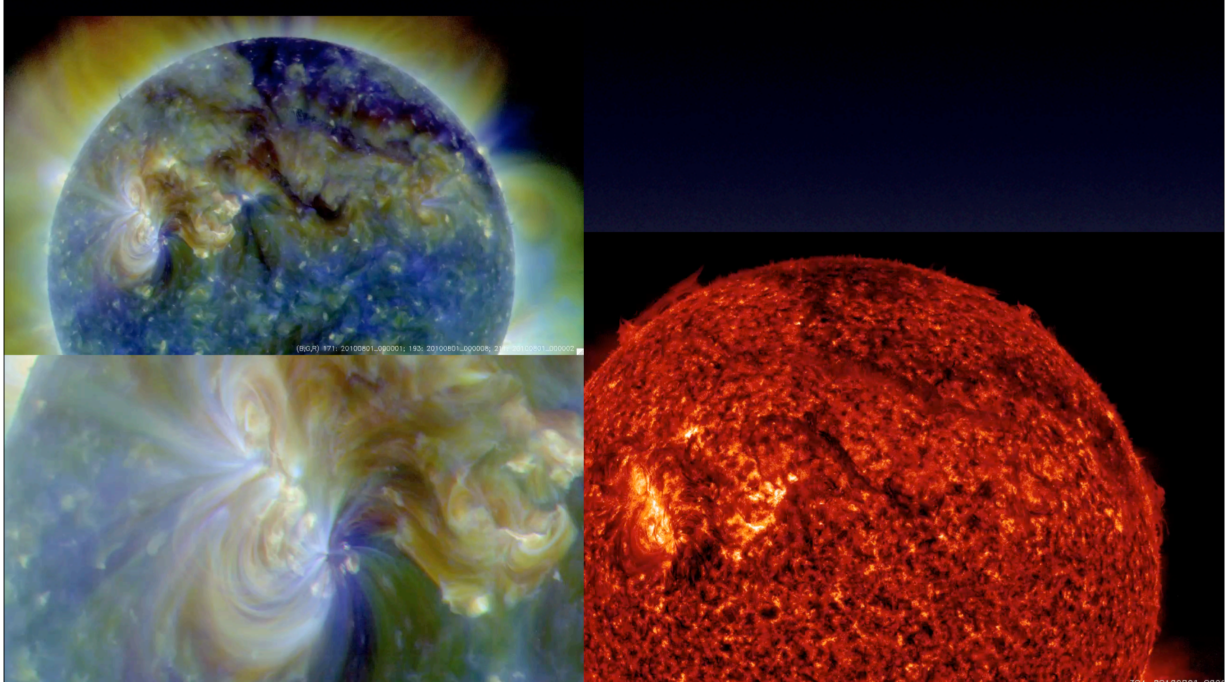
SDO/AIA 304A

Coupled events

SDO/AIA 211/193/171A - ~2/1.5/1MK

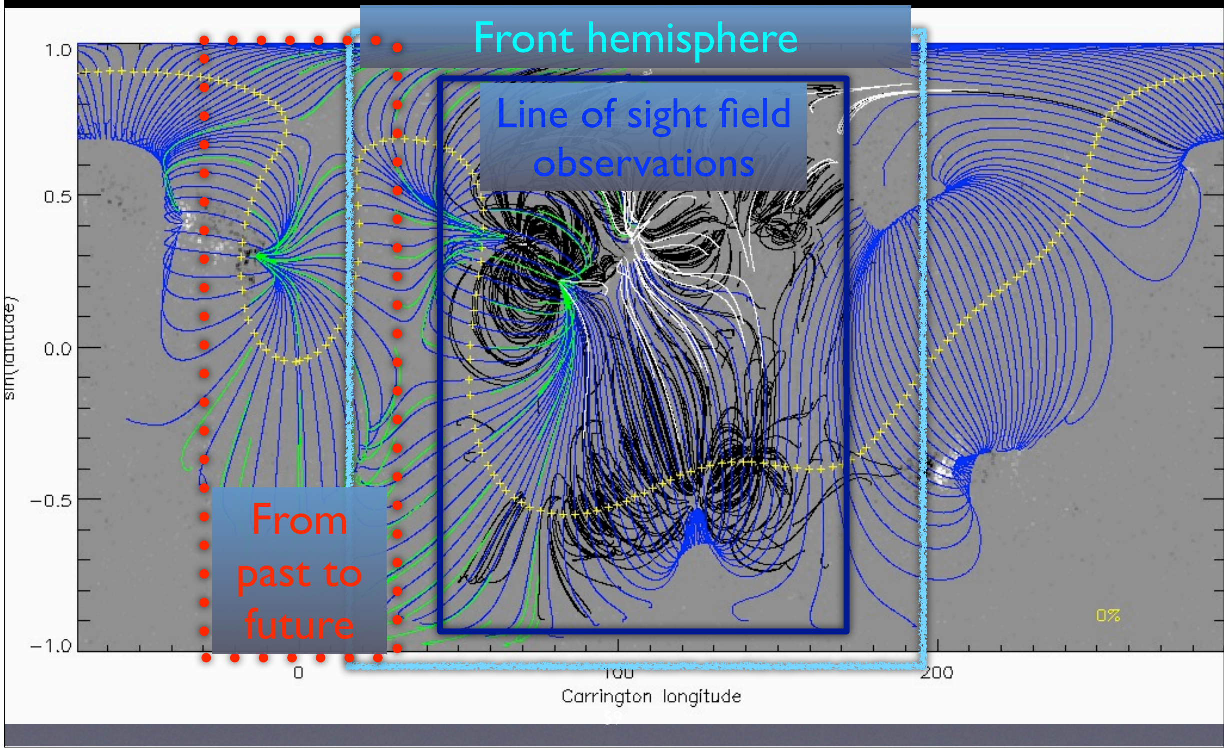


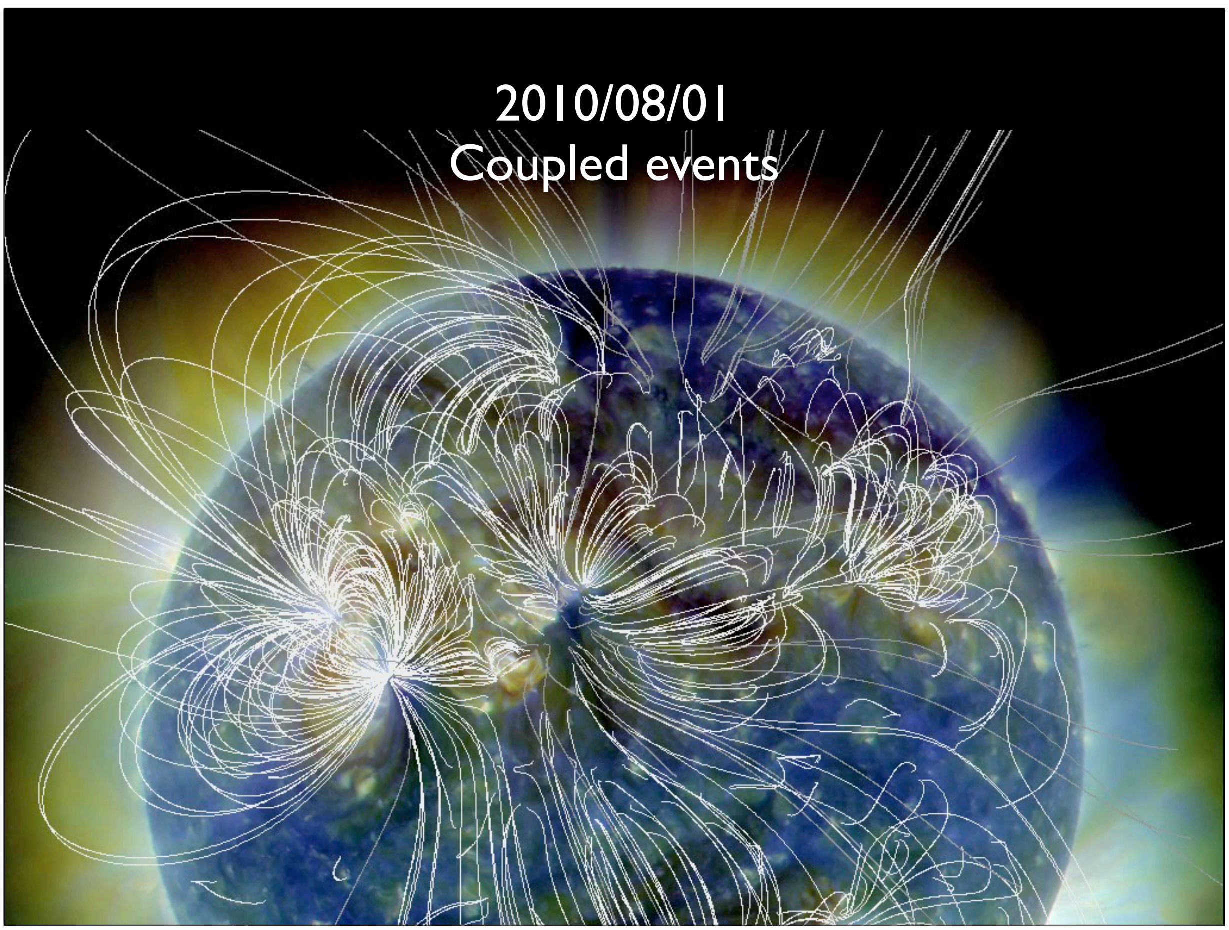
2010/08/01
Coupled events



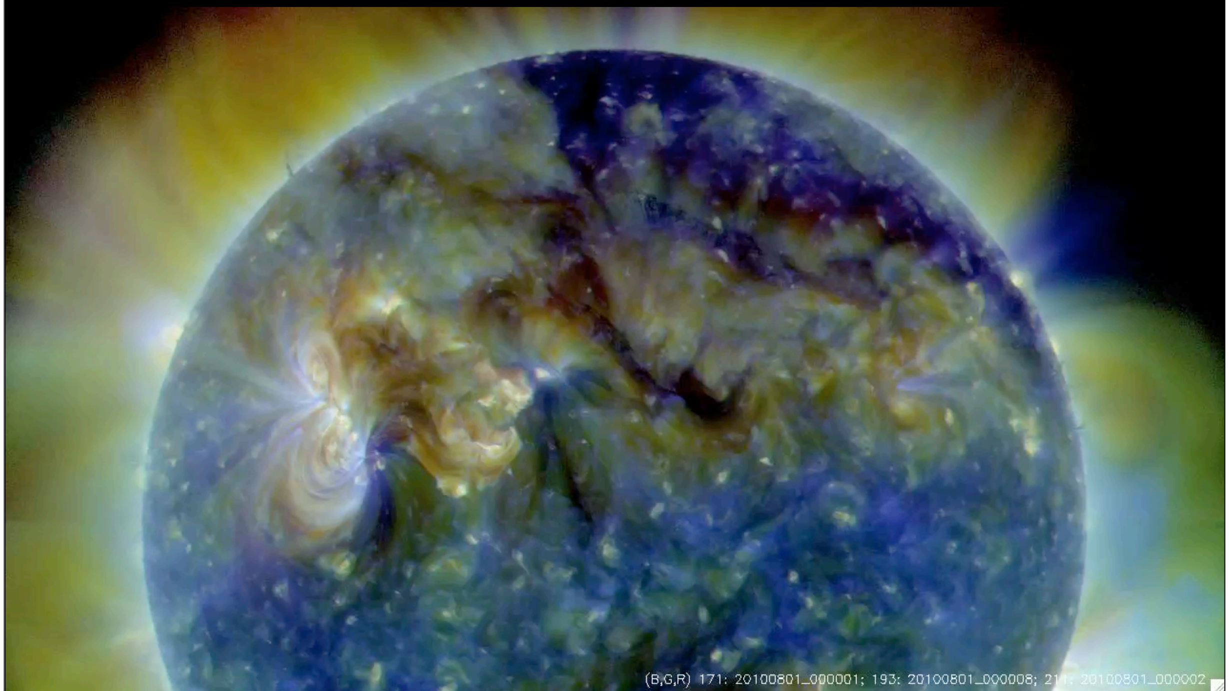
Experimenting with the "potential-field source-surface" model

mixing past and future information

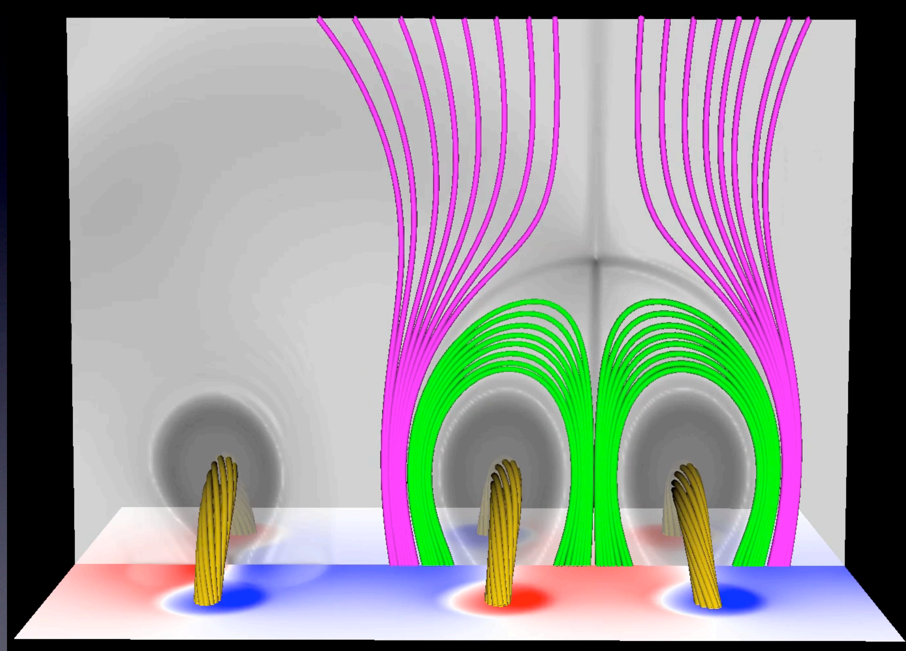




2010/08/01
Coupled events



3D Simulation of Coupled Destabilizations of Flux Ropes



Török et al. (2011)

2010/08/01: Sun to heliosphere

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