Magnetic activity in the Sun and the stars

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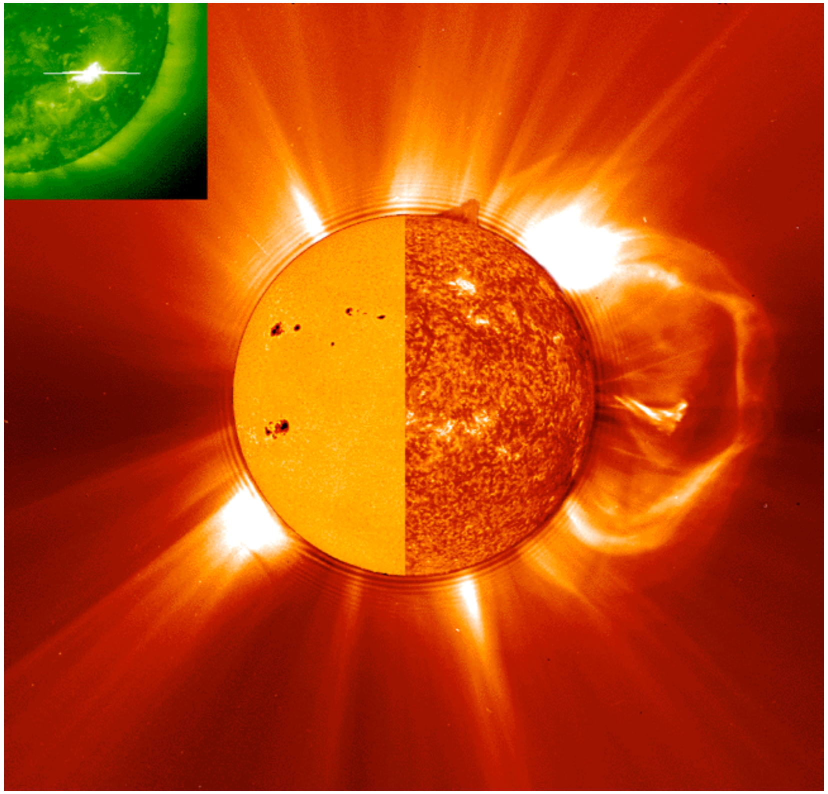
Outline

- Solar magnetism
  - Phenomena
  - Sun-Earth connection
- Stellar activity
  - Which stars are active?
  - How to observe stellar activity
- A bit of dynamo theory



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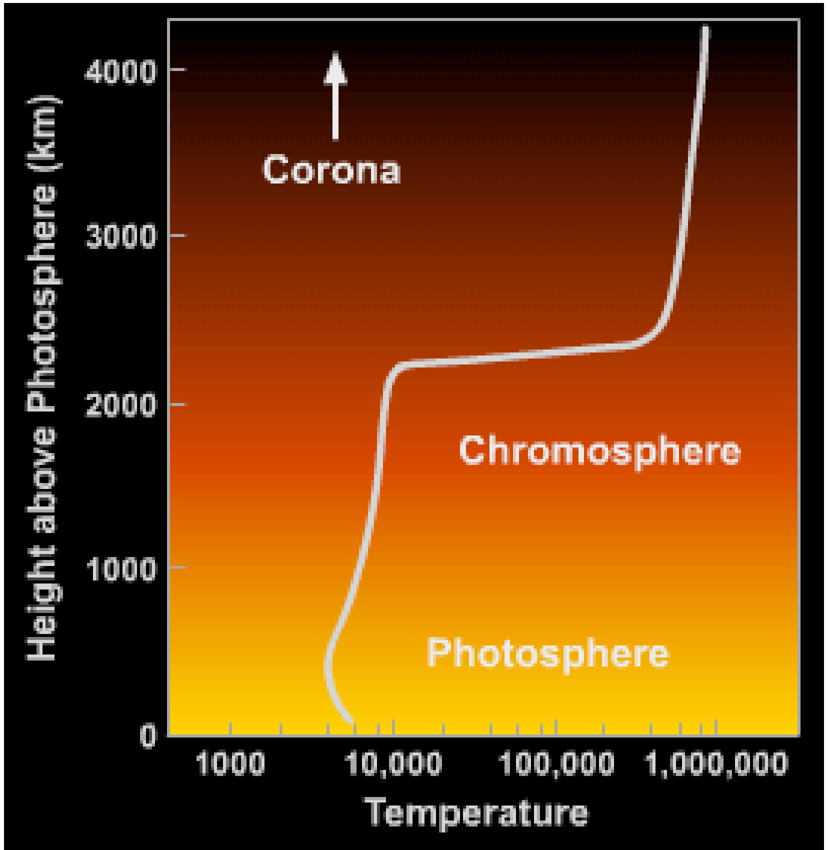
Solar atmosphere

- Photosphere
  - Temperature minimum region
- Chromosphere
  - Transition region
- Corona
- Solar wind



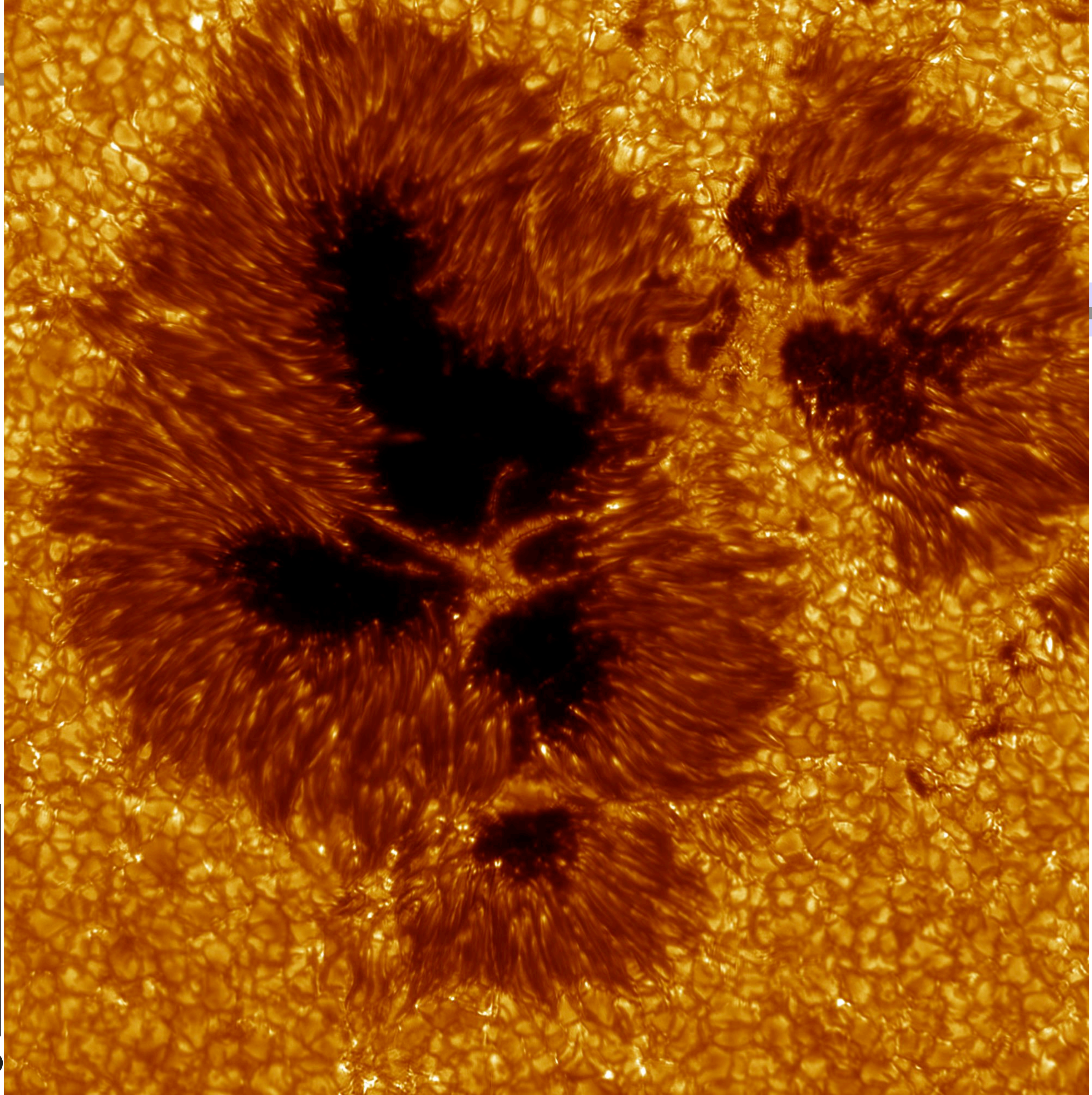
Solar Temperature above Photosphere

Solar photosphere

- ‚Visible surface‘ of the Sun
- Temperature: 5780 K
- Eventhough the densest part of the solar atmosphere its pressure is still 0.0001 atm
- H^{-} absorb the radiation coming from the interior
- Observed usually in G-band
- The most visible features are the sunspots

Sunspots in 2001

MDI, Tom Bridgman



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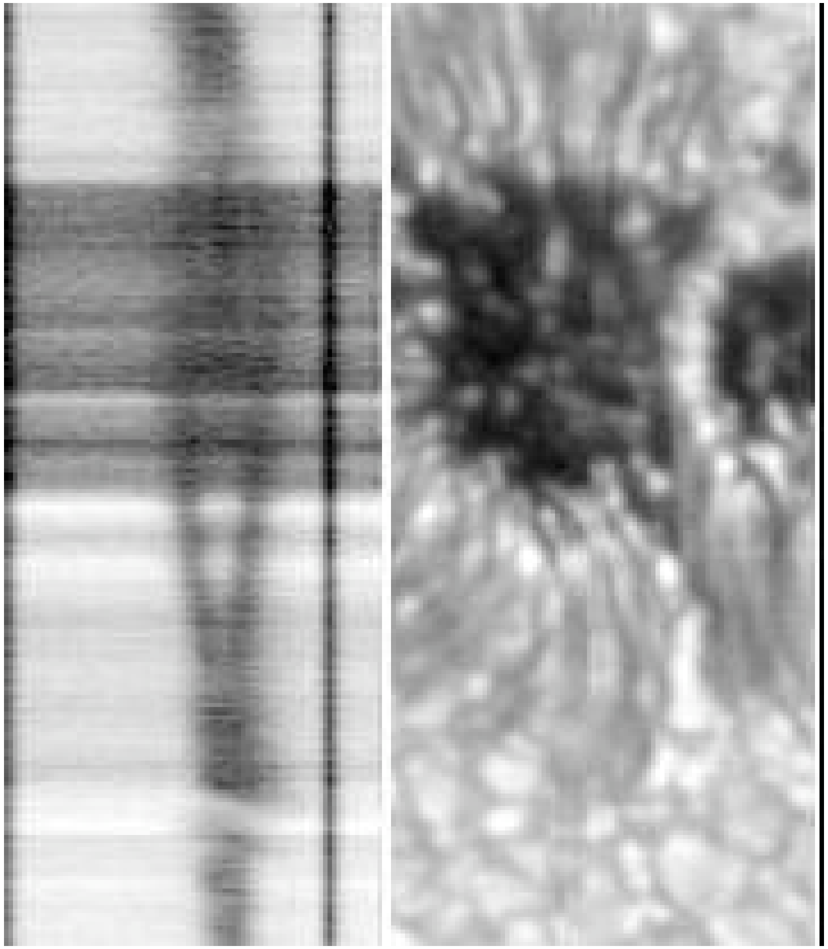
Spots are magnetic

- Sunspots are caused by magnetic field
- First detected by Hale (1908)
- Zeeman splitting is largest in the center of the sunspot



Inside a sunspot

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From Kosovichev

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Inside a sunspot II

- Intense magnetic field below weakens convection
  - Spot cooler and therefore darker than its surroundings
- The material above the plug cools and becomes denser, causing a downflow as fast as 4800 km/hr
- Surrounding plasma and magnetic field drawn inward toward the sunspot's center
- Concentrated field promotes further cooling
  - Self-perpetuating cycle
- As long as the magnetic field remains strong, the cooling effect will maintain an inflow that makes the structure stable.
- Outflows seen right at the surface are in a very narrow layer.

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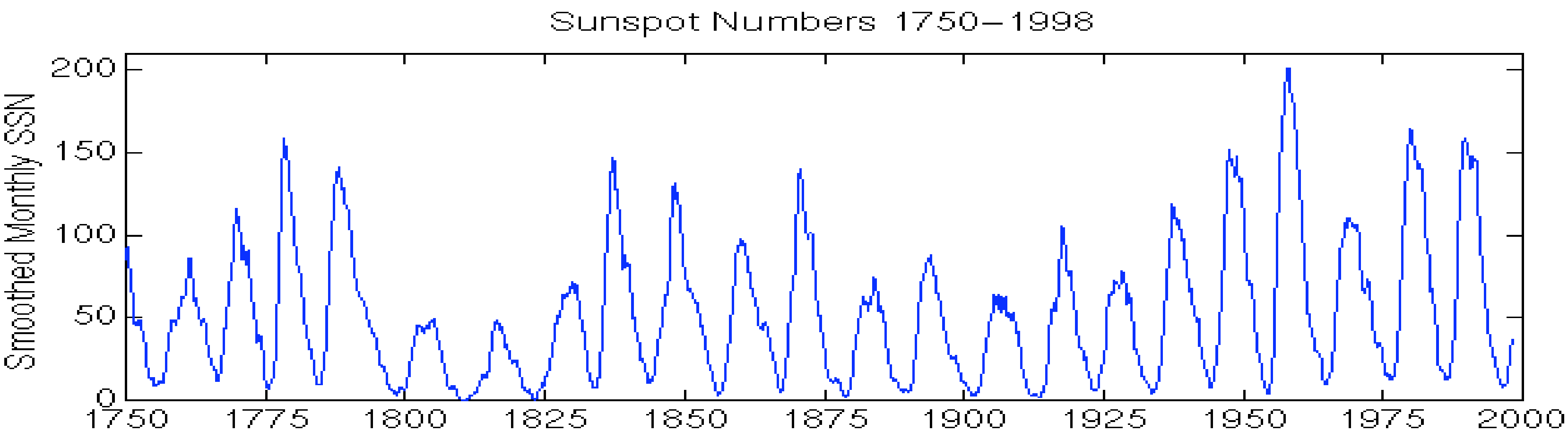
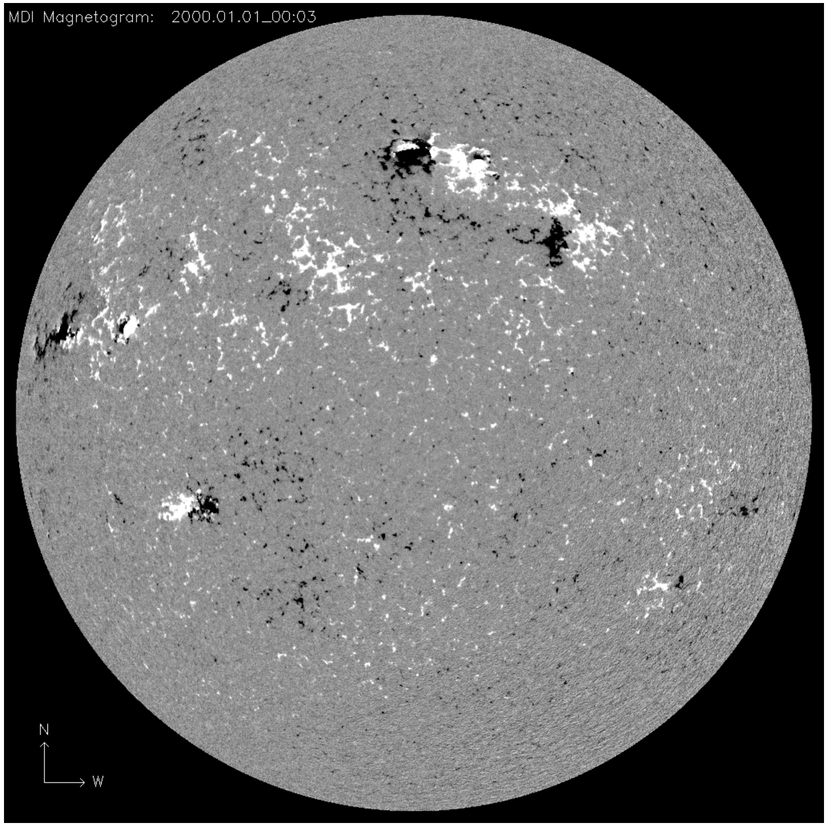
Solar cycle



- Solar activity has on average 11 year cycle
- Cycle length changes between 9 and 13 years

Solar magnetic cycle

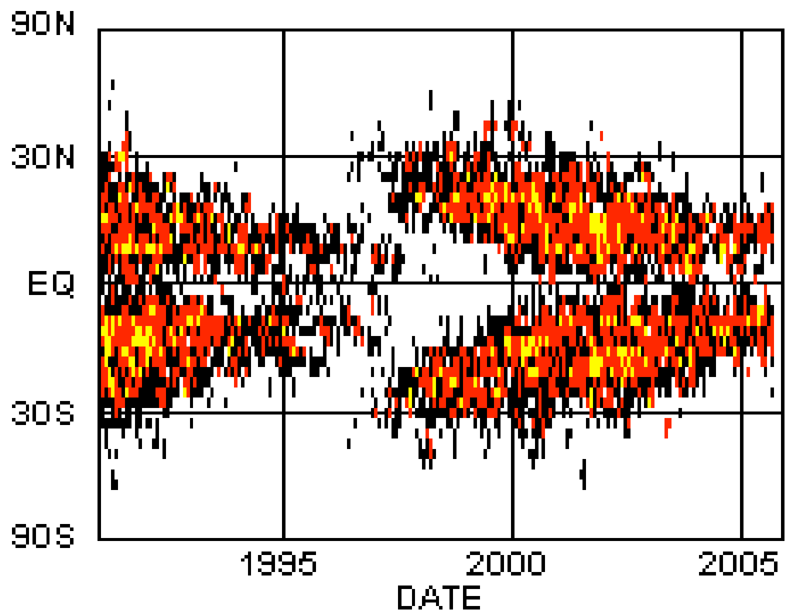


- Sunspot pairs have opposite polarities
- Leading sunspots in groups in one hemisphere have the same polarity
- Polarity of the leading spots are opposite at the two hemispheres
- During the next sunspot cycle the polarity of the leading spots in each hemisphere is opposite from what it was in the previous cycle

Butterfly diagram

- First spots of the new cycle at latitude ~30-35°
- Last spots of the cycle within ±10 ° of the equator

→ Butterfly diagram



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Solar chromosphere

- Thin layer, only ~2.5*10^6 meters thick
- Seen during a total eclipse as a thin reddish ring
- Temperature: upto ~10 000K
- Density: 1/1 000 000 of the photosphere
- Not dense enough to create absorption lines, but the gas is heated to incandescence

→ emission lines

- Observed for example in: Hα , Ca II H&K, Mg II h&k and certain ion lines

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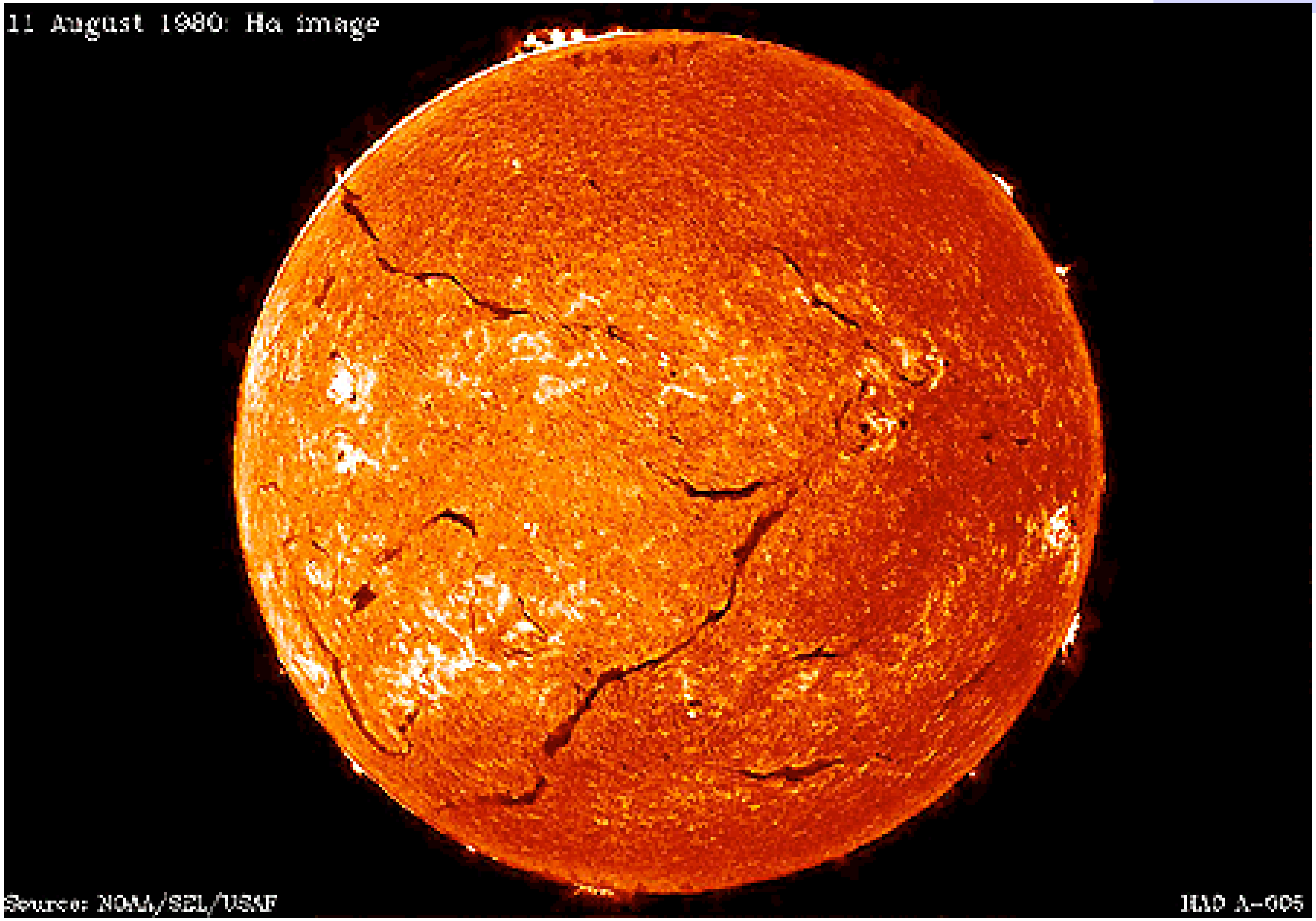
Chromosphere in Hα



NOAA/SEL/USAF

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Corona

- Seen when solar visible disk blocked out, e.g. by an eclipse
- Temperature: > 1 000 000 K
- Density: 10^15 e⁻/m^3 (in lower corona)
- Observed with UV and X-ray radiation

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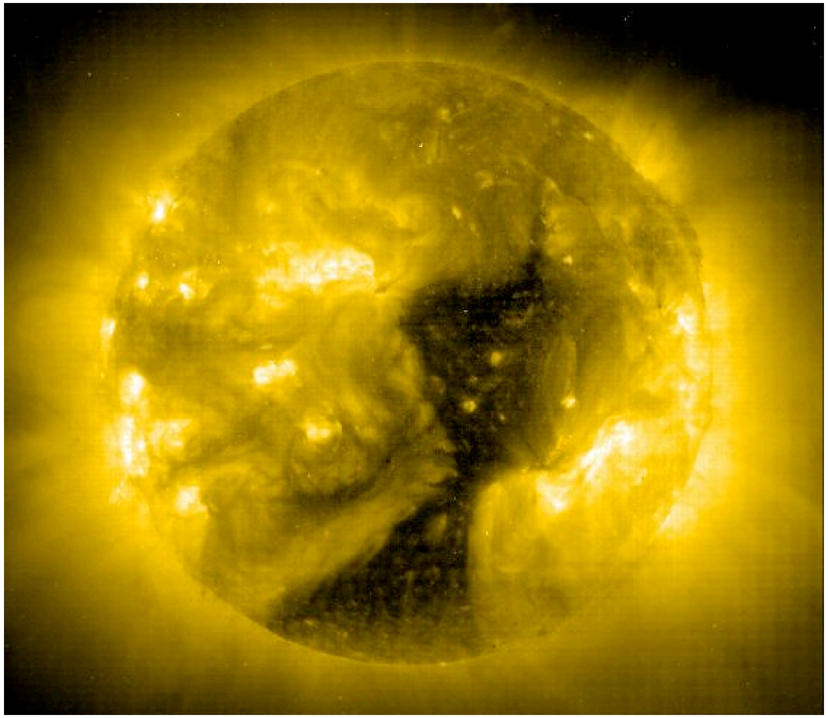
Coronal holes

- Coronal holes are coronal regions with open magnetic field structure
- During the solar minimum they are confined to the polar regions, while at solar maximum they can be found at all latitudes.
- The fast-speed solar wind originates form the coronal holes



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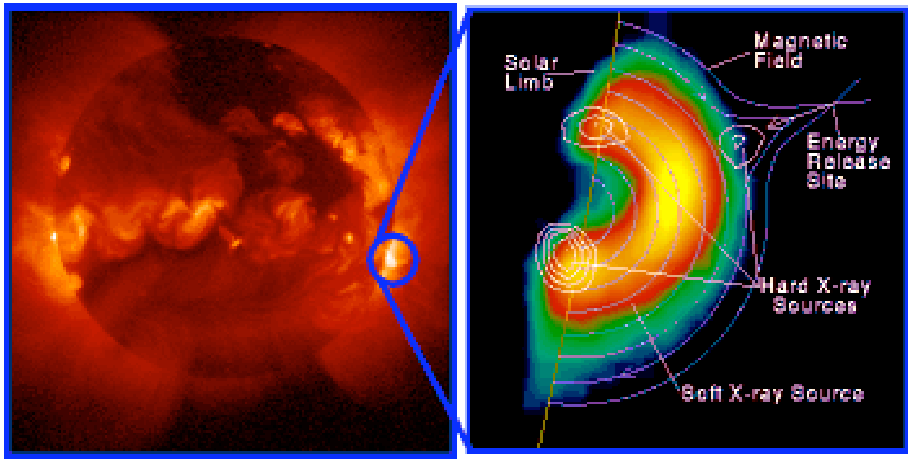
Flares

- Intense, temporary releases of energy
- Last from minutes to hours
- Caused by reconnection of strong magnetic fields
- Radiate throughout the electromagnetic spectrum



Yohkoh

ESO

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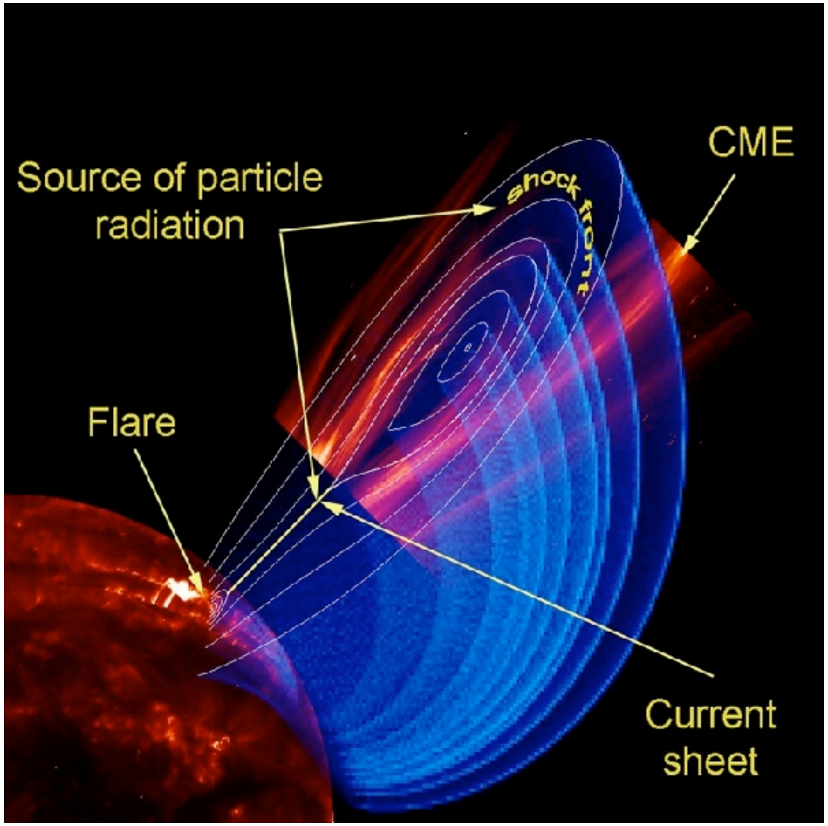
CME's

- 5*10^12-5*10^13 kg
- Speeds ~ 4*10^5 m/s
- Often accompanied by flare
- Flares and CMEs are related phenomena, but one does not cause the other



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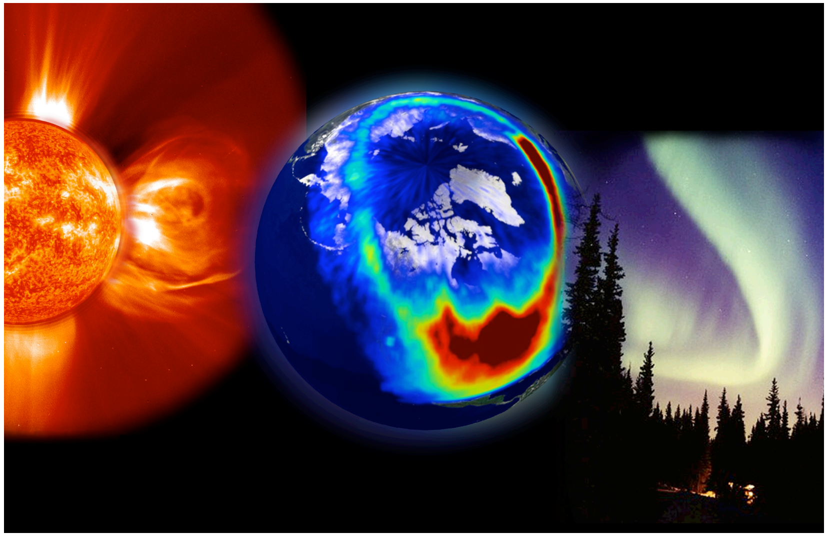
Solar-Terrestrial connection

- Episodic solar activity has a number of effects that are of interest to Earth
- It can can cause problems on Earth and also create spectacular aurora



Earth-Space Activities disrupted by solar and geomagnetic events

- Satellite operations
- Navigation
- Space Shuttle and Space Station activities
- High-altitude polar flights
- Electric power distribution
- Long-line telephone communication
- HF radio communication
- Pipeline operations
- Geophysical exploration
- ...

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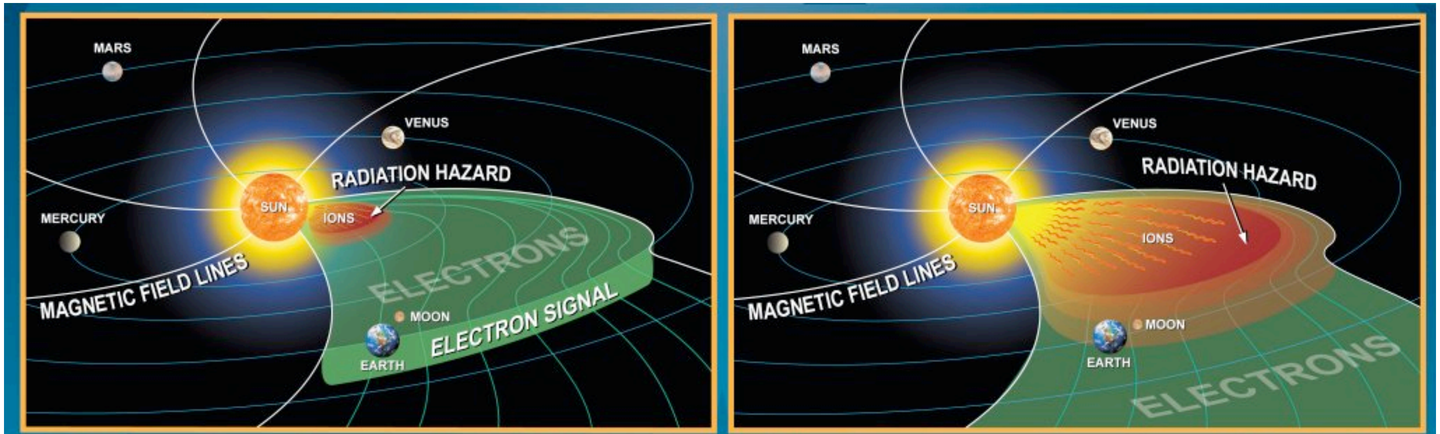
Artist‘s illustration, from SOHO website (sohowww.estec.esa.nl)

Predicting

- Solar storms consist of electrons, protons and heavy ions
- The last pose danger to space-borne electronics and to humans outside the Earth's protective magnetic field
- Ion‘s arrival time can be predicted from the electron data



This sketch images the inner solar system at the time the light and electrons from solar activity reach the Earth. Fast electrons and the slower ions follow magnetic lines of force. A newly discovered method now allows explorers to use the electron "signal" for their safety. In this situation, the arrival of hazardous radiation is imminent.

At the time the hazardous ions arrive, typically tens of minutes later, human explorers on the moon or on the way to Mars would have performed actions for their own protection. Equipped with a warning system, this method can, in extreme cases, prevent a mission-threatening health condition: Acute Radiation Sickness.

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Stellar magnetic activity

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Spectral classification

Morgan-Keenan spectral classification

Class	Temperature	Colour	M	R	L	Spectral lines
O	30 000-60 000 K	Blue	60	15	1 400 000	Ionized atoms, especially helium
B	10 000-30 000 K	Blue-white	18	7	20 000	Neutral helium, some hydrogren
A	7500-10 000 K	White	3.2	2.3	80	Strong hydrogen, some ionized metals
F	6000-7500 K	Yellow-white	1.7	1.3	6	Hydrogen and ionized metals, such as calcium and iron
G	5000-6000 K	Yellow	1.0	1.0	1.0	Ionized calcium and both neutral and ionized metals
K	3500-5000 K	Orange	0.9	0.9	0.4	Neutral metals
M	2500-3500 K	Red	0.4	0.4	0.04	Strong molecules, e.g., titanium oxide and some neutral calcium

E
A
RL
Y

--

L
AT
E

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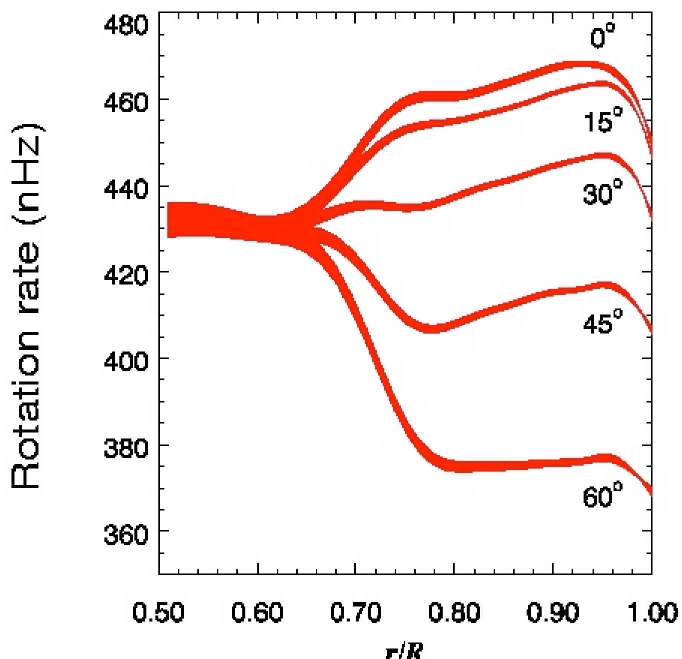
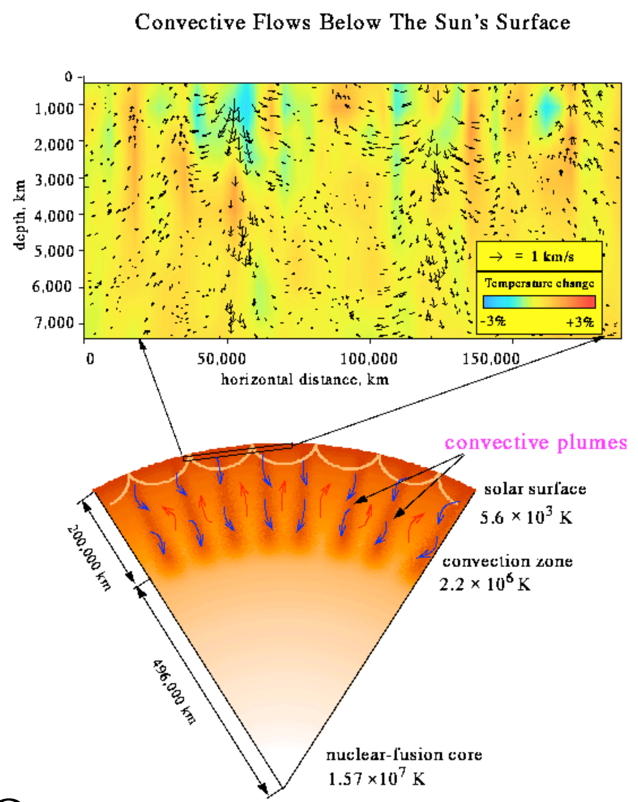
Ingredients for magnetic activity

- Internal structure
- Shear layer, e.g. tacocline maybe needed for generation and storage of magnetic fields
- Rapid rotation enhances dynamo





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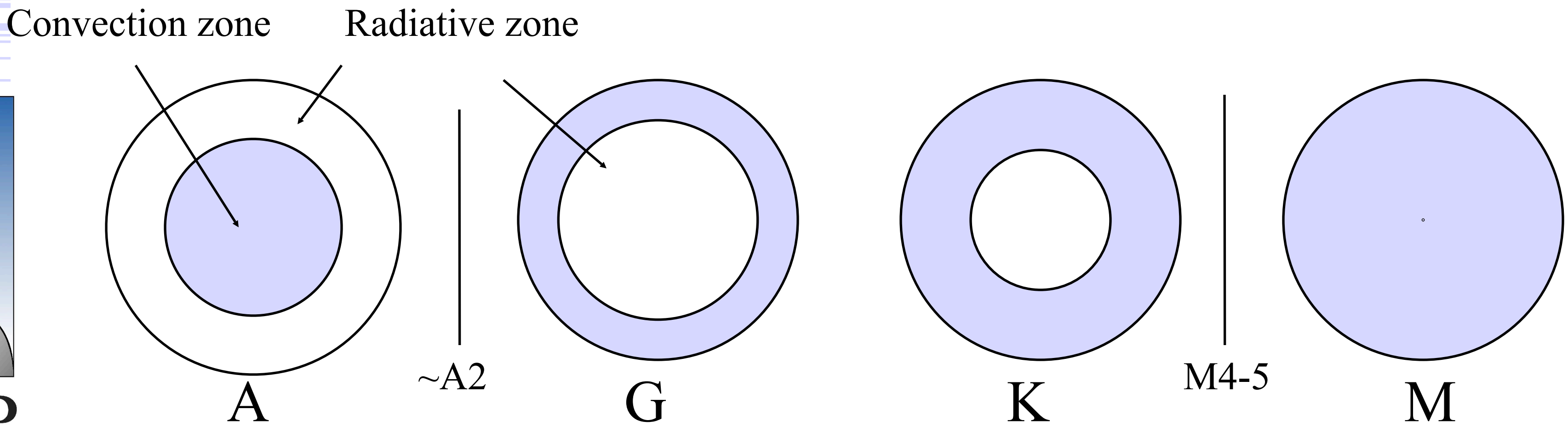
Which stars show dynamo action?

fusion core + radiative zone + convection zone
= cool star ~1.5-0.03 M



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Stellar rotation at the main sequence

- Early-type stars (O, B and A) have large rotational velocities, typically between 100 and 200 km/sec
- At spectral type F, there is a rapid decline from about 100 km/sec at F0 to 10 km/sec at G0.
- The Sun (G2) rotates at about 2 km/sec
- Redder stars have usually rorational velocity of 1 km/sec and slower

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Magnetic breaking

- Many stars at ZAMS rotate rapidly, but the late type stars brake fast during the first ~ tens of millions of years
- The breaking is caused by:
  - Angular momentum loss through magnetised stellar wind
  - Evolutionary changes in the moment of inertia
- At main sequence cool stars enter a weak braking phase that lasts billions of years

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Which stars rotate rapidly

- Young stars that have not yet slowed down
- Close binaries due to tidal locking:
  - Tidal interaction tries to synchronise the rotational spin and orbital evolution causing increase in the rotation rate
  - Loss of angular momentum due to stellar winds drives the binary components closer to each other and thus further speeding the rotation

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Stellar magnetic activity

- Not straigth forward to observe from a point source
- Photometric variability
- High resolution spectra
- Bias towards really extreme forms of activity

Sun shows many forms of magnetic activity, but it would be classified as inactive if it was observed from far away.

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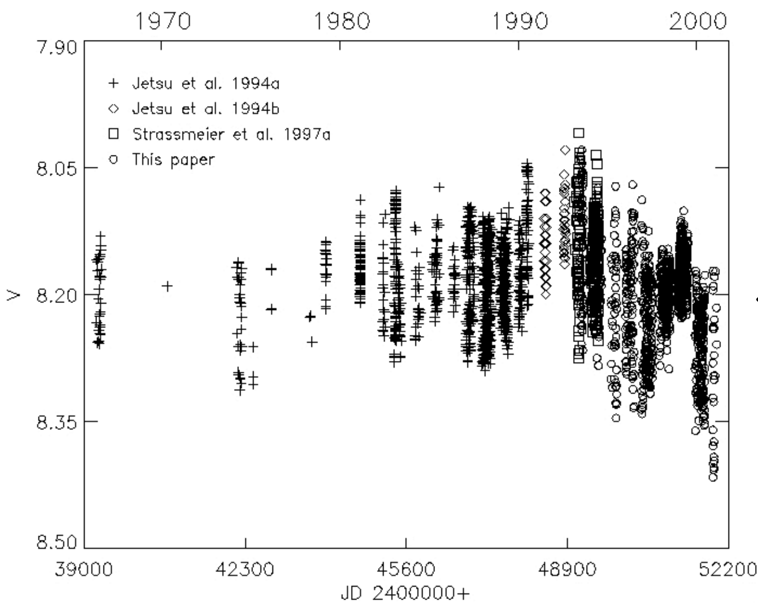
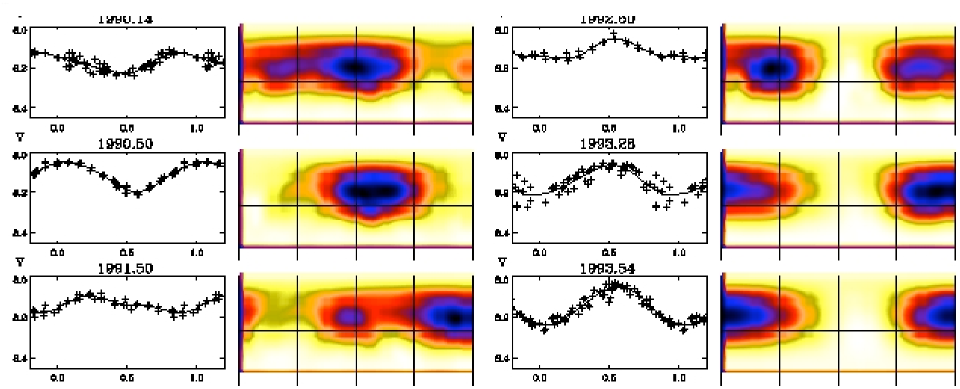
Photosphere



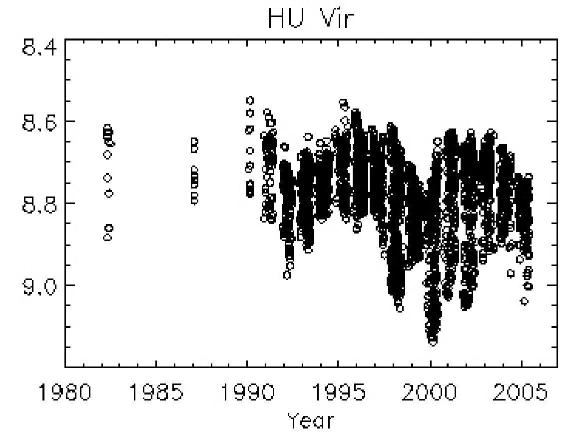
Long-term V band observations of FK Com (Korhonen et al. 2001)

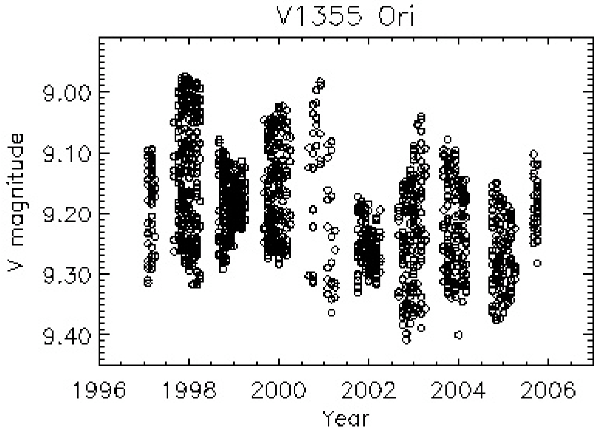
Phased light-curves of FK Com for 1990-1993 (Korhonen et al. 2002)



Stellar cycles

- Many active stars exhibit long term cyclic changes in their photometry
- Often with multiple cycle lengths





Starspots in detail?

- Stars are point sources, no possibility for spatially resolved observations
- For detailed observations of stellar surface indirect means are needed

⇒ Doppler imaging

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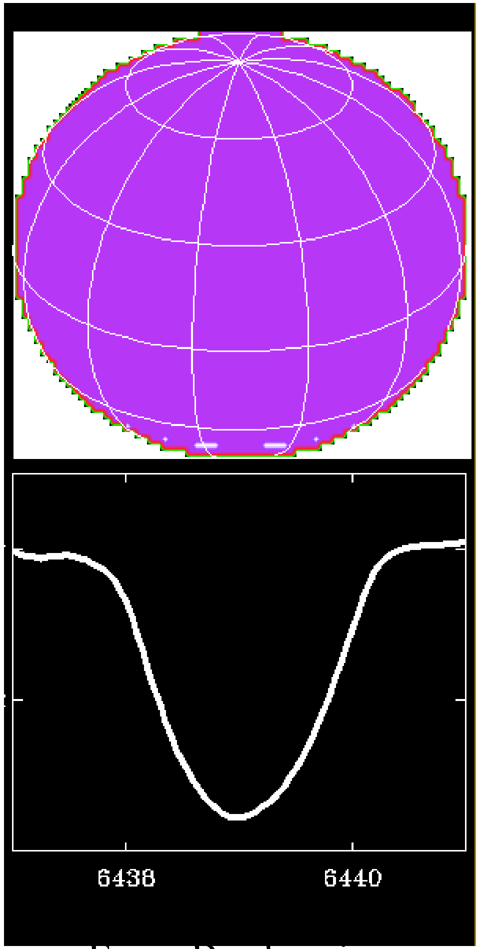
Doppler imaging

- In Doppler imaging the distortions appearing in the observed line profile due to the presence of spots and moving due to the stellar rotation
- Ill-posed inversion problem
- Many methods for solving: Maximum Entropy Method (e.g., Vogt et al 1987), Tikhonov Regularization (e.g., Piskunov et al 1990), Occamian Approach (Berdyugina 1998), Principal Components Analysis (Savanov & Strassmeier 2005)



From Berdyugina

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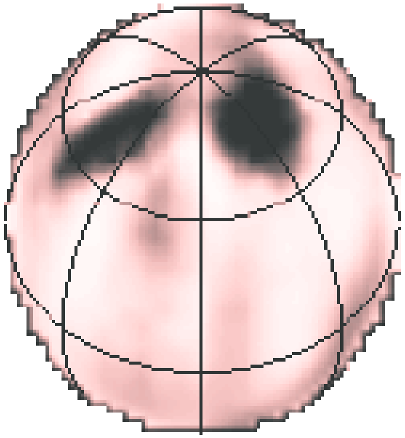
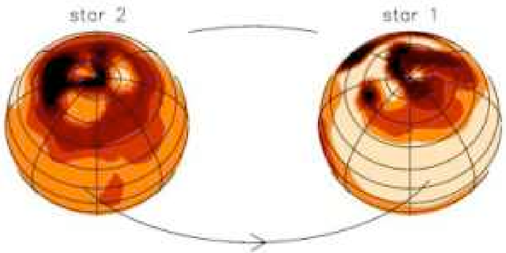
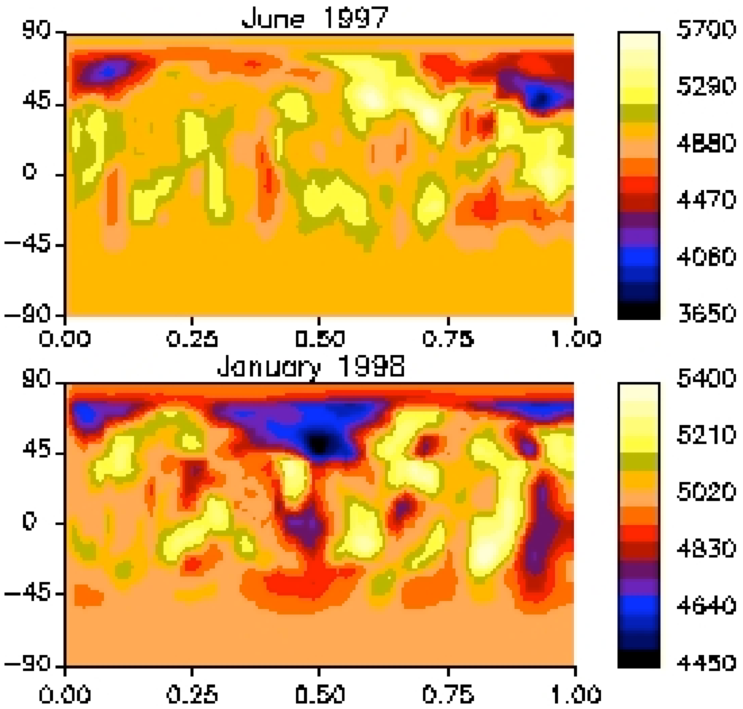
Doppler imaging results



II Peg: Berdyugina et al 1998



σ^2 CrB: Strassmeier & Rice 2003



FK Com: Korhonen et al 2001

What have we learned with DI?

- Spots/spot groups on active stars are large
- Often high latitude spots
- Often two active longitudes
- Spot configuration changes often slow on giant stars and fast on young stars

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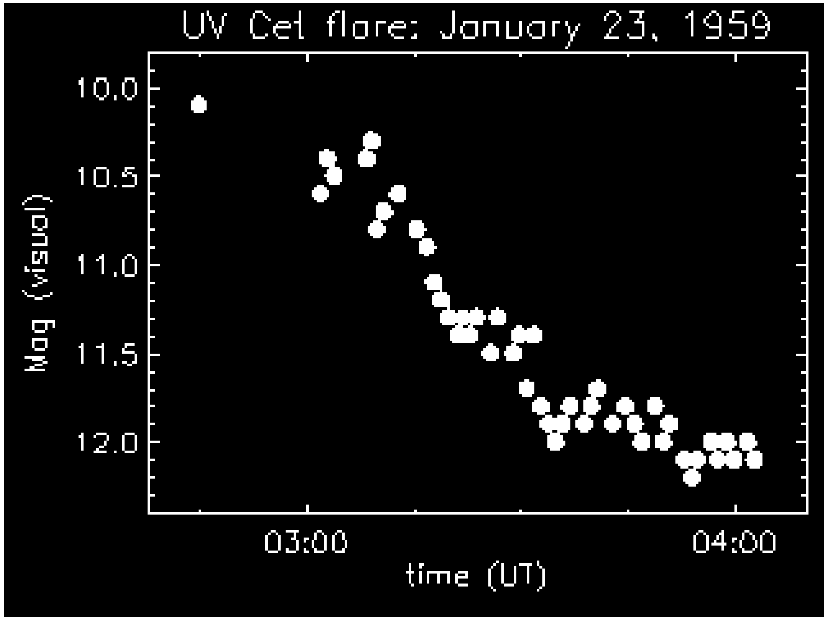
Stellar flares



AAVSO

- Many very cool stars show numerous large flares
- light-curves, especially seen in the U band
- From spectra as emission lines, especially in Balmer lines
- Can release 100-1000 times more energy than most energetic solar flares

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Stellar chromospheres

- Schwarzschild & Eberhard (1913) discovered that some late type stars had emission components in the cores of Ca II H&K lines
- This discovery was followed by several papers with more stars showing this effect
- From early on it was thought that the mechanism causing this was similar to the solar chromosphere

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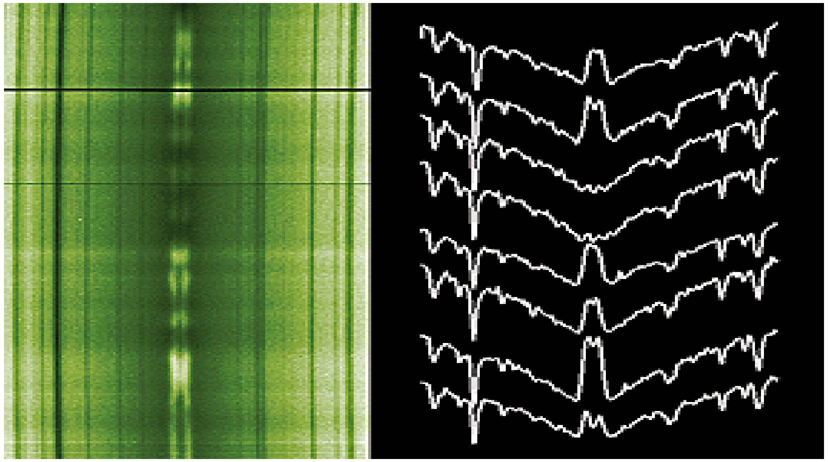
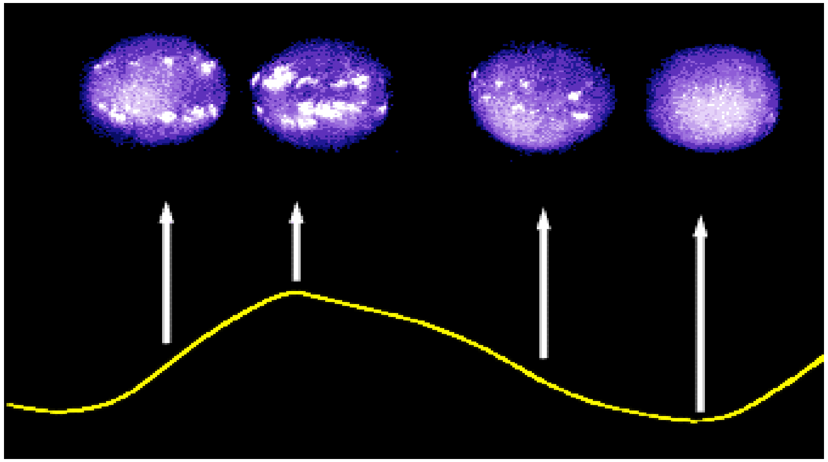
Sun as a star:chromosphere



If we place the slit of a spectrograph across the surface of the Sun, we can trace the change in the emission of the calcium K line



The size and extent of chromospheric active regions on the Sun varies dramatically over the course of the activity cycle

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HK Survey

- Most famous study of stellar chromosphere is the Mt. Wilson HK survey
- Started by Olin Wilson in 1950's
- Has monitored hundred stars continuosly since then
- In total more than 400 stars monitored, both dwarfs and giants

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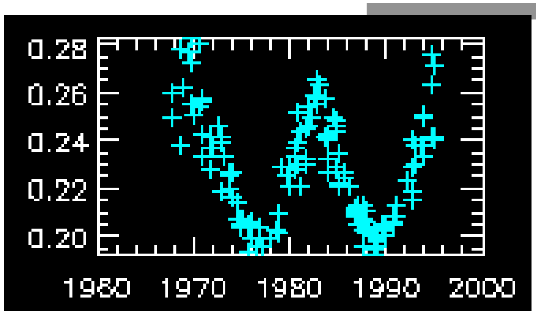
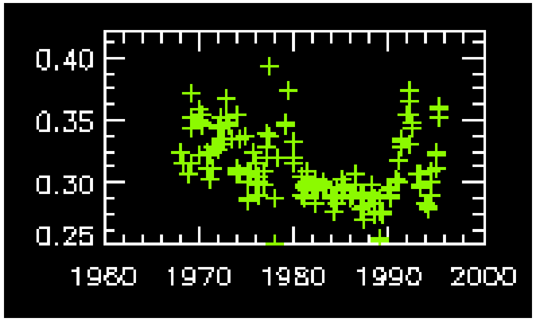
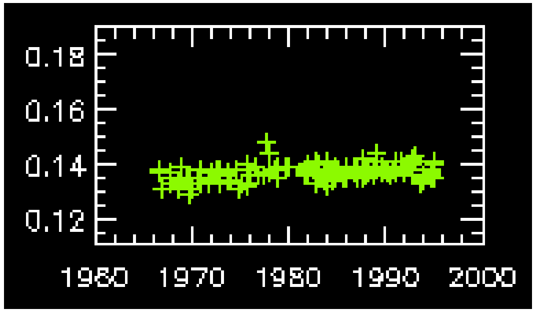
HK Survey: results



- HD 16160
  - Spectral type K3V
  - Cycle length 13.2 yrs

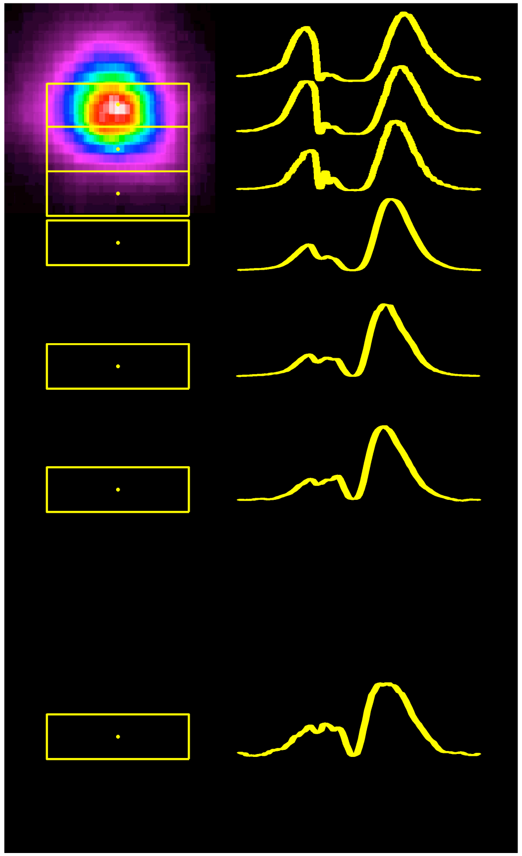


- HD 101501
  - Spectral type G8V
  - No cycles, but variability



- HD 9562
  - Spectral type G2V
  - Flat

Extended chromosphere



- Here observations of Betelgeuse's chromosphere
- Warm chromosphere extending more than 50 times the radius in visible
- The hot gas co-exsists with the cool gas in the circumstellar dust envelope

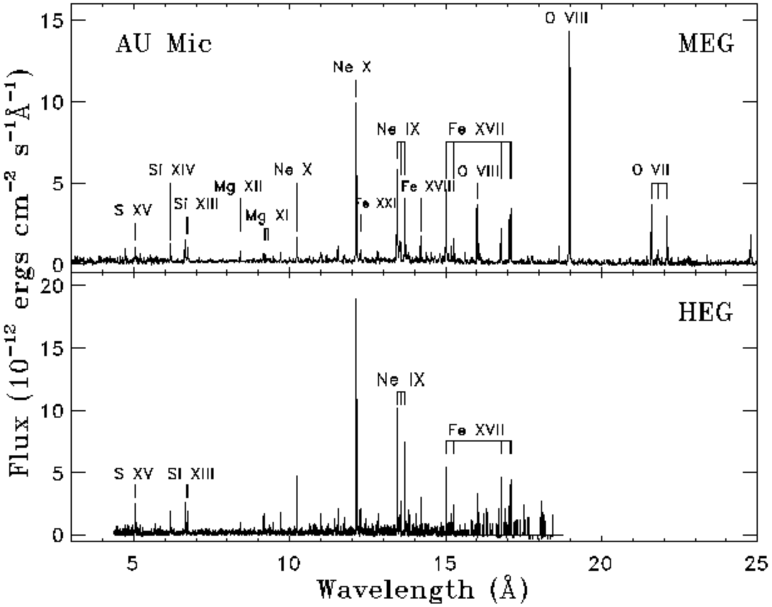
Lobel et al. 2004

Stellar corona

- The structure of stellar corona can only be investigated indirectly using spectroscopic tools
- UV ad X-ray spectra: One needs a satellite!
- It is not easy to recover coronal temerature structure from disk integrated spectra

→ An inverse problem!

Observations of stellar coronae I

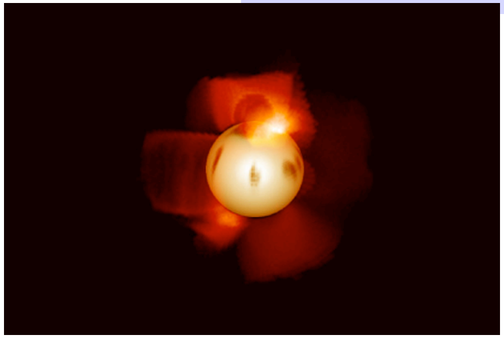


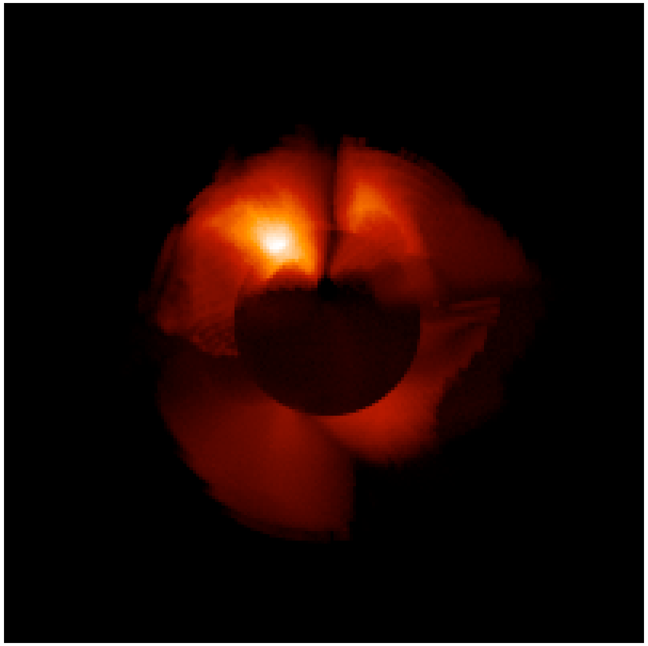
Chandra observations from Linsky

- X-ray spectra allow to determine the thermal structure, densities, and dynamics of stellar coronae
- Chandra spectrum of the dM1e dwarf star AU Mic with the important emission lines marked
- Analysis of the line fluxes leads to the emission measure distribution, electron densities, and a model for the coronal plasma of the star

Observations of stellar coronae II

- Surface fields from the Zeeman-Doppler imaging maps
- Coronal fields extrapolated from the surface fields
- Here example for AB Dor:
  - ZDI Donati et al.
  - Coronal extrapolation Jardine et al.





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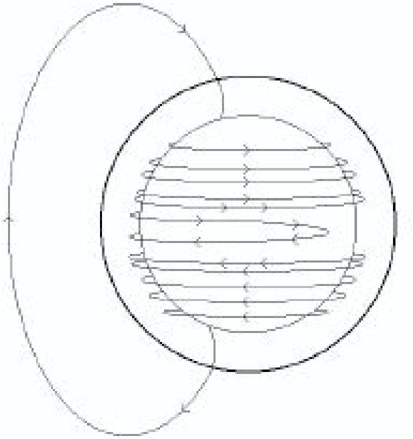
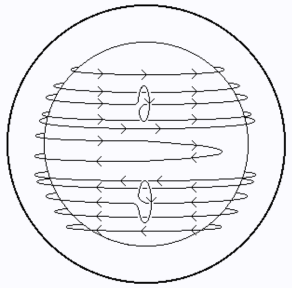
Some theory

αΩ-dynamo

- Solar magnetic fields are created by dynamo processes. In them the poloidal and toroidal fields are chenged to each other.
- In Ω-effect the poloidal field lines are streched out and wound around the Sun by differential rotation forming toroidal field lines.
- Twisting of the toroidal field lines into poloidal filed lines is caused by effects of solar rotation, so called α-effect.



The Ω-effect



The α-effect

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Importance of differential rotation to Dynamo theory

- Crucial ingredience in the $\alpha\Omega$-dynamo
- Oscillating solutions for α^2-dynamo are extremely rare

⇒ Cyclic stellar activity can be considered as a strong indication of of internal differential rotation (Rüdiger et al. 2003)

- Models by Kitchatinov & Rüdiger (1999) predict that:
  - DR in stars decreases with decreasing rotation period
  - DR for giants larger than for dwarfs

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Solar surface differential rotation

- For at least a century astronomers have known that sunspots at different latitudes have different speeds

→ Sun rotates differentially

Latitude	Period
0	25.67 d
30	26.64 d
75	33.40 d

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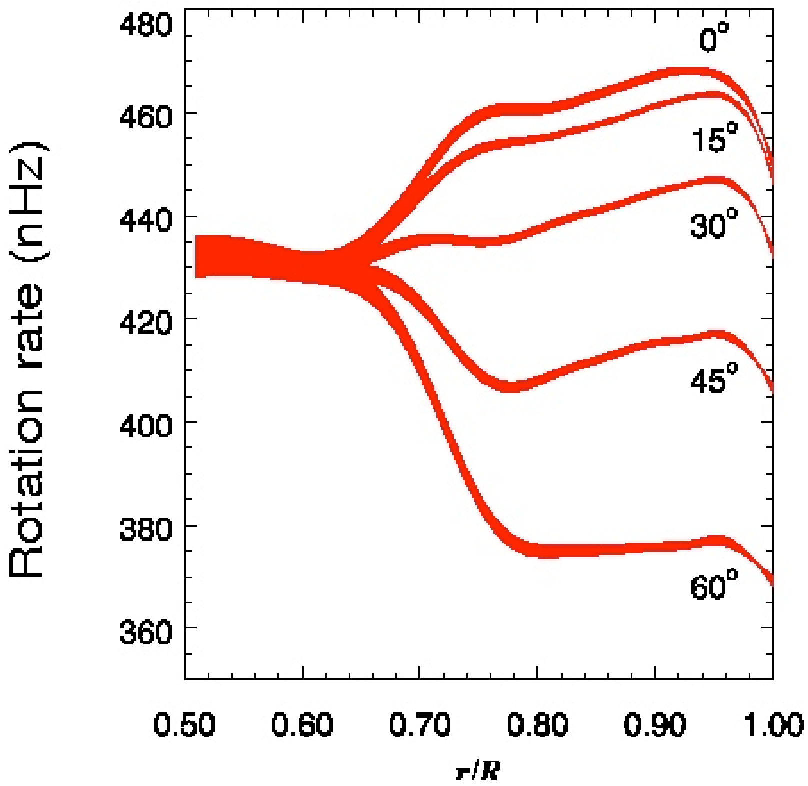
Solar internal differential rotation



- With helioseismolgy one can investigate the solar internal rotation
- Differential rotation persist to the bottom of the convection zone 28.7% of the way down
- Below that uniform rotation

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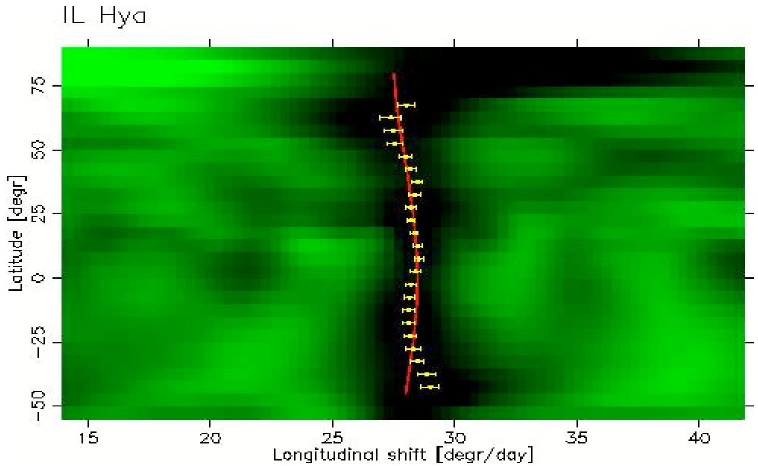
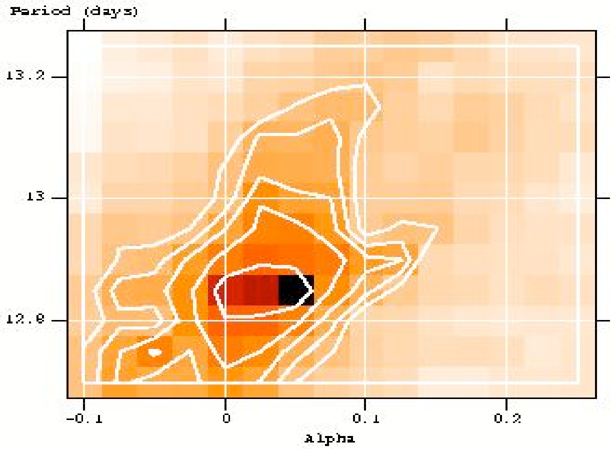
Stellar differential rotation

- Only the surface differential rotation can be measured with the current technigues, no internal DR
- Possible methods:
  - Photometric timeseries
  - Comparing two Doppler images and tracing spot changes
  - Using DR as a parameter in Doppler imaging
  - Investigation of the spectral line shapes





Weber et al 2005

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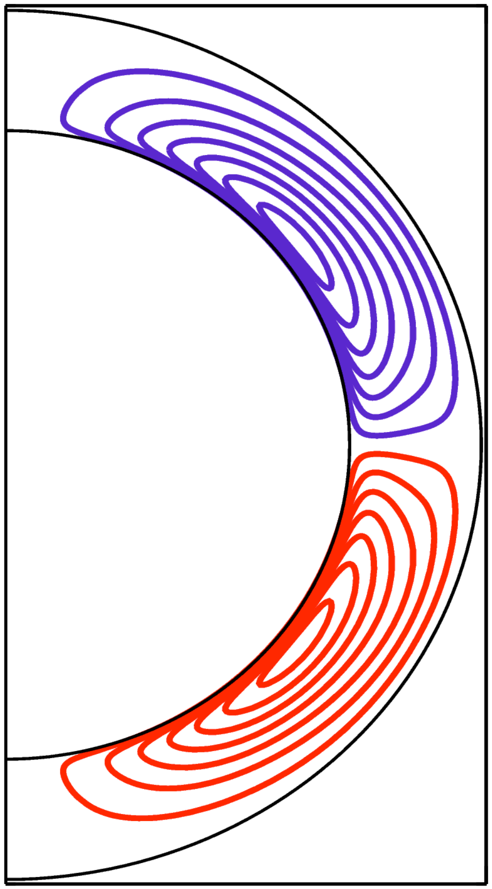
Meridional flow



- To explain
  - Positive δΩ/δr in the solar convection zone
  - Behaviour of the solar magnetic field
- In addition to the α and Ω effects, an additional effect is needed

Meridional flow

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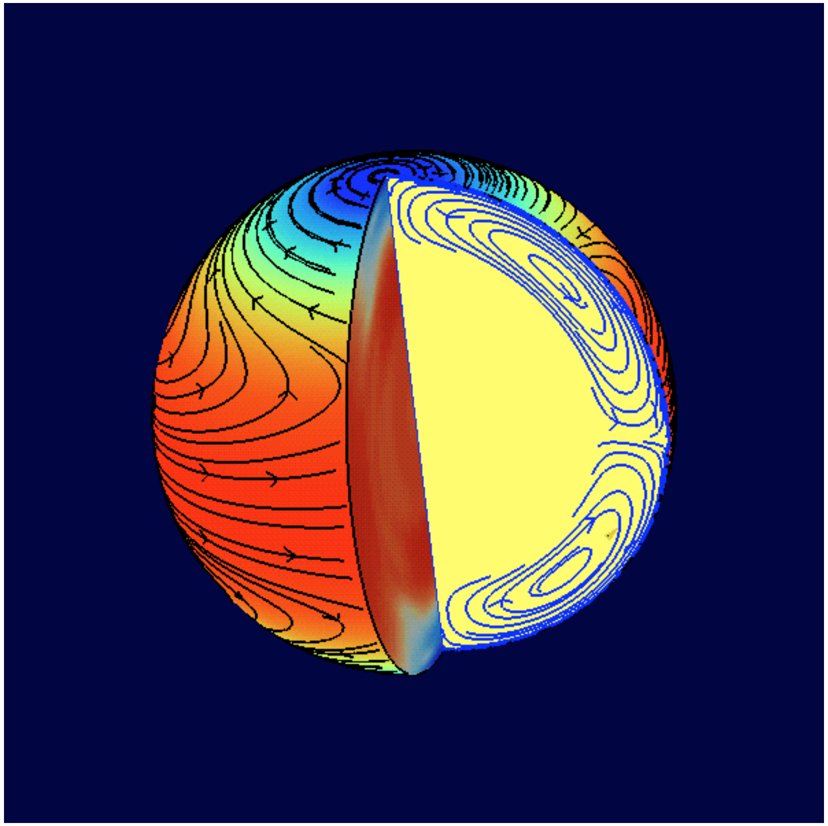
Solar meridional flow

- On the surface polewards, peak velocity 20 km/s
- Return flow in the lower convection zone



SOHO, MDI

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Stellar meridional flow

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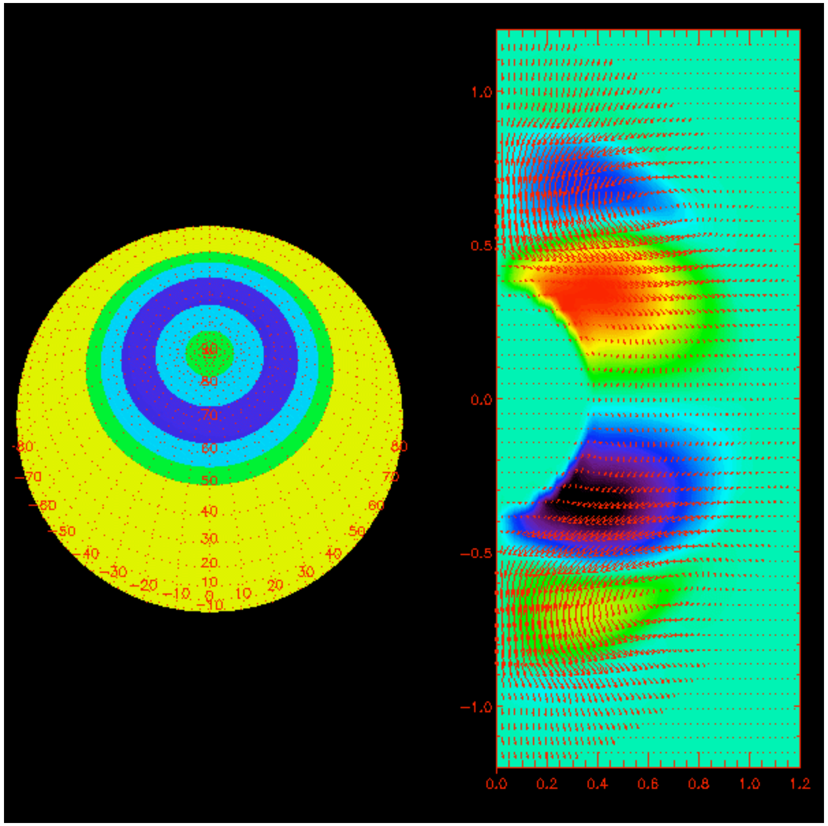
Axisymmetric dynamo



Elstner & Korhonen 2005

- Solar dynamo is axisymmetric, i.e. the spots do not show preferred longitudes
- In this model the spot migration during the cycle is towards the poles due to positive α (induction coefficient) on the northern hemisphere
- Cyclic behaviour

Figure:

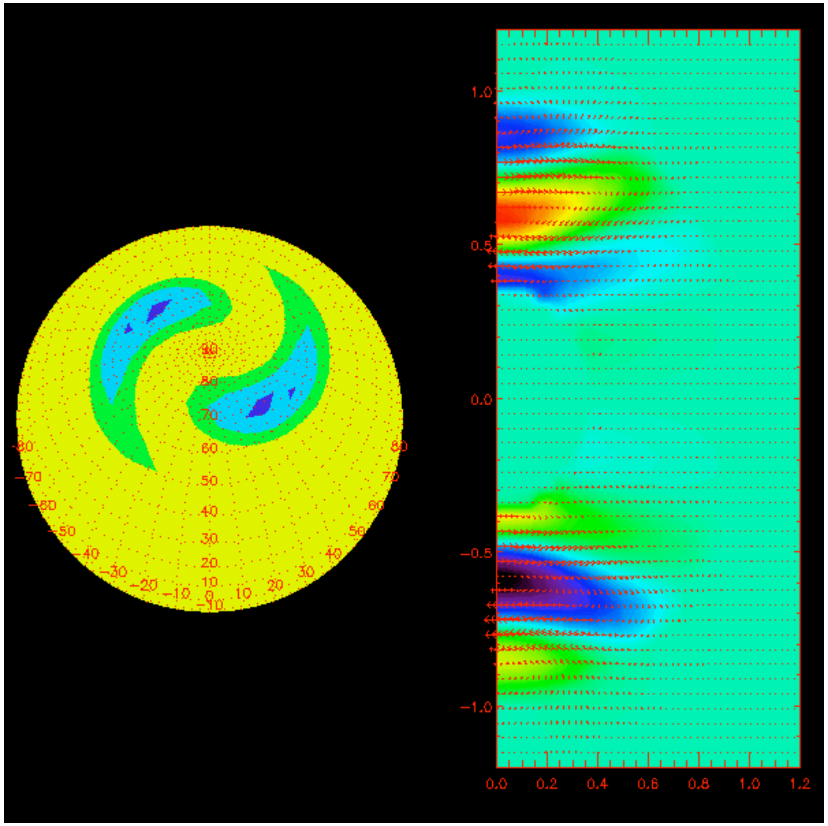
Stellar view: magnetic pressure on the surface

Cut view: mg field vectors (arrows)

vertical mg field (colours)

red=positive; blue=negative

Non-axisymmetric dynamo



- With more rapid rotation higher dynamo modes can get excited
- Spots occur on preferred active longitudes that are 180° apart
- No cyclic behaviour

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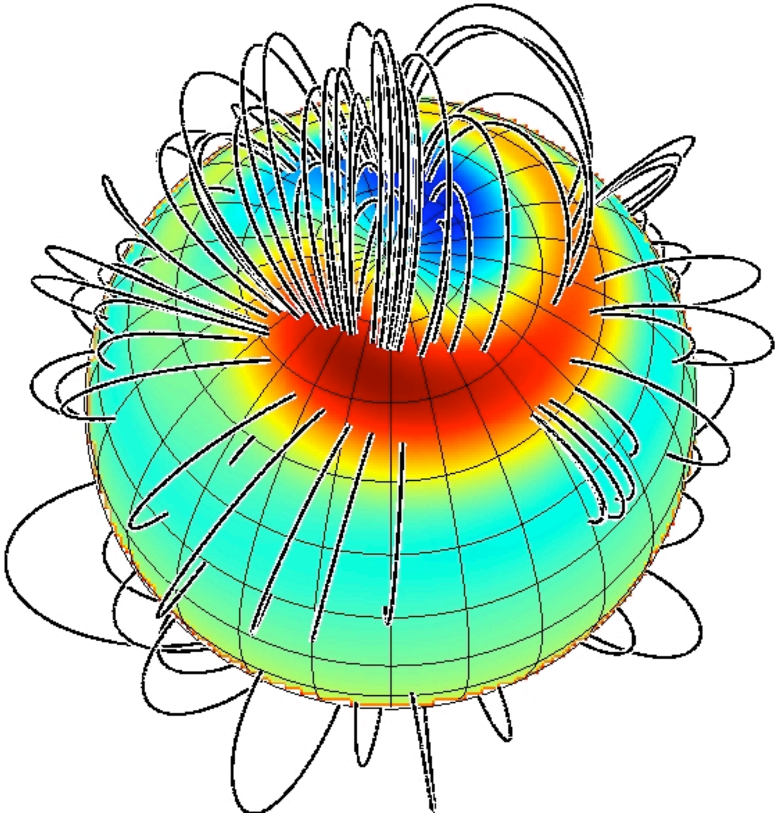
Elstner & Korhonen 2005

‚Theoretical corona‘

- Potential field extrapolation from dynamo models showing surface flux distribution and 100 randomly selected closed field lines presenting hot corona
- Model confirms that the high latitude spots of opposite polarity will harbour closed loops that will give rise to pole dominated emission
- Also loops connecting from the high latitude spots to the lower latitudes are seen → significant rotational broadening which is often observed in active stars



Drake et al. 2007

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