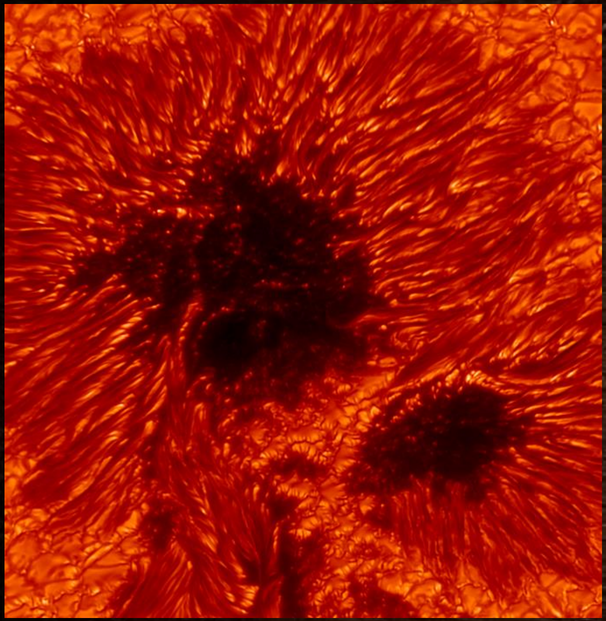
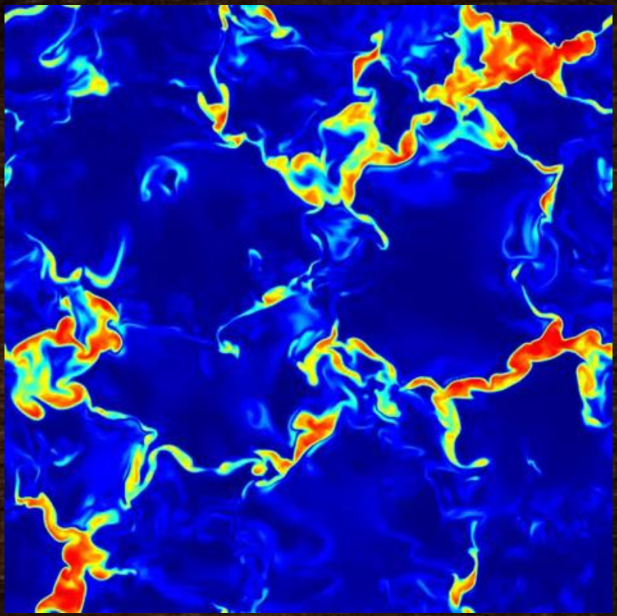
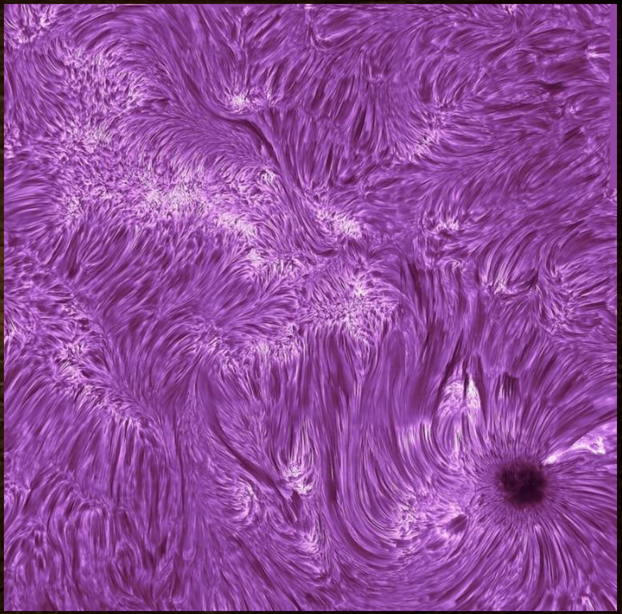

Physical processes at the Sun’s surface

SAMI K. SOLANKI

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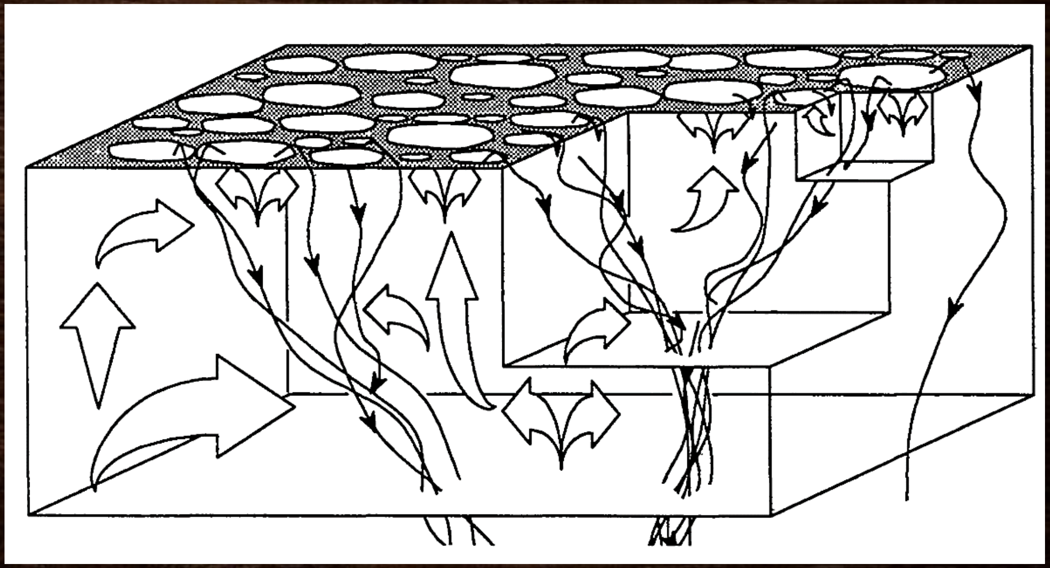
Main processes at the solar surface

- Main physical processes acting (or visible) at the Sun's surface:
  - Convection at different scales
  - Magnetoconvection: Interaction of magnetic foe;d with convection
  - Rotation and differential rotation
  - Large scale flows, such as meridional circulation
  - Oscillations and waves
  - Radiative transfer of energy
- These processes must act also on other stars with outer convection zones, although properties will differ
- Main processes causing structuring: magnetic field and convection

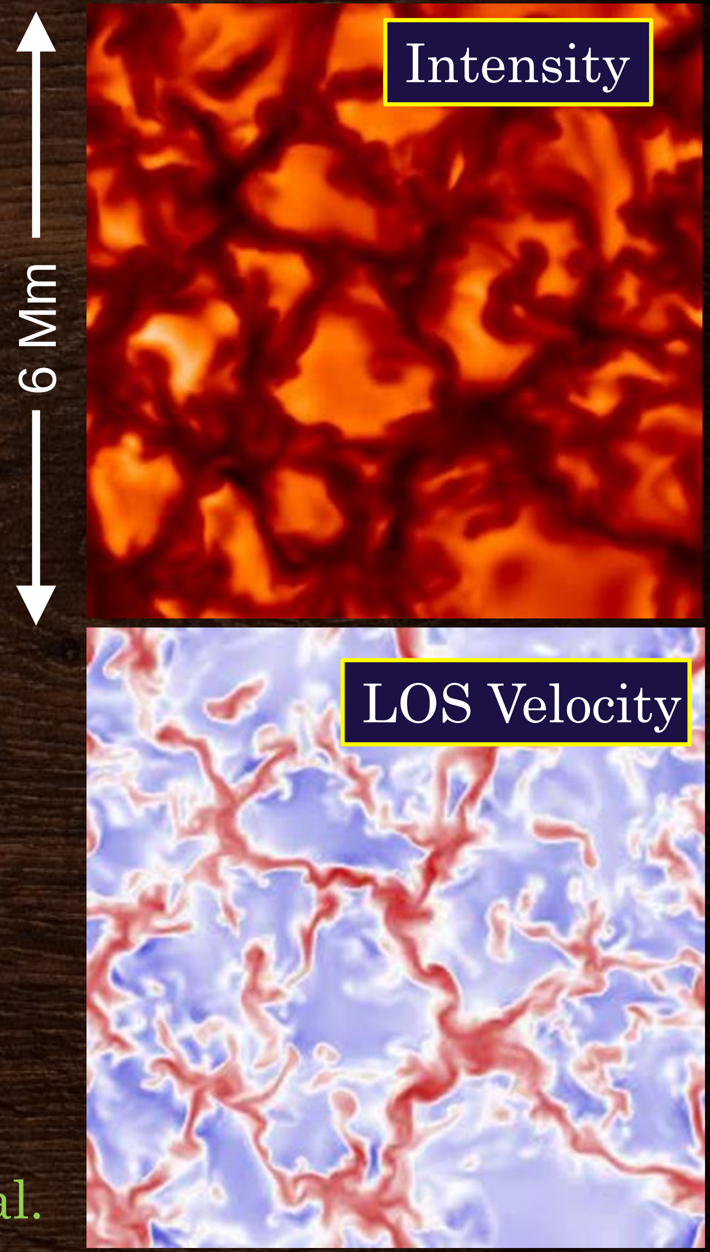
Convection

- Overturning convection is the main source of energy transfer just below solar surface
- In solar photosphere we observe overshooting convection (i.e. gas is convectively stable)
- Main scale of convection visible at surface is granulation
- Also clearly present is supergranulation
- Still larger scales are seen in simulations below the surface and have been claimed to be observed



Surface manifestation of convection: Granulation

- Typical size: 1–2 Mm
- Lifetime: 5–8 min
- Velocities: 1–2 km/s (but peak velocities > 10 km/s, i.e. supersonic)
- Brightness contrast: ~15% RMS in visible (green) continuum
- All quantities show a continuous distribution of values
- At any one time 10^6 granules on Sun



HD simulation by Vögler et al.

Surface manifestation of convection: Supergranulation

- 1 h average of Dopplergrams (averages out oscillations)
- Dark-bright: flows towards/away from observer
- No supergranules visible at disk centre ➔ velocity is mainly horizontal
- Size: 15-30 Mm
  Lifetime: days
  Horiz. speed: 400 m/s
  No contrast in visible

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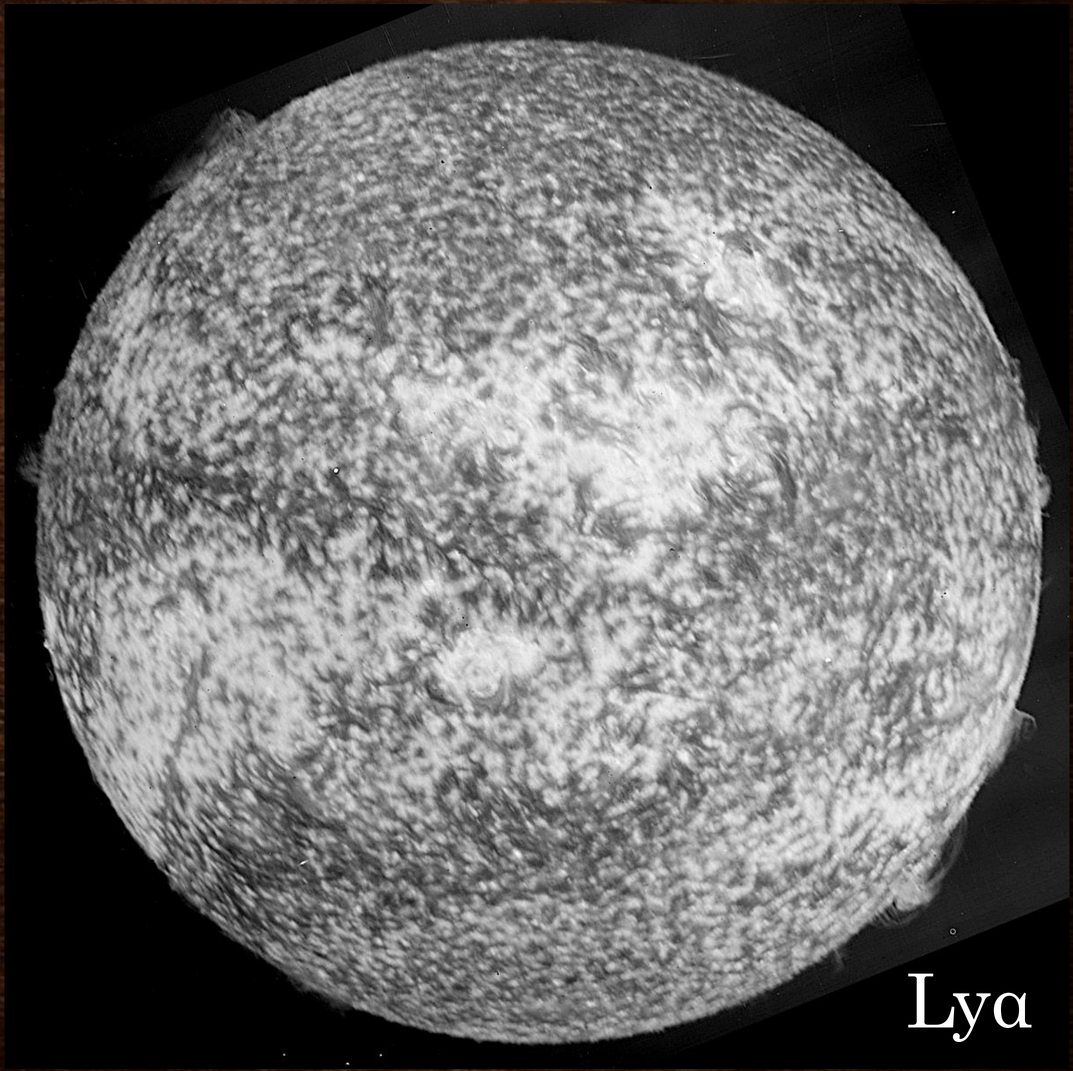
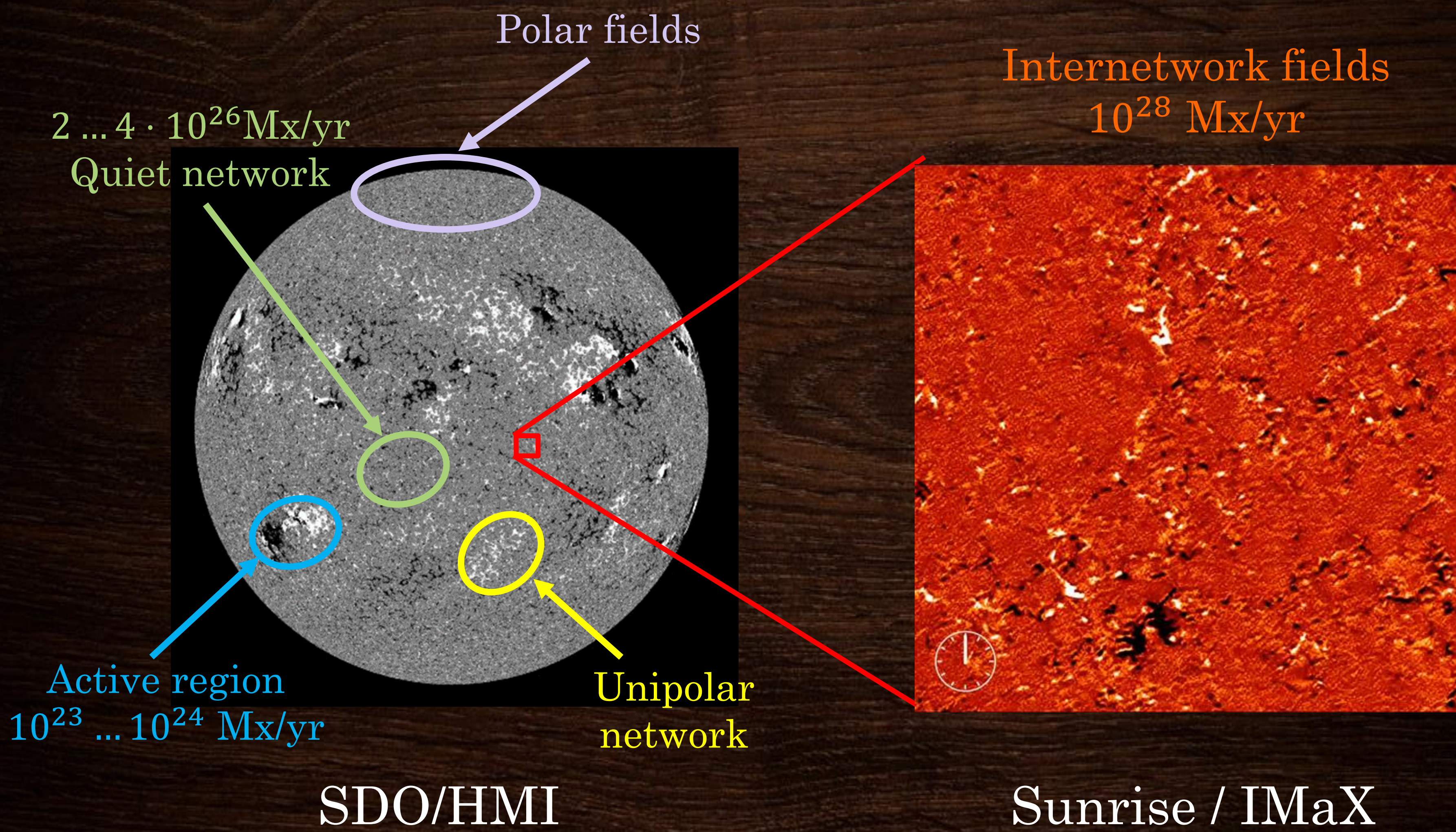


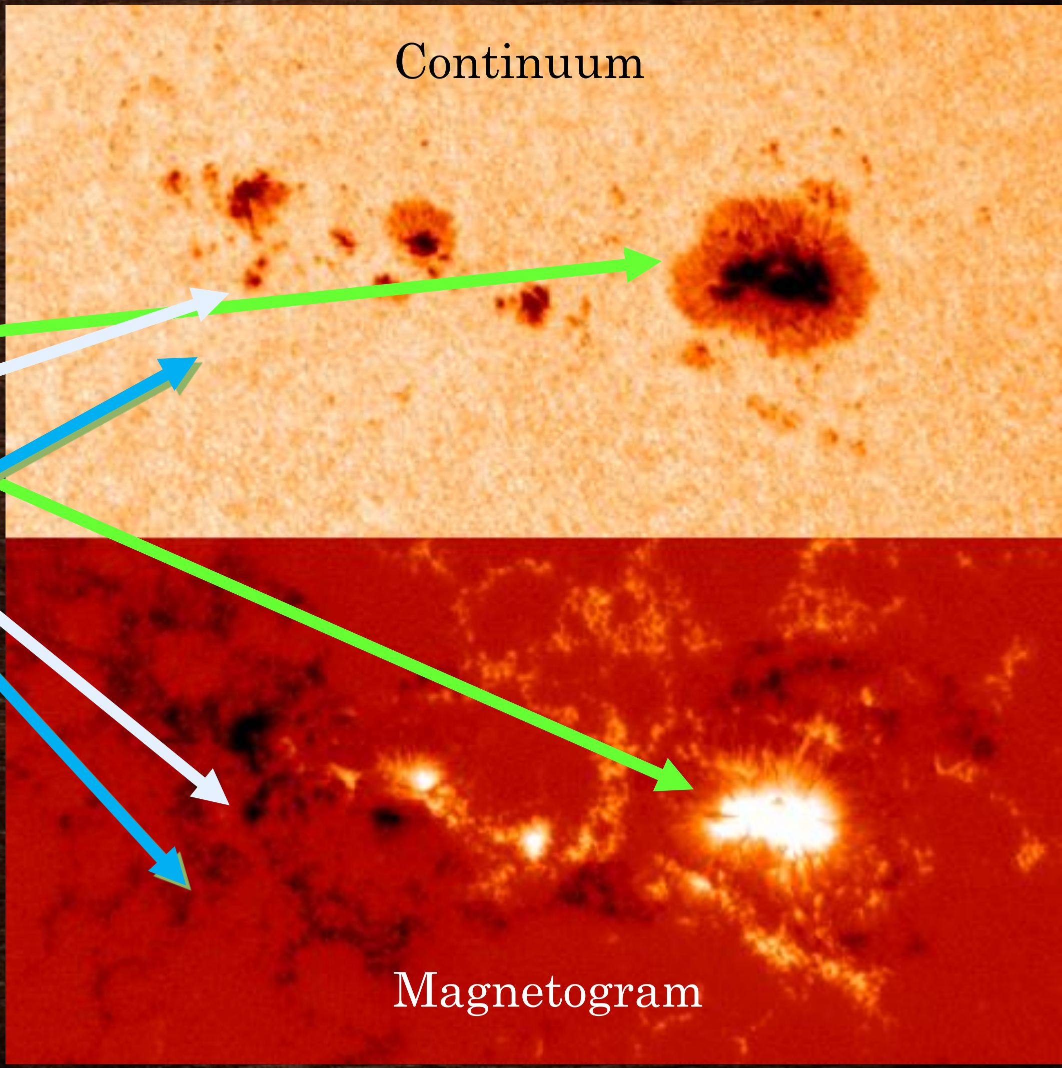
Magnetic fields



What are active regions composed of?

Magnetic structure of active regions is determined by

- sunspots
- pores
- plage or facular magnetic elements



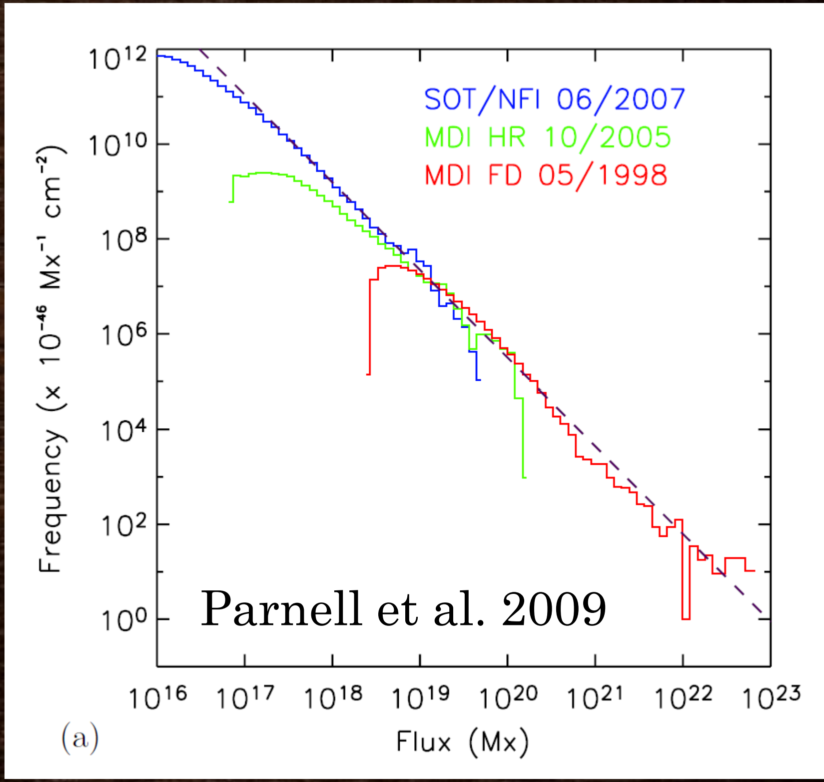
- Flux per feature:
  - Spot: $\Phi=10^{20}\text{-}10^{22}$ Mx
  - Pore: $\Phi=3\cdot10^{18}\text{-}3\cdot10^{20}$ Mx
  - ME: $\Phi=10^{17}\text{-}3\cdot10^{18}$ Mx

How much magnetic flux in different types of features?

- Parnell+ 2009: single power law with exponent –1.85 covers frequency of features with fluxes $10^{17} - 10^{22}$ Mx

- Single power law
  - ➔Do all magnetic features have same source?

- On a star we typically only resolve the largest features
  - ➔Power law: There are many more that we cannot resolve
  - ➔Many seemingly large features may be clusters of smaller ones



Magnetic flux per feature

Sunspots

Umbra Penumbra Granules + lanes

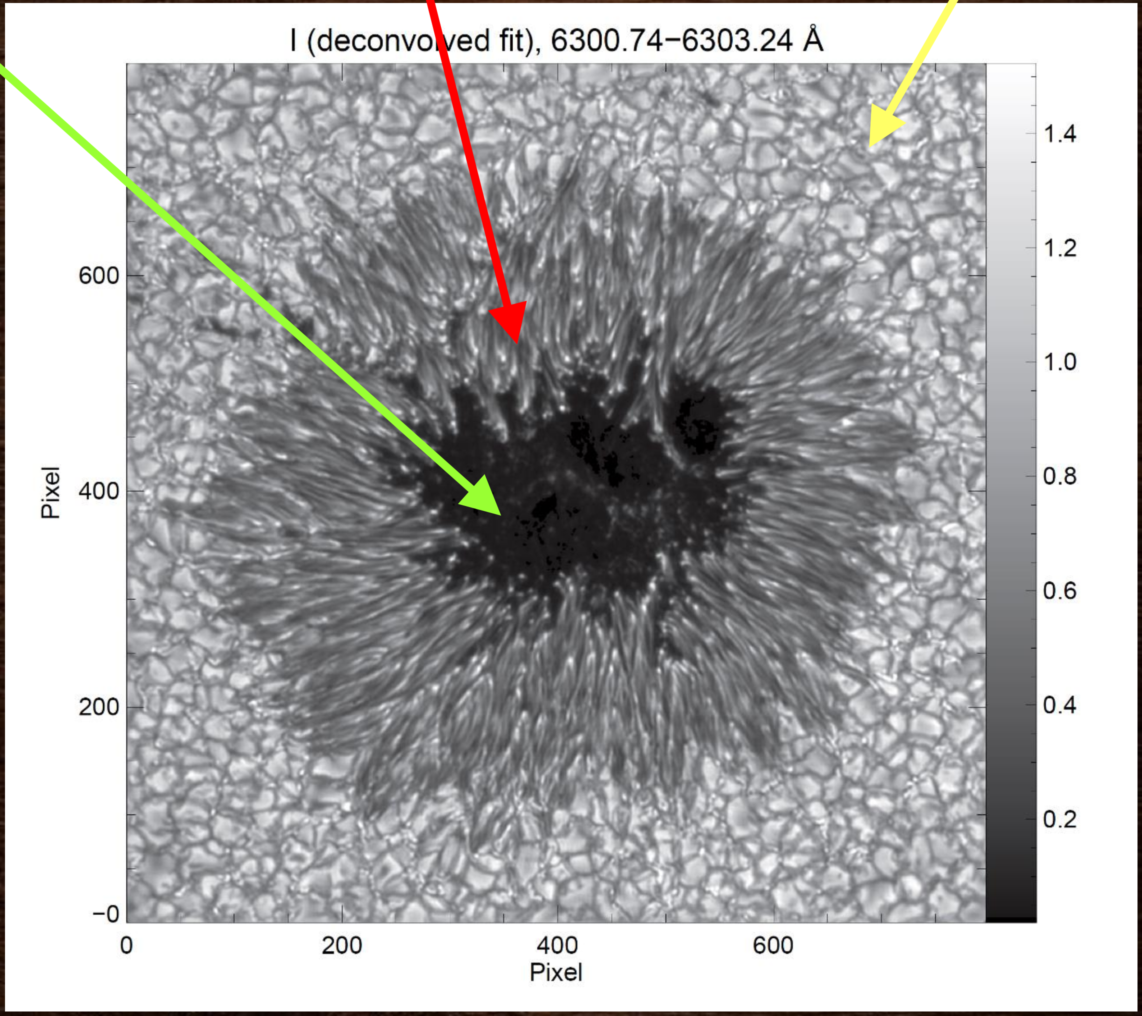
$T_{\text{eff}} \approx 5800$ K

$T_{\text{eff}} \approx 5500$ K

$I_{\text{pen}} = 0.75 I_{\odot}$

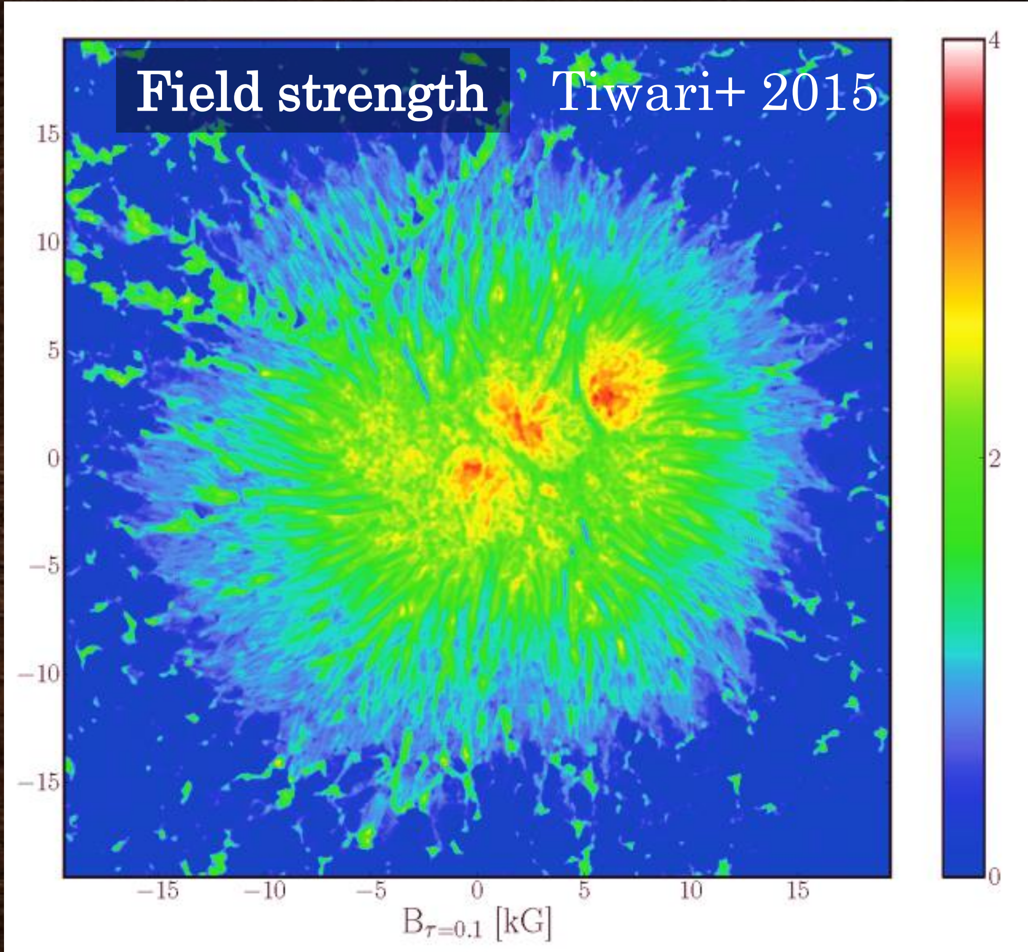
$T_{\text{eff}} \approx 4500$ K

$I_{\text{umb}} = 0.20 I_{\odot}$



Sunspots

- Field: B_{max} = 2500–4500 G; vertical in umbra, nearly horizontal at outer edge
- Brightness: umbra: 20% of quiet Sun, penumbra: 75%
- Evershed flow: horizontal, radially outwards directed flow. Averaged speeds: 1–2 km/s, locally 10km/s
- Sizes: Log-normally distributed (= Gaussian on a logarithmic scale)
- Lifetimes: hours–months: Gnevyshev-Waldmeier rule: Liftetime ~ max spot area



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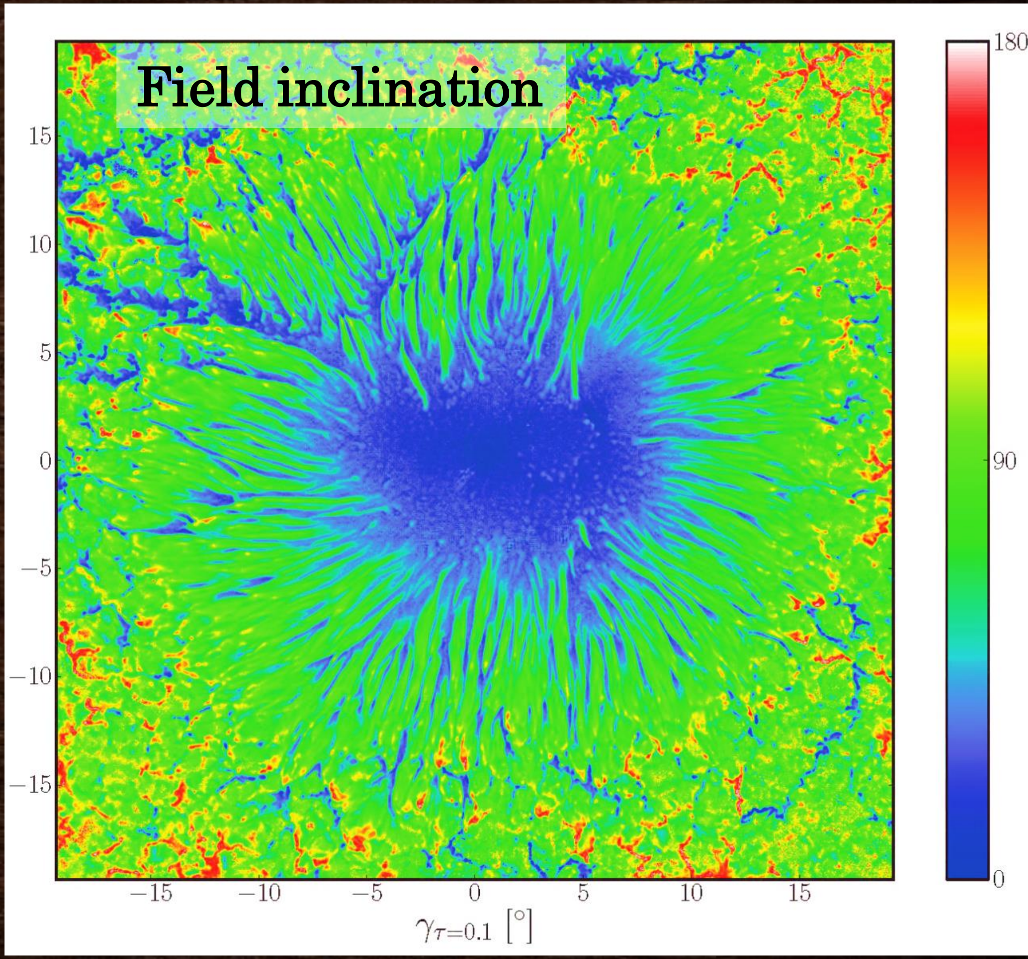

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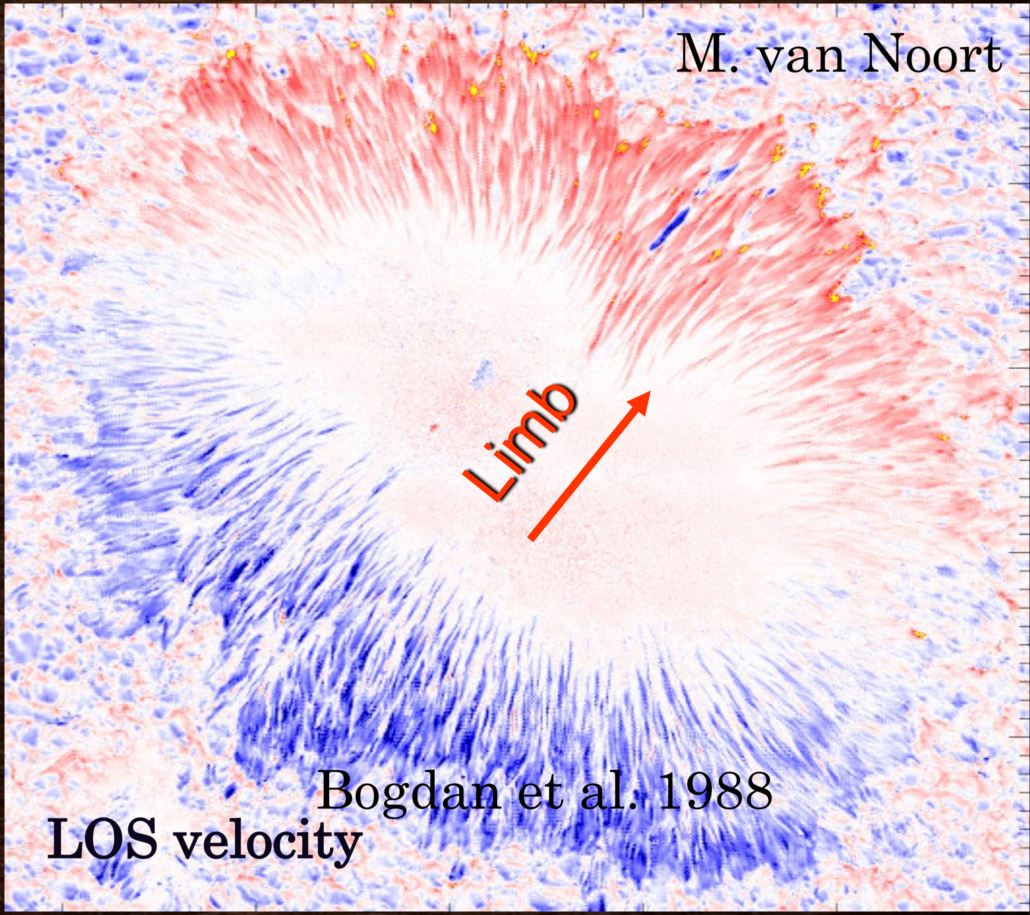

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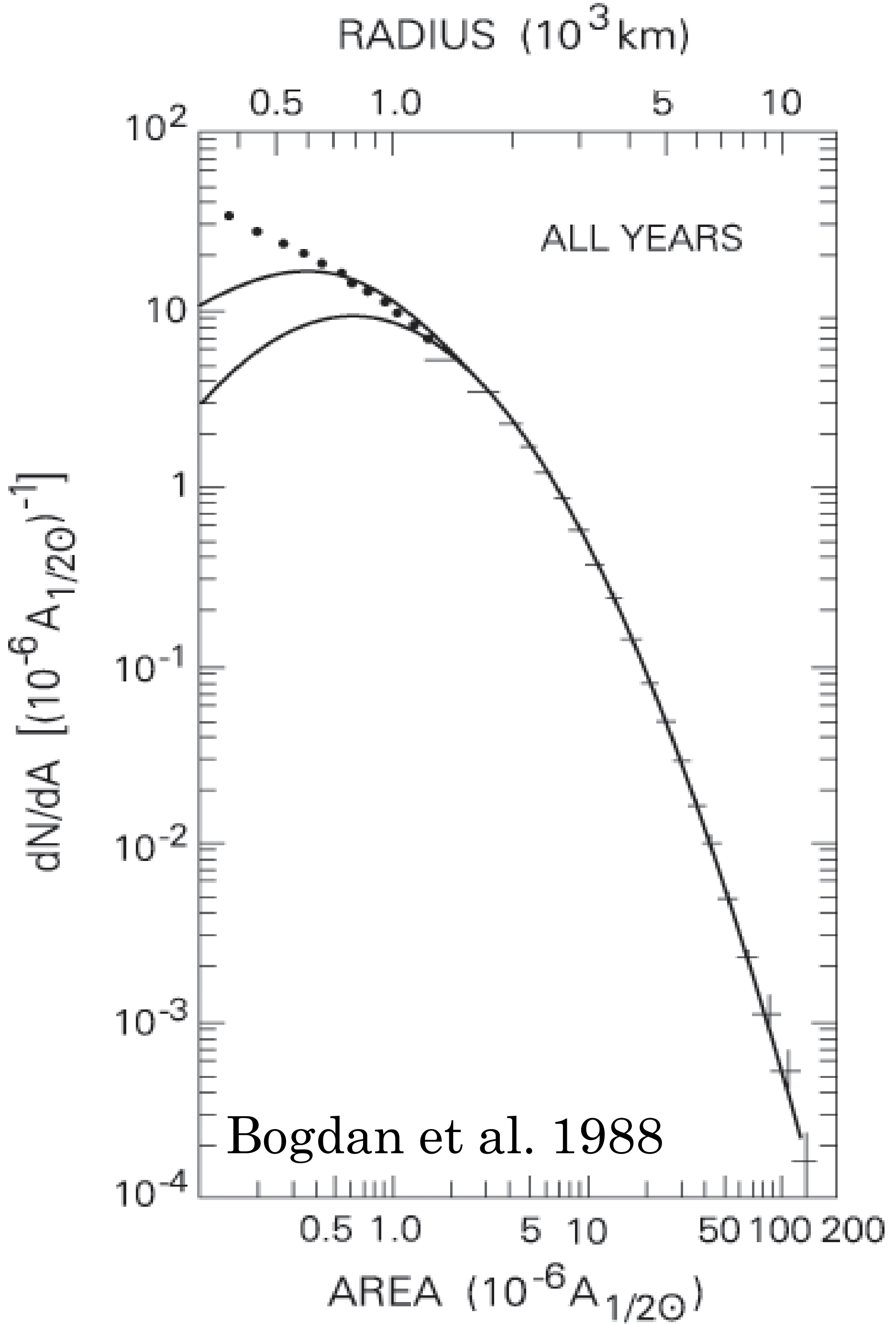
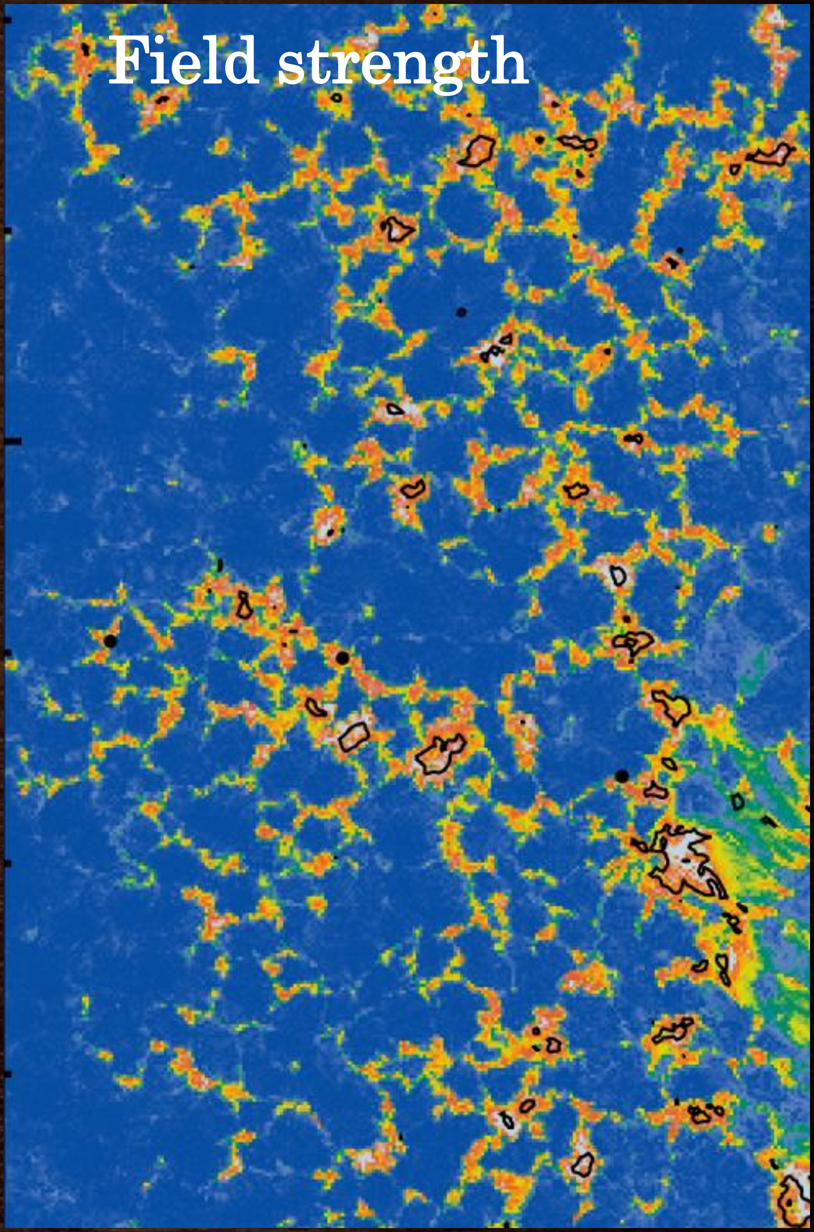


Bogdan et al. 1988

Active region plage

- Plage is composed of magnetic elements: 100-500 km wide; 1500 G field strength near solar surface
- Field strength drops with height and the field expands
- Located in the downflowing lanes surrounding granules
- Each element constantly interacting with convection and with other magnetic features

Bühler et al. 2015



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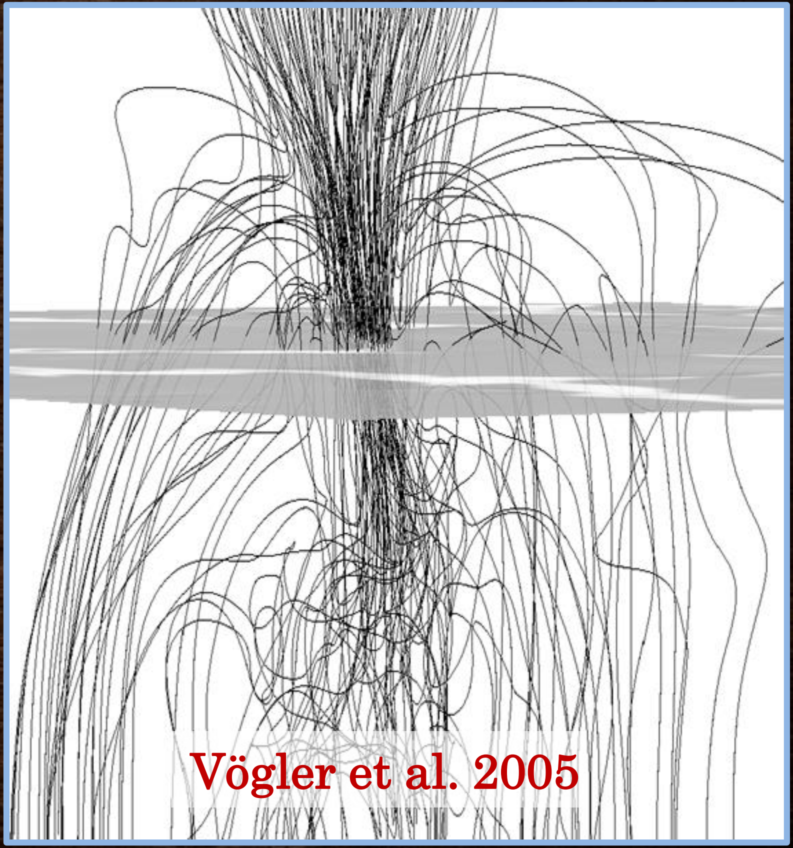

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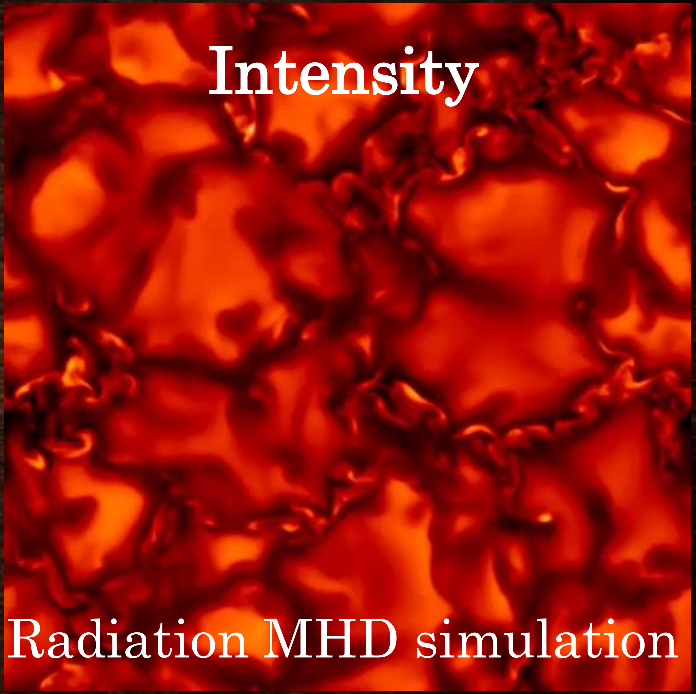
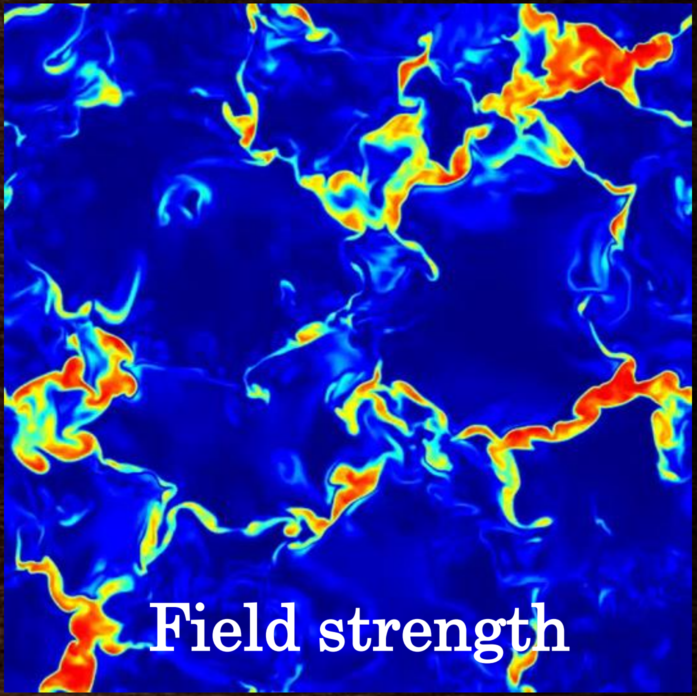
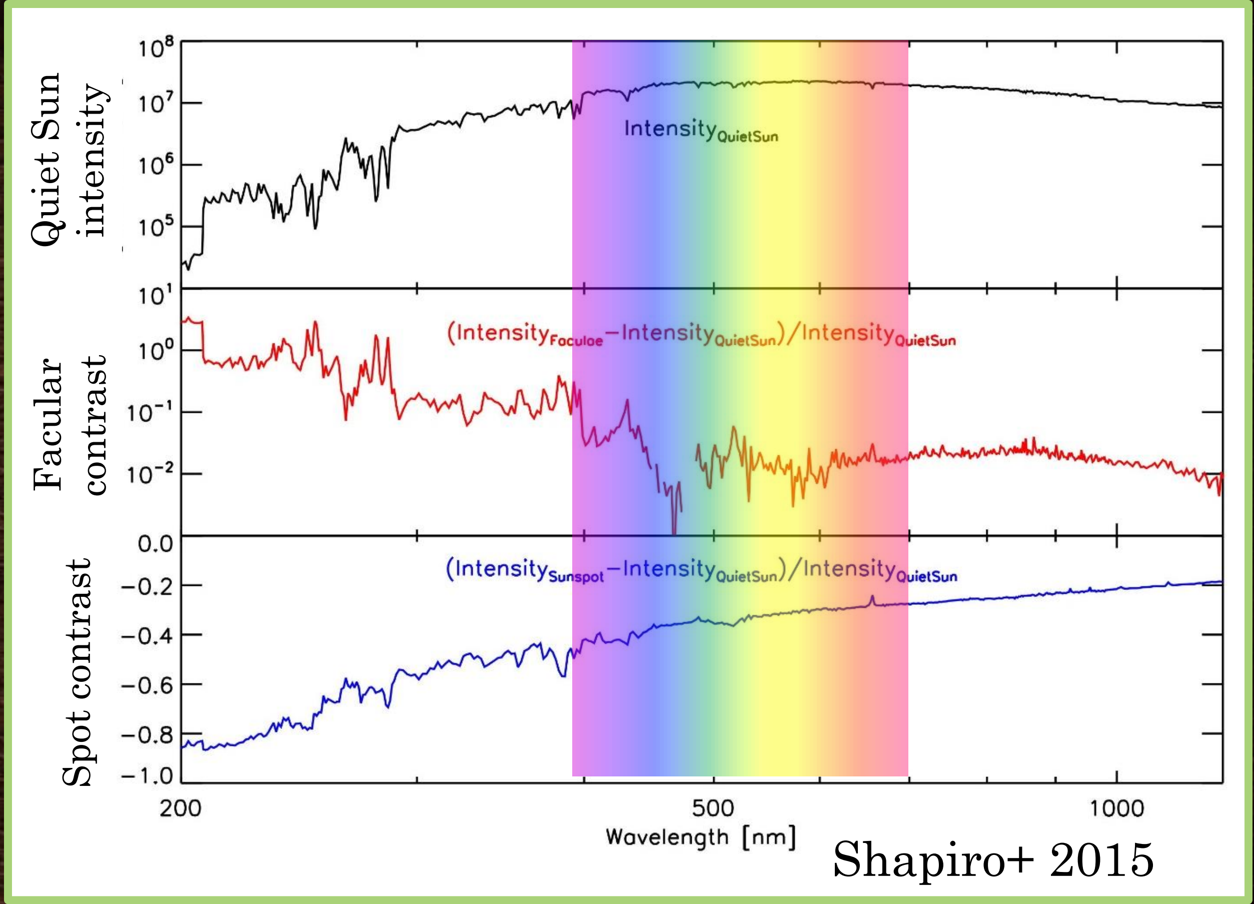
M. Schüssler, R. Cameron





Spectra



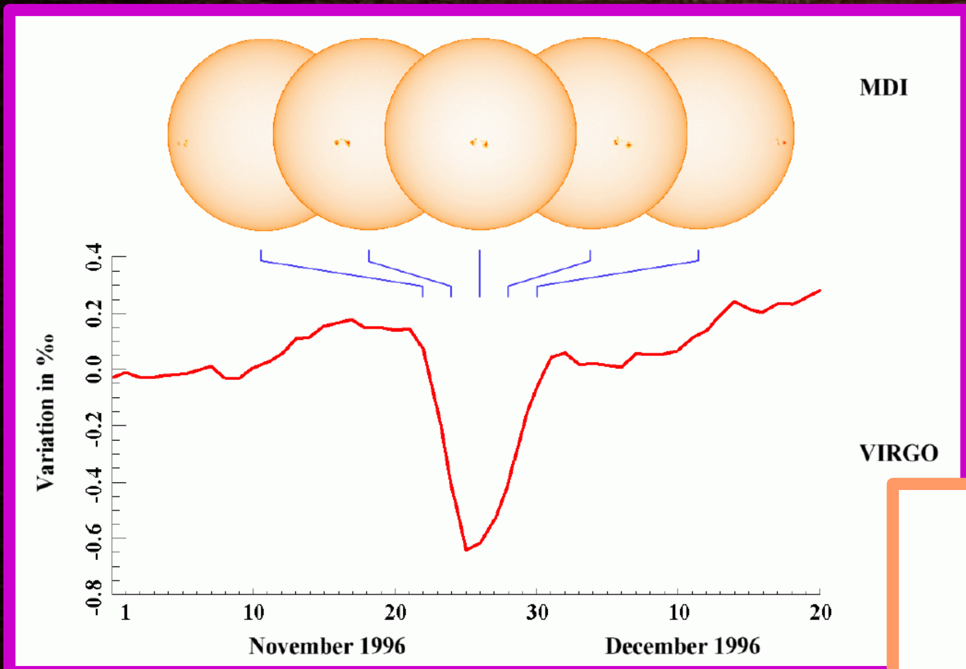
Sun:
UV dominated by facular brightening

IR dominated by spot darkening

Visible: mixture of both (depends on timescale

Other stars: Depends on spectral type and activity level
Low activity G+K stars behave qualitatively like the Sun
Highly active stars tend to be spot dominated in the visible

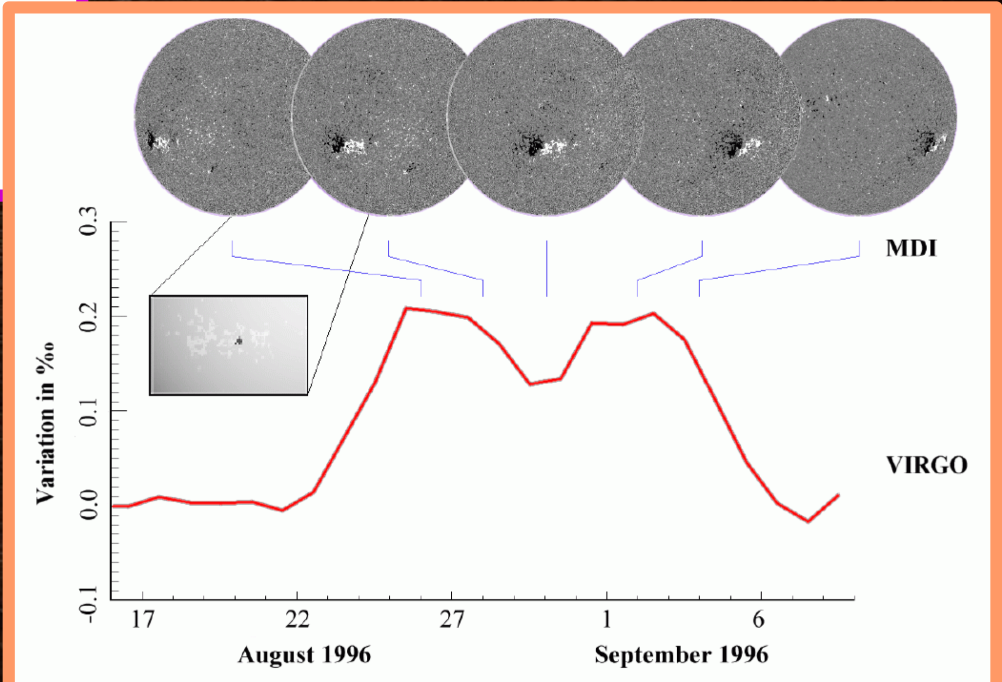
Solar brightness, sunspots and faculae



Sunspots produce a global darkening of the Sun, while faculae lead to a brightening (Fligge et al. 2000; Krivova et al. 2003)

Starspots → darkening of their host stars (amount depends on spectral type)

Effect of faculae (even the sign) depends on spectral type (Beeck+ 2015)



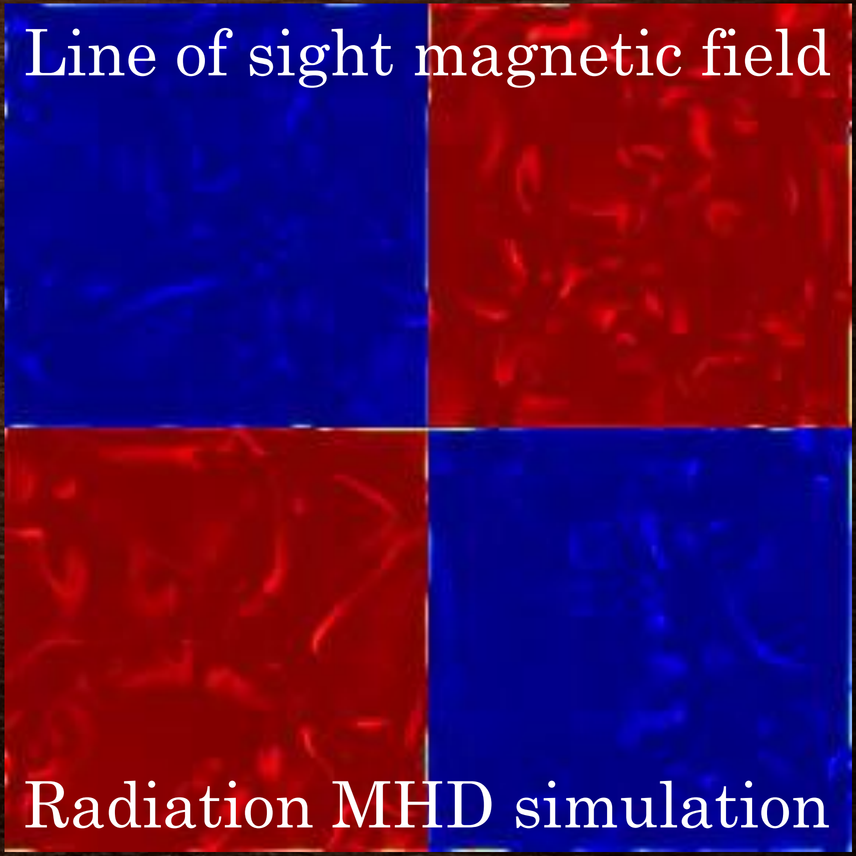
Magnetic flux cancellation

- Opposite magnetic polarities cancel when they come together
- Ohmic dissipation at current sheets leads to a destruction of magnetic flux
- If left to itself, the magnetic flux on the Sun would soon dissipate

➔ There must be constant replenishment by new magnetic flux

Positive magn. polarity

Negative magn. polarity



Cameron et al. 2008

Magnetic flux emergence

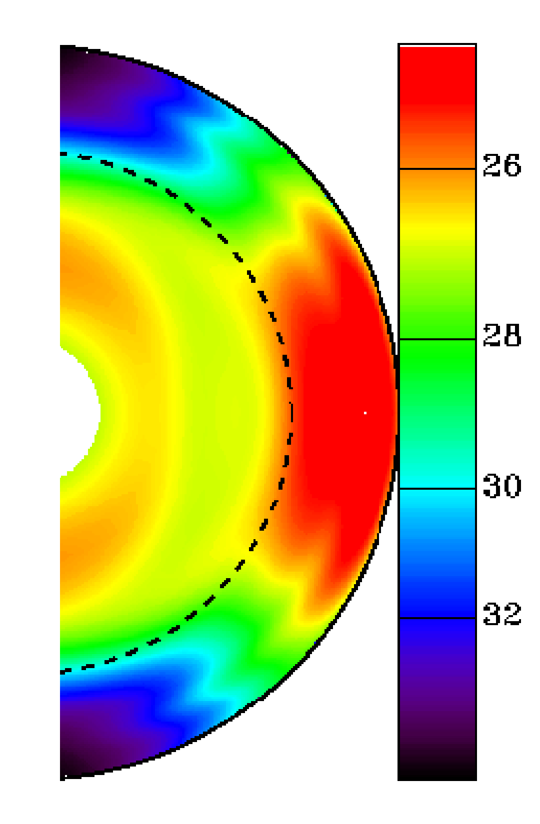
- Magnetic flux, built up in the solar interior by a dynamo process, constantly emerges at the solar surface
- It replenishes the flux lost by cancellation
- Most of the new flux appears in the form of small bipolar features (power law distribution of magnetic flux per bipole)

SOHO/MDI

Differential rotation & meridional circulation

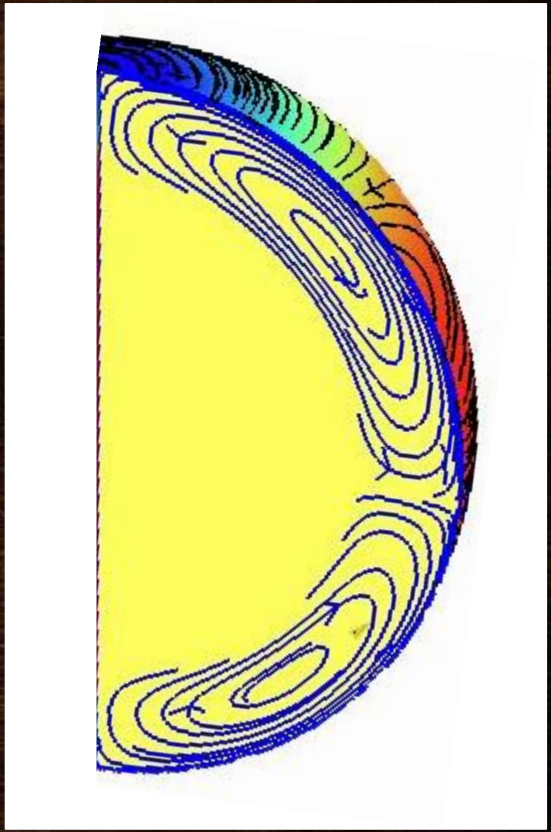
- Solar equator rotates in roughly 25 days (sidereal), poles in 30+ days
- There is a slow (10-20 m/s) flow from equator to poles at solar surface
- Properties at poles are very uncertain
- Both produced by interaction between convection & rotation

Cutaways through Sun. North pole at top



Differential rotation

Schou et al. 1998



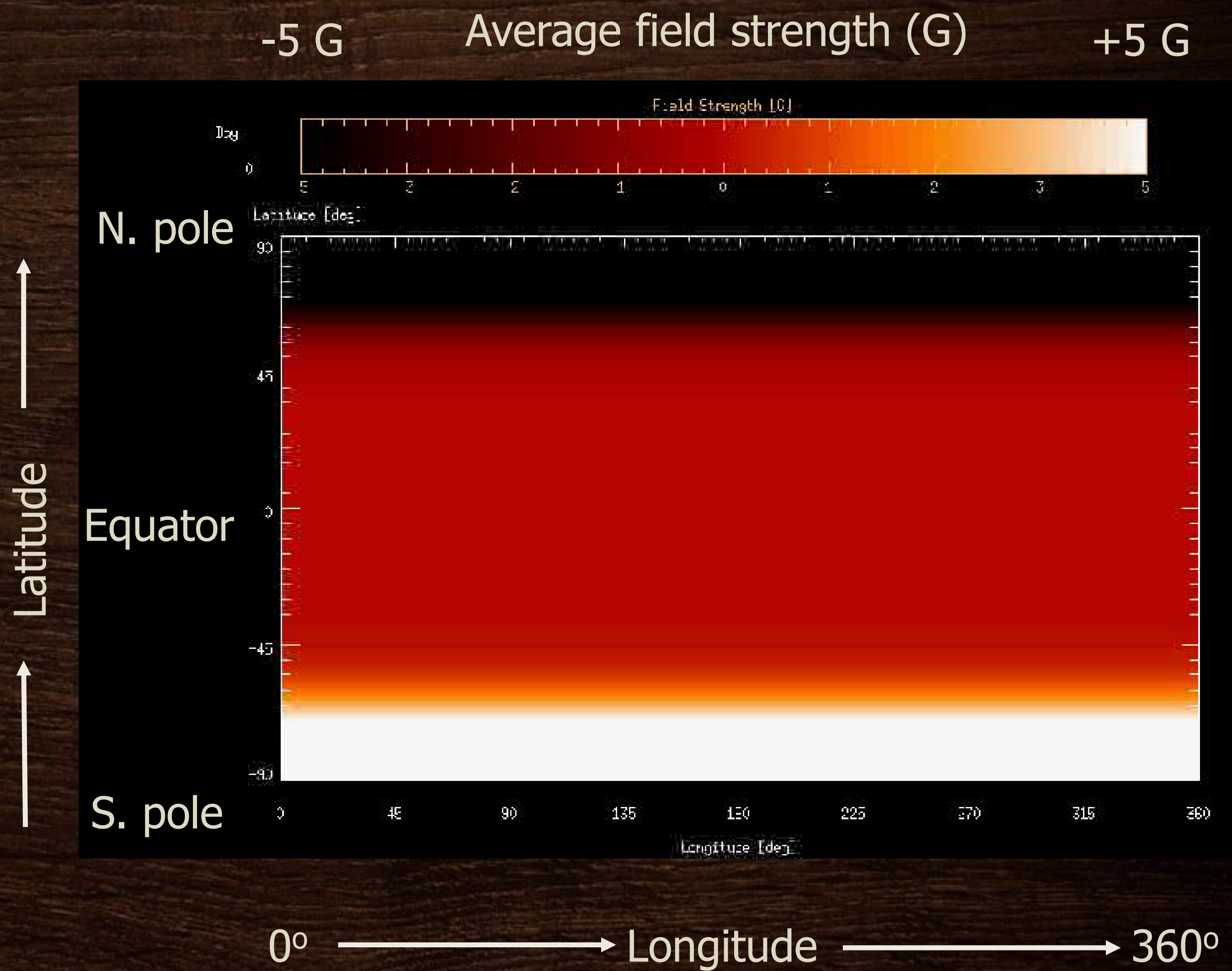
Meridional circulation

Hathaway 2012, Gizon et al. 2017

Effect of surface velocity fields

Surface flux transport model with solar-like cyclic eruption of bipolar magnetic regions

Includes main processes: differential rotation, meridional circulation & diffusion



I. Baumann

Thank you for your attention