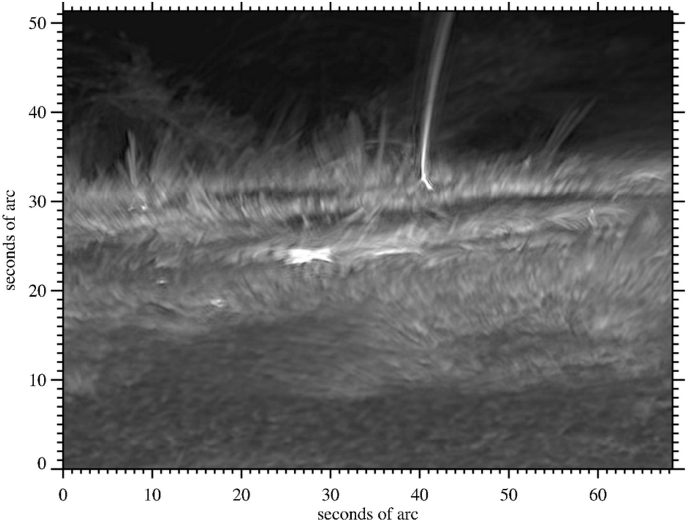
Lecture 12: Flux Tubes

Outline

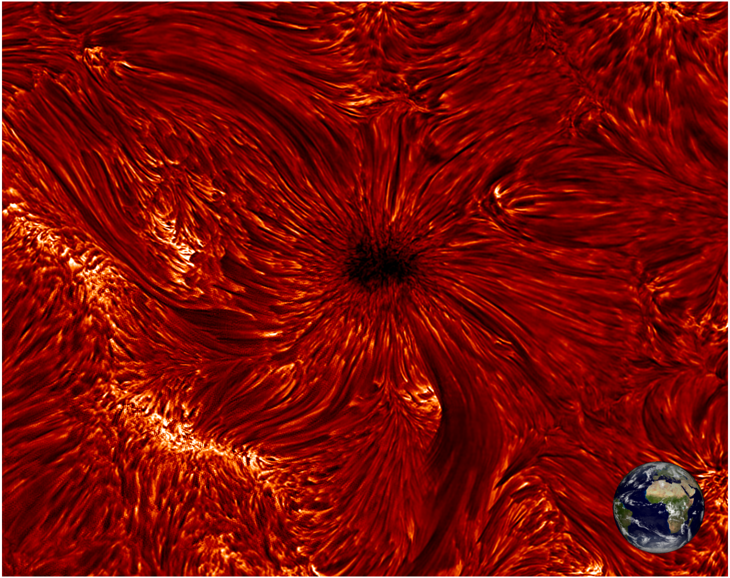
1. Evidence for Flux Tubes
2. Thin Flux Tube Approximation
3. Small-Scale Magnetic Elements
4. Faculae

Observational Evidence

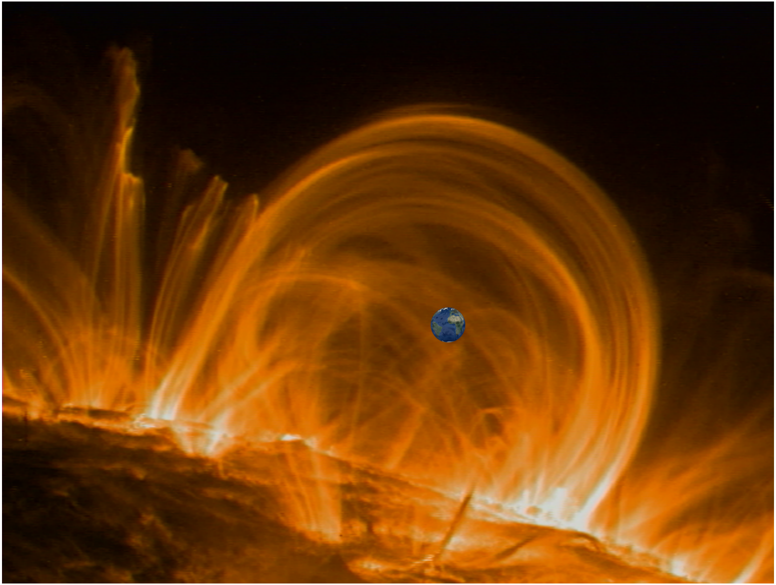
DOT CaII K image close to the limb



DOT Hα image

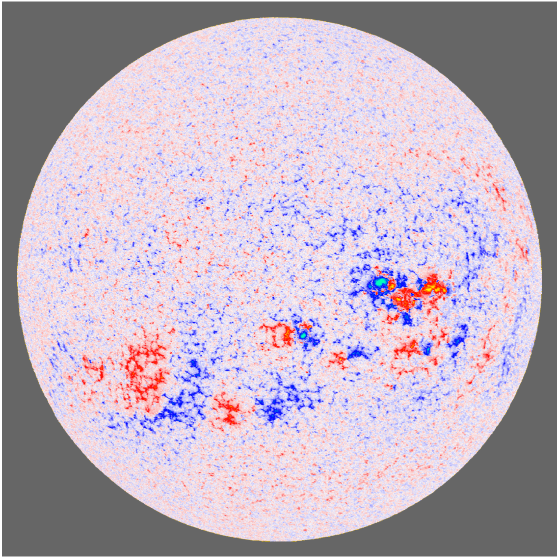


TRACE Loops



www.gsfc.nasa.gov/gsfc/spacesci/sunearth/tracecl.htm

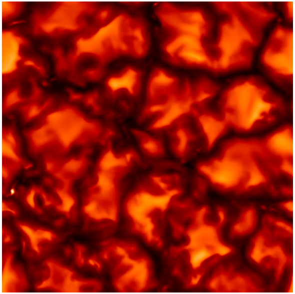
SOLIS VSM Magnetic Field Distribution



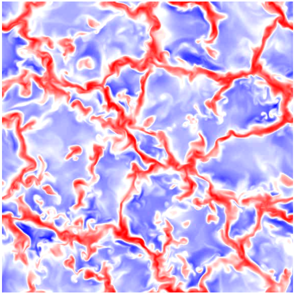
solis.nso.edu

Evidence from MHD Simulations by A. Vögler

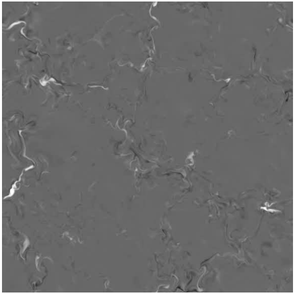
Intensity



Vertical Velocity



Vertical Mag. Field



Magnetic Field Lines

Observational Evidence

- structures reminiscent of magnetic field lines
- often many field lines in parallel
- clear distinction between magnetic and non-magnetic areas
- cross-sections of magnetic flux tubes?

Thin Flux Tube Approximation

Force Balance

- all relative length scales are large compared to tube diameter
- neglect diffusion term in induction equation
- equation of motion

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\vec{v}\cdot\nabla\vec{v}\right)=-\nabla p+\vec{j}\times\vec{B}+\vec{F}_{\mathrm{gravity}}+\vec{F}_{\mathrm{viscosity}}$$

- magnetohydrostatic ($\vec{v}=0\Rightarrow F_{\mathrm{viscosity}}=0$)
- force balance

$$\nabla p-\vec{j}\times\vec{B}=\vec{F}_{\mathrm{gravity}}$$

- with $\mu_0\vec{j}=\nabla\times\vec{B}$ and $\vec{B}\times\left(\nabla\times\vec{B}\right)=\frac{1}{2}\nabla B^2-\left(\vec{B}\cdot\nabla\right)\vec{B}$

$$\nabla\left(p+\frac{B^2}{2\mu_0}\right)-\frac{1}{\mu_0}\left(\vec{B}\cdot\nabla\right)\vec{B}=\vec{F}_{\mathrm{gravity}}$$

Radial Force Balance

- force balance in general coordinate system

$$\nabla\left(p+\frac{B^2}{2\mu_0}\right)-\frac{1}{\mu_0}\left(\vec{B}\cdot\nabla\right)\vec{B}=\vec{F}_{\mathrm{gravity}}$$

- in cylindrical coordinates for vertical field, radial component

$$\frac{\partial}{\partial r}\left(p+\frac{B^2}{2\mu_0}\right)-\frac{1}{\mu_0}\left(B_r\frac{\partial B_r}{\partial r}+B_z\frac{\partial B_r}{\partial z}-\frac{B_\phi^2}{r}\right)=0$$

- with $B_{r,\phi}=0$

$$\frac{\partial}{\partial r}\left(p+\frac{B^2}{2\mu_0}\right)=0$$

- and therefore *horizontal pressure balance*

$$p_{\mathrm{inside}}+\frac{B^2}{2\mu_0}=p_{\mathrm{outside}}$$

Plasma Beta

- horizontal presure balance

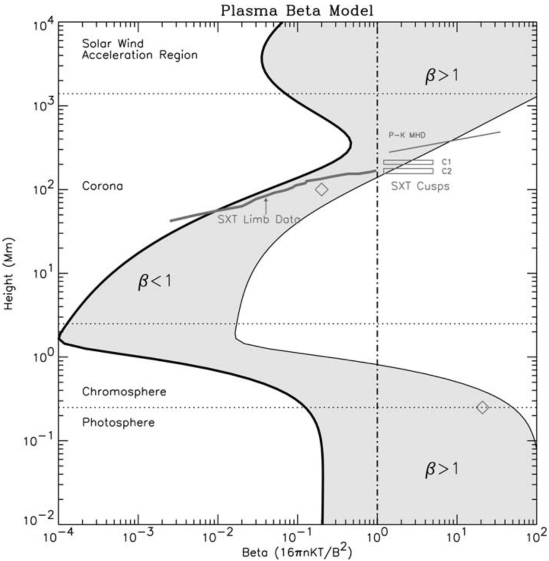
$$p_{\text{inside}} + \frac{B^2}{2\mu_0} = p_{\text{outside}}$$

- plasma beta

$$\beta = \frac{2\mu_0 p}{B^2}$$

- *Plasma* β: ratio of gas pressure to magnetic pressure
- determines whether gas pressure or magnetic field 'pressure' is more important

Plasma Beta



- $\beta = \frac{2\mu_0 P}{B^2}$
- model by G. A. Gary (2001)
- photosphere and solar wind are pressure dominated
- corona is magnetic-field dominated

Vertical Force Balance

- in the z-direction (along the field lines)

$$\frac{\partial p}{\partial z} = -\rho g$$

- with ideal gas law $\rho = \frac{\mu p}{kT}$

$$\frac{\partial p}{\partial z} = -\frac{\mu g}{kT} p$$

- pressure as a function of height z

$$p\left(z\right) = p\left(z_0\right) \exp\left(-\int_{z_0}^{z} \frac{1}{H\left(z'\right)} dz'\right)$$

- with the *pressure scale height*

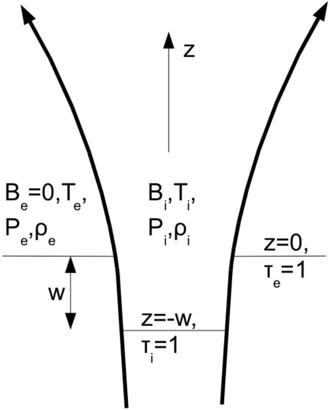
$$H\left(z\right) = \frac{kT}{\mu g}$$

Wilson Depression

- thin flux tube in stratified atmosphere
- horizontal pressure balance

$$p_i + \frac{B^2}{2\mu_o} = p_e$$

- $p_i < p_e$
- thermal equilibrium ($T_i = T_e$) and therefore $\rho_i < \rho_e$
- flux tube is buoyant and therefore nearly vertical
- opacity in flux tube is less than outside
- see deeper into magnetic fields



Vertical Expansion

- assume $T_i = T_e \Rightarrow H_i = H_e$
- stratification

$$p_{i,e}(z) = p_{i,e}(z_0) \exp\left(-\int_{z_0}^{z} \frac{1}{H(z')} dz'\right)$$

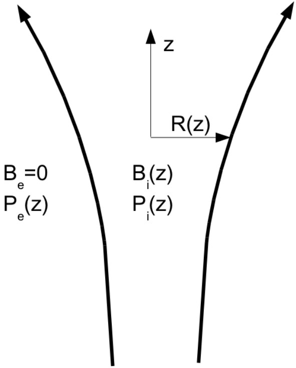
- magnetic flux is conserved

$$\pi R(z)^2 B(z) = \text{constant}$$

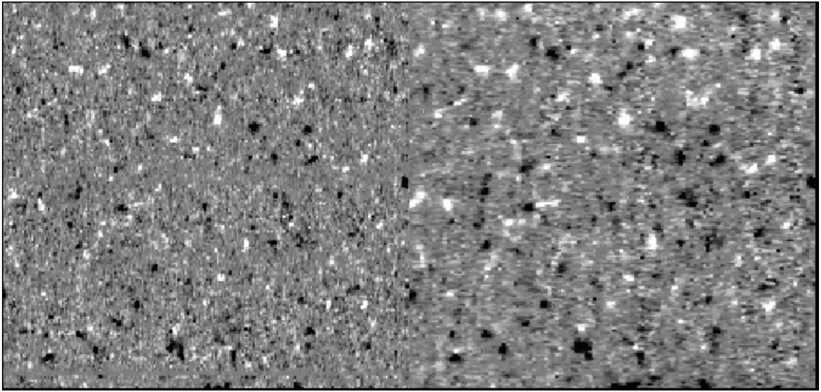
- magnetic field is given by gas pressure difference

$$B(z)^2 = 2\mu_0 (p_e - p_i)$$

- therefore $B(z) \sim \sqrt{P_e}$
- therefore $R(z) \sim P_e^{-\frac{1}{4}}$

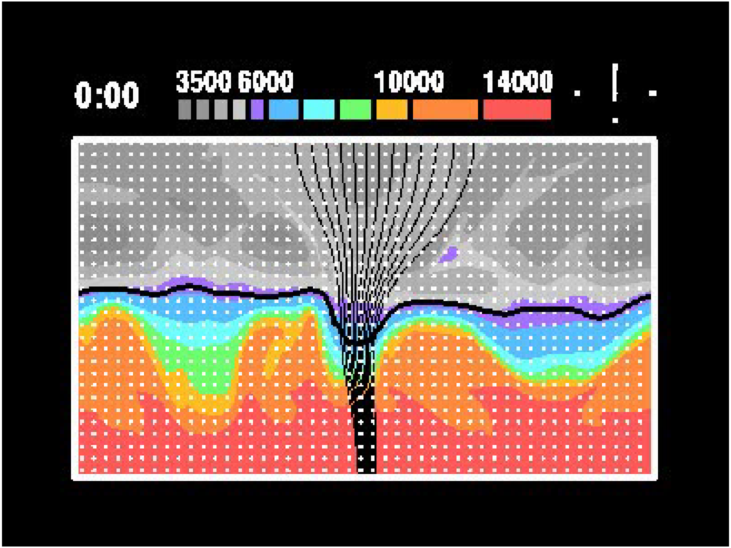


Simultaneous Photospheric and Chromospheric Magnetograms



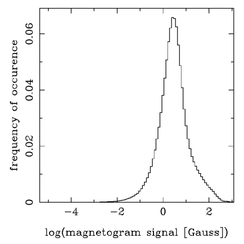
Original data courtesy K.Harvey

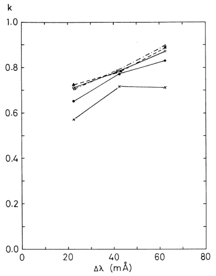
2-D Simulations by Oskar Steiner



http://www3.kis.uni-freiburg.de/˜steiner

Small-Scale Magnetic Elements

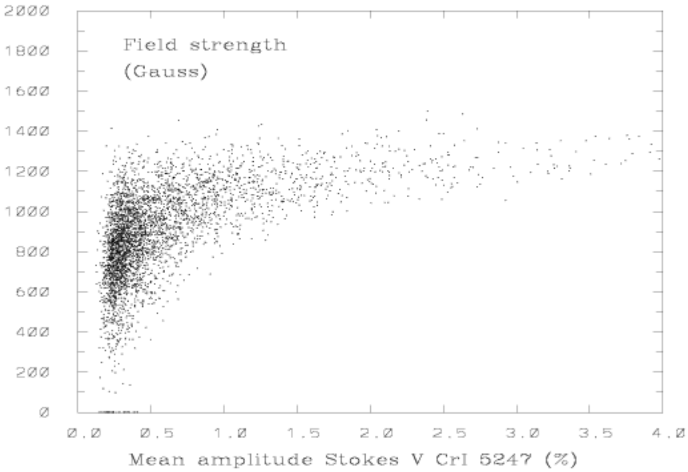




A Little History

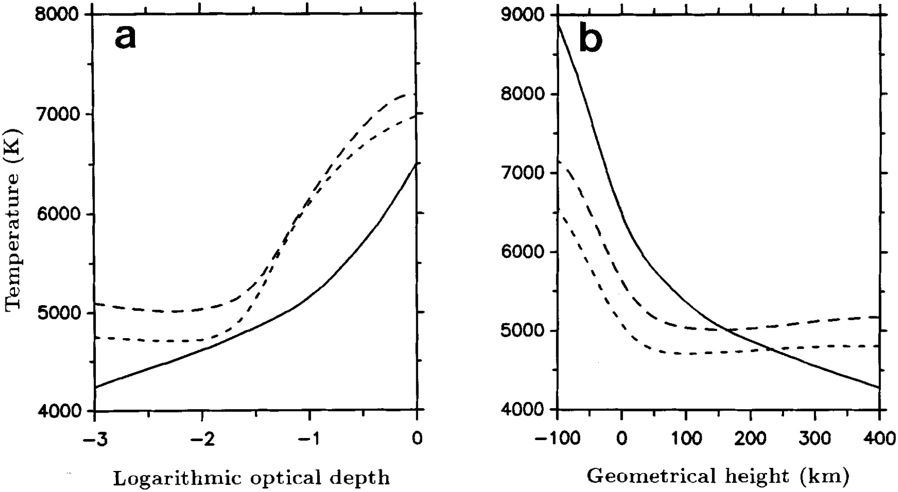
- much of measured magnetogram signal 0-100 Gauss
- ratio of magnetograms in 2 spectral lines with “only” different Landé g-factors (line ratio technique)
- indicates high field strengths of 1000-2000 Gauss
- indicates that magnetic field is not space-filling
- *filling factor* describes fraction of resolution element filled with magnetic field

Flux vs. Field Strength



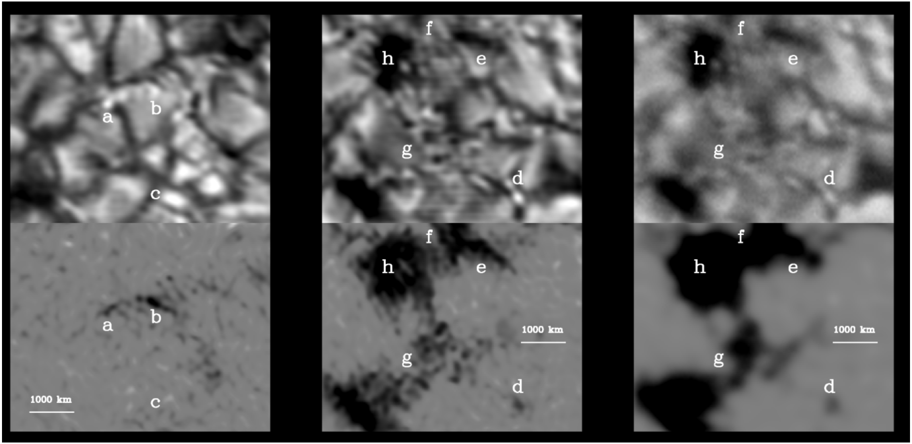
Grossmann-Doerth, Keller, Schüssler 1996

Temperature Structure



Keller et al. 1990

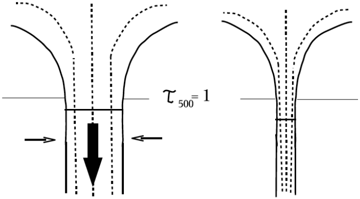
Direct Detection of Concentrated Fields



Keller 1992

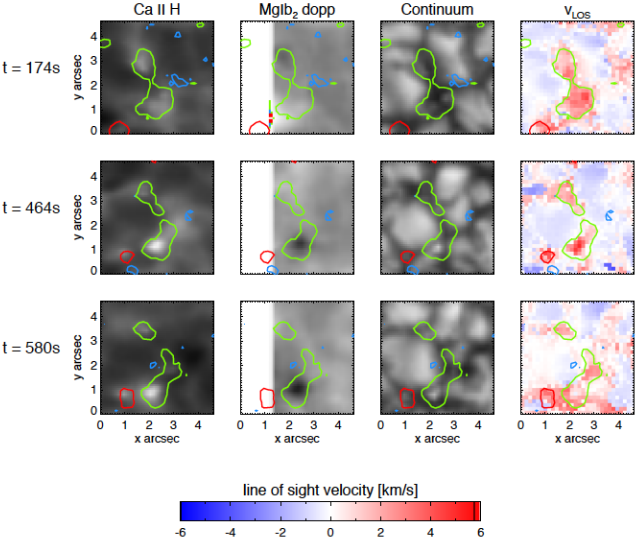
Convective Collapse

A Description



- kinetic equipartition field strength $\frac{B^2}{2\mu_0} = \rho\frac{v^2}{2}$
- typical values in the photosphere: 400 G
- magnetic field inhibits convection
- reduced heating leads to lower temperature
- correspondingly higher density makes material sink

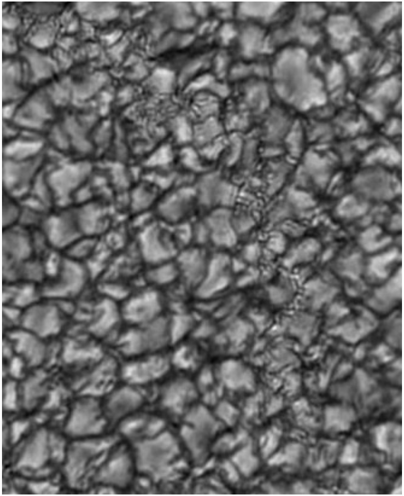
Observation of Convective Collapse



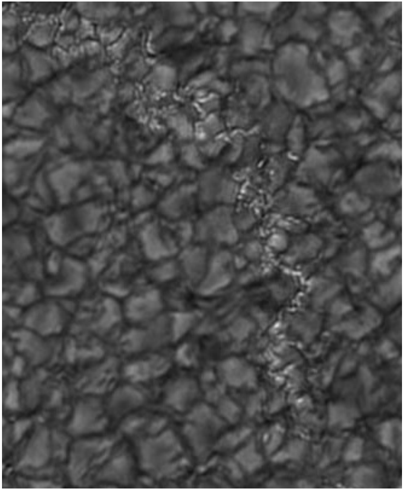
Fischer et al. (2009)

G-Band Bright Points from DOT

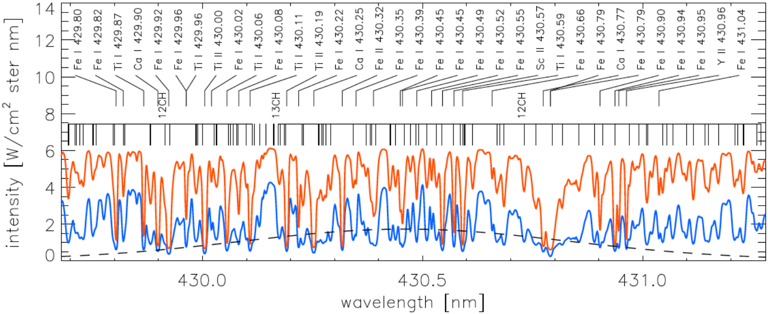
Blue Continuum



G-Band



G-Band Explained

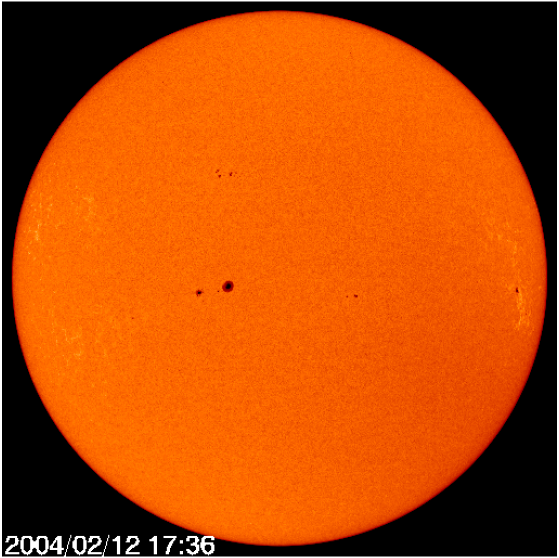


without magnetic field (blue) and with magnetic field (red); Steiner et al. 2001

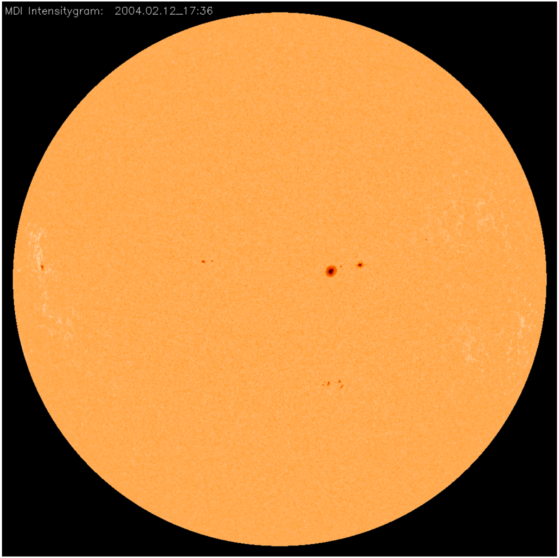
- G-band due to CH molecules
- upper layers of flux tubes are hotter than surrounding photosphere
- higher temperature dissociates CH
- continuum shines through CH forest

Faculae

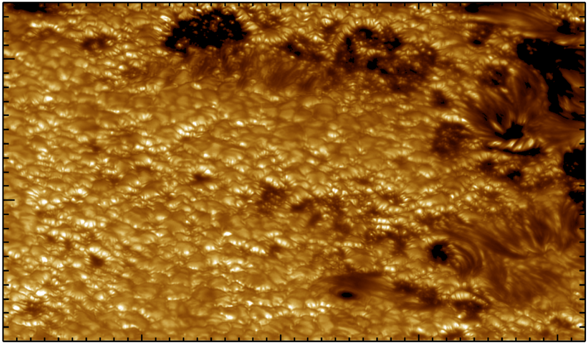
The Sun in White Light from SOHO/MDI



The Sun without Limb Darkening from SOHO/MDI



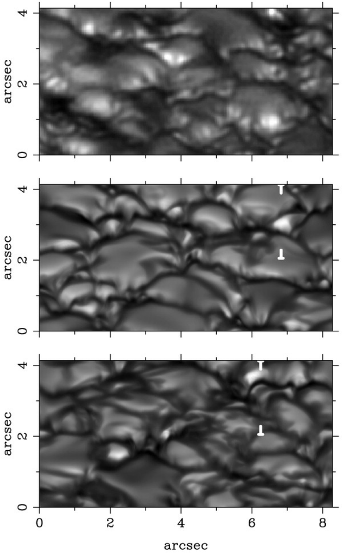
1-m Swedish Solar Telescope Observations by Lites et al. (2004)



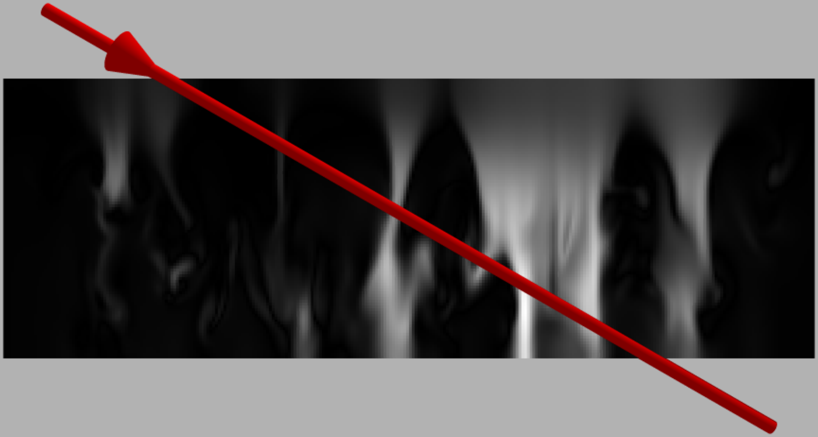
- 3-D impression when looking at images
- Faculae appear predominantly in plages
- Facular brightenings on disk-center side of granules
- Brightening can extend over about 0.5 arcsec
- Narrow, dark lanes centerward of the facular brightening

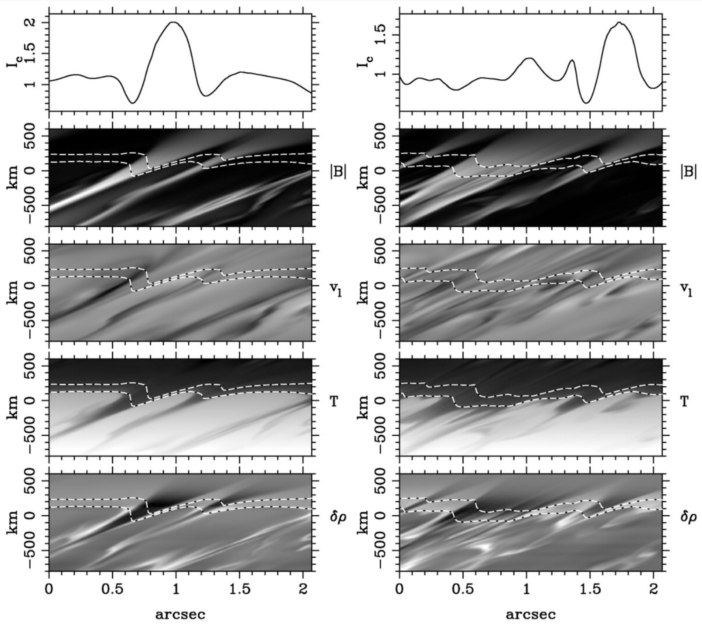
Comparison of Observations and Simulations

- observations by Lites et al. (2004) at top
- simulations for 200G and 400G average field strength below
- simulations very similar to observations



Keller et al. 2004





I_c
1
1.5
2
km
500
0
−500
|B|
v_1
T
δρ
0
0.5
1
1.5
2
arcsec

Faculae Explained

- largely consistent with earlier “bright wall” model (Spruit 1976)
- expansion of flux concentrations leads to large facular size
- narrow, dark lanes are due to the same effect