SOLAR PHOTOSPHERE

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What is the Solar Photosphere?

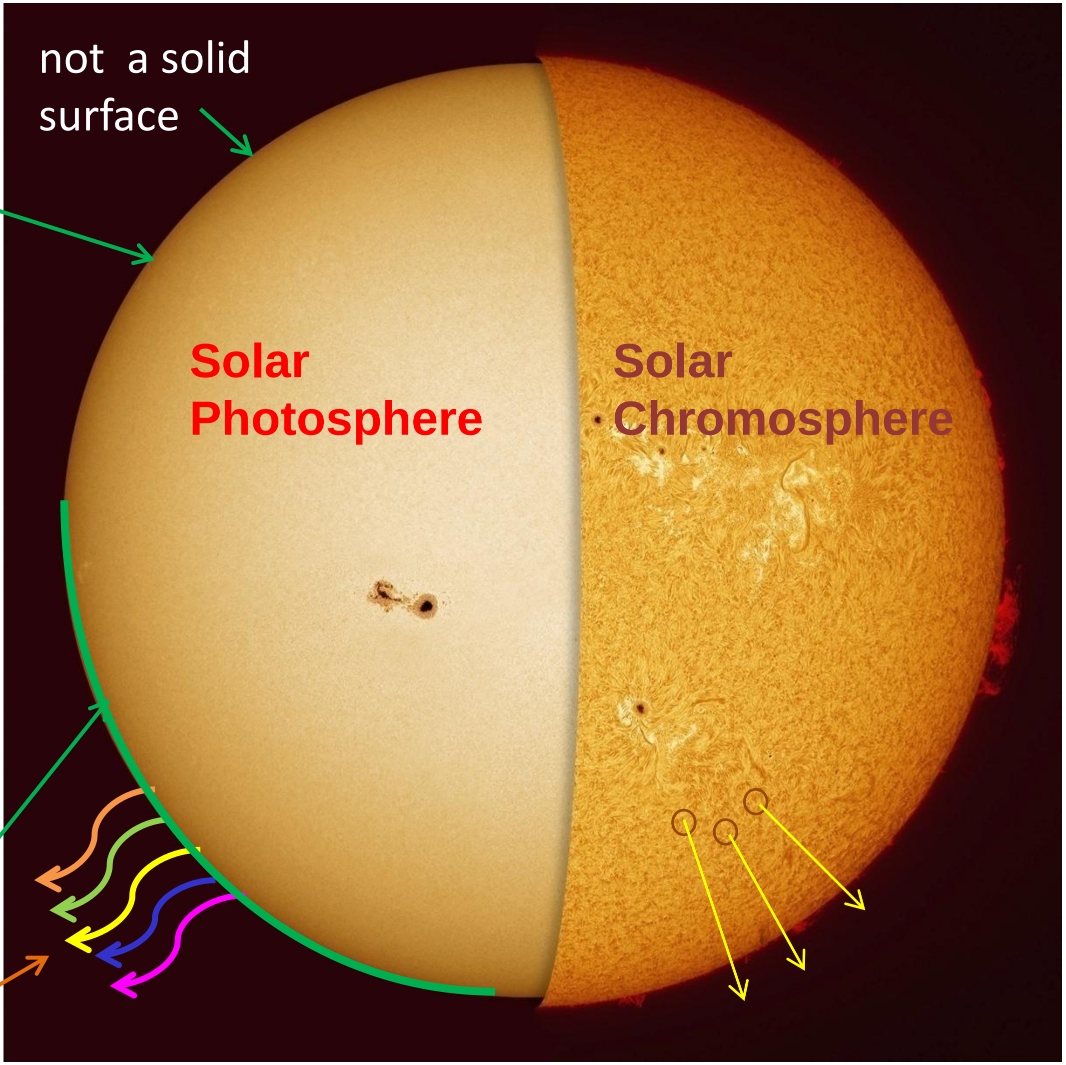
The photosphere is:
the depth of a solar outer shell from which light is radiated
or
The photosphere is:
the visible "surface" of the Sun

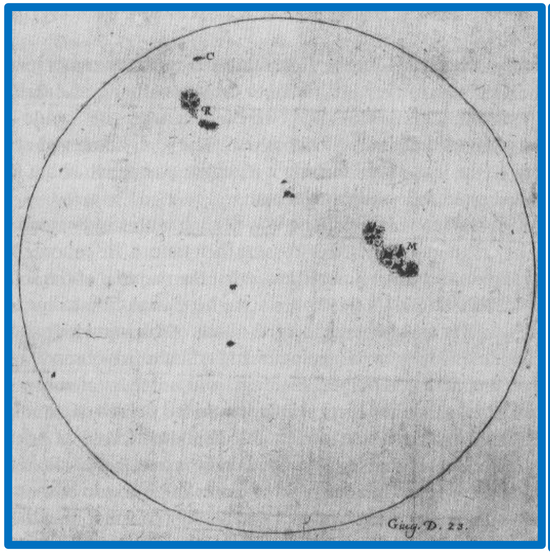
The term itself is derived from ancient Greek roots:
φῶς, φωτός/phos, **photos** meaning „light“

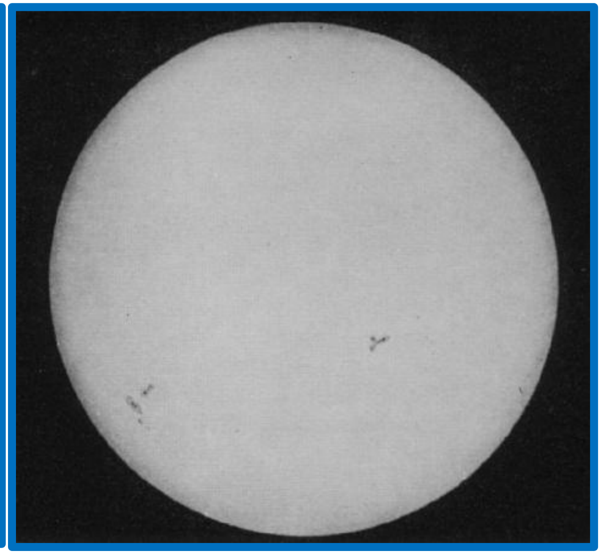
and

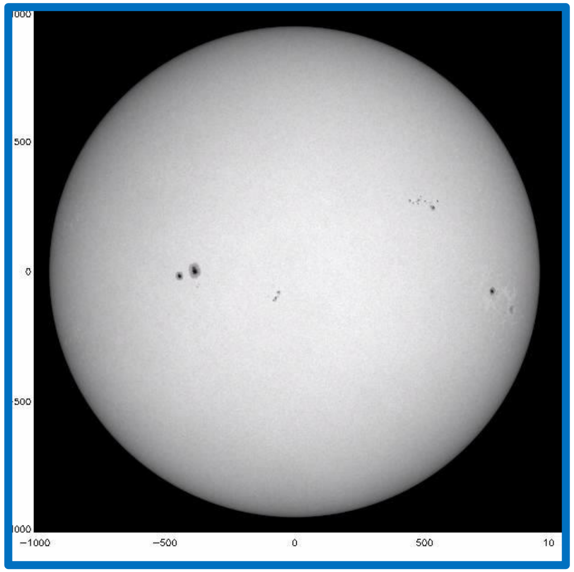
σφαῖρα/ **sphaira** Meaning „sphere“

in reference to the fact that it is a **spherical surface** that is perceived to emit **light**









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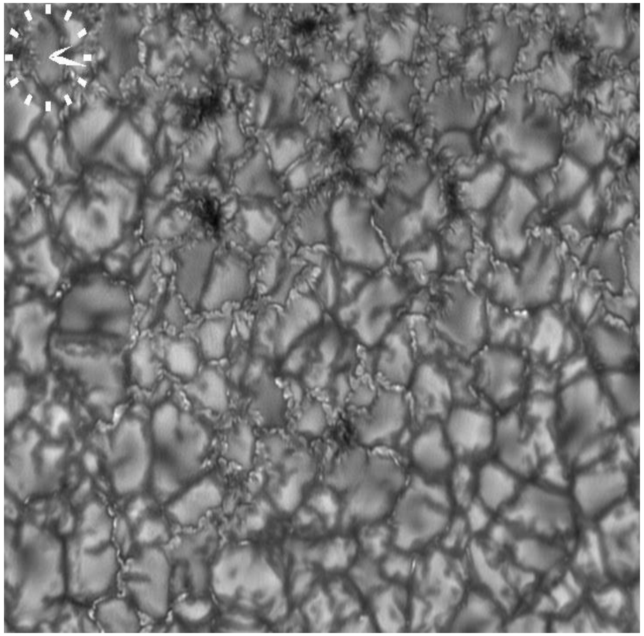


2014

Goal of this talk:

What is the progress in our knowledge on the

PHOTOSPHERE

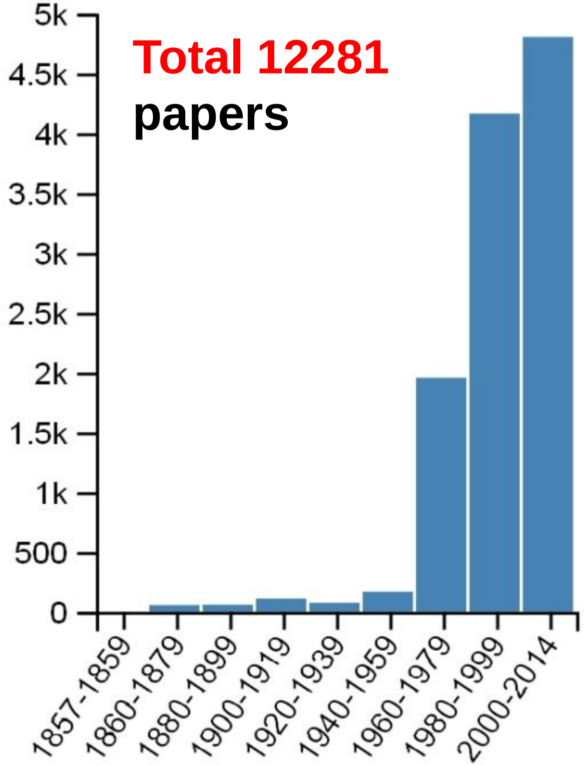
in

404 YEARS

described in

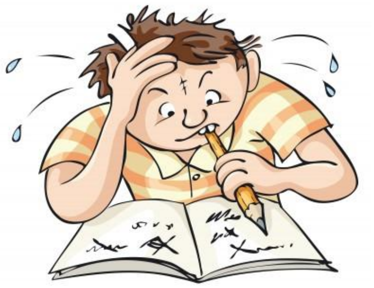
12281 !! papers

?



Structure of the talk:

As promised care-freely and desperately in the abstract, months ago.



1. **Basic physical properties of the solar photosphere**
2. **Photosphere radiation, formation of absorption spectral lines, optical depth, limb darkening**
3. **Velocity and magnetic fields taking place in the photosphere**
4. **Principles of modeling of the photosphere**
5. **Comparison of the photosphere with the other layers of the solar atmosphere and with the layer located below the solar photosphere**

Structure of the talk:

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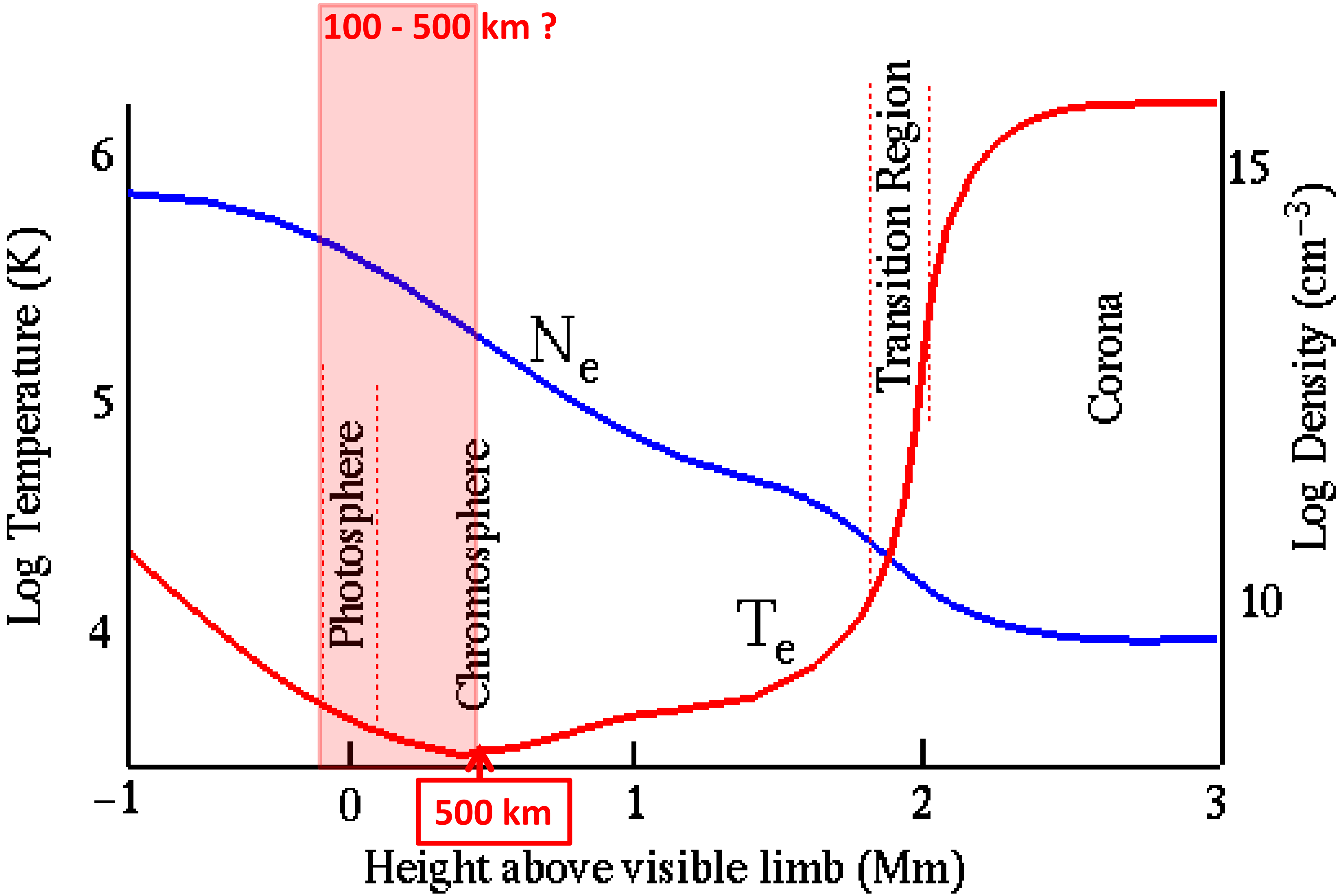
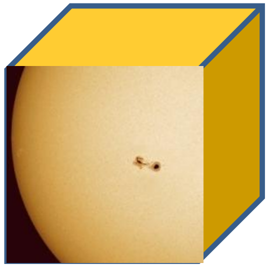
1. Basic physical properties of the solar photosphere

Photosphere thickness – not clear! Everyone says different



1. Basic physical properties of the solar photosphere

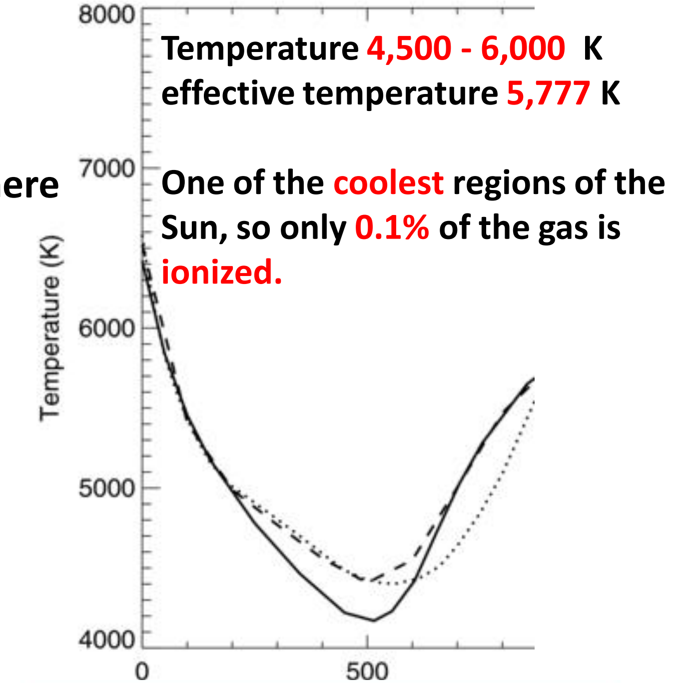


Solar Photosphere

Densest part of the solar atmosphere,
but is still tenuous compared to Earth's atmosphere
(0.01% of the mass density of air at sea level).

Density of about	$0.0002\ kg/m^3$
Pressure (top)	0.00085 Atm
Pressure (bottom (τ = 1))	0.123 Atm

Photosphere major elements:
H - 90.965%, He - 8.889%



Terrestrial Atmosphere

Surface density	1.2170 kg/m3
Surface pressure	1.0007 Atm

Water

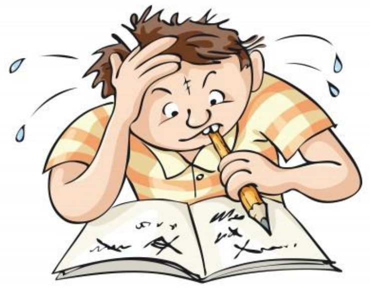
density	1000.0000 kg/m3

Solar Photosphere as a Function of Depth

Depth (km)	% Light from this Depth	Temperature (K)	Pressure (bars)
0	99.5	4465	6.8×10^{-3}
100	97	4780	1.7×10^{-2}
200	89	5180	3.9×10^{-2}
250	80	5455	5.8×10^{-2}
300	64	5840	8.3×10^{-2}
350	37	6420	1.2×10^{-1}
375	18	6910	1.4×10^{-1}
400	4	7610	1.6×10^{-1}

Source: Fraknoi, Morrison, and Wolf, *Voyages through the Universe*

Structure of the talk:



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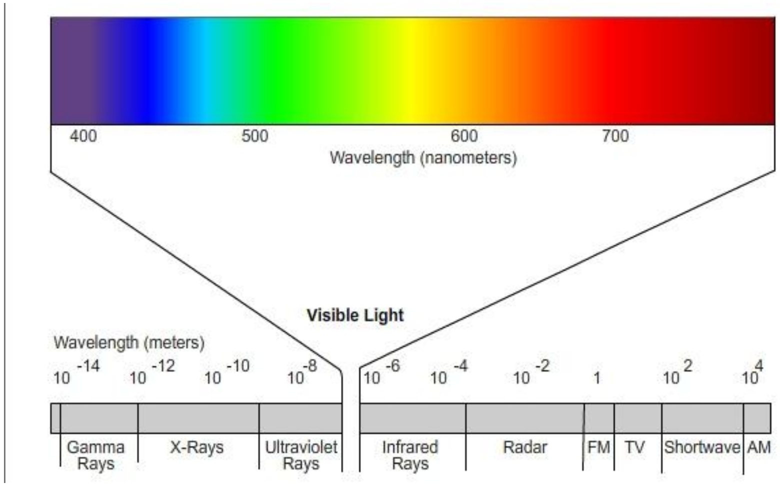
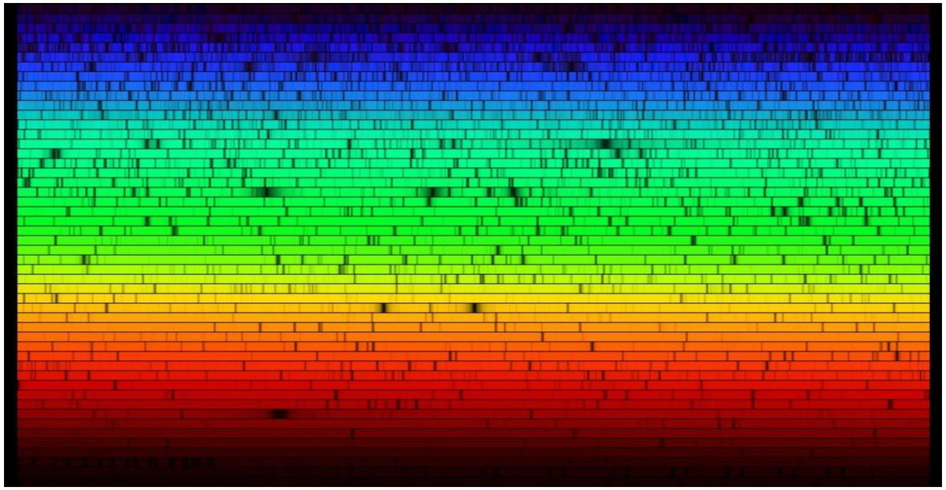
2. **Photosphere radiation**, formation of absorption spectral lines, limb darkening, optical depth

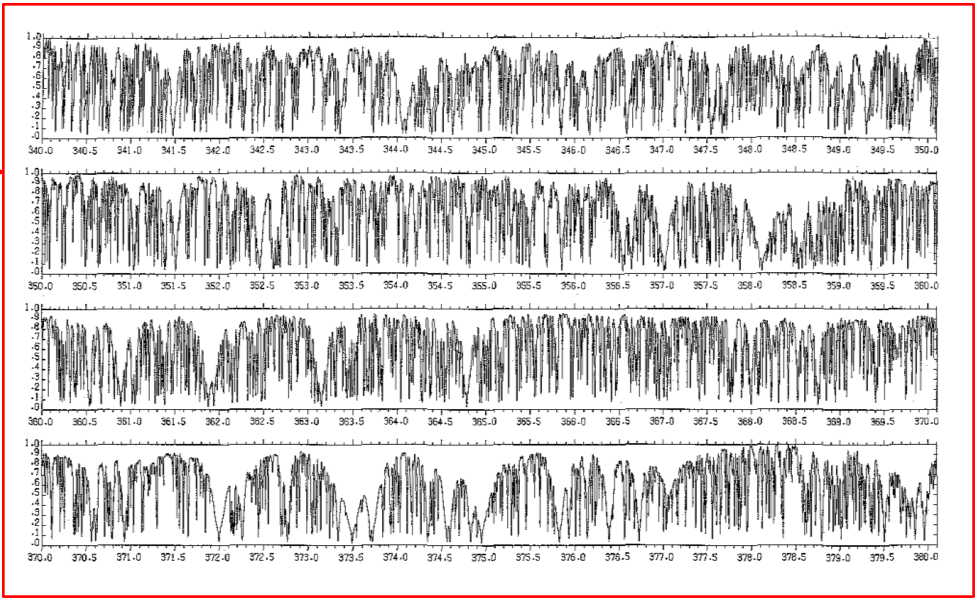




„Visible“ light: from 390 nm to 700 nm

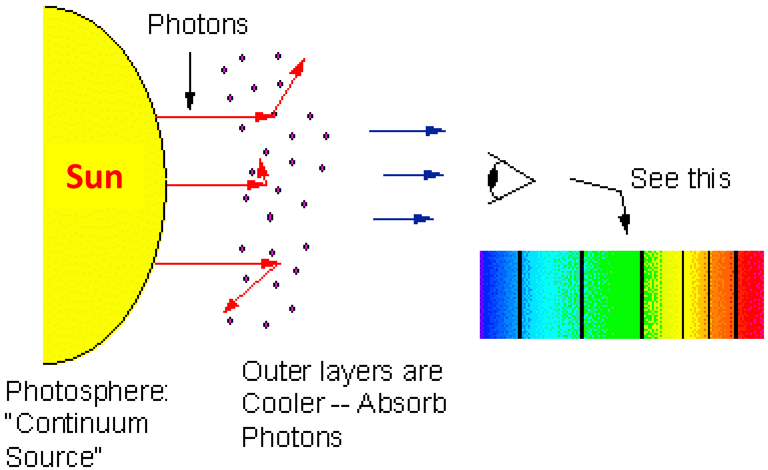
A detailed solar spectrum shows tens of thousands of spectral lines →

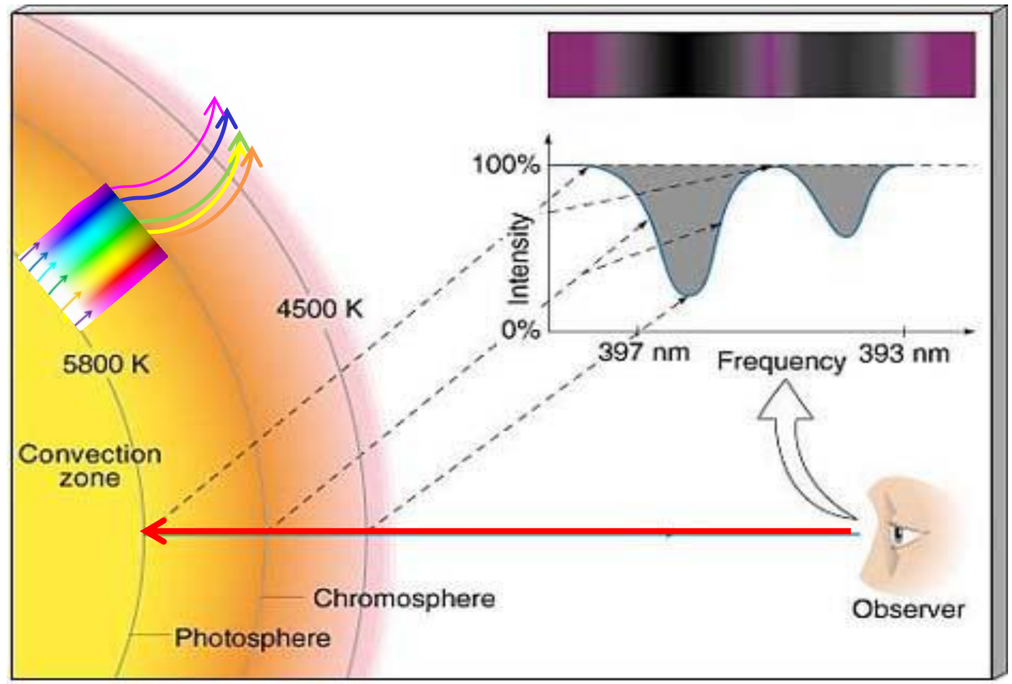
67 elements have been identified in the photosphere, in various states of ionization and excitation



An example of a small part of the atlas of the solar spectrum

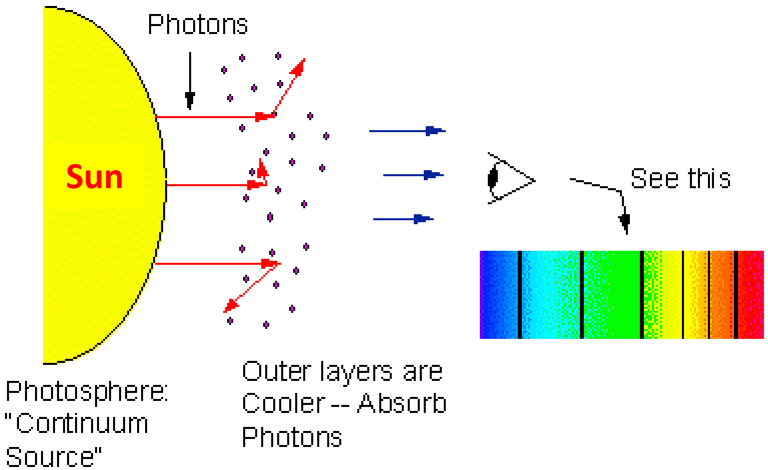
2. Photosphere radiation, formation of absorption spectral lines, optical depth, limb darkening

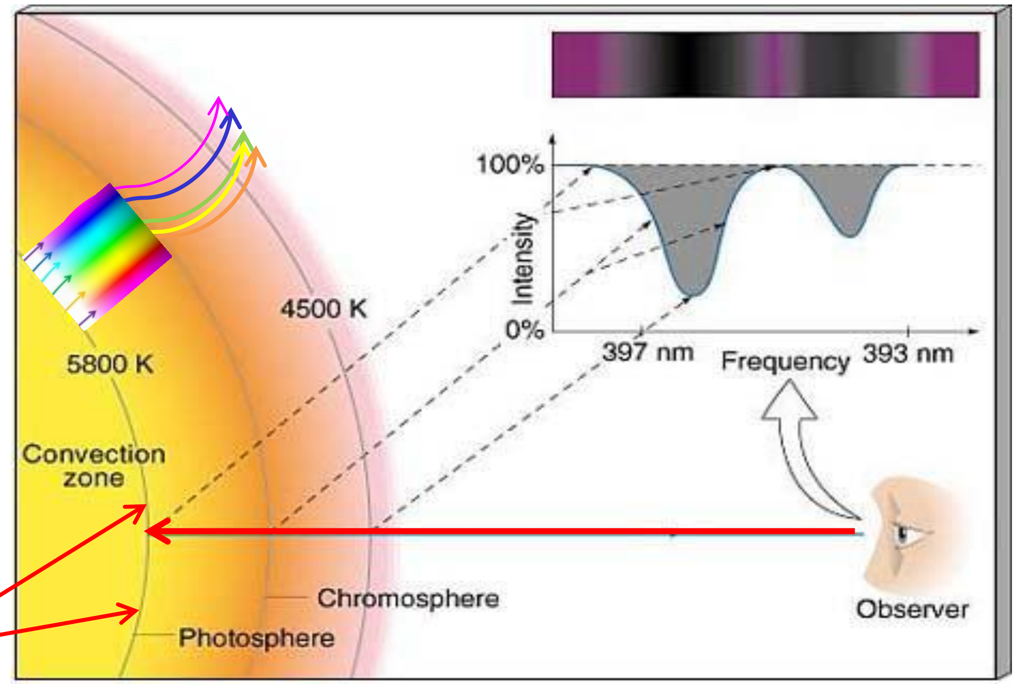




Photons with energies well away from any atomic transition can escape from relatively deep in the photosphere, but those with energies close to a transition are more likely to be reabsorbed before escaping, so the ones we see on Earth tend to come from higher, cooler levels in the solar atmosphere. Here we show a close-up tracing of two of the thousands of solar absorption lines, the "H" and "K" lines of calcium at about 395 nm.

2. Photosphere radiation, formation of absorption spectral lines, optical depth, limb darkening





High photospheric opacity.
We can see only to this depth.
This we call solar surface.

Photons with energies well away from any atomic transition can escape from relatively deep in the photosphere, but those with energies close to a transition are more likely to be reabsorbed before escaping, so the ones we see on Earth tend to come from higher, cooler levels in the solar atmosphere. Here we show a close-up tracing of two of the thousands of solar absorption lines, the "H" and "K" lines of calcium at about 395 nm.

2. Photosphere radiation, formation of absorption spectral lines, **optical depth**, limb darkening

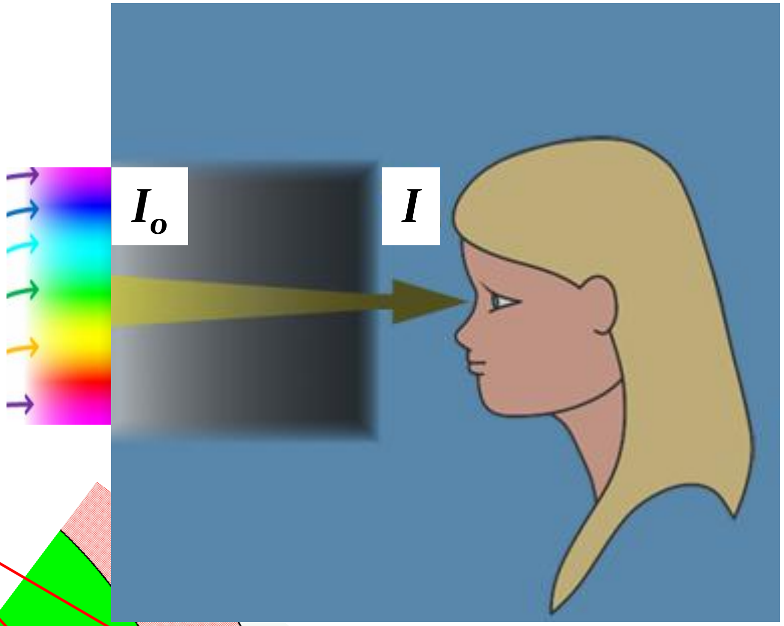
Why high photospheric opacity? **Because of: free electrons and negative hydrogen ion, H^-**

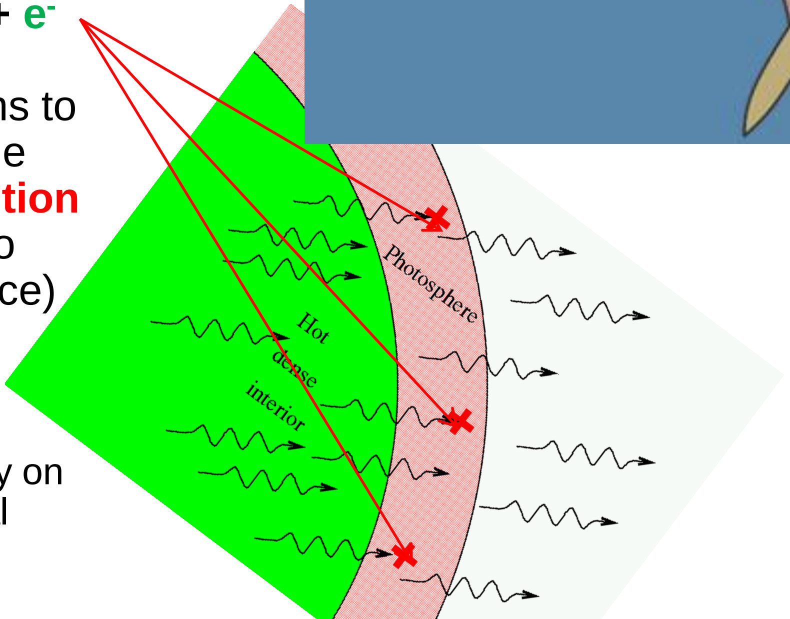
In the photosphere, there are neutral atoms (of H, He, etc.) and some ions (once-ionized Na, Mg, Fe) and **free electrons e^-.**

The **free electrons** attach themselves to neutral **H** atoms to form a **negative hydrogen ion, H^- :** $H + e^- \rightarrow H^-$

Then an **H^-** ion absorbs **photons *hv*** with wavelength < 1600nm, i.e. from the visible to the infrared: $H^- + h\nu \rightarrow H + e^-$

In the photosphere, there are only **10^{-8} H^-** ions to every **H** atom, but this is still enough to be the main cause of solar **opacity** (i.e. the **absorption of photons**). Tthus, observer can see only to limited depth of the photosphere (solar surface) namely to **optical depth** $\tau_{500} = 1$





(Is difficult to define where the photosphere ends and the chromosphere begins. Aastrophysicists rely on the **Eddington Approximation** to derive the formal definition of $\tau_{500} = 2/3$)

2.Photosphere radiation, formation of absorption spectral lines, optical depth limb darkening

Optical depth is a measure of the absorptivity up to a specific 'depth' of the photosphere

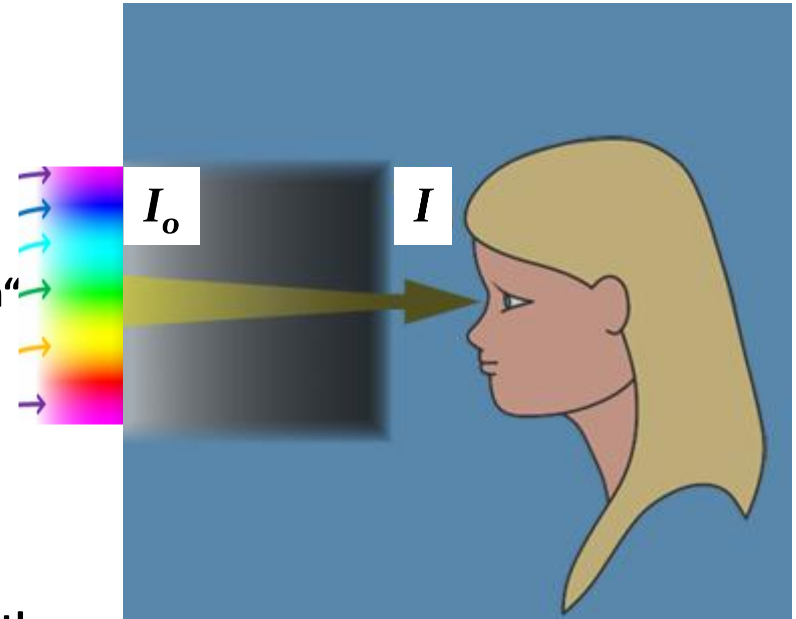
It is measured downwards from the top of the atmosphere, so it increases downward as *s* - geometrical depth decreases.

opacity density „length“

$$\frac{I}{I_0} = e^{-\kappa \rho s}$$

$$= e^{-\tau}$$

optical depth

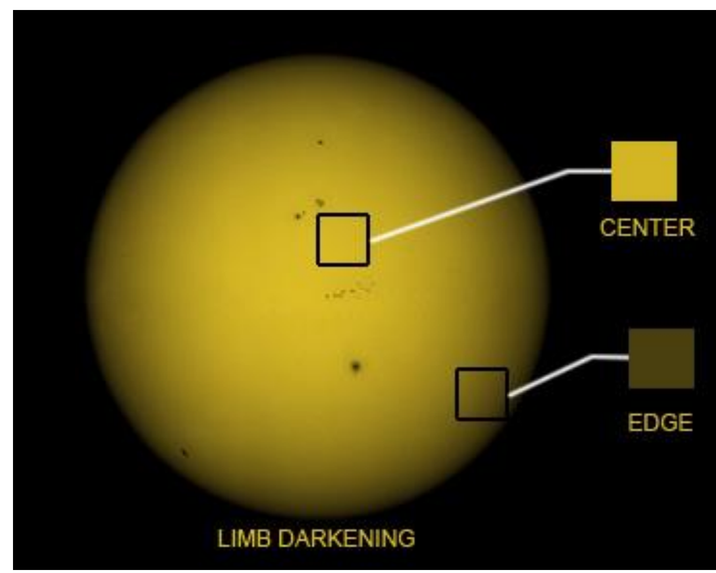


$$\tau = \kappa \rho \cos\theta \, ds$$

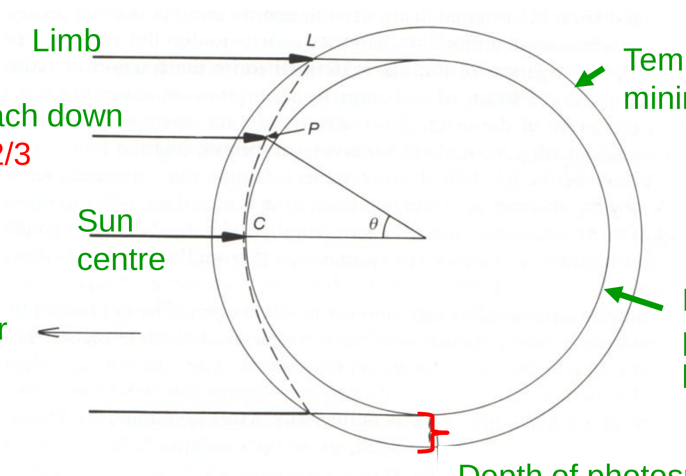
Limb darkening is an optical effect seen on Sun and stars where the **center** part of the disk appears **brighter** than the **edge** or limb. Limb darkening occurs as the result of **two effects:**

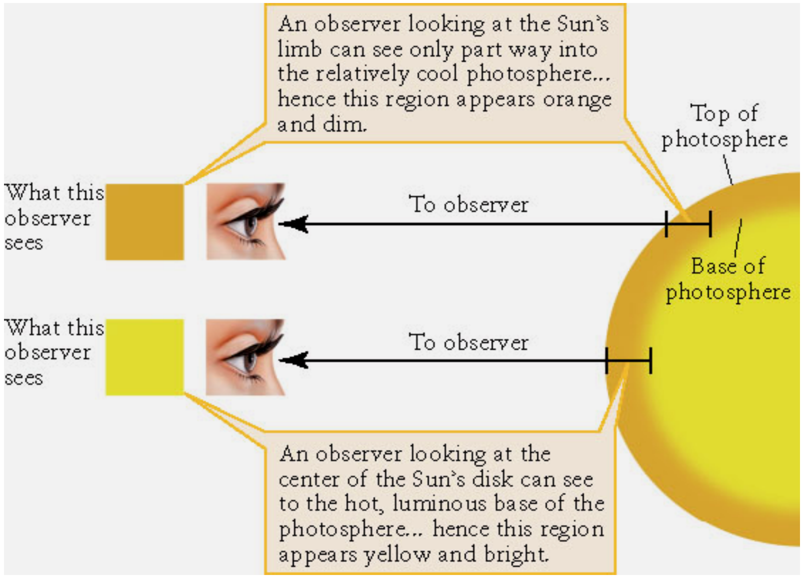
1) The **density** of the star diminishes as the distance from the center increases

2) The **temperature** of the star diminishes as the distance from the center increases



2.Photosphere radiation, formation of absorption spectral lines, **optical depth limb darkening**



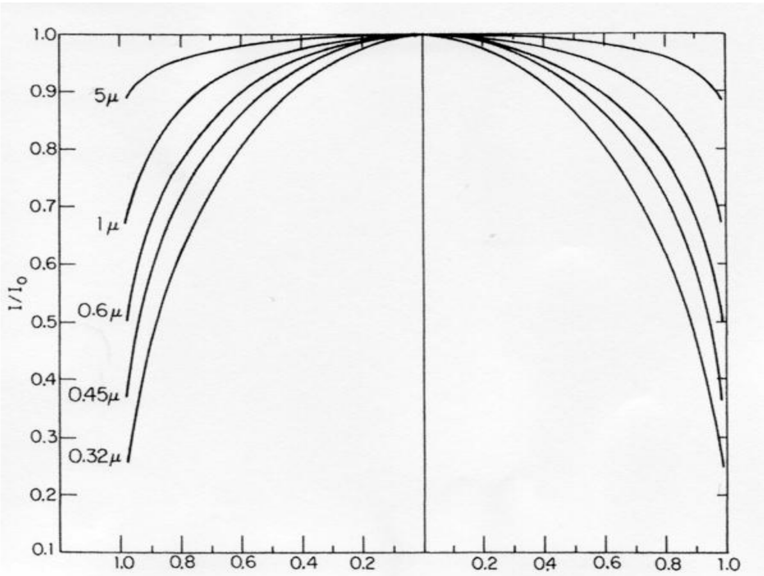


The Sun's effective and surface temperature

Sun's effective temperature is a measure of the Sun's radiation coming from the deepest photosphere (T = 6400K) visible at Sun centre to the "upper photosphere" or temperature minimum region (T = 4400K) visible at the limb. Thus, there is a limb darkening (decrease of solar intensity with angle θ).

T_{eff} is a kind of average of the kinetic temperatures in the photosphere.

An optical depth =1 is that thickness of absorbing gas from which a fraction of 1/e photons can escape. This defines the **visible edge of a star** since it is at an optical depth of **1** that the star becomes opaque. The radiation reaching us is closely approximated by the sum of all the emission along the entire line of sight, up to that point where the optical depth is =**1.**



Observed limb darkening as a function of wavelength

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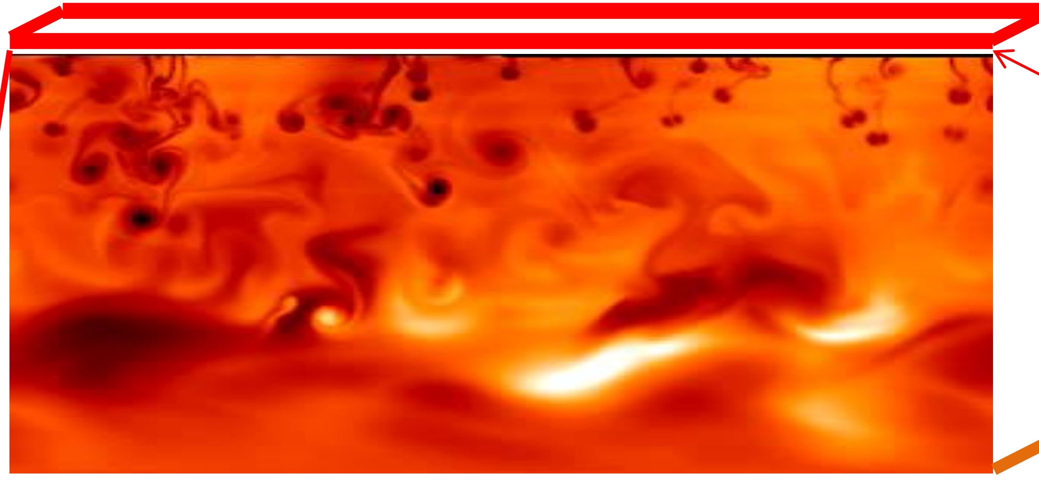
3. Velocity and magnetic fields taking place in the photosphere

Photosphere is very dynamic environment. Several types of motions and waves take place in the photosphere. All the photospheric motions and waves are driven by

convection,



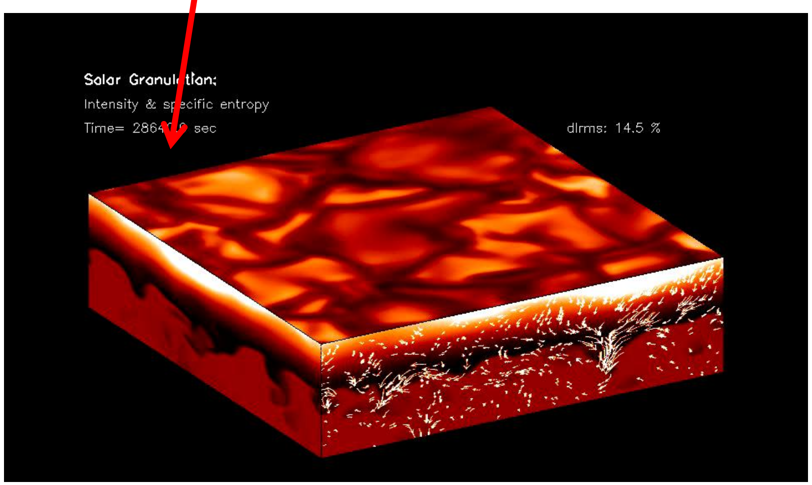
photosphere

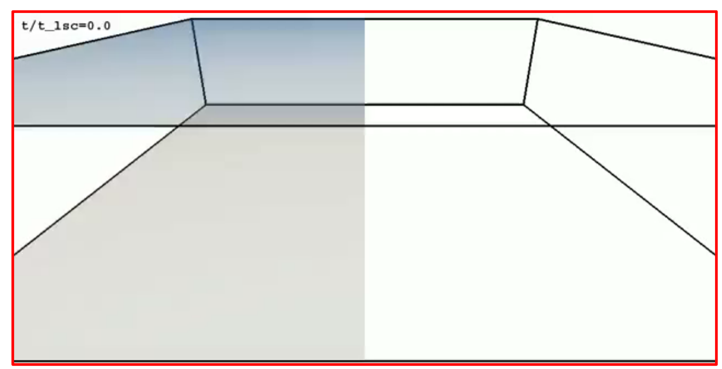
Turbulent mixing in Astrophysics.

Convective penetration in stelar interiors

Simulation: Malagoli, Dubey, Cattaneo, (1994)

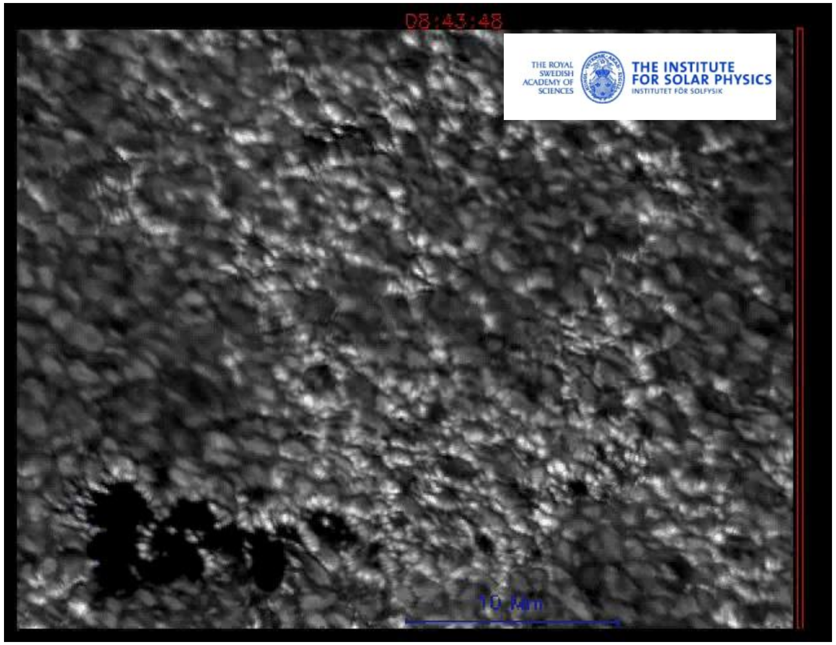
surface convection **and turbulent convection**





Temperature and Vertical velocity in Turbulent Rayleigh-Bénard Convection

3. Velocity and magnetic fields taking place in the photosphere

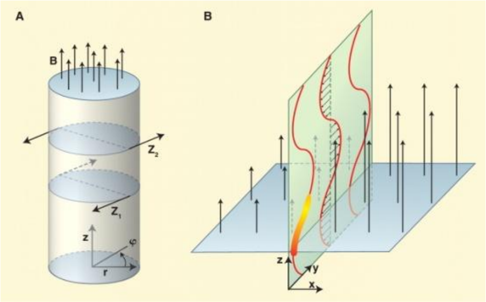


As a consequence of the mentioned drivers we see in the photosphere

Plasma motions.

1. **Upflows from granulation up to 500 km height**
2. **Horizontal flows in granulation**
3. **Horizontal flows in mezohranulation**
4. **Downflows in intergranular lanes**

and

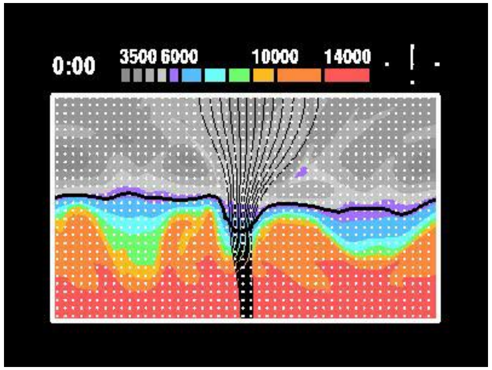


Waves:

1. **Acustic waves**
2. **Alfvén waves**

Five minute oscillations

Shocks



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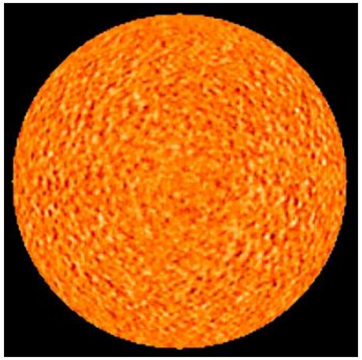
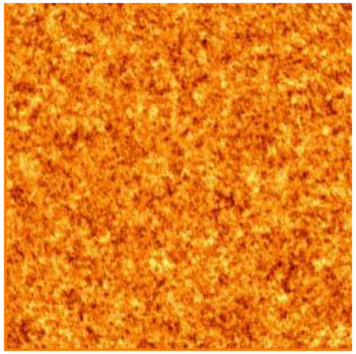
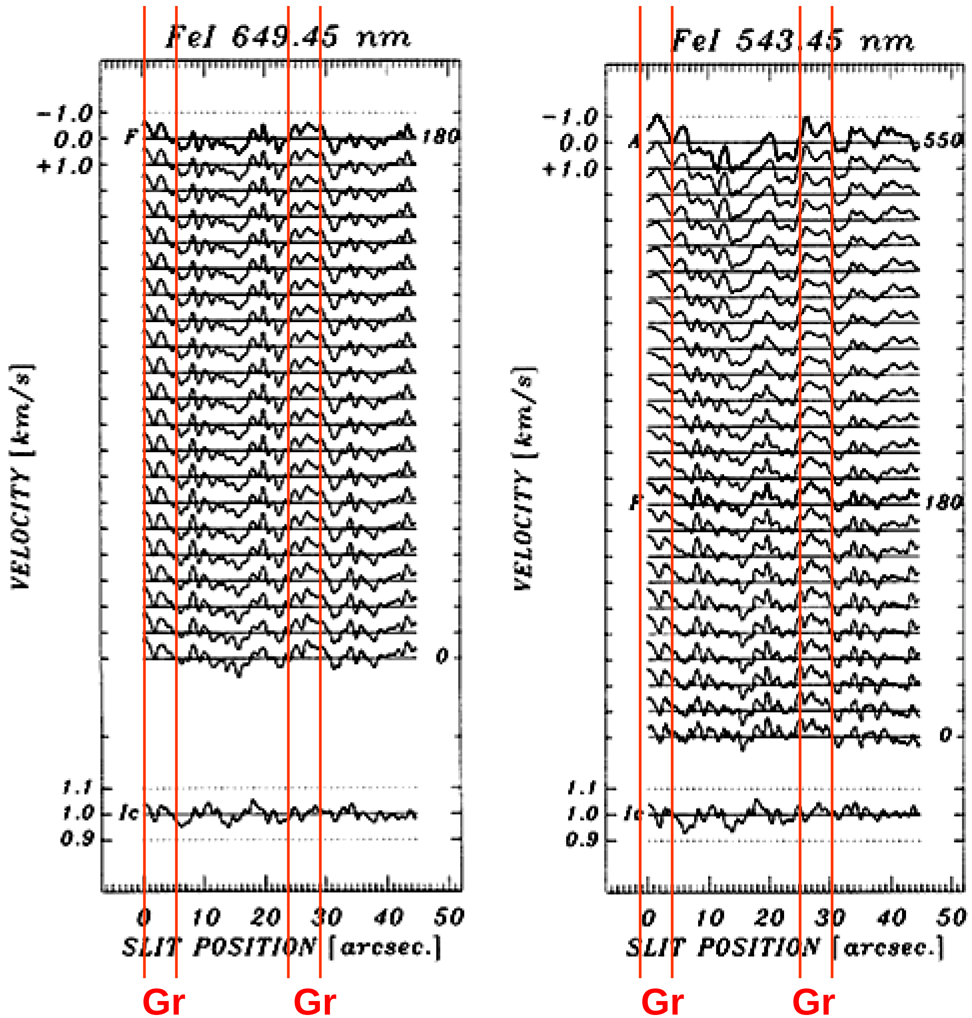




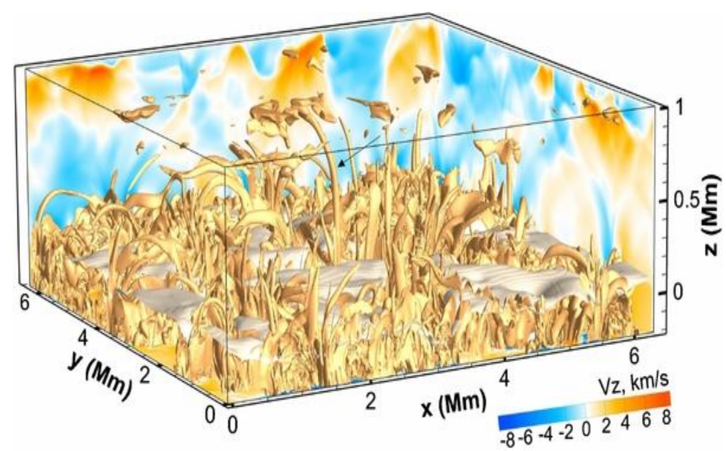
3. Velocity and magnetic fields taking place in the photosphere

Upflows in the photosphere 1 km/s



Velocity fluctuations associated to granules (negative values in the image, marked by red lines) appear almost through the whole photosphere

There are shown in figure, the velocity fluctuations along the slit, at different heights in the photosphere for two Fe I lines.



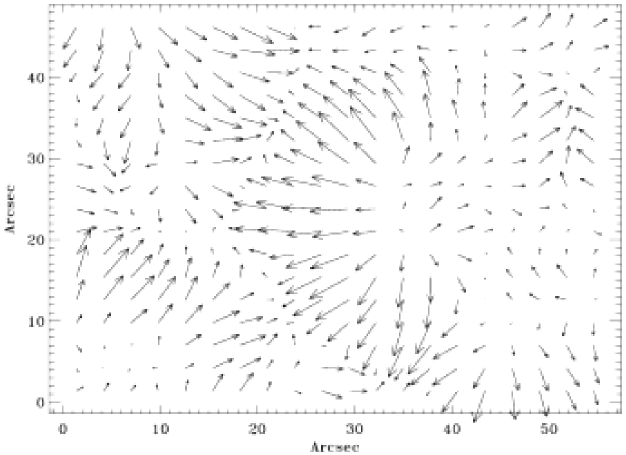
Modern simulation predict much higher vertical velocities (up to ± 4 km/s)

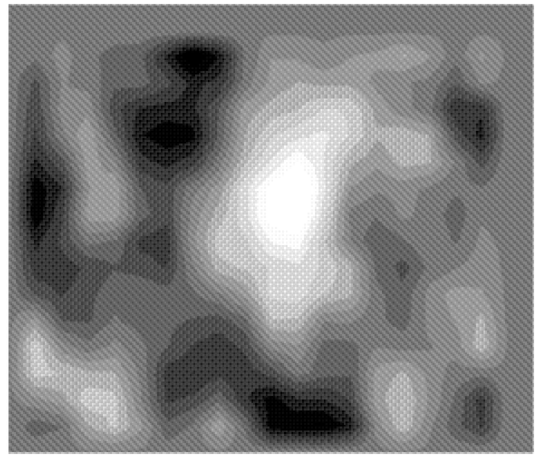
Kucera, A., Balthasar, H., Rybak, J., & Woehl, H.., 1998, Astronomy & Astrophysics, v.332, p.1069

Kitiashvili et. all The ApJ Letters, 751:L21 (7pp), 2012 May 20

3. Velocity and magnetic fields taking place in the photosphere

Horizontal flows in the photosphere





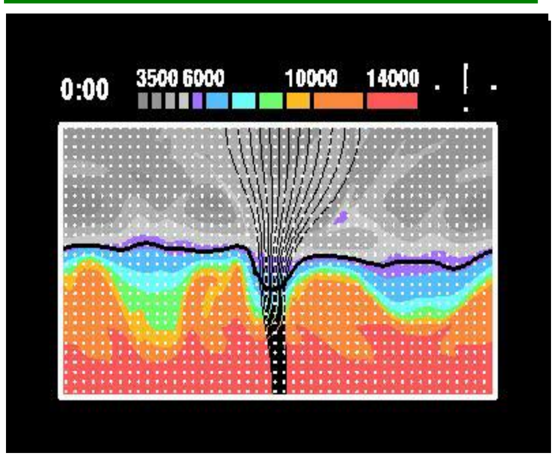
Example of the velocity field (left) and divergence (right) obtained from big data set of images. Here data are time-averaged over the total length of the sequence (3h)

Roudier, Th., Rieutord, M., Malherbe, J.M., Vigneau, J., 1999, Astron. Astrophys., vol. 349, p.311

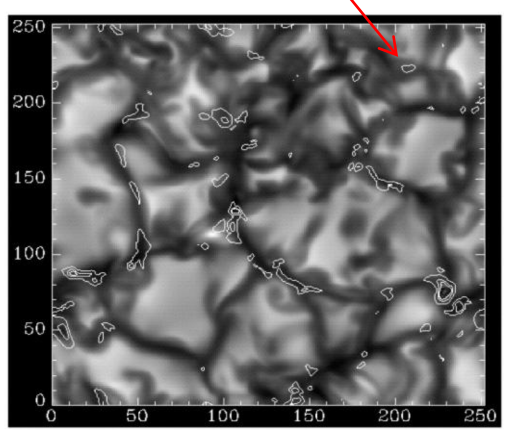
Typical horizontal flows in the photosphere are:

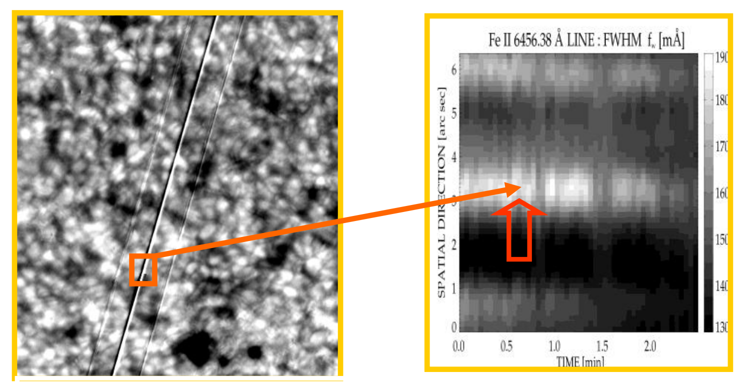
- 1.6. km/s inside the granule directing to edge of the granule
- then 1 km/s to the edge of mesogranule lasting 20 minutes
- then 0.5 km/s along the edge of the mesogranule

Shocks and downflows in the photosphere



Shocks: Velocity of plasma flow exceeds the sound speed in the enviroment.

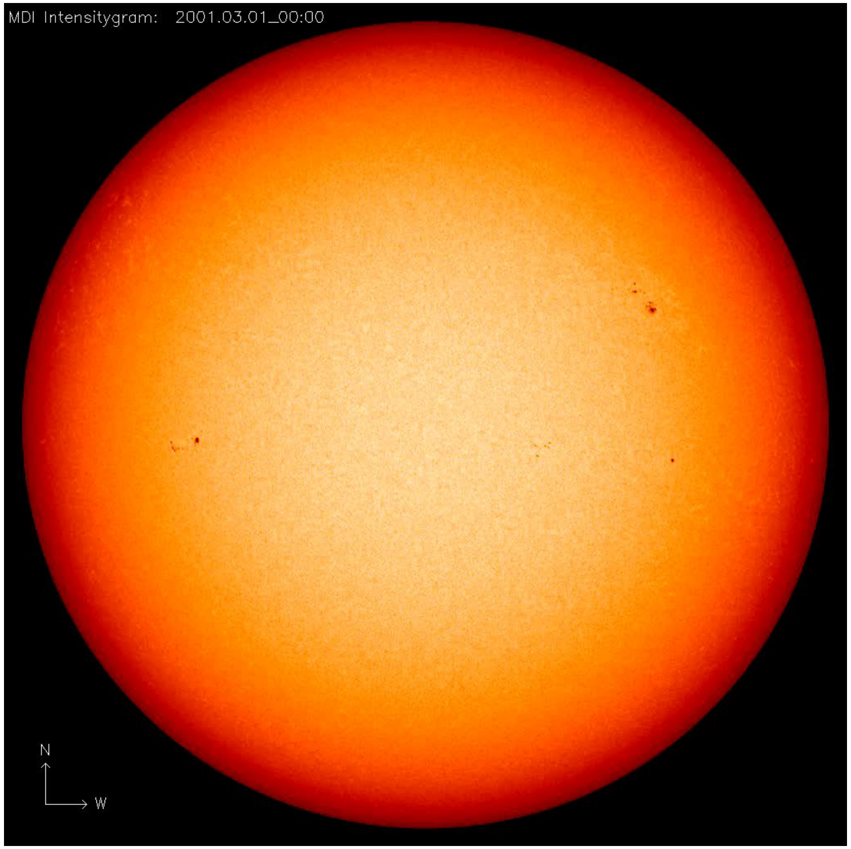




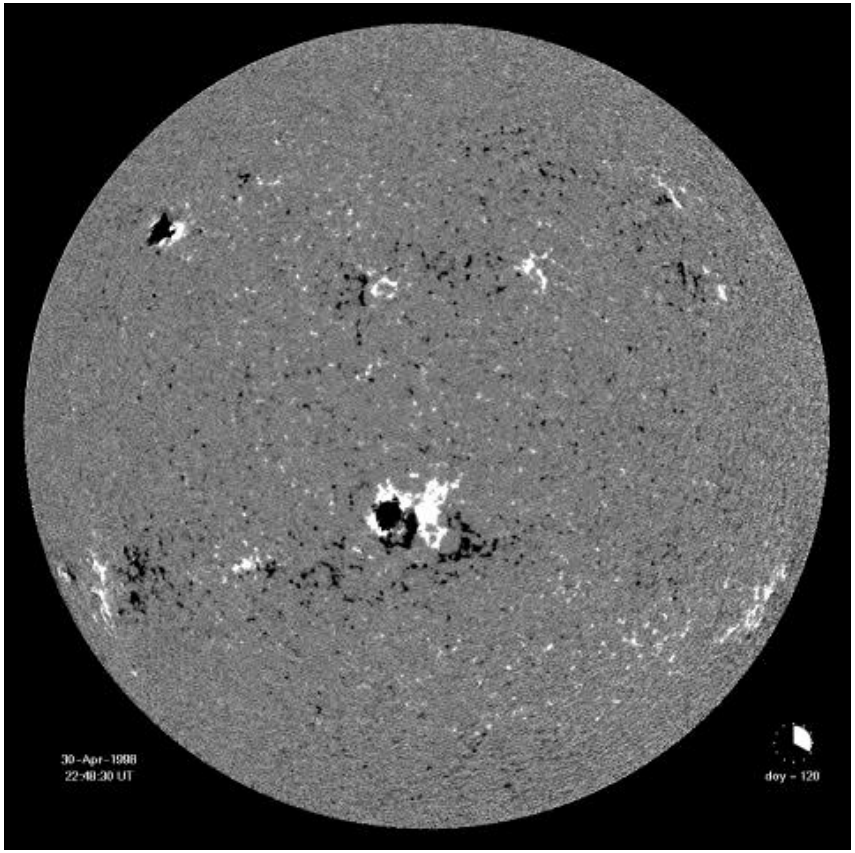
Experimental evidence of the shock

J. Rybák, H.Wöhl, A. Kučera, A. Hanslmeier, O. Steiner, A&A 420, 1141–1152 (2004)

3. Velocity and **magnetic fields** taking place in the photosphere



Solar photosphere.

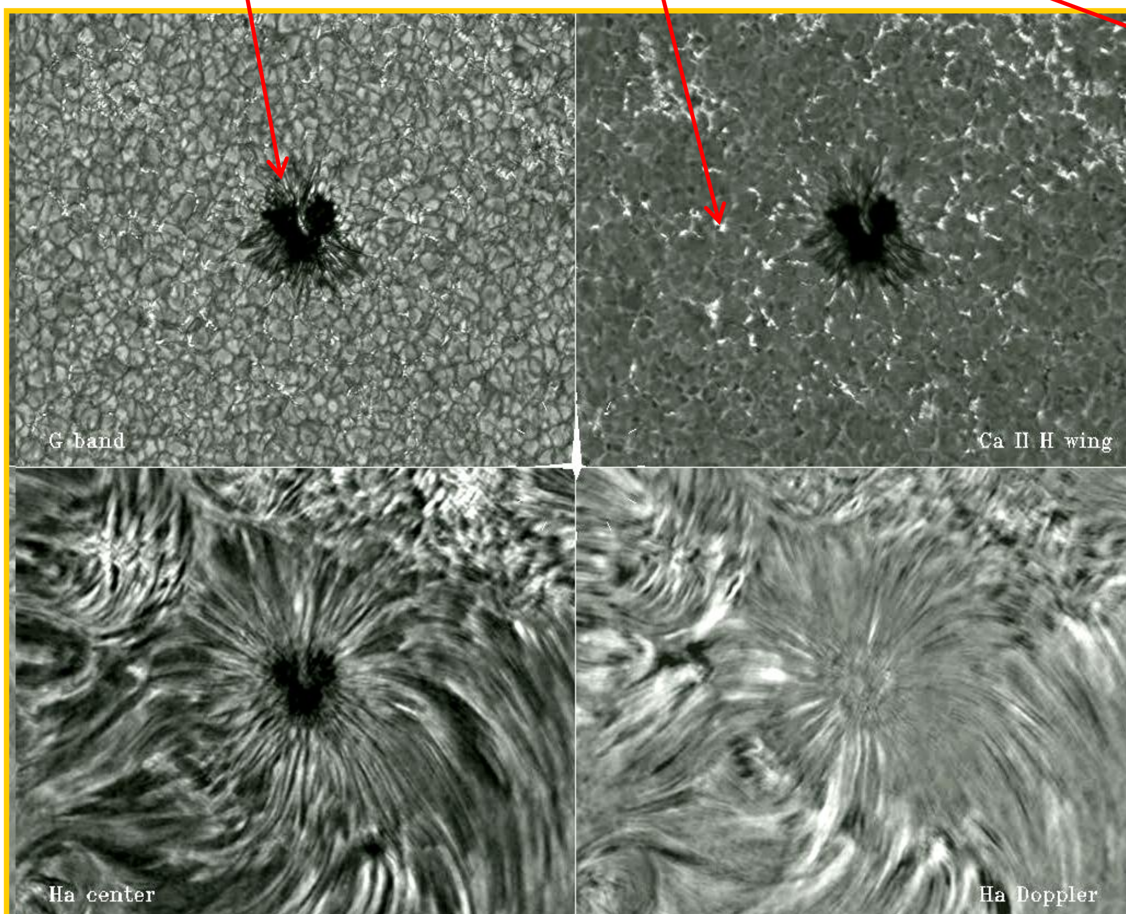


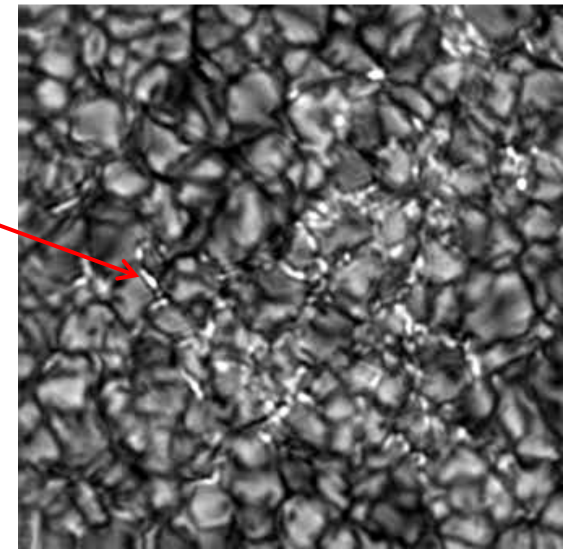
Magnetic field in the solar photosphere

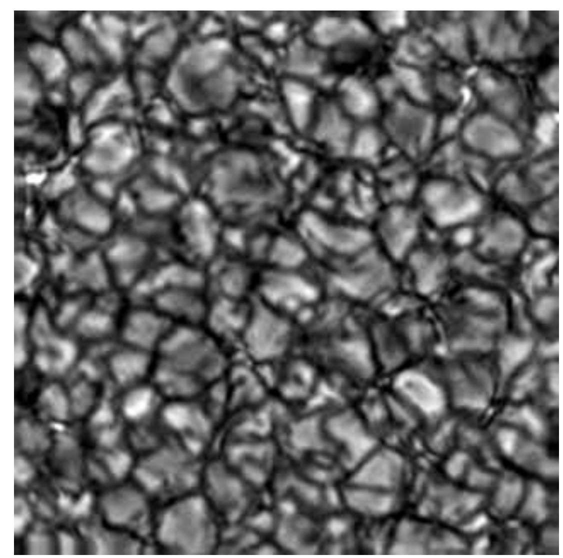
3. Velocity and magnetic fields taking place in the photosphere

Magnetic field in the photosphere has different scales from very small intergranular fluxtubes (les than 0.5“) up to large sunspots.

Dark sunspots and brihgt points and lines indicate presence of enhanced magnetic field



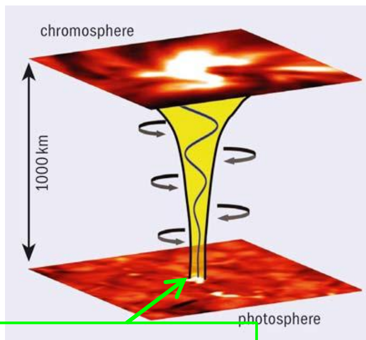




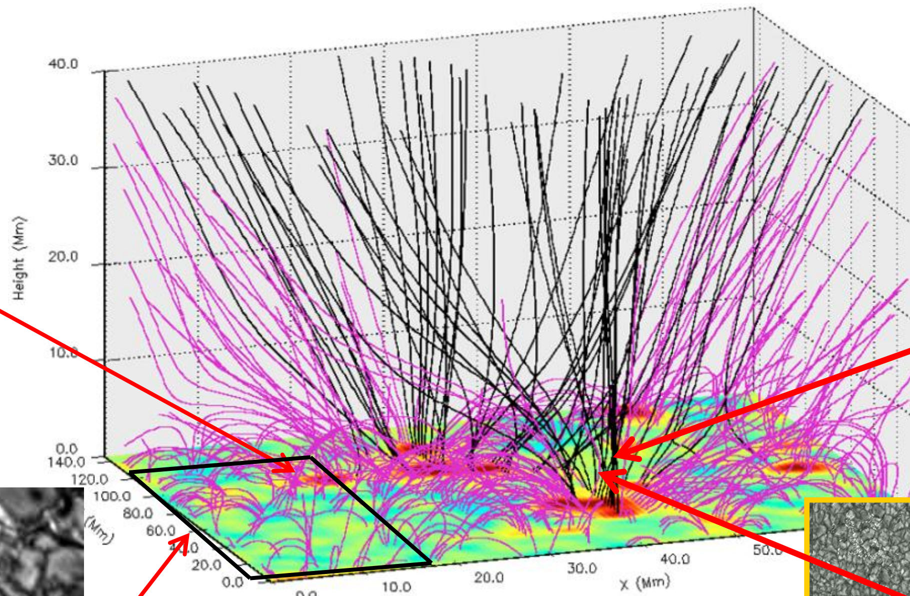
3. Velocity and **magnetic fields** taking place in the photosphere

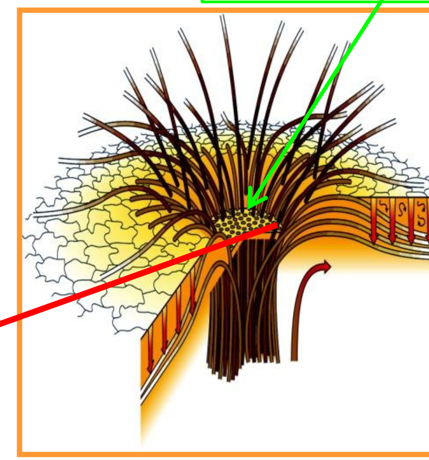
We measure small scale magnetic field using Hanle efect and strong magnetic field using Zeeman efect

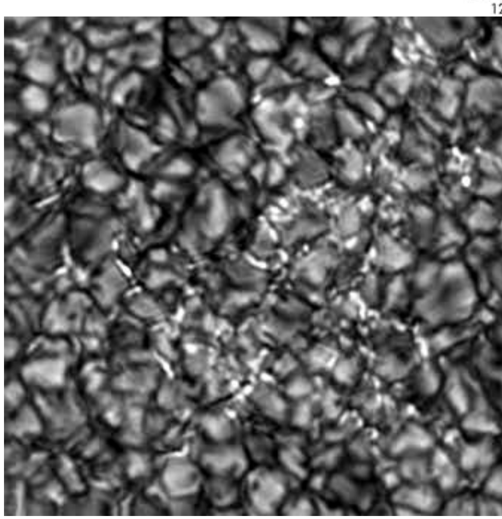
mag.field ~3T

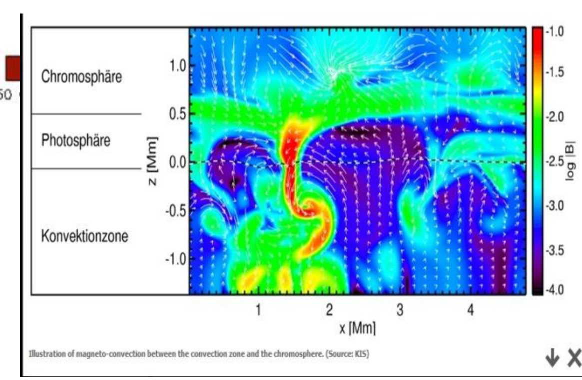


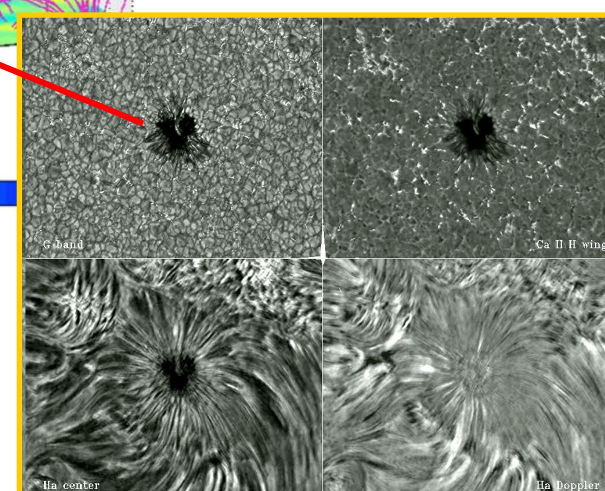
mag.field ~0.1T



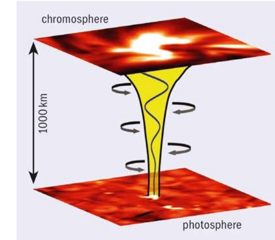








3. Velocity and magnetic fields taking place in the photosphere



Example of small scale magnetic field penetrating (emerging) into higher levels of the solar atmosphere

SPECTROPOLARIMETRY OF A SMALL-SCALE MAGNETIC LOOP EMERGENCE

TIP:
Overview of the dataset (Fe I 1564.85 nm)

v **(black ~ blue shift)**

20"

5"

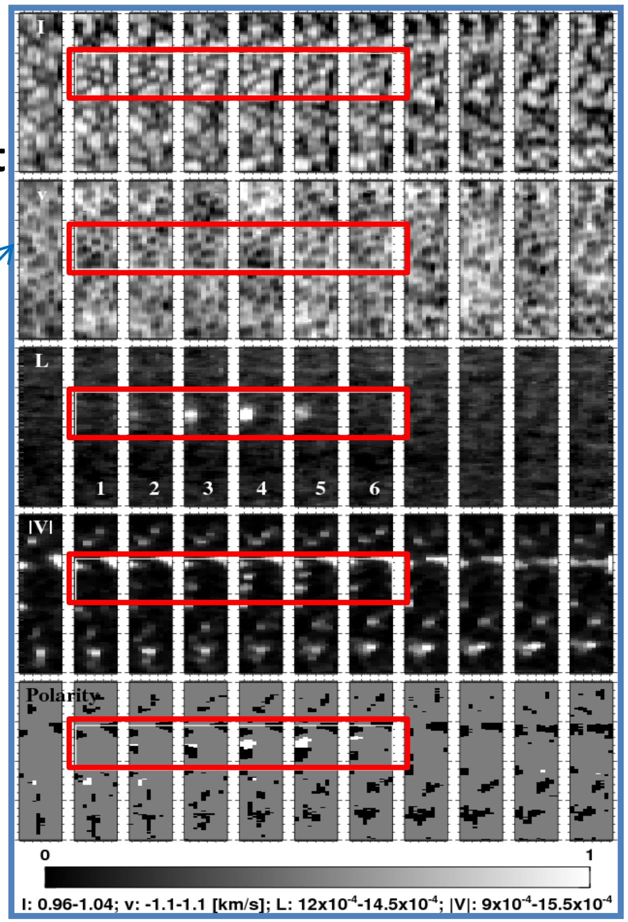
cont

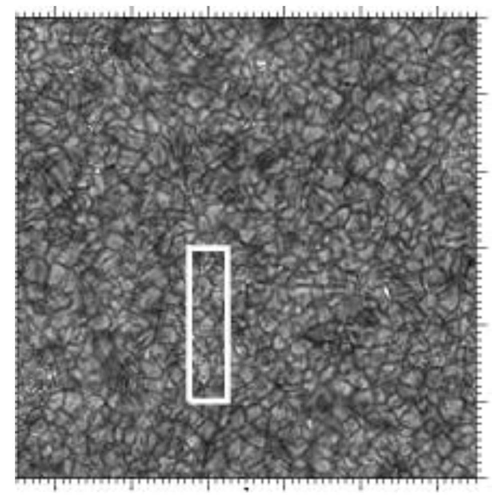
v

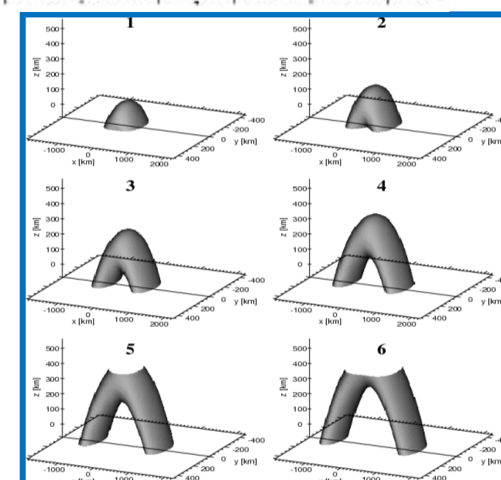
Lin. p

|V| circ

polarity







magnetic flux of around 3 × 10^{17}Mx
duration 12 min, loop rises through the photosphere with a speed of about 1 km/s

Gömöry, P.; Beck, C.; Balthasar, H.; Rybák, J.; Kučera, A.; Koza, J.; Wöhl, H., 2010 A&A...511A..14G

Structure of the talk:

1. Basic physical properties of the solar photosphere

2. Photosphere radiation, formation of absorption spectral lines, optical depth, limb darkening

3. Velocity and magnetic fields taking place in the photosphere

4. Principles of modeling of the photosphere

5. Comparison of the photosphere with the other layers of the solar atmosphere and with the layer located below the solar photosphere

4. Principles of modeling of the photosphere

Requirements for models of solar photosphere:

a) **Density stratification**: Different flow regimes - werticaly and horizontally.

b) **Radiative transfer**: Extreme **increase of opacity** with height implicate that the exchange of heat by radiation is dominant in very thin layer only (100 km). Radiative loses from this layer estimate the temperature difference between upflows and downflows

c) **Opacity and equation of state**: Estimation of the opacity and thermodynamic **parameters of partially ionised plasma** must reflect very well the reality to describe correctly the energy exchange between the gas and radiation.

d) **Geometry of the model**: **2-D or 3-D models** are required because the real processes on theSun have neither **space-symmetry** nor **time periodicities** in sense of particular part of the photosphere. **Complex structures** and **chaotic behaviour** are typical for this region. So the **modelled domain** must be **big enough** but the **spatial sampling** (grid) must be **sufficiently small** to map all small-scale processes well.

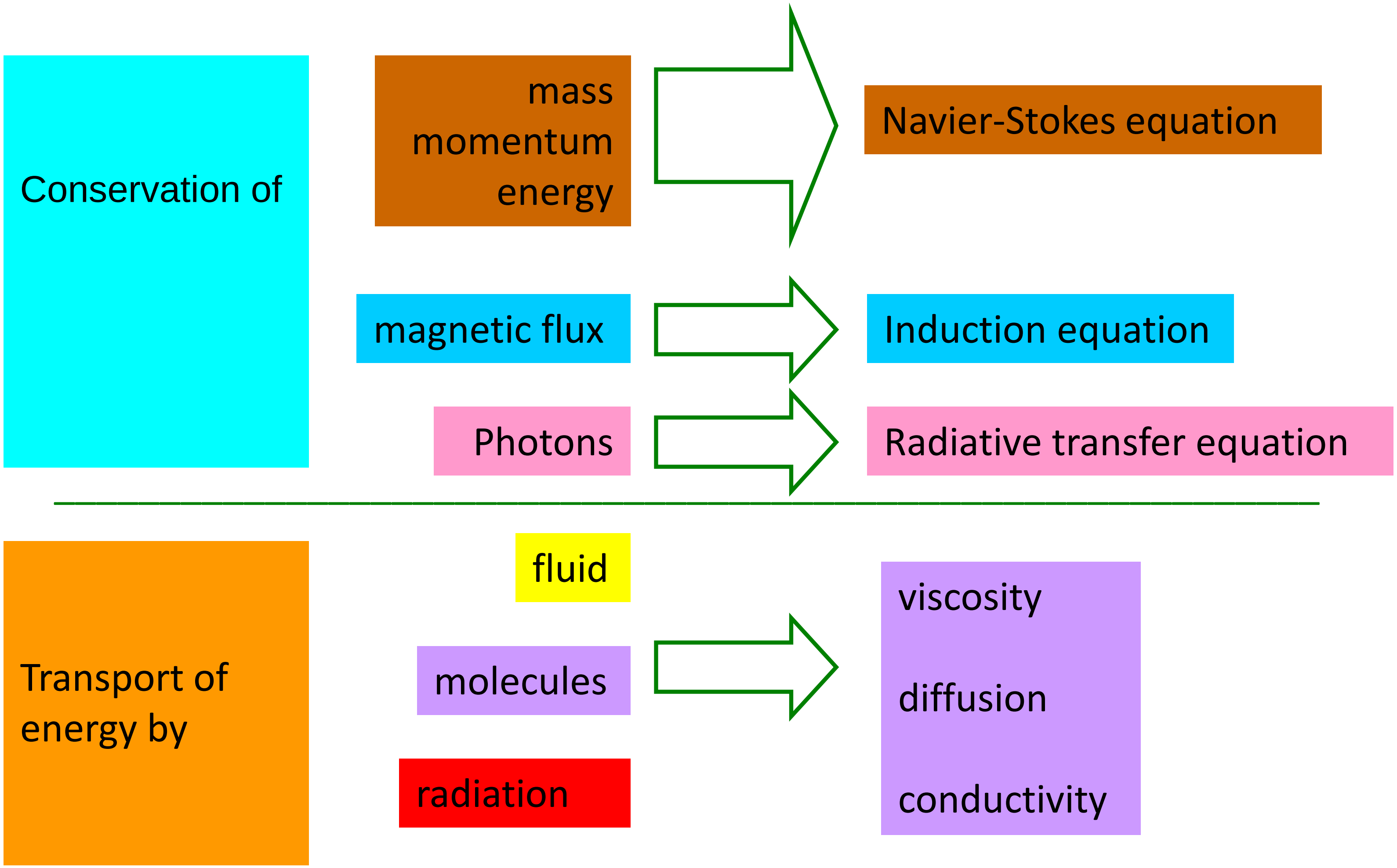
e) **Magnetic field**: Magnetic field **had to be** included. It brings more realistic description of the magneto-hydrodynamics and map better the regime of supersonic flows and shocks.

f) **Free parameters**: It is useful to use **minimum of free parameters** in equations and in models

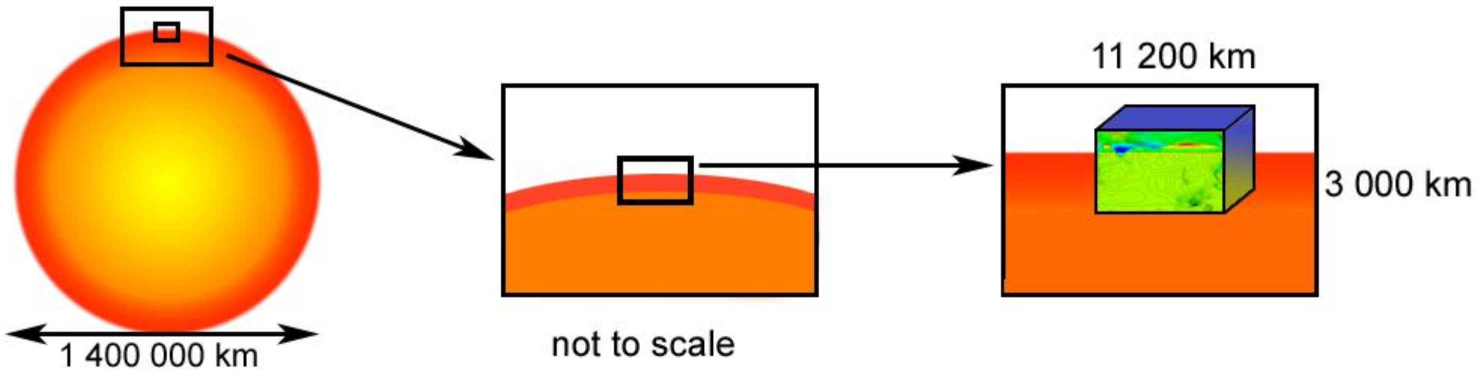
g) **Observing data**: Use the up to date data acquired with **high spatial** and **temporal resolution**.

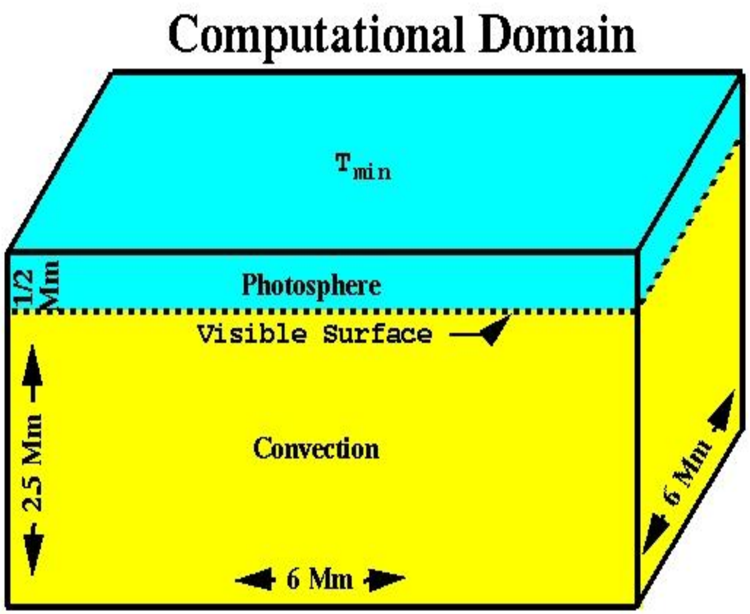
4. Principles of modeling of the photosphere

A) Mixing-lenght theory
B) Fluid dynamics



4. Principles of modeling of the photosphere

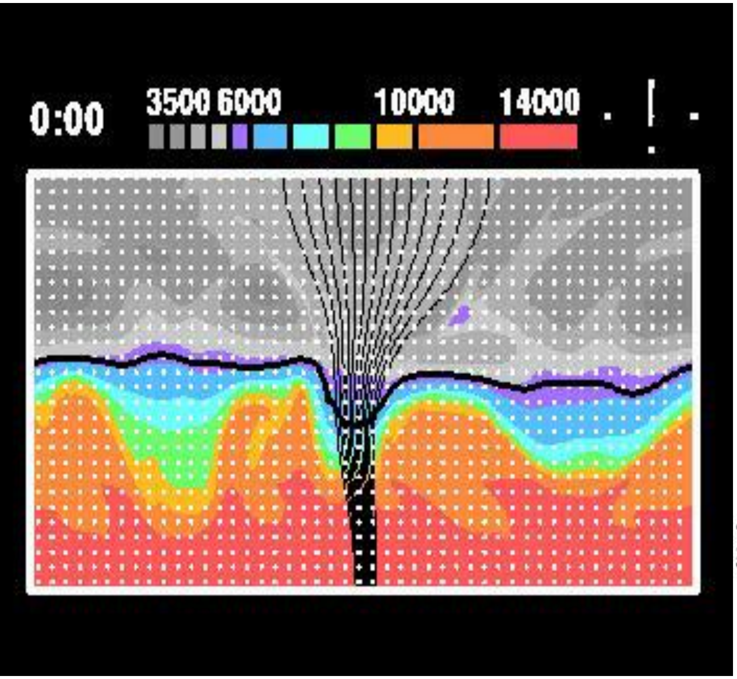




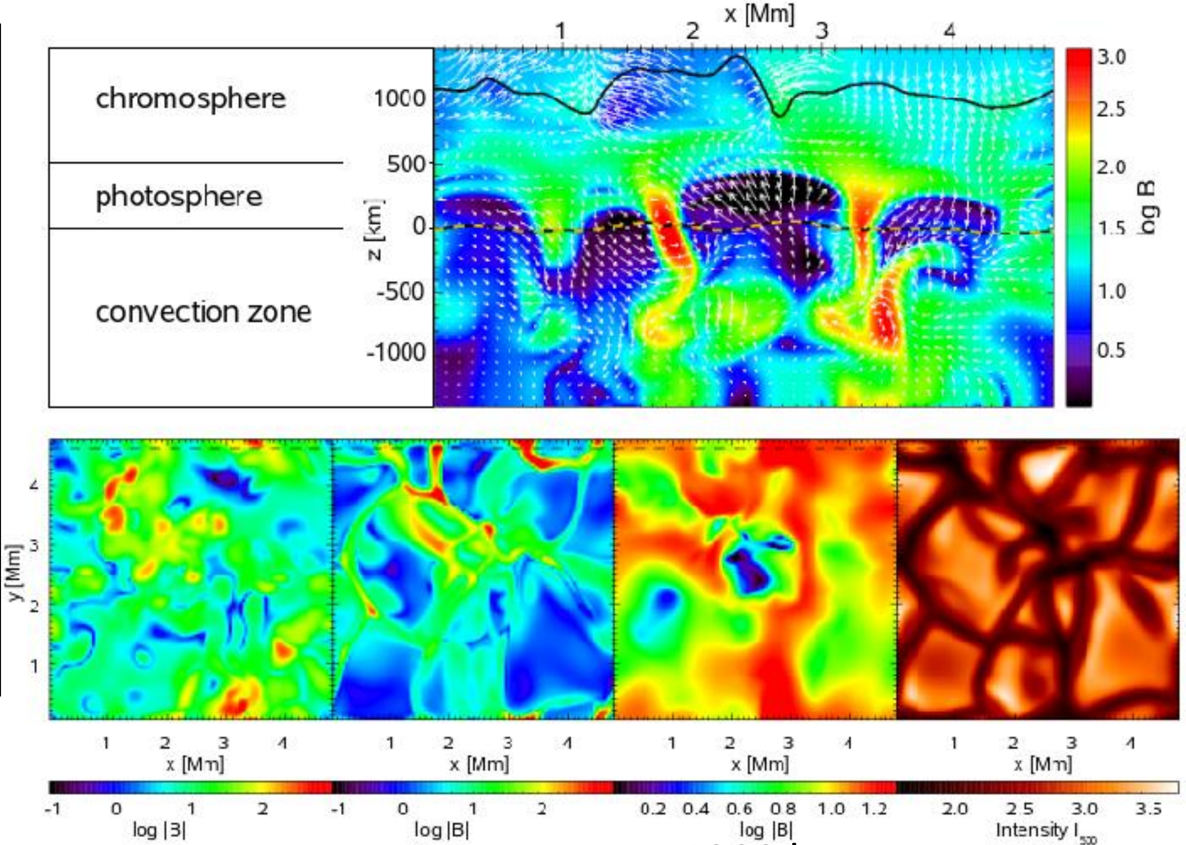
4. Principles of modeling of the photosphere

Several results

2002 MHD sim **2D**



2006 MHD sim **3D**



-1210 km

60 km

1300 km

Magnetohydrodynamic simulation from the convection zone to the chromosphere
W. Schaffenberger, S. Wedemeyer-Böhm, O. Steiner & B. Freytag: 2006, in Chromospheric and Coronal Magnetic Fields, D. Innes, A. Lagg, S. Solanki, & D. Danesy (eds.), ESA Publication SP-596 (CD-ROM)

4. Principles of modeling of the photosphere

2003

A. Vögler and M. Schüssler: Studying magneto-convection by numerical simulation 401

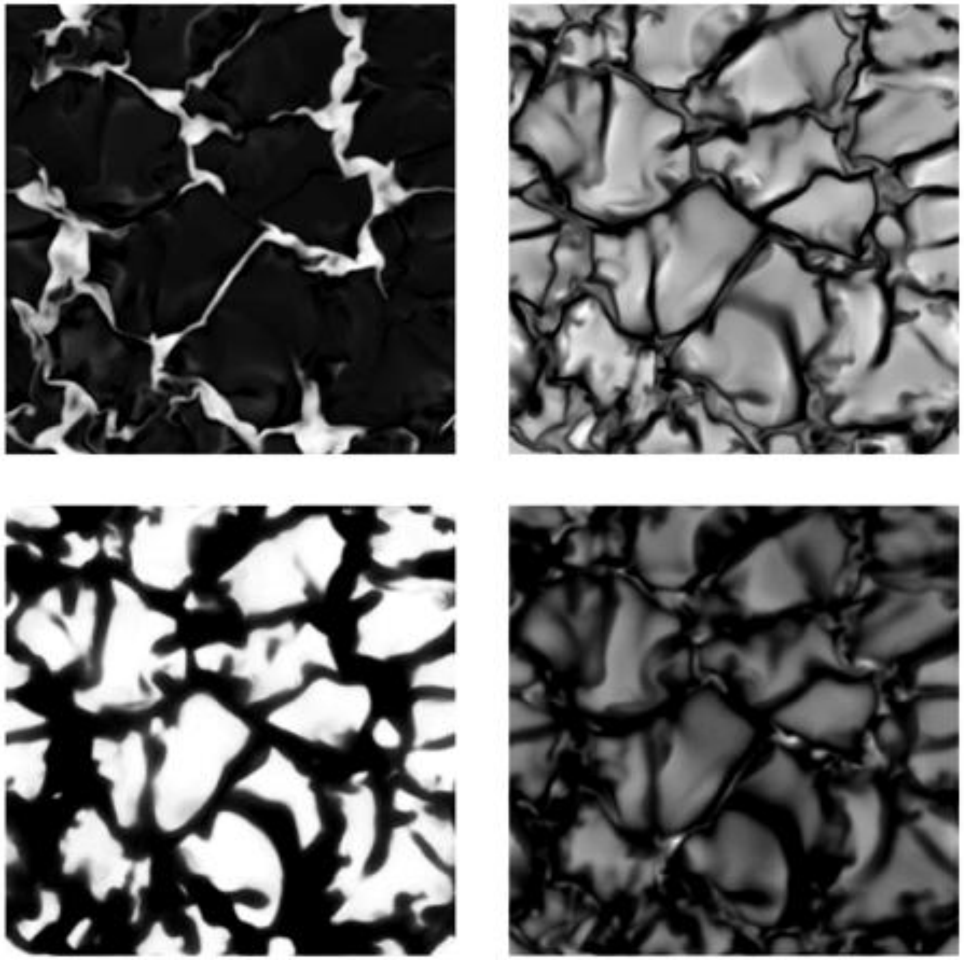


Fig. 1. Brightness map (lower right) and horizontal cuts at the average geometrical height corresponding to optical depth unity of vertical magnetic field (upper left), vertical velocity (upper right) and temperature (lower left). Light and dark shades indicate higher and lower values, respectively. The velocity plot shows granular upflows shaded in light grey separated by intergranular downflow lanes. In the magnetic-field plot, the strong sheet- and pore-like magnetic field concentrations appear in white. They are organized mainly in a 'meso-scale' network with a typical size significantly larger than the spatial scale of the granulation.

upper left: vertical magnetic field at geometrical height correspon-ding to optical depth unity
upper right: vertical velocity
lower left: temparatire
lower right: brightness map

Studying magneto-convection by numerical simulation, Vögler, A.; Schüssler, M., 2003 Astronomische Nachrichten, Vol. 324, No. 4, p. 399-404

4. Principles of modeling of the photosphere

Several results

2011

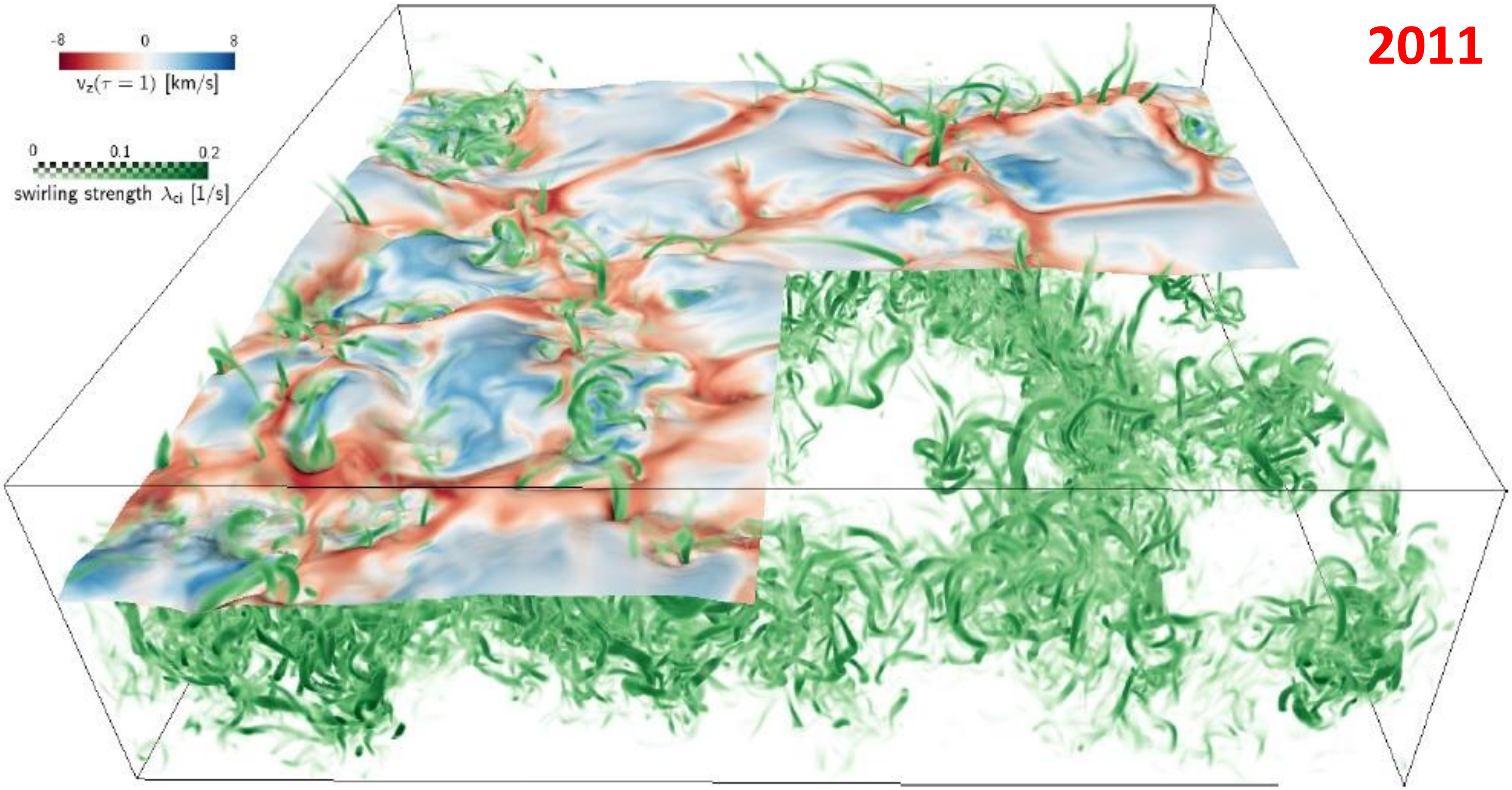


Fig. 1. Snapshot of the swirling strength (green volume rendering) and the optical surface color-coded with vertical velocity (downflows in red and upflows in blue) in Run C. The size of the box shown is $4.8 \times 4.8 \times 1.4$ Mm^3. The optical surface is hidden in the lower right quadrant, uncovering the swirling structure in the subsurface layers. An animated plot that shows the temporal evolution of the swirling strength without the optical surface is available in the electronic edition of the journal.

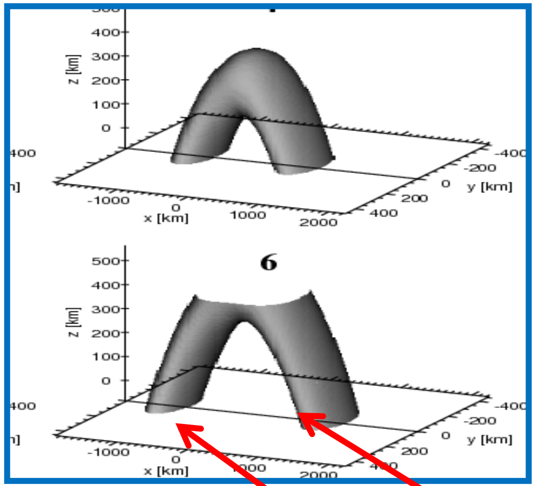
Vortices in simulations of solar surface convection
R. Moll, R. H. Cameron, and M. Schüssler, 2011, A&A 533, A126 (2011)

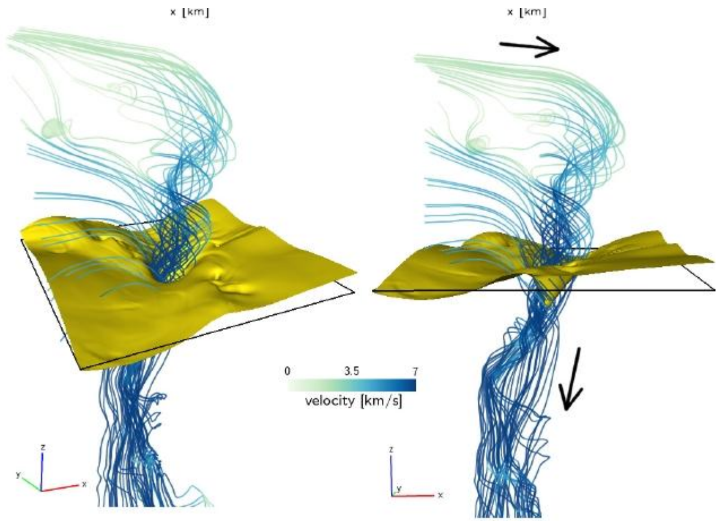
4. Principles of modeling of the photosphere

Several results

2011

Strong vortex flows are created in downdrafts when the plasma returns to the solar interior after radiating its energy at the surface and cooling down





700 km

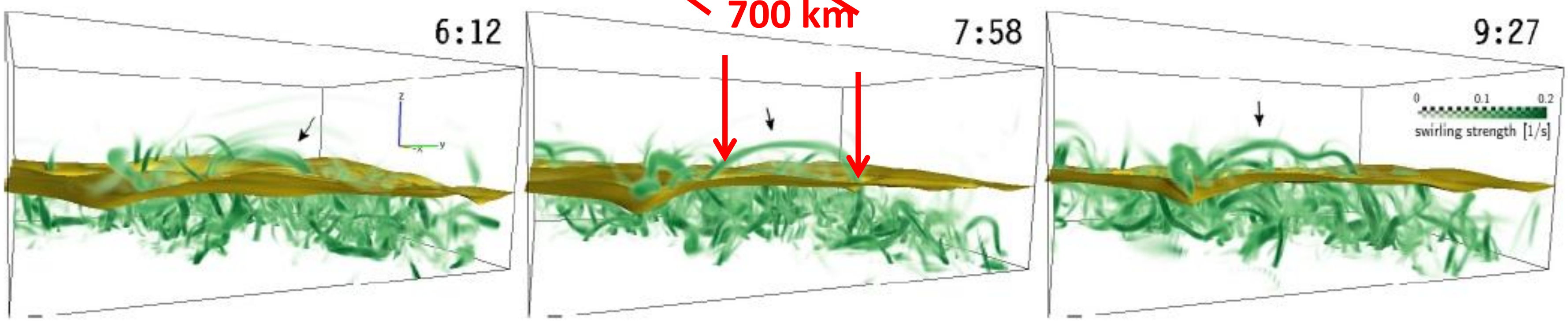


Fig. 10. Rise and fall of a vortex arc in Run C. The plots display the swirling strength (green volume rendering) and the optical surface (yellow) at three different times (labels are in minutes). The size of the box shown is $1.5 \times 1.5 \times 0.8$ Mm^3. An animated version of this plot is available in the electronic edition of the journal.

Vortices in simulations of solar surface convection
R. Moll, R. H. Cameron, and M. Schüssler, 2011, A&A 533, A126 (2011)

2012

DYNAMICS OF MAGNETIZED VORTEX TUBES IN THE SOLAR CHROMOSPHERE
I. N. Kitiashvili, A. G. Kosovichev, N. N. Mansour, and A. A. Wray, 2012

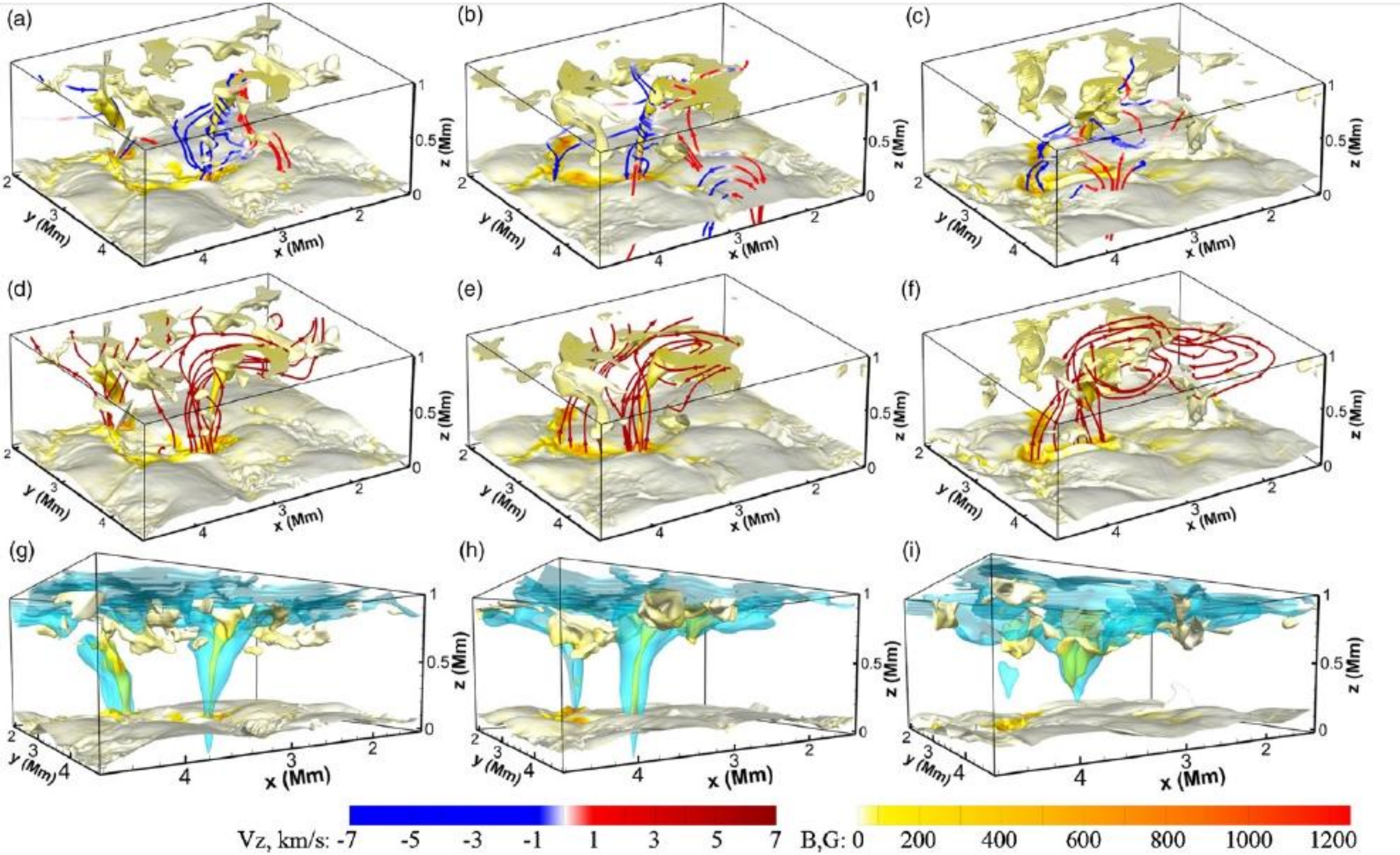
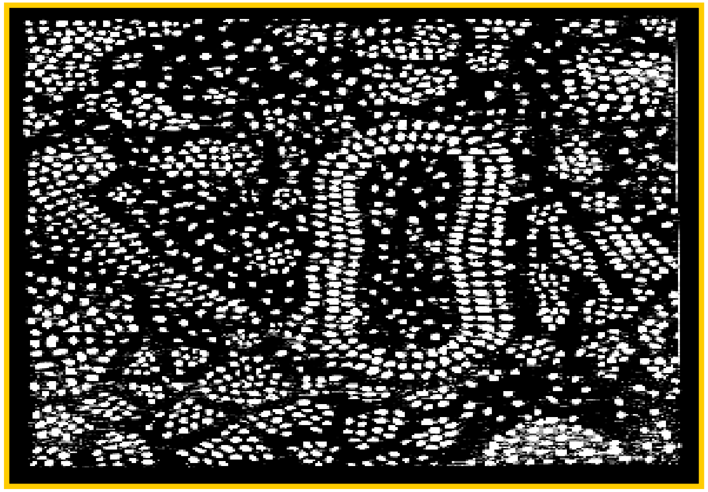


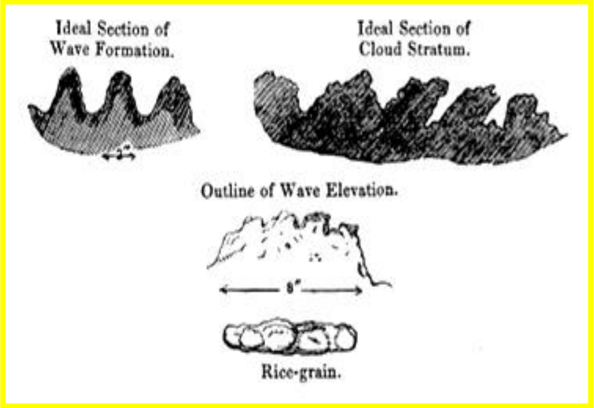
Figure 4. Evolution of the velocity field (streamlines in panels (a)–(c)), magnetic topology (streamlines in panels (d) and (e)), and plasma parameter β (blue isosurface for $\beta = 3$ in panels (g)–(i)). Each column corresponds to simulation data 3 minutes apart. The gray isosurface shows $T = 5800$ K; additional coloring from light yellow to orange indicates variations of the magnetic field strength in the range from 0 to 1200 G. Coloring of the velocity streamlines in panels (a)–(c) corresponds to vertical velocities from -7 km s^{-1} (blue) to $+7$ km s^{-1} (red).

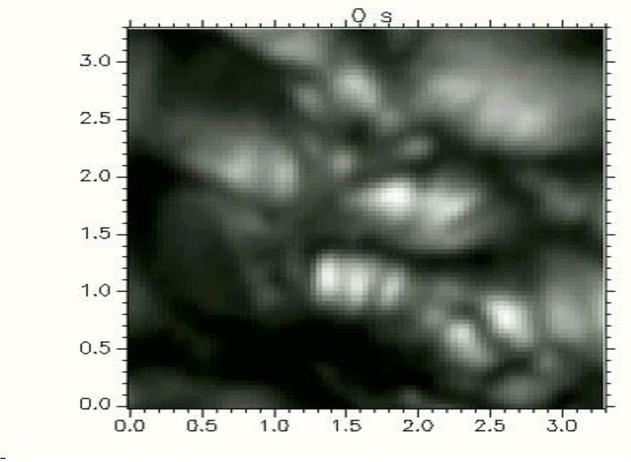
4. Principles of modeling of the photosphere

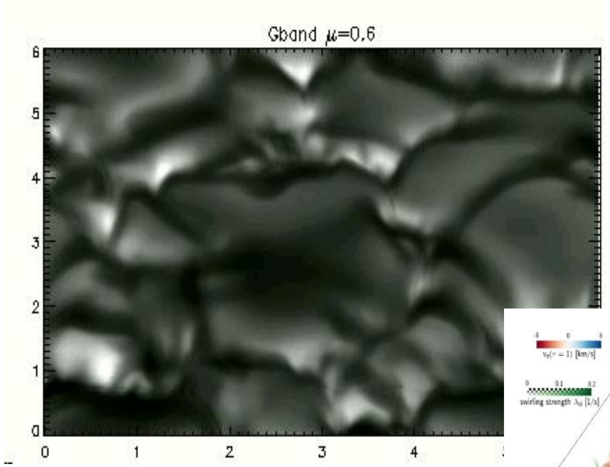
1865 observations

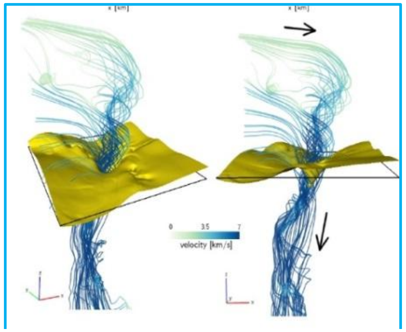


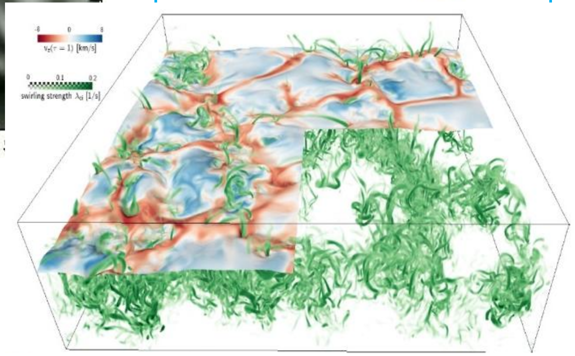
1865 theory - clouds











3D magnetoconvection, MAGNETIZED VORTEX

Structure of the talk:

Final !!

1. Basic physical properties of the solar photosphere

2. Photosphere radiation, formation of absorption spectral lines, optical depth, limb darkening

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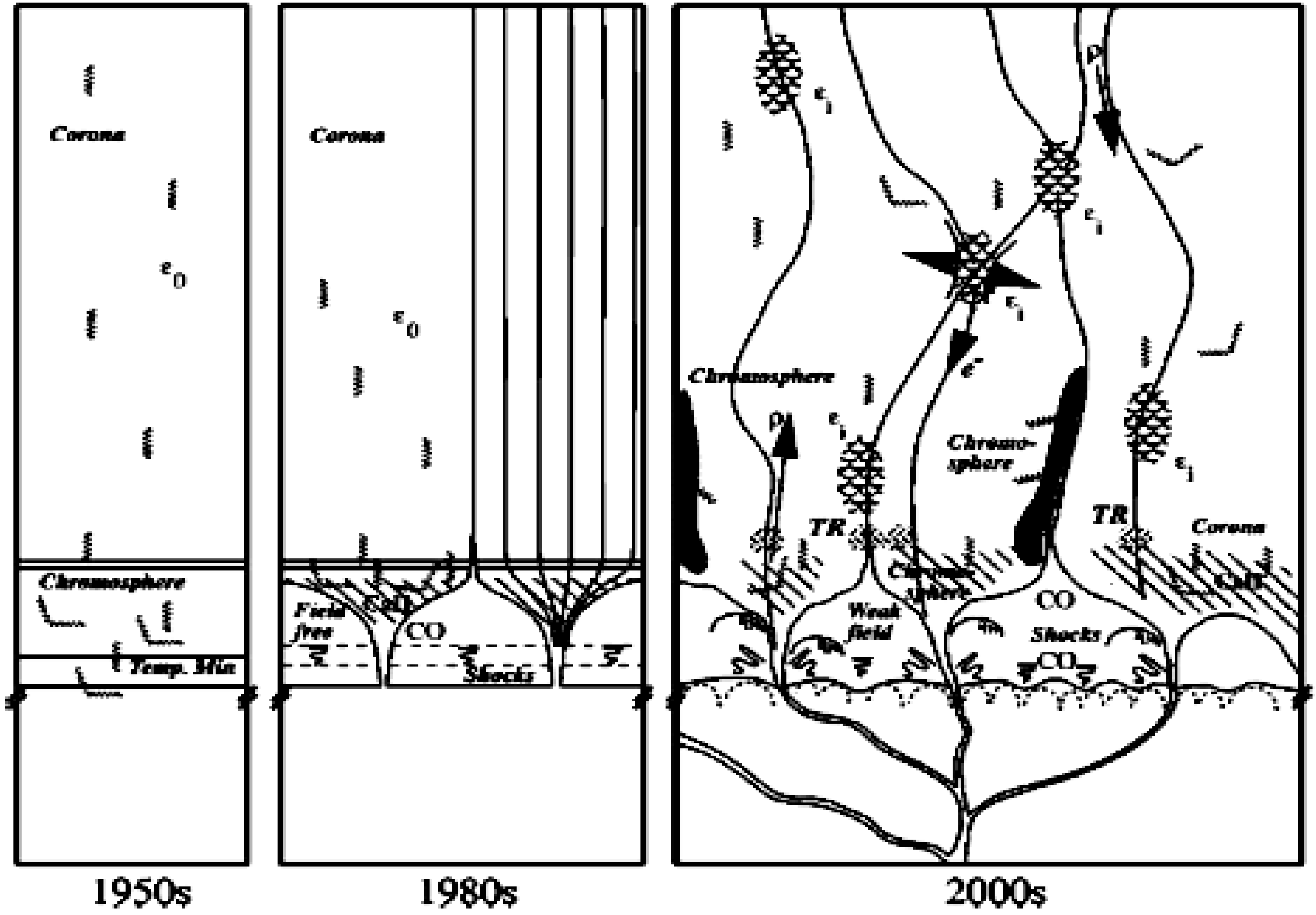
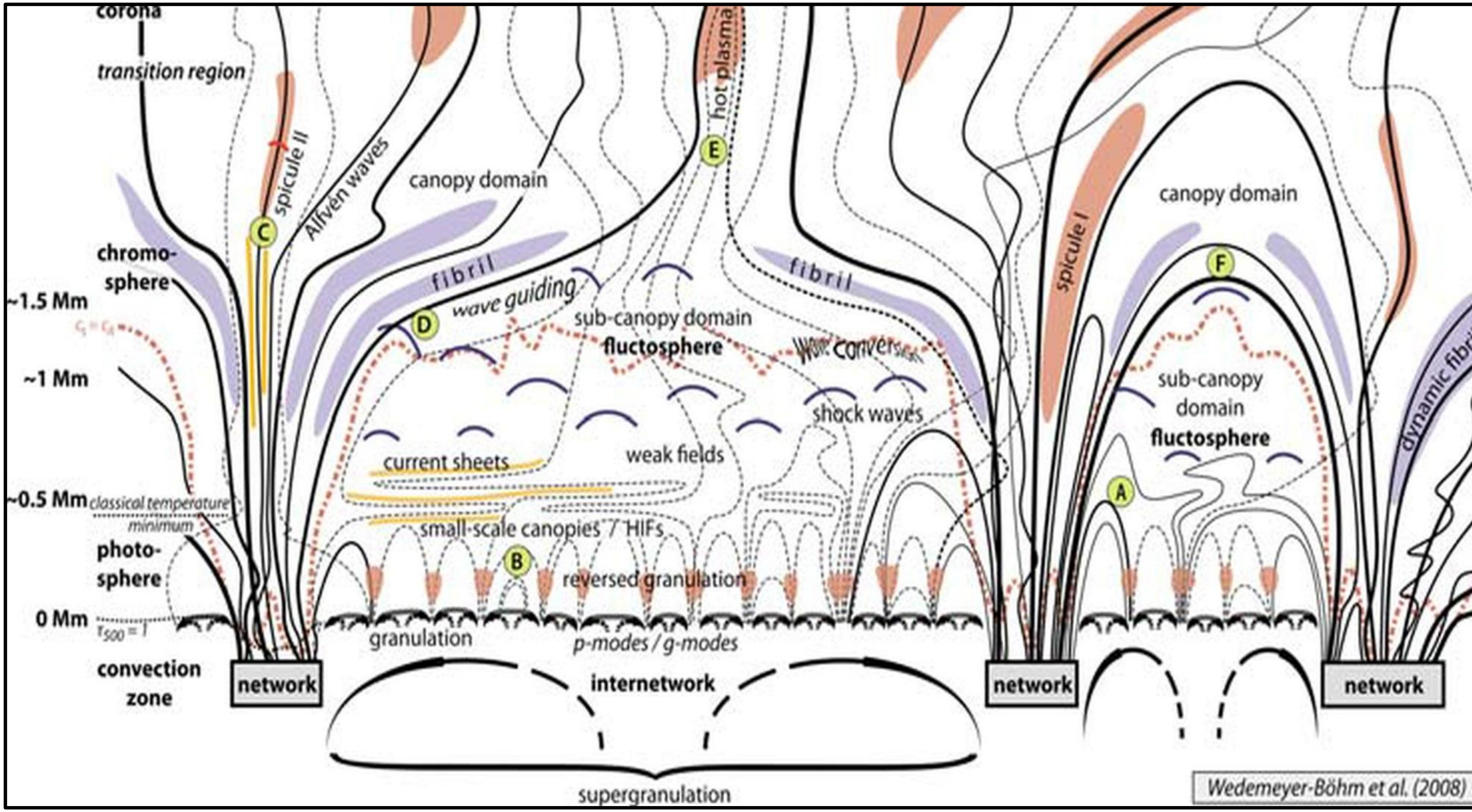


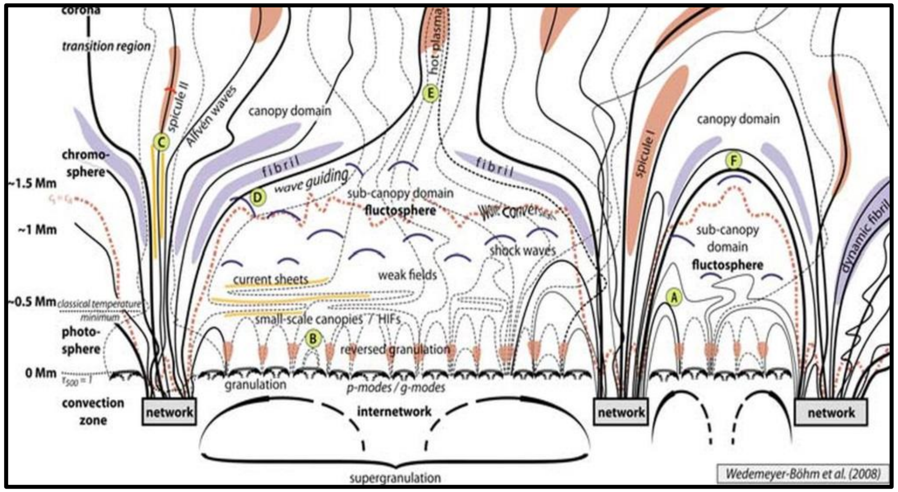
5. Comparison of the photosphere with the other layers of the solar atmosphere and with the layer located below the solar photosphere

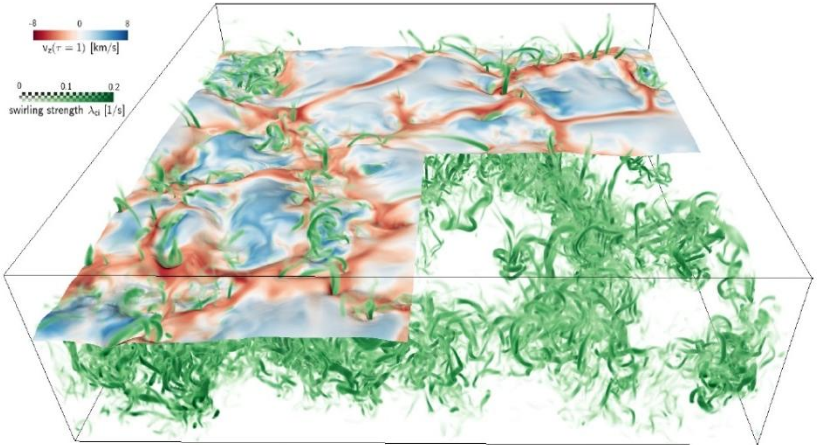


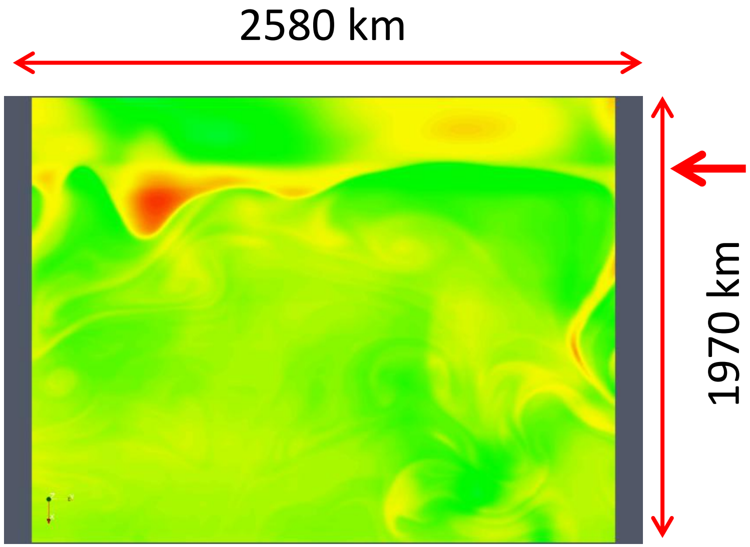
2014s

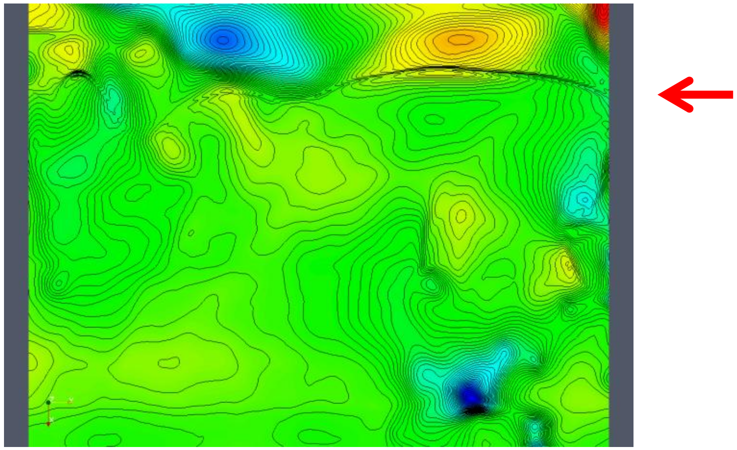
5. Comparison of the photosphere with the other layers of the solar atmosphere and with the layer located below the solar photosphere

2013





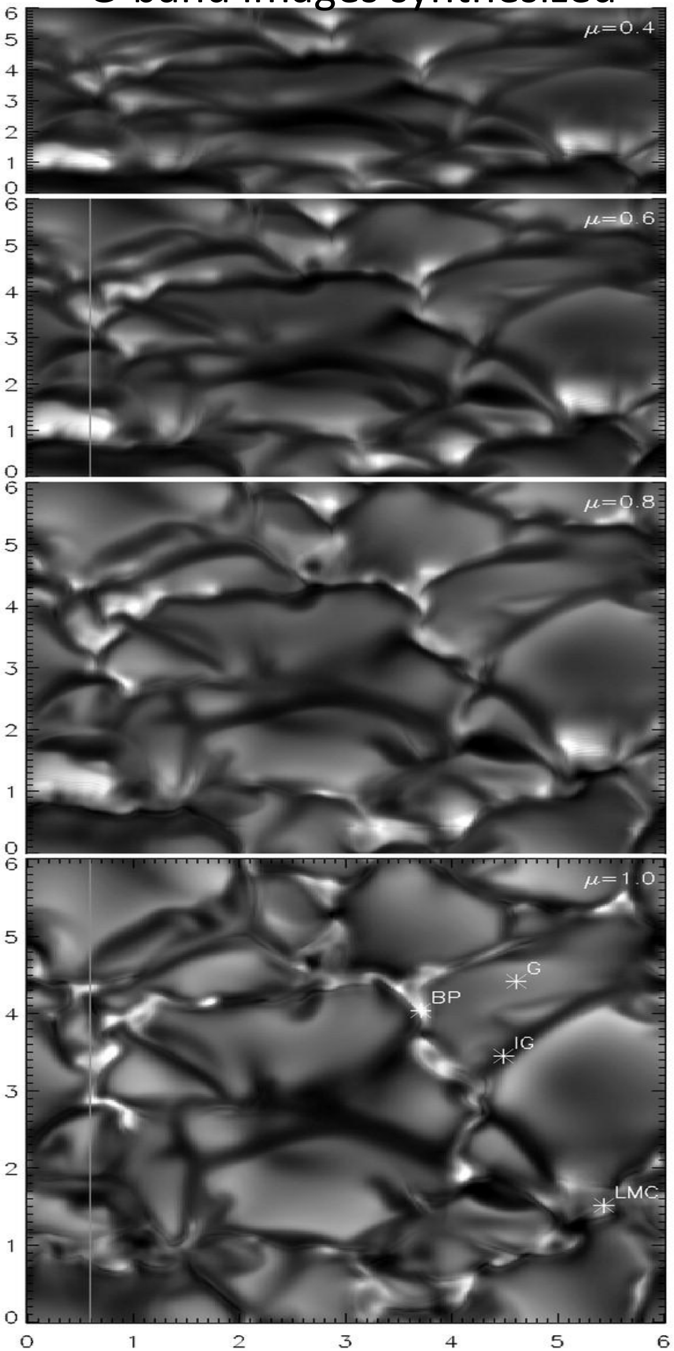




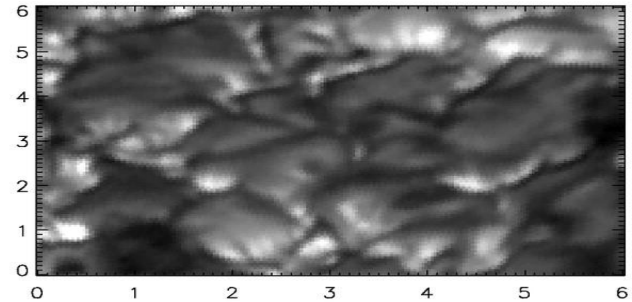
High-resolution models of solar granulation: the 2D case, Muthsam et al., 2013, Mon. Not. Roy. Astr. Soc. 380, 1335-1340

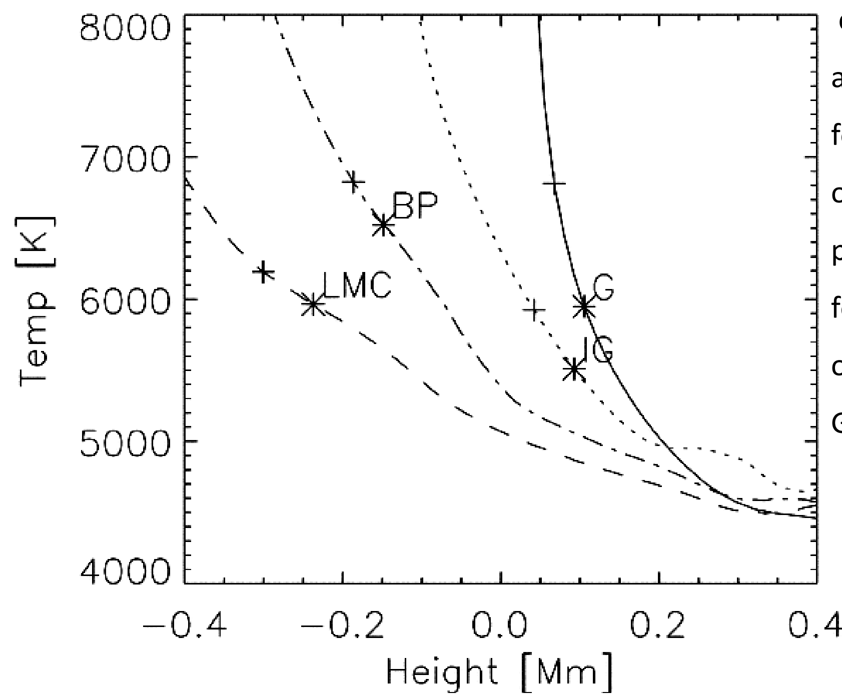
Interpretation of Solar granulation – Results

G-band images synthesized



G-band image observed with Swedish 1m solar Telescope at μ=0.63



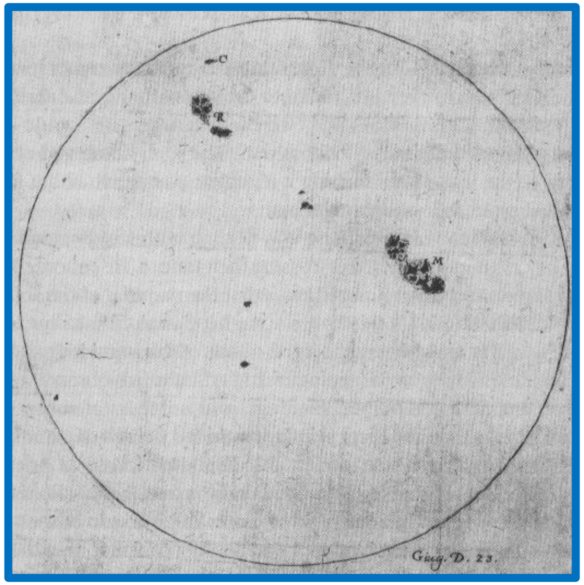


Temperature vs. height for four locations: G= granule, Ig =interganular lane, BP = magnetic bright point LMC = large magnetic flux concentration.

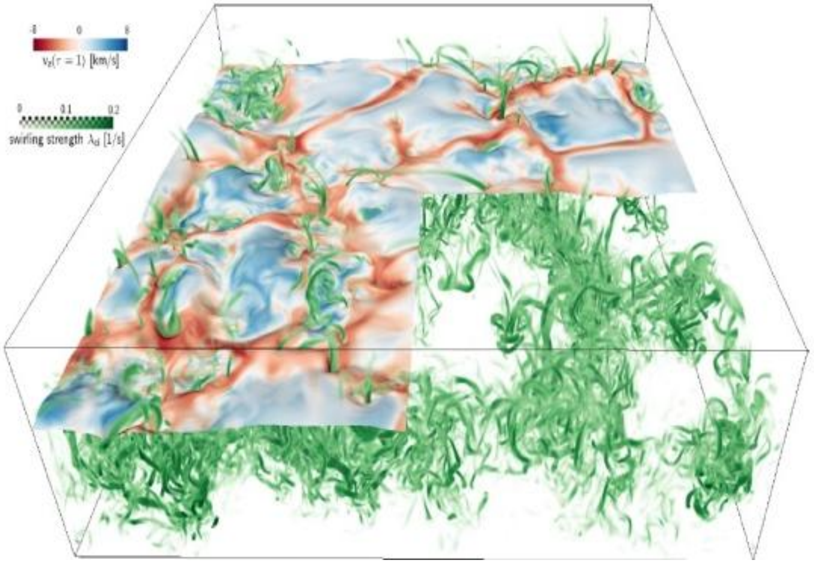
asterisks = mean formation height of the g-band

pluses = mean formation height of the G-continuum

THE END ?



1610



2014