SOLAR PHOTOSPHERE AND CHROMOSPHERE

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Contents

1 Introduction

Importance of solar/stellar photosphere and chromosphere:

- photosphere emits 99.99 % of energy generated in the solar interior by nuclear fusion, most of it in the visible spectral range
- photosphere/chromosphere visible “skin” of solar “body”
- structures in high atmosphere are rooted in photosphere/subphotosphere
- dynamics/events in high atmosphere are caused by processes in deep (sub-)photospheric layers
- chromosphere: onset of transport of mass, momentum, and energy to corona, solar wind, heliosphere, solar environment
  chromosphere = burning chamber for pre-heating
  non-static, non-equilibrium

Extent of photosphere/chromosphere:

- barometric formula (hydrostatic equilibrium):

$$\mathrm{d}p = -\rho g \mathrm{d}z \qquad \text{and} \qquad \mathrm{d}p = -p\frac{\mu g}{\mathcal{R}T}\mathrm{d}z \tag{1}$$

$$\Rightarrow \quad p = p_0 \exp[-(z-z_0)/H_\mathrm{p}] \tag{2}$$

  with “pressure scale height” $H_\mathrm{p} = \frac{\mathcal{R}T}{\mu g} \approx 125\,\mathrm{km}$
  (solar radius $R_\odot \approx 700\,000\,\mathrm{km}$)

- extent: some 2 000 – 6 000 km (rugged)
- “skin” of Sun

In following: concepts, atmospheric model, dyanmic atmosphere

2 A coarse view – concepts

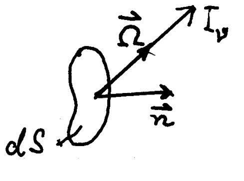
2.1 The data

radiation ($\widehat{=}$ energy)
solar output: measure radiation at Earth’s position, distance known

$$\Rightarrow \quad \mathcal{F}_\odot = \sigma \mathrm{T}^4_{\mathrm{eff},\odot} = L_\odot/(4\pi R^2_\odot) = 6.3 \times 10^{10}\ \mathrm{erg\,cm^{-2}\,s^{-1}} \tag{3}$$

$$\Rightarrow \quad \mathrm{T}_{\mathrm{eff},\odot} = 5780\,\mathrm{K}\,. \tag{4}$$

specific intensity $I_\nu = I(\vec{r}, \vec{\Omega}, \nu, t)$ = from surface $\mathrm{d}S$ into direction $\vec{\Omega}$ emitted energy [erg/(cm^2 s Hz sterad)]
$|\vec{\Omega}| = 1$
(or $I_\lambda, \nu = c/\lambda, |\mathrm{d}\nu| = \mathrm{c}/\lambda^2|\mathrm{d}\lambda|$)



- I depends on wavelength λ (or frequency ν),
- meaurements in: UV, optical (visible), IR/FIR, mm, radio
- absorption lines = Fraunhofer lines, emission lines in UV
- I depends on direction ($\vec{\Omega}$) and time (t)

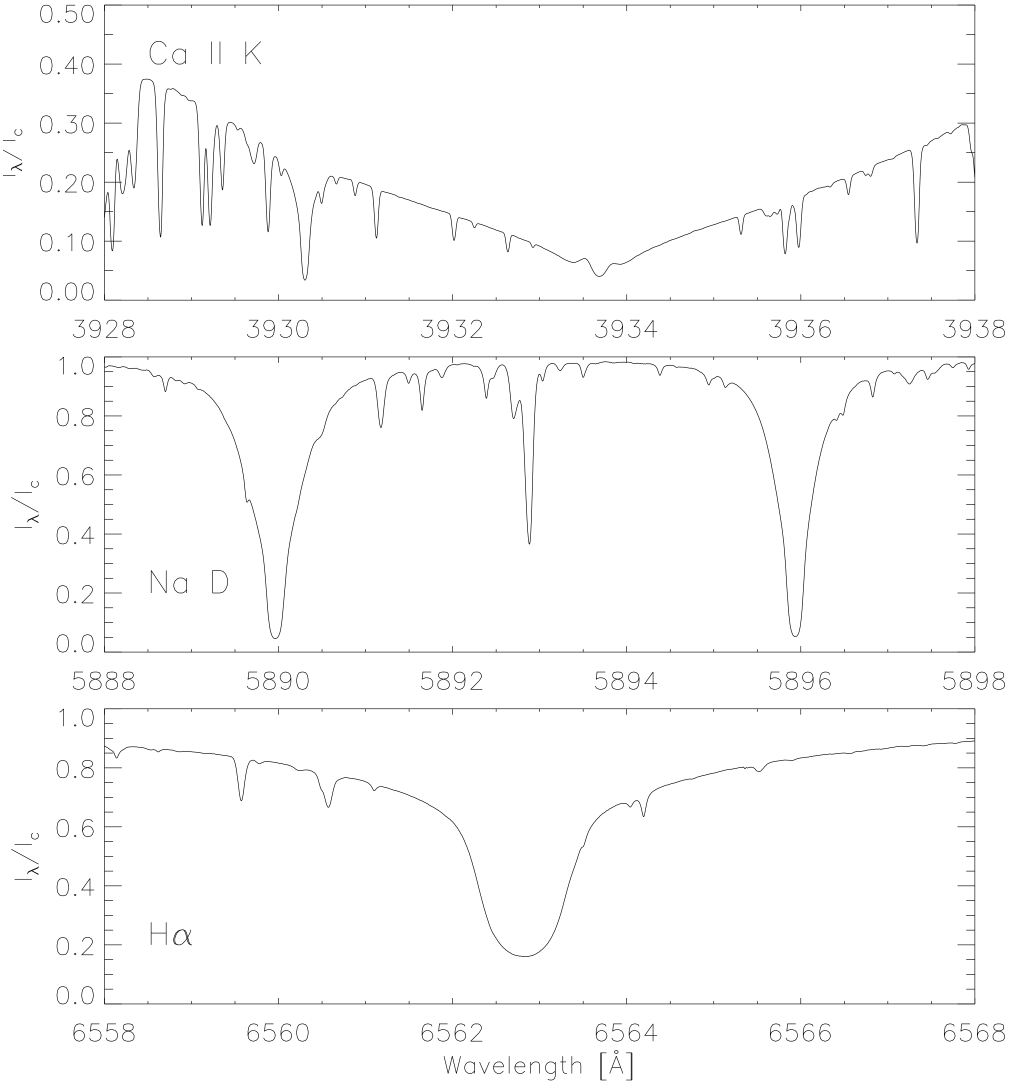
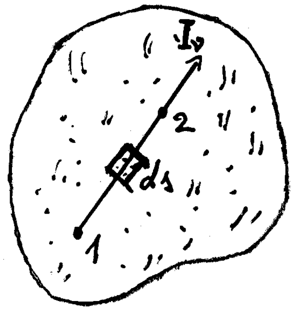


Figure 1: Examples of Fraunhofer lines in the visible spectral range near Ca II K, Na D_1 and Na D_2, and Balmer Hα; from Kitt Peak *Fourier Transform Spectrometer Atlas.*

2.2 Interpretation – first approach

a) Transfer of radiation



$$\mathrm{d}I_\nu = -\kappa_\nu I_\nu \mathrm{d}s + \varepsilon_\nu \mathrm{d}s \tag{5}$$

κ_ν = absorption coefficient, ε_ν = emission coefficient, to be specified,

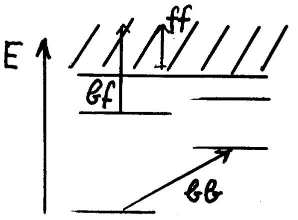
$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\kappa_\nu I_\nu + \varepsilon_\nu \;;\; \vec{\Omega} \cdot \nabla I_\nu = -\kappa_\nu I_\nu + \varepsilon_\nu \,. \tag{6}$$

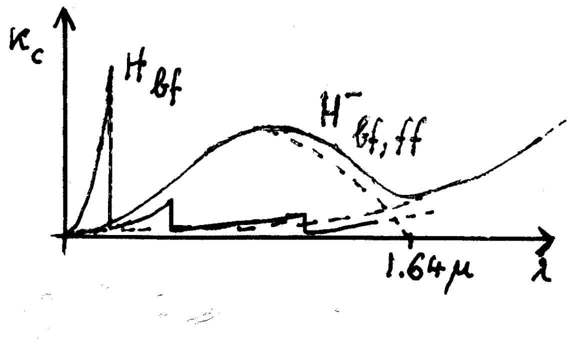
b) Optical thickness, absorption coefficients, source function

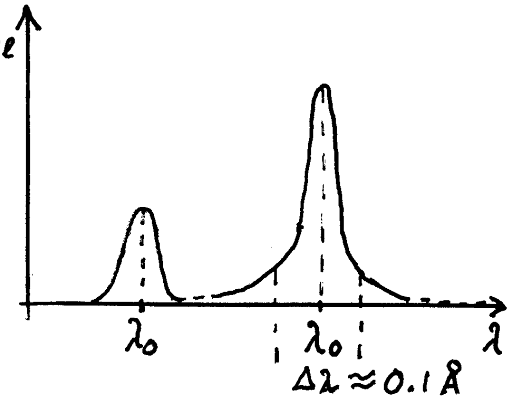
- optical thickness:

$$\mathrm{d}\tau_\nu = -\kappa_\nu \mathrm{d}s \quad ; \quad \tau_1 - \tau_2 = -\int_2^1 \kappa \mathrm{d}s \tag{7}$$

- absorption coefficients: 1) from continuous atomic transitions (bound-free, free-free), slowly varying
  2) from transitions between discrete atomic energy levels (bound-bound), broadened by thermal and turbulent motions (Doppler effect), by radiative and collisional damping







- source function:

$$S_\nu = \frac{\varepsilon_\nu}{\kappa_\nu} \quad ; \quad \text{in LTE} \quad S_\nu \equiv B_\nu(\mathrm{T}) = \left(\frac{2h\nu^3}{c^2}\right) \frac{1}{\exp[h\nu/(k\mathrm{T})] - 1} \tag{8}$$

c) Concept of Local Thermodynamic Equilibrium – LTE

atomic level populations according to Boltzmann-Saha statistics with local temperature (from Maxwellian distribution of electron velocities)

$$\Rightarrow \quad \frac{\varepsilon_\nu}{\kappa_\nu} = B_\nu(\mathrm{T}) \tag{9}$$

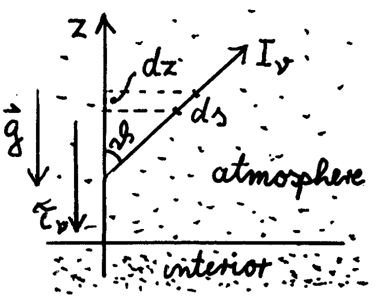
not much dependent on ν, “constant” across any spectral line.
We have to check the LTE concept.

d) Formal solution

$$I(\tau_2) = I(\tau_1)e^{-(\tau_1-\tau_2)} + \int_{\tau_2}^{\tau_1} Se^{-(\tau'-\tau_2)}\mathrm{d}\tau' \tag{10}$$

or: $I(\tau_2) =$ (intensity irradiated at point 1, i.e. τ_1) $\times\, e^{-(\tau_1-\tau_2)}$
+ integral over (intensity emitted underway at τ') $\times\, e^{-(\tau'-\tau_2)}$

e) Plane parallel atmosphere



define $\mathrm{d}\tau_\nu \equiv -\kappa_\nu \mathrm{d}z$, $\mathrm{d}s = \mathrm{d}z/\cos\theta$, $\cos\theta \equiv \mu$,
$\tau_\nu = -\int_\infty^z \kappa_\nu \mathrm{d}z$
$\Rightarrow$ emergent intensity

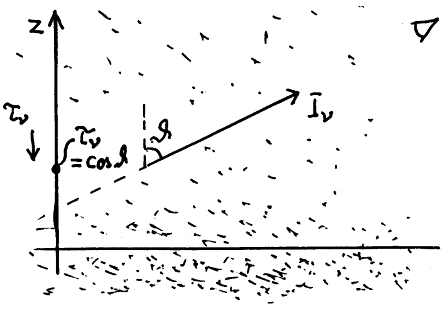
$$I_\nu(\tau_\nu = 0, \mu) = \int_0^\infty S_\nu(\tau'_\nu)e^{-\tau'_\nu/\mu}\mathrm{d}\tau'_\nu/\mu \tag{11}$$

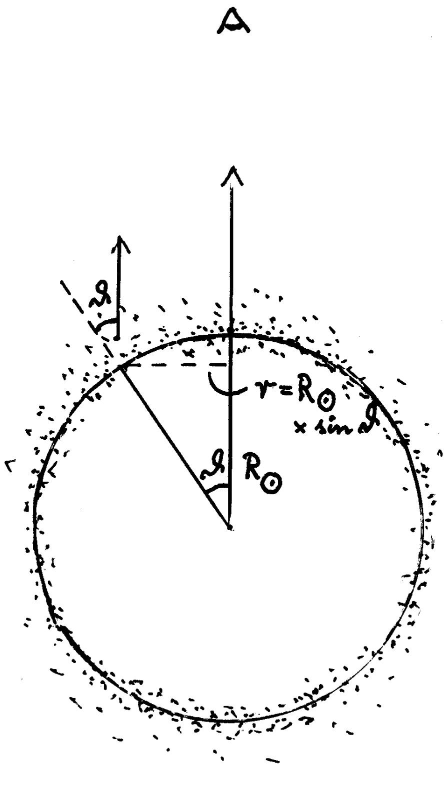
f) Eddington-Barbier approximation

Taylor expansion of $S(\tau')$ about τ^*:
$S(\tau') = S(\tau^*) + (\tau' - \tau^*)\frac{\mathrm{d}S}{\mathrm{d}\tau}|_{\tau^*} + \ldots$
$\Rightarrow$ at $\tau^* = \mu = \cos\theta$ (Eq. 11)

$$I_\nu(\tau_\nu = 0, \mu) \approx S_\nu(\tau_\nu = \mu)\,, \tag{12}$$

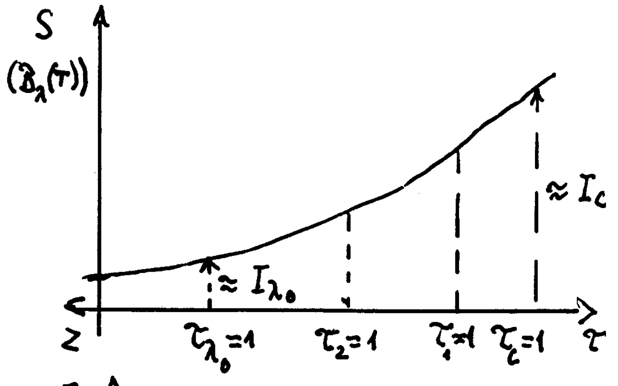
i.e. observed intensity $\approx$ source function at $\tau_\nu = \cos\theta$ (not at $\sin\theta$)

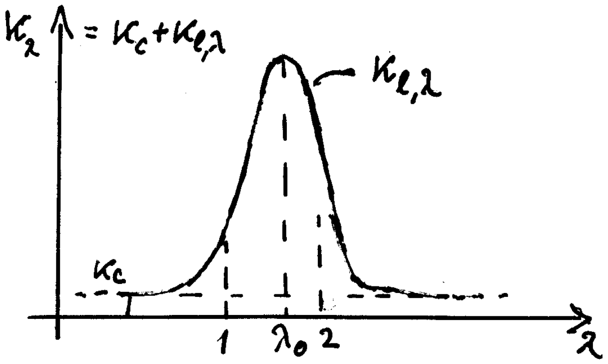


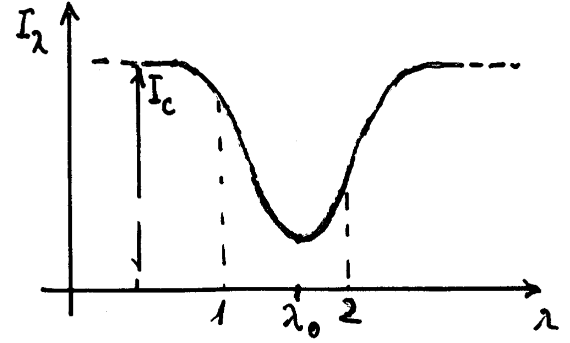


g) Formation of Fraunhofer lines, schematically

mapping of source function (e.g. $B_\nu(\mathrm{T})$) onto emergent intensities via absorption coefficients (disk center, $I_\lambda(0,\mu=1) \approx S_\lambda(\tau_\lambda=1)$)



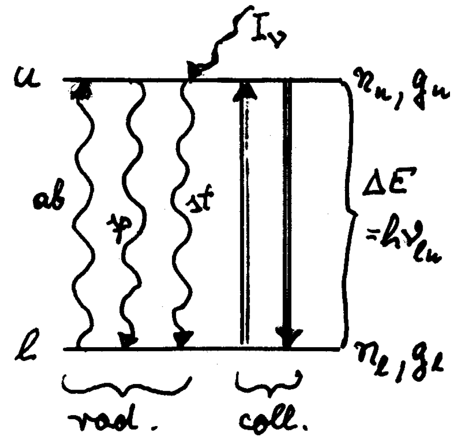




intensity I_λ depends on "height of formation", thus on amount of absorption, mumber density of absorbing particles, abundance, level populations, atomic absrоption coefficient

2.3 non-Local Thermodynamic Equilibrium – non-LTE

calculate source function for very specific case:
only atoms of one species, possessing just two atomic levels,
+ electrons for collisions,
electrons have Maxwellian velocity distribution (defines temperature T)



a) Absorption

on ds absorbed specific intensity I_ν
= probability q_ν that an atom absorbs a photon
× number density of absorbing atoms n_l
× intensity I_ν × ds

$\Rightarrow \quad \kappa_\nu I_\nu \mathrm{d}s = q_\nu n_l I_\nu \mathrm{d}s$

Einstein:
$q_\nu = B_{lu} \frac{h\nu_{lu}}{4\pi} \phi_\nu$ where ϕ_ν = Gauss-, Voigt profile,
frequency dependence is separated out and $\int_{\text{line}} \phi_\nu \mathrm{d}\nu = 1$

classically: harmonic damped oscillator

$$\int_{\text{line}} q_\nu \mathrm{d}\nu = \frac{\pi e^2}{m_e c} f_{lu} \tag{13}$$

b) Spontaneous emission

$\varepsilon_{\nu,\mathrm{sp}} = n_u A_{ul} \frac{h\nu_{lu}}{4\pi} \phi_\nu$

c) Stimulated emission

$\varepsilon_{\nu,\mathrm{st}} = n_u B_{ul} \frac{h\nu_{lu}}{4\pi} \phi_\nu I_\nu$

relations: $A_{ul} = \frac{2h\nu^3}{c^2} B_{ul}$, $\quad g_l B_{lu} = g_u B_{ul}$

d) Rate equations

Boltzmann equation for level i:

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \vec{v}_i) = (\textit{production} - \textit{destruction}) \textit{ per unit time} \tag{14}$$

assume that production and destruction fast processes (atomic transitions)
$\Rightarrow \quad (\textit{production} - \textit{destruction}) \approx 0$ or

$$n_l(B_{lu}\bar{J} + C_{lu}) = n_u(A_{ul} + B_{ul}\bar{J} + C_{ul}) \tag{15}$$

with angle and frequency averaged intensities

$$J_\nu = \int I_\nu \mathrm{d}\Omega/(4\pi)\,, \text{ and } \bar{J} = \int_{\text{line}} J_\nu \phi_\nu \mathrm{d}\nu \tag{16}$$

e) Collisions

collisions with electrons dominate those with other particles
(density n_e, they are fast, Maxwellian velocity)

$$C_{lu} = n_e \Omega_{lu,\mathrm{c}}(\mathrm{T}) \quad \text{and} \quad C_{ul} = n_e \Omega_{ul,\mathrm{c}}(\mathrm{T}) \tag{17}$$

Gedankenexperiment: in thermal equilibrium ($n_l^*,\ n_u^*$), Boltzmann populations

$$\Rightarrow \frac{n_u^*}{n_l^*} = \frac{g_u}{g_l} e^{-h\nu/(k\mathrm{T})} \tag{18}$$

When collicions with thermal electrons dominate over radiative transitions

$$\Rightarrow \text{Boltzmann level populations} \Rightarrow \frac{C_{lu}}{C_{ul}} = \frac{g_u}{g_l} e^{-h\nu/(k\mathrm{T})} \tag{19}$$

otherwise, from rate equation

$$\frac{n_l g_l}{n_u g_u} = \frac{A_{ul} + B_{ul}\bar{J} + C_{ul}}{B_{ul}\bar{J} + C_{ul}\exp[-h\nu/(k\mathrm{T})]} \tag{20}$$

population densities depend on collisions <u>and</u> on radiation field

f) absorption coefficient, source function

$$\kappa_\nu = n_l B_{lu} \frac{h\nu_{lu}}{4\pi} [1 - \frac{n_u g_l}{n_l g_u}] \phi_\nu \tag{21}$$

define: $\varepsilon' \equiv \frac{C_{ul}}{A_{ul}}(1 - \exp[-h\nu/(k\mathrm{T})])$; $\quad \varepsilon \equiv \frac{\varepsilon'}{1+\varepsilon'}$

$$\Rightarrow \quad S_{lu} = (1-\varepsilon)\bar{J} + \varepsilon B_\nu(\mathrm{T}) \tag{22}$$

$S_{lu} \approx$ independent of ν across spectral line, like $B_\nu(\mathrm{T})$
$S_{lu} = B_\nu(\mathrm{T})$ (or LTE) for $\varepsilon \to 1,\ \varepsilon' \to \infty,\ C_{ul} \gg A_{ul}$ <u>or</u> for $\bar{J} = B_\nu(\mathrm{T})$

g) estimate ε'

(approximate $\exp[-h\nu/(k\mathrm{T})] \ll 1$, Wien limit)
$A_{ul} \approx 10^8\ \mathrm{s}^{-1}$, (atomic level life time for resonant lines $t = 1/A_{ul} \approx 10^{-8}$ s)
$n_e \approx 10^9 \ldots 10^{14}$ per cm^3 in $\odot$ atmosphere
$\Omega_{ul} \approx \sigma_{ul}\bar{v}_e\,, \sigma_{ul} \approx 10^{-15}\,\mathrm{cm}^2,\,,\ \bar{v}_e \approx 4 \times 10^7 \mathrm{cm\,s}^{-1}$
$\Rightarrow \quad \varepsilon' = 4 \times 10^{-2} \ldots 4 \times 10^{-7} \ll 1; \quad \varepsilon \approx \varepsilon'$

h) solution of transfer equation

for simplicity with $B_\nu(\mathrm{T})$, ε, ϕ_ν all independent of height (of optical depth)

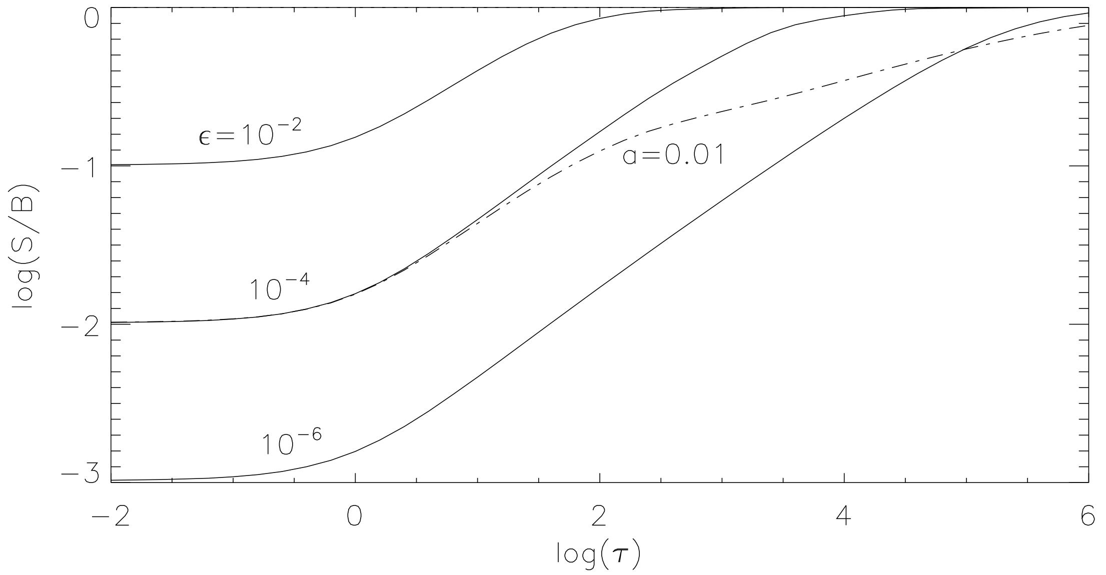
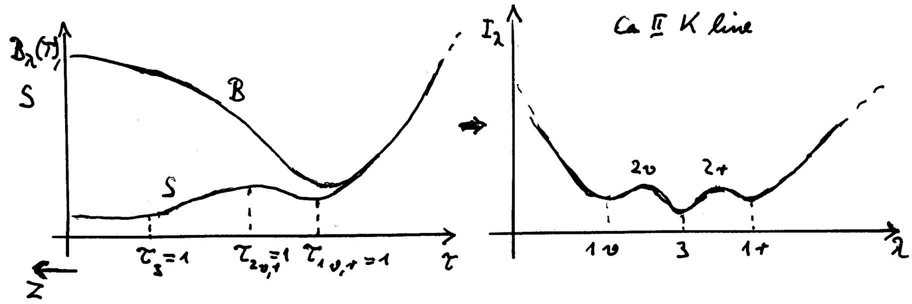


Figure 2: Run of $S_{lu}/B_\nu(\mathrm{T})$ with optical depth (at line center) in an atmosphere with constant properties. Solid curves: Gaussian apsortion profiles; dash-dotted: $\varepsilon = 10^{-4}$ and normalized Voigt profile with damping constant $a = 0.01$.

- $S_{lu} \ll B_\nu(\mathrm{T})$ near surface, photons escape from deep layers,
  $\Rightarrow \quad \bar{J} \ll B_\nu(\mathrm{T})$
- We would see an absorption line although T is constant with depth (see above, formation of Fraunhofer lines, mapping of S onto emergent intensity $I_\lambda(0,\mu)$)
- temperature rise and "self-reversal"



- Normally, atoms, molecules, and ions have many energy levels/transitions
  $\Rightarrow$ complicated, but possible to calculate (let the computer do it)

2.4 Polarized light

- polarized light is produced by scattering and in the presence of magnetic fields
- described by the *Stokes* vector $\vec{I_\nu} = (I_\nu, Q_\nu, U_\nu, V_\nu)^{\mathrm{T}}$ with

  $I_\nu \equiv$ total intensity

  $Q_\nu, U_\nu \equiv$ contribution of linearly polarized light in two independent orientations

  $V_\nu \equiv$ contribution of circularly polarized light
- transfer of *Stokes* vector

$$\frac{\mathrm{d}\vec{I}}{\mathrm{d}s} = -\mathbf{K}(\vec{I} - \vec{S}) \quad ; \quad \vec{S} = (S, 0, 0, 0)^{\mathrm{T}} = \text{ source function} \tag{23}$$

  infromation on magnetic field (e.g. Zeeman splitting) is contained in absorption matrix $\mathbf{K}$

2.5 Atmospheric model

a) Assumptions

- hydrostatic equilibrium: $\mathrm{d}p = -\rho g \mathrm{d}z$
- plane parallel, gravitationally stratified
- micro-, macro-turbulence (small-scale random motions, for broadening of lines)
- static: $\frac{\partial}{\partial t} = 0\,;\ \vec{v} = 0\,;\ \Rightarrow \quad \frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \vec{v}) = 0$
- kinetic equilibrium: electrons possess Maxwellian velocity distribution
- equation of state: $p = n_{\mathrm{tot}} k \mathrm{T}$
- charge conservation: $n_e = n_p + n_{\mathrm{He}^+} + n_{\mathrm{He}^{++}} + n_{\mathrm{Fe}^+} + \ldots$
- chemical composition given: abundances $\Rightarrow \quad \rho$, absorption coefficient, electron density
- atomic parameters known: $f_{lu},\ \Omega_{lu},\ \ldots$

b) Model construction

- adopt model of temperature $\mathrm{T}(z)$
  (zero level $z = 0$ arbitrary, usually shifted to $\tau_{\mathrm{c,5000A}} = 1$ at end of modelling)
- solve simultaneously/iteratively:

  – transfer equations for important lines and continua:

  – H, other elements important as electron donors (Fe, Mg, Si, . . .)

  – rate equations for the according levels and continua

  – obey hydrostatic equilibrium and charge conservation

⇒ mass density $\rho(z)$, electron density $n_e(z)$,
absorption and emission coefficients $\kappa_\nu(z)$, $\varepsilon_\nu(z)$

- calculate emergent intensities and compare with observations
- modify T(z), if necessary (disagreement between data and calculated intensities)
- otherwise ⇒ MODEL

c) Example

Vernazza, Avrett, & Loeser (1981, [23]) ⇒ VAL A–F, VAL C

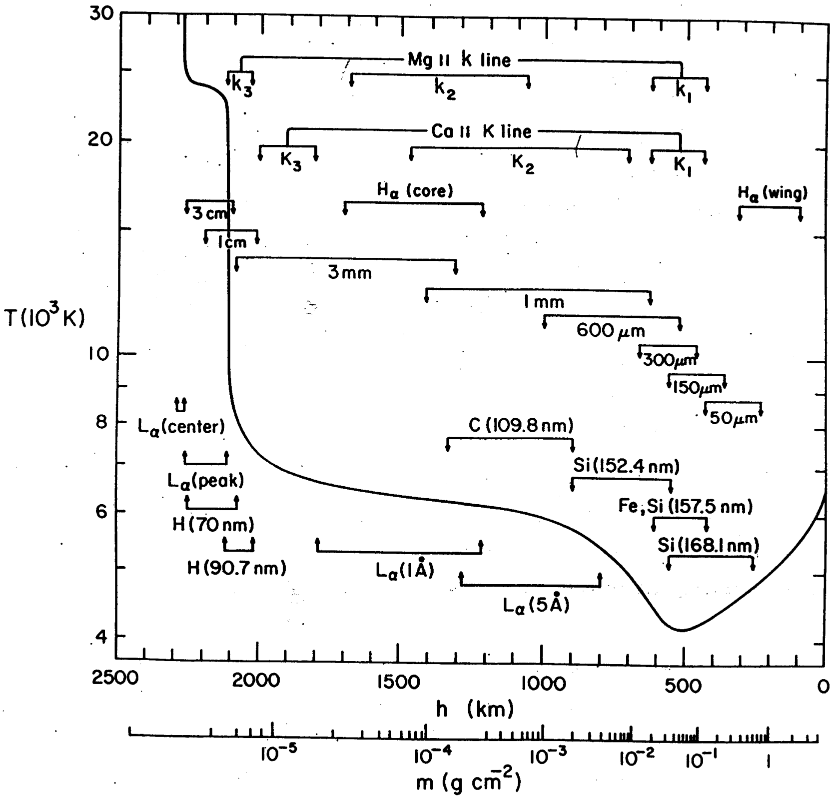


Figure 3: Run of temperature with height in the solar atmosphere. The formation layers of various spectral features are indicated. From Vernazza, Avrett, & Loeser (1981, [23]).

3 A closer view – the dynamic atmosphere

- The Sun shows many inhomogeneities, known since about 150 years
- inhomogeneities are time dependent – dynamic
- temperature rise to high coronal values only possible with non-radiative energy supply
- most energy is needed for chromospheric heating
- dynamics: convection – waves – dynamic magnetic fields
- more descriptive than theoretical presentation (see references and other lectures)

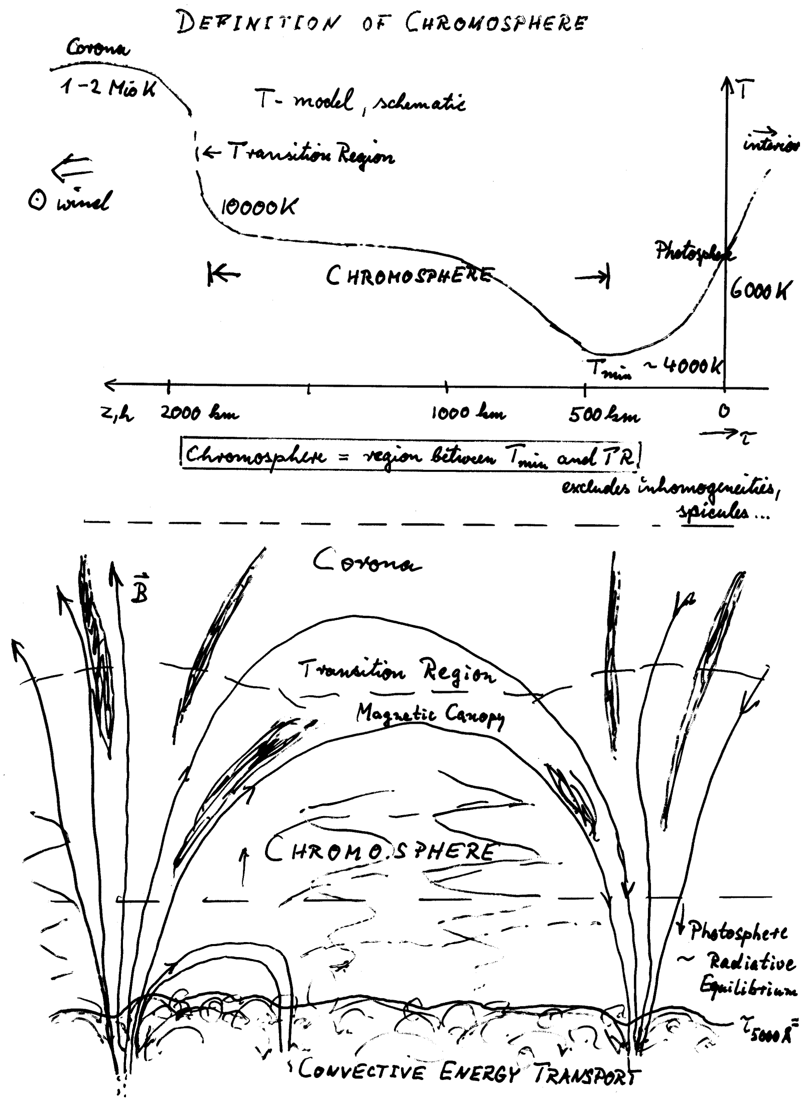


Figure 4: Homogeneous temperature structure of the solar atmosphere (upper part, [23]) and sketch of inhomogeneities with dynamic features as granules, waves, spicules, and magnetic fields.

3.1 Convection – granulation

a) Convection

- down to approx. 200 000 km the solar interior is convective:
  high opacity and low c_p/c_v (ionization of H $\Rightarrow$ many degrees of freedom) favour convection, "Schwarzschild criterion"
- convection very efficient in energy tranport
- photosphere: $\tau_{\mathrm{cont}} \approx 1$, energy escapes to Universe by radiation
- photosphere convectively stable, boundary layer to convective interior

b) Granulation (– supergranulation)

- top of convection zone
- size $\bar{l} \approx 1000\,\mathrm{km} \gg$ scale height (Muller 1999 [11]), life time $\approx 10\,\mathrm{min}$
- velocities: bright upflows → radiative cooling → cool downflows,
  $v_{\mathrm{max}} \approx 2\,\mathrm{km\,s^{-1}}$ (vertical and horizontal)
- intensity fluctuations and velocities highly correlated
  (down to resolution limit $\approx 300\,\mathrm{km}$)

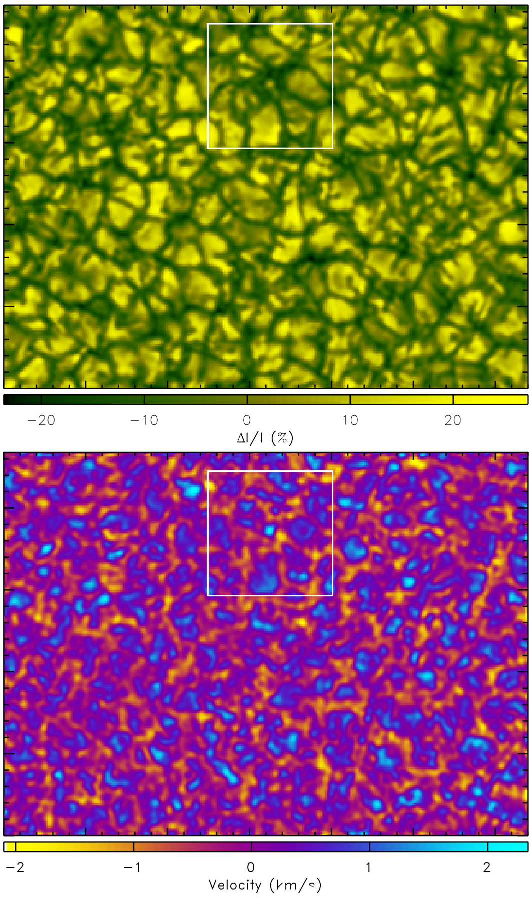


Figure 5: Intensity and velocity fluctuations of granulation ([8]).

c) Turbulence

- Rayleigh number $Ra \approx 10^{11} \quad \Rightarrow \quad$ motion expected highly turbulent
- kinetic enegy spectrum $\propto k^{-5/3}$, on which scale? (see Muller 1999 [11], Krieg et al. 2000 [8])

3.2 Waves

a) Atmospheric waves

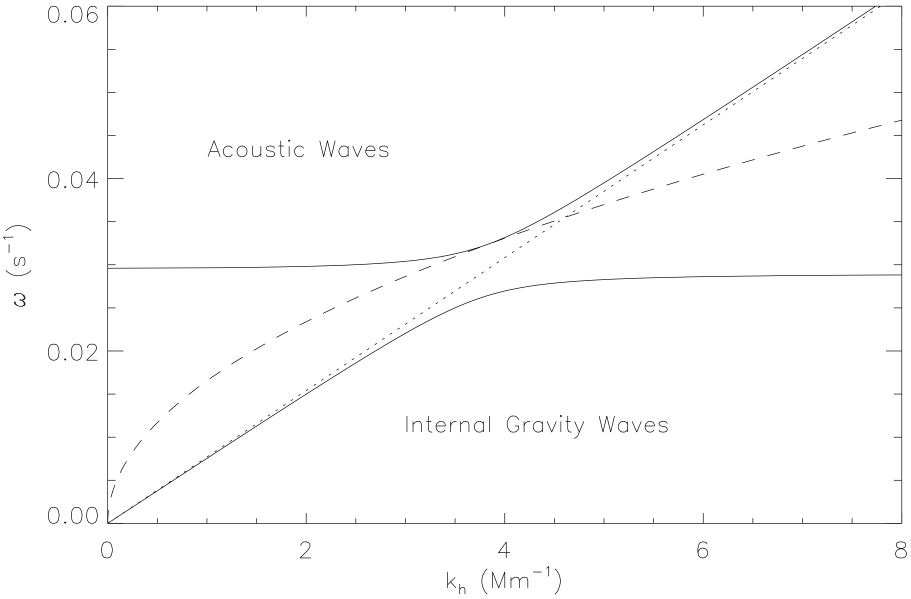


Figure 6: Regimes in the k_h-ω plane with predominantly acoustic wave and predominantly gravity wave properties, separated by the regime of evanescent waves. Dotted line: Lamb waves; dashed: divergence-free or surface gravity waves; $\mathrm{T}_0 = 6\,000$ K, $c_p/c_v = 5/3$, molar mass $\mu = 1.4$.

- assume gravitationally stratified atmosphere
- assume constant temperature, $c_p/c_v = 5/3 =$ constant
- conservation of mass, momentum, and energy (assume adiabatic motion, i.e. no energy exchange)
- linearize $\quad \Rightarrow \quad$ dispersion relation
  $k_h = 2\pi/\Lambda$, $\Lambda =$ horizontal wavelength (parallel to "surface")
  $\omega = 2\pi/P$, $P =$ period
- $\Rightarrow$ regions of wave propagation and of evanescent waves

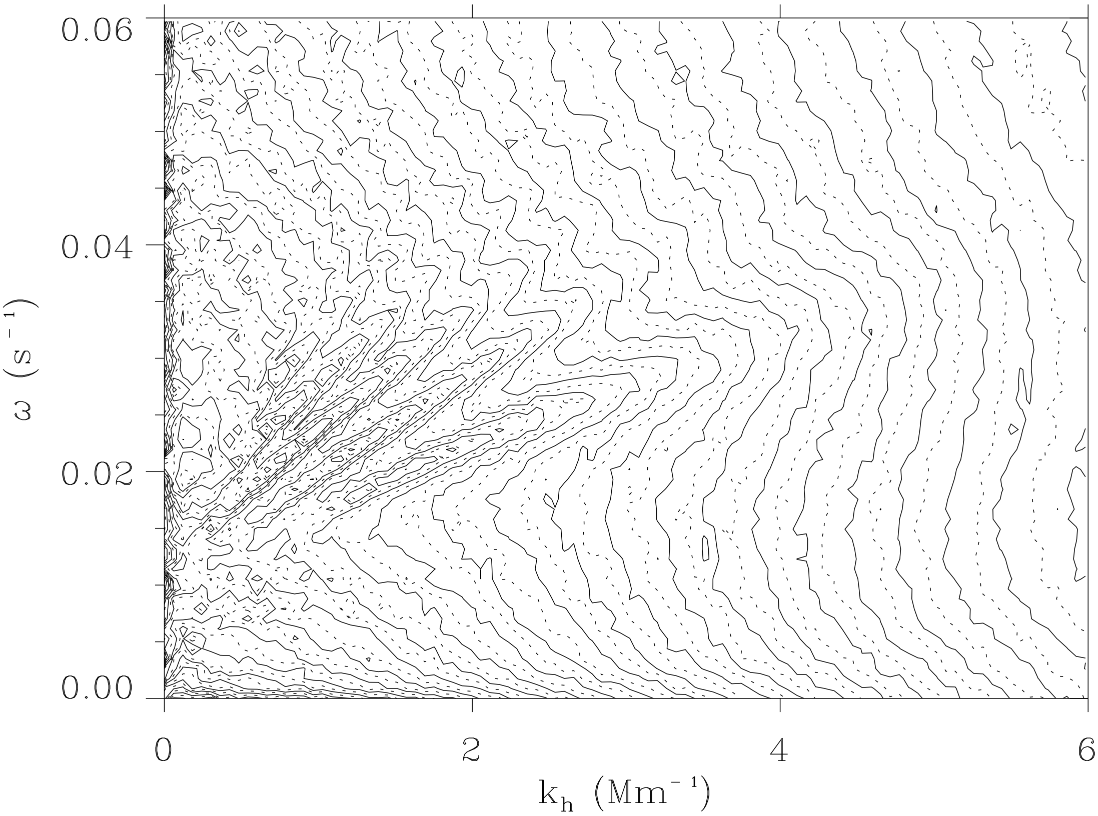
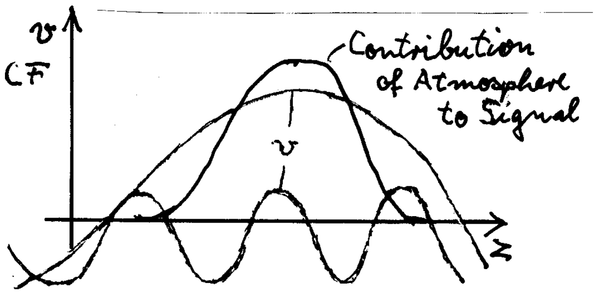
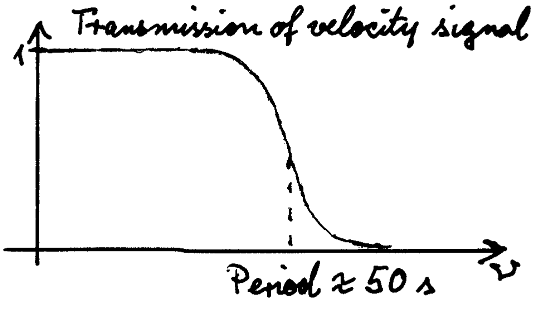


Figure 7: k_h-ω diagram, power spectrum of intensity fluctuations obtained from a time series of Ca II K filtergrams (from the chromosphere).

b) Observations

- observations are dominated by evanescent waves:
  "5-min oscillations" = acoustic waves in solar interior (resonator),
  evanescent in atmosphere
- gravity waves do exist, very likely (e.g. Al et al [1]),
  generated by granular up- and downflows
- acoustic waves:
  important (see e.g. Ulmschneider et al. 1991 [21], Ulmschneider et al. 2001 [22]),
  expected: generated by turbulence → noise (Lighthill mechanism)
  small-scale ⇒ high spatial resolution needed
  periods: 10 s ... 50 s ... 100 s
  snag: low signal, hard to detect





(see also work of Maren Wunnenberg, future work of Aleksandra Andjic)

3.3 Magnetic fields

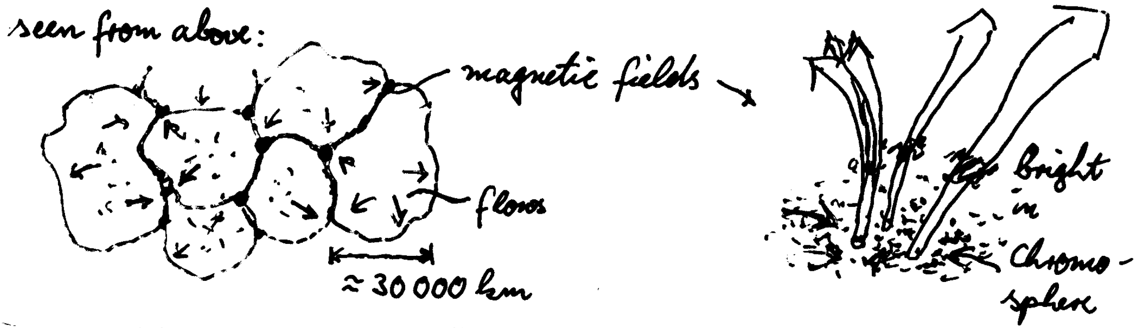
(see also lecture by M. Schüssler)

a) In general

- signature by Zeeman effect: line splitting, polarization
- magnetic fields often related to conspicuous intensities:
  sunspots, pores, bright points
- essential for coronal dynamics and dynamics of heliospheric plasma
- magnetic fields are a very important ingredient to solar/stellar atmospheric dynamics
  many dedicated conferences (e.g. Sigwarth 2001 [19]),
  dedicated telescopes

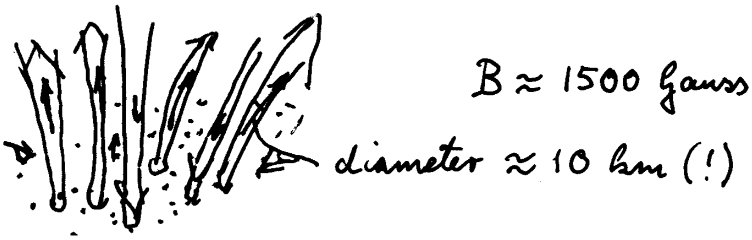
b) Small-scale magnetic fields

- small-scale: 300 km … 100 km … 10 km
- related:
  magnetic network – chromospheric network – supergranular flows



  bundles of flux tubes, $B \approx 1500$ Gauss,
  almost empty because magnetic pressure balances external gas pressure

- Intra-Network fields: ubiquitous,
  more magnetic flux through solar surface than the flux in sunspots
- MISMA hypothesis (MIcro-Structured Magnetic Atmosphere)
  (e.g. Sánchez Almeida & Lites 2000 [17])

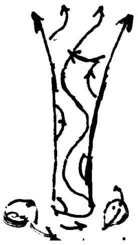


(work of Itahiza Domínguez Cerdeña)

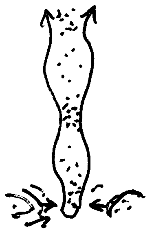
c) Magnetic fields and waves

- important for chromospheric and coronal heating
  excited by granular flows

- magnetoacoustic gravity waves ⇒ multitude of modes, e.g.



torsional
$c_{\mathrm{A}} = B/(4\pi\rho)^{1/2}$

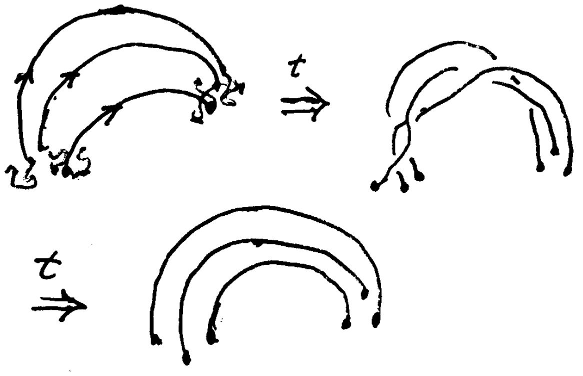


sausage
$c_t = c_s c_{\mathrm{A}}/(c_s^2 + c_{\mathrm{A}}^2)^{1/2}$

kink
cutoff for low frequencies

d) Topological complexity

footpoints are pushed around
→ "braiding" of magnetic fields
→ reordering/reconnection
→ release of magnetic energy



(work of Katja Janßen and Oleg Okunev)

3.4 Chromosphere

Name stems from eclipses (Lockyer and Frankland 1869):
shortly before/after totality vivid red color: emission in Hα (Secchi 1877 [18])
layers above photosphere, very inhomogeneous, very dynamic

a) Quiet chromosphere

- spicules (Beckers 1972 [2], Wilhelm 2000 [24]): $v \approx 30\,\mathrm{km\,s^{-1}}$ into corona
  100 times more mass than taken away by solar wind

- chromospheric network:
  diameter ≈ 30 000 km, life time ≈ 24 h
  consists of boundaries, bright in Ca K line,
  co-spatial with magnetic fields, cospatial with convective flow:
  supergranulation

- cell interior:
  tiny, quasy-periodic bright points, few times repetitive, 120 s . . . 250 s

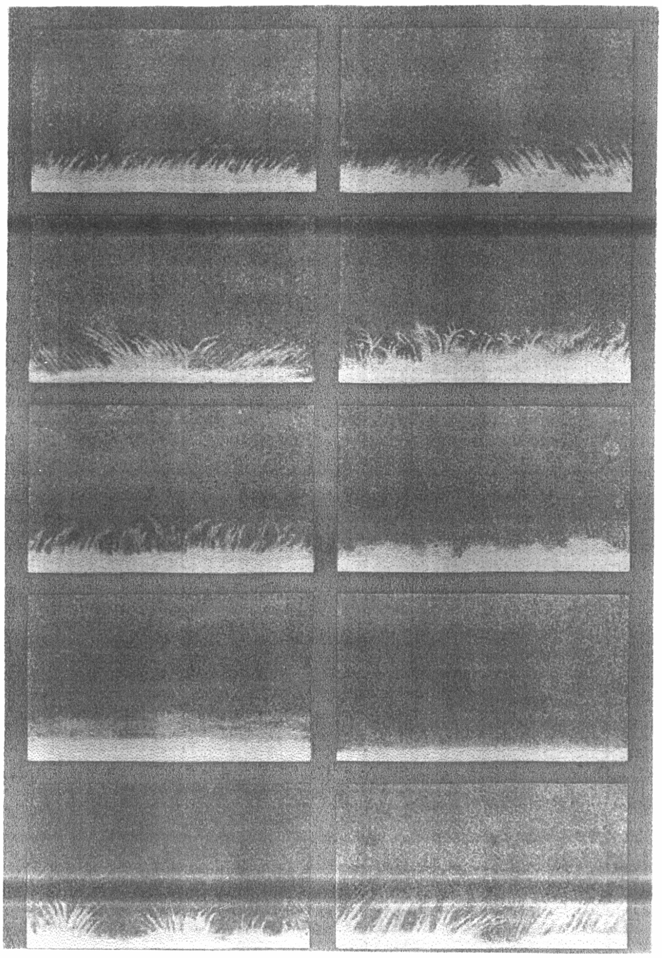
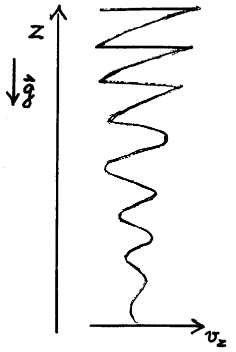


Figure 8: Spicules at the solar limb, hand drawings by Secchi (1877 [18]).

b) Problem of heating



- short-period waves
  generated by turbulent convection
  wave spectrum with periods: 10 s ... 50 s ... 100 s
  waves travel into higher layers
  acoustic energy flux: $F_{\mathrm{ac}} = \rho v^2 c_s = const$
  $c_s \approx const, \rho \approx \rho_0 e^{-z/H} \quad \Rightarrow \quad v \approx v_0 e^{z/(2H)}$
  $\Rightarrow$ acoustic shocks $\Rightarrow$ deposit of energy
- numerical simulations (Carlsson & Stein 1997 [5], Rammacher 2002 [13]):
  1) shock trains develop from short period waves, periods ≈ 200 s
  to be identified with bright points?
  2) no temperature increase on average
- way out: average temperature deduced, not measured, from average observations
  $\Rightarrow$ reproduce (average) observations by numeric simulation of dynamics
  then deduce from modelled observations average temperature

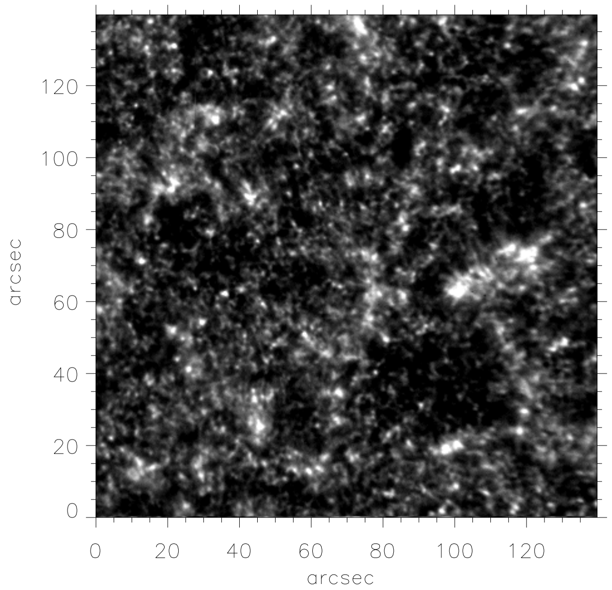
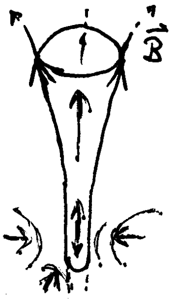


Figure 9: Ca II K filtergram from the quiet chromosphere at disk center.

c) Network boundary – active chromosphere (plages)

- increasing emission – increasing involvement of magnetic fields
- more and more braiding/reconnection
- acoustic wave emission along magnetic flux tubes:
  much more efficient than in free turbulence

free turb.: quadrupole emission



flux tube: dipole emission

- problem generally: to observe the dynamics, waves, reconnection!

4 Conclusions

- Solar / stellar photosphere and chromosphere are essential parts of the Sun / of (late type) stars.
- Photosphere and chromosphere are very dynamic.
- We see a huge plasma laboratory at work, we may learn much physics.
- Finestructure and dynamics determine outer layers:
  corona, solar wind, heliosphere.
- Thus, the processes in photosphere and chromosphere are important for Earth.

- There are means to learn about the stucture and the processes.
- It remains so much one would like to understand!

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