SOLAR PHOTOSPHERE AND CHROMOSPHERE

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Contents

1 Introduction 2

2 A coarse view – concepts 2
   2.1 The data 2
   2.2 Interpretation – first approach 4
   2.3 non-Local Thermodynamic Equilibrium – non-LTE 6
   2.4 Polarized light 9
   2.5 Atmospheric model 9

3 A closer view – the dynamic atmosphere 11
   3.1 Convection – granulation 12
   3.2 Waves 13
   3.3 Magnetic fields 15
   3.4 Chromosphere 16

4 Conclusions 18
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):
  \[ dp = -\rho g dz \quad \text{and} \quad dp = -p \frac{\mu g}{RT} dz \]  
  \[ \Rightarrow p = p_0 \exp\left[-\frac{(z - z_0)}{H_p}\right] \]  
  with "pressure scale height" \( H_p = \frac{RT}{\mu g} \approx 125 \text{ km} \)  
  (solar radius \( R_\odot \approx 700,000 \text{ km} \))
- extent: some 2 000 – 6 000 km (rugged)
- “skin” of Sun

In following: concepts, atmospheric model, dynamic atmosphere

2 A coarse view – concepts

2.1 The data

radiation (\( \equiv \) energy)
solar output: measure radiation at Earth’s position, distance known

\[ \Rightarrow \mathcal{F}_\odot = \sigma T_{\text{eff}, \odot}^4 = \frac{L_\odot}{4\pi R_\odot^2} = 6.3 \times 10^{10} \text{ erg cm}^{-2} \text{s}^{-1} \]  
\[ \Rightarrow T_{\text{eff}, \odot} = 5780 \text{ K} \.]  

specific intensity \( I_\nu = I(\vec{r}, \vec{\Omega}, \nu, t) \)  
from surface \( dS \) into direction \( \vec{\Omega} \)  
emitted energy \([\text{erg/(cm}^2\text{s Hz sterad)}]\)  
|\( \vec{\Omega} \)| = 1  
(or \( I_\lambda, \nu = c/\lambda, |d\nu| = c/\lambda^2|d\lambda| \))
• $I$ depends on wavelength $\lambda$ (or frequency $\nu$),
• measurements 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 H$\alpha$; from Kitt Peak *Fourier Transform Spectrometer Atlas.*
2.2 Interpretation – first approach

a) Transfer of radiation

\[ dI_\nu = -\kappa_\nu I_\nu ds + \varepsilon_\nu ds \quad (5) \]

\( \kappa_\nu \) = absorption coefficient, \( \varepsilon_\nu \) = emission coefficient, to be specified,

\[ \frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + \varepsilon_\nu ; \quad \vec{\Omega} \cdot \nabla I_\nu = -\kappa_\nu I_\nu + \varepsilon_\nu . \quad (6) \]

b) Optical thickness, absorption coefficients, source function

- optical thickness:

\[ d\tau_\nu = -\kappa_\nu ds \quad ; \quad \tau_1 - \tau_2 = -\int_1^2 \kappa ds \quad (7) \]

- 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:

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

c) Concept of Local Thermodynamic Equilibrium – LTE

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

\[ \Rightarrow \frac{\varepsilon_\nu}{\kappa_\nu} = B_\nu(T) \quad (9) \]

not much dependent on \( \nu \), “constant” across any spectral line.

We have to check the LTE concept.
d) Formal solution

\[ I(\tau_2) = I(\tau_1)e^{-(\tau_1 - \tau_2)} + \int_{\tau_2}^{\tau_1} Se^{-(\tau' - \tau_2)} d\tau' \]  

or: \[ I(\tau_2) = (\text{intensity irradiated at point 1, i.e. } \tau_1) \times e^{-(\tau_1 - \tau_2)} \]  

+ integral over (intensity emitted underway at \( \tau' \)) \times e^{-(\tau' - \tau_2)}

\[ \] 

e) Plane parallel atmosphere

\[ \text{define } d\tau_\nu \equiv -\kappa_\nu dz, \quad ds = dz / \cos \theta, \quad \cos \theta \equiv \mu, \]

\[ \tau_\nu = -\int_{\infty}^{z} \kappa_\nu dz \]

⇒ emergent intensity

\[ I_\nu(\tau_\nu = 0, \mu) = \int_{0}^{\infty} S_\nu(\tau'_\nu)e^{-\tau'_\nu/\mu} d\tau'_\nu/\mu \]  

\[ \] 

f) Eddington-Barbier approximation

Taylor expansion of \( S(\tau') \) about \( \tau^* \):

\[ S(\tau') = S(\tau^*) + (\tau' - \tau^*) \frac{dS}{d\tau}|_{\tau^*} + \ldots \]

⇒ at \( \tau^* = \mu = \cos \theta \) (Eq. 11)

\[ I_\nu(\tau_\nu = 0, \mu) \approx S_\nu(\tau_\nu = \mu), \]  

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. \( B_\nu(T) \)) onto emergent intensities via absorption coefficients
(disk center, \( I_\lambda(0, \mu = 1) \approx S_\lambda(\tau_\lambda = 1) \))

intensity \( I_\lambda \) depends on “height of formation”, thus on amount of absorption, number density of absorbing particles, abundance, level populations, atomic absorption 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 \( I_\nu \)
= probability \( q_\nu \) that an atom absorbs a photon
\( \times \) number density of absorbing atoms \( n_t \)
\( \times \) intensity \( I_\nu \) \( \times \) ds
\( \Rightarrow \ k_\nu I_\nu ds = q_\nu n_t I_\nu ds \)

Einstein:
\( q_\nu = B_\nu \frac{h \nu c}{4 \pi} \phi_\nu \)
where \( \phi_\nu \) = Gauss-, Voigt profile,
frequency dependence is separated out and \( \int_{\text{line}} \phi_\nu d\nu = 1 \)

classically: harmonic damped oscillator

\[
\int_{\text{line}} q_\nu d\nu = \frac{\pi e^2}{m_e c} f_{lu} \quad (13)
\]
b) Spontaneous emission
\[ \varepsilon_{\nu,sp} = n_u A_{ul} \frac{h \nu}{4\pi} \phi_{\nu} \]

c) Stimulated emission
\[ \varepsilon_{\nu,st} = n_u B_{ul} \frac{h \nu}{4\pi} \phi_{\nu} I_{\nu} \]
relations: \( A_{ul} = \frac{2h \nu^3}{c^2} B_{ul} \), \( g_u B_{lu} = g_l B_{ul} \)

d) Rate equations
Boltzmann equation for level \( i \):
\[ \frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \vec{v}_i) = (\text{production} - \text{destruction}) \text{ per unit time} \tag{14} \]
assume that production and destruction fast processes (atomic transitions) \( \Rightarrow (\text{production} - \text{destruction}) \approx 0 \) 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
\[ J_{\nu} = \int I_{\nu} d\Omega/(4\pi), \text{ and } \bar{J} = \int_{\text{line}} J_{\nu} \phi_{\nu} d\nu \tag{16} \]

e) Collisions
collisions with electrons dominate those with other particles (density \( n_e \), they are fast, Maxwellian velocity)
\[ C_{lu} = n_e \Omega_{lu,c}(T) \quad \text{and} \quad C_{ul} = n_e \Omega_{ul,c}(T) \tag{17} \]
Gedankenexperiment: in thermal equilibrium \((n^*_l, n^*_u)\), Boltzmann populations
\[ \Rightarrow \frac{n^*_l}{n^*_u} = \frac{g_u}{g_l} e^{-h\nu/(kT)} \tag{18} \]
When collisions with thermal electrons dominate over radiative transitions \( \Rightarrow \text{Boltzmann level populations} \Rightarrow \frac{C_{lu}}{C_{ul}} = \frac{g_u}{g_l} e^{-h\nu/(kT)} \tag{19} \)
otherwise, from rate equation
\[ \frac{n_l g_l}{n_u g_u} = \frac{A_{ul} + B_{ul} \bar{J} + C_{ul}}{B_{ul} \bar{J} + C_{ul} \exp[-h\nu/(kT)]} \tag{20} \]
population densities depend on collisions and on radiation field

f) absorption coefficient, source function
\[ \kappa_{\nu} = n_l B_{lu} \frac{h \nu}{4\pi} [1 - \frac{n_u g_l}{n_u g_u}] \phi_{\nu} \tag{21} \]
define: \( \varepsilon' \equiv \frac{C_{ul}}{A_{ul}} (1 - \exp[-h\nu/(kT)]) \); \( \varepsilon \equiv \frac{\varepsilon'}{1 + \varepsilon'} \)
\[ \Rightarrow S_{lu} = (1 - \varepsilon) \bar{J} + \varepsilon B_{\nu}(T) \tag{22} \]
\( S_{lu} \approx \text{independent of } \nu \text{ across spectral line, like } B_{\nu}(T) \)
\( S_{lu} = B_{\nu}(T) \) (or LTE) for \( \varepsilon \rightarrow 1 \), \( \varepsilon' \rightarrow \infty \), \( C_{ul} \gg A_{ul} \) or for \( \bar{J} = B_{\nu}(T) \)
g) estimate $\varepsilon'$

(approximate $\exp[-h\nu/(kT)] \ll 1$, Wien limit)

$A_{ul} \approx 10^8 \text{ s}^{-1}$, (atomic level life time for resonant lines $t = 1/A_{ul} \approx 10^{-8} \text{ s}$)

$n_e \approx 10^{9} \ldots 10^{14} \text{ per cm}^3$ in $\odot$ atmosphere

$\Omega_{ul} \approx \sigma_{ul} \bar{v}_e$, $\sigma_{ul} \approx 10^{-15} \text{ cm}^2$, $\bar{v}_e \approx 4 \times 10^7 \text{ cm s}^{-1}$

$\Rightarrow \varepsilon' = 4 \times 10^{-2} \ldots 4 \times 10^{-7} \ll 1; \quad \varepsilon \approx \varepsilon'$

h) solution of transfer equation

for simplicity with $B_\nu(T)$, $\varepsilon$, $\phi_\nu$ all independent of height (of optical depth)

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

- $S_{lu} \ll B_\nu(T)$ near surface, photons escape from deep layers,
  $\Rightarrow J \ll B_\nu(T)$

- 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”

\[
\begin{align*}
\text{• Normally, atoms, molecules, and ions have many energy levels/transitions}
\end{align*}
\]

$\Rightarrow$ 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 \( \vec{I}_\nu = (I_\nu, Q_\nu, U_\nu, V_\nu)^T \) with
  \[ I_\nu \equiv \text{total intensity} \]
  \[ Q_\nu, U_\nu \equiv \text{contribution of linearly polarized light in two independent orientations} \]
  \[ V_\nu \equiv \text{contribution of circularly polarized light} \]
- transfer of Stokes vector
  \[ \frac{d\vec{I}}{ds} = -\mathbf{K}(\vec{I} - \vec{S}) ; \quad \vec{S} = (S, 0, 0, 0)^T = \text{source function} \]

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

2.5 Atmospheric model

a) Assumptions

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

b) Model construction

- adopt model of temperature \( T(z) \)
  (zero level \( z = 0 \) arbitrary, usually shifted to \( \tau_{c,5000A} = 1 \) at end of modelling)
- solve simultaneously/iteratively:
  - transfer equations for important lines and continua:
  - H, other elements important as electron donors (Fe, Mg, Si, \ldots)
  - 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 transport
- photosphere: $\tau_{\text{cont}} \approx 1$, energy escapes to Universe by radiation
- photosphere convectively stable, boundary layer to convective interior

b) Granulation (– supergranulation)

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

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

- Rayleigh number $Ra \approx 10^{11}$ $\Rightarrow$ motion expected highly turbulent
- kinetic energy 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 $k_h$-$\omega$ 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; $T_0 = 6000$ K, $c_p/c_v = 5/3$, molar mass $\mu = 1.4$.](image)

- assume gravitationally stratified atmosphere
- assume constant temperature, $c_p/c_v = 5/3 = \text{constant}$
- conservation of mass, momentum, and energy (assume adiabatic motion, i.e. no energy exchange)
- linearize $\Rightarrow$ dispersion relation
  
  $k_h = 2\pi/\Lambda, \Lambda = \text{horizontal wavelength (parallel to “surface”)}$
  
  $\omega = 2\pi/P, P = \text{period}$

$\Rightarrow$ regions of wave propagation and of evanescent waves
Figure 7: $k_h$-$\omega$ 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 $\rightarrow$ noise (Lighthill mechanism)
  
  small-scale $\Rightarrow$ 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

b 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])

(c) Magnetic fields and waves

- important for chromospheric and coronal heating
  excited by granular flows

(work of Itahiza Domínguez Cerdeña)
• magnetoacoustic gravity waves ⇒ multitude of modes, e.g.

\[
c_A = B/(4\pi \rho)^{1/2}
\]

torsional

\[
c_t = c_sc_A/(c_s^2 + c_A^2)^{1/2}
\]

sausage

\[
c_t = c_A
\]

kink
cutoff for low frequencies

\[\Rightarrow\]

\[\Rightarrow\]

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]): \( v \approx 30 \text{ km s}^{-1} \) into corona
  100 times more mass than taken away by solar wind

• chromospheric network:
diameter \( \approx 30,000 \text{ km} \), life time \( \approx 24 \text{ h} \)
  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
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: \( F_{ac} = \rho v^2 c_s = \text{const} \)
  \( c_s \approx \text{const}, \rho \approx \rho_0 e^{-z/H} \) \( \Rightarrow v \approx v_0 e^{z/(2H)} \)
  \( \Rightarrow \) acoustic shocks \( \Rightarrow \) deposit of energy

- numerical simulations (Carlsson & Stein 1997 [5], Rammacher 2002 [13]):
  1) shock trains develop from short period waves, periods \( \approx 200 \text{s} \)
     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
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 structure and the processes.
• It remains so much one would like to understand!

References


