Lecture 3:
Stellar atmospheres: microphysics and comparison with observations

NORDITA Master Class 2006

Equation of state

- <u>Density:</u> $\rho = \dfrac{\bar{m} P_{gas}}{kT}$

  where mean molecular weight $\bar{m}$ depends on partial pressures of the constituents P_{sp}:
  $$\bar{m} = \sum m_{sp} P_{sp} / P_{gas}$$

- <u>Absorption:</u> Photons are absorbed in three processes:

  - transition between two discreet levels i→j with energies $E_i < E_j$ (bound-bound)
  - Transition between bound and unbound level (bound-free)
  - Transition between two unbound levels (free-free)

  All these processes are proportional to the number of absorbers and intensity of light at relevant frequencies.
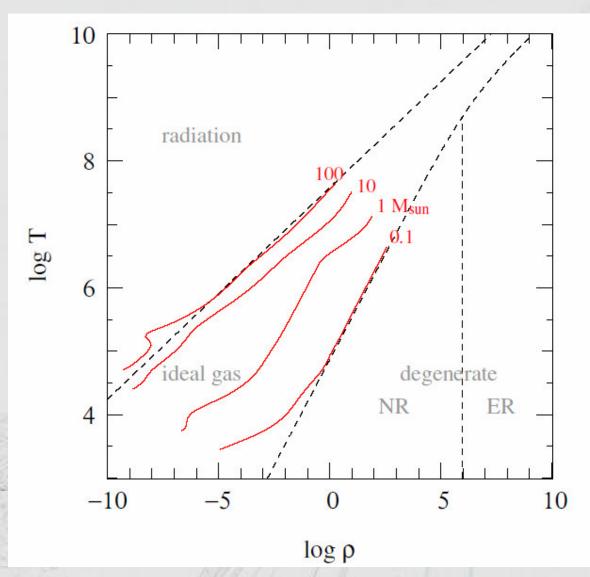
Equation of state

- <u>Emission:</u> Photons are emitted in similar three processes where starting energy is larger than the energy of the final state.

- There are also <u>stimulated emission</u> processes.

  Again all these processes are proportional to the number emitters!

To get the number of absorbers/emitters
we need to relate the partial pressures of all
species with the total pressure and temperature

EOS inside stars

radiation:
$$P = \tfrac{1}{3}aT^4$$

ideal gas:
$$P = \frac{\mathcal{R}}{\mu}\rho T$$

degenerate electrons:

NR: $P = K_{NR}\left(\dfrac{\rho}{\mu_e}\right)^{5/3}$

ER: $P = K_{ER}\left(\dfrac{\rho}{\mu_e}\right)^{4/3}$

Molecular and Ionization Equilibrium

- Abundances $(Z_A = N_A/N_{tot})$:

$$\sum_{sp} P_{sp} \left(n_A^{sp} - Z_A n_{tot}^{sp} \right) = 0$$

- Particle conservation:

$$\sum_{sp} P_{sp} \left(1 + q^{sp} \right) = P_{gas}$$

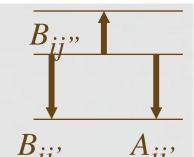- Charge neutrality:

$$\sum_{sp} P_{sp} q^{sp} = P_e$$

Molecular and Ionization Equilibrium

- Needs only T, P_{gas} and abundances
- We solve for fictitious partial pressures of constituent atoms and for free electrons:

$$P_{sp} = \frac{Ip(T)}{Kp(T)} P_e^{q_{sp}} \prod_A P_A^{n_A^{sp}}$$

- Works well from 600000 K down to 400 K and pressures between 10^{-13} and 10^8 dynes
- Below the lower limit chemical time scales become larger than HD times and we need chemical kinetics (time-dependent reaction equations)
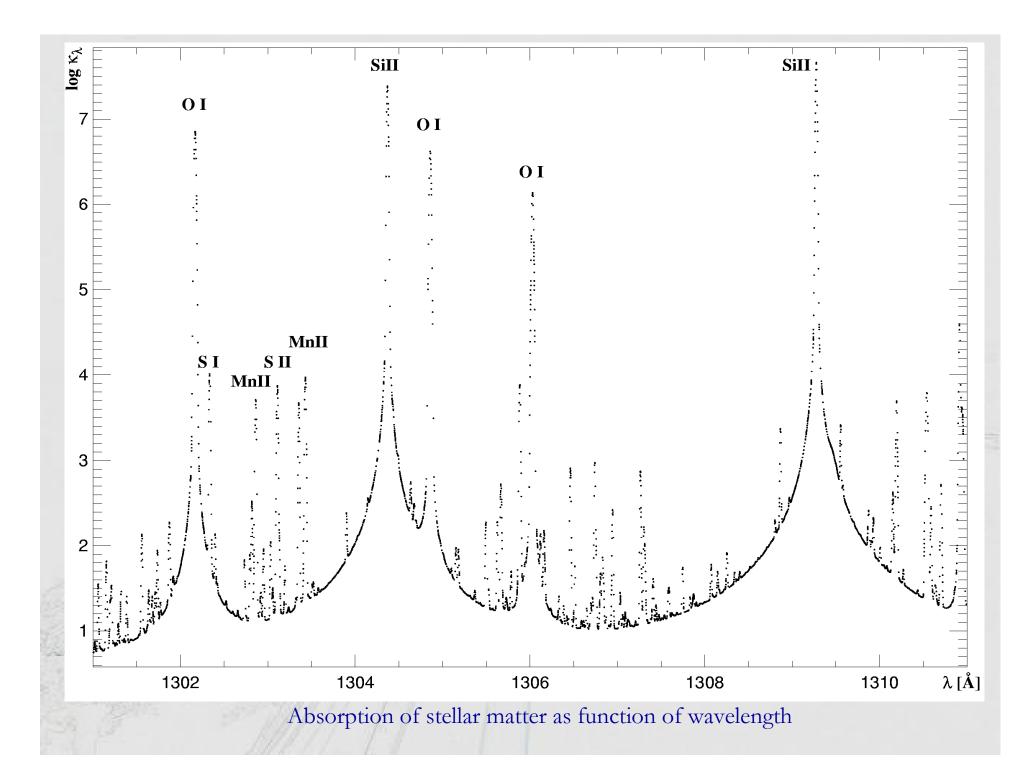
Absorption/Emission

B_{ij}'' B_{ij}' A_{ij}'

- In order to obtain mass absorption/emission coefficient we need to know
    1) absorption/emission per particle (lab spectroscopy)
    2) number of particles of a given species per unit volume (equation of state)
    3) energy level population

- This last fraction is given in LTE by the Boltzmann distribution but at the stellar surface it is controlled by radiation coming from some distance. Therefore, we need to solve the statistical equilibrium equations:

$$\frac{dn_i}{dt} = \sum_{j \neq i} n_j P_{ji} - n_i \sum_{j \neq i} P_{ij} = 0$$

$$P_{ij} = R_{ij} + C_{ij}$$

where
$$R_{ij} = \begin{cases} A_{ij} + B_{ij} \cdot \overline{J}_{ij}, & i > j \\ B_{ij} \cdot \overline{J}_{ij}, & i < j \end{cases}$$

Absorption of stellar matter as function of wavelength

"Convection"

- A convective cell adiabatically rising through the atmosphere expands. This is described by polytropic approximation: $P \propto \rho^{\gamma}$
- We are interested in vertical gradient:

$$\delta P = \gamma \rho^{\gamma} \frac{\delta \rho}{\rho} = P \gamma \frac{\delta \rho}{\rho} \Rightarrow \frac{d \log \rho}{d \log P} = \frac{1}{\gamma}$$
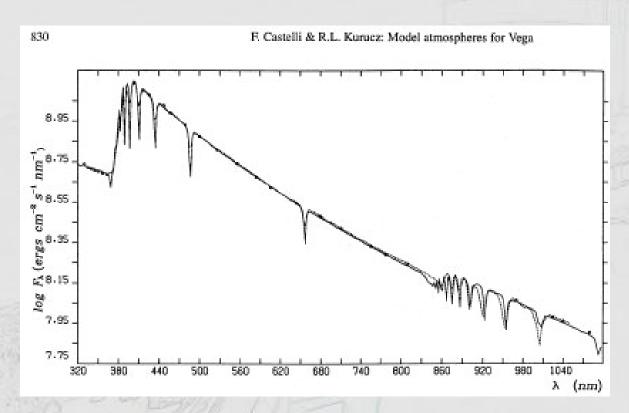
- In order for a cell to continue to rise this gradient should be larger than the radiative gradient in photosphere:

$$\left. \frac{d \log \rho}{d \log P} \right|_{cell} > \left. \frac{d \log \rho}{d \log P} \right|_{rad}$$

The density of a cell drops faster than the density in the photosphere.

Results

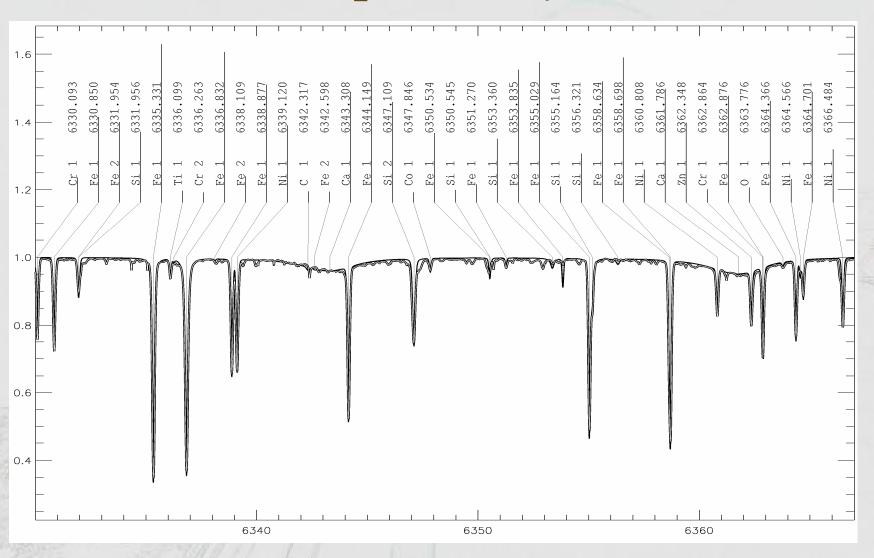## Spectral energy distribution for stars with temperatures between 3000 and 60000 K
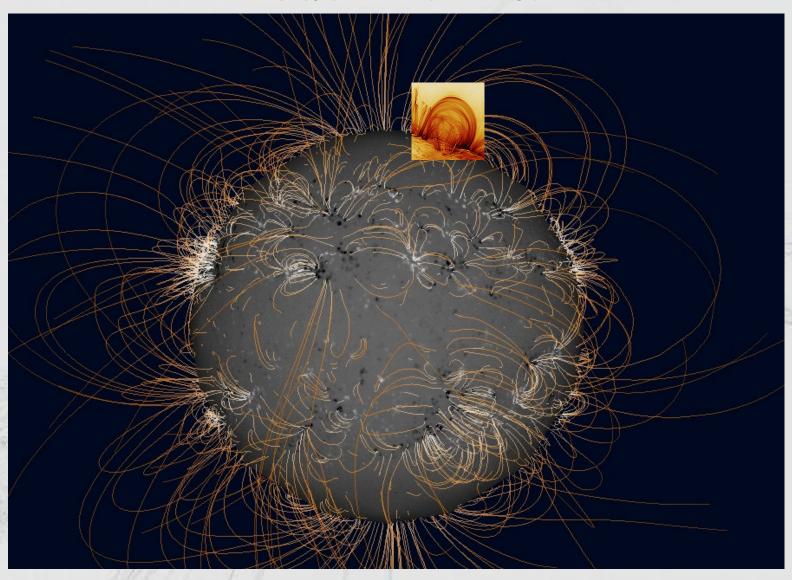

Vega (10000 K)
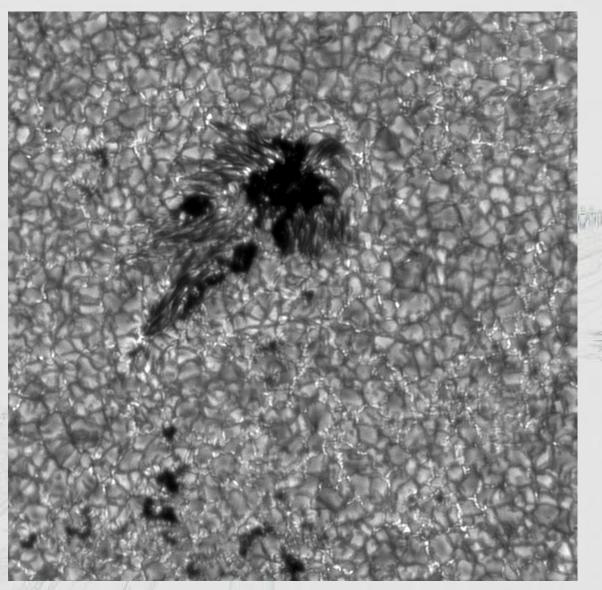
Detailed spectral synthesis

Main shortcomings

- Steady state prevent us from simulating convection and other motions

- 1D forces the ratio between energy transport by radiation and convection to be a unique function of the radius

- There are no possibilities to properly account for the effects of magnetic fields
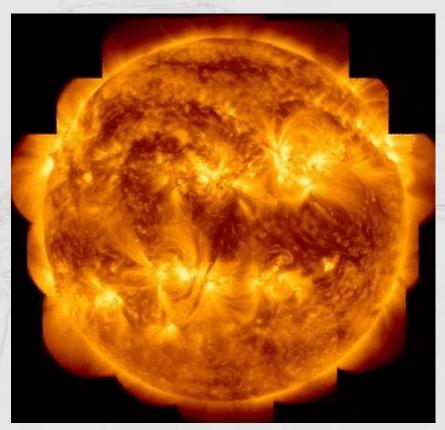
Ideally we would want to produce a model like this:

Stellar surfaces

Courtesy of Göran Scharmer/Swedish Solar Vacuum Telescope
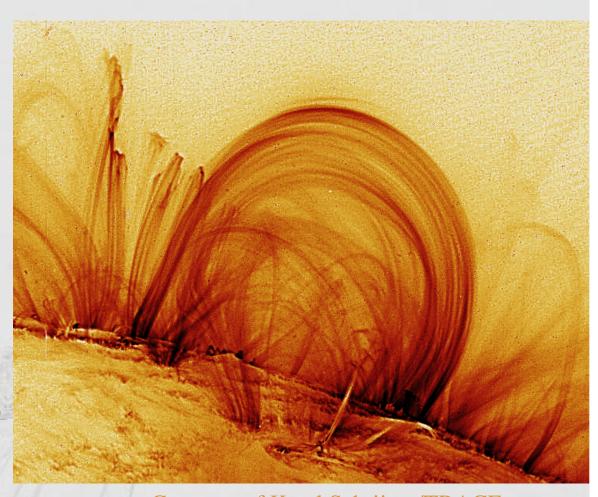
Solar corona

- Low density: $<10^7$ particle/cm^3
- Hot: $>10^6$ K
- Optically thin
- Temperature of radiation is very different from the kinetic temperature

Courtesy of SOHO
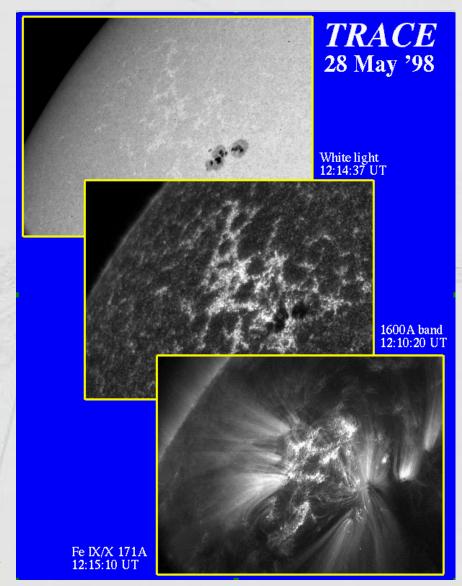
Coronal arcades on the Sun

- Heating of the outer layers is part of the energy transport

- Magnetic fields play a major role

- Coherent motions at the photosphere layers dissipate in the corona making it hot

Courtesy of Karel Schrijver/TRACE

Wavelength dependence

- At visual spectral range photosphere dominates the total flux

- UV lines allow to see chromospheric structures

- Going to X-ray is required to observe solar corona

Courtesy of Karel Schrijver/TRACE

TRACE
28 May '98

White light
12:14:37 UT

1600A band
12:10:20 UT

Fe IX/X 171A
12:15:10 UT

Next lecture:
3D dynamical models