Non-equilibrium helium ionization and its effects on He II 304 and He I 10830

Thomas Peter Golding, Jorrit Leenaarts and Mats Carlsson.
Institute of Theoretical Astrophysics, University of Oslo.

ABSTRACT

Helium plays an important role in the energy balance of the upper chromosphere and transition region, and helium spectral lines are often used diagnostics. Its non-equilibrium ionization balance and radiative losses should therefore be treated in detail in numerical simulations of the solar atmosphere. We perform 1D radiation-hydrodynamics simulations and show that the helium ionization balance is mostly set by photoionization (chromosphere) and electron collisions (transition region) counteracted by radiative recombination cascades. We derive a simplified 3-level helium model atom that mimics this behavior and is suitable for use in 3D stellar atmosphere simulations. We studied the formation of He I 10830 and He II 304 spectral lines in the 1D simulation. The helium ionization-recombination relaxation timescale is up to 100 seconds in the line-forming regions. This leads to significant differences in the emergent intensity compared to statistical equilibrium computations. Inversions and interpretations of the observations of these lines should therefore be viewed with caution.

Motivation

- Helium important in energy balance of chromosphere and transition region.

$$\frac{de}{dt} = -\nabla \cdot e\mathbf{u} - P\nabla \cdot \mathbf{u} + Q_{\rm rad} + Q_{\rm other}$$
$$e = \frac{3}{2}kTn_{\rm tot} + \sum_i n_i \chi_i$$

- Need to solve rate equations to keep track of population densities.

$$\frac{dn_i}{dt} = -\nabla \cdot n_i\mathbf{u} + \sum_j n_j P_{ji} - n_i \sum_j P_{ij}$$
$$P_{ij} = P_{ij}(J)$$

- Involves solving the radiative transfer problem which in 3D is very CPU intensive

Simulations

- We simulate a dynamic solar atmosphere with the 1D radiation-hydrodynamic code RADYN using a 33 level helium model atom.
- We use the simulation to identify the dominating processes for the ionization of helium. See figure 1.

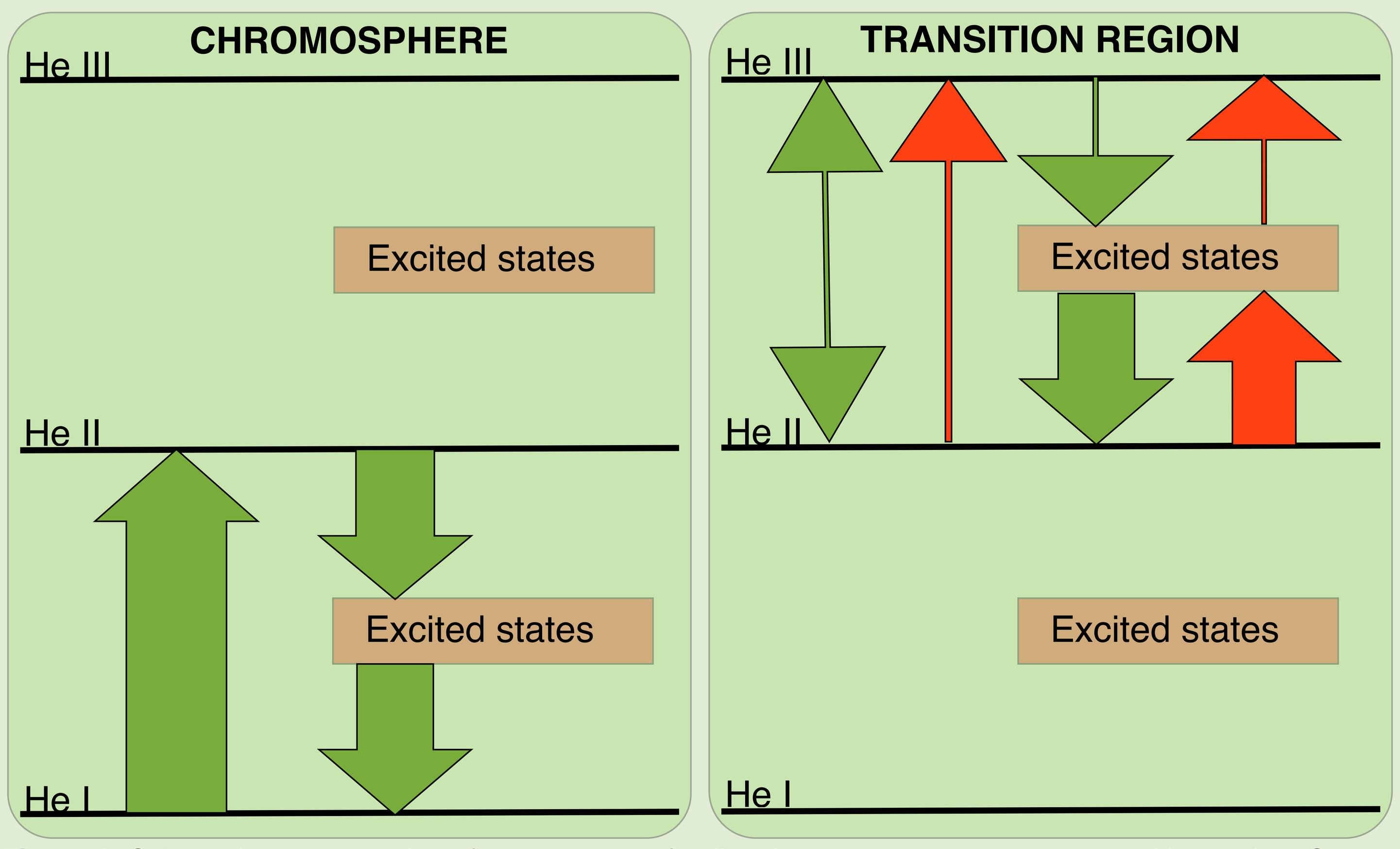

Figure 1: Schematic representation of the net rates of helium in the chromosphere and transition region. Green arrows are radiative transitions and red arrows are collisional transitions.

Simplified 3-level model atom

- Assume that no ionization from excited states occurs and that excited states only serve as intermediate steps in recombination cascades.
- Remove all excited states and keep the ground states. Take the recombination cascades into account by introducing an effective recombination rate.

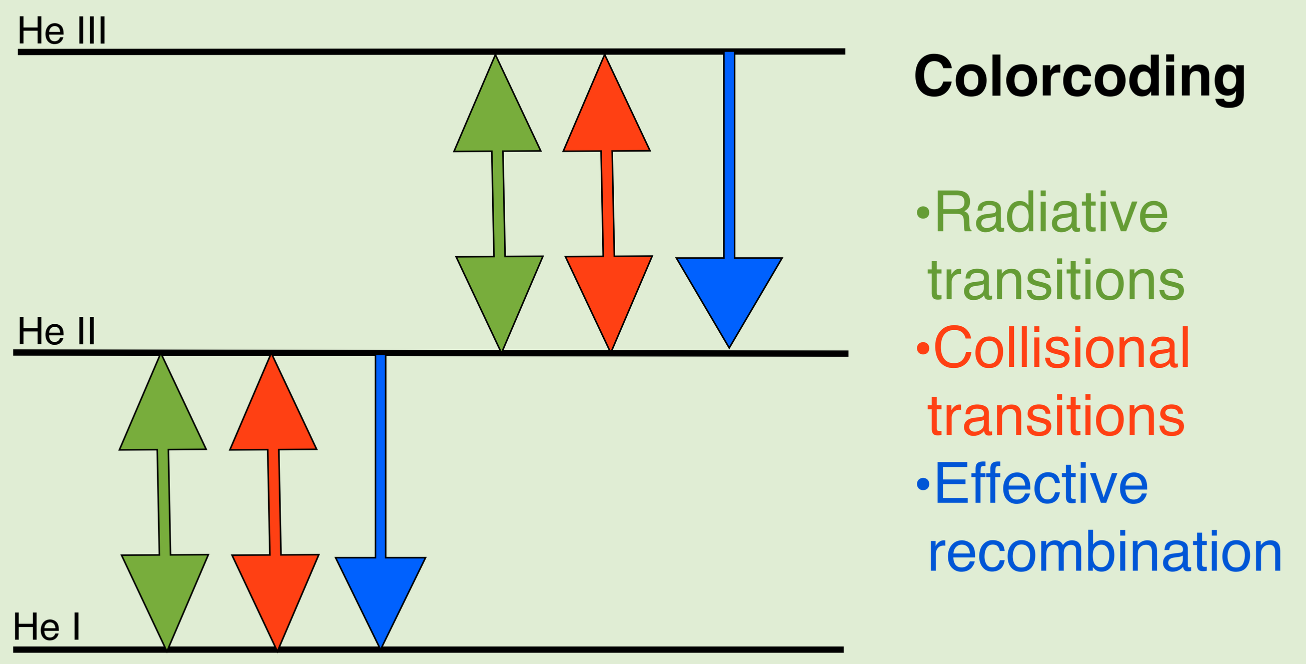

Figure 2: Included transitions in the simplified model atom

How well does the 3-level simplified model atom perform?

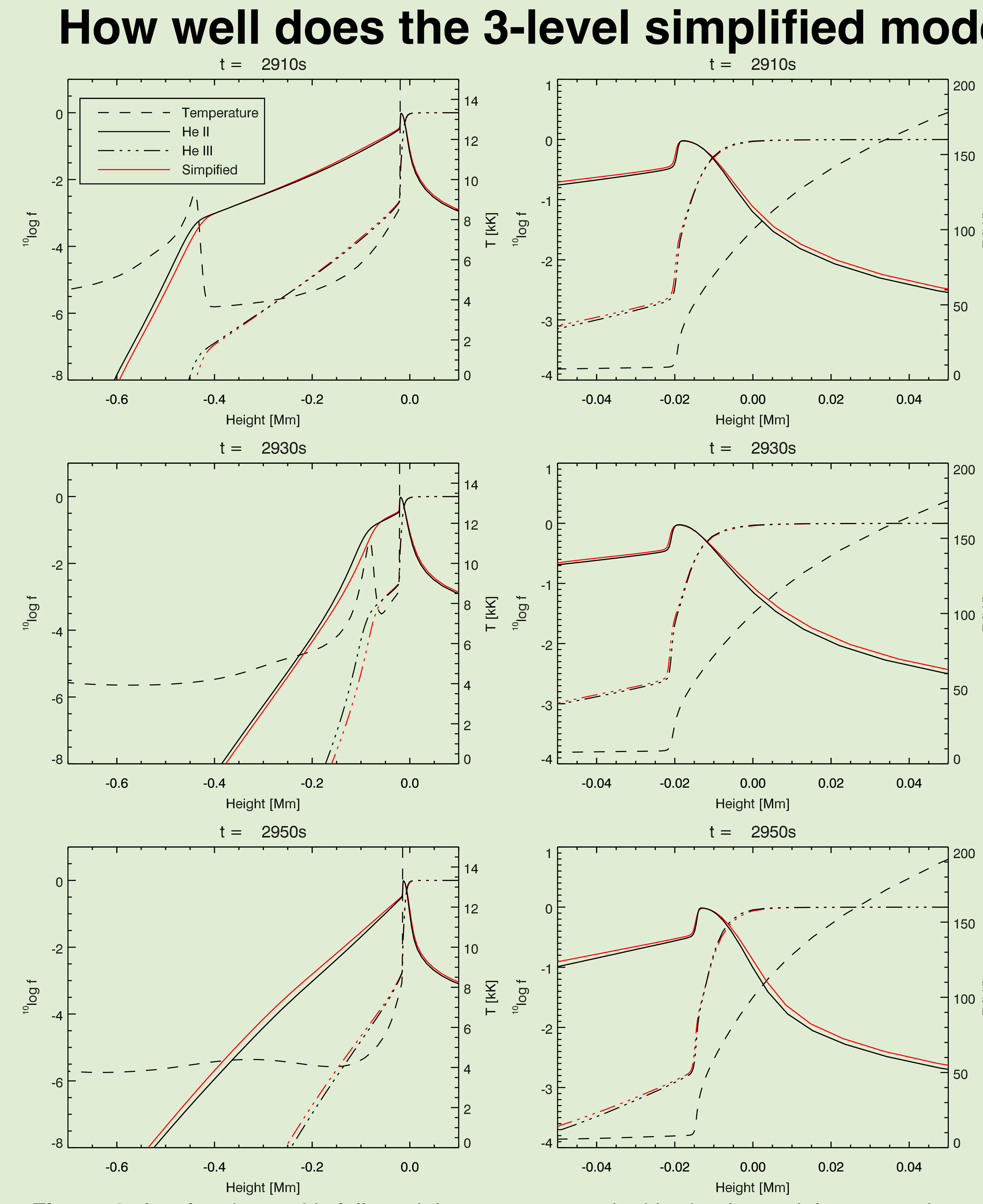

Figure 3: Ion fractions with full model atom compared with simple model atom at three three different times, during which a shock wave propagates through the chromosphere (left panels) and transition region (right panels). Height set to zero at T=100kK.

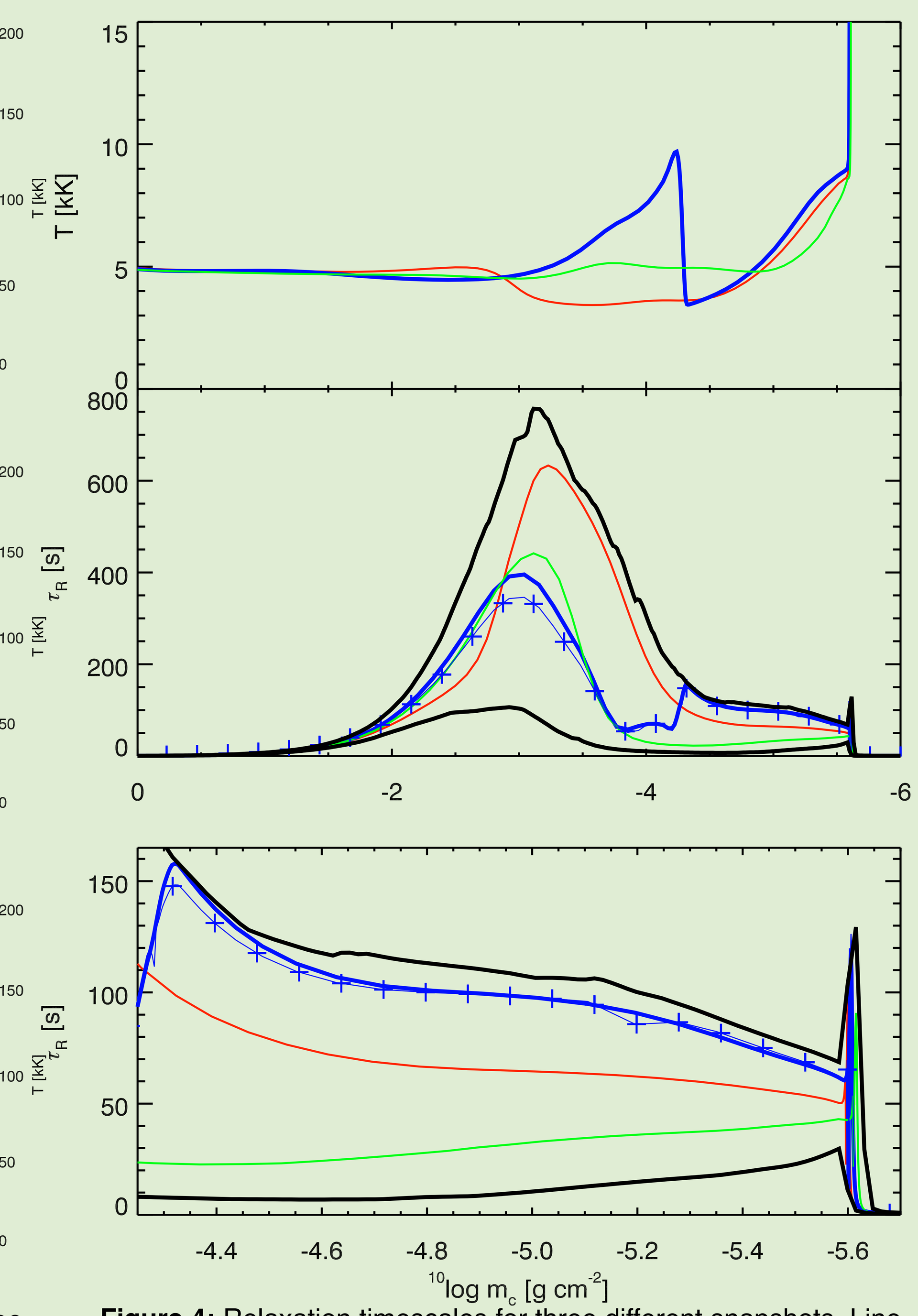

Figure 4: Relaxation timescales for three different snapshots. Line with + signs represent value obtained with simplified model atom.

- Simple 3-level model atom reproduces both the ion fractions and relaxation timescales obtained with the 33-level model atom.

Observable non-equilibrium effects on the 304 and 10830 lines

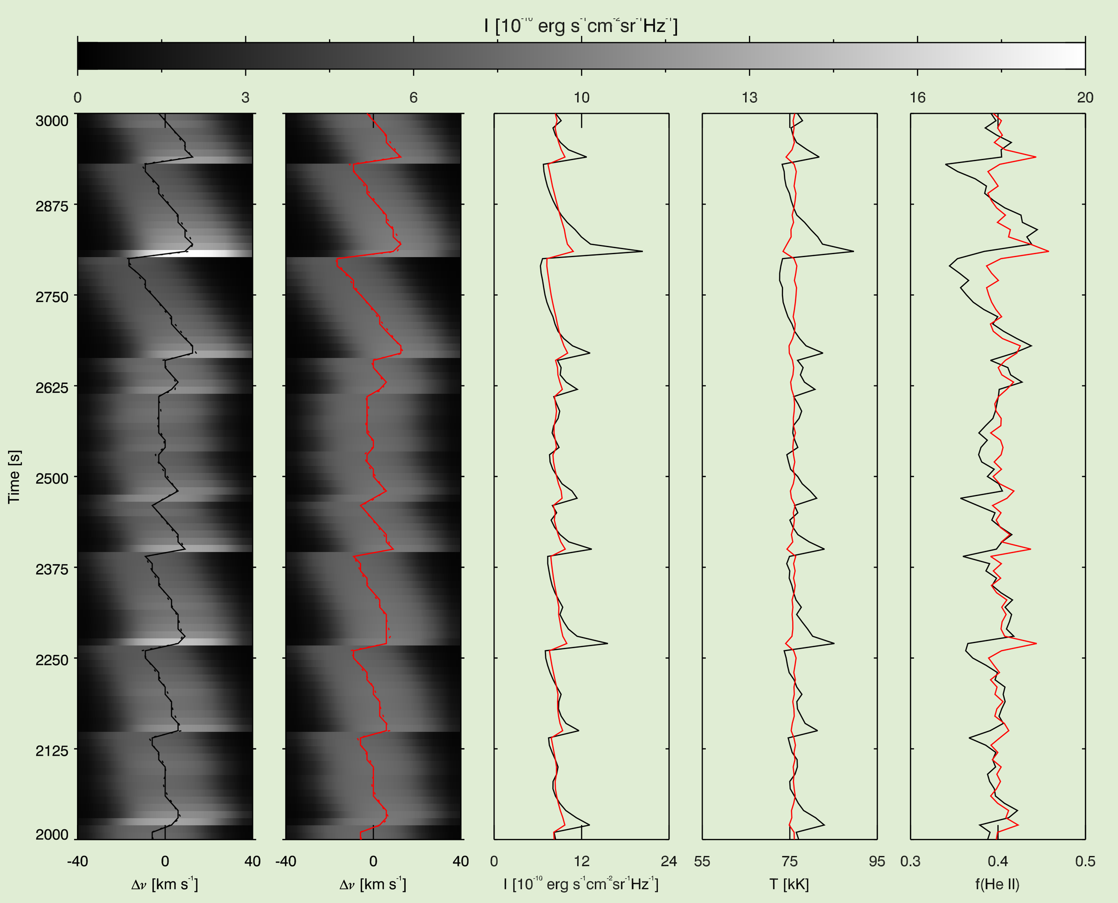

Figure 5, He I 304. All panels: black indicates a non-eq. simulation, red indicates a statistical eq. simulation. Two left panels: emergent intensity for the two runs. Middle to right panels: line core intensity, temperature and fraction of He II. The two latter are evaluated at line core optical depth unity. Line core frequency (solid line) and plasma velocity at optical depth unity (dotted line) is indicated (for the two runs) in the two left panels.

- He 304 forms in the TR by collisional excitation followed by radiative decay.
- Periodic brightening associated with the propagating shocks through the TR.
- Brightening not reproduced when assuming helium in statistical equilibrum.

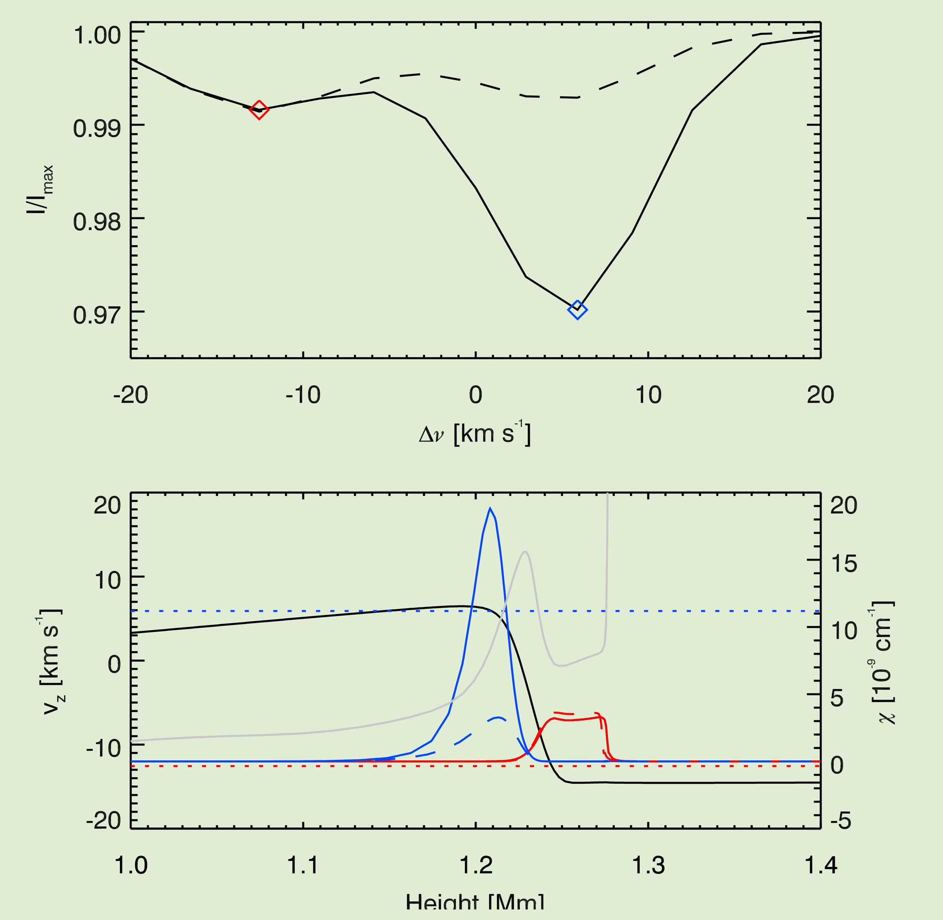

Figure 5, He I 10830. Both panels: solid lines indicate a non-eq. simulation, dashed lines indicate statistical eq. simulation. Upper panel: line profile from a snapshot of the simulation. Lower panel: Velocity (black) and opacity (blue and red, scales to the right) as functions of height. Temperature (grey) shown for orientation. The red and blue opacities are evaluated at the frequencies of the red and blue depression cores, indicated by diamonds.

- He 10830 red-shifted depression core forms in front of shock, blue-shifted core forms behind shock.
- Spectral distance of cores: a measure of shock amplitude?
- Double core profiles weaker or not present when assuming helium in statistical equilibrium

FUTURE PLANS AND OUTLOOK

- Develop a non-equilibrium helium ionization module for the stellar atmosphere code Bifrost. Bifrost already includes the effects of non-equilibrium hydrogen ionization.
- Carry out a simulation of the 3D solar atmosphere where non-equilibrium ionization effects of both hydrogen and helium are taken into account.
- Study further the formation of helium spectral lines with the new 3D numerical model.