Bifrost simulations with a non-equilibrium EOS

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Ionization state of H and He in the solar atmosphere:

- Dense, LTE
- Partially ionized, time dependent
- Mostly ionized
modelling the EOS

\[ e = \frac{3}{2} k T \left( \sum_i n_i + n_e \right) + \sum_i n_i \epsilon_i \]

Determining the population densities

LTE

Non-equilibrium: rate equations for atomic states, \( n_i \)

\[ n_i = f(e, \rho) \]

\[ \frac{\partial n_i}{\partial t} = \sum_j n_j P_{ji} - n_i \sum_j P_{ij} \]

\[ P_{ij} = C_{ij} + R_{ij} \]
Non-eq hydrogen ionization

- Bifrost as numerical framework (Gudiksen, 2011)
- Prescribed radiative rates for H (Leenaarts, 2007)
New feature: Lyman-α

Simplify the radiative transfer: one frequency only

\[ \eta \sim n_2 E(\tau) A_{21} \]
\[ \chi \sim n_1 B_{12} \]

\[ R_{21} = E(\tau) A_{21} \]
\[ R_{12} = B_{12} J \]
Non-eq. helium ionization

Corona and transition region

Chromosphere

Photosphere

EUV radiation emitted

\( \eta = \rho n_e f(T) \)

EUV radiation absorbed by He and H

\( \chi = \sigma n_{\text{He}} \)

Compute \( J \) and solve the rate equations for helium
# Four 2d simulation runs

<table>
<thead>
<tr>
<th>Name</th>
<th>EOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTE</td>
<td>All elements LTE</td>
</tr>
<tr>
<td>HION</td>
<td>Non-eq. hydrogen</td>
</tr>
<tr>
<td>L YA-HION</td>
<td>Non-eq. hydrogen including lyman alpha</td>
</tr>
<tr>
<td>HELIUM</td>
<td>Non-eq. hydrogen and helium + lyman alpha</td>
</tr>
</tbody>
</table>
No longer preferred temperatures

Height-temperature, 2d histogram

LTE

HION

LYA-HION

HELlUM

$t = 790s$
Higher temperatures in shocks
LTE EOS: chromospheric mass density too low

associated with preferred temperature plateaus
Mean MgII k, Lyman-α heats chromosphere

The graph shows the intensity at different wavelengths for three different runs: LTE-run, HION-run, and LYA-HION-run. The intensity is measured in J Hz m^-2 s^-1 sr^-1. The graph is computed with RH1.5.
Summary

- Bifrost non-eq. EOS now takes into account the non-equilibrium ionization of both helium and hydrogen.
- This leads to higher temperature variations in upper chromosphere.
- Gas in temperature range 6-10 000 K gets denser with non-eq EOS.
- Higher Mg II intensities with Lyman-α heating.
- Model provides non-equilibrium helium ion fractions that can be used as constraints in radiative transfer computations.