Quantitative Spectroscopy with 3D Model Red Giant Atmospheres

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MPA - Garching

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Red giant stars

- Large diameters and high luminosities
- Extended convective envelopes
- Observational targets of choice for stellar spectroscopy
- Important for galactic chemical evolution studies
ID Models

- + >>1,000,000s wavelengths
- ID geometry
- Hydrostatic, stationary
- Convection with Mixing Length Theory
Real stellar atmospheres

Credit: L. R. van der Voort & M. van Noort (2004) with SST
Convection simulations

- Stagger-Code (Copenhagen)
- “Box-in-the-star”
- Mass, momentum, energy conservation + RT
- Long characteristics
- 3D, time dependent
Input Physics

- Realistic Equation-of-state (Mihalas et al. 1988)
- Continuous and line opacities (Gustafsson et al. 1975, Kurucz et al. 1995)
- Opacity-binning (Nordlund et al. 1982)
Granulation pattern (output)

$T_{\text{eff}} = 4400\, \text{K} \quad \log g = 1.5 \quad [\text{Fe/H}] = -3$ (Collet et al. 2009, in prep)
Surface Convection

Temperature

$T_{\text{eff}} = 4400 \text{ K} \quad \log g = 1.5 \quad [\text{Fe/H}] = -3$
Opacity gradients

Teff=4400K logg=1.5 [Fe/H]=-3
Radiative transfer solver

- Local adaptive radiation scale refinement: crucial for red giant simulations!

without  with
Temperature stratification

Solar metallicity

Collet et al. 2007
Temperature stratification

Very low metallicity

\[ T_{\text{eff}} = 4400 \text{ K} \]
\[ \log g = 1.50 \text{ [cgs]} \]
\[ [Z/H] = -3.0 \]
Solar vs. Metal-poor

- Competition between adiabatic cooling and radiative heating:

\[ \frac{\partial e}{\partial t} = -u \cdot \nabla e - \frac{P}{\rho} \nabla \cdot u + Q_{\text{rad}} + Q_{\text{visc}} \]
3D line formation

- Temperature-velocity inhomogeneities
- Doppler shifts accounted for
Spectral line profiles

Fe I 3727.6 Å
χ = 0.958 eV
log gf = −0.631
log ε = 2.01

HE0107−5240

3D
1D
Fe, 3D-1D LTE

Fe lines at 5000 Å

3D - 1D Abundance (dex)

Excitation potential (eV)

3D - 1D Abundance (dex)

Fe I

Fe II
Fe I fraction

$T_{\text{eff}} = 4400$ K

$\log g = 1.50$ [cgs]

$[Z/H] = -3.0$
Molecules, 3D-1D LTE

- Large, Negative, abundance corrections

Graph showing the relationship between 3D - 1D Abundance (dex) and Excitation potential (eV) for Oxygen, with a notable trend in abundance corrections for OH 3100 Å.
Molecules, 3D-1D LTE

Carbon

3D - 1D Abundance (dex)

Excitation potential (eV)

CH 4310 Å
C2 5160 Å
Molecules, 3D-1D LTE

Nitrogen

3D - 1D Abundance (dex)

Excitation potential (eV)

NH 3360 Å
CN 3880 Å
C,N,O abundances

3D-1D LTE corrections for the extreme halo giant HE 0107-5240

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<table>
<thead>
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<tbody>
<tr>
<td>CH</td>
<td>-1.1</td>
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Surface Temperature (I)

Opacity binning vs. ODFs

$T_{\text{eff}} = 4858$ K
$log \, g = 2.2$ [cgs]
$[\text{Fe/H}] = -3.0$

(Collet et al. 2007)
Surface Temperature (2)

1D with & without Scattering

(K. Eriksson, OS-MARCS)
Non-Equilibrium Physics and Chemistry?

- Neutral Fe lines: prone to non-LTE effects at low metallicity
- Photo-dissociation of molecules? Asensio Ramos et. al 2003: CO line formation in the Sun; low metallicity case still under investigation
- Water vapor on Arcturus (Ryde 2002): are 1D models too hot for that?
Summary

- **3D** model atmospheres of **metal-poor** giants are **cooler** than 1D models

- Large 3D-1D **LTE** abundance corrections for minority species and molecules:
  - -1.0 ... -0.5 dex for C,N,O
  - -0.8 ... -0.5 dex for Fe I

- Departures from LTE can however correct abundances upwards