New light on metal-poor stars

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Stellar spectroscopy

Stellar parameters
\( T_{\text{eff}}, \log(g), [\text{Fe/H}], [X/\text{Fe}], \ldots \)

Radiative transfer

Physical assumptions
1D+MLT, LTE, opacities, ...
Stellar atmospheres

\[ \mathcal{F}_{\text{tot}} = \mathcal{F}_{\text{rad}} + \mathcal{F}_{\text{conv}} \]

\[ \mathcal{F}_{\text{rad}} = \int F(\lambda) \, d\lambda \]

\[ \mathcal{F}_{\text{conv}} \propto \alpha_{\text{MLT}} (\nabla T - \nabla_{\text{ad}}) \]

\[ \alpha_{\text{MLT}} = \frac{l}{H_p} \quad \nabla T = \frac{d \ln T}{d \ln P} \]
MLT from spectroscopy: $\alpha \sim 0.5$

Fuhrmann, Axer, Gehren 1993
The value of $\alpha$ affects strongly the effective temperature of stars with convective envelopes. The 'canonical' calibration is based on reproducing the solar radius with a theoretical solar models (Gough & Weiss 1976). We should always keep in mind that there is a priori no reason why $\alpha$ should stay constant within a stellar envelope, and when considering stars of different masses and/or at different evolutionary stages.

<table>
<thead>
<tr>
<th>Code</th>
<th>Solar Z/X</th>
<th>$\alpha$</th>
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<tr>
<td>STARS</td>
<td>0.0262</td>
<td>2.09</td>
</tr>
<tr>
<td>STARS</td>
<td>0.0195</td>
<td>2.025</td>
</tr>
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<td>V-R</td>
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<td>Y²</td>
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</table>

Image credit: M. Salaris

Stancliffe, Fossati, Passy+ 2016
5.3. Temperature Structure
Near the surface, the divergence of the convective, radiative, and kinetic energy fluxes are large, but the sum of the divergence of all three is small, and vanishing on the average (if exotic terms such as viscous flux are neglected). The radiation cooling time near the solar surface is very short (of the order of seconds), so the fluid energy balance adjusts very rapidly. Since the dominant $H_\alpha$ opacity is very temperature sensitive, it produces an extremely steep vertical temperature gradient near the surface (Fig. 14).

The temperature gradient is much larger in the ascending flow ($D \approx 100$ K km$^{-1}$) than in the mean structure ($D \approx 30$ K km$^{-1}$). The smaller value for the average gradient comes about because the steep temperature drop in ascending flows occurs at different depths in different granules and because the temperature rise in the downdrafts occurs at larger depths and is more gradual than in the updrafts.

Above the surface, the fluid is nearly in radiative equilibrium, with a little radiative heating balancing expansion cooling over granules and a little radiative cooling balancing compressional heating in the converging flow over the intergranular lanes. Changes due to the convective motions are a small perturbation on this basic structure. Energy transport switches from convective below the surface to radiative above the surface. The fluid is always approximately in radiative-convective equilibrium for the atmospheric structure through which it is moving.

The upflows transfer their internal energy to radiation between optical depths $\Delta q \approx 30$ and $\Delta q \approx 1$. Between those depths they have a temperature gradient close to but slightly less than the gray radiative equilibrium value of $T_{eq}$ (Fig. 15). Their temperature gradient is slightly less than the radiative equilibrium value because the radiative flux is increasing as the optical depth decreases due to the transfer of energy from convection to radiation. This well-known gradient on an optical depth scale corresponds to an extremely steep gradient on a geometric depth scale because of the extreme temperature sensitivity of the dominant $H_\alpha$ opacity, so that a small increase in temperature produces a large increase in opacity and hence a large increase in optical depth over a very small geometrical depth range. (A Lagrangian perspective, following a fluid parcel, of this Eulerian behavior, is presented at the end of this section.) As a result, there is a much wider spread in temperatures ($D \approx 5000$ K) at a given geometric depth (just below the surface; than there is on a local optical depth scale (Fig. 14). This clearly reveals the crucial role of radiation in controlling the structure of the solar surface and the closeness of the atmosphere at each point on the surface to instantaneous radiative equilibrium near local optical depth unity. Thus, even though it is tempting to believe that plasma is monotonically cooling as it overturns in the visible photosphere, that is not a correct picture. The overturning plasma is actually close to radiative equilibrium at all times and is often being heated, rather than cooled, by radiation as it traverses the optically thin layers.

5.4. Energy Fluxes
Near the surface, upflows and downflows transport approximately equal amounts of energy. With increasing depth the downflows come to dominate the energy transport.
No. 2, 1998 SIMULATIONS OF SOLAR GRANULATION. I.

from Ñuid that overturns without having visited the surface. Thermal di†usion with their higher entropy surroundings also heats the

Ðlamentary downdrafts. The mean entropy of the descending Ñuid thus increases steadily with depth (Fig. 13).

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T

10

), it produces an extremely steep vertical temperature gradient near the surface (Fig. 14).
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100 K km

~1

) than in the mean structure (D

30 K km

~1

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q

D

30 and

q

D

1.

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T

P

q

1@4

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Non-LTE = Statistical equilibrium

\[
0 = \frac{dn_i}{dt} = \sum_{j \neq i} n_j (R_{ji} + C_{ji}) - n_i \sum_{j \neq i} (R_{ij} + C_{ij})
\]

Radiative transitions: \( R_{ij} = A_{ij} + B_{ij} \mathcal{J}_\nu \)

Collisional transitions: \( C_{ij} \)

Radiation field is non-local!
Non-LTE = Statistical equilibrium

\[ 0 = \frac{dn_i}{dt} = \sum_{j \neq i} n_j (R_{ji} + C_{ji}) \]

Radiative transitions: \[ R_{ij} = A_{ij} + B_{ij} \bar{J}_\nu \]

Collisional transitions: \[ C_{ij} \]

Particle number
Incoming transitions

Radiation field
Planck function

Radiation field is non-local!

Bergemann, Lind, Collet+ 2012
3D RHD model atmospheres

See also Magic, Collet, Asplund+ 2013-2015

Click to download movie

TN, Amarsi, Lind+ 2017
Non-LTE in 3D

\[ 0 = \frac{dn_i}{dt} = \sum_{j \neq i} n_j (R_{ji} + C_{ji}) - n_i \sum_{j \neq i} (R_{ij} + C_{ij}) \quad R_{ij} = A_{ij} + B_{ij} \bar{J}_\nu \]
SMSS 0313-6708 in 3D NLTE

Δ log $W_{\lambda, \mu}$ (NLTE − LTE)

Li I

Mg I

Fe I

x [Mm] 0 200 400 600 800 1000

y [Mm] 0 200 400 600 800 1000

Δ log $W_{\lambda, \mu}$ (NLTE − LTE)

-0.4 -0.2 0.0 0.2 0.4

-1 0 1

TN, Amarsi, Lind+ 2017
Extremely metal-poor stars

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Australian National University - Mount Stromlo

SkyMapper Extremely Metal-Poor Star Group

ANU: Martin Asplund, Michael Bessell, Gary Da Costa, Dougal Mackey, Anna Marino, TN, John Norris, Brian Schmidt
Monash: Andrew Casey, Alexander Heger; MIT: Anna Frebel; MPIA: Karin Lind; UNSW/ADFA: Simon Murphy
The SkyMapper EMP search

[Fe/H] = -5

Relative flux / throughput

u v g r i z

Wavelength [Å]

0.0 0.2 0.4 0.6 0.8 1.0

0 0.2 0.4 0.6 0.8 1.0

Metallicity-proxy, v-g - 1.5(g-i)

Effective temperature [K]

5750 5250 5000 4750 4500

0 0.2 0.4 0.6 0.8 1.0

-4 -3 -2 -1 0

Effective temperature-proxy, g-i

Da Costa, Bessell, Mackey, TN+ submitted
The SkyMapper EMP search

[Fe/H] = $-4$

Da Costa, Bessell, Mackey, TN+ submitted
The SkyMapper EMP search

Da Costa, Bessell, Mackey, TN+ submitted
The SkyMapper EMP search

$[\text{Fe/H}] = -2$

Da Costa, Bessell, Mackey, TN+ submitted
The SkyMapper EMP search

[Fe/H] = −1

Da Costa, Bessell, Mackey, TN+ submitted
The SkyMapper EMP search

Da Costa, Bessell, Mackey, TN+ submitted
The SkyMapper EMP search

Slope ~ 1.5 dex/dex

Observational data: GALAH DR2 + 2.3m + Norris (priv)

Da Costa, Bessell, Mackey, TN+ submitted
The SkyMapper EMP search

Slope \sim 1.5 \text{ dex/dex}

Da Costa, Bessell, Mackey, TN+ submitted
SMSS 0313-6708: \([\text{Fe/H}] < -6.5\)

Keller, Bessell, Frebel+ 2014
TN, Amarsi, Lind+ 2017
The Metallicity Distribution Function (MDF) for the Skymapper EMP search

The situation is not as straightforward for the CEMP stars. For this group, five stars are within the window but both of which were identified as EMP-candidates in the commissioning-era survey (Jacobson et al. 2015). We conclude that errors in the DR1.1 photometry, even for stars within the selection window with metallicities, \([\text{Fe/H}]\) of around –2.84, mean that the use of the current photometry will underestimate the EMP-candidate stars.

As regards the carbon-rich stars (5-pt star symbols in the figure), 

- The median \([\text{Fe/H}]\) for the 176 stars shown in Fig. 15, assuming a solar carbon abundance of 8.43. Both abundances are based on 1D, LTE analyses.
- Examples of known carbon-normal stars outside the selection window include SMSS J091210.40–064427.9 (\([\text{Fe/H}] = –2.73\)), SMSS J133532.32–210632.9 (\([\text{Fe/H}] = –2.64\)) and HE0057–5959, which has \([\text{Fe/H}] = –2.09\) (Yong et al. 2013). A recent study by Jacobson et al. (2015) identified a few EMP candidates with metallicities below –2.63.

The metallicity distribution of EMP candidates is shown in Fig. 16: symbols are the same as for Fig. 15. Unlike Yoon et al. (2016) we have not re-determined the sample to only stars with \([\text{C}/\text{Fe}]\) values generally just below the lower boundary. The metallicity distribution to that for the stars within the selection window results in an underestimate of less than 10% of the expected total number of carbon-normal stars.

The location in the SkyMapper metallicity-sensitive diagnostic diagram can be found in the commissioning-era survey. As for Fig. 15, 5-pt star symbols are for carbon-enhanced stars while circles are used for carbon-normal stars. The metallicity distribution for the stars within the selection box is shown.

The slope of the diagonal dashed lines are for \([\text{C}/\text{Fe}]\) = +1.0, 0.0 and –0.7 dex, respectively. The linear fit to the relation gives a slope \(\Delta \log N / \Delta [\text{Fe/H}] \approx 1.5\) dex/dex.

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For example, the median \([\text{Fe/H}]\) is –2.84 (n=13) for stars that are metal-rich, \([\text{Fe/H}]\) = –2.09 (Yong et al. 2013), and which was later discovered as an EMP-candidate in the commissioning-era survey (Jacobson et al. 2015). The most metal-poor known-abundance carbon-normal star outside the current selection window is the star HE0057–5959, which has \([\text{Fe/H}] = –2.09\) (Yong et al. 2013). A recent study by Jacobson et al. (2015) identified a few EMP candidates with metallicities below –2.63.

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Da Costa, Bessell, Mackey, TN+ submitted

Figure 16.

Group I
[C/H] = -1

Group III
[C/Fe] = 1

Group II

Slope ~ 1.5 dex/dex
The first $[\text{Fe/H}] = -6$ star: SMSS1605

$11.2 \, \text{M}_\odot, \ 0.3 \, \text{B}, \ \log(f_{\text{mix}}) = -1.8$

$50.0 \, \text{M}_\odot, \ 1.5 \, \text{B}, \ \log(f_{\text{mix}}) = -1.0$
The Astrophysical Journal

The mass spectrum of the stars is shown.

Figure 7.

Figure 8.

The redshift evolution of SFRD of Population III.1 and III.2.

(a) III.1

Susa, Hasegawa, Tominaga 2014

Hirano, Hosokawa, Yoshida+ 2015
Summary

- MLT good enough for stellar atmospheres?
- 3D NLTE now feasible. Use at low [Fe/H]!
- EMP MDF slope = 1.5 dex/dex
- Carbon-normal MDF drops at [Fe/H] ~ -4
- Evidence for 10 Msol Pop III star?