Stellar spectroscopy for Galactic archaeology: current techniques, future prospects

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Looking back *and* ahead

In what follows, I will essentially give you my perspective on the field of stellar spectroscopy and how it has developed over the past 20 years.

The idea is not to be too concrete (pardon me if you don’t get an honorary mention!), neither too philosophical. I will **highlight the things that** I have found to **matter** in this sort of work.

M.C. Escher (1935): see his works at Palazzo della Cultura in Catania!
The goal of Galactic archaeology

Use stars as tracers of the dynamical and chemical evolution of the Milky Way to unravel its formation and evolutionary history.

What are the life-long tags we can use?
What will (not) be covered

• Standard spectroscopic techniques
• The current state of the art
• Interfaces with neighbouring fields
• The new data-mining approach

• (Hot stars; purely empirical methods
• Galactic dynamics, the flipside of chemodynamical studies of the MW)
Stars are... dynamical systems!

What are the life-long tags?
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Life-long tags for non-giant stars: $M$, $t$, $[A/B]$

What are the life-long tags?
Stars are...

dynamical systems!

Life-long tags for non-giant stars: $M, t, [A/B]$

They are not observables!
Stellar spectroscopy today

**Observation vs. Theory**

- Telescope
- Spectrograph
- CCD

**Concepts**

**Approximations**

**Numerical Model**

**Comparison**

to constrain thermodynamic variables and abundances

**Observed Solar Spectrum**

**Synthetic Spectrum**

3p 3P – 4s 3S
Stellar parameters: $T_{\text{eff}}$

Not even a handful spectroscopic methods that are in widespread use:

- excitation equilibria (Fe I, Ti I)
- Balmer lines
- line-depth ratios (very precise!)
- spectrophotometry (soon from Gaia!)

Important alternative/complementary techniques: photometry (IRFM!), interferometry
$H\alpha$: problems in the Sun

VCS + BPO

$T_{\text{eff}} = 5680K$

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Korn (2002), PhD thesis
**Hα: problems in the Sun**

Balmer lines are hard to get right
- theoretically *and*
- observationally.

They don’t seem to work so well in 1D.

\[ T_{\text{eff}} = 5680\text{K} \]

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But e.g. Fuhrmann uses them!

Fuhrmann (2004)
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Careful *differential* work (with the old Ali & Griem resonance broadening)
Line-to-line scatter

\[ \log \varepsilon (Fe I) \]

- O’Brian et al. (1991)
- May et al. (1974)
- Blackwell et al. (1976, 1979a, 1979b, 1980, 1982a, 1982b)
- Gehren et al. (2001)
Line-to-line scatter

Absorption spectroscopy is strictly asymmetric!
One Y/Y line says more than a thousand N/N lines!

May et al. (1974)
Bard et al. (1991, 1994)

Gehren et al. (2001)
Stellar parameters: $\log g$

Just like with $T_{\text{eff}}$, not so many different spectroscopic techniques for $\log g$ exist:

- ionization equilibria
- wings of strong lines (in LTE!)
- Balmer jump (metal-poor stars).

Important alternative/complementary techniques:  
**photometry** (Balmer jump!),  
**asteroseismology** (Ben’s talk; *easily* more precise, but see e.g. Masseron & Hawkins (2017) on remaining problems for RGB stars)
But e.g. Fuhrmann uses them!

Mg I triplet

Fe I/II

Fuhrmann (2004)
But e.g. Fuhrmann uses them!

Achieving accuracy is hard, often unattainable. Astounding precision possible when using weak lines (see Meléndez et al. 2009).

Fuhrmann (2004)
Stellar parameters: \( M \)

An inferred life-long tag, usually via evolutionary tracks or asteroseismology.

**Empirical calibration of the width of Balmer lines** allows one to constrain \( M \) to about 0.15 \( M_\odot \).

Competitive precision (see Ness et al. 2016).

Bergemann et al. (2016)
The \([Y/Mg]\) abundance ratio seems to be a very sensitive clock (Nissen 2015).

Using it, the solar twin in M67 (Önehag et al. 2011) is 4.5 Gyr old, somewhat older that cluster ages based on isochrones (which suffer from problems with the blue-hook morphology around the turnoff, VandenBerg et al. 2007).

However, this clock does not seem to work across different Galactic populations (Feltzing et al. 2017).
Departures from LTE

When densities are low (fluxes high), photons can travel far and carry non-local information. This will inevitably happen in any star, at some radius. The stellar interior is not affected, due to the generally small mean free paths of photons.

In the atmosphere, non-local information will systematically affect the level population of elements, invalidating the LTE approximation.
Non-LTE modelling

Solving even the restricted non-LTE problem is $10^3 \text{ - } 10^5$ more involved than doing LTE.

Lind et al. (2011)
All lines at all wavelengths...

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

Radiative rates generally better known than collisional rates.

Late-type stars: inelastic collisions with neutral hydrogen are important, but their cross-section is generally not known for complex atoms.

New quantum-mechanical computations \((X + H \rightarrow XH \rightarrow X^* + H^*)\) are finally removing this free parameter (Barklem, Belyaev).
Successes of non-LTE

\[ [\text{Ca/H}]_{\text{NLTE}} = -0.14 \pm 0.03 \]

Procyon: differential CaI in NLTE (\( S_\text{H} = 0.1 \))

\[ [\text{Ca/H}]_{\text{LTE}} = -0.12 \pm 0.04 \]

Procyon: differential CaI in LTE

Mashonkina et al. (2007)
Successes of non-LTE

Lind et al. (2012)
The art of non-LTE

- It is not the aim to produce the largest possible non-LTE effects.
- When atomic data is lacking, an empirical calibration is necessary. Even when atomic data is deemed complete, a validation is required.
- Depending on the approach taken, non-LTE effects are strictly speaking only valid in the chosen modelling framework.
Apropos calibration / validation

It is generally a great idea to try putting one’s results on firm grounds. **Support your atomic physicist!** (Ulrike’s & Maria Teresa’s talk)

Example: **The Gaia Benchmark Stars**, an epoch-shaping legacy of Gaia+GES. However, what does the interferometric $T_{\text{eff}}$ of **HD103095** (4820K, Creevey *et al.* 2012) tell us which is now found to be 300 K / 6σ too low?! It tells us that we are not in full control of the systematic errors in our analyses!
3D, convection and granulation

Computationally expensive
No free parameters,
but *choices* to be made

cheap

\( \alpha_{\text{MLT}}, \xi_{\text{micro}}, \bar{E}_{\text{rad}} \)

“full glory” possible
3D successes

The better physical description afforded by hydrodynamic models leads to line profiles in better agreement with observations (line shifts, line asymmetries). The same is true for the Solar centre-to-limb variation, velocity fields etc.

**Better abundances**, in part very different (esp. for metal-poor stars). Models are still improving…

However, the new Solar Z leads to **aggravated problems with helioseismology** (in terms of $\nu(R)$ and $R_{\text{BCZ}}$). No easy way out…
Grids of 3D models are now available (STAGGER, CO5BOLD).

3D + non-LTE is finally here: see Nordlander et al. (2017) on SMSS0313-6708 (Keller’s star): Li, Na, Mg, Al, Ca and Fe. This is the future!

An interesting avenue to explore is average 3D models that capture the 3D-modified $T$-$\tau$ relations, but neglect granulation effects. For most elements, this allows one to do 3D + non-LTE at the same computational cost as 1D + non-LTE. However, opinions on the usefulness of this approach diverge.
Hydrogen, helium and metals will move inside a stars under the effect of the prevailing forces. \([A/H]\) can change by a few tenths of a dex!

While hydrostatic equilibrium is a good approximation for the star as a whole (for most of its lifetime), it does not hold for individual elements. Atomic diffusion affects MS turn-off stars, dredge-up more evolved ones. These effects are not fully understood, but need to be considered to get to the initial abundances.
All traditional methods...

... apply these techniques, whether they collapse line strengths into single numbers or fit swaths of spectra.

Additionally, there are methods that are clever at avoiding local minima in the fitting hyperspace.

Other methods yet are clever in the way the comparison between theory and observation is done (e.g. projection MATISSE, Recio-Blanco et al. 2006; distance minimization GAUGUIN, Guillaume’s talk, decision tree DEGAS, all developed for Gaia-RVS).
The numbers we want to get at are not observables. Additionally, there is hardly any ground truth, certainly not regarding chemical abundances.

| Milky Way objects | Scientific results |
Data-driven methods 2.0

The numbers we want to get at are not observables. Additionally, there is hardly any ground truth, certainly not regarding chemical abundances.

Develop a detailed noise model of your filter. This is what The Cannon (Ness et al. 2015) does. **This is (also) the future!** Expect teething problems!
The future with Gaia (2020+)

Gaia will enable us to conduct chemodynamical studies well beyond the solar neighbourhood. This is what Gaia was built for.

However, let’s not forget its merits beyond astrometry: homogeneous sub-mmag spectrophotometry, RVS spectra and constraints on stellar binarity/multiplicity (see Timo’s talk).

Importantly, Gaia will allow us to construct clean stellar samples! For now, blindly imposing Gaia priors from DR1/2 is likely not a good idea (binaries)…
The future is bright!

After 200+ years, stellar spectroscopy is alive and kicking. This is the century of spectroscopy!

2018 marks the 200th birthday of Angelo Secchi.

Live, grow and bloom, stellar spectroscopy!

Vivat, crescat, floreat