Stellar and Galactic Archaeology with Bayesian Methods

Maria Bergemann
Max Planck Institute for Astronomy
Heidelberg
**Spectroscopy**

- Temperature, surface gravity, chemical abundances: Li, Be, Be,CNO, a-group, Fe-peak, s-r process, U,Th
- Rotation velocity
- Activity
- Radial velocity
- Mass, age
- Distances

**Physics of stars**

- Galactic archaeology and the first stars

**Nucleosynthesis and the origin of chemical elements**

- Chemical evolution of galaxies

**Key topics**

- Abundance trends
- Chemo-dynamic correlations
- Age-, mass-metallicity relations
- Metallicity gradients
Major progress in observations in the past 10 years:
VLT’s and, soon, ELT’s

Ongoing large-scale stellar spectroscopic surveys:
SDSS (Apogee, SEGUE), RAVE, Gaia-ESO, GALAH

Future:
4MOST (20 million spectra, optical),
MOONS (IR)
Observed stars

model Galaxy

movies under www.mpi.a.de/~bergemann/outreach
Stellar parameters: effective temperature, surface gravity, velocities, chem. abundances: up to 100 dimensions!

Model atmosphere:
- Physics
- Basic model atmosphere theory: non-LTE (NLTE), 3D hydrodynamics, magnetic fields, winds, sphericity, molecular opacities, binarity, chromospheres, etc.

Comparison:
- Observed spectrum
- Model spectrum
- Spectrum synthesis

Statistics
What are the physical conditions of the most likely model?

? ? ?

the orbit of Jupiter

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What are the physical conditions of the most likely model?
What are the physical conditions of the most likely model?

- all observed stars are point sources
- observed spectra are not perfect -> noise + data reduction problems
- stellar models are not perfect
- stellar spectra are in reality not so different → parameter degeneracies and correlations
<table>
<thead>
<tr>
<th>The physical challenge</th>
<th>The statistical challenge</th>
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<tbody>
<tr>
<td>1. What is a <strong>good</strong> stellar model?</td>
<td>1. What is the <strong>best-fit</strong> stellar model?</td>
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<tr>
<td>2. What type of physics can we afford computationally?</td>
<td>2. Do we have prior knowledge from previous or complementary experiments?</td>
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</table>
Even the best observed spectra are worth nothing without good model comparison methods
Max-Likelihood Spectroscopy

‘observed’ spectrum $\rightarrow$ the goal is to estimate $T_{\text{eff}}, \log(g), \text{ and metallicity}$ of a star

What if we rely only on the classical approach: maximum-likelihood $L$?

$L \sim \exp(-\chi^2/2)$

$$\chi^2 = \sum_j \left( \frac{D_{j}^{\text{obs}} - D_{j}(T_{\text{eff}}, \log(g), Z)_{\text{theor}}}{\sigma_j} \right)^2$$

where $D_j, j = 1... n$ are observables, i.e., spectrum in a given frequency bin

However, $L$ attains its global maximum only if for each model characterized by $[T_{\text{eff}}, \log(g), [\text{Fe/H}]]$ there is a unique model spectrum
Metal-free star

Metal-rich star

movies under www.mpi.a.de/~bergemann/outreach
movies under www.mpia.de/~bergemann/outreach
Metal abundances

Surface gravity

Surface Temperature

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Max-Likelihood stellar parameters

The contours contain 30, 50, 70, 90% of the data.

A correlation between the error in two parameters indicates that a systematic error in one parameter influences the result in the other:

\[ \Delta \log(g) = 1 \text{ dex} \quad \Rightarrow \quad \Delta T_{\text{eff}} = 1000 \text{ K} \]
‘Orthodox’ (standard) methods are suitable:
• selection effects lead to major biases
• *imperfect* data often disregarded
• parameter degeneracies caused by physical limitations of the models
• correlated errors, ...
• often there is just not enough information in the observed spectrum

Ad-hoc ‘correction’ of stellar parameters using stellar models
R \sim 200\,000, the spectrum of the Sun
At low R and S/N most of spectral information is washed out

R ~ 2000, the SDSS spectrum of a solar-like ‘twin’
High-resolution observations

The Milky Way disk

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Schönrich 2010
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More metal-rich
Small errors (high-quality data) $\rightarrow$ well-defined PDF
low-quality data $\rightarrow$ blurred or multi-component PDF
Bayesian model testing
Complementary experiments

large stellar surveys observe millions of stars

spectroscopy:
Sloan Digital Sky Survey, Gaia-ESO, Apogee...
→ stellar spectra: Luminosity, Temperature

photometry:
VISTA, 2MASS, PS1, Skymapper ...
→ magnitudes in different filters:

asteroseismology, stellar evolution:
CoRoT, Kepler →
mass, age of a star

astrometry:
Hipparcos, Gaia (launched 2013) →
distances
Bayesian model testing

Stellar Spectroscopy
Bayesian spectroscopy

1) In our context, the ‘core’ parameter space is defined by: metallicity (expressed by iron abundance), effective temperature, and surface gravity

\[ T_{\text{eff}}, \log g, [\text{Fe/H}] \]

2) Their plausibility is estimated based on the information contained in:

- observed stellar spectra
- model stellar spectra
- stellar evolution models (not all luminosities, masses, and ages are possible)
- parallaxes, photometry (constraints on \( \log g (\pi) \) and \( L \) (color))
- WMAP \( \rightarrow \) constraints on the max age
a set of parameters $X = X_1, \ldots, X_n$

a set of observations $O = O_1, \ldots, O_m$

The goal is to construct a full posterior PDF in all parameters

$$P(X|O) = \frac{P(X)}{P(O)} P(O|X),$$
The goal is to construct a full posterior PDF in all parameters:

\[
P(R|O_{sp}, O_{ph}) \sim P(O_{sp}|R) \cdot P(O_{ph}|R) \cdot P_{mod}(R) \cdot P_{pr}(R) \cdot P_{i,ph,astr}
\]

- Spectra + photometry
- SDSS
- Stellar evolution models
- IMF, age-metallicity prior
- Distances
- Hipparcos mission
- GAIA

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\(L(\text{max})\) attains its global maximum for \textbf{all} three isochrones!

In standard \(L(\text{max})\) approach, ages suffer from a ‘terminal age bias’, i.e., short-lived evolution stages get \textbf{un-physically} high probability.

Jørgensen & Lindegren 2005
run over the full multi-D grid of spectroscopic models

\[ \chi^2 = \sum_j \left( \frac{D_j^{\text{obs}} - D_j(\text{Teff, logg, } Z)^{\text{theor}}}{\sigma_j} \right)^2 \]

use adaptive, iteratively refined mesh guided by photometry + prior

Final values of $T_{\text{eff}}$, $\log(g)$, $[\text{Fe/H}]$:

$$P(X_j | O) = \int \int P(X_1, \ldots, X_n | O) \, dx_1 \ldots \, dx_{j-1} \, dx_{j+1} \ldots \, dx_n.$$  

\[(29)\]
Results

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Photometric PDF

Spectroscopy PDF

Final combined PDF

Bayesian Teff

Spectra + photometry + parallaxes

full method

T_{eff, bay} vs. T_{eff, ref}
Bayesian gravity

Spectra + photometry

\[ \log(g)_{\text{bay}} \]

\[ \log(g)_{\text{ref}} \]

-10
-9
-8
-7
-6
-5
-4
-3
-2

Q

-10
Bayesian gravity

Spectra + photometry + parallaxes

Schoenrich & Bergemann 2014
Stars from Sloan Digital Sky Survey

Bayesian

Spectroscopic only

Bayesian: summary

✓ Pros
  – All parameters (stellar parameters, distances, ages) within one single, consistent analysis
  – Automatic detection of pathologic (or interesting...) cases
  – Ability to quantify systematic shifts/errors

✓ Cons
  – The analysis scheme is too rigid: we cannot handle objects with physical properties that are not within the pre-computed model grids
  – Expanding the basic parameter set is expensive 3D → 4D (?). We need 30
  – Inclusion of priors – all stellar populations are different (the rate of star formation, IMF?)
Even the best observed spectra and good statistics are worth nothing without good models
models of stellar atmospheres
Basic model atmosphere theory – the models are usually trained on a given class of stars.

We do not have a single consistent set of models which describe all types of stars found in nature:

- rotate up to 100 km/s
- pulsate
- lose mass in winds
- magnetic fields (kG)
- exist as binaries or multiple systems (overlapping spectra)
- mass motions (inflows, outflows)
- Circumstellar dust shells

Ayres (2010)
Classical stellar atmosphere models

- local thermodynamic equilibrium
- Hydrostatic equilibrium
- 1-dimensional
- plane-parallel → semi-infinite
- plus about 30 ad-hoc free parameters

\[ \cos \theta \frac{dI_\nu}{dz} = \kappa_\nu I_\nu - \eta_\nu \]

\[ F = \frac{L}{4\pi R^2} = \sigma T_{\text{eff}}^4 \]

\[ \int_0^{\infty} J_\nu(\tau)d\nu = \int_0^{\infty} S_\nu(\tau)d\nu \]

\[ \nabla P_{\text{tot}} = -\rho \frac{GM_r}{r^2} \]

\[ \nabla P_{\text{rad}} = -1/c \int_0^{\infty} (\kappa_\nu + \sigma_\nu)F_\nu d\nu \]

~4000 citations the most widely-used grid of stellar spectra in astronomy


Kurucz+

Maria Bergegemann
Classical stellar atmosphere models

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The first paper on 3D hydro-dynamical model atmospheres of stars

\[ \nabla P_{\text{rad}} = -1/c \int_0 \left( \kappa_\nu + \sigma_\nu \right) F_\nu dv \]

~3400 citations
the most widely-used
1D p-p grid of stellar spectra
in astronomy

Kurucz+

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✓ local thermodynamic equilibrium
✓ Hydrostatic equilibrium
✓ 1-dimensional
✓ plane-parallel $\rightarrow$ semi-infinite
✓ plus about 30 ad-hoc free parameters

Does that work?

No

The observed image of the Sun
Swedish Solar Telescope (1m)
State-of-the-Art

- 3D hydrodynamics
- non-LTE (consistent treatment of the radiation field and physical state of the gas → gas must respond to the radiation loss from the surface)
- ab initio
- complete sampling of opacity sampling (up to 100 million spectral lines)
- no for unphysical calibrations ('mixing length', 'microturbulence')
3D Hydrodynamical models

the same scales - both images 20x20 Mm (!)

Matloch+ (2010)
(c) Asplund

Nordlund+ (2009), observed SST
average spatially \((x,y)\)

e.g., collapsing opacity surface to a single \(z\)-dependent value

3D NLTE spectroscopy

\[
\chi_1(z) \quad \chi_2(z) \quad \chi_3(z)
\]

Non-LTE radiative transfer on different chemical elements

Stagger convec,ons

average spatially \((x,y)\)
average spatially $(x,y)$

- Interpolate to the finer parameter grid, e.g., collapsing opacity surface to a single $z$-dependent value.

- NLTE radiation transport in millions atomic lines.

Bergemann et al. 2012
New way for survey spectroscopy with 3D NLTE

Teff=6000, log(g)=4.00, [Fe/H]=-1.0

3D Fe NLTE
1D LTE

Bergemann et al. in prep.
What classical (1D LTE) models can do for us

Bergemann et al. in prep.
State-of-the-Art <3D> NLTE: no free parameters

Sun, log(Mg) = 7.59 dex

HD 140283, [Mg/Fe] = 0.40 dex

HD 84937, [Mg/Fe] = 0.43 dex

HD 122564, [Mg/Fe] = 0.45 dex

Bergemann et al. in prep.
Summary

Stellar model atmospheres
need consistent improvements on models: 1D-3D, (N)LTE, rotation, stellar evolution

Bayesian-type (full –Prob.) schemes
• All parameters within one single, consistent analysis
• Automatic detection of pathologic (or interesting...) cases
• direct ability to quantify systematic shifts/errors,
  in future: reddening, distances, binary fractions, He

Good algorithms efficiently combining models and Bayesian are needed:
4MOST survey (2021) – 20 million stellar spectra with distances & kinematics
(Gaia follow-up)