The Science of Gaia: 
Stellar Atmospheres
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Who is this guy?

Born in 1972, raised in Marburg
MSc in Astrophysics (1996, U of London)
Diploma in Physics (1998, U of Heidelberg)
PhD in Astrophysics (2002, U of München)
Postdoc at MPE in Garching

since 2003 research fellow in Uppsala (German and Swedish funding)

Research interests: stars from B to K, esp. at low(est) metallicity, chemical evolution of the Galaxy, quantitative spectroscopy, atomic diffusion

Gaia involvement: coordinating the computation of synthetic observables (fluxes, spectra), refined modelling of cool stars
The role of stars in the Gaia context

The 1-billion-star Galactic census Gaia will perform shall provide astrophysicists with a detailed view of the 6D phase space of our Galaxy ($x, y, z, v_x, v_y, v_z$). The positions and space motions of stars are an integrated record of the dynamical history and evolution of the Galaxy.

Stars as probes of the current and past dynamical state of the Galaxy

How can this be achieved?

Gaia is primarily an astrometry mission (formerly known as Global Astrometric Interferometer for Astrophysics) ⇒ $x, y, z + v$ components perpendicular to the line of sight

To complete the 6D phase-space information, radial velocities need to be determined

⇒ Gaia needs spectroscopic capabilities
⇒ Radial Velocity Spectrometer (RVS) high resolution desirable, low signal-to-noise acceptable

In the Astrium design, RVS sits far off-axis causing problems with the image quality.
Is this enough?

No. Gaia has scientific goals many of which could not be met by collecting phase-space information alone.

Even the fundamental task of identifying merging subsystems (Galactic building blocks) in the halo will require additional pieces of information.

Brown et al. (2005): separation on kinematics alone “very challenging”

What more?

Determine physical parameters (“astrophysical coordinates”) of stars:

- $T_{\text{eff}}$, $\log g$, $[X_i/H]$, $v_{\text{rot}} \sin i$, ...
  stellar-atmosphere view
- $M$, $\mathcal{L}$, $X$, $Y$, $Z$, $R$, $v_{\text{rot}}$, $t$, ...
  stellar-structure view

Combining kinematical, chemical and age information has led to important discoveries in recent years, e.g. in connection with the Galactic Thick Disk (Fuhrmann 1998, 2004; Bensby et al. 2003, 2004, 2005).
Quantitative spectroscopy

observation vs. theory

telescope  concepts
spectrograph  approximations
CCD  numerical model

comparison

Quantitative spectroscopy (cont’d)

the source of all our knowledge about the cosmos

need to know: atomic (and nuclear) physics  microphysical description
QM (matter light interaction)
plasma physics
thermodynamics (TE, LTE, non-LTE)
hydrodynamics

can determine: plasma quantities (temperature, density,
chemical composition, magnetic field strength)
⇒ mass, radius, luminosity

⇒ stellar evolution, galactic structure, galaxy evolution,
cosmic structure, cosmic origin and evolution
stellar atmospheres: a definition

descriptive: the layers of a star from which we receive photons = the layers we can see

physical: \( \tau_v \leq 10 \)

where \( \tau_v = \int_0^L \kappa_v \rho \, dx \) is the optical height,

\( x \) measures the geometrical path [cm],

\( \rho \) is the mass density \([g \, cm^{-3}]\),

\( \kappa_v \) is the mass absorption coefficient \([cm^2 \, g^{-1}]\) and \( L \) is the path length (see Gray, ch. 5, p. 113)

optical depth (results in a sign change)

simple extinction law: \( I(\nu) = I_0(\nu) \exp(-\tau_v) \)

stellar atmospheres: typical figures

The Sun

\[ M = 2 \times 10^{33} \, g = M_\odot \]
\[ R = 7 \times 10^{10} \, cm = R_\odot \]
\[ \mathcal{L} = 4 \times 10^{33} \, erg/s = L_\odot \]

photosphere:
\( \Delta R \approx 200 \, km < 10^{-3} \, R_\odot \)
\( n \approx 10^{15} \, cm^{-3} \)
\( T \approx 6000 \, K \)

an O star

\( M \approx 50 \, M_\odot \)
\( R \approx 20 \, R_\odot \)
\( \mathcal{L} \approx 10^6 \, L_\odot (\propto M^3) \)

photosphere:
\( \Delta R \approx 0.1 \, R_\odot \)
\( n \approx 10^{14} \, cm^{-3} \)
\( T \approx 40 \, 000 \, K \)

wikipedia: stellar classification
The Sun is one of the few stars whose surface we can resolve to measure the so-called specific intensity

$$\mathcal{I}_\nu = \frac{dE_\nu}{\cos \theta \, dA \, d\Omega \, dt \, d\nu} \quad [\text{J/m}^2 \text{rad s Hz}]$$

Usually, we measure stellar fluxes

$$\mathcal{F}_\nu = \int dE_\nu / dA \, dt \, d\nu \quad [\text{J/m}^2 \text{s Hz}]; \text{Gaia: } [\text{W/m}^2 \text{nm}]$$

Clearly, the flux $\mathcal{F}_\nu = \int \mathcal{I}_\nu \cos \theta \, d\Omega$ and it measures the anisotropy of the radiation field.

Example: the Solar flux above the Earth’s atmosphere

$$\mathcal{F}(\odot) = 1.36 \text{kW/m}^2$$

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**Morgan-Keenan(-Kellman) classification**

Spectral Sequence of Stars (1940s/50s)

- He I
- H\(\delta\), H\(\gamma\), H\(\beta\), H\(\alpha\)
- Ca H & K
- G band (= CH)
- Mg b
- Na D, TiO

Wien's law:

$$\lambda_{\text{max}} = 2.9 \times 10^7 \text{Å} / T[\text{K}]$$
Assumptions

To make the modelling of stellar atmospheres manageable, a variety of assumptions are traditionally made about stellar photospheres:

1. plane-parallel vs. spherical geometry
2. homogeneity
3. stationarity
4. hydrostatic equilibrium
5. flux constancy (radiative equilibrium)
6. local thermodynamic equilibrium

Fundamentally speaking: **Stars are dynamical systems!**

plane-parallel geometry

stars are essentially spherical ⇒ spherical geometry should be used

exceptions:  
- rapidly-rotating B stars ($v_{\text{rot}} \approx 300 \text{ km/s}$; axisymmetry)
- extended non-spherical regions like stellar coronae
- stellar-structure models that treat effects of rotation and/or magnetic fields

but:  
in many cases the photosphere is very thin: $\Delta R / R \ll 1$
in which case we can assume plane-parallel geometry without introducing significant errors

examples:  
solar $(\Delta R / R)_{\text{phot}} = 5 \times 10^{-4}$ (but solar $(\Delta R / R)_{\text{corona}} \approx 3$),
generally a decent assumption for all non-supergiant stars, but not for expanding shells around O stars or M giants.
homogeneity

Let’s denote the mass fraction of H, He and all other elements ("metals") by $X$, $Y$ and $Z$. Homogeneity then implies that

$$X, Y, Z \neq f(r, \theta, \phi)$$

exceptions: • the granular pattern of stars with convection
• (magnetic) spots
• chemical spots and stratification (Ap stars)
• atomic diffusion (on long timescales)

Since we cannot usually resolve stellar surfaces (rapid progress is being made in this field, e.g. Doppler imaging techniques), we assume a homogeneous atmosphere as an averaged model. It is hoped that this average model describes the average stellar properties well.

stationarity

Roughly speaking, the spectra of stars are time-independent on human time scales

exceptions: a plethora of time-dependent phenomena
• granulation (convection)
• pulsations (Sun, RR Lyrae stars, Cepheids etc.)
• magnetic activity (HgMn stars ⇒ “weather”)
• mass loss (stellar winds, mass overflow in binaries)
• explosions (supernovae)

Even if there are time-dependent phenomena on time scales shorter than or comparable to the exposure time, one hopes that one can observe and describe average stellar properties.

In the following, we will generally assume $\frac{d}{dt} = 0$
The Sun is not expanding or contracting macroscopically. Its atmosphere is globally at rest.

Newton: \( \frac{dm}{dt} \frac{dv(x,t)}{dt} = \sum dF_i = 0 \)

What forces act on an atmospheric volume element?

- **Gravitational force:** \( dF_{\text{grav}} = -G M_r \frac{dm}{r^2} = -g(r) \, dm \)
- **Pressure force:** \( dF_p = -A (P(r+dr) - P(r)) \)
- **Radiation force:** \( dF_{\text{rad}} = g_{\text{rad}} \, dm \)

The radiation force is primarily important in hot stars \( (\propto T^4) \).

\[
\sum dF_i = 0 \quad \Leftrightarrow \quad -g(r) \, dm + g_{\text{rad}} \, dm - A \, \frac{dP}{dr} \, dr = 0
\]

\[
\frac{dP}{dr} = -\rho(r) \left( g(r) - g_{\text{rad}} \right) \quad \text{hydrostatic equation}
\]

We will disregard the radiative acceleration in the following.

For all practical purposes, the mass contained in a stellar atmosphere is negligible (solar \( \Delta M / M \approx 10^{-12} \)).

\[
g(r) = g = G M / R^2 \quad \log g = \log \left( G M / R^2 \right)
\]

Typical values:

<table>
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<tr>
<th></th>
<th>4.44</th>
<th>4</th>
<th>0.0</th>
<th>8</th>
<th>(2.99)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>MS star</td>
<td>supergiant</td>
<td>WD</td>
<td>(Earth)</td>
<td></td>
</tr>
</tbody>
</table>
### flux constancy

Stellar atmospheres are much too cool and tenuous to fuse nuclei \( \Rightarrow \) the energy coming from the stellar core is merely transported through the atmosphere, either by radiation or convection.

\[
\mathcal{F}(r) = \text{energy} / \text{unit area} / \text{unit time} \quad [\text{J m}^{-2} \text{s}^{-1}] = [\text{W m}^{-2}]
\]

The total energy output of a star is called its **luminosity**

\[
\mathcal{L} = 4\pi r^2 \mathcal{F}(r) = \text{const.}
\]

The temperature gradient in a stellar atmosphere \( T(r) \) will arrange itself to fulfill this equation \( \forall r \).

If \( \mathcal{F}_{\text{rad}} \gg \mathcal{F}_{\text{conv}} \), then one speaks of **radiative equilibrium**.

(Karl Schwarzschild 1873–1916)

### The spectra of stars

Luckily, stars (and other celestial bodies) are not in thermodynamic equilibrium (TE) and do not shine like blackbodies.

(Astronomy would be the dullest of all sciences!)

In contrast to \( B_\lambda \), \( I_\lambda \) depends on plasma properties and the viewing angle. One cannot use TE to describe starlight.
Boltzmann, Maxwell & Saha

Particle velocities are assumed to be Maxwellian:

\[
\frac{n(v)}{n_{\text{tot}}} \, dv = \left( \frac{m}{2\pi kT} \right)^{\frac{3}{2}} e^{-\frac{m v^2}{2kT}} \, dv
\]

Excitation follows Boltzmann statistics:

\[
\frac{n_u}{n_{\text{tot}}} = \frac{g_u}{u(T)} e^{-\frac{\chi_u}{kT}}
\]

Ionization can be computed via the Saha equation:

\[
\frac{n_{II}}{n_I} P_e = \frac{(2\pi m_e)^{3/2} kT^{5/2}}{\hbar^3} \frac{2u_{II}(T)}{u_I(T)} e^{-\frac{l}{kT}}
\]

In LTE, these are applied \textit{locally}.

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The basics of radiative transfer

When the stellar photons interact with the stellar-atmosphere matter, photons can be absorbed and re-emitted. This is the basic message of the \textit{radiative transfer equation}.

\[
\frac{dI_v}{d\tau_v} = -\kappa_v \rho I_v \, dx + j_v \rho \, dx \quad \text{or} \quad j_v: \text{emission coefficient}
\]

\[
\frac{dI_v}{d\tau_v} = -I_v + S_v \quad \text{with} \quad S_v = j_v / \kappa_v \\
\text{the \textit{source function}}
\]

In LTE, \( S_v = B_v \) \textit{the Planck function}

\( B_v \) has a number of wonderful properties: it \textit{does not depend on material properties (only} \( T \text{) and increases monotonically with increasing} \( T \text{) for all} \ v \).

The integral \( \int B \cos \theta \, d\Omega \) yields \( \sigma T^4 \) (Stefan-Boltzmann law).
Applying TE locally

The existence of a radial temperature gradient in stellar atmospheres means that two different volume elements
d\(V_1(T_1, r_1), d\nu_2(T_2, r_2)\) with \(r_1 < r_2\) and \(T_1 > T_2\)
cannot be in TE with each other.

The simplest adaption of the basic ideas of TE to the specific case of stellar atmospheres is to assume the validity of TE locally. We refer to this concept as local thermodynamic equilibrium (LTE).

While LTE may be an acceptable approximation for the atmospheres of cool stars as a whole, it is not applicable for hot stars. Generally, LTE may or may not hold for a specific spectral line one would like to use in an abundance analysis.

Computing model atmospheres

In practice, one solves the RTE together with
\[
\int \kappa_v J_v \, d\nu = \int \kappa_v S_v \, d\nu \quad \text{Milne equation}
\]

and
\[
\int F_v \, d\nu = \sigma T_{\text{eff}}^4 \quad \text{definition of } T_{\text{eff}}
\]

Iteration scheme:

\(T_{\text{eff}}, T(x), \kappa_v, S_v = B_v (T(x)) \Rightarrow \text{RTE: } J_v (x), F_v (x)\)

\[
\int \kappa_v (J_v - B_v) \, d\nu = 0 ?
\]

\[
\int F_v \, d\nu = \sigma T_{\text{eff}}^4 ?
\]

\(\Rightarrow \Delta T(x), \Delta \kappa_v(x), \Delta B_v(x) \Rightarrow \text{start next iteration}\)

Solve this set of equations for typically 100 depth points, 10 000 frequencies and millions of opacity sources.
Limb darkening and \( T_{\text{eff}} \)

If one assumes a linear dependence of \( S_\nu \) on optical depth, then the surface intensity as a function of \( \cos \theta \) samples the source function between \( \tau_\nu = 0 \) and 1 (Eddington-Barbier relation):

\[
I_\nu(0, \cos \theta = 1) = S_\nu(\tau_\nu = 1) \quad \text{Solar disk centre}
\]

\[
I_\nu(0, \cos \theta = 0) = S_\nu(\tau_\nu = 0) \quad \text{Solar limb}
\]

At the Solar disk centre, one sees deeper (and hotter) layers than close to the limb. At 5000 Å and \( \cos \theta = 0.3 \), the flux is only half that at the disk center. This explains in qualitative terms the so-called **limb darkening**.

Assuming \( \kappa \neq f(\nu) \) (the unrealistic **grey case**), one can further show that \( T_{\text{eff}} \approx T(\tau = 2/3) \).

Opacities

**Continuous opacity**
Caused by \( bf \) or \( ff \) transitions
In the optical and near-IR of cool stars, \( H^- \) dominates:
\[
\kappa_\nu = \text{const.} \ T^{-5/2} \ P_e \ \exp(0.75/kT)
\]

**Line opacity**
Caused by \( bb \) transitions
Need to know \( \log gf \), damping and assume an abundance

implemented either via so-called opacity distribution functions (ODFs) or via direct sampling.
How spectral lines originate

The formation of absorption lines can be qualitatively understood by studying how $S_v$ changes with depth.

Spectral lines as a function of $A$

Abundances scales tend to be logarithmic:

$$\log \epsilon (X) = \log \left( \frac{n_X}{n_H} \right) + 12$$
$$[X/Y] = \log \left( \frac{n_X}{n_Y} \right) - \log \left( \frac{n_X}{n_Y} \right)_\odot$$

The curve of growth describes how the line strength varies with $A$:
Broadening of spectral lines

There are numerous broadening mechanisms which influence the apparent shape of spectral lines:

1. natural broadening
   (reflecting $\Delta E \Delta t \geq h/2\pi$)

2. thermal broadening

3. microturbulence $\xi_{\text{micro}}$
   (treated like extra thermal br.)

4. isotopic shift, $hfs$, Zeeman effect

5. collisions ($H: \gamma_6, \log C_6; e^-: \gamma_4$)
   (important for strong lines)

6. macroturbulence $\Xi_{\text{rt}}$

7. rotation

8. instrumental broadening

Essentially all lines have a certain sensitivity to $T_{\text{eff}}$ (via Boltzmann), but it may be surpassed by other sensitivities.

Sensitivity to $\log g$ in cool stars?

Case 1: (weak) neutral line of an element that is mainly ionized

$W_\lambda$ is proportional to the ratio of line to continuous absorption coefficients, $l_\nu / \kappa_\nu$.

$\frac{n_{r+1}}{n_r} = \Phi(T) / P_e \iff n_r \approx \text{const. } P_e$

$\Rightarrow l_\nu / \kappa_\nu \neq f(P_e)$

neutral lines do not depend on $\log g$

Case 2: ionized line of an element that is mainly ionized

$\log g$ sensitive via the continuous opacity of $H^-$
Fuhrmann (2004): LTE at its best

\( \alpha \)-element enhancement (iron deficiency) can be explained by the exclusive enrichment through type-II SN explosions (Tinsley 1979)

\( \alpha \)-elements: C + \( \alpha \rightarrow \) O, Mg, Si, S, Ca, Ti; beyond: iron group: e.g. Cr, Fe, Ni

How good can such analyses be?

Statistically speaking, the spectroscopic stellar parameters are in perfect agreement with the Hipparcos astrometry.

Nominally, a 0.5% offset translates into 10 K offset in \( T_{\text{eff}} \) and 0.005 in log \( g \) (but there is a small hidden \( T_{\text{eff}} \) dependence)
Treating convection properly: 3D models

In recent years, hydrodynamic stellar-atmosphere models have been applied to the Sun and a few other stars. They have somewhat different temperature gradients and cooler surface temperatures.

These models predict lower CNO abundances for the Sun making it 30% less metal-rich. Effects in metal-poor stars are even larger, but still disputed.

Does Gaia see and need 3D effects?

Yes, at least in some (extreme) cases.

1. need to determine convective line shift from 3D models to get \( v_{\text{rad}} \) accurately.

2. need 3D models to predict abundance ratios like \([\text{Ca}/\text{Fe}]\) without large systematic biases.

Current challenge: to model 3D and NLTE simultaneously.

3. need star-in-a-box models to predict how the photocentre of nearby giants (e.g. Betelgeuze, below) moves due to convection. May mimic a large parallax.

from http://www.astro.uu.se/~bf/
Departures from LTE

Assuming LTE and temperatures that decrease with \( r \), one expects to see absorption lines (see Solar spectrum).

In the IR, several emission lines (of Mg I, Al I, Si I) are present in the spectra of solar-type stars. These have been shown to be of photospheric origin, but require departures from LTE (NLTE). Their formation can be understood by modelling in details how the levels in these atoms are populated by radiative \((R)\) and collisional \((C)\) processes.


LTE vs. NLTE

Occupation, excitation & ionization are local properties
\( \Rightarrow \) Saha-Boltzmann statistics

Once the stellar atmosphere is constructed, all you need to know to calculate a line strength is

(a) the level energies and statistical weights involved
(b) the transition probability
(c) broadening mechanisms (microturbulence, van-der Waals damping)

Photons carry non-local information

Occupation, excitation & ionization depend on the microphysics (radiation field, collisions etc.)

One needs to know (and master) a whole lot of atomic physics.

One needs a powerful code to solve the complex numerical problem of radiative transfer plus rate equations:

\[
 n_i \Sigma_{j \neq i} (R_{ij} + C_{ij}) = \Sigma_{j \neq i} n_j (R_{ji} + C_{ji})
\]
The line source function depends on the ratio of the populations involved in the transition, $n_u/n_l$:

$$ S_1 = \frac{2h\nu^2}{c^2} \frac{1}{\frac{g_u}{g_l} \frac{n_u}{n_l} - 1} $$

If the populations follow Saha-Boltzmann statistics, then $S_1 = B_\nu(T)$. But the above formulation is of general validity and can be applied to the non-LTE case.

Note that if both level populations depart from LTE in the same way ($b_l = n / n_{LTE} = b_u$), then we have a non-LTE situation in which $S_1 = B_\nu(T)$. This means that $S_1 = B_\nu$ is not a sufficient condition for LTE.

**Procyon = α Canis minor**

Procyon is a nearby ($d_{HIP} = 3.5$ pc), hot ($T_{eff} = 6510$ K, from $F_{bol}$ and $R = 2.07 R_\odot$) turnoff-point star ($\log g = 4.0$, from $R$ and $M = 1.4 M_\odot$, the latter via its WD companion). Thus, all stellar parameters (except composition: more or less solar) are known.

Mashonkina, Korn & Przybilla (2007)
Atomic diffusion

In spite of convective envelopes, unevolved solar-type stars may appear more metal-poor than they really are, as metals have a tendency to diffuse downward. This is a small effect in the Sun ($\approx -0.05 \text{ dex}$), but can reach $-0.2 \text{ dex}$ in metal-poor turnoff stars (Mg in TOP, see right).

Giant stars (RGB) have well-mixed atmospheres due to deep outer convection zones. They can, however, show nuclear-burning products (C, N, O) in their atmospheres.

Stars in different evolutionary phases in the metal-poor globular cluster NGC 6397 (observed with VLT/FLAMES-UVES). The observed abundance trends are compared with three different stellar-structure models treating the effects of atomic diffusion (from Korn et al. 2007).

Stellar continua as seen by RP/BP

The dispersion of Gaia’s photometers is low, RP: $50 \text{ Å} < \Delta \lambda < 150 \text{ Å}$; BP: $50 \text{ Å} < \Delta \lambda < 300 \text{ Å}$, therefore only the broadest spectral features (molecular bands in cool stars, Balmer lines in A stars, Ca H $&$ K in stars of intermediate $T_{\text{eff}}$) will be visible. The classification via RP/BP thus has to rely on the run of the (pseudo-)continua with wavelength. Here are simulated RP spectra of 4000 K dwarfs:

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Giant stars (RGB) have well-mixed atmospheres due to deep outer convection zones. They can, however, show nuclear-burning products (C, N, O) in their atmospheres.
Of all stellar parameters, $T_{\text{eff}}$ has the largest influence on stellar fluxes.

NB: reddening has a large influence and needs to be determined as well!

Like in hot stars, $T_{\text{eff}}$ variations dominate the fluxes of cool stars. The attainable precision is between 2 and 5%, accuracy to be safeguarded by calibrations with fundamental stars.
The slope of near-IR spectra (Rayleigh-Jeans regime) is primarily sensitive to $T_{\text{eff}}$. But the RVS resolution is high enough to analyse individual spectral lines to further constrain stellar parameters and derive abundance ratios.

<table>
<thead>
<tr>
<th>$V$</th>
<th>S/N</th>
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<tr>
<td>8</td>
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<tr>
<td>9</td>
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<td>13</td>
<td>55</td>
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<tr>
<td>14</td>
<td>25</td>
</tr>
</tbody>
</table>

transition to $R = 5500$ at $V \approx 11$

The Ca II triplet lines are broadened by elastic collisions with hydrogen:

$$\text{Ca} + \text{H} \rightarrow \text{Ca}^* + \text{H}^*$$

Progress in the QM description of this interaction has led to a better understand of the profiles of these (and many other) lines (Anstee & O’Mara 1991, 1995).

\[
\log \gamma_6 = -7.94
\]

\[
\log \gamma_6 = -7.68
\]
Ca II 8498 in a metal-poor turnoff star

HD 84937: $T_{\text{eff}} = 6350$ K, $\log g = 4.0$, $[\text{Fe/H}] = -2$

LTE can fit the observed profile with $[\text{Ca/Fe}] = 0.64$ (unusually high) and lowered external broadening.

NB: This will no longer be possible in 3D, as the external profile is part of the model prediction.

$\Delta_{\text{NLTE}} = -0.26$

line core suffers from NLTE

Stellar parameters from Gaia data

$T_{\text{eff}}$: from RP/BP continua, but need to determine other stellar parameters and $A_V$ (!) simultaneously (potentially exploit diffuse interstellar band in RVS range).

$\log g$: in principle from RVS, but log $g$ sensitivity of the Ca II triplet lines is masked by damping (as long as the lines are strong); the parallax will be the key observable to constrain log $g$.

$v_{\text{rot}}$: from RVS (line shapes; requires good S/N)

$[\text{Fe/H}]$: from RP/BP (all stars) and RVS (stars brighter than $V \approx 14$)

$[\alpha/\text{Fe}]$: from RP/BP (some constraint) and RVS ($[\text{Ca/Fe}]$ for stars brighter than $V \approx 14$)

activity: from the cores of the Ca II triplet lines (chromospheric line filling)

$t$ (age): if all stellar parameters are well-determined and the star is in a favourable HRD position (e.g. near the turnoff)
The Gaia challenge

Gaia will collect data on Galactic objects covering the full inventory of the HRD. Still, we would like to be able to classify stars chemically which requires a precision of 0.2 dex in, e.g., [Mg/Fe] or [Ca/Fe].

Can this be achieved?

Two different cases:

a) comparing like with like: doable based on RP/BP, at least for $T_{\text{eff}} \leq 5000 \text{ K}, G \leq 16.5, \text{ low } A_V$ (Willemsen, Kaempf & Bailer-Jones 2006)

b) comparing, e.g., abundances of giants and dwarfs: numerous sources of systematic errors at the 0.2 dex level. Need to improve the modelling and perform calibrations.

Gaia’s impact on stellar-atmosphere research

The main strength of Gaia lies in astrometry, Gaia’s impact is likely to be largest here.

Gaia will determine accurate distances and thereby define the surface-gravity/pressure scale of objects for which this still is a large uncertainty. Examples are C stars and AGB stars. But even for normal giants $\log g$ is often the least constrained parameter. This is also where Hipparcos had its largest impact.

Even with its limited accuracy in [X/Fe], Gaia will define samples of stars with well-defined properties (and known biases) which can be vetted by ground-based telescopes equipped with spectrographs with multiplex capabilities. Clean samples can be defined to, e.g., study the impact of varying essentially one stellar parameter on spectral-line formation.
Eclipsing binaries will ultimately link stellar atmospheres to stellar structure, giving answers to questions like the effective-temperature scale, the cosmic $\Delta Y/\Delta Z$ and accurate age determinations to, e.g., understand how the Galaxy formed.

Another area is stellar activity and variability (of all kinds): e.g. understanding in full detail the $P$-$L$-[$Fe/H$] relation of Cepheids and exploit the full capability of such stars as distance indicators beyond the volume sampled by Gaia. Understand how the Sun fits in with its low visual micro-variability.

Last but not least, Gaia will discover new things serendipitously:

Therefore, prepare for the unexpected!

References

  (corrections at http://www.astro.uwo.ca/~dfgray/Photo3-err.html)
Holweger H. 1996, Physica Scripta T65, 151