Stellar physics with GAIA

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1000 million objects measured to $l = 20$

Horizon for proper motions accurate to 1 km/s

Dark matter in disc measured from distances/motions of K giants

Dynamics of disc, spiral arms, and bulge

Horizon for distances accurate to 10 per cent

1 microarcsec/yr = 300 km/s at $z = 0.03$
(direct connection to inertial)

Proper motions in LMC/SMC individually to 2-3 km/s

General relativistic light-bending determined to 1 part in $10^5$

>20 globular clusters
Many thousands of Cepheids and RR Lyrae

Mass of galaxy from rotation curve at 15 kpc

30 open clusters within 500 pc

Horizon for detection of Jupiter mass-planets (200 pc)
GAIA

• Scope of GAIA: Galactic formation and evolution, dynamics
  ⇒ stars are markers (kinematics, chemistry, ...)

• Also, of course: reference frame, cosmological distance scale, exoplanets, fundamental physics, solar system, dark matter, ...
Stars as targets per se

- **Stars can be studied** with GAIA: we will gain insight into various aspects of stellar physics:
  - Distances -> luminosities, radii, etc
  - Masses, ....

- **Preparation of GAIA** induces better stellar physics, and new tools

- My talk will illustrate these two points
What will GAIA provide?

- $10^9$ stars to $V<20$ (300µas) (completeness)
- $26\times10^6$ stars to $V<15$ (20µas)
  - Sun @1kpc: $\Delta d/d=0.02$
  - Red Giant @2.5kpc: $\Delta d/d=0.05$
  - M-L dwarf @100pc: $\Delta d/d=0.03$
- $3\times10^6$ stars better than 1%
- $30\times10^6$ stars better than 10%

- Proper motions 50% better than parallaxes
- Radial velocities at 1-10km/s to $V=16$

=> Masses for binaries

- Multiple epochs => stellar variability, rare types of stars/stages of stellar evolution: $18\times10^6$ variables (Eyer & Cuypers 2000)
What will GAIA bring us for stellar physics?

- Good distance => accurate $L$, the most commonly missing parameter in Galactic star studies
- $L$ combined with $T_{\text{eff}}$ (from photometry/spectrophotometry) => $R$ ($L=4\pi R^2 \sigma T_{\text{eff}}^4$)
- $M$ and $R$ => gravity $g$ (difficult to derive from spectroscopy, and often affected by NLTE effects)
- In addition, synergy with seismology which provides, e.g., $M/R^3$
Stellar evolution (1)

• Modeling of stellar evolution:
  – Good physics: EOS, nuclear reaction rates, opacities, atomic diffusion, atmospheres, ...
  – Special difficulties for cool, dense stars, late stages, and accurate modeling (e.g. Sun)

• Predictions: $L(t), R(t), T_{\text{eff}}(t), z(t), ...$

• Validation with well known systems (Sun, $\alpha$ Cen binary, ...)
Stellar evolution (2)

- Atmospheres:
  - Boundary condition
  - Transformation $L - T_{\text{eff}} \Rightarrow M_\nu, B_C_\nu, T_{\text{eff}} - \text{color}$
  - Extraction of stellar parameters from observations: $T_{\text{eff}}, \log g, \text{chemical composition, ...}$

Great recent progress: opacities, 3D, NLTE, ...

But still relatively large systematic errors for cool giants, hot stars, metal-poor stars
Ages from isochrones

Principle straightforward: place a star $T_{\text{eff}}$, $L$, [M/H] => age, mass, [M/H]$_0$

Not always easy, nor unambiguous: Isochrones overlap. In any case, need for very precise, and accurate $L$, $T_{\text{eff}}$, and [Fe/H], (and mass!)

Jørgensen & Lindegren 2005
Stellar evolution (3)

- Validation

Example of $\alpha$ Cen

$M_A = 1.105 \pm 0.007$, $R_A = 1.224 \pm 0.003$, $\log g_A = 4.307 \pm 0.005$

$M_B = 0.934 \pm 0.006$, $R_B = 0.863 \pm 0.005$, $\log g_B = 4.538 \pm 0.008$

Spectroscopic determination of $T_{\text{eff}}$

Porto de Mello et al. 2008
Alpha Cen: spectroscopic determination of $T_{\text{eff}}$

Fel and Fell line fitting

But, scatter in $T_{\text{eff}}$ from various authors is about 300K!
And abundance scatter is large too!
Stellar evolution (3)

• Validation

Example of $\alpha$ Cen

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Note that $\log T_{\text{eff}}$ from $L$ and $R$
are: 3.77 and 3.74
$\Rightarrow$ $L$ is wrong?
$\Rightarrow$ $T_{\text{eff}}$ from spectroscopy not good?

$\Rightarrow$ Find a consistent solution =
constraint for atmosphere and evolution models
i.e. $L$, $g$, $T_{\text{eff}}$, $M_V$, BC, etc from atmos.,
and then test evolutionary tracks
Remaining difficulty: abundances!
GAIA will bring tight constraints on $L$, $T_{\text{eff}}$ for many stars.

But, degeneracy is still a problem: MS and TO.

Seismology is very complementary!

Lebreton & Montalbán 2010
Clusters

- HR diagrams of clusters

=> same ages, and initial chemical composition

Hyades (de Bruijne et al. 2001, and Lebreton et al. 2001)
Clusters and He abundance

Hyades M-L diagram:

$vB22A$ & $B$ allow to determine the He abundance.

But:

degeneracy $[\text{Fe/H}], \text{He}$

$(0.09,0.25) \ (0.14,0.26) \ (0.19,0.27)$

...and Mixing-length, EOS, ...

=>$\text{Need more data!}$

(Torres et al. 1997, Lebreton et al. 2001)
Abundances : NLTE effects

Requiring ionization equilibrium (LTE) => gravity

Fuhrmann et al. 1997 (Procyon)
NLTE effects

• In fact FeI/FeII or CaI/CaII depend on collisions (e- and H), and photo-ionization.

• **Collisions with H not well known.** Draw in approximation with factor $S_H$ between 0 (no collisions) and 1-3 (closer to LTE)
NLTE effects

Plot of spectroscopic distance error

Use reference stars, with known distances (thus L), $T_{\text{eff}}$ (thus R), and masses (thus g) to calibrate NLTE corrections!

GAIA will provide large such samples
Transport processes; abundance anomalies

CN processed RGs with high N/C, low $^{12}\text{C}/^{13}\text{C}$, no Li

Thermohaline mixing?


Spite et al. 2007
Mixing

Na-Al overabundance for field stars, as seen in globular cluster stars. But are these AGBs?

=> Need for better L, and logg

Spite et al. 2007
Diffusion and turbulent mixing

Element diffusion inside stars, with unknown amount of turbulent mixing

Impact on determination of “real” abundances from surface abundances (Li, ...)

=> Test on clusters

Korn et al. 2007
Diffusion; further validation

Isochrone computed using the same diffusion model.

Good stellar parameters needed!

Do it on field stars?
=> know precisely their evolutionary stage!
Explain Li in EMP stars?

Sbordone et al. 2010
GAIA preparation: Global Stellar Parametrizers

• Powerful **algorithms to quickly extract APs from large number of spectra (GSP-spec)**
  – Optimization: APs derived from distance minimization
  – Projection: observations projected on a set of vectors defined during learning phase -> MATISSE (Nice)
  – Classification: pattern recognition -> DEGAS (Nice)
GSP-spec: Matisse & Degas

Test on $S^4N$ (Allende Prieto et al. 2004) and CFLIB spectral libraries (Valdes et al. 2004)

Kordopatis et al. 2011
GAIA preparation: large homogeneous samples of stars

WP “provide calibration of training data” CU8 (C. Soubiran)

General Stellar Parametrizers are trained on synthetic spectra
⇒ systematic errors in AP’s
⇒ Need for external calibration with reference stars.

Determine high quality AP’s on homogeneous scale
• A few 10’s fundamental calibrators (too bright for GAIA)
• 500 to 5000 primary calibrators, with differentially determined AP’s
• 1000’s of secondary calibrators for large scale validation

In recent years many large samples analyzed by various authors. Analyses will be homogenized.

Challenge! Huge effort! Also important to validate stellar models!
Large samples of stars

Example for secondary calibrators:

90000 SDSS spectra

(allende Prieto et al. 2007, and GAIA-C8-TN-UAO-UH-001-1)
GAIA preparation: 3D models, photo-center and parallax accuracy

Consequences of Gaia measurements

Hipparcos => GAIA

• 100 binary system with M at 1% => 17000
• 200 stars with π at 1% => 21x10^6, and 7x10^5 at 0.1%
• 120 clusters (d<1kpc) precision better than Hyades now
• Parallaxes for subdwarfs, subgiants, ...
• Distance to stars in 20 globular clusters at <10%

• This unprecedented data set, combined with interferometry (R/d), and asteroseismology (f(M, R, T_{eff})) will allow stringent tests of models (atmospheres and evolution), and quantitative understanding of physical processes (mixing, rotation, ...)