Measuring Stellar Parameters

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We can test the formation history of the Milky Way if we can precisely measure stellar ages and abundances.

PROBLEM: Are our tools up to the task?
Overall Picture

- Equations of Stellar Structure
- Mass, Composition, Age (plus rotation and magnetic fields) specify the properties of a star
- Classic Observables: L, R, Teff, log g, kinematics
- New (Seismic) Observables: Core properties; surface CZ depth
Global Stellar Properties & Their Dynamic Ranges

- Energy output ($L$) is related to the surface temperature and radius through

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

Where $T_{\text{eff}}^4$ is the flux per unit area that a blackbody would have.

- $L_{\text{sun}} = 3.844 \times 10^{33}$ erg/s

- For normal stars $10^{-4} L_{\text{sun}} < L < 10^{6} L_{\text{sun}}$
Luminosity

Historical Path
- Measure Fluxes
- Correct for Extinction
- Infer Distance

All of these methods scale well to surveys

Complications
- **Absolute photometry is astonishingly difficult to do well**
- Blends (esp. binaries) affect fluxes and colors
- Reconstructing the SED is quite model dependent
- Extinction is important

Key Future Development: Gaia
The HR Diagram

- Distinct Populations
- Important features give information about galactic populations and relative timescales

Hipparcos CMD, \( \sigma < 20\% \)
Gaia and Hipparcos

**Hipparcos:**
- $10^5$ stars
- $\sigma = 1$ mas

**Gaia:**
- $10^9$ stars
- $\sigma = 0.003$ mas (12)
- $\sigma = 0.01$ mas (15)
- $\sigma = 0.2$ mas (20)

Hipparcos CMD, $\sigma < 5\%$
Binaries are Fundamental
Astrophysical Calibrators

- EB are efficiently found in time domain surveys
- VB – Gaia!

Complications:
- Detectability – Visual
- Detectability – Eclipsing
- Labor and Resource Intensive Followup
- Difficult to measure composite properties
- Peculiar Systems

Figure 11. Distribution of periods for all the stars identified as eclipsing binaries in the Kepler Q1 data set. The baseline was 34 days (44 with Q0). The bars are stacked by morphology types (detached, semi-detached, overcontact, ellipsoidal, and uncertain). The inset depicts the number of systems in log scale.

Prsa et al. 2011
The Binary M-R Relationship

Fig. 2 $R$ vs. $M$ for the stars in Table 2; error bars are smaller than the plotted symbols. A theoretical zero-age main sequence (ZAMS) for solar metallicity from Girardi et al. (2000) is shown by the dashed line.

Torres, Anderson & Gimenez 2009
The Fundamental Mass-Luminosity Relationship

Fig. 5 The mass-luminosity relation for the stars in Table 2. Error bars are shown, and stars classified as giants are identified by open circles. See Sect. 6 for a discussion of the effects of evolution in this diagram.
Scatter in the HR Diagram is real and tied to composition

Fig. 6 Close-up of the 1–2.5 $M_\odot$ range of the mass-luminosity relation in Fig. 5. The very significant scatter in log $L$ at each mass value is due to the combined effects of stellar evolution and abundance differences (see text). Open circles: stars classified as giants.
There are also strong M-R and M-Teff relationships.

Note: Radii exhibit evolutionary effects.
Effective Temperature

- $L = 4\pi R^2 \sigma T_{\text{eff}}^4$ defines the effective temperature
- The effective temperature scale is defined rigorously only for stars of known $R$.
- Calibrated relationships that are commonly used:
  - Photometric estimates based on colors (Wien’s law) or SED fitting; IRFM
  - Spectroscopic estimates based on stellar absorption lines (Boltzmann/Saha equations)
- Solar $T_{\text{eff}} = 5,770$ K

For normal stars $3,000$ K < $T_{\text{eff}}$ < $50,000$ K
Interferometry and Radius

With the advent of optical interferometry we can now measure direct angular diameters with uncertainties ~0.05 mas.

L + R => Teff!
The Interferometric Sample

Boyajian et al. 2013
The Temperature Paradox

Temperature is the single most important determinant of a star's visible properties.

We have numerous and powerful diagnostics testable with fundamental data.

Yet

There are significant disagreements between them that are not resolved.
Interferometry Vs. IRFM/Binaries
Interferometry Vs. Spectroscopy

Spectroscopic (SPOCS)

- Mean relative temperature change: $<\Delta T/T> = -1.7\%$
  - Standard deviation: $\sigma = 2.1\%$

- Mean relative radius change: $<\Delta R/R> = 3.4\%$
  - Standard deviation: $\sigma = 5.1\%$

- Mean relative mass change: $<\Delta M/M> = -3.9\%$
  - Standard deviation: $\sigma = 4.8\%$
Systematic Errors in Interferometry Data?

Casagrande et al. 2014 (1401.3754)
The Outer Layers of Cool Stars are Turbulent and Generate Waves

Swedish Solar Telescope
Solar-like Oscillations in Kepler

16 Cyg A
Metcalfe et al. 2012

Pure p-mode pattern
The observed MS pattern is a strong function of \( \log g \).

From Chaplin & Miglio 2013
Interiors: What Do We Learn?

\[
\frac{\Delta \nu}{\Delta \nu_\odot} = \sqrt{\frac{M/M_\odot}{(R/R_\odot)^3}}
\]

\[
\frac{\nu_{\text{max}}}{\nu_{\text{max, } \odot}} = \frac{M/M_\odot}{(R/R_\odot)^2 \sqrt{(T_{\text{eff}}/T_{\text{eff, } \odot})}}
\]

Sample power spectrum of red giant KIC4351319 from Di Mauro et al. (2011)
A Working Tool for Bulk Populations

Dwarf stars with detected sun-like oscillations from Kepler

Radius + Independent $T_{\text{eff}}$ yields distance and luminosity (Chaplin et al. 2011, 2013)
Giants and Kepler

- Giants are high-amplitude pulsators
  - Periods of days to months
- Long period is a huge advantage
  - Accessible with 30 minute cadence
  - 14,000 stars monitored, essentially all detected (Mosser et al. 2009; Hekker et al. 2010)
- Observed frequency pattern is complex!
Giant and Dwarf Frequency Patterns Compared
The Complex Giant Pattern is Explained by Mixed Modes

- Mixed modes propagate as p-modes in the convective envelope and g-modes in the deep core; especially strong impact on $l=1$
- $l=0$ modes are pure p-modes
- Seen in red giants (Bedding et al. 2010) because the p and g mode frequencies become commensurate
- Comparing the two yields distinct diagnostics of core and envelope properties
Distinct Patterns in Different Evolutionary States

Dwarf

Subgiant

RGB

RC

CM

13
The APOKASC Approach: DR10

- APOGEE sample: ~2,400 Red Giants
  - 1916 stars that pass quality control checks
- Analyze light curves, extract mean asteroseismic properties ($\Delta\nu$, $v_{\text{max}}$)
- R+M from Scaling Relations + Grid-based Modeling
A Test of Atmospheres

The difference between asteroseismic and spectroscopic log g is different for RC, RGB

Is this an atmospheres or asteroseismic systematic?
Rodrigues et al. 2014: SED Fitting and the KIC Extinction Map

Bottom Line: Inferred extinction ~0.41-0.42 KIC (also SAGA)

SFD (Maximum) Extinction Map

KIC Extinction Map
Results: Snapping Into Focus

Photometry

Spectroscopy

Asteroseismology + Spectroscopy
Mass Trends, Fixed [Fe/H]  

Metallicity Trends, Fixed Mass
Trouble In Halo-Land

Epstein et al. (2014)

Halo Star Masses From SR Are Well Above Expected Values....
Do We Need to Go Beyond Scaling Relations?

Calibrate…Correct…OR

Boutique Modeling: Reasonable Mass!

Parallax + $\Delta \nu$: Reasonable Mass!