Introduction to ASTR 565

Stellar Structure and Evolution

Jason Jackiewicz

January 23, 2024

---

1 Main goal

Order in the H-R Diagram!!
See Figure 1.

Motivation: Understanding the H-R Diagram
See Figure 2.

H-R Diagram (2)
See Figure 3.

H-R Diagram (3)
See Figure 4.

2 Structure of stars

Basic structure - highly non-linear solution
See Figure 5.

Massive-star nuclear burning
See Figure 6.

Topics: what does a star look like inside?

- Nuclear interactions
- Hydrogen burning, T dependence, neutrinos
- Equation of state (ideal gas, degenerate gas)
- Hydrostatic equilibrium

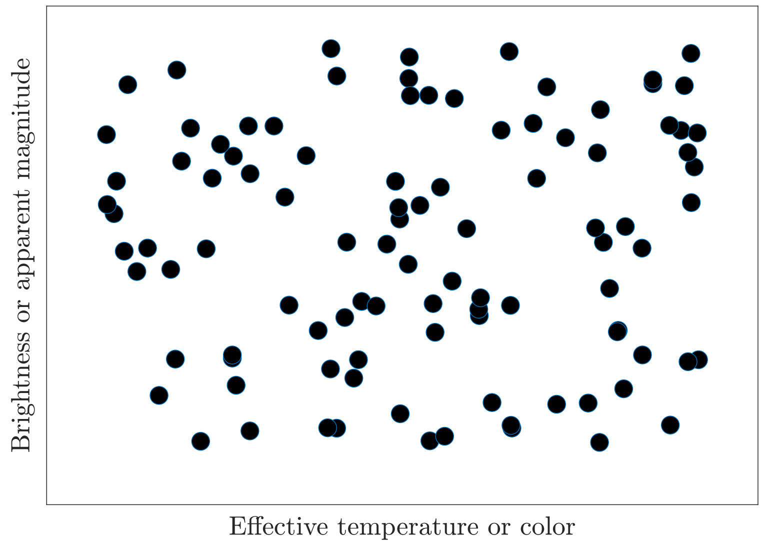

Figure 1: The H-R diagram can be a powerful tool, but not when the wrong quantities are used. What is the problem with this figure?

- Polytrope solutions to basic equations
- Transport: radiation, conduction, and convection
- Convectively stable and unstable regions
- Opacity
- MESA

What parameters are in play?

- Mass
- Composition (He + metals)
- Opacity calculations
- Mixing length of convection
- Overshoot of convection
- Chemical diffusion, radiative levitation
- Rotation (primordial, mixing, structure)
- Mass loss
- Magnetic fields (primordial vs. generated)

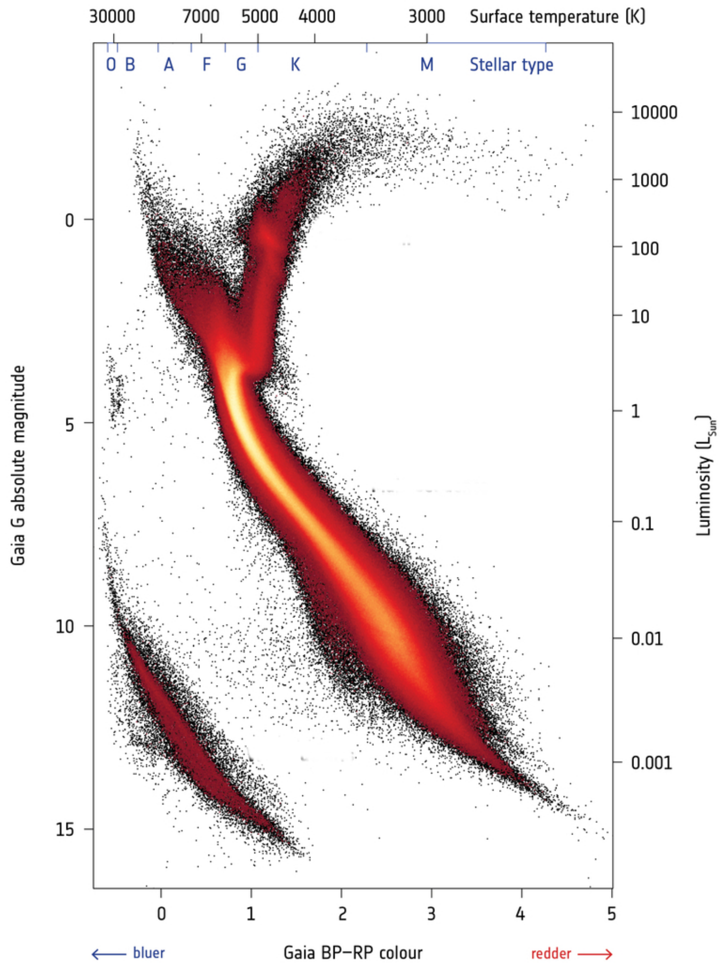

Figure 2: The color-magnitude diagram (CMD) from Gaia observations of the solar neighborhood (within 5 thousand light years). There are four million stars here. Understanding the details of this is the motivation for the course. In principle, the calculation of stellar structure models and their evolution gives the H-R diagram, in $T_{\rm eff}$ and L. Atmospheric models, coupled with bandpass information, are needed to generate a theoretical CMD where the axes become magnitudes and colors. That is the crucial step connecting theory to observations, touched on in Sec 4.

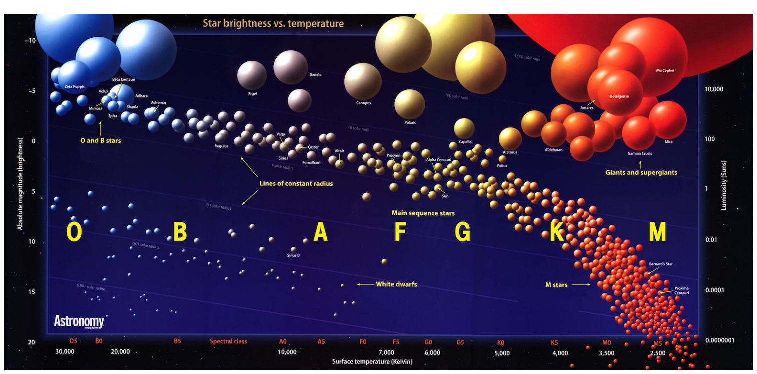

Figure 3: Another HRD with some of your favorite stars labeled. Luminosity classes are also given.

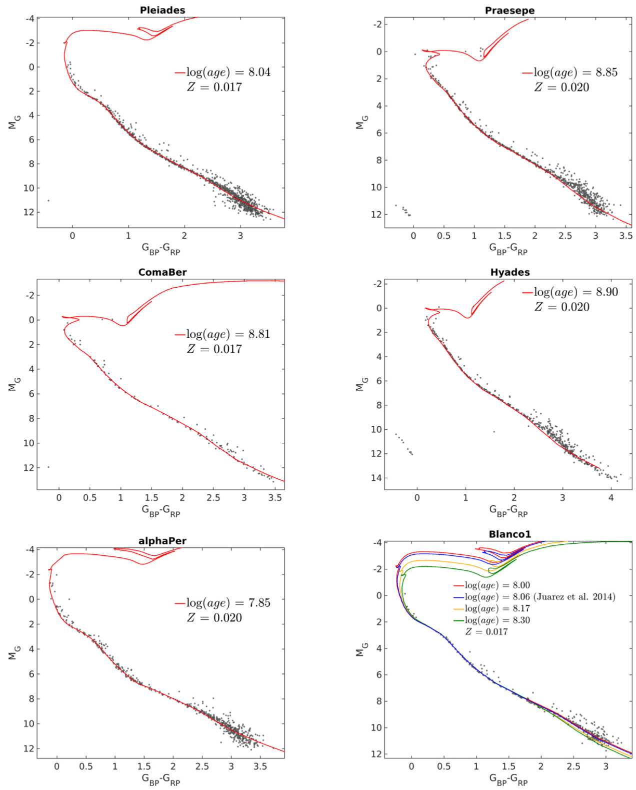

Figure 4: Several open clusters observed by Gaia in the second data release. The (PARSEC) isochrones are computed from models, and our goal is to understand what ingredients are needed in the models to match the data. From DOI 10.1051/0004-6361/201832843.

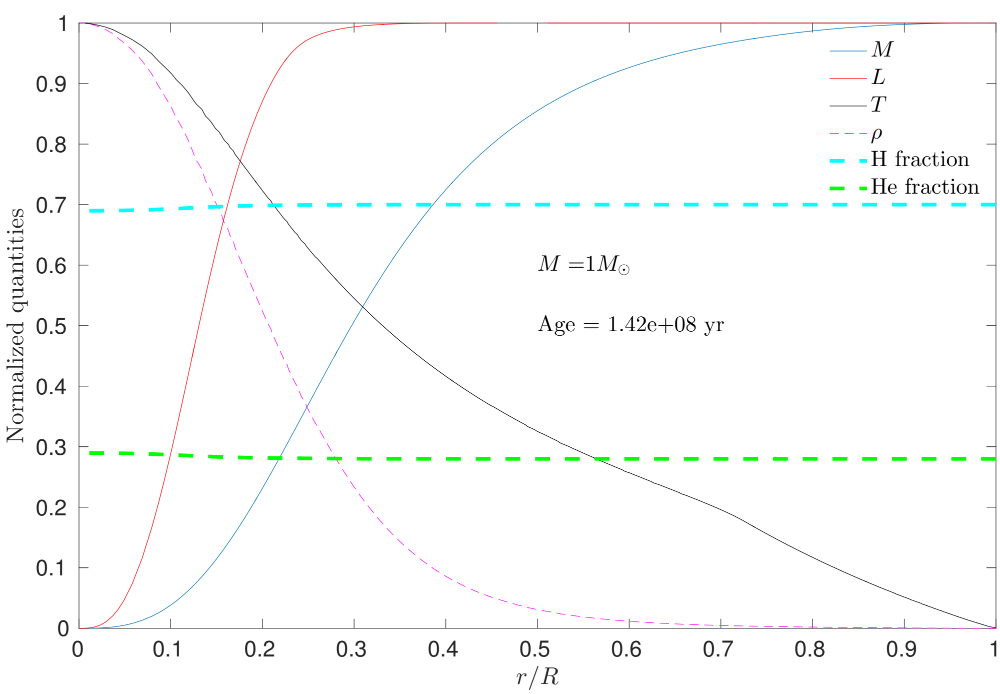

Figure 5: A few interior properties as a function of radius for a stellar model that just began nuclear fusion.

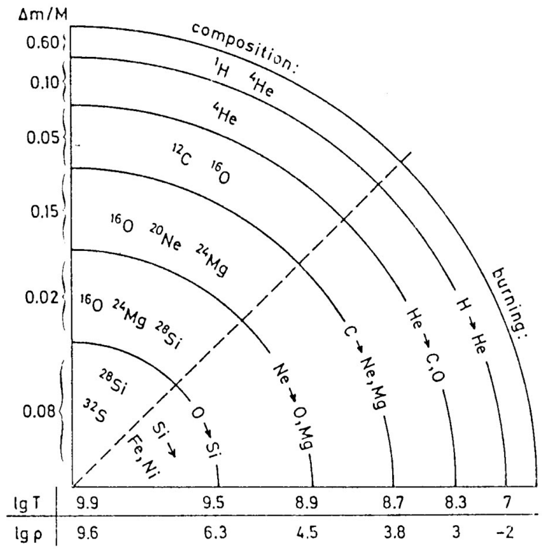

Figure 6: The interior structure of the core region of an evolved massive star. From Kippenhahn & Weigert (1990).

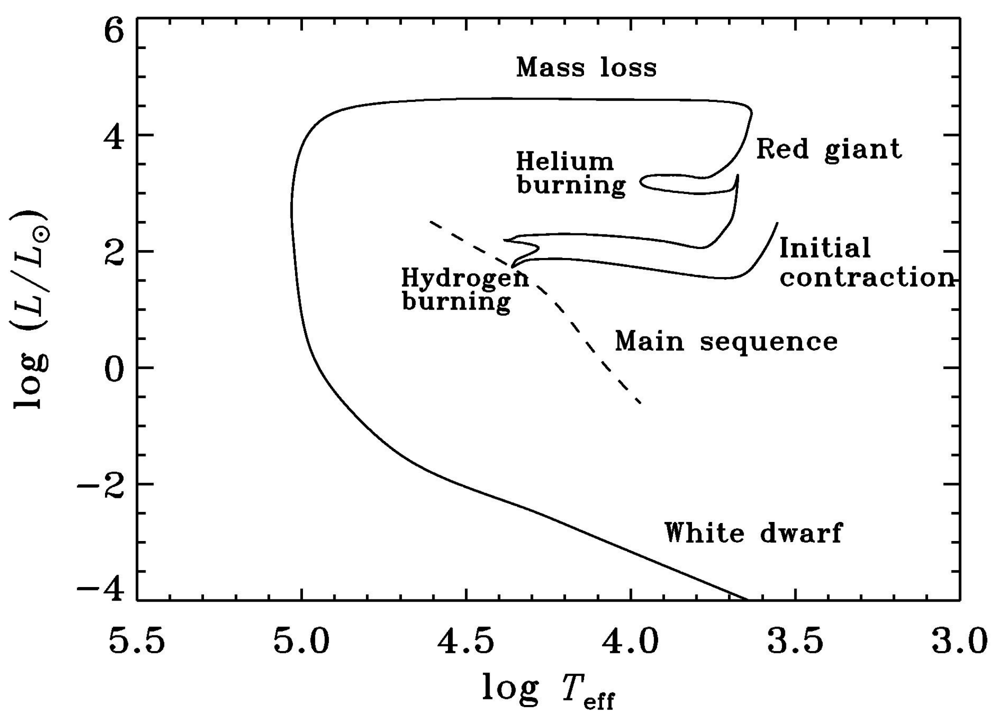

Figure 7: Evolution of a modest mass star in surface temperature and luminosity. The zero-age main sequence is the dashed line. Clearly, the surface properties of a given star must change with time, and so do the interior properties. From Christensen-Dalsgaard (2008).

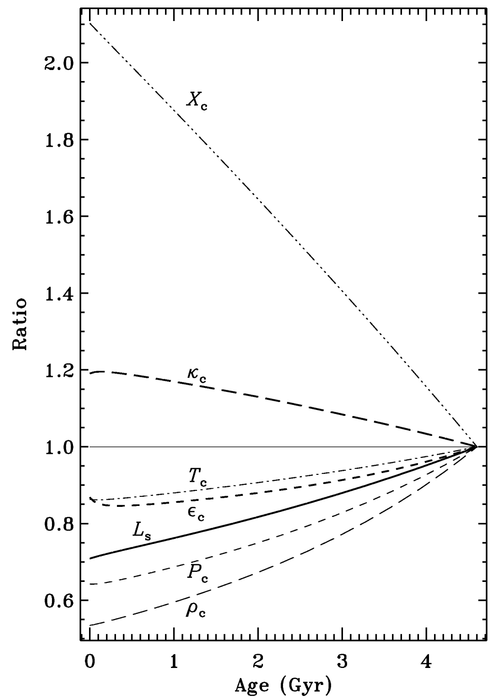

Figure 8: Evolution of the Sun's properties over time, normalized to today's values. Do these trends with time make sense? From Christensen-Dalsgaard (2008).

3 Evolution of stars

Evolution - surface and interior changes
See Figure 7.

Solar properties over time
See Figure 8.

H-R diagram and mass
See Figure 9.

H-R diagram and isochrones
See Figure 10.

Topics: what changes take place in a star over time?

- Main sequence, homology relations
- Schönberg-Chandrasekhar limit, or core mass
- Subgiant and RGB properties
- Helium burning

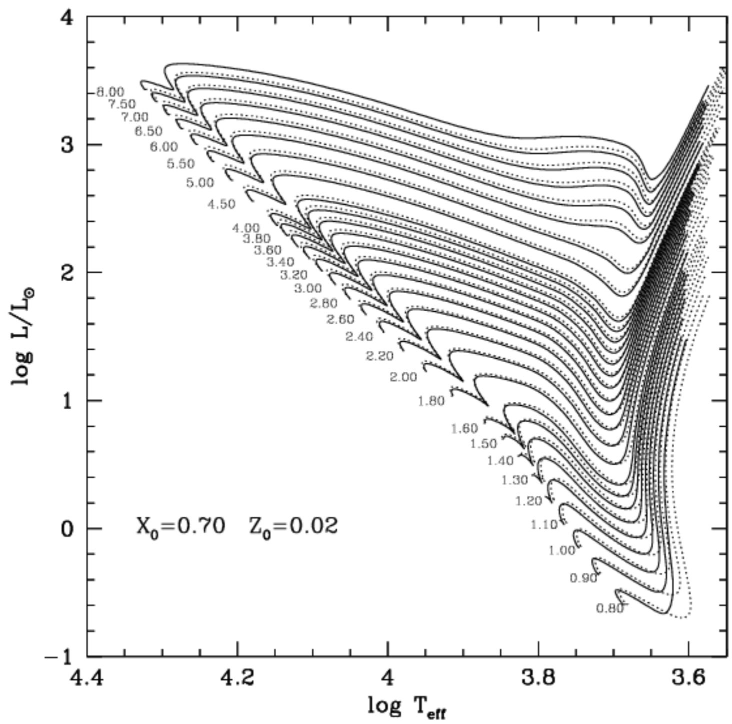

Figure 9: Theoretical models for post-main sequence evolution for many different initial masses From Montalban et al. (2008).

- Horizontal branch, thermal pulses
- Nebulae, Supernovae
- Compact objects
- Instability strip
- MESA

4 Applications to observations

Connection to observables
See Figure 11.

Populations: Open clusters $\longrightarrow$ ages
See Figure 12.

Populations: RGB luminosity bump modeled
See Figure 13.

Populations: bump measured (GC He abundance, etc.)
See Figure 14.

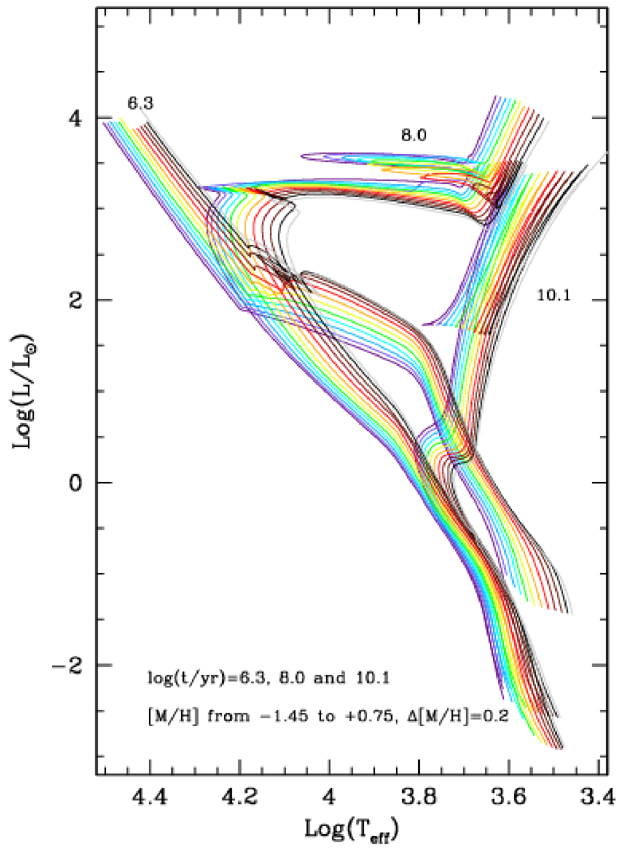

Figure 10: Theoretical isochrones at 3 fixed ages, with metallicity varying across a wide range in equal step sizes. From Bresson et al. (2012).

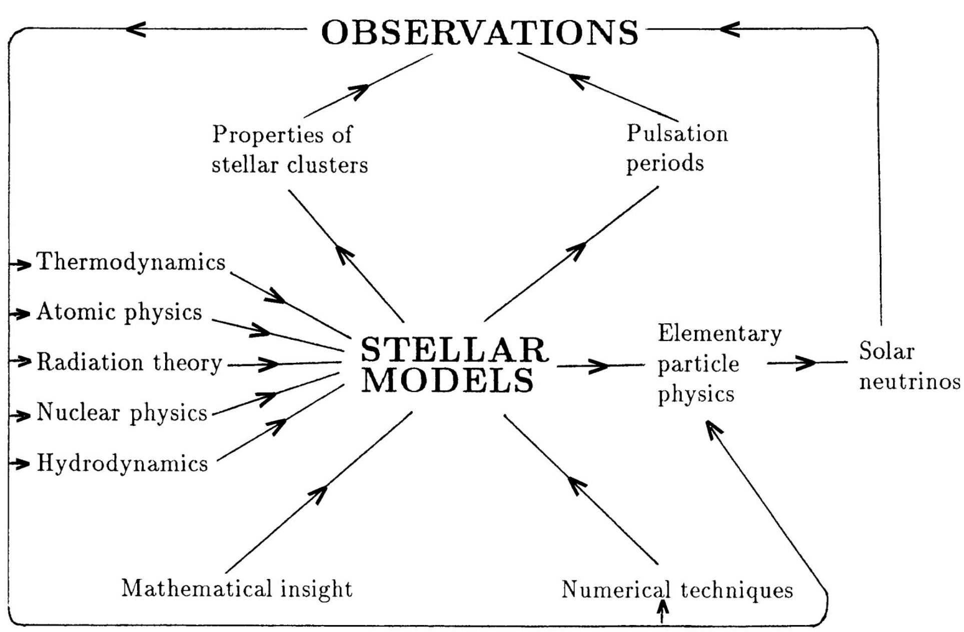

Figure 11: The relation between models and observations. Stellar models can be used to predict observations, from clusters to pulsators to neutrinos. From Christensen-Dalsgaard (2008).

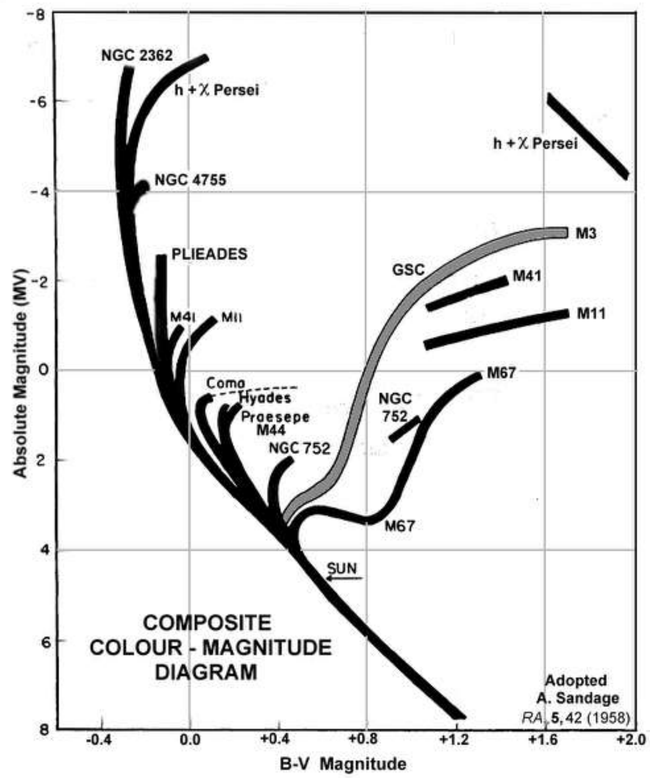

Figure 12: CMDs of mostly open clusters in the galaxy. Age is easily comparable among these clusters. Of course knowing stellar ages helps understand galaxy formation scenarios.

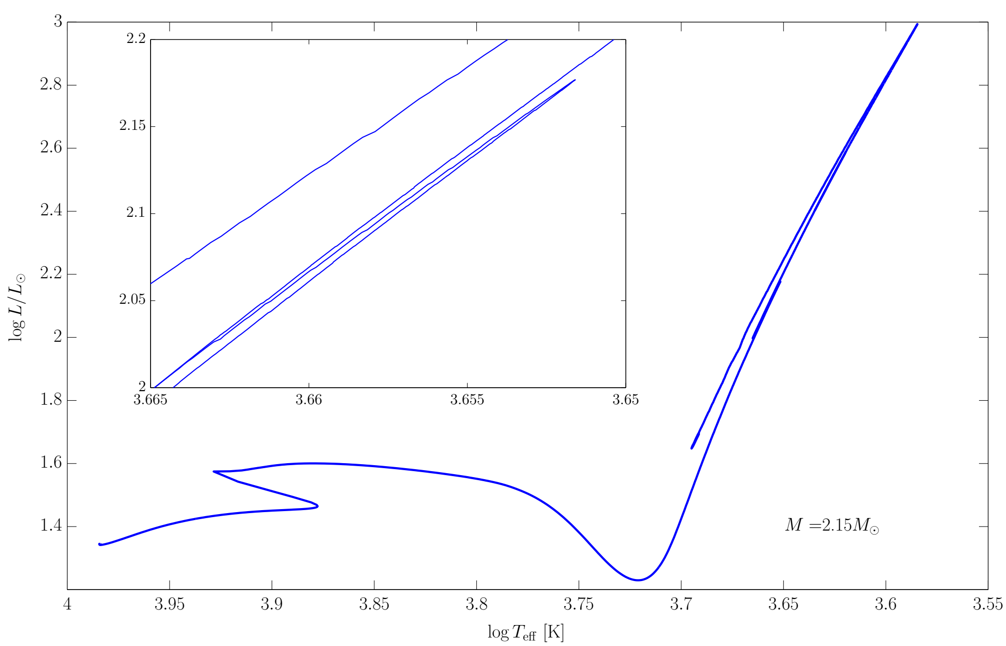

Figure 13: Stellar evolution models show a peculiar short-lived reversal on the RGB. As we'll see, the reason for this is the deeply penetrating surface convection zone and expansion of the H-burning shell.

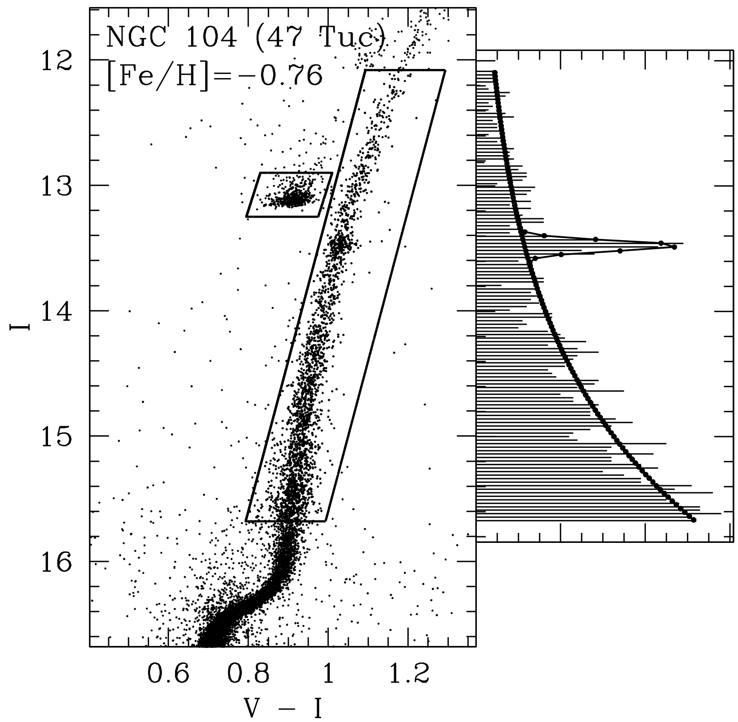

Figure 14: HST photometry of the old globular cluster 47 Tuc, showing very clearly a concentration of stars along the RGB, where the evolution stalls. As we'll see, the location of the bump depends strongly on metallicity, He content, and mass, thus can be an important tool for stellar populations. From Nataf et al. (2013).

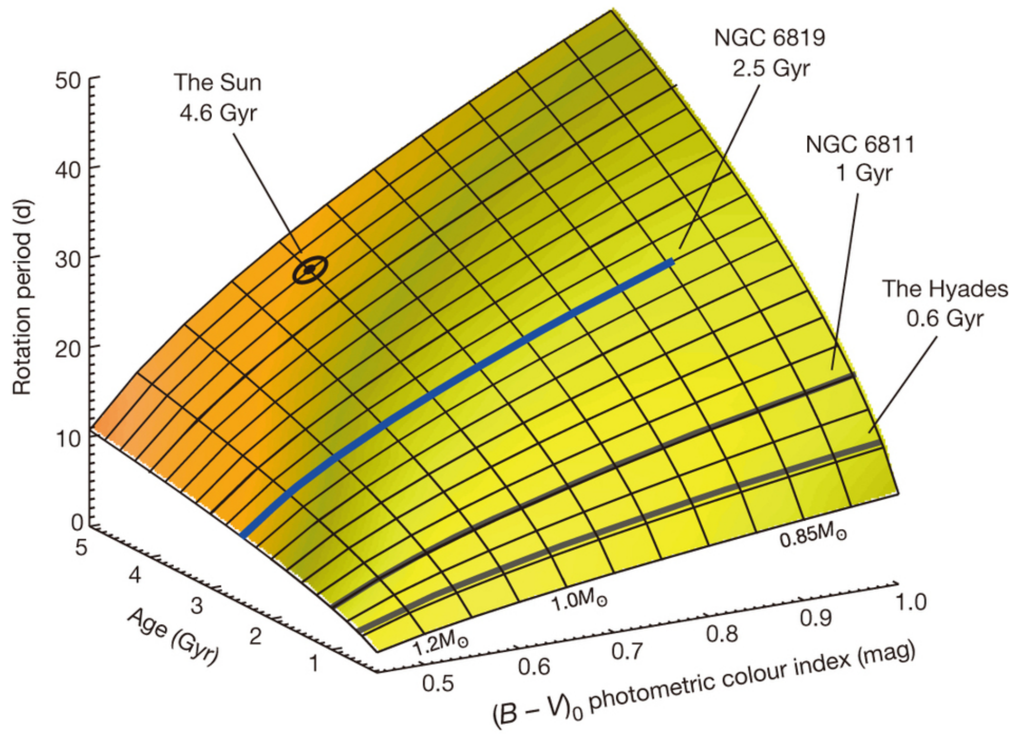

Figure 15: The hypothetical relationship between rotation period, age and color (mass) extrapolated (yellow) to greater ages from the color–period relations in young clusters using a particular $P - t$ relation, and assuming that the Sun (marked by the black solar symbol;) resides on it. Earlier ages are not useful as young cluster stars have a relatively random distribution of rotation periods. From Meibom et al. (2015).

Rotation: ages (gyrochronology)
See Figure 15.

Asteroseismology: mass and radius
See Figure 16.

$$\frac{M}{M_\odot} = \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{3/2}$$

$$\frac{R}{R_\odot} = \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right) \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{1/2}$$

- Consequence of our deep understanding of stellar structure

Asteroseismology: evolutionary state, age
See Figure 17.

Anomalies and other keys for astrophysics

- ZAHB/RGB luminosity at tip (cosmology)

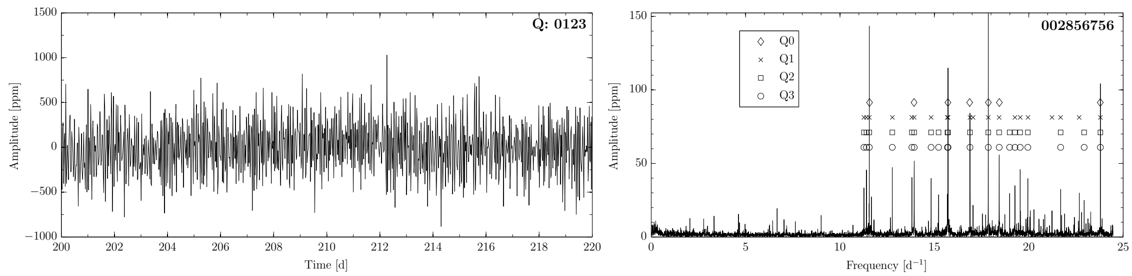

Figure 16: Light curve and power spectrum from an oscillating star. The features in the power spectrum can be used to infer mass and radius using the given equations.

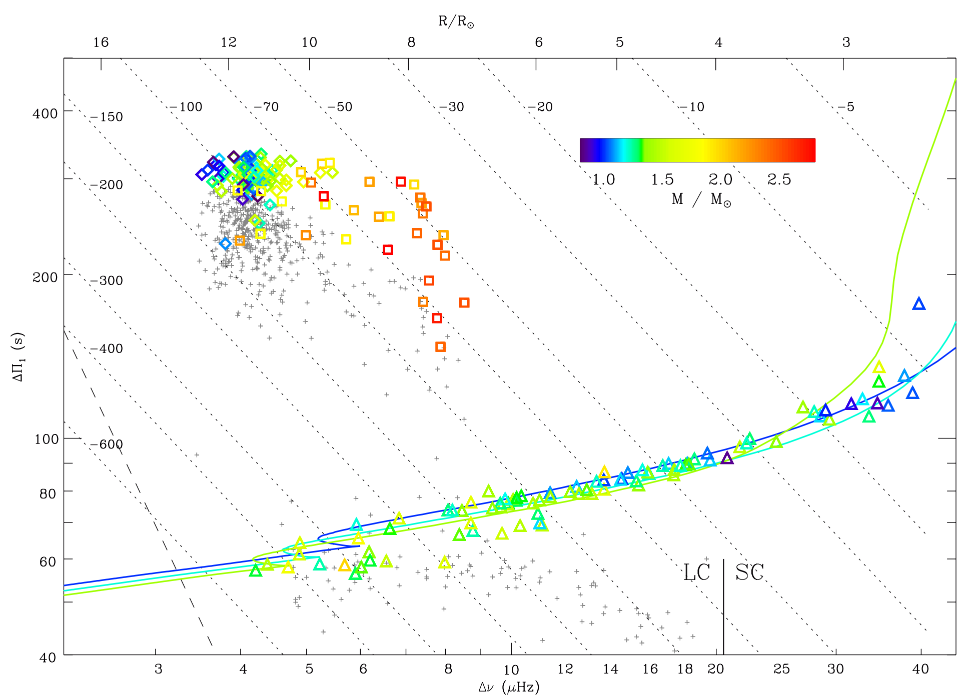

Figure 17: Mixed-mode period spacings vs. acoustic mode large frequency separation for a sample of Kepler giants and subgiants. Triangles are RGB stars, diamonds are red-clump stars, and squares are more massive red-clump stars that have not undergone a He flash. From Mosser et al. (2012).

- Cepheid pulsations (cosmology)
- Binaries (CMD, mass)
- Blue stragglers (cluster TO, mergers, mass transfer)
- Blue horizontal branch stars in GCs (mass loss, metallicity, binarity?)

5 Overview of course

Things we probably won't cover

- Star formation
- Rotation (angular momentum transport)
- Magnetic fields (dynamo)
- Mixing and diffusion
- Mass loss, stellar winds
- Binarity, mass transfer
- Pulsation driving
- Numerical techniques

Details

- Course homepage[1]
- Syllabus
- Canvas app (or using browser)
- MESA

[1] http://astronomy.nmsu.edu/jasonj/565/

Assignment

- Read the syllabus carefully
- Read the MESA overview, and see if you can get the code to run
- If you can't get things going by tonight, send me an email!
- Complete first assignment for next week, Computer Problem 0