PHYS2160 – Lecture 3 – The Milky Way (2)

Last time

- Equatorial & Galactic co-ordinate systems. Proper motions & Velocities
- Milky Way components (disk, spheroid, stellar halo)
- Differential rotation & Oort Constants
- First evidence that the Galactic rotation curve is flat in the solar neighbourhood.

And in case you hadn’t noticed “Milky Way” ≡ “Galaxy” . And as opposed to “galaxy” which just refers to any galaxy.

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Stars

A detailed exploration of the complex physics of stars is beyond the scope of this course. However its worth noting a few aspects of how stars work, because this impacts on how we interpret the workings of our Milky Way, other galaxies and the Universe in general.

Stars are spheres of gas held together by self-gravity, and balanced against collapse by pressure gradients supported by the energy generated by nuclear fusion reactions.

It is a useful approximation to consider the *interiors* and the *atmospheres* of stars separately.

– The *atmosphere* (or more specifically the *photosphere*) is the part of the star from which emerges the photons we actually see.
– The *interior* is the rest of the star.

Photons are generated in the core (by nuclear reactions) strongly interact with the matter in the interior and are absorbed and remitted repeatedly as they percolate on a random walk through progressively less dense layers – as a result they are in thermodynamic equilibrium.

Near the surface, however, the photon mean free path becomes comparable to the length scale of the atmosphere and the photons decouple, eventually escaping from the star.

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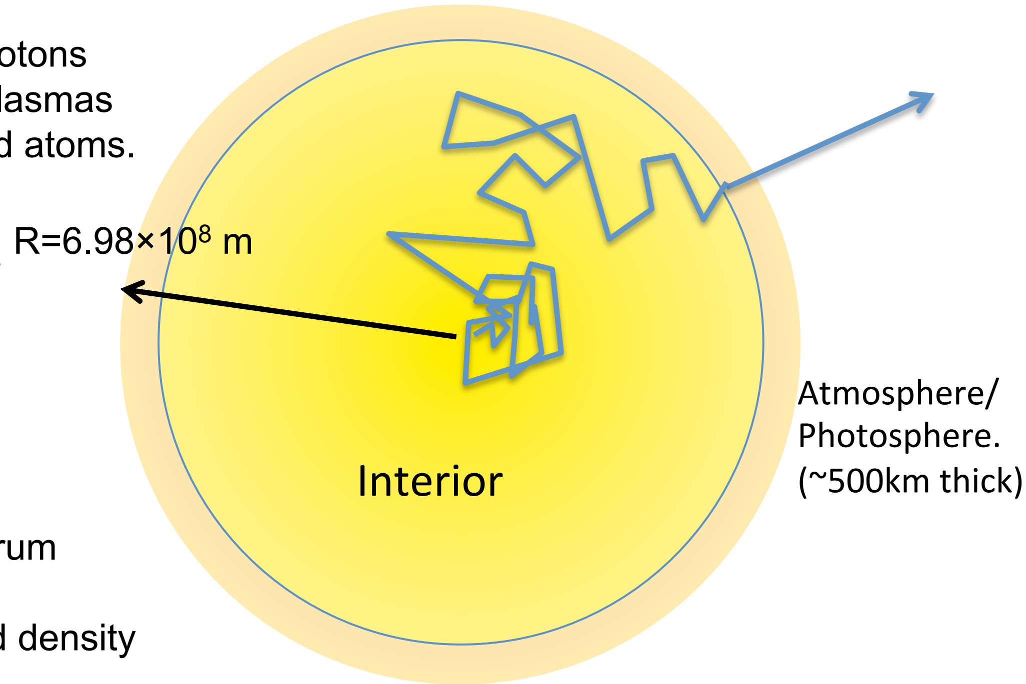
Stars

Using the Sun* as an example, $M=1.99\times10^{30}$ kg, $R=6.98\times10^{8}$ m
so mean density is just 1.4×10^{3} kg/m^3 = 1.4 g/cm^3. Central density 1.6×10^{5} kg/m^3.
Surface temperature is 5778K and central temperature is 1.57×10^{7}K.

The temperatures present at the surfaces of a star (~3000-40,000K) mean that the photons escaping the surface are passing through plasmas containing neutral, singly- or multiply-ionised atoms.

As a result the opacity of the *atmospheric* material depends strongly on wavelength. If the wavelength is the same as a strong electronic transition, the opacity will be high. At other wavelengths the opacity will be relatively low.

The result is the formation of a stellar spectrum that can be rich in features – these reflect the elemental composition, temperature and density of the atmosphere.



* http://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html

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Stars

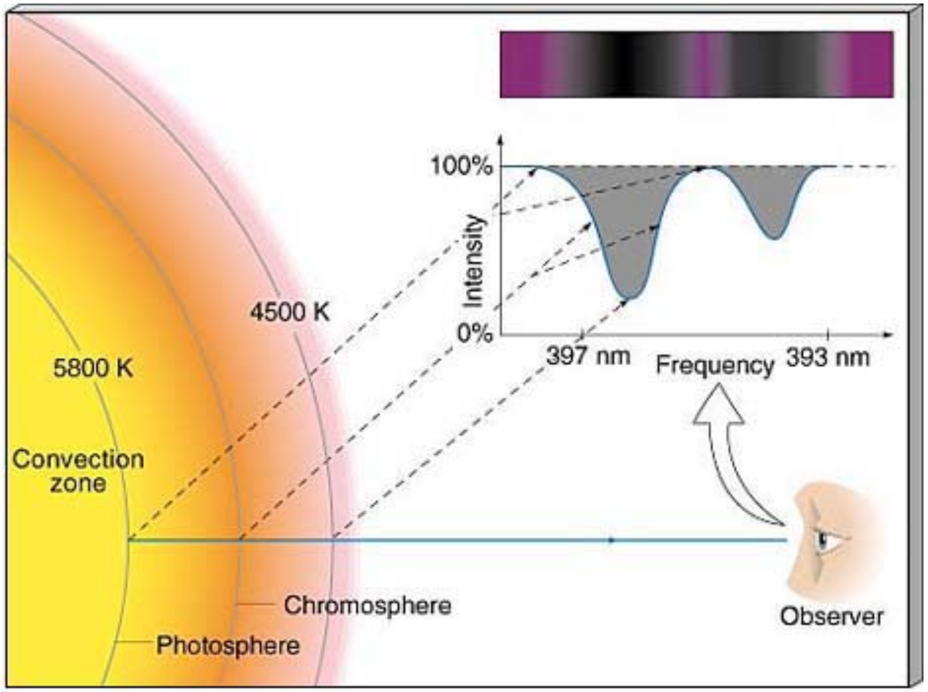
A useful way to think about this is that when we look at a star, we are "peering down into its atmosphere". How far we see will depend on the opacity at that wavelength.

If the opacity is high (for example in the core of a strong atomic transition) we won't see very far, and so will observe the outer, and cooler (and so darker) layers of the star.

If we observe away from that line, we will see to deeper layers, where the star is hotter (and so brighter).

This absorption can be quantified by the *optical depth*, τ

$$I_{obs} = I_{unabs}\, e^{-\tau}$$



Thought about in this way, we can see why stars can also be seen with spectral lines in emission – due to having tenuous outer regions (the chromosphere and corona) where there is a temperature inversion. (Strictly the "atmosphere" is the combination of the "photosphere" with these hotter layers above).

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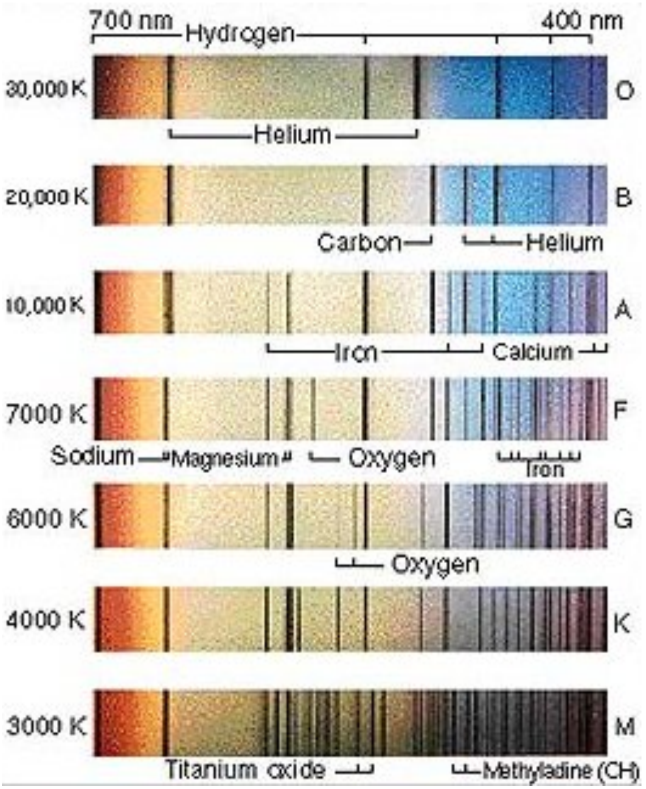
Stars

The specific atoms and ions and transitions that are prominent in the stellar spectrum will therefore depend on the combined temperature and density of the atmosphere at $\tau{\sim}1$.

This physics gives rise to the "spectral type" classification sequence given to stellar spectra. (To remember "Oh Be A Fine Girl/Guy Kiss Me")



Stars: spectral types

Spectral Type	Colour	Temperature (K) Surface / core	Spectral characteristics
M	Red	3000	Molecular lines (e.g. TiO, vanadium oxide), very strong neutral metal lines
K	Orange	4000	Strong Ca lines, strong neutral metal lines, ± TiO, extremely weak hydrogen lines
G	Yellow	6000	Ca^+ lines strong, ionised metal lines weakening, neutral metal lines weakening, CH strong, hydrogen lines very weak
F	White	8000	Ionised (e.g. Fe^+, Mg^+, Si^+) and neutral metal lines, hydrogen lines weakening
A	White/blue	10 000	Hydrogen lines strong, ionised metal lines strong, weak neutral metal lines
B	Blue/UV	25 000	Strong He lines, strong hydrogen lines, Mg^+ and Si^+ lines
O	Blue/UV	50 000	Strong He^+ lines, weak He and hydrogen Balmer lines, Si^{3+}, O^{2+}, N^{2+} and C^{2+} lines

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Stars

The physics of stellar interiors is governed by four key equations

- Hydrostatic equilibrium
- Conservation of Mass
- Radiative Transfer
- Conservation of Energy

Which form a linked set of differential equations involving density, temperature, opacity and energy generation as a function of radius. These can be solved if you know (1) how the pressure reacts to the local conditions (the "Equation of State") and (2) how the opacity does the same.

These models tell us the equilibrium configuration a star will reach as a function of its bulk properties (primarily its mass, but to a lesser degree the distribution of elemental abundances or "metallicity"). In particular models predict the luminosity (L) and radius (R) of the star.

Then you can lay a model for the same equations over the top (paying much more attention to the opacity and the radiative transfer as a function of wavelength) to create a model of the emergent spectrum of the star as a function of those bulk properties.

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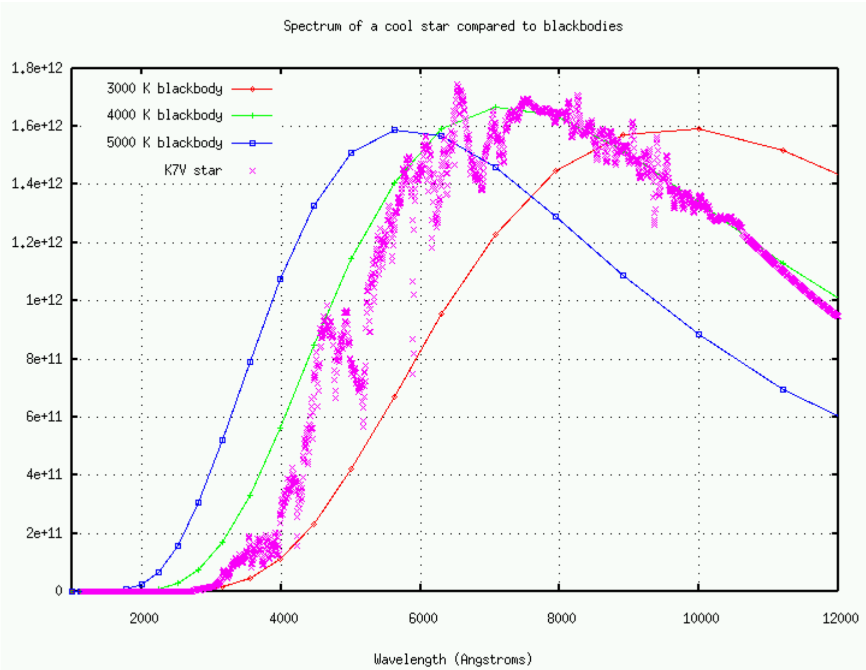
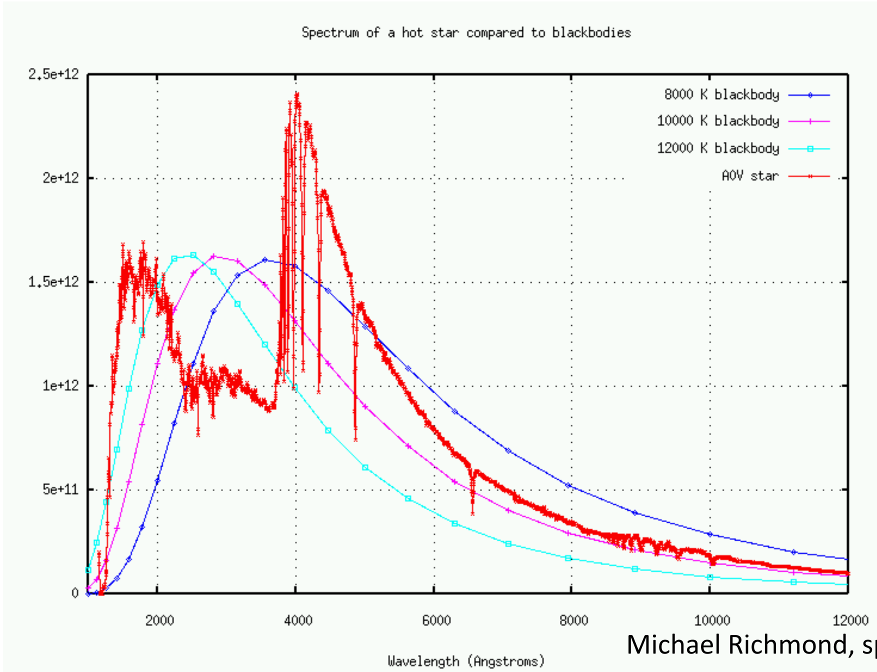
Stars

The Luminosity and Radius of an object tell us what its temperature will be. For a blackbody they actually *define* that object's temperature. A helpful quantity to bear in mind when thinking about stars of different masses, radii and luminosities is the *effective temperature* (T_{eff}) that a blackbody of the same radius (R) and luminosity (L) would have.

$L = 4\pi r^2 \ \sigma T_{eff}^4$ where σ is the Stefan-Boltzman constant.

While stellar spectra are not true blackbodies (they have all those spectral absorption lines after all), this is nonetheless a helpful approximation in many cases.





Michael Richmond, spiff.rit.edu

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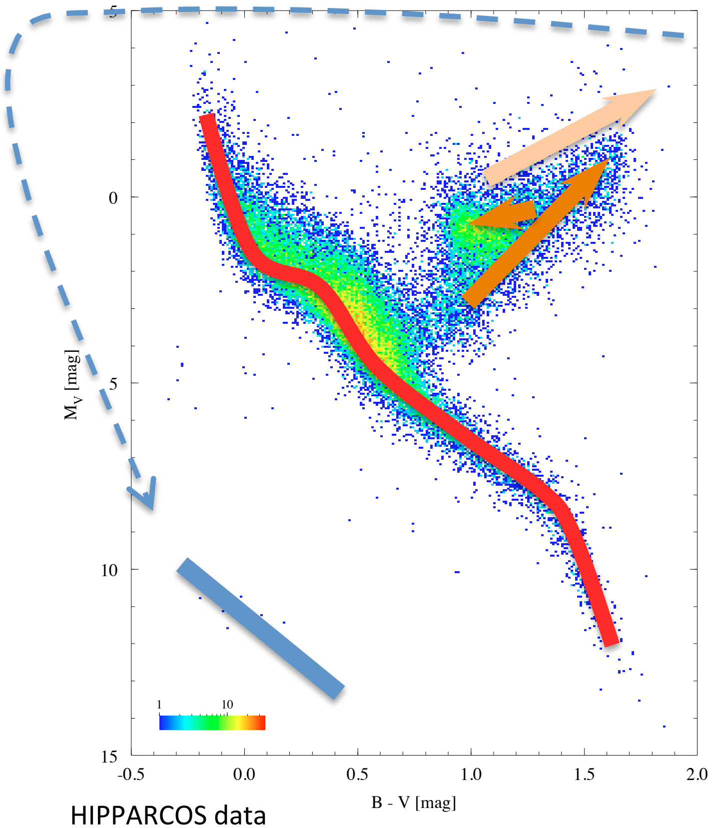
Populations of stars

The when looking at large numbers of stars, its helpful to examine them in a "Hertzsprung-Russell" diagram – a plot of stellar luminosity vs effective temperature. These can be examined either as theoretical constructs, or (more usefully) as observational diagrams of colour (as a proxy for temperature) vs absolute magnitude (as a proxy for luminosity).

The H-R diagram can often be interpreted as an evolutionary diagram for how stars evolve as they age. That is, imagine you start with a population of different masses at one time, in which case different stars will evolve to different locations in the diagram, with more massive stars evolving faster.

Obvious features are the **main sequence** (the sequence of hydrogen burning stars) and the **giant branches** (stars burning H in a shell about their core, burning He in their core, burning He in a shell).

Less obvious are the **white dwarfs** (degenerate remains of highly evolved stars) and the **subdwarfs** (very metal poor stars).



HIPPARCOS data
www.rssd.esa.int/index.php?project=HIPPARCOS&page=HR_dia

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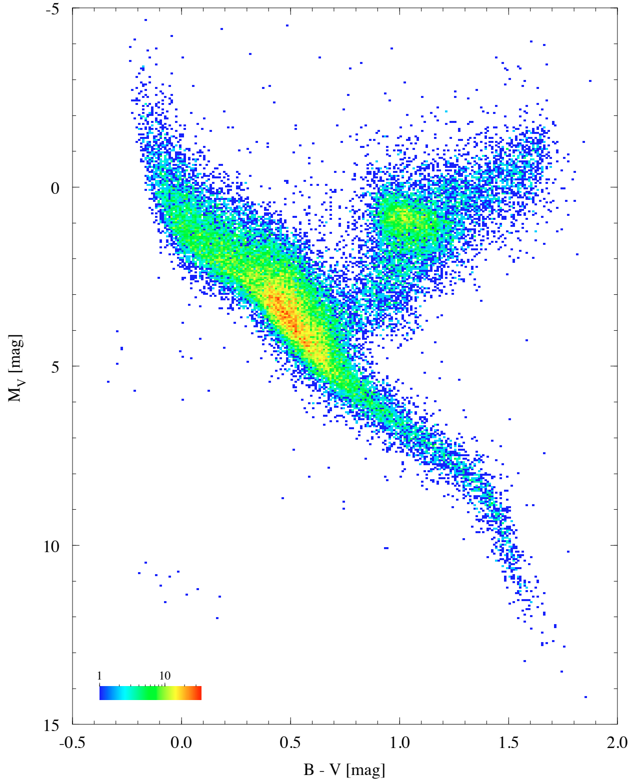
Populations of stars

An observed H-R diagram

A theorist's H-R diagram



HIPPARCOS data for stars
in the Solar Neighbourhood

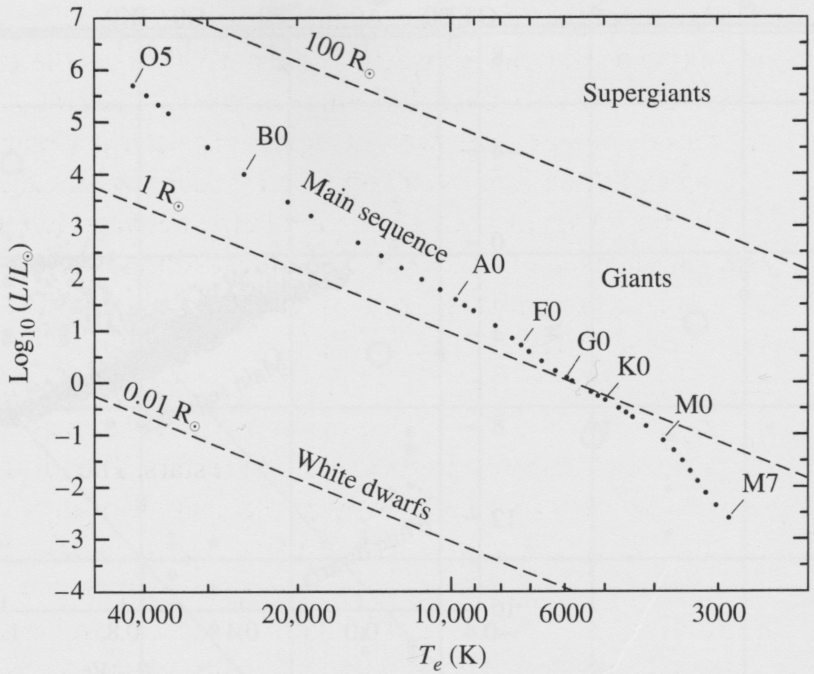


FIGURE 6.23 The theorist's Hertzsprung–Russell diagram. The dashed lines indicate li
stant radius.

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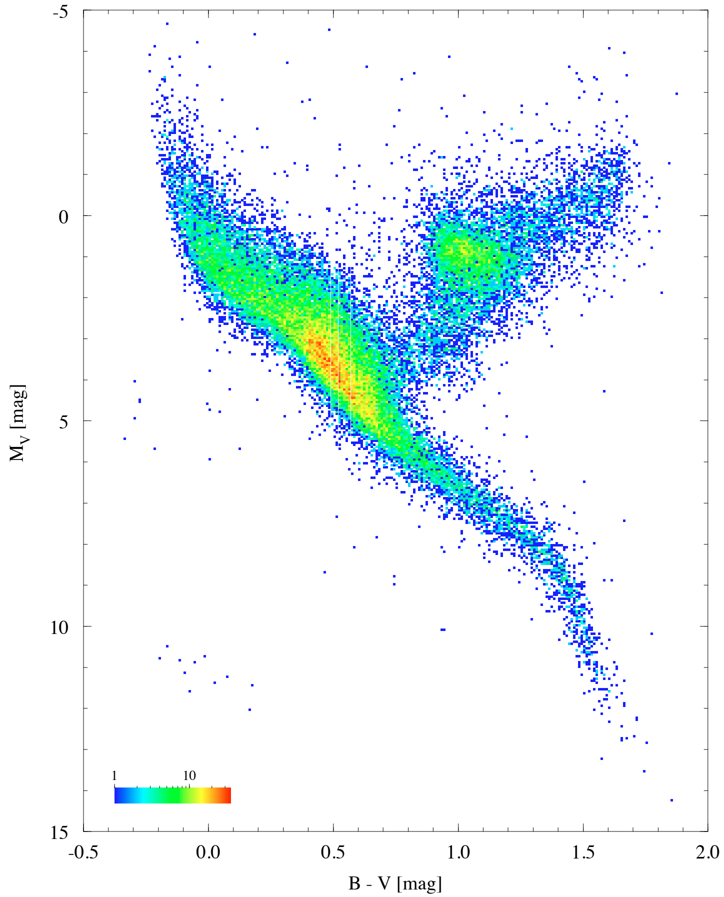
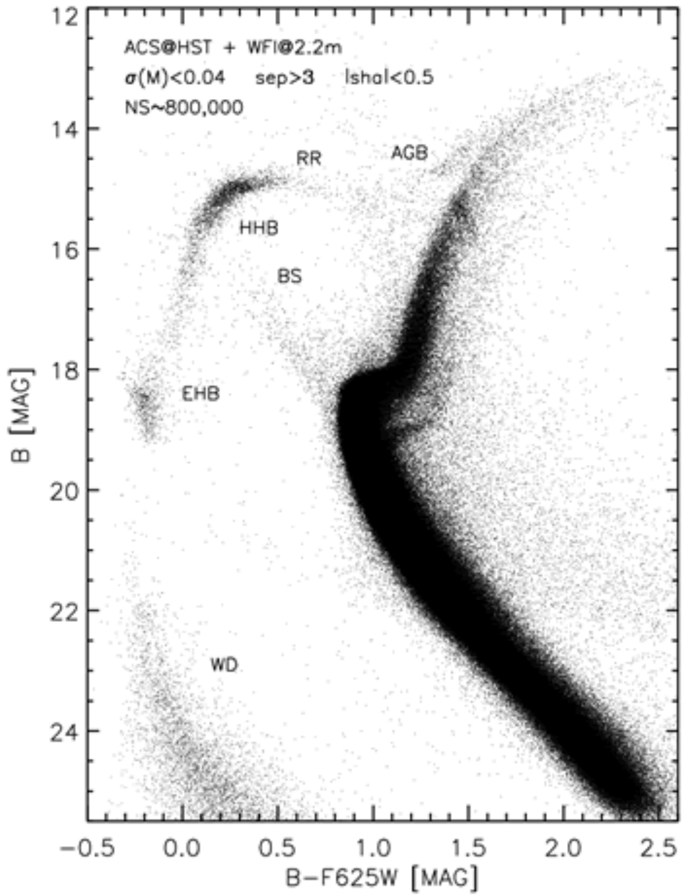
Populations of stars

Mixed populations of stars



A single cluster of stars (Omega Cen) all at the same distance and similar age.



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Stars

Some useful scaling relations for stars on the main sequence ....

$R \sim M^{0.8}$ for $M < 1.0M_{\odot}$;
$M^{0.57}$ for $M > 1.0M_{\odot}$;

$L \sim M^{2.3}$ for $M < 0.4M_{\odot}$;
M^{4} for $0.4\,M_{\odot} < M < 2.0M_{\odot}$;
$M^{3.5}$ for $2\,M_{\odot} < M < 20M_{\odot}$

Main Sequence Lifetime ~ 10Gyr $(M/M_{\odot})^{-2.5}$

So, at masses below about $0.3M_{\odot}$, stars will stably sit on the main sequence for 200Gyr (more than 10 times current age of the Universe).

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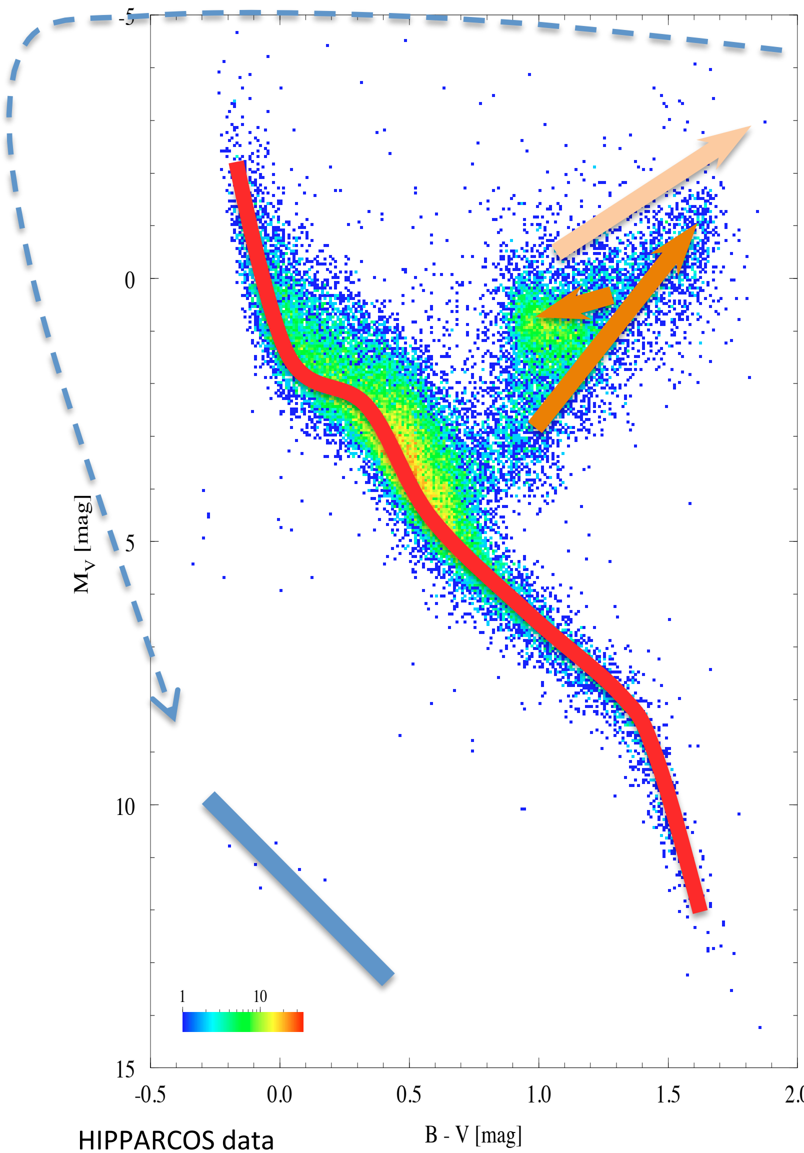
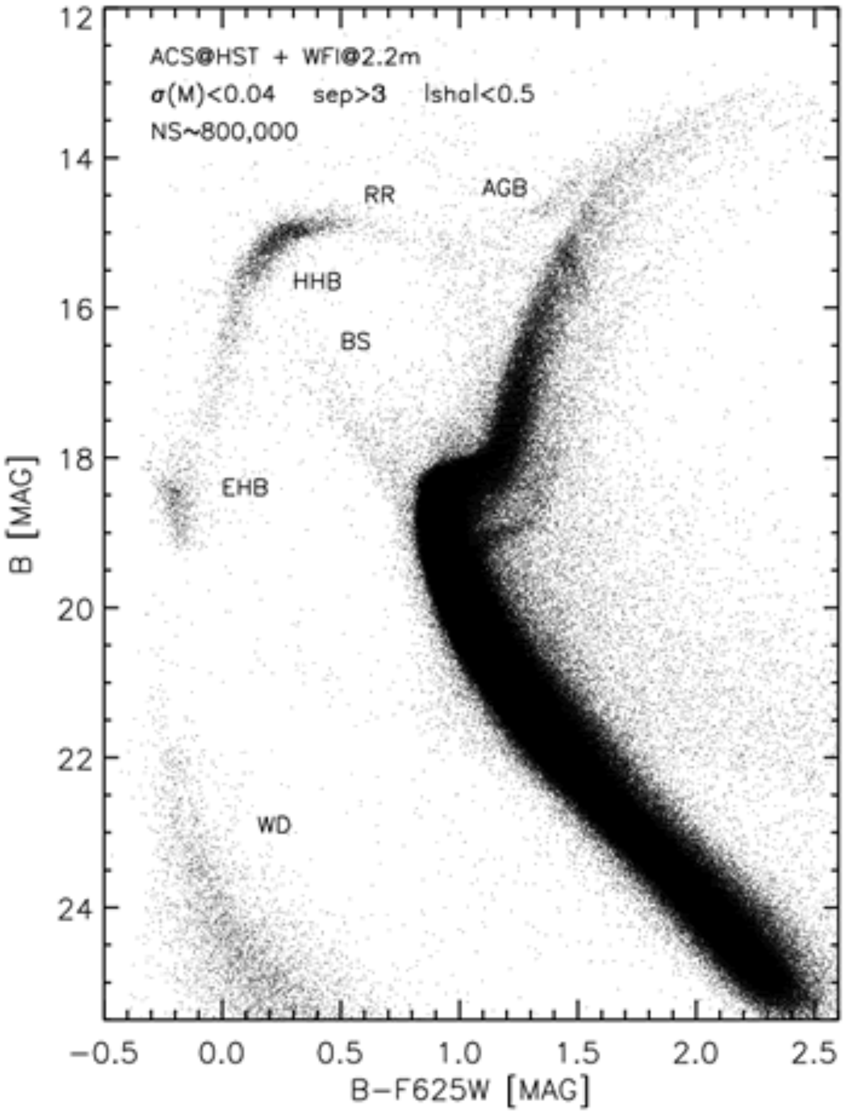
Stars

At masses above 8$M_\odot$, the stellar core collapses in free-fall after Fe burning exhausted (because its core mass exceeds the Chandreskar limit of 1.4$M_\odot$). That collapse is eventually stopped by neutron degeneracy and a neutron star forms. The resulting 'bounce' releases a shockwave of neutrinos which deposits so much energy into the remaining envelope that it is detonated, returning vast amounts of processed stellar material to the Interstellar Medium (ISM). This is called a "Type II Supernova" (or SN - plural Sne). *How long does it take before a 10$M_\odot$ does that?*

At masses in between, the stellar core exhausts its H and contracts. It becomes hotter causing the outer shells to puff up and expand – the star expands and becomes more luminous but cooler as it ascends the "Giant Branch". Eventually the core contracts enough to start He burning and the star moves sideways onto the "Horizontal Branch". Eventually He in the core is exhausted, and the core contracts again – He burning starts in a shell (with some H burning in a shell outside that) and the star ascends the "Asymptotic Giant Branch". The burning in these shells is unstable and this instability causes the star to pulse. These slow pulsations (together with the exhaustion of H and He supplies in the core) eventually cause star to shed its envelope back to the interstellar medium, while the core collapses into a compact (and very hot) "white dwarf". This is the ***other*** way in which stellar material is returned to the ISM



HIPPARCOS data
www.rssd.esa.int/index.php?project=HIPPARCOS&page=HR_dia



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More on Metallicities

You'll recall we said last time that metallicities are measured as the numerical abundance of atoms of an element relative to hydrogen, and then measured as this ratio relative to that in the Sun.

$$[Fe/H] = \log[\ n(Fe_{\star})/n(H_{\star})\ \ /\ n(Fe_{\odot})/n(H_{\odot})\ \ ]$$

so that a star with [Fe/H]=4 has 1/10,000th the metallicity of the Sun.

One can also use a mass fraction, which simply compares the total mass of all elements other than H and He, with that total mass in the Sun. In this parameterisation X is the total mass fraction in H, and Y the total mass fraction in He. For the Sun we have …

$$X_{\odot} = 0.73,\ Y_{\odot} = 0.25,\ Z_{\odot} = 0.02$$

These two forms of expressing metallicity can be related if we assume there is a fixed relationship between the abundance of Fe and the total metallic content (M) of a star via a constant of proportionality (i.e. [M/H] = A [Fe/H]) in which case it can be shown that

$$\log[\ (Z/X)\ /\ (Z_{\odot}/X_{\odot})] = A\ [Fe/H]$$

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Galactic Stellar Populations

Pop I: When astronomers first began looking more closely at the structure of the Milky Way, they first noticed the stars of Disk. These are far and away the most common stars near the Sun, and so these got the (somewhat boring) name “Population I”. These Pop I stars

- Had a vertical scale height in the disk of around 330pc, and appeared to rotate as a disk
- Had spectra revealing similar metallicities to the Sun

Pop II: The stars in globular clusters, and the local stars of the halo population (revealed as “high velocity stars”) were seen to have different properties, and became known as Pop II stars.

- They appeared as sub-dwarfs in H-R diagrams (cf. two pages back)
- When spectra were taken they appeared to be lower in metallicity
- And of course the local examples tended to have very different kinematics to the disk

These facets come together in a consistent picture if you think of the Pop II stars as being a population formed earlier in the Galaxy’s history, when the average metallicity in the interstellar medium (ISM) from which stars form, was much lower. And Pop I stars have been formed from material enriched by subsequent generations of stars. It also suggests an evolutionary sequence from an “old” spherical geometry for the ISM to a “current” disk-like geometry. The dividing line between Pop I and Pop II is often drawn at $Z=0.01$ (i.e. less than 1% of the heavy element abundance of the Sun).

Pop III: this evolutionary sequence suggests that there must have been a “first” Pop III burst of stars that were formed when there were no elements heavier than Boron in the Universe. No example has ever been found. The most metal poor star found so far has [Fe/H]<-7 (see Keller et al. ref in last lecture)

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Measuring Metallicities

Spectra allow one to measure the strength of the metal lines (for example data for F stars from the SEGUE survey – www.sdss3.org/surveys/segue2.php)

Note that while the key CaI line at 3933A gets weaker at lower metallicity, so does the overall level of the "noisy" opacities covering the whole spectrum.

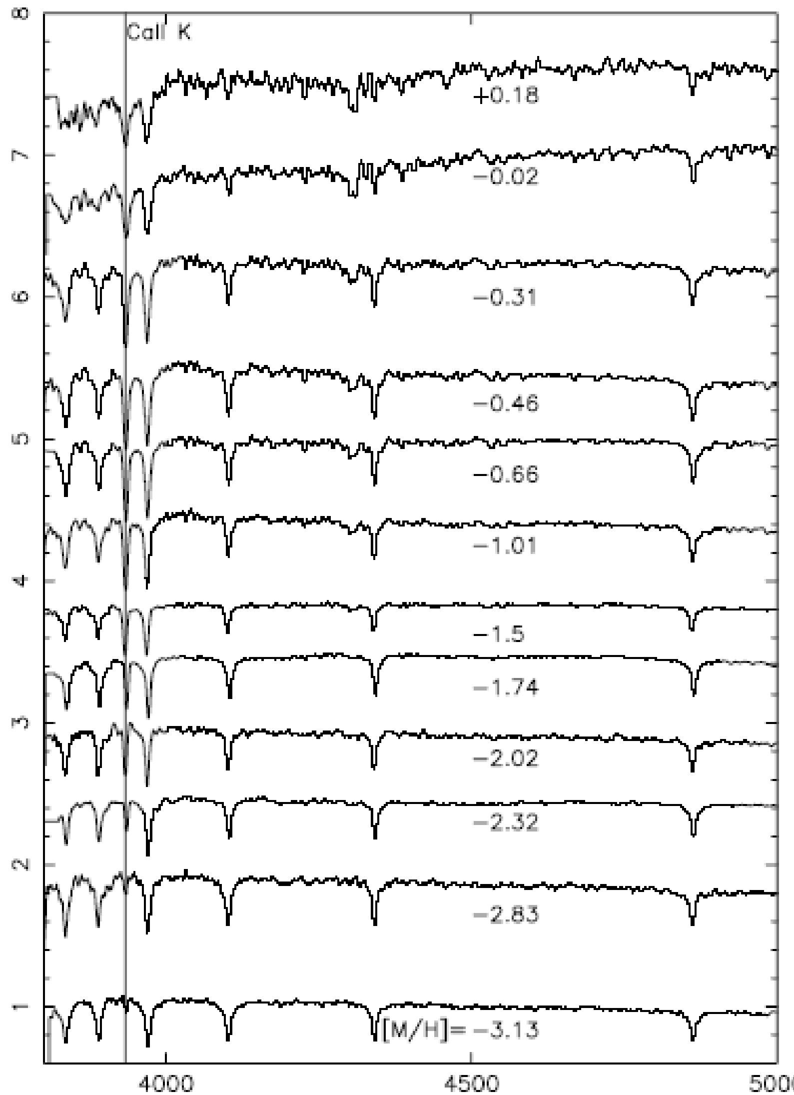

Figure 7. F star metal sequence—a set of SEGUE F stars, selected to show the range of metallicities sampled by the F subdwarf, F/G, spectrophotometric standard and reddening standard categories. All 13 stars have similar effective temperatures, near 6500 K, but the strength of the Ca K line at λ3933 indicates metallicities ranging from less than 0.001–1.5 times Solar.

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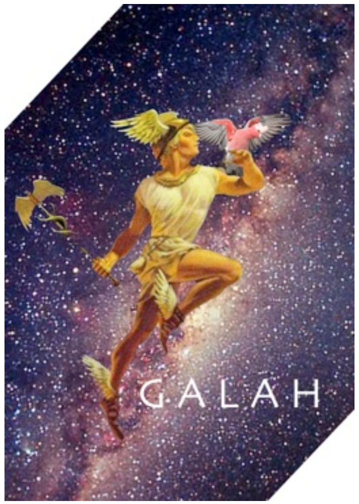
Measuring Metallicities

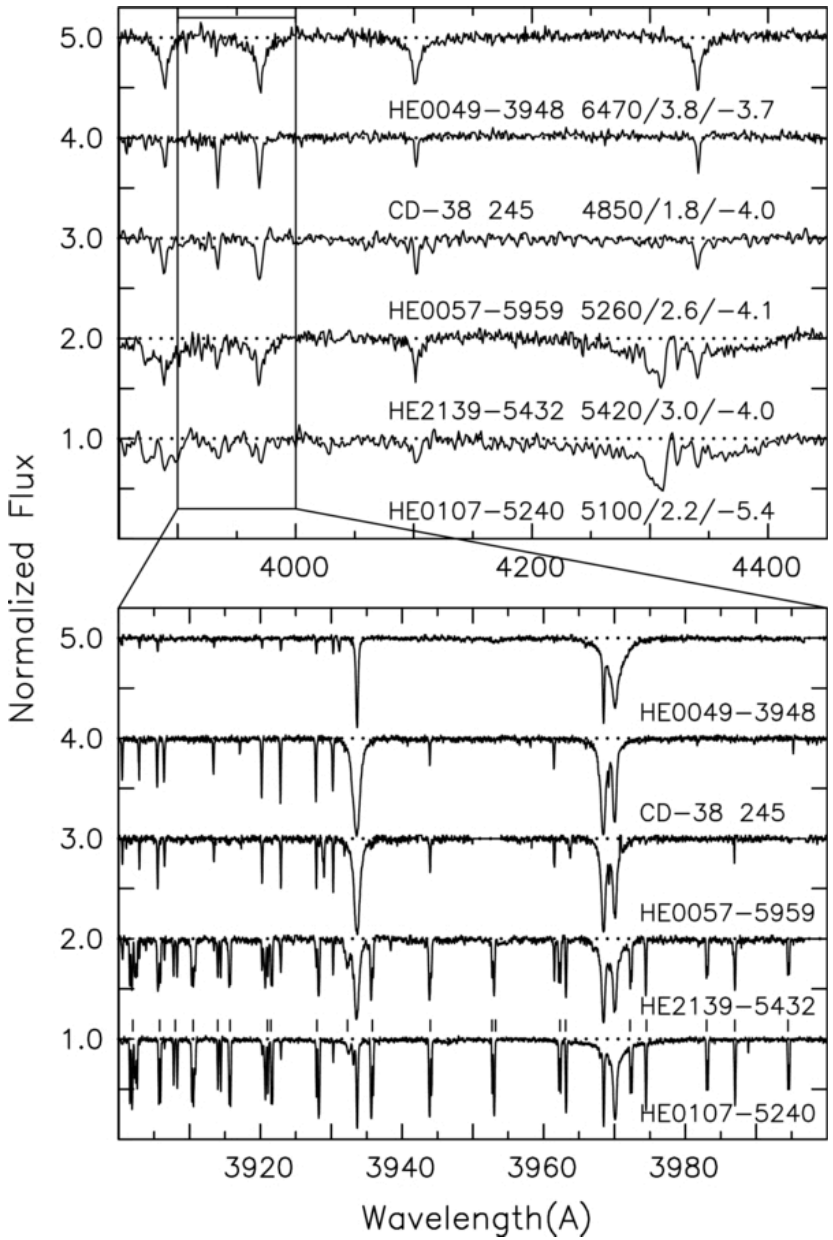
To get a more detailed answer, you have to do some detailed modelling of the stars' properties – Temperature, Gravity ($\log(g)=\log(GM/r^2)$) and [Fe/H]

This sort of data is used to probe the properties of the Population II stars (e.g. to the right is from Norris et al. 2013) – as well as the detailed properties of the Pop I system of the Galaxy.

A major survey to do the latter has just started here in Australia. GALAH will eventually probe the detailed properties of a million Southern stars.



http://www.mso.anu.edu.au/galah/home.html



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  - GALAH Survey Website http://www.mso.anu.edu.au/galah/home.html
  - SEQUE Survey Website http://www.sdss3.org/surveys/segue2.php
- Bibliography
  - Shu, F. The Physical Universe, Chapter 11
  - Zeilick & Gregory Ch 15

Useful constants, units, and formulae:

Gravitational constant	G	=	6.67	×	10^{-11}	N m^2 kg^{-2}
Speed of light	c	=	3.00	×	10^{8}	m s^{-1}
Planck constant	h	=	6.626	×	10^{-34}	J s
Boltzmann constant	k	=	1.38	×	10^{-23}	J K^{-1}
Stefan-Boltzmann constant	σ	=	5.67	×	10^{-8}	W m^{-2} K^{-4}
Mass of the hydrogen atom	m_H	=	1.67	×	10^{-27}	kg

Solar mass	$M_\odot$	=	1.99	×	10^{30}	kg
Solar radius	$R_\odot$	=	6.96	×	10^{8}	m
Earth mass	$M_\oplus$	=	5.98	×	10^{24}	kg
Equatorial radius of Earth	$R_\oplus$	=	6.378	×	10^{6}	m
Mass of moon	M_{moon}	=	7.3	×	10^{22}	kg
Astronomical unit	AU	=	1.496	×	10^{11}	m
Parsec	pc	=	3.086	×	10^{16}	m
Hubble's constant	H_0	=	70			km s^{-1} Mpc^{-1}

Distance modulus	$m - M$	=	$5\log d - 5$ (d in pc)
Apparent magnitude	$m_2 - m_1$	=	$2.5\log\frac{f_1}{f_2}$
For small recession velocities	v/c	=	$\Delta\lambda/\lambda$
Definition of redshift	$(1+z)$	=	$\lambda_{obs}/\lambda_{rest}$
Energy and frequency	E	=	$h\nu$
Frequency and wavelength	c	=	$\nu\lambda$