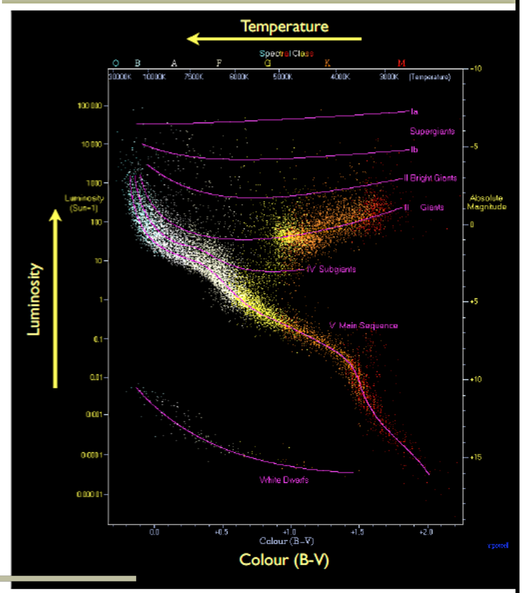
Stellar Populations of Galaxies- **2** Lectures

parts of sec 2.2 and 6.3 in S&G; not really covered well
Parts of this are covered in Carroll and Ostlie in 3 different chapters)

Top level summary

- stars with $M<0.9M_{\odot}$ have MS lifetimes $>t_{Hubble}$
- $M>10M_{\odot}$ are short-lived:$<10^8$years $\sim 1t_{orbit}$
- Only massive stars are hot enough to produce HI–ionizing radiation
- massive stars dominate the luminosity of a young SSP (simple stellar population)



HERTZSPRUNG-RUSSELL DIAGRAM

Plots luminosity of stars, versus their temperature.

Stars populate distinct regions of this plane, corresponding to particular evolutionary phases.

H-R(CMD) diagram of region near sun
H-R is theoretical
CMD is in observed units (e.g. colors)

HST Image of M31

Assumptions

- I assume that you all have
  - understood the magnitude system (ch 1 pg 21-24 of S&G) – see homework
  - the black body law (not in text, but in Astro 120)
  - coordinate systems (RA and Dec) and galactic coordinates (l,b)
  - a little bit about astronomical spectra (lots of jargon)

Why are **We** Studying Stars???

- The UV-near IR band is one of the prime regions for studying galaxies and most of the light in that band comes from stars.
- The stellar populations of galaxies hold vital clues to their formation histories
  - Stellar spectra contain information about
    - age of system
    - metallicity and abundance patterns (origin of elements)
    - star formation rate history (conversion of gas into stars)
    - dynamics of the system (ability to measure formation processes and dark matter)
- Understanding stellar spectra allows measurement of dust and dust distribution
- One needs to understand stellar spectrum to obtain information about the Initial Mass Function of stars.

Stars
S&G Chap 1.1 and 2.2 page 67-89

- Directly produce most of the visible+UV light in galaxies and (indirectly) the infrared light
- Responsible for producing all the elements heavier than boron
- Inject energy into the interstellar medium (winds and supernova)
- Tracers of the dynamics of galaxies (rotation, spiral arms etc)

- Have a wide range of masses, luminosity, chemical composition and ages.
  - MW has ~10^{11} stars.
  - Distributed as a luminosity function (#/unit luminosity/volume)
  - Distributed as a mass function (#/unit mass/volume)
- Are dynamic entities – born, age and die

(see Bender lecture in web page additional material)

Galactic Evolution

- Stars of different masses have vastly different main-sequence lifetimes
  - massive stars have main-sequence lifetimes much shorter than the age of the Universe
- Thus when we observe a galaxy today we are observing the light from the stars that have evolved to the present time.

  - Main-sequence stars with $M_s \sim M_\odot$ observed today include all stars of such masses that have formed during the past ~10^{10} yr, While the main-sequence stars with $M_s \sim 10M_\odot$ observed today are formed only during the past 10^7 yr.

- Thus, the stellar population observed from a galaxy depends strongly on its star-formation history.

Why are Stars Interesting- Rev 2

- Stellar data allow
  - high precision abundances for multiple elements in stars across the Galaxy, and the distributions of these chemical properties
  - kinematical data constrain dynamical models for the disk, bulge, bar and halo (where and how much matter is there)
  - explore the history of Galaxies by inferring the properties of stars as a function of age
  - From "The Apache Point Observatory Galactic Evolution Experiment (Apogee):Majewski et al 2015

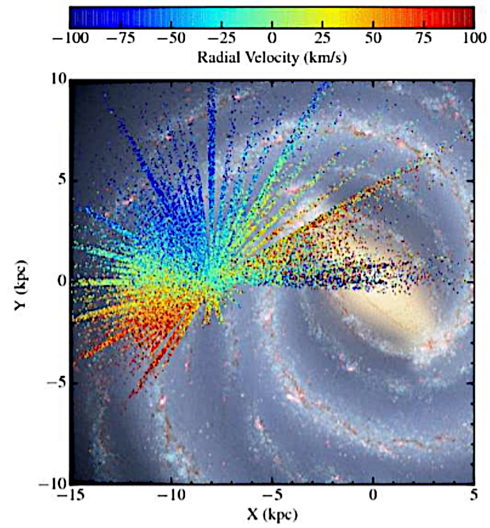


FIG. 24.— Star-by-star APOGEE heliocentric velocities as a function of Galactic X-Y position and projected on an artist's conception image of the Milky Way. The points represent main APOGE

Velocity field of stars in MW

Why are we Studying Stars???

– To quote from Conroy et al 2013

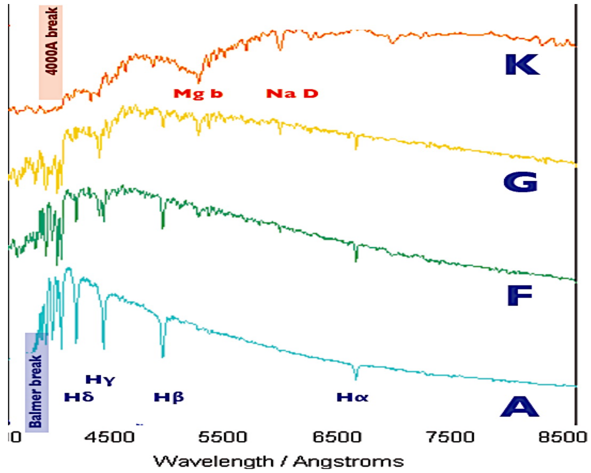
From an empirical point of view, the formation and evolution of galaxies can be probed via two general techniques.

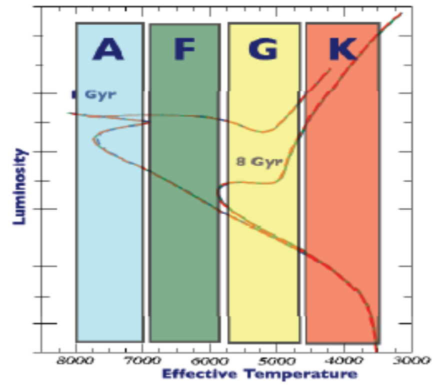
1) look back studies where one observes, statistically, the progenitors of present day galaxies at progressively higher redshifts -e.g. observing high redshift galaxies

2) studying the present day properties of galaxies, including their stellar populations, structure, and kinematics, in order to learn about their past evolution.

Spectra of Individual Stars

- Stellar spectra (spectral type (OBAFGKM)_
- effective temperature T_{eff}
- chemical (surface) abundance
  - [Fe/H]+much more e.g [α/Fe]
    - absorption line strengths in stellar spectra depend on T_{eff} and[Fe/H]
    - (see http://miles.iac.es/)
- Luminosity class- (giant/ dwarf)
- Stellar properties determined by ***mass***, chemical composition, age and spin



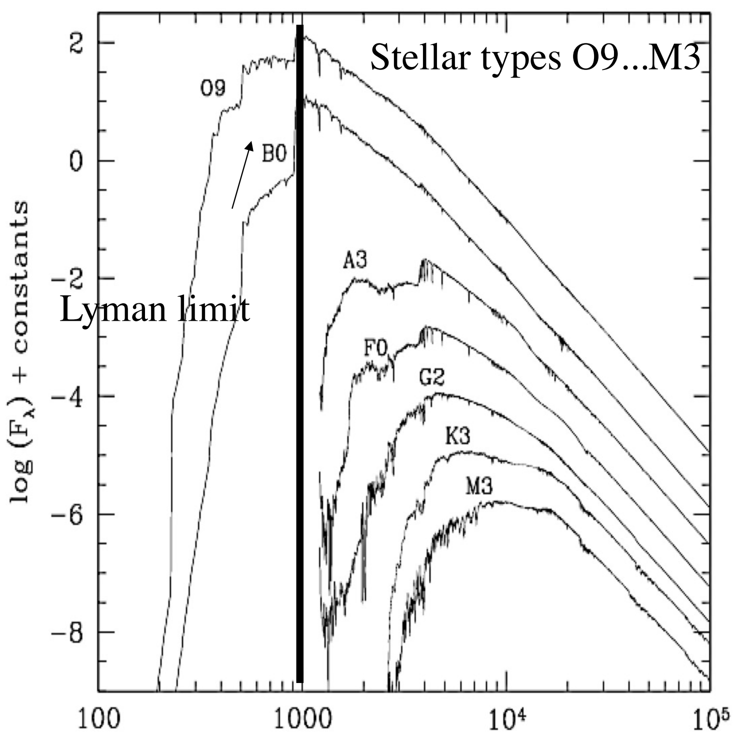


Luminosity

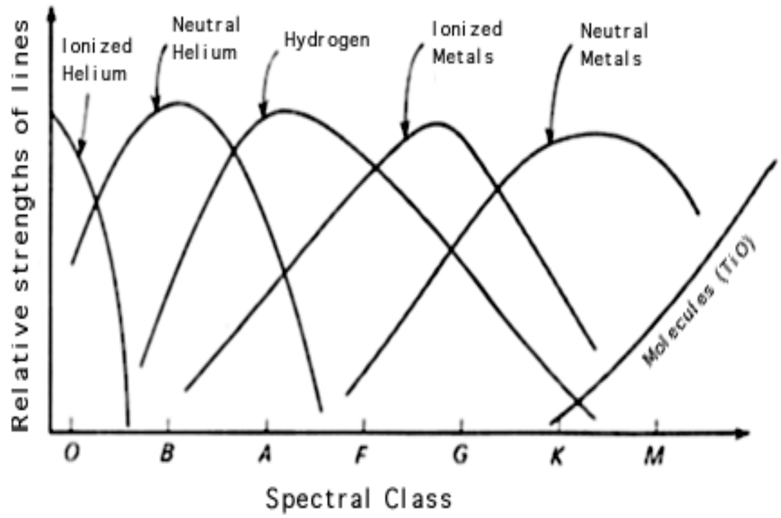
H.Rix

Stellar Spectra by Types

- 0.01-10μ micron spectra of main sequence stars
  - Notice the presence of 'unique' spectral signatures and the vast difference in the UV flux of the stars
  - Lyman limit- below this wavelength the ISM is optically thick-spectra are 'cut-off' from distant objects; photons below the Lyman limit ionize hydrogen



Basic Physics of Stellar Classes



- The spectra of stars from each class is dominated by different physical processes in the stars atmosphere-but there is strong overlap between classes

Again- horrible nomenclature eg. GOV, Wolf-Rayet, giants, dwarfs etc etc tables 1.4-1.6 in S+G
Huge (~ 10^9)range in luminosities (table 1.4)

Mass and age are the prime determinant of stars properties

Physical Origin of Range of Stellar Parameters

- For stars above $100M_{\odot}$ the outer layers are not in stable equilibrium, and the star will begin to shed its mass. Very few stars with masses above $100M_{\odot}$ are known to exist,
- a mass $>0.1M_{\odot}$ is required to produce core temperatures and densities sufficient to provide a significant amount of energy from nuclear processes.
  - range of stellar masses spans a factor of 10^3 in mass.
- Parameters
  - sizes range from $10^{-3}R_{\odot}<R<10^3R_{\odot}$; on the main sequence.
- On main sequence,
  - observed mass-radius relation $M \sim R^{4/3}$ (range of 200 in size)
  - luminosity $10^{-4}L_{\odot}<L<10^6L_{\odot}$ (10^{10} in L)

- For M<2 $M_{\odot}$ stars 'burn' via the p-p chain; the main sequence lifetime of a low mass star consists of a steady energy output from hydrogen burning in an environment of steadily increasing helium.

The 0.08$M_\odot$ limit is set by the stellar core not being hot enough to ignite hydrogen stably.

Objects with masses slightly below this

limit are called brown dwarfs, and are "star-like" in the sense that nuclear burning of deuterium occurs in their core. Below a mass of 0.015M☉ (roughly 16 times the mass of Jupiter) deuterium burning cannot occur

- Thus there is a natural lower limit to what constitutes a star. (Massey and Meyer)
- Its not clear what the mass of the most massive stars are (~150-325$M_\odot$)

More Details

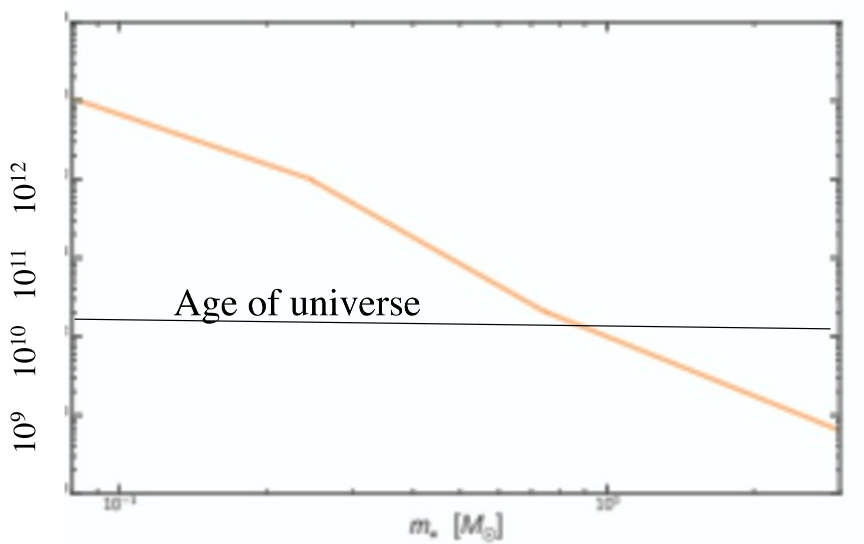
- spectra of individual stars reveals - detailed metallicity, gravity, rotation rate
- BUT for composite stellar systems in real galaxies such info much harder to obtain this information due to
  - velocity of stars broadens features
  - composite spectra are not unique
  - *Integrating (averaging) destroys information*
- For young populations (<300 Myrs)
  – massive, young MS stars dominates integrated $L_{bolometric}$
- For old populations (>2Gyrs)

– red giants (moderate mass, wide range of ages) dominate integrated $L_{bolometric}$

$L_{bolometric}$ is the total luminosity, as opposed to the luminosity in some band

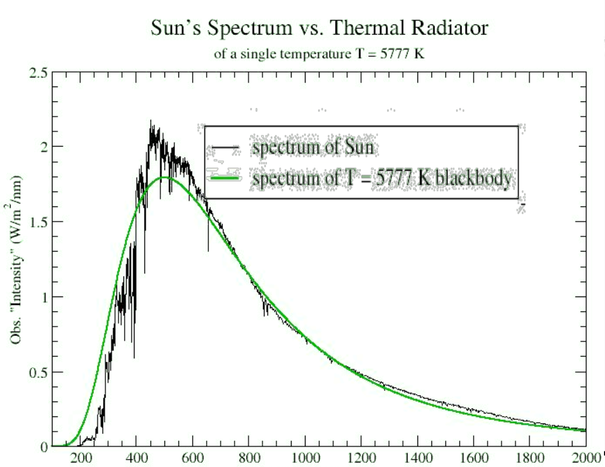
Stellar Lifetimes

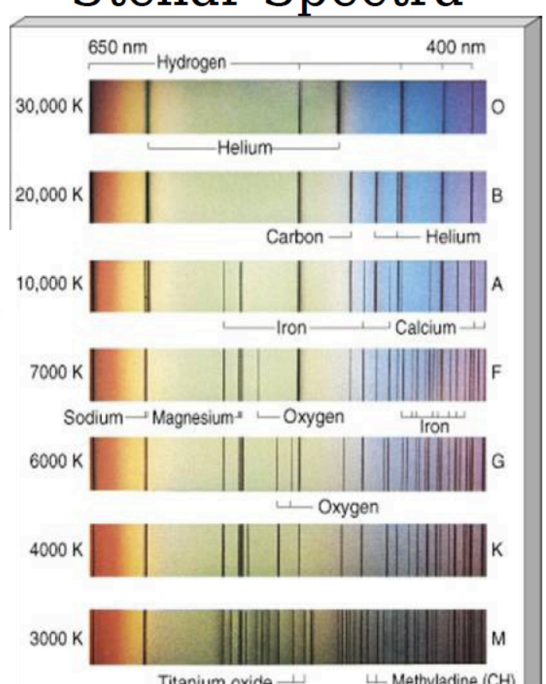
- $t_\ell \sim 1.0 \times 10^{10} (M_\star/M_\odot)^{-2.5}$ yrs $\quad 0.75M_\odot < M_\star < 3M_\odot$
- $t_\ell \sim 7.6 \times 10^{9} (M_\star/M_\odot)^{-3.5} \quad 0.25M_\odot < M_\star < 0.75M_\odot$
- $t_\ell \sim 5.3 \times 10^{10} (M_\star/M_\odot)^{-2.1} \quad 0.08M_\odot < M_\star < .25M_\odot$



Stellar Spectra

- To zeroth order stellar spectra can be approximated as *black bodies* of the appropriate temperature. − If true, comparison of flux in 2 well separated bands (e.g 'color') can determine the temperature





http://homepages.wmich.edu/~korista/sun-images/solar_specbb.jpg

discovery of quantum levels

Luminosity, Size, Temperature

- Black body
  - $B(T) =[2hc^2/\lambda^5]*[1/\exp(hc/k_B T) - 1]$
- The maximum energy is emitted at a wavelength defined by Wien's Displacement law:
  - $\lambda_{max} =(3 \times 10^7 A) (T/k_B)^{-1}$
- stars of different type have different **effective temperatures** T_{eff}
- related to luminosity L and radius R of the star:

  $L = 4R^2T^4_{eff}$

Bender et al

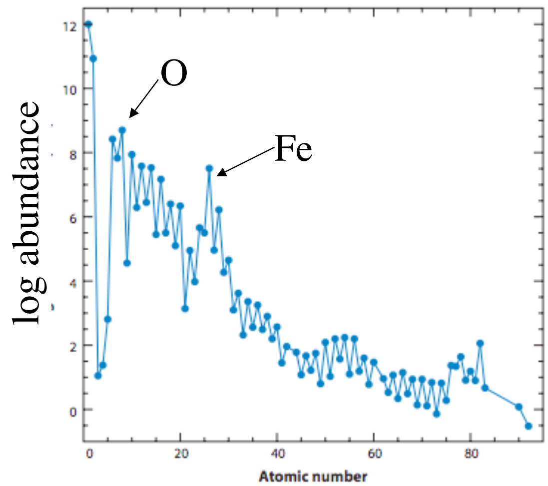
Simplest Physics of Stellar Spectra

- "hot" opaque bodies emits a continuous spectra.
- "hot" low density gas emits a sequence of emission lines. - a neon sign.

- "cold" low density gas, placed in front of a hot opaque body, produces a continuous spectrum with dark lines on top (absorption lines). - light from the sun.
- Every element (Hydrogen, Oxygen, Nitrogen etc.) produces
  - a unique set of emission and absorption lines
    - which contains information on the ionization state of the element, its velocity and elemental abundance

Chemical Composition of Stars

- Frequently normalize the chemical composition of an astrophysical system to the sun- ; total abundance of metals by mass (Z) in sun is ~0.013
- There are 2 types of variation:
  - total abundance of 'metals' (elements heavier than He)
  - relative abundance of elements
- to zeroth order (more later) there are 4 sources of metals
  - BBN-H,He Li, Be
  - Type I SN -Fe, Ni etc
  - Type II SN - O, Ne, etc
  - Other (stellar winds, planetary nebulae etc) - N, C - still to be understood .



Atomic Number

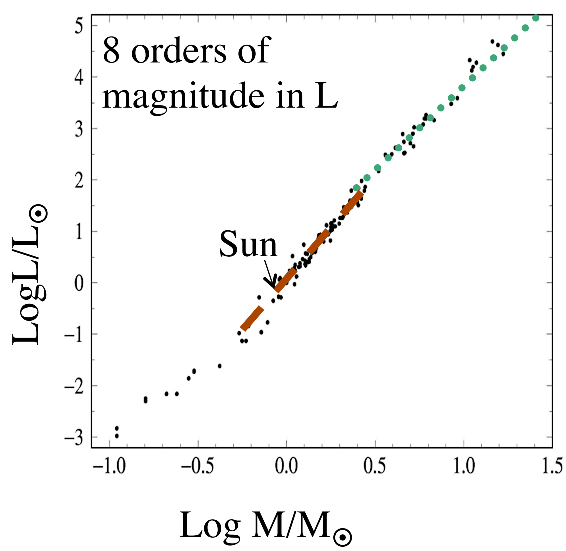
Luminosity Mass Relation (MBW ***10.1.4-10.1.5)***

- On the main sequence (MS) stars of the same age and metallicity have simple scaling relations (first order) **between mass, temperature, luminosity and size**
  - Basic physics of stellar structure eqs (MBW sec 10.1.4 eq 10.61) stars on the main sequence: L~

    $81(M/M_\odot)^{2.14}$; $M>20M_\odot$

    $1.78(M/M_\odot)^{3.5}$; $2M_\odot<M<20M_\odot$

    $0.75(M/M_\odot)^{4.8}$; $M<2M_\odot$



Log $M/M_\odot$

Luminosity temperature **$L \sim T^b$** with b~4.1 at low and 8.6 at high mass

α~0.7,β~5

$$R \propto R_\odot \left(\frac{M}{M_\odot}\right)^\alpha, L \propto L_\odot \left(\frac{M}{M_\odot}\right)^\beta$$

Notice the very strong dependences

Lifetime on MS ~M/L~M^{-3}

Relations for the main sequence

- Mass–luminosity relation ($0.1M_\odot < M < 100M_\odot$):
  - $L \propto M^4$ for $M > 0.6M_\odot$
  - $L \propto M^2$ for $M < 0.6M_\odot$
- Mass–radius relation:
  - $R \propto M^{0.6}$ for $M > 0.6M_\odot$
- Luminosity–temperature relation:
  - $L \propto T^7_{eff}$

- Lifetime $t \sim 10^{10}(M/M_\odot)^{-2.5}$ yrs
  - – from dimensional analysis for $M > 0.6M_\odot$

    $t \propto M/L \propto M/M^4 \propto M^{-3}$

Estimating Lifetimes – MS (MBW 10.1.3)

26.7 MeV released every time 4H $\rightarrow$ He + ν + photons

The difference in mass of 4H and He is

$4m_{proton} - 3.97m_{proton} = 0.0267m_{proton}$

The efficiency of converting mass to energy with p-p process is 0.03 / 4 = 0.007, or 0.7% (some of the energy goes into neutrinos)

- So, $t_{MS} = (0.007\ \alpha M\ c^2) / L$

α is the total mass of H converted to He while the star is on the main sequence- varies with mass : nuclear burning regions takes up a larger percentage of the stellar interior as one goes to low mass star.

In terms of useful units, $t_{MS} \sim 10^{10}(M/M_{solar})/(L/L_{solar})$; $\sim M^{-3}$

(eq. 1.9 in S&G)

Why nucleosynthesis stops at Fe