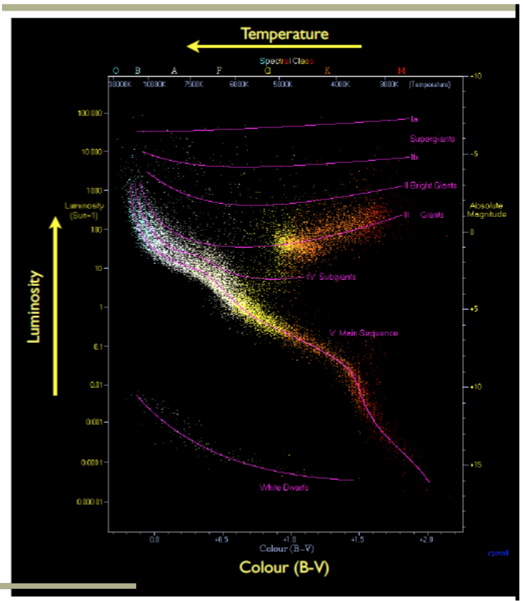
Stellar Populations of Galaxies-
2 Lectures

see MBW10.3- (sec 10.1-10.2 for stellar structure theory- will not cover this) parts of sec 2.2 and 6.3 in S&G

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
  - 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 light and 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)
- 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 pas t~10^{10} yr, While the main-sequence stars with $M_s \sim 10M$ observed today are formed only during the past 10^7 yr.
- Thus, the stellar population observed from a galaxy depends strongly on its <u>star-formation history</u>.

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

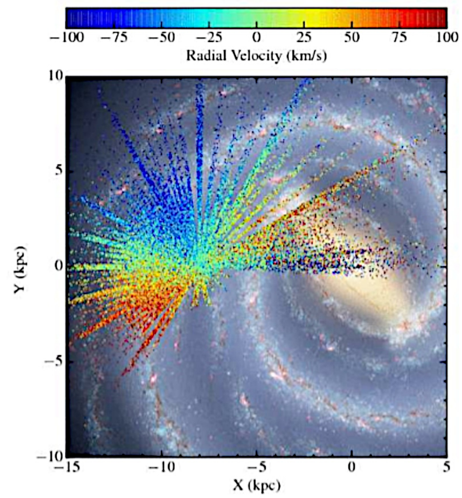


FIG. 24.— Star-by-star APOGEE heliocentric velocities as a function of Galactic X-Y position and projected on an artist's conception image of the Milky Way. The points represent main APOGEE

Velocity field of stars in MW

Why are we Studying Stars???

– To quote from Conroy et al 2013

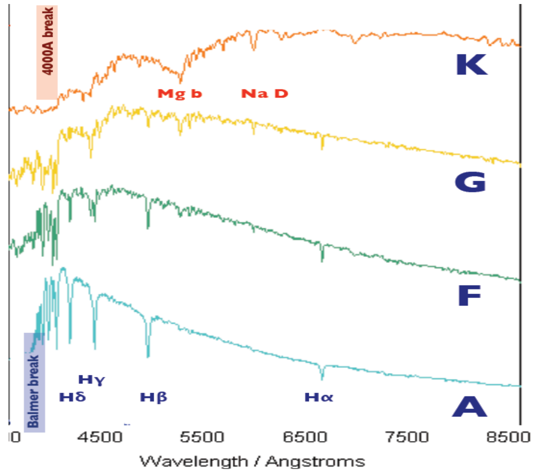
From an empirical point of view, the formation and evolution of galaxies can be probed via two general techniques.

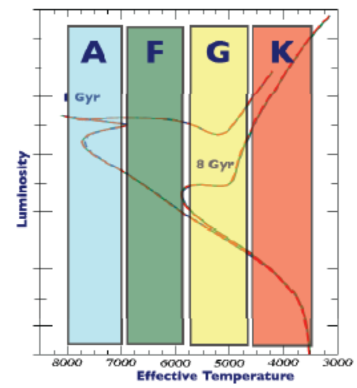
1) look back studies where one observes, statistically, the progenitors of present day galaxies at progressively higher redshifts
e.g. observing high redshift galaxies

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]
- Luminosity class- (giant/dwarf)
- Stellar properties determined by mass, chemical composition, age and spin



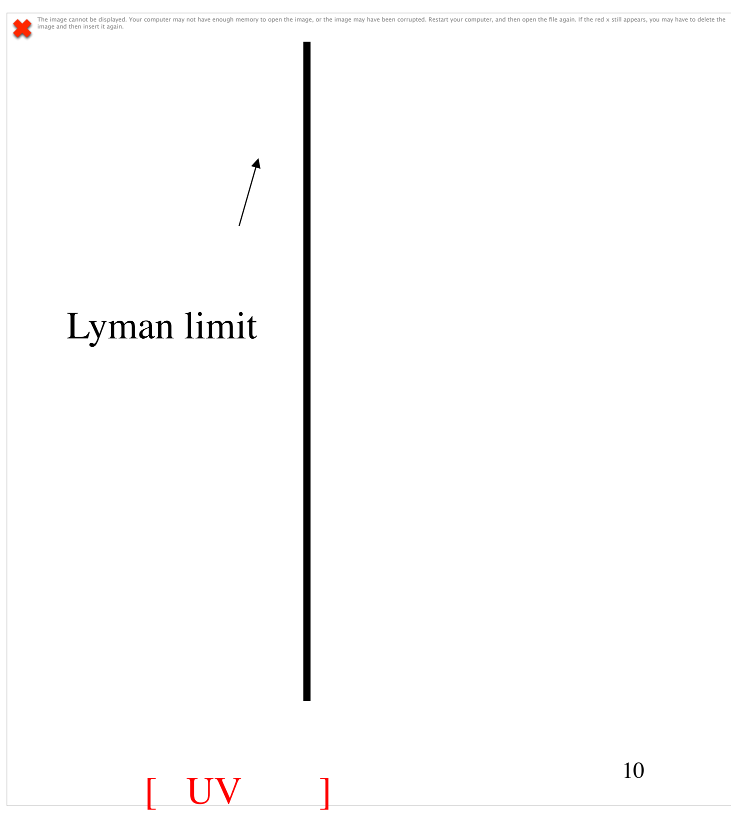


Luminosity

H.Rix

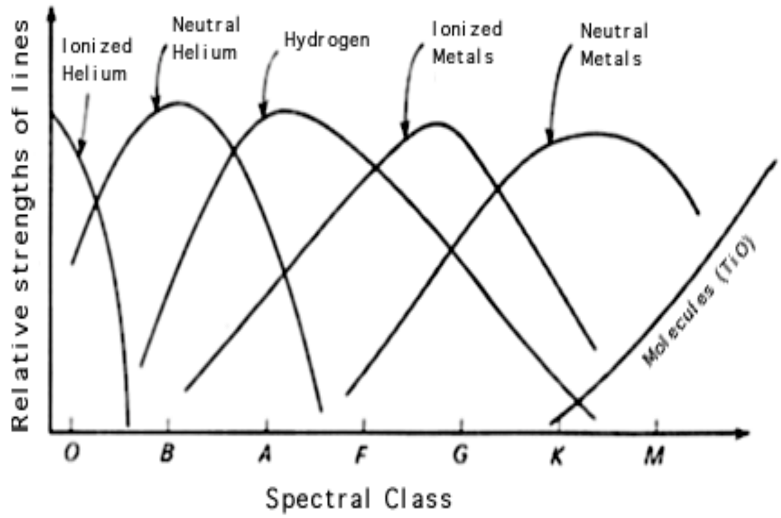
Stellar Spectra by Types

- 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



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 are known to exist,
- a mass of about $0.1M_\odot$ 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.

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
  -

  information
- For young populations (<300 Myrs)

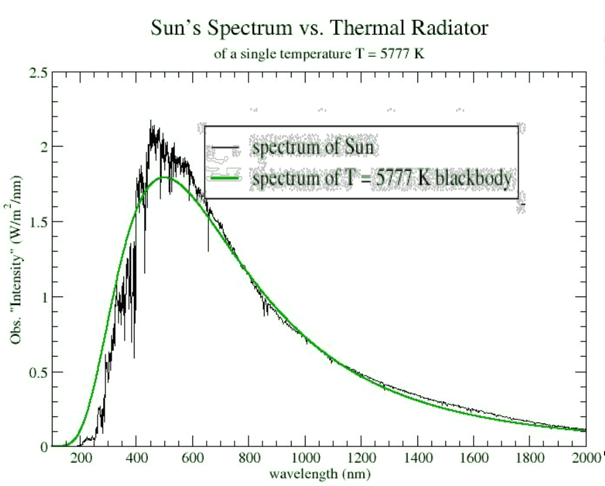
  – massive, young MS stars dominates integrated $L_{bolometric}$

- For old populations (>2Gyrs)

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

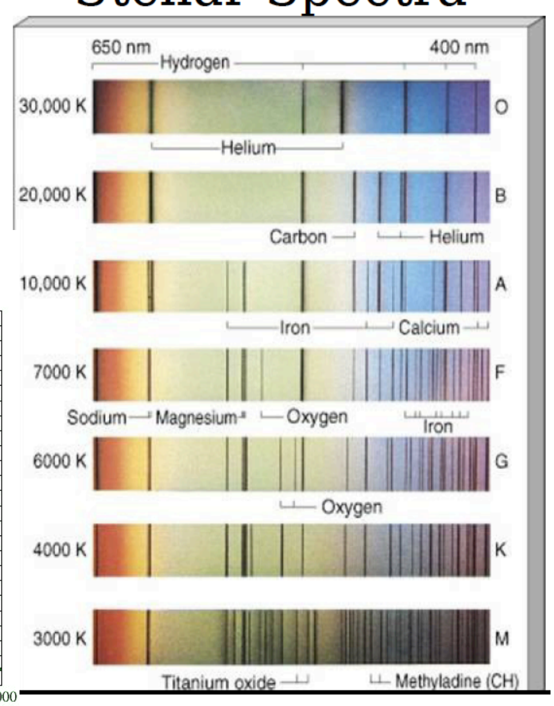
$L_{bolometric}$ is the total luminosity, as opposed to the luminosity in some band

- To zeroth order stellar spectra can be approximated as *black bodies* of the appropriate temperature. - If this is 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

Stellar Spectra



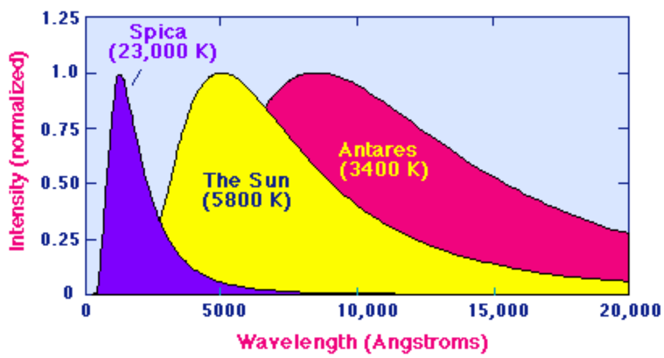
discovery of quantum levels

Luminosity, Size, Temperature

- Black body
  - $B(T) = [2hc^2/\lambda^5]*[1/\exp(hc/k_BT) - 1]$
- 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

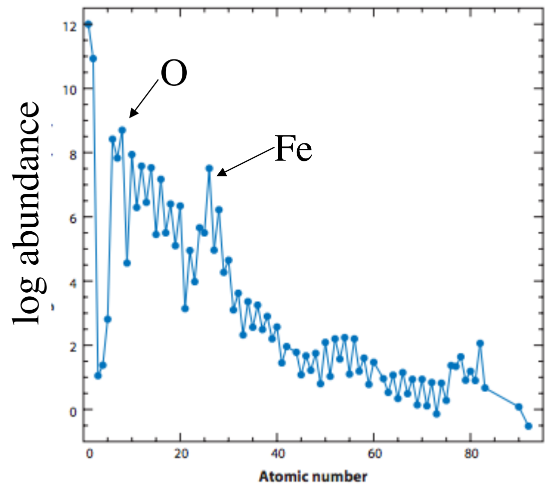


Simplest Physics of Stellar Spectra

- "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

•in nearby stars, 40-80% of the carbon is due to low- and intermediate-mass stars.

•The stellar origin of carbon is uncertain

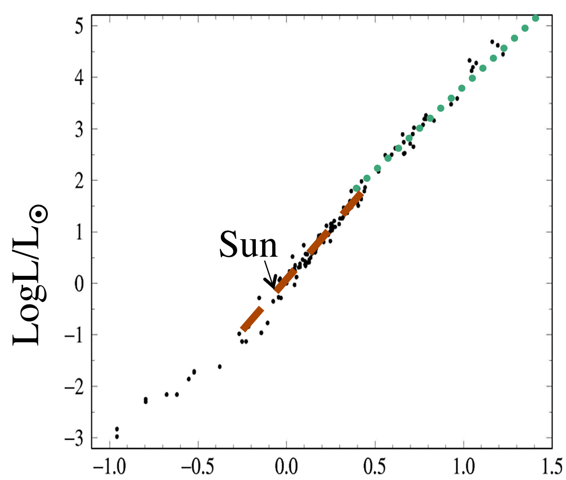
Luminosity Mass Relation (MBW ***10.1.4-10.1.5)***

- 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~

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

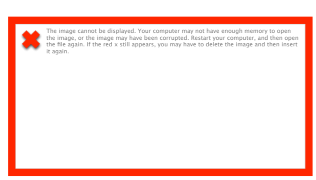
    $1.78(M/M_\odot)^{3.5}$; $2M_\odot<M<20M_\odot$

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



Log $M/M_\odot$

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



α~0.7,

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 → 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)

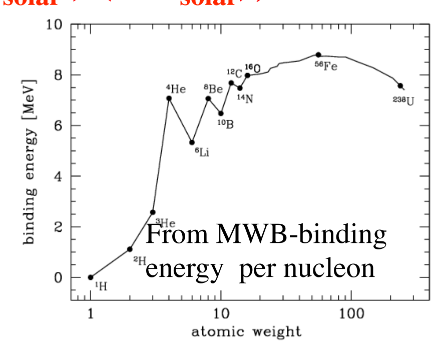
- So, $t_{MS} = (0.007\ \alpha M c^2) / L$

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

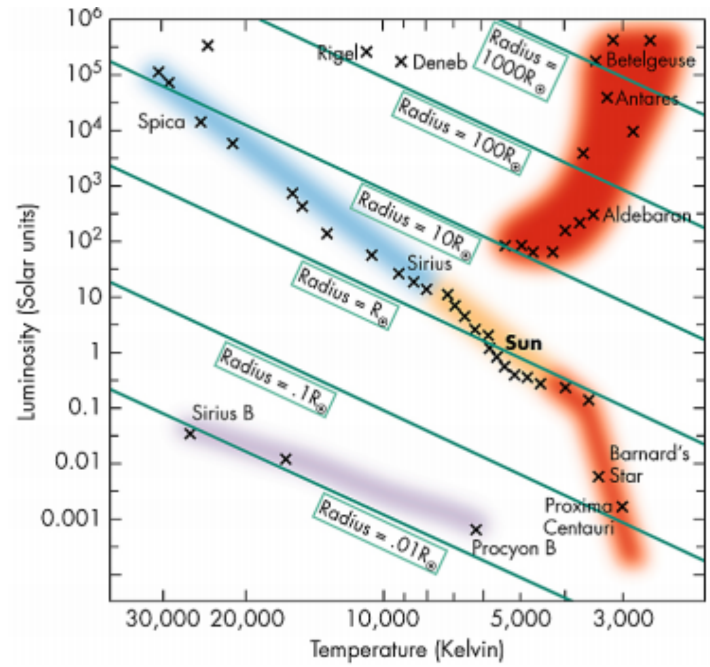


Stellar Sizes/Luminosity/Temperature

Stefan-Boltzman law- Lines $L \sim AT^4$

(T= temperature, A= area) eq. 1.3 in S&G

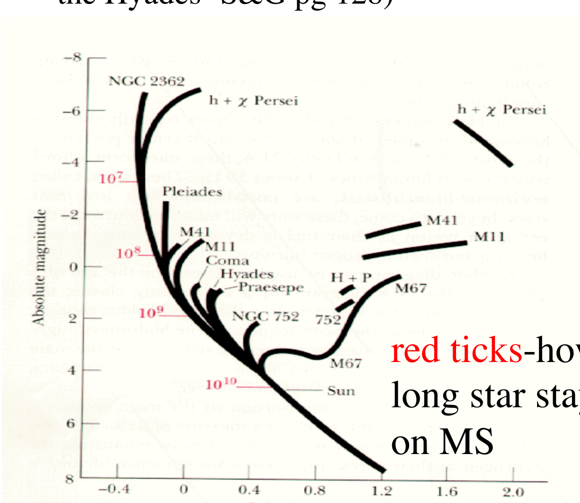
- Over a wide range in luminosity stars radiate close to a Black body spectrum in the optical band



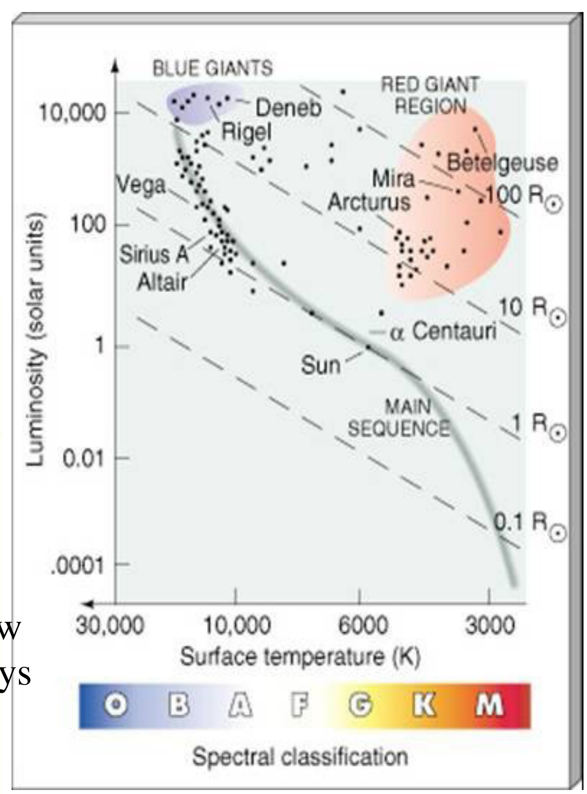
http://www.physics.isu.edu/~hackmart/spectral_class.pdf

H-R Diagram for Visible Stars in MW

- The brightest stars in the visible sky do NOT sample the H-R diagram well -how does one construct an appropriate sample?
- Need to go much fainter, find 'co-eval' populations (e.g. **open clusters** like the Hyades- S&G pg 128)



red ticks-how long star stays on MS



Stellar evolution reminder

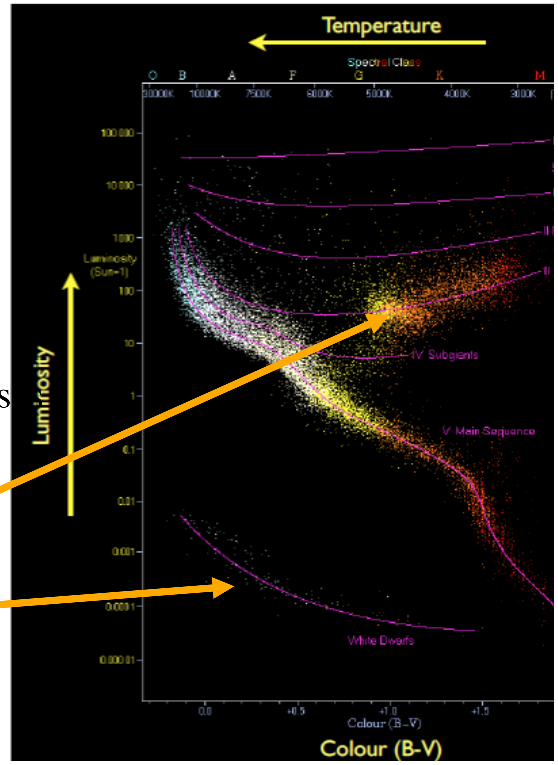
HERTZSPRUNG-RUSSELL DIAGRAM

Russell Smith Durham

Plots luminosity of stars, versus their temperature.

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

H-R diagram organizes the observed optical properties of stars
Main sequence
white dwarfs
giant branch
MBW 10.2)

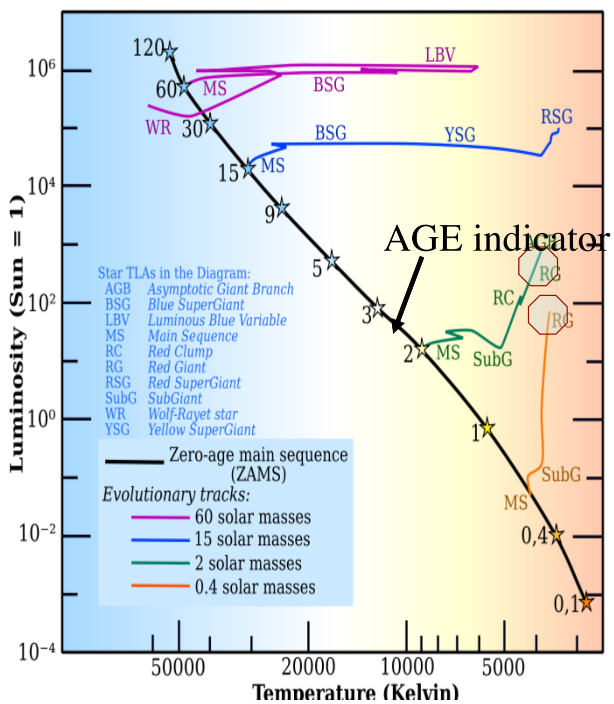


TRACKS

"Tracks" are trajectories of individual stars in the H-R

Stellar evolutionary tracks trace the evolution of a given mass star vs time in luminosity, temperature plane

as a function of initial mass (and initial chemical composition).



Russell J. Smith Durham
http://astro.dur.ac.uk/~rjsmith/stellarpops.html

Isochrones

Theoretical lines in the H-R diagram of a given age for stars of different masses of a 'simple' stellar population

details depend on color used and stellar metallicity

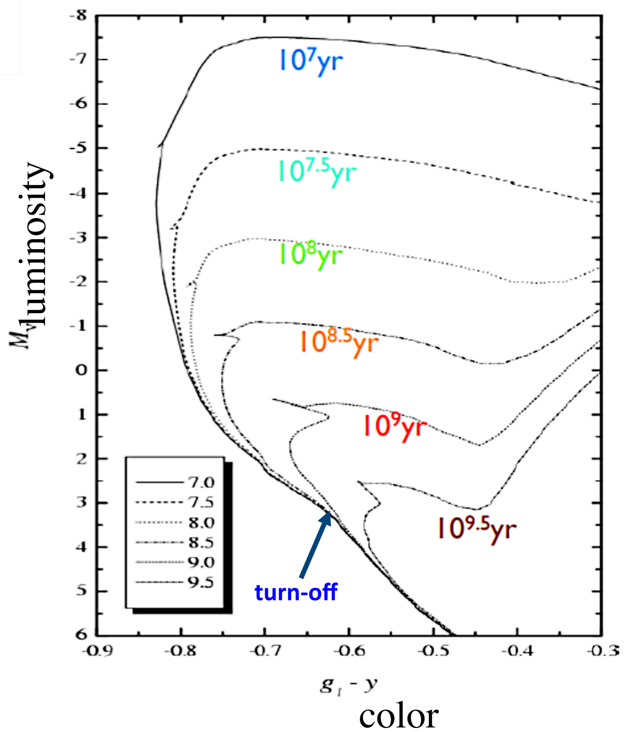
'Simple' stellar population (SSP)

has one age and metallicity

Theoretical models-allow estimate of age **from MS turn-off**

metallicity **from** giant branch color

See MBW fig 10.3



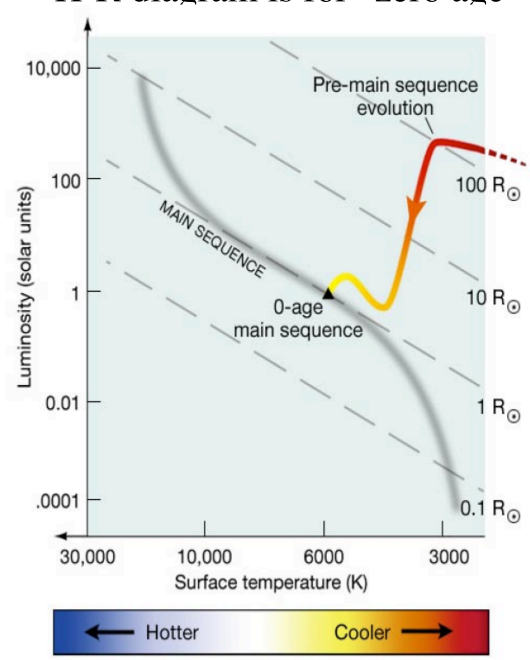
Russell J.Smith Durham

http://astro.dur.ac.uk/~rjsmith/stellarpops.html

Main Sequence

H-R diagram is for 'zero age'

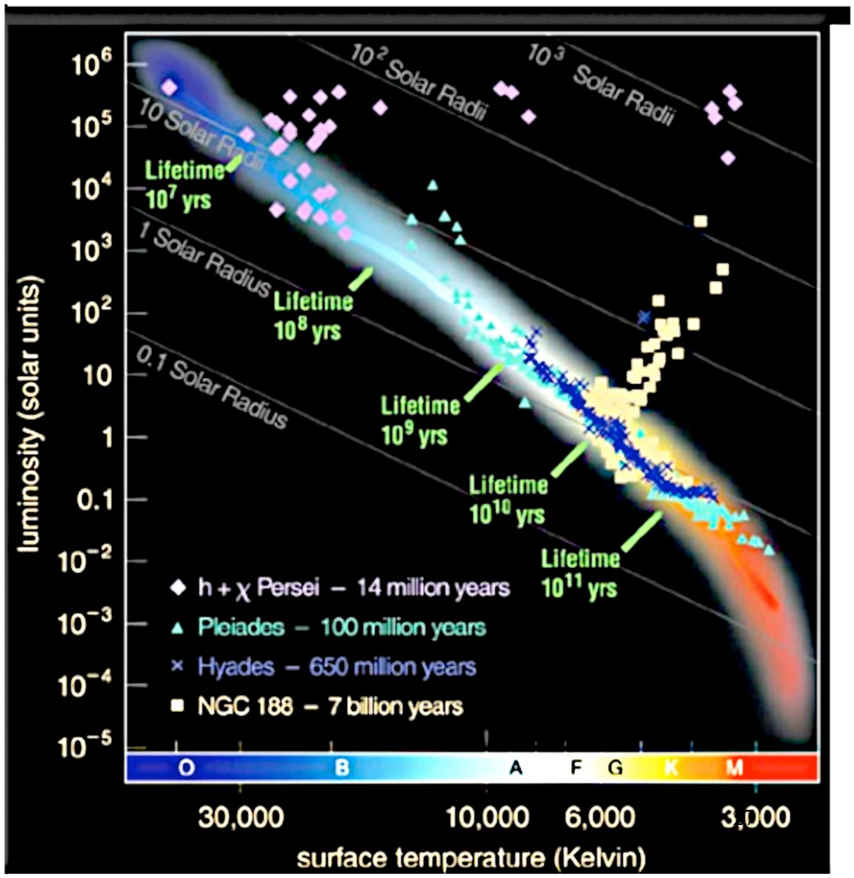
- 'low' mass stars evolve slowly-'stay' on the M-S for a long time
- On the M-S hydrogen nuclear fusion in the core generates energy, the pressure is balanced by gravity-hydrostatic equilibrium.
  - Stars spend ~80% of their lifetime on the M-S fusing hydrogen into helium.
- The position in the HR diagram changes slowly with time, e.g. the Sun will brighten and its color vary over its ~10^{10} year life on the Main Sequence. By the end of its MS lifetime, ~ twice as luminous as now



Dr. Christopher Palma PSU

Measuring Age of a Stellar System

- Main sequence turnoff is primarily a age indicator.



A Young SSP

- H-R diagram of the Pleiades (S&G fig 2.12) a nearby young open cluster.
- Notice thinness of the H-R diagram
  - scatter probably due to binaries

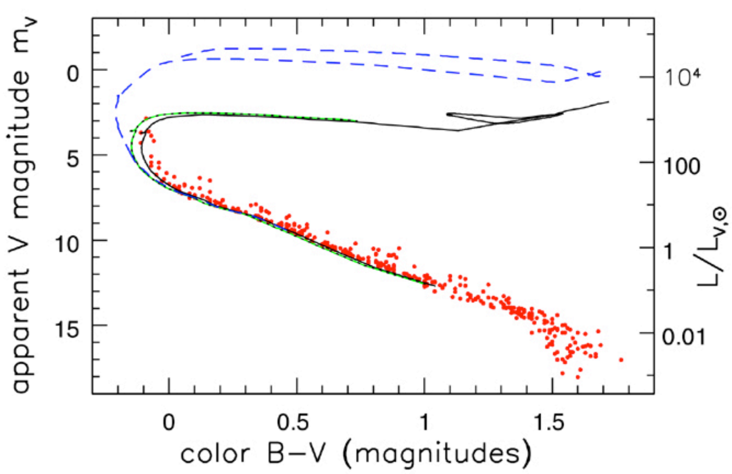
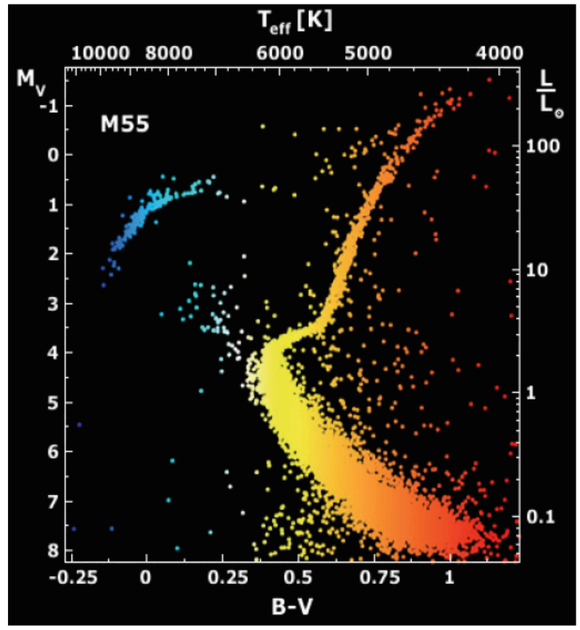


Fig 2.12 (J.-C. Mermilliod) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

A Old SSP

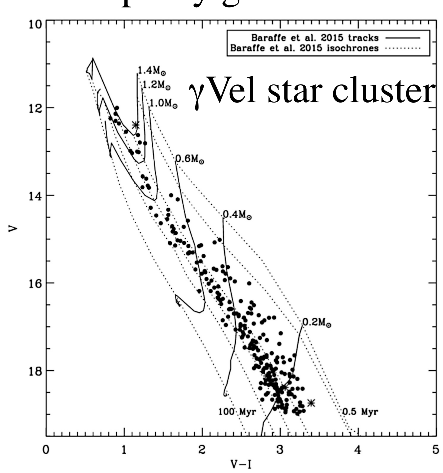
- Color-magnitude (H-R) diagram for stars in the globular cluster M55
- an old population of equal age +metallicity with no recent star formation ; e.g. a SSP
- To first order most Globular clusters are SSPs (some show metallicity variations)



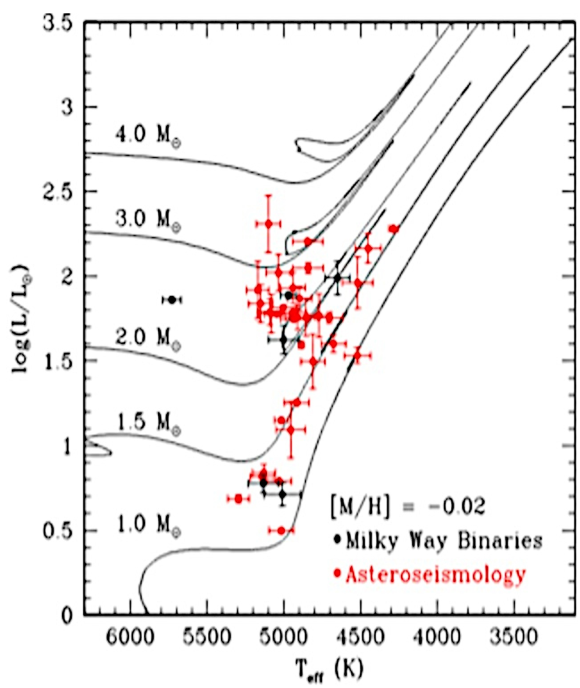
astronomy picture of the day

How Good are the Models??

For many purposes we must reply on stellar evolution models to determine stellar parameters- Models pretty good!



g. 10. Color magnitude diagram of the confirmed (dots) d possible members (crossed dots). Theoretical tracks and ›chrones (0.5, 1, 5, 10, 20 and 100 Myr) by Baraffe et al.)15) are also shown with solid and dotted lines, respectively.

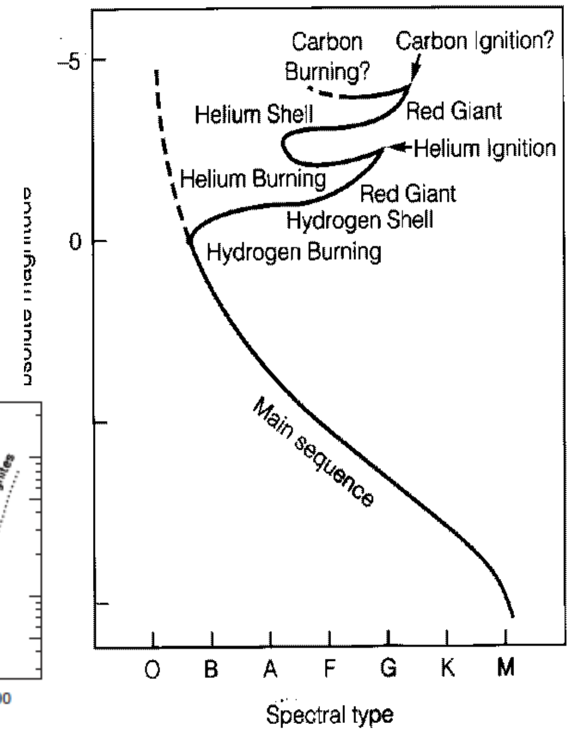


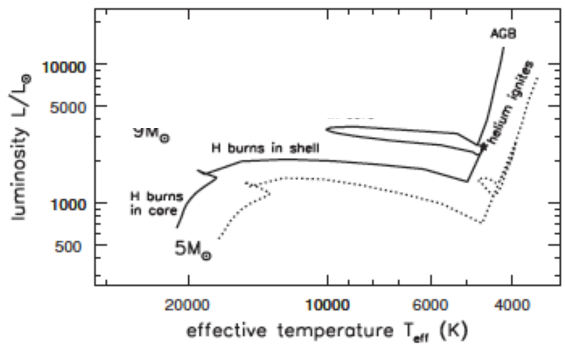
Off the MS

- He burning only releases ~20% of the energy that H burning produces
- Lifetime in the He burning phase is short…

~ 2×10^9 yrs for a solar mass star

- However stars on the giant branch are *very* luminous and can dominate the luminosity of old stellar systems





MASS-DEPENDENT LIFETIMES

Lifetime in each evolutionary phase depends sensitively on initial mass.

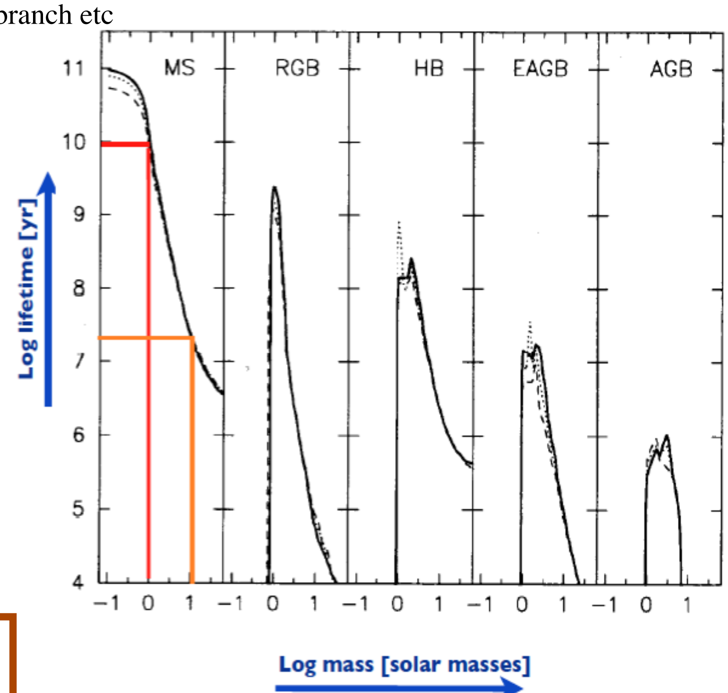
MS lifetime is ~10^{10} $(M/M_{sun})^{-2.5}$ yrs: so 10 Gyr at 1 solar mass, but only ~20 Myr for 10 $M_\odot$

Subsequent phases shorter-lived.

Below ~ 0.9 $M_\odot$, the MS lifetime is longer than age of Universe!

Mass-vs-lifetime relation is one of the crucial tools for age-dating populations.

MS= main sequence, RGB= red giant branch HB= horizontal branch etc



Russell J. Smith Durham
http://astro.dur.ac.uk/~rjsmith/stellarpops.html

Stellar Properties (S&G table 1.1

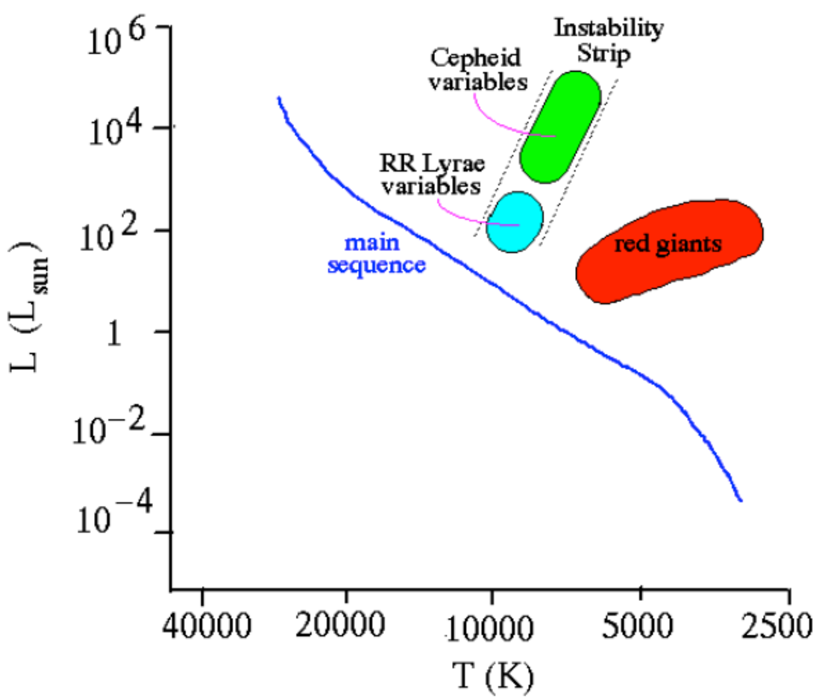
Table 1.1 Stellar models with solar abundance, from Figure 1.4

Mass ($\mathcal{M}_\odot$)	L_{ZAMS} ($L_\odot$)	T_{eff} (K)	*Spectral type*	τ_{MS} (Myr)	τ_{red} (Myr)	$\int(L\,d\tau)_{MS}$ (Gyr × $L_\odot$)	$\int(L\,d\tau)_{pMS}$ (Gyr × $L_\odot$)
0.8	0.24	4860	K2	25 000		10	
1.0	0.69	5640	G5	9800	3200	10.8	24
1.25	2.1	6430		3900	1650	11.7	38
1.5	4.7	7110	F3	2700	900	16.2	13
2	16	9080	A2	1100	320	22.0	18
3	81	12 250	B7	350	86	38.5	19
5	550	17 180	B4	94	14	75.2	23
9	4100	25 150		26	1.7	169	40
15	20 000	31 050		12	1.1	360	67
25	79 000	37 930		6.4	0.64	768	145
40	240 000	43 650	O5	4.3	0.47	1500	112
60	530 000	48 190		3.4	0.43	2550	9
85	1 000 000	50 700		2.8		3900	
120	1 800 000	53 330		2.6		5200	

Note: L and T_{eff} are for the zero-age main sequence; spectral types are from Table 1.3; τ_{MS} is main-sequence life; τ_{red} is time spent later as a red star ($T_{eff} \lesssim 6000$ K); integrals give energy output on the main sequence (MS), and in later stages (pMS).

Some Especially Interesting Places in HR Diagram

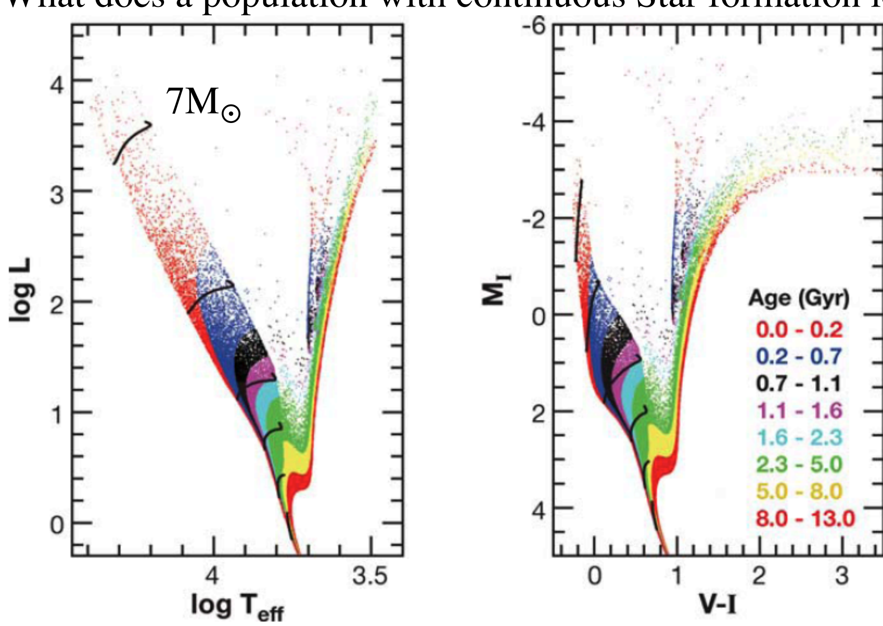
- Cepheids are used to determine absolute distances
- Red giants are very luminous **with narrow range of parameters**- can be used for distance determinations (called 'tip of red giant branch' TGB)



Important for Galaxies

- stars of different masses have 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 (i.e. at redshift $z = 0$), we are observing the light from the stars that have evolved to the present time.
- stars on the main-sequence today with $M \sim M_\odot$ include all stars of similar masses that have formed during the past **9×10^9 yr**
- But stars on the main-sequence today with $M \sim 10 M_\odot$ have formed during the past **10^7** yr.
- **Consequently, the stellar population observed from a galaxy depends strongly on its star-formation history**
- **Inverting this idea we can learn a lot about the star formation history of a galaxy from studying its stellar population.**

What does a population with continuous Star formation look like??



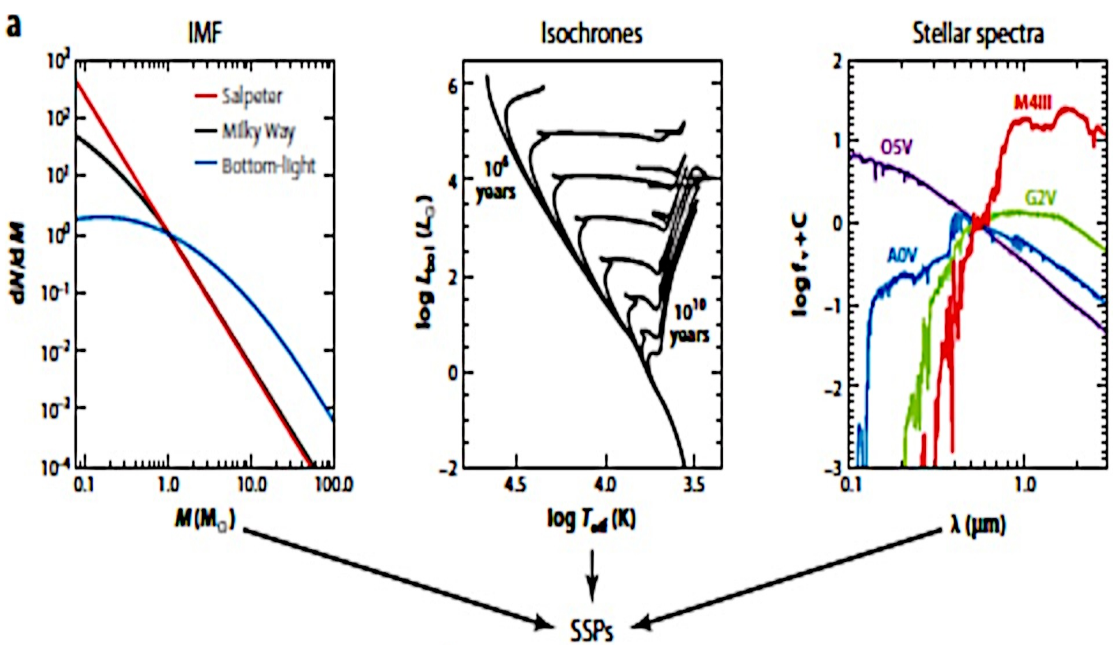
- **Theoretical space (left), observational space (right)**
- **Constant SFR** from 13Gyr ago to the present time, Z =0.0198, IMF slope-2.3
- **stellar evolutionary tracks for stars of masses 7, 3, 1.9, 1.5, 1.2, and1$M_\odot$**

Where are We Going

- How to build up the galaxies we observe from what we know about stars !

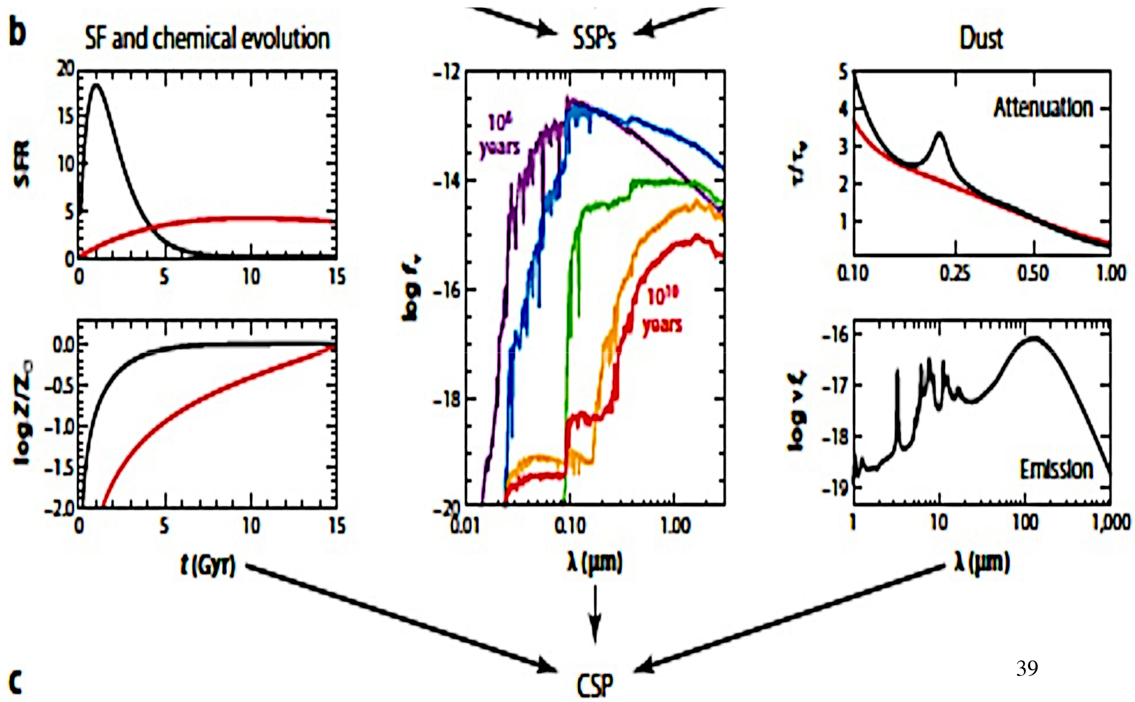
What is the Process –MWB sec 1.3 Conroy 2013

Taking stellar models and data and constructing a galaxy spectrum



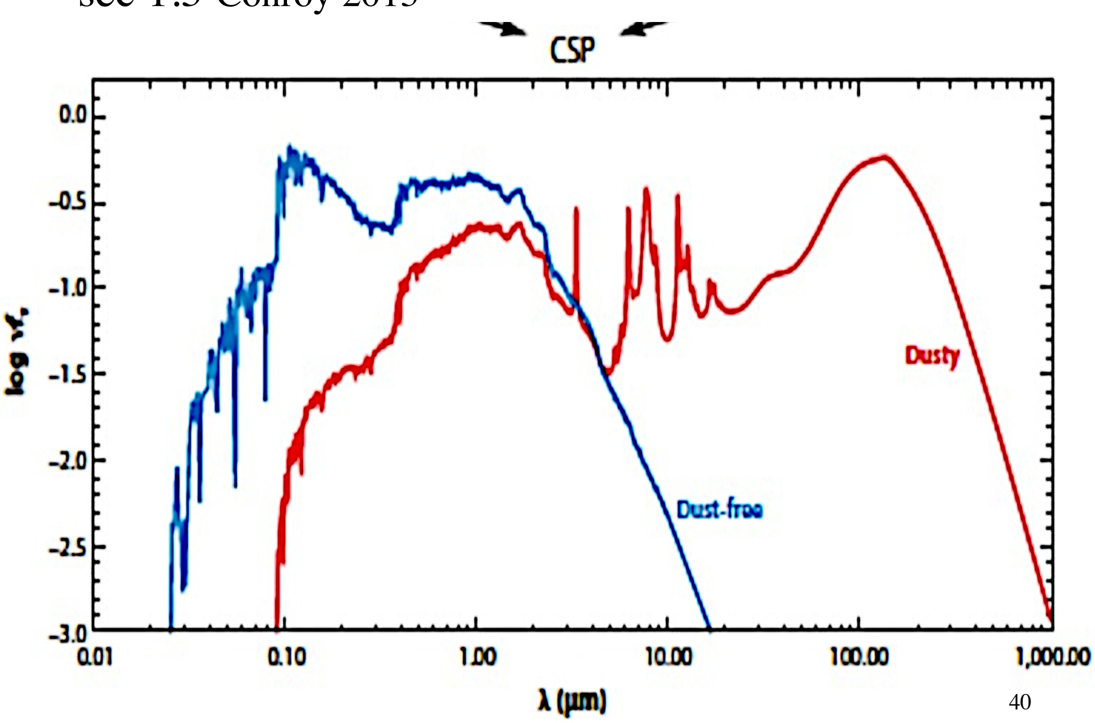
What is the Process –MWB

sec 1.3 Conroy 2013

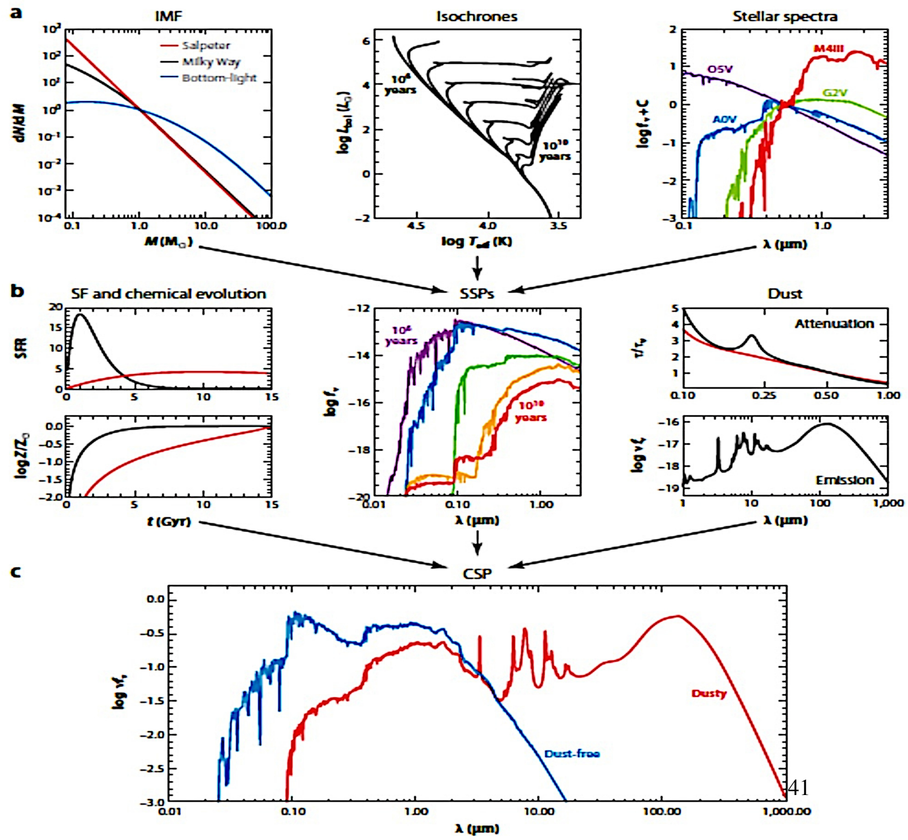


What is the Process –MWB

sec 1.3 Conroy 2013



What is the Process – MWB sec 1.3 Conroy 2013



Next Time

- More star stuff...