Astronomy 730

Stellar Populations

Outline

- Stellar populations
  - Big picture
  - Stellar classification and properties
  - Stellar evolution
- Understanding stellar populations
  - H-R diagrams
    - Reading: Noël et al. (2007, AJ, 133, 2037), Lewis et al. (2015, ApJ, 805, 183)
    - What is the data they use? Compare their CMDs.
  - Integrated light as a function of stellar luminosity: assignment
- Stellar Population Synthesis
  - Key ingredients
  - Fuel Consumption theorem
  - Differential Populations Synthesis
  - Simple Populations Synthesis and why it works
- Nucleosynthesis
  - Abundance patterns: definitions and observations
  - Chemical evolution

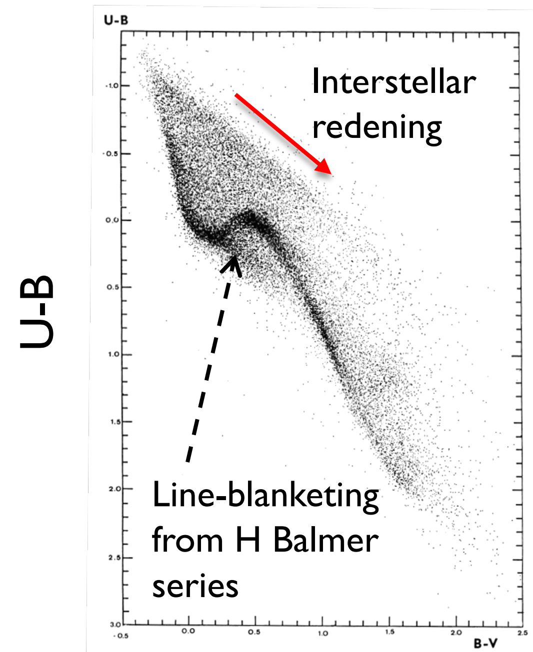
Role of Stars in Extragalactic Astronomy

- Dynamics
  - Stars are point masses –
    - collisionless tracers of the potential
  - Distinctions between stars irrelevant
    - But, which stars most accurately trace the "true" morphology and dynamics of a galaxy?
- Chemical evolution
  - Stars are responsible for producing and distributing the elements
- Metric of evolution
  - Star formation rate (SFR)
  - Star formation history (SFH)
    - H-R diagram are all diagnostics of evolution
- Feedback
  - evolution/organization of ISM in galaxies driven by gravity, hydrodynamics, and input of energy from stars

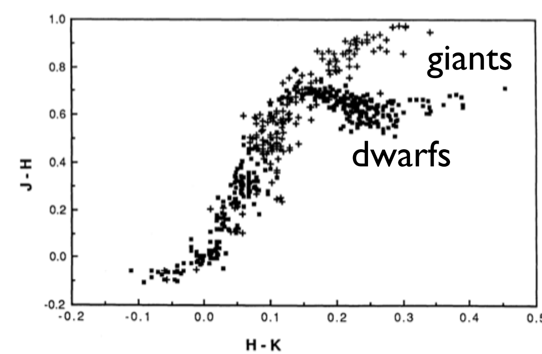
Stellar Classification

- Photometry : Based on optical and near-infrared (NIR) colors
  - First order: stars are blackbodies, so any two flux-points constrain temperature
  - Combination of two bands yield "color" = temperature
  - Second-order: stars have line-blanketing, so e.g., colors are degenerate for massive stars
  - Need observations in at least three bands.
  - NIR can break degeneracy between cool giants and dwarfs.

- Spectroscopy : individual line ratios very tightly constrain temperature, surface gravity, etc.
  - Yields the OBAFGKM classification
  - Further sub-classification is the luminosity class



Nicolet (1980)



Bessell & Brett (1988)

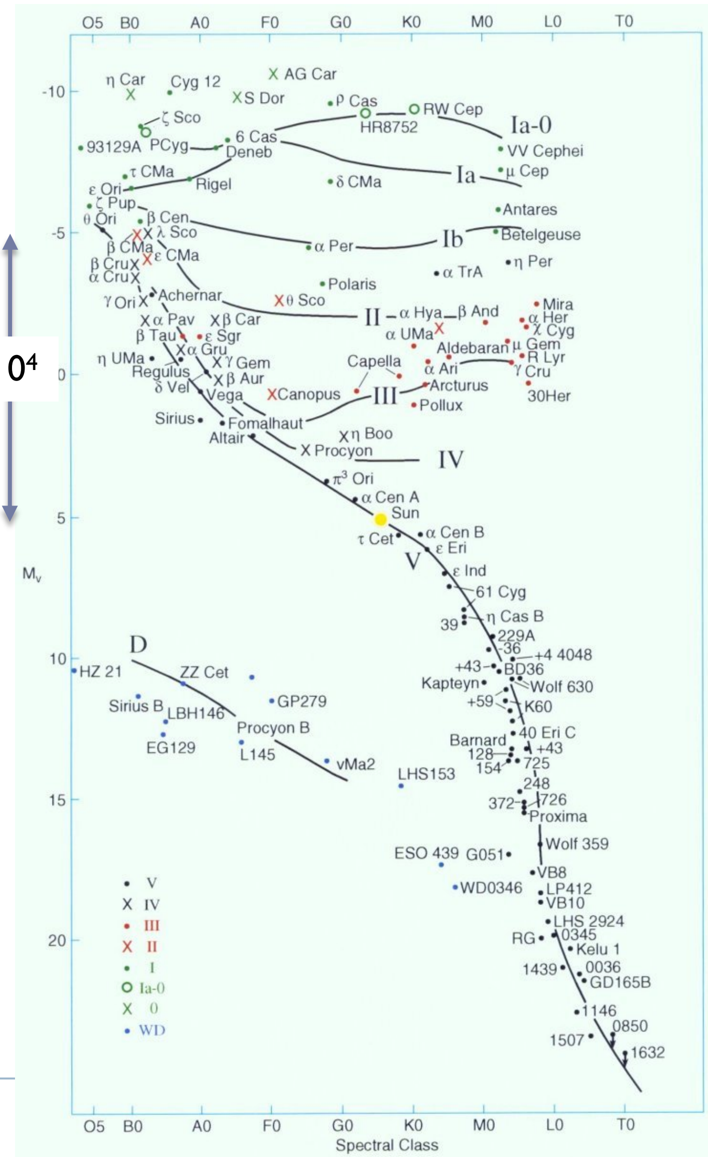
Basic Properties of Stars

Spec. type	Absorption lines	T_{eff} (K)	M_V (V, I)	(B-V)
O	He II, C III	40-50,000	-6,-8	<-0.33
B	He I, S III, H	12-30,000	-1.5, -7	-0.2
A	H, Mg II	7-9,000	1.0, -7	0
F	Ca II	6-7,000	3.0,-7	0.4
G	Ca II, CH	5.5-6,000	5.0,-7	0.6
K	CH, CN	4-5,500	6.0,-7	1.2
M	TiO	2.5-4000	9.0,-7	1.6

Luminosity class

- Ia – most extreme supergiants
- Ia – moderate supergiants
- Ib – less luminous supergiants
- II – bright giants
- III – normal giants
- IV – subgiants
- V - dwarfs

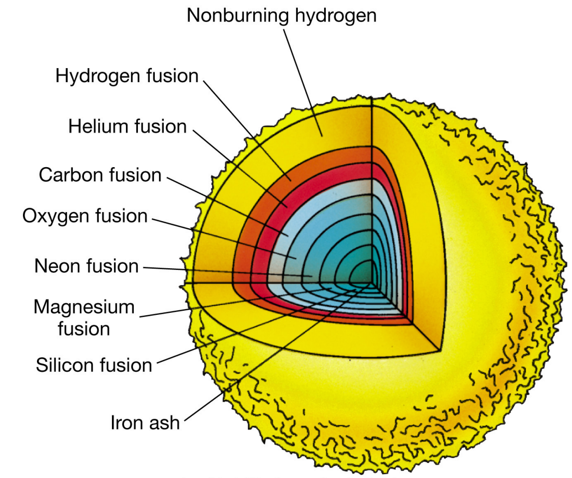
$\times 10^4$

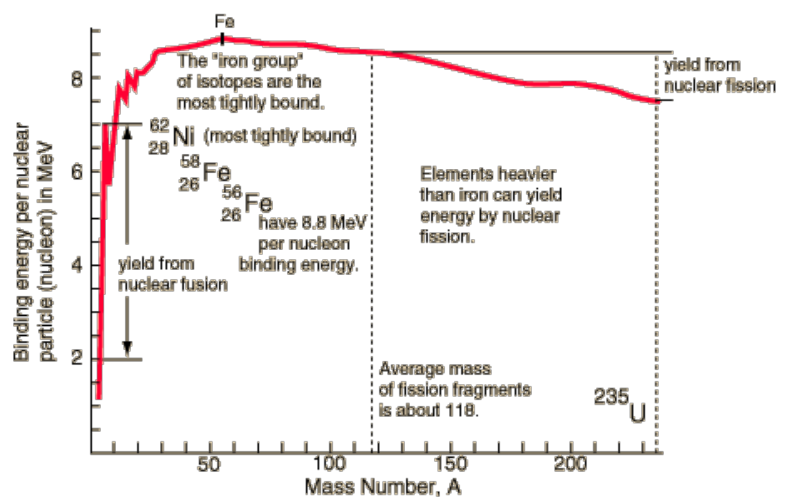


Kaler 2006

Fundamentals of Stellar Evolution

- History: BBNS cannot account for the abundances of all the elements; Burbridge, Burbridge, Fowler, & Hoyle laid out the model for stellar nucleosynthesis.
- Main sequence: H to He fusion via proton-proton chain & CNO bi-cycle
- Post-MS: H depletion in core, interior pressure decreases, collapse of core and interior, H shell burning ignites, envelope expands and star becomes a red giant.
- Later phases: repeat with heavier and heavier elements via α-processes, faster and faster rates (more energy production per unit time), more and more shells.
- Fusion ends depending on mass sufficient to overcome core degeneracy, or when core burns to Fe.





MS Stellar Lifetimes

- Because H burning lifetime depends on mass there is a nice correlation between turn-off mass and age
  - Spectral types are determined by surface-temperature (T_{eff})
  - T_{eff} set by mass *on the main sequence*:
  - more mass burns brighter and hotter

    - $L_{MS}/L_{\odot} \sim (M/M_{\odot})^{2.14}$ $(M/M_{\odot} > 20)$
    - $L_{MS}/L_{\odot} \sim (M/M_{\odot})^{3.5}$ $(2 < M/M_{\odot} < 20)$
    - $L_{MS}/L_{\odot} \sim (M/M_{\odot})^{4.8}$ $(M/M_{\odot} < 2)$

So: $\tau_{MS} = 10\ (M/M_{\odot})(L/L_{\odot})^{-1}$ Gyr

Stellar Lifetimes through core He-burning

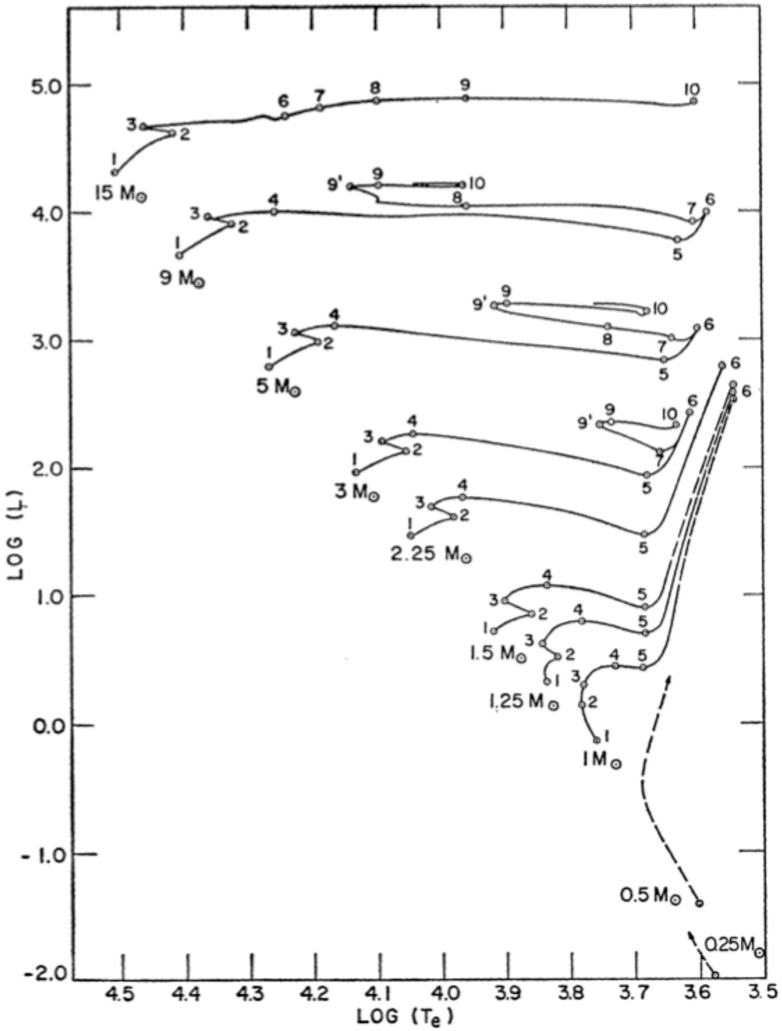


TABLE III

Stellar Lifetimes (yr)[a]

Mass ($M_\odot$) \ Interval ($i-j$)	(1–2)	(2–3)	(3–4)	(4–5)	(5–6)
15	1.010 (7)	2.270 (5)		7.55 (4)	
9	2.144 (7)	6.053 (5)	9.113 (4)	1.477 (5)	6.552 (4)
5	6.547 (7)	2.173 (6)	1.372 (6)	7.532 (5)	4.857 (5)
3	2.212 (8)	1.042 (7)	1.033 (7)	4.505 (6)	4.238 (6)
2.25	4.802 (8)	1.647 (7)	3.696 (7)	1.310 (7)	3.829 (7)
1.5	1.553 (9)	8.10 (7)	3.490 (8)	1.049 (8)	≥2 (8)
1.25	2.803 (9)	1.824 (8)	1.045 (9)	1.463 (8)	≥4 (8)
1.0	7 (9)	2 (9)	1.20 (9)	1.57 (8)	≥1 (9)

[a] Numbers in parentheses beside each entry give the power of ten to which that entry is to be raised.

TABLE IV

Stellar Lifetimes (yr)[a]

Mass ($M_\odot$) \ Interval ($i-j$)	(6–7)	(7–8)	(8–9)	(9–10)
15	7.17 (5)	6.20 (5)	1.9 (5)	3.5 (4)
9	4.90 (5)	9.50 (4)	3.28 (6)	1.55 (5)
5	6.05 (6)	1.02 (6)	9.00 (6)	9.30 (5)
3	2.51 (7)	4.08 (7)		6.00 (6)

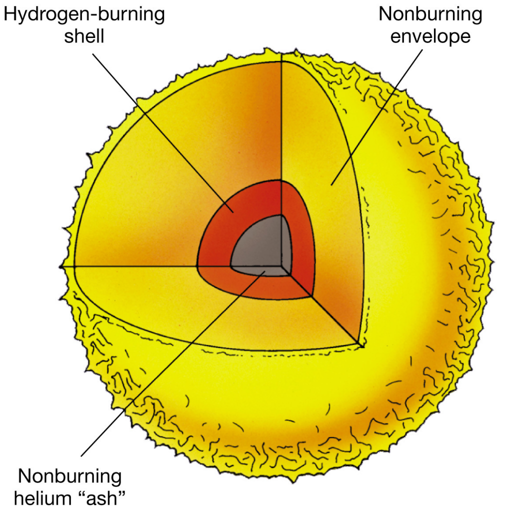
[a] Numbers in parentheses beside each entry give the power of ten to which that entry is to be raised.

- Note changing morphology with mass in
  - RGB
  - HB
- Wanted: phases later than 6 for M<3M⊙
- Wanted: phases later than 10 for higher mass
- Wanted: modern counterparts

Iben 1967, ARAA, 5, 571

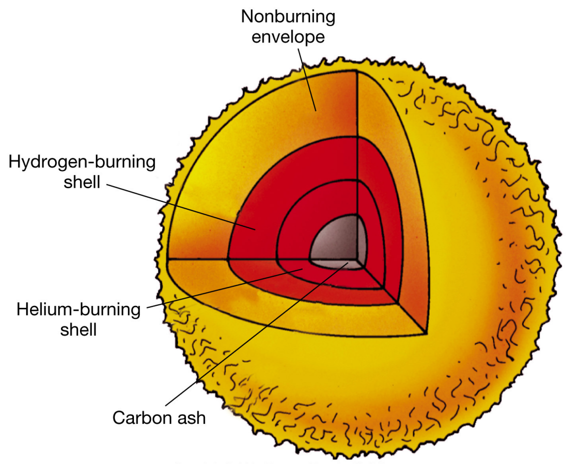
Post-MS Stellar Evolution

- RGB to Horizontal Branch (HB)
  - Core contraction/core mass increases
  - T~10^8 K, ρ ~ 10^4 g cm^{-3} get He burning
    - $2\alpha \rightarrow {}^8Be$, ${}^8Be + \alpha \rightarrow {}^{12}C$
    - In stars w/ M > 2M$_\odot$, its not degenerate and we get core expansion
    - Essentially a He-burning main sequence
    - In more massive stars get ${}^{12}C + \alpha \rightarrow {}^{16}O$; for stars with M up to 8 M$_\odot$ we're left with a degenerate CO core (white dwarf)
  - He-burning lifetime ~10^8 years
- Evolution to Asymptotic Giant Branch (M > 0.8 M$_\odot$) – *you are going to check this*
- Further Burning Stages…



Fundamentals of Stellar Evolution

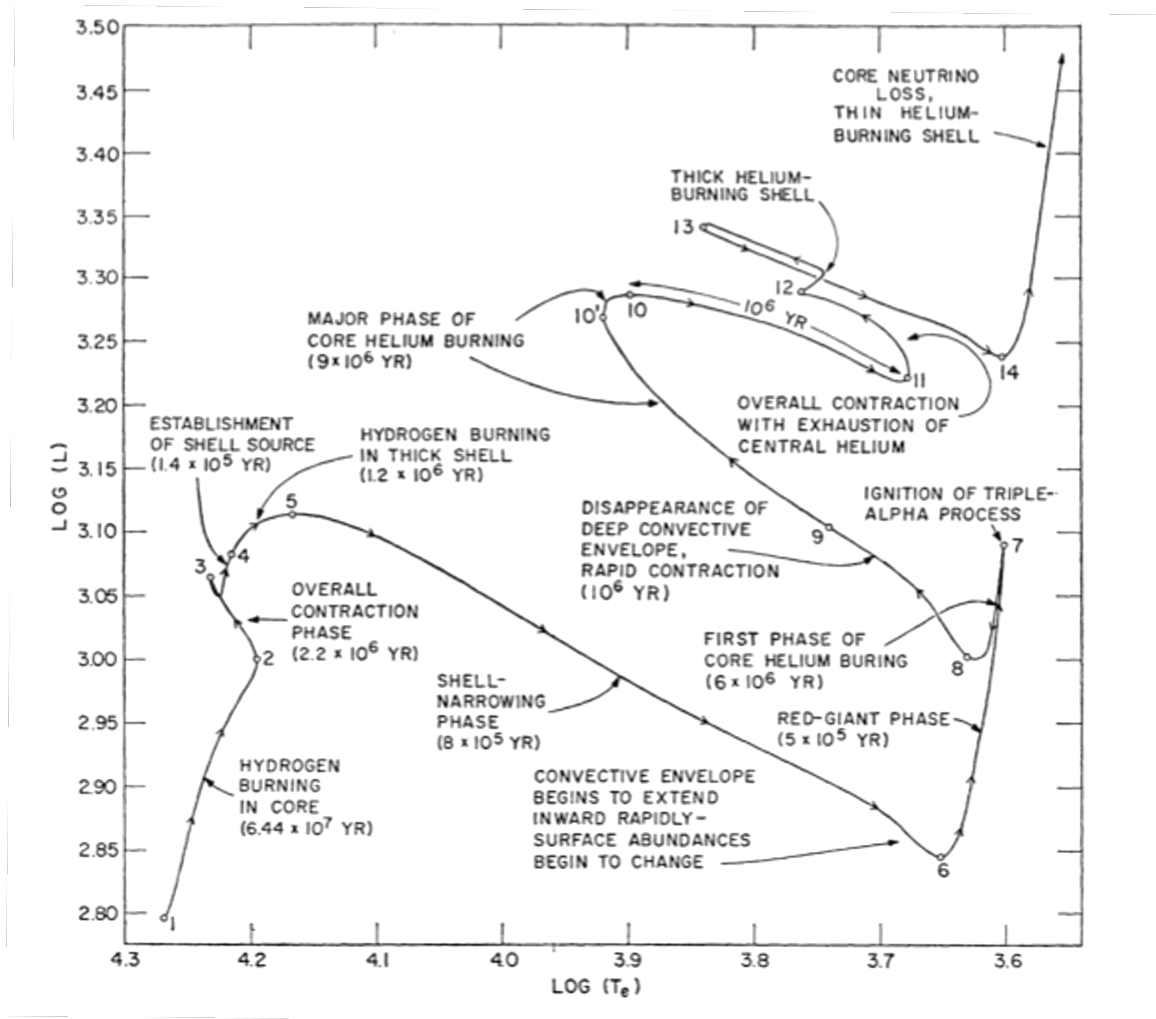
- Evolution to AGB
  - He-burning, growing CO core
    - Low mass stars can't lift degeneracy, end up as planetary nebula + white dwarf
  - Eventually get He shell burning that drives expansion of envelope and luminosity increases (plus unburned H, H shell burning)
    - Occurs with a series of "dredge-ups" that produce chemically bizarre stars (convection)
    - Site of "s-process" nucleosynthesis



- Neutron capture processes
  - S-process ("slow") – yields elements like Ba and Tc largely in AGB stars (all those free n from previous burning processes)
  - R-process ("rapid") – yields very heavy elements like Ur, usually in SNe

Path of 5 $M_\odot$ metal-rich star

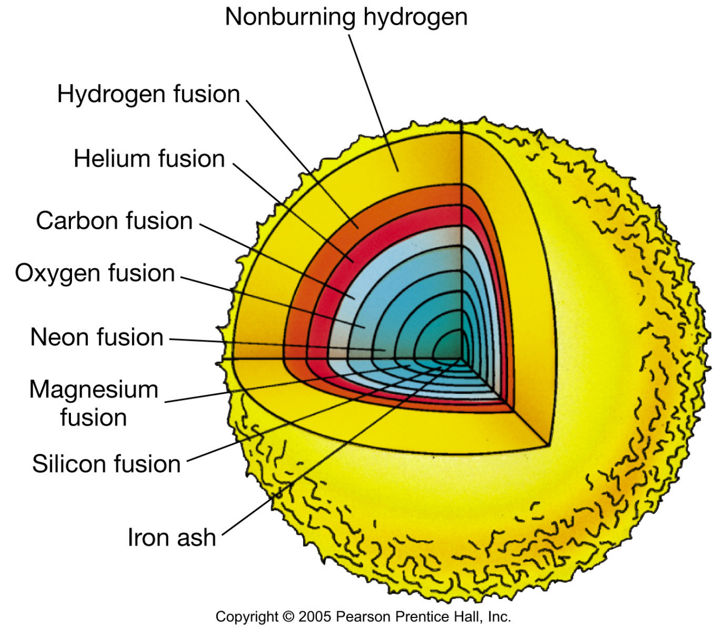
$L_\odot = 3.86 \times 10^{33}$ erg/s



- Iben 1967, ARAA, 5, 571

Fundamentals of Stellar Evolution

- Further Burning Stages ($M>8M_\odot$)
  - $^{12}C + {}^{12}C \rightarrow {}^{20}Ne + \alpha$
  - $^{16}O + {}^{16}O \rightarrow {}^{28}Si + \alpha$
  - $^{20}Ne + {}^{4}He \rightarrow {}^{24}Mg + \gamma$
  - Leads ultimately to the production of ^{56}Fe, core collapse, and supernova explosion (Type II SNe)
  - Can also get n production via, e.g., $^{12}C + {}^{12}C \rightarrow {}^{23}Na + n$

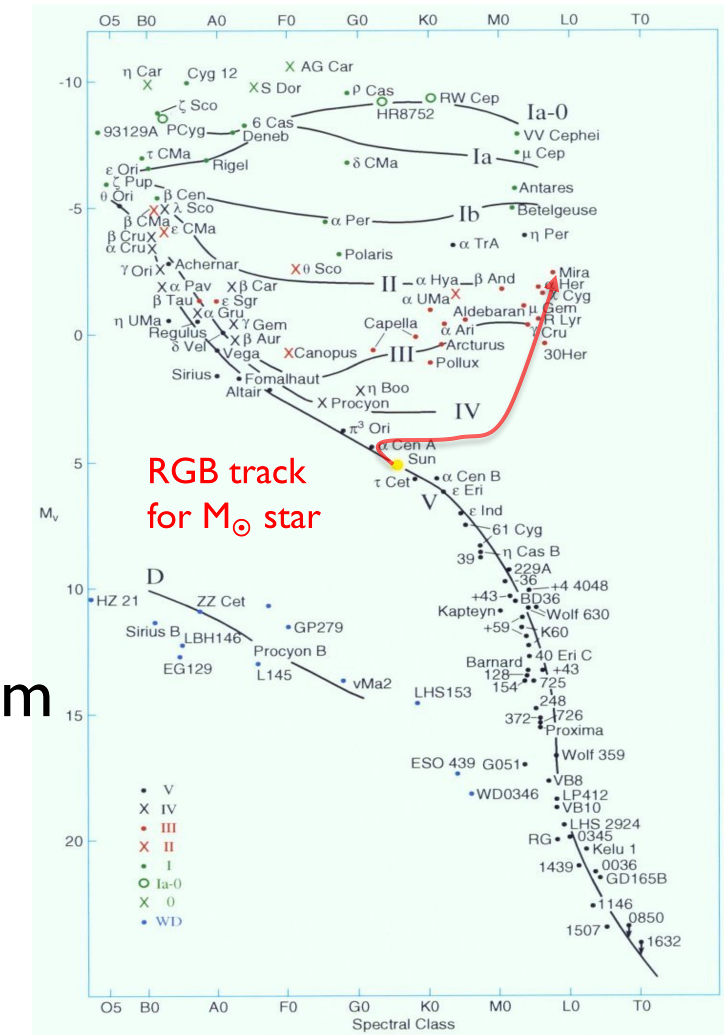


Modern evolutionary tracks

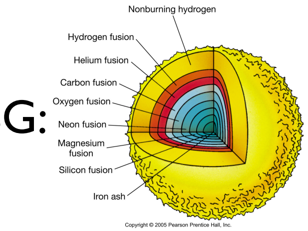
- A few links:
  - Awesome web tool by our very own RICH TOWNSEND:
    - http://www.astro.wisc.edu/~townsend/static.php?ref=ez-web-movie
  - Two other very nice tools for exploring evolution of individual stars:
    - http://stellar.dartmouth.edu/models/
    - http://astro.u-strasbg.fr/~koppen/starpop/StellarEvolution.html
  - Watch a simple stellar population (SSP) evolve in the HR diagram:
    - http://www.kitp.ucsb.edu/~paxton/extras/movie10K.mpg
  - Where to go to build your own stellar population syntehsis (SPS) code:
    - http://stev.oapd.inaf.it/cgi-bin/cmd
    - http://www.astro.yale.edu/demarque/yystar.html -- for old populations
    - http://iopscience.iop.org/article/10.3847/0004-637X/823/2/102/pdf
- ***Your assignment:***
  - Explore the above.
  - What is the lower mass-limit for core He burning?
    - what happens after Iben's #6 for $M<3M_\odot$?
  - What is the lower mass-limit for core-burning beyond He?
    - How long-lived and luminous are these phases?

Summary

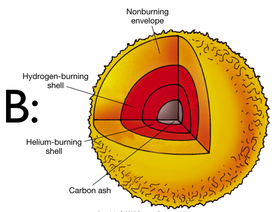
- Stellar types:
  - Classification – photometry & spectroscopy
  - τ_{MS}
- Stellar evolution:
- Burning phases
- Paths in the HR diagram (tracks)
- Elemental yields
- Metrics of evolution



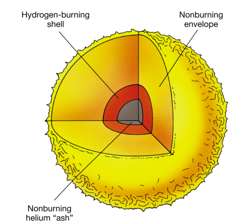
SG:



AGB:



RGB:

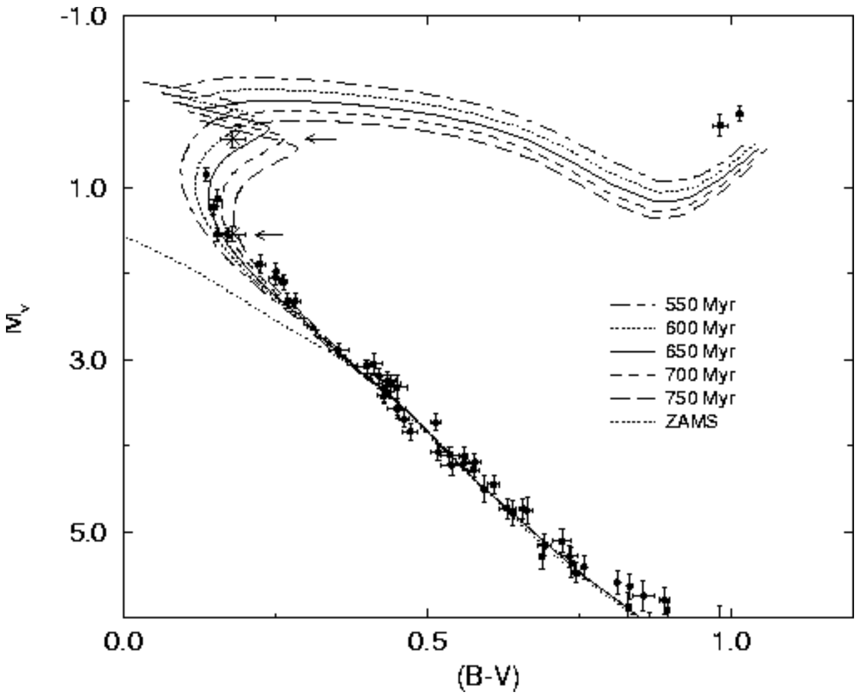


Understanding Stellar Populations

- Color – temperature – mass – lifetime relationships mean the observed "color-magnitude" diagram (CMD) can tell us something about the age/evolutionary status of a stellar population (especially if it's a single age)
- CMD can also hint at the production of metals

H-R Diagrams

- Stars spend most of their lives on the "main sequence"
- "turn-off" age is primary indicator of the age of a stellar population

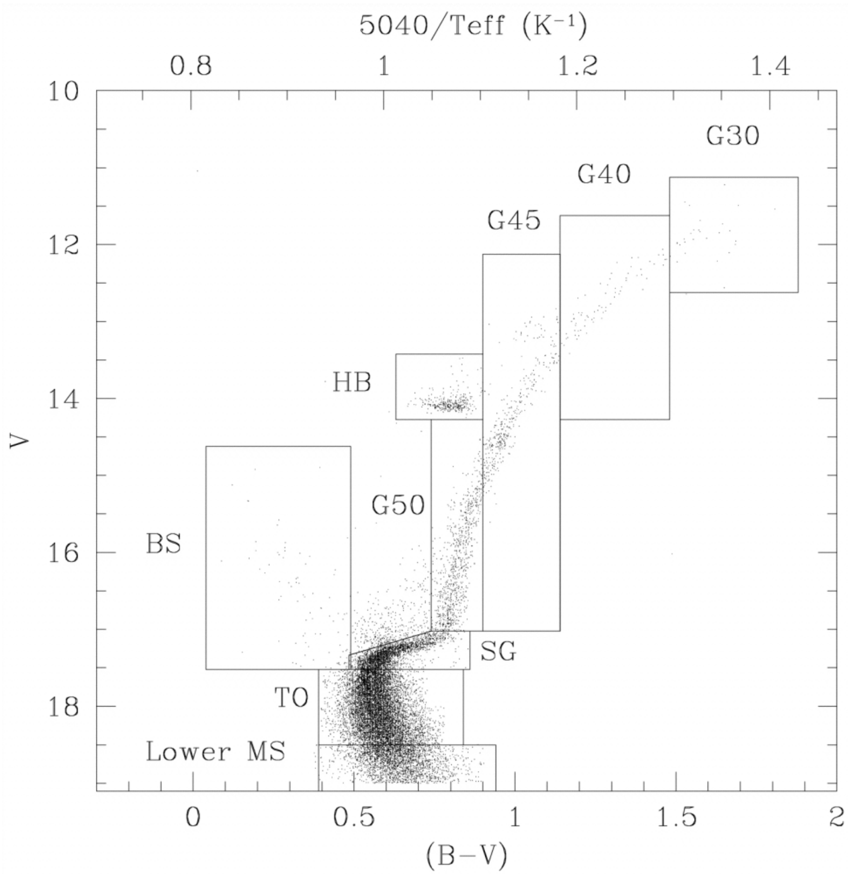


Hyades open cluster; Perryman et al. 1998

Aldeberan – not part of cluster

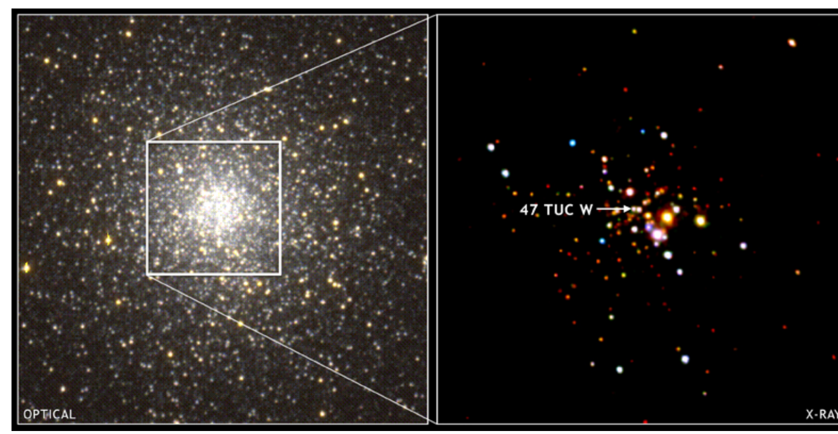
ZAMS = zero-age main sequence

H-R Diagrams *continued*

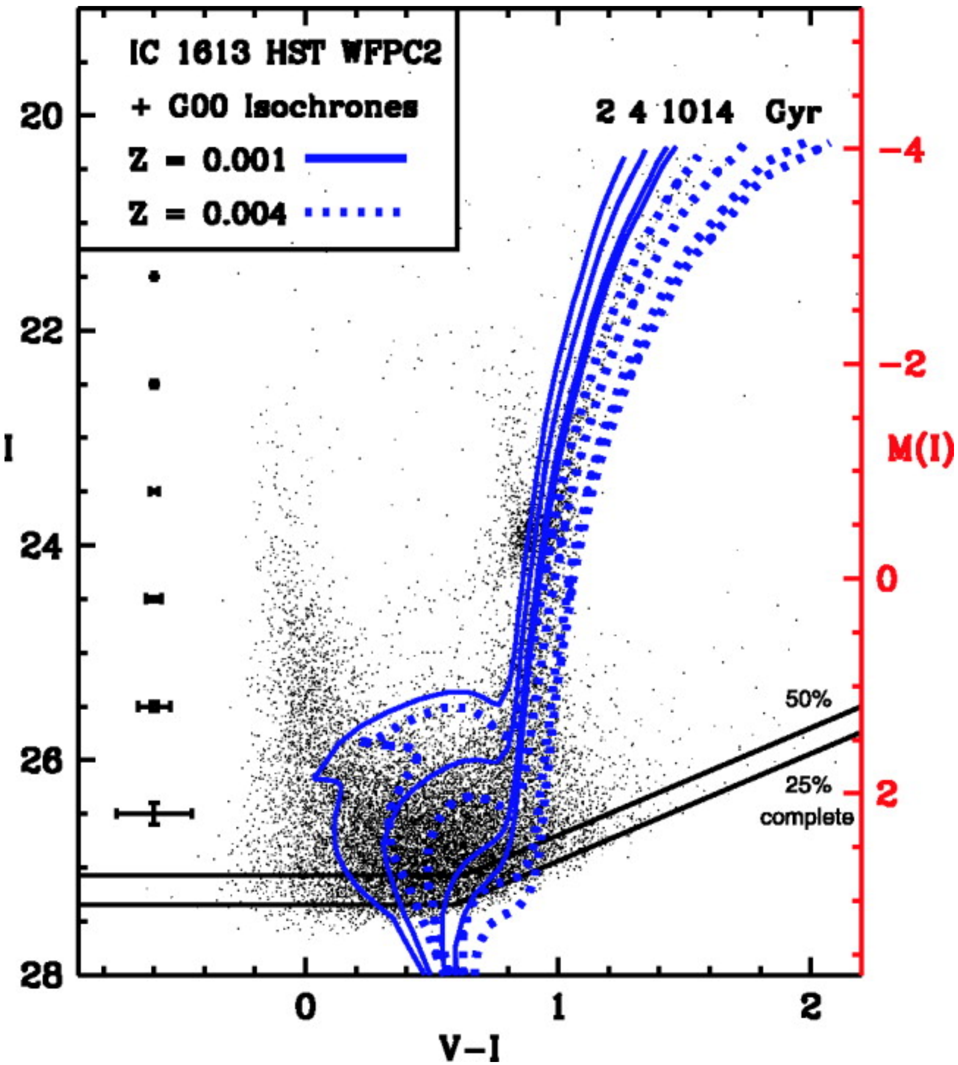


Globular cluster 47 Tuc
(Edmonds et al. 2002)

- Tracing evolution of a stellar population
- (B-V) ➔ temperature
- V ➔ luminosity



H-R Diagrams *continued*

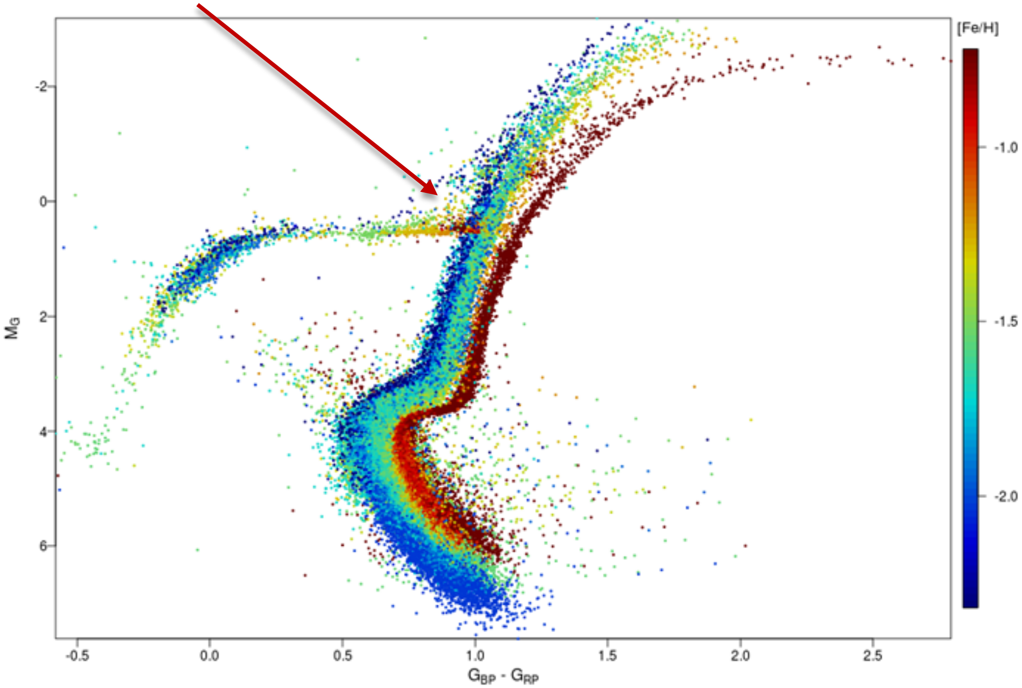


- Gets more complicated with a mixed-age stellar population
- Multiple turn-offs, multiple HBs
- Dwarf spheroidal galaxies are ideal labs for this

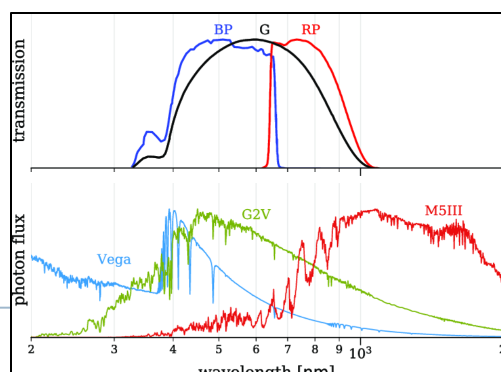
H-R Diagrams *continued*

Red clump appears above [Fe/H] ~ -1.25

Absolute Magnitude



Blue-Red color



- Metallicity drives shifts in giant branch and turn-off location in HRD due to changes in line-opacity
- It also changes the Horizontal Branch morphology

- Gaia DR2
- 14 globular clusters

Statistical Stellar Astrophysics

- Stellar initial mass function
  - $dN = N_o \xi(M) dM$
  - $N_o \int dM\, M\, \xi(M)$ = total mass of burst/episode
  - Observationally: $\xi(M)$ goes as $(M/M_\odot)^{-2.35}$
    - "Salpeter IMF"
    - Slight variation with mass (time? environment?), according to some
    - Upper mass limit in the 80-120 $M_\odot$
      - but note small-number statistics become important
    - Turn-over likely below 0.1 $M_\odot$
    - Other estimates of the IMF:
      - Miller-Scalo
      - Chabrier *
      - diet-Salpeter
      - Kroupa *
      - bimodal (e.g., Larson)

* Common in modern SPS

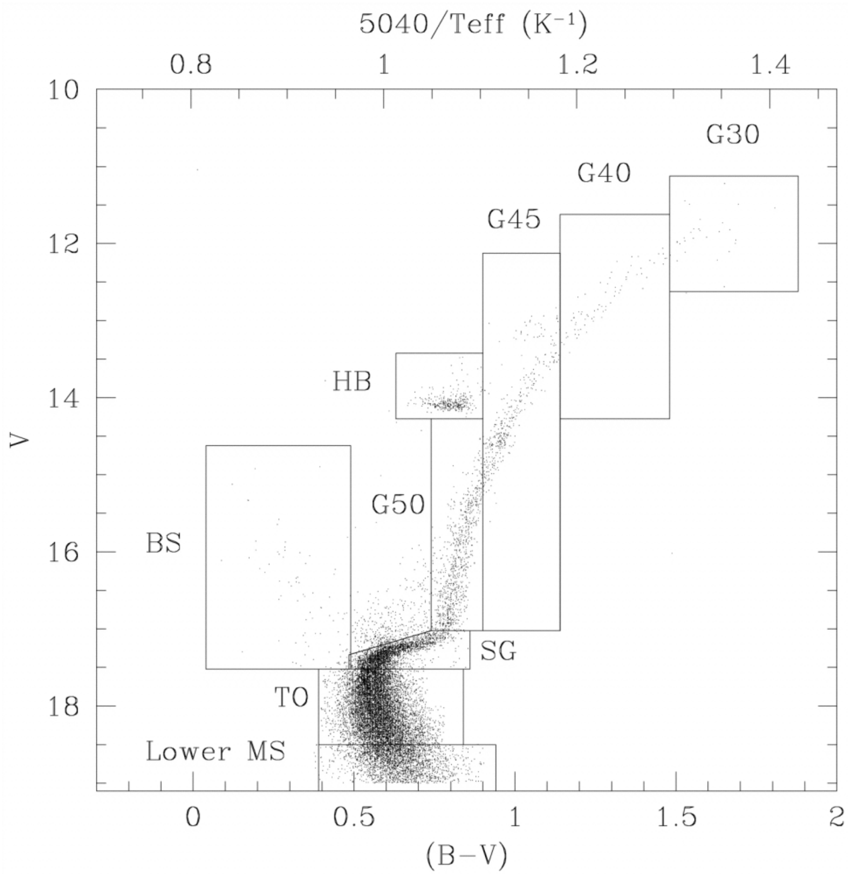
Stellar Populations

- Integrated Colors
  - Population I – "Disk Population" – open clusters, circular orbits, confined to a disk, "blue"
  - Population II – "Halo Population" – globular clusters, large random velocities, elliptical orbits, spherical distribution, "red"
  - Population III – extremely metal poor, not yet detected
    - Cosmic Mystery #2: Where are the Pop-III stars?
- Correlations
  - Color vs kinematics
    - Blue stars are disk-like
  - Color vs metallicity
    - Red stellar populations tend to be metal poor, strong Galactic correlation between kinematics and metallicity

Interpreting CMDs

- Density of any locale on a CMD is a function of IMF, SFR, mass, and age
  - $C(M_V, V\text{-}I) = \iint \xi(\log m, t) \times SFR(t)\, dt\, d\log m$
    - Small mass bin (i.e. single mass)
    - Constant IMF (ξ)
    - Can recover star formation history from a complex CMD
- Statistical Approach
  - What is the probability that a certain distribution of points on the CMD came from one particular set of stellar evolution models (Tolstoy & Saha 1996)

HR Diagrams revisited



H-R diagram for 47 Tuc

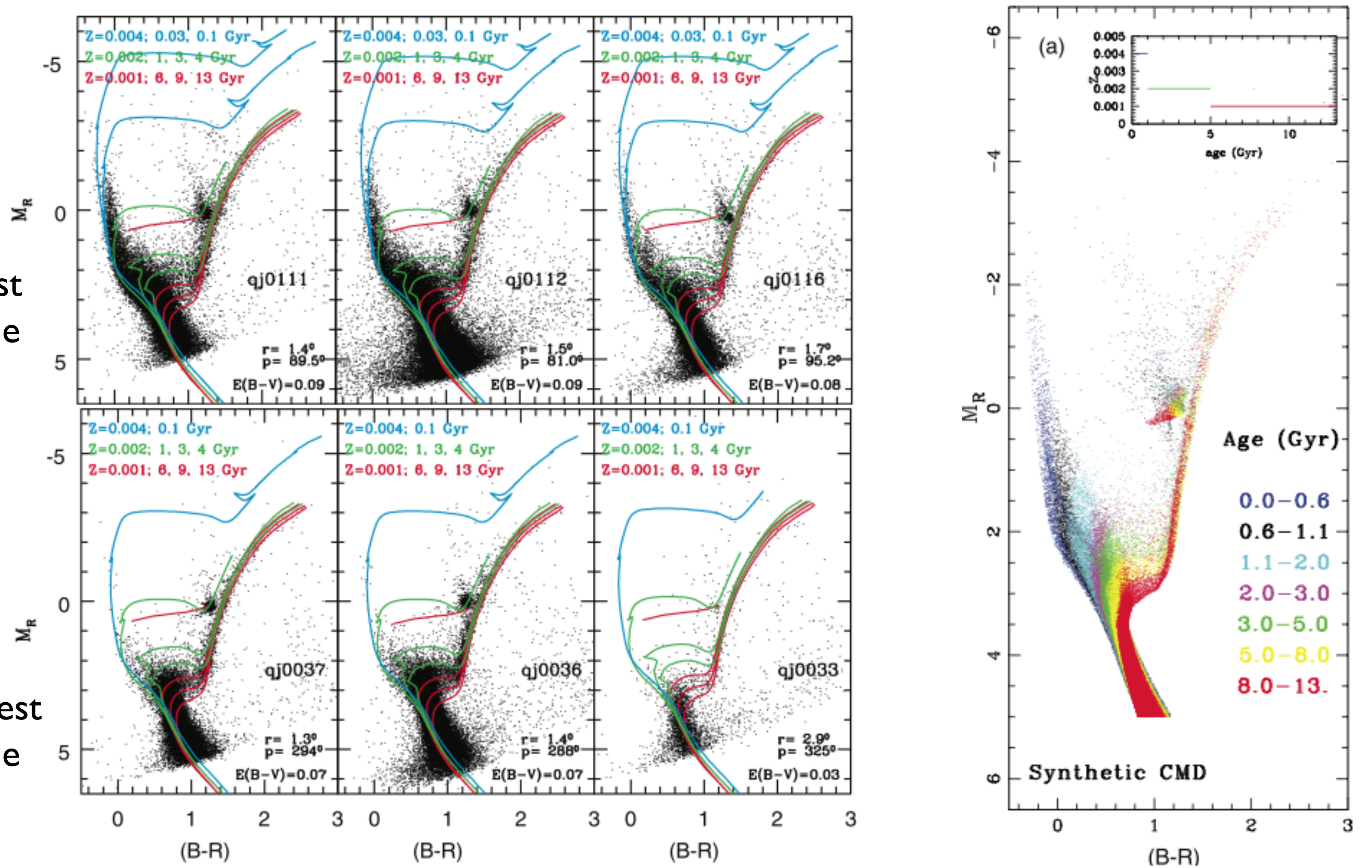
[Fe/H] = -0.75

- Evolution + nucleosynthesis – each box is a different burning stage
- Could you sketch the H-R diagram of this cluster and label all of the major burning stages?

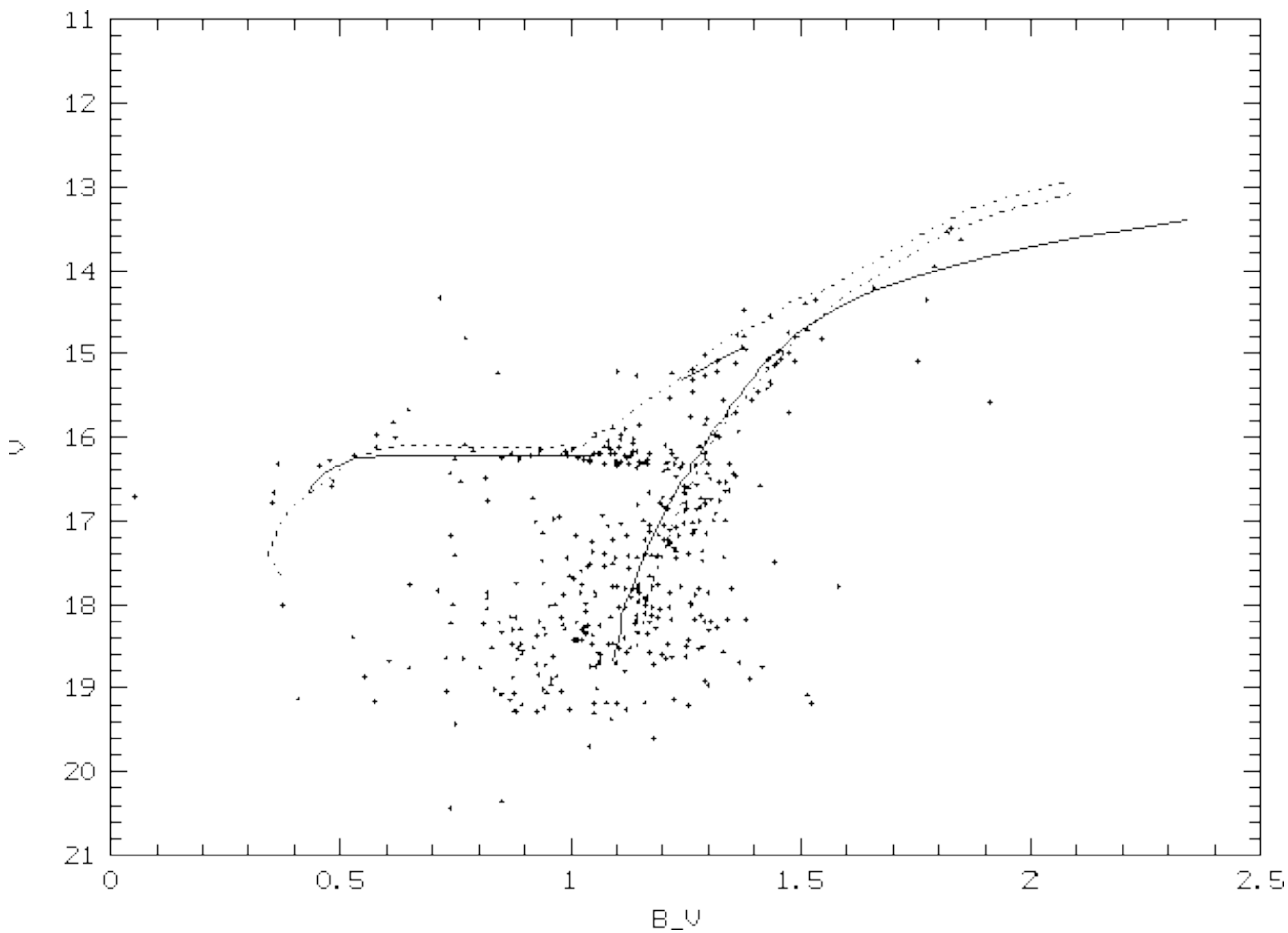
SMC: Noel et al. 2007

East side

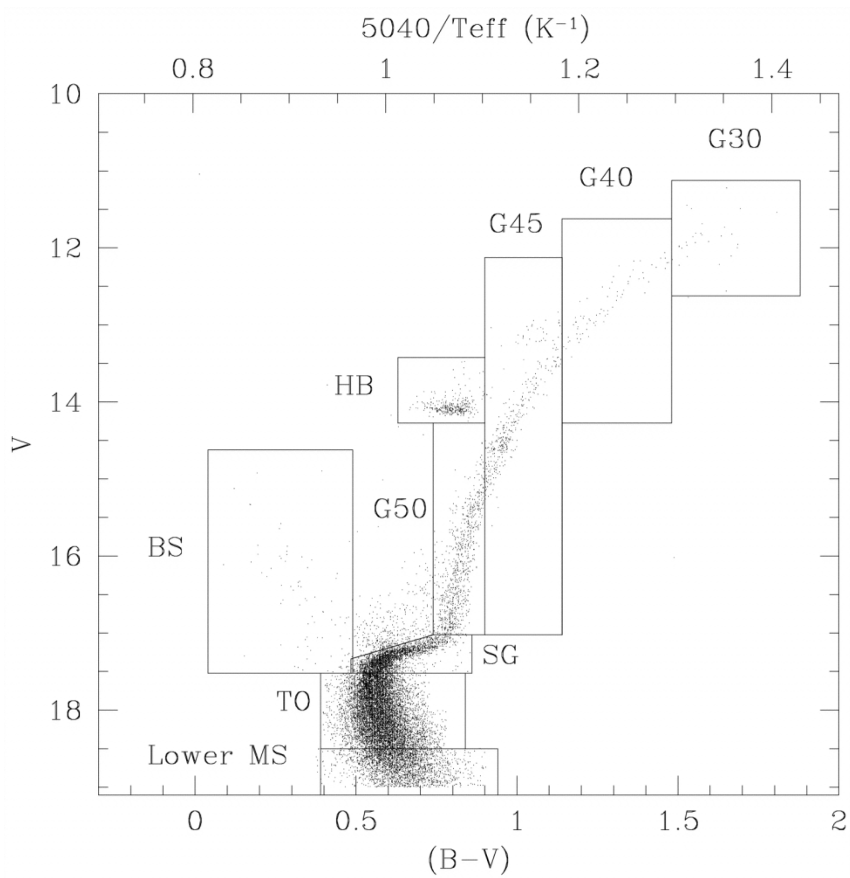
West side



How old is this cluster? Why?



Summary: stellar populations



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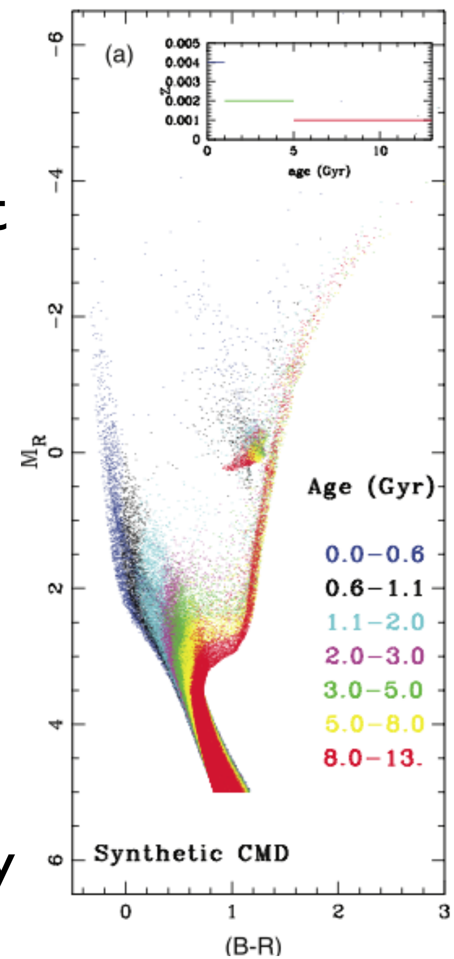
    - Constant IMF (ξ)
    - Can recover star formation history from a complex CMD
- Statistical Approach
  - Probability distribution of points on the CMD from one particular set of stellar evolution models (Tolstoy & Saha 1996)
- Stellar initial mass function
  - $dN = N_o \xi(M) dM$
  - $N_o \int dM\, M\, \xi(M)$ = total mass
  - Observationally: $\xi(M)$ goes as $(M/M_\odot)^{-2.35}$
    - Upper mass limit in the 80-120 $M_\odot$
    - Turn-over likely below 0.1 $M_\odot$

Questions to answer:

- What is the fraction of the total integrated luminosity of a stellar population as a function of the limiting stellar absolute magnitude (i.e., the integral of all stars brighter than some limit compared to the total integral).
  - How does this depend on wavelength, population age (star-formation history) and metallicity?
  - How can you estimate this crudely but easily?
  - How can you estimate this more precisely?
  - Are there tools already available?

- What are the resolution limits in ground or spaced-based imaging in the MW, Local Group galaxies (e.g., LMC, SMC, M31, M33) and nearby galaxies outside the LG?



To get you started:

- Analytic solution:
  - IMF, MS lifetime, M-L relations
- Trilegal (Girard+2005,2016)
  - http://stev.oapd.inaf.it/cgi-bin/cmd
  - http://stev.oapd.inaf.it/cgi-bin/trilegal
- Dartmouth
  - http://stellar.dartmouth.edu/models/
- MATCH (Dolphin 2002; see also Beerman+2012, Weisz+2015, Lewis+2015)
- IAC-STAR (Aparacio & Gallart 2004; Gallart+2005, Pietrinferni+04)
- Noel+2007
- Dalcanton+ 2012a,b, Williams+2015

Stellar Population Synthesis (SPS)

Z = metallicity, e.g., Fe/H
'Metals' are anything heavier than He
A = abundance, i.e., any metal relative to Fe
(R,θ,φ) = spatial cell in a galaxy

- Key ingredients
  - IMF(t,ρ,Z)
  - SFR(t; R,θ,φ)
  - Isochrones (theoretical HR diagram)
  - Stellar library with parameters (log g, Te, Z,A) to map to HR
  - Chemical evolution: Z(t;R,θ,φ), A(t; R,θ,φ)
  - Density evolution: ρ(t; R,θ,φ)
    - or whatever else the IMF depends on, e.g., turbulence, magnetic fields
  - Dynamical diffusion rate
  - Resonant scattering (e.g., radial migration)

If you want to know what stars you should expect to find at some time in some cell of the galaxy (R,θ,φ) then you need the ingredients in red; these are beyond most SPS models, but are explored in various types of numerical models that explore galaxy formation and evolution.

- Renzini & Pecci (ARAA, 1988, 26, 199)

SPS and the Fuel Consumption Theorem

- Fuel Consumption theorem (FCT)
  - The relative *bolometric* contribution of stars (L_j) in any evolutionary phase (j) is equal to the relative amount of fuel (F_j) that each evolving star burns during that phase

$$L_j/L_{\mathrm{T}} = \sim 9.75 \times 10^{10} B(t) F_j,$$

Amount of fuel burned by stars of turn-off mass $M_{TO}(t)$:

$$F_j = \Delta M_j^{\mathrm{H}} + 0.1 \Delta M_j^{\mathrm{He}}$$

He fusion liberates only 10% energy per unit mass compared to H

Total (integrated) luminosity

Number of stars in any post-main sequence stage of duration t_j :

$$N_j = B(t) L_{\mathrm{T}} t_j,$$

Death-rate per unit luminosity, i.e., the specific evolutionary flux; *B(t)* ranges from 0.5×10^{-11} to 2×10^{-11} stars per year per L as age increases from 10^7 to 10^{10} yr

- Renzini & Pecci (ARAA, 1988, 26, 199)

Fuel-consumption *continued*

- FCT particularly useful for old stellar populations
  - For $t \geq 10^{10}$ yr, $B(t) \sim 2.2\times10^{-11}$ stars $L_{\odot}^{-1}$ yr^{-1}

$$\frac{L_j}{L_T} \simeq 2 \times F_j[M_{\mathrm{TO}}(t)] \, .$$

  - Accurate to about 10%
  - When you don't trust the isochrones FCT is the best solution and always a good sanity check.

Examples: M3 and 47 Tuc

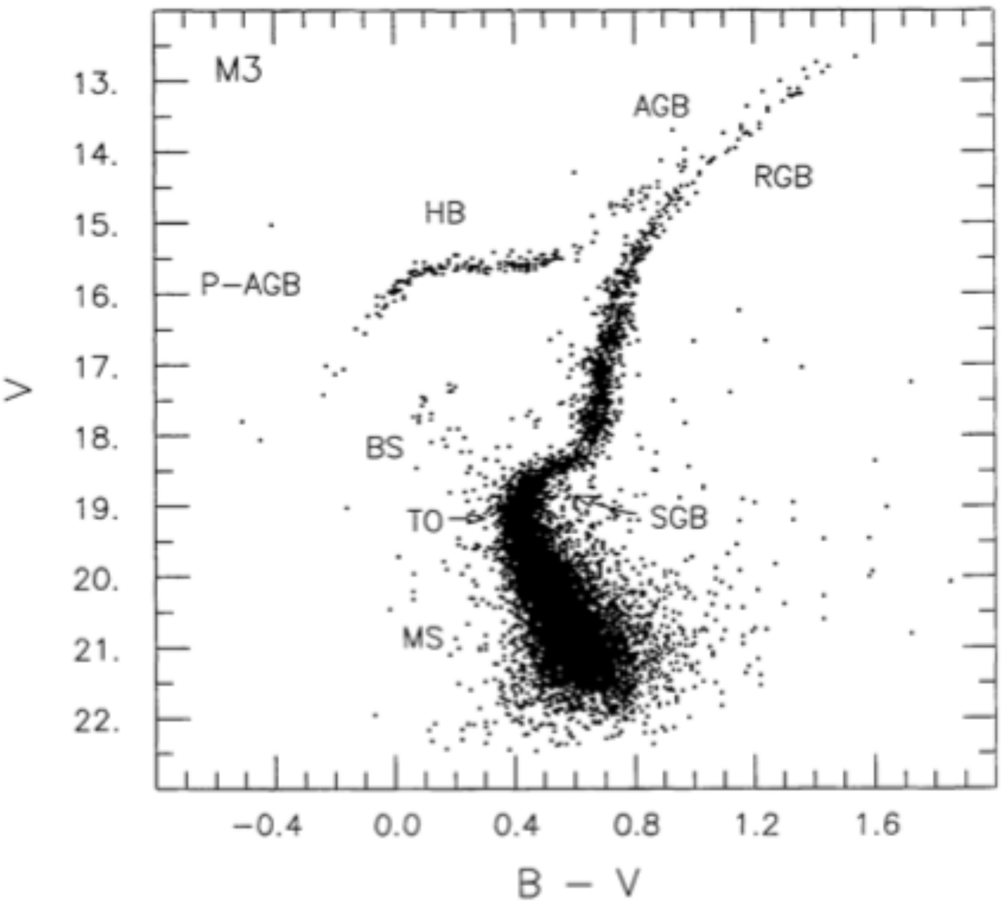


Figure 1 The CMD of the cluster M3 (Buonanno et al. 1986a, 1987). In this diagram, 10,637 stars are plotted, 9879 from a sample that is complete down to $V = 21.5$ and totals $\sim 30{,}000\ L_{\odot}$ of cluster light, while the remaining 758 stars are drawn from a sample that is complete down to $V = 18$ and totals $\sim 50{,}000\ L_{\odot}$ of cluster light. The stars brighter than $V = 18$ therefore belong to a sample totaling $\sim 80{,}000\ L_{\odot}$ of cluster light ($\sim 30\%$ of the total luminosity of M3). More information on this diagram can be found in Table 2. The following classification has been adopted for the various evolutionary stages: 1. main sequence (MS)—core hydrogen-burning phase; 2. blue stragglers (BS); 3. subgiant branch (SGB)—shell hydrogen-burning phase, from the MS turnoff (TO) to the Hayashi line; 4. red giant branch (RGB)—shell hydrogen-burning phase along the Hayashi line, until helium ignition in the core; 5. horizontal branch (HB)—core helium-burning phase; 6. asymptotic giant branch (AGB)—shell hydrogen- and helium-burning phase; 7. post-AGB (P-AGB)—final evolution from the AGB to the white dwarf (WD) stage.

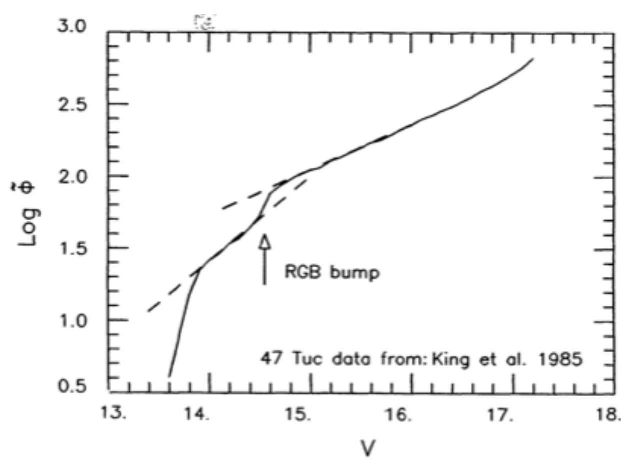
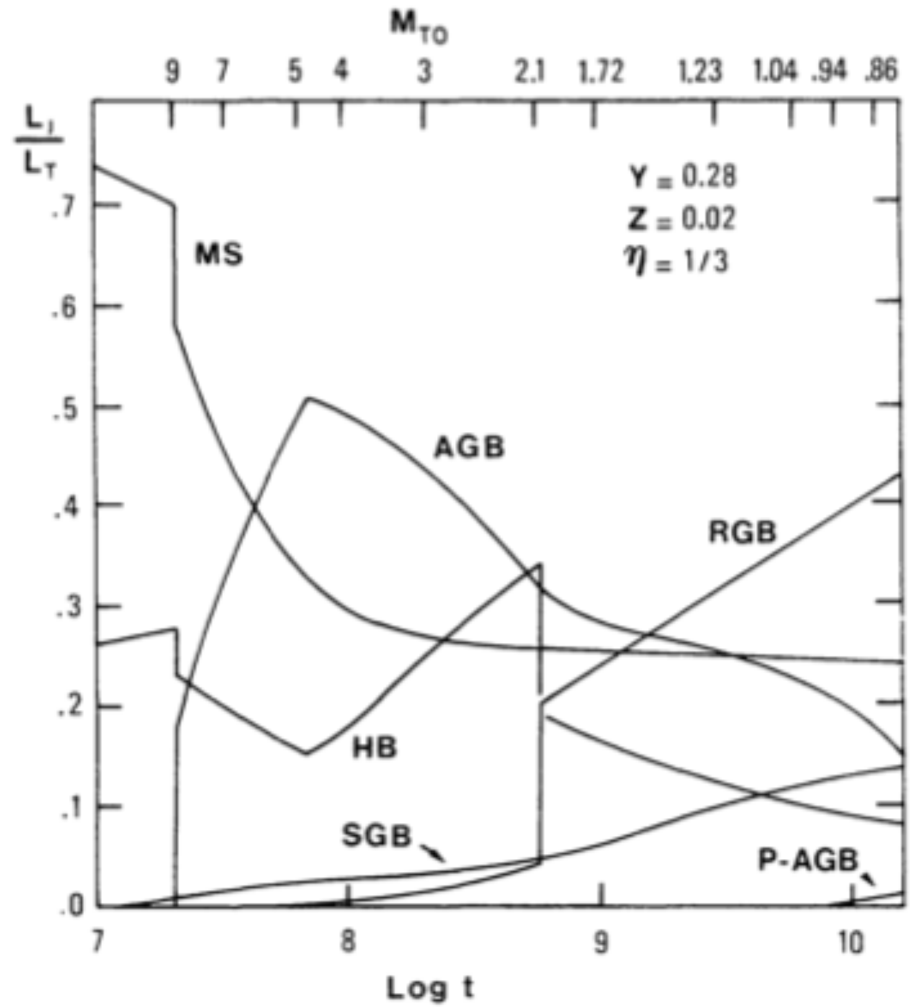


Figure 4 The cumulative luminosity function $\tilde{\Phi}$ for the RGB stars of the cluster 47 Tuc, obtained from Figure 4 of King et al. (1985). The RGB bump and the associated change in slope are clearly visible.

M3: [Fe/H] = -1.34 to -1.5
47 TUC: [Fe/H] = -0.75

- RP88

Bolometric contributions by time and phase



- RP88

Contributions by time, phase, and λ

- Updated with modern stellar population synthesis (SPS)

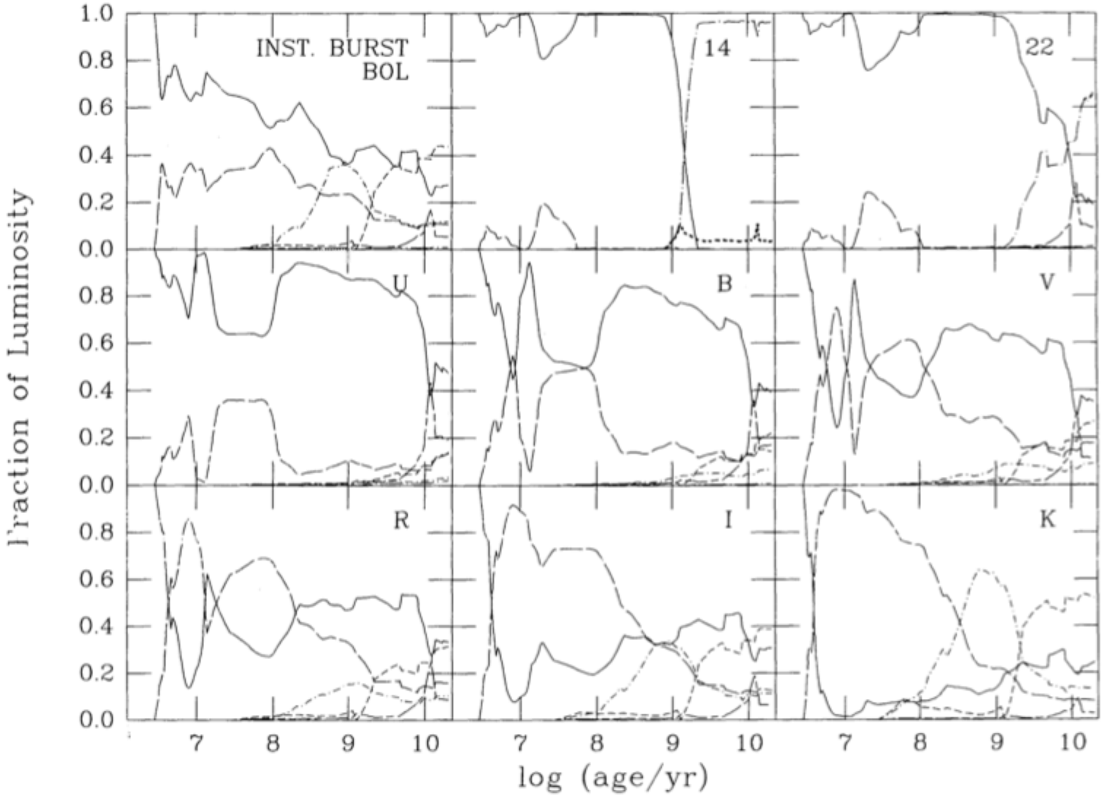


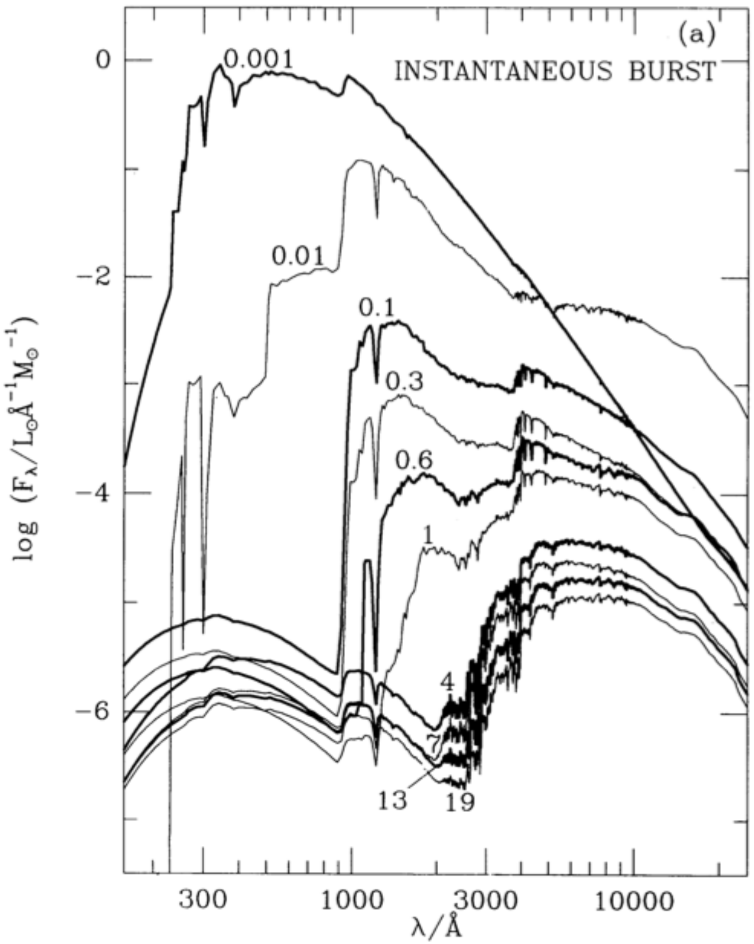
FIG. 2.—Fractional contribution to the integrated light of an instantaneous-burst population by the various stellar evolutionary stages, as predicted by the present model of spectral evolution (isochrone synthesis). The nine panels indicate the contributions to the bolometric light, to the fluxes at 1400 and 2200 Å, and to the broad-band *UBVRIK* fluxes. In each panel the different curves correspond to the following stellar evolutionary stages (acronyms defined in § 3.5): main sequence (*solid line*), SGB (*short-dash–long-dash line*), RGB (*dashed line*), CHeB (*long-dashed line*), AGB (*dot–short dash line*), PNN (*dot–long dash line*), and WD (*short-dashed line*).

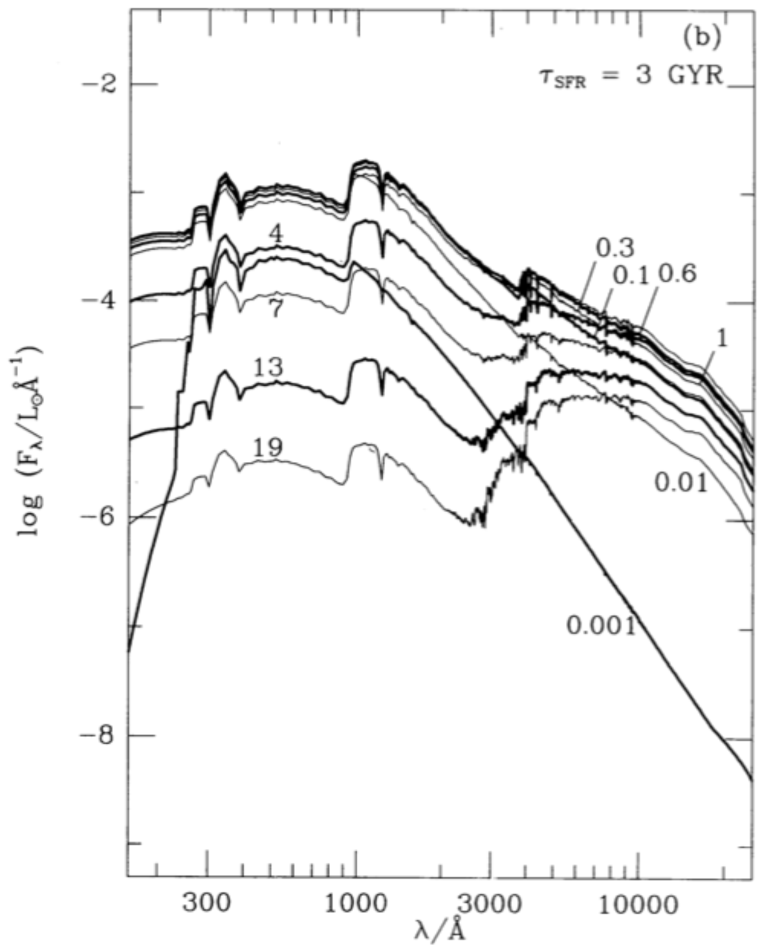
Bruzual & Charlot (1993, ApJ, 405, 538)
Bruzual & Charlot (2003, MNRAS, 334,1000)
http://www.cida.ve/~bruzual/bc2003

See also PEGASE and PEGASE-HR (Le Borgne et al. 2004, http://www2.iap.fr/pegase/); PEGASE-HR covers 400-680nm at R = 10,000.

- See also Portinari et al. 2004, Maraston et al., Conroy et al. : chem. evol., late phases.

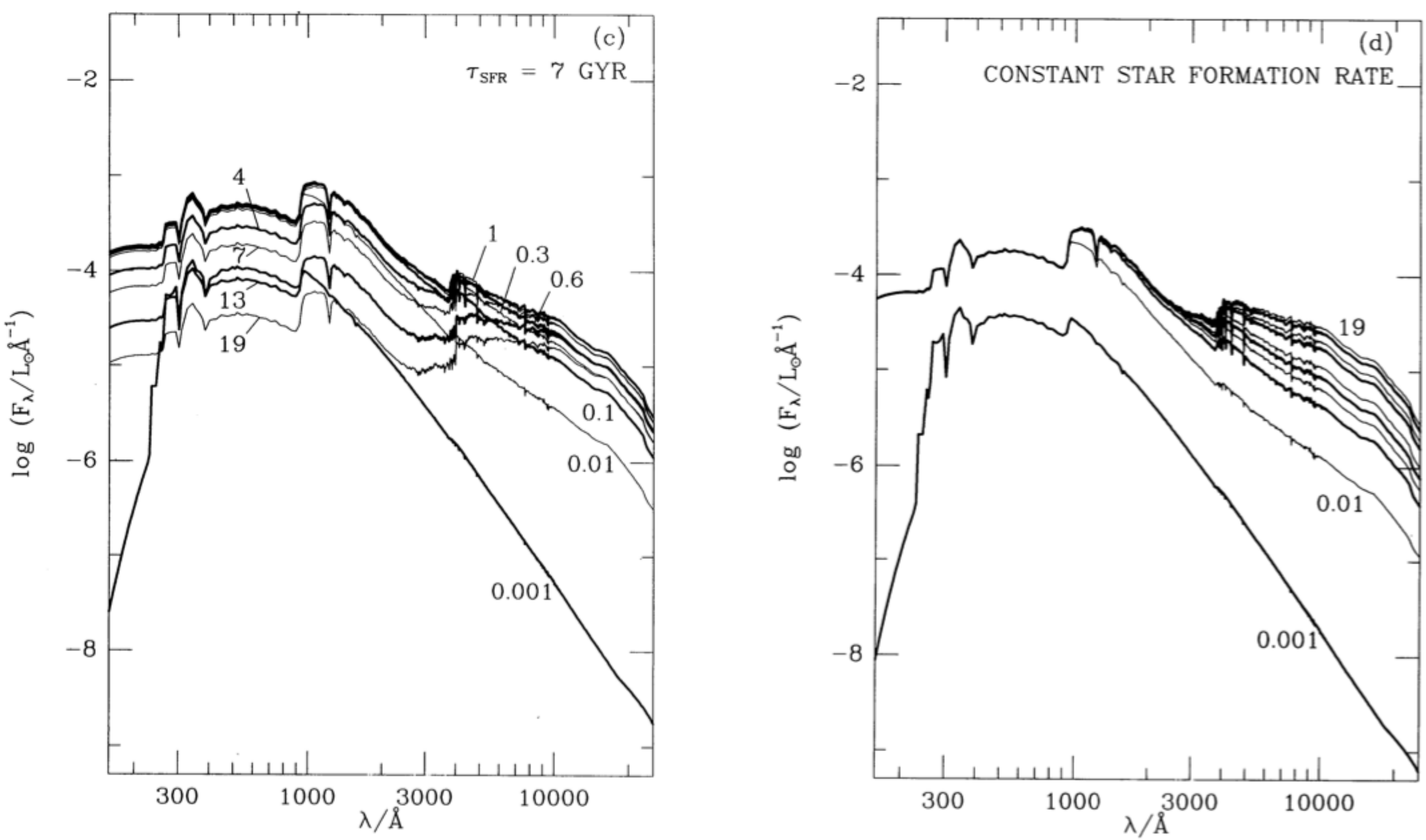
SPS Evolution: early star-formers





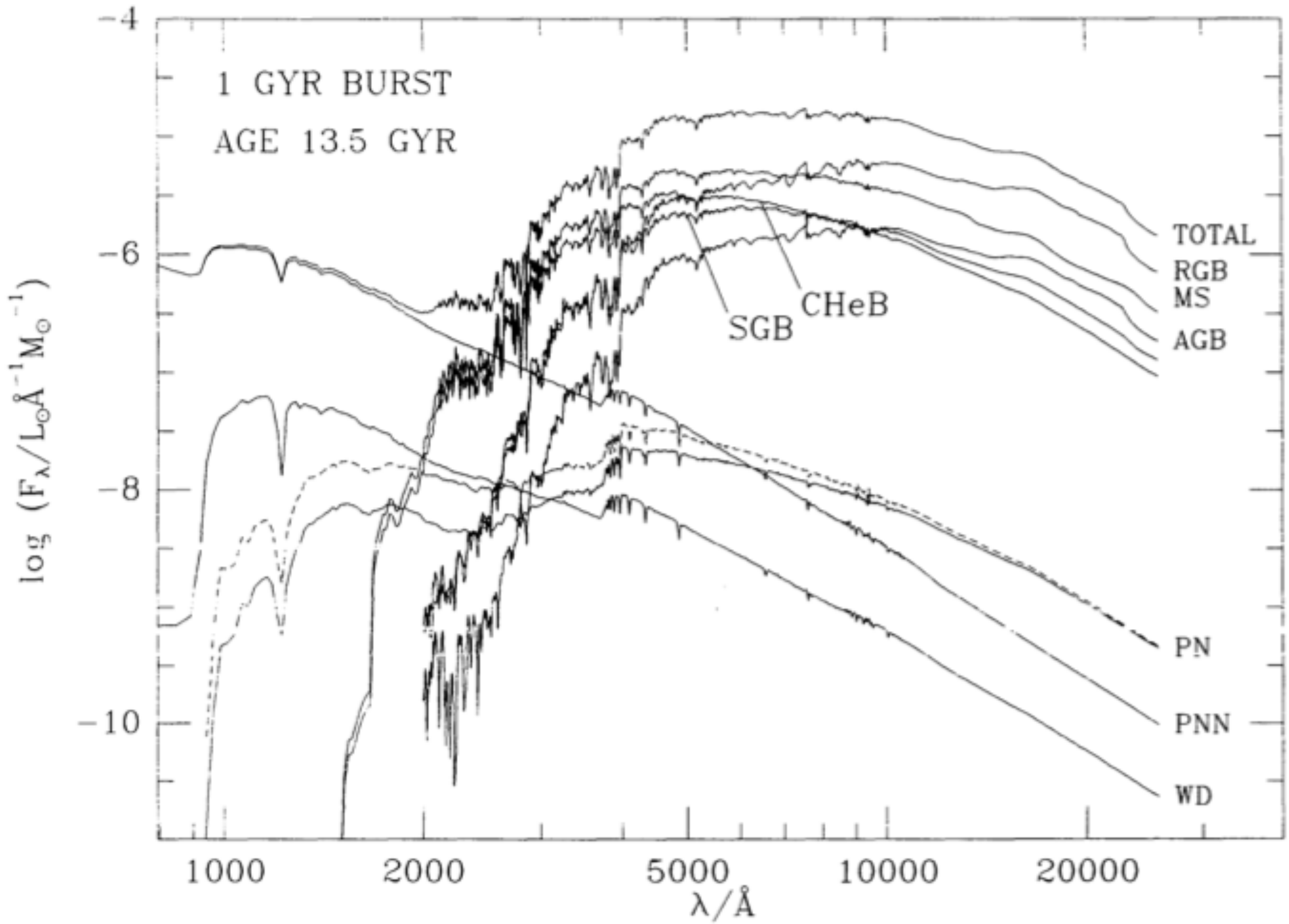
- BC93

SPS Evolution: on-going star-formers



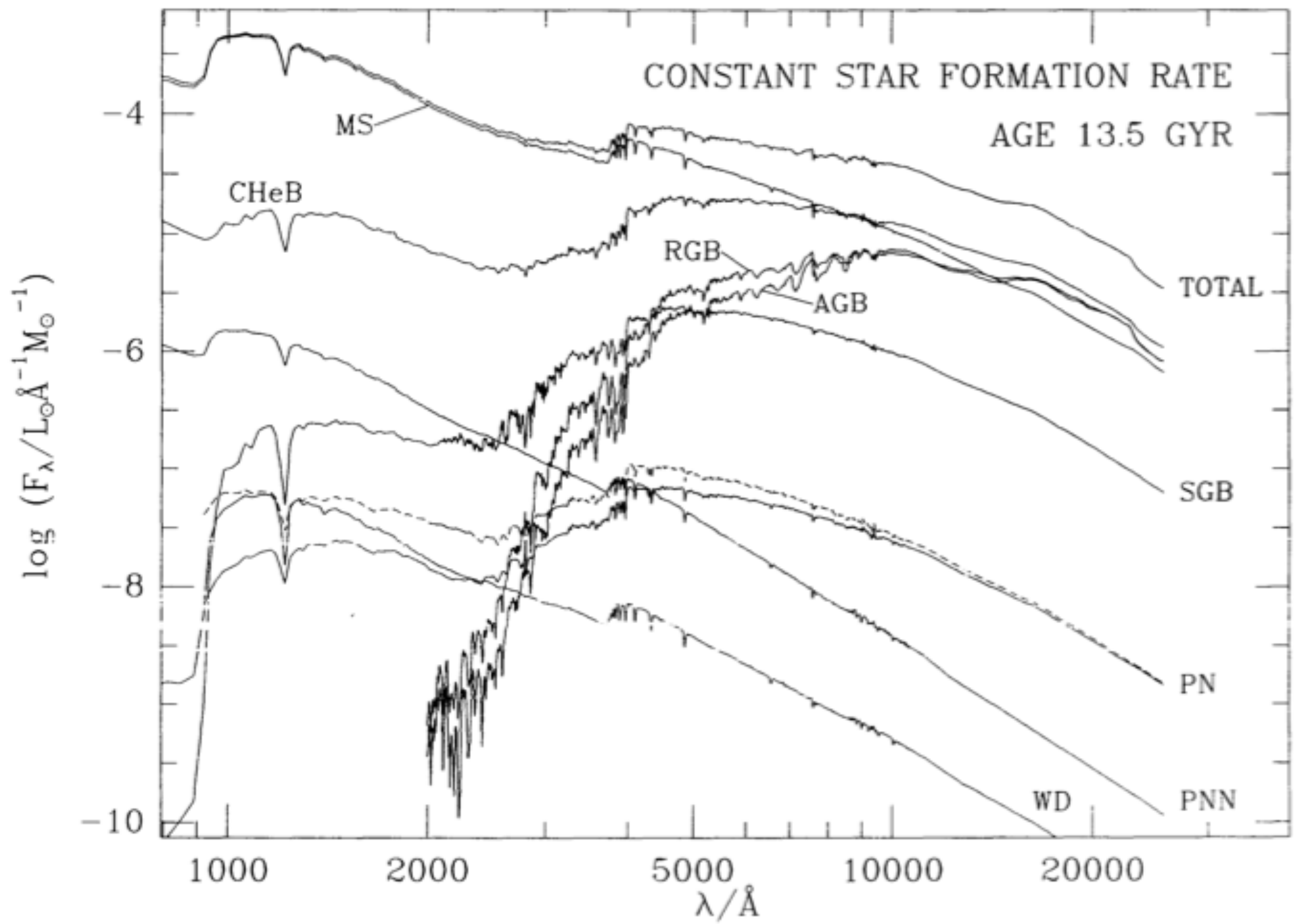
- BC93

SPS Contributions today: early star-formers



- BC93

SPS Contributions today: on-going star-formers



- BC93

List of modern SPS

- Bruzual & Charlot (2003, ApJ)
- Conroy, Gunn & White (2009, ApJ, 699, 486)
- Maraston & Strömbäck (2011, MNRAS, 418, 2785)
- Vazdekis et al. (2015, MNRAS, 449, 1177)

Differential populations synthesis

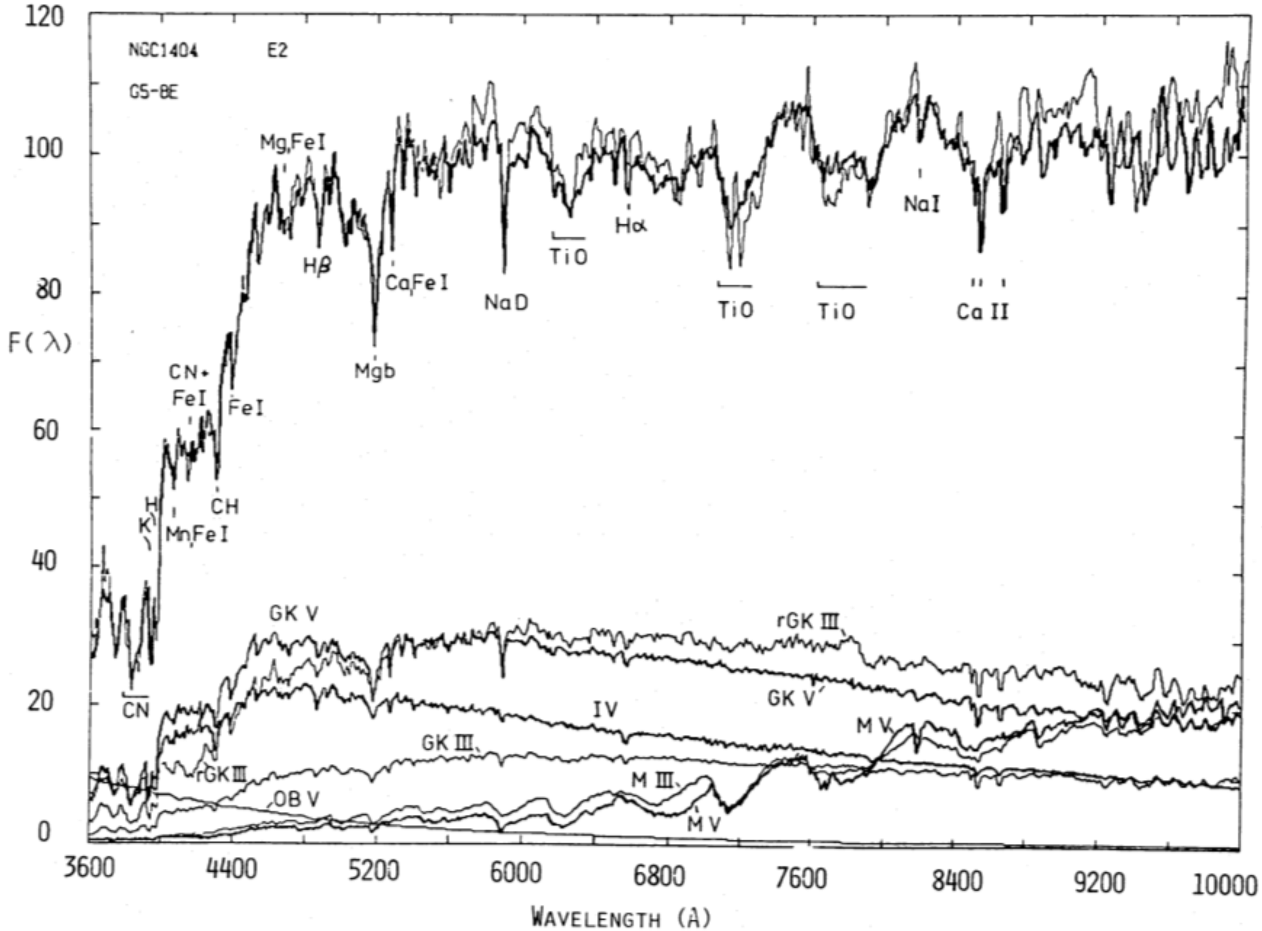
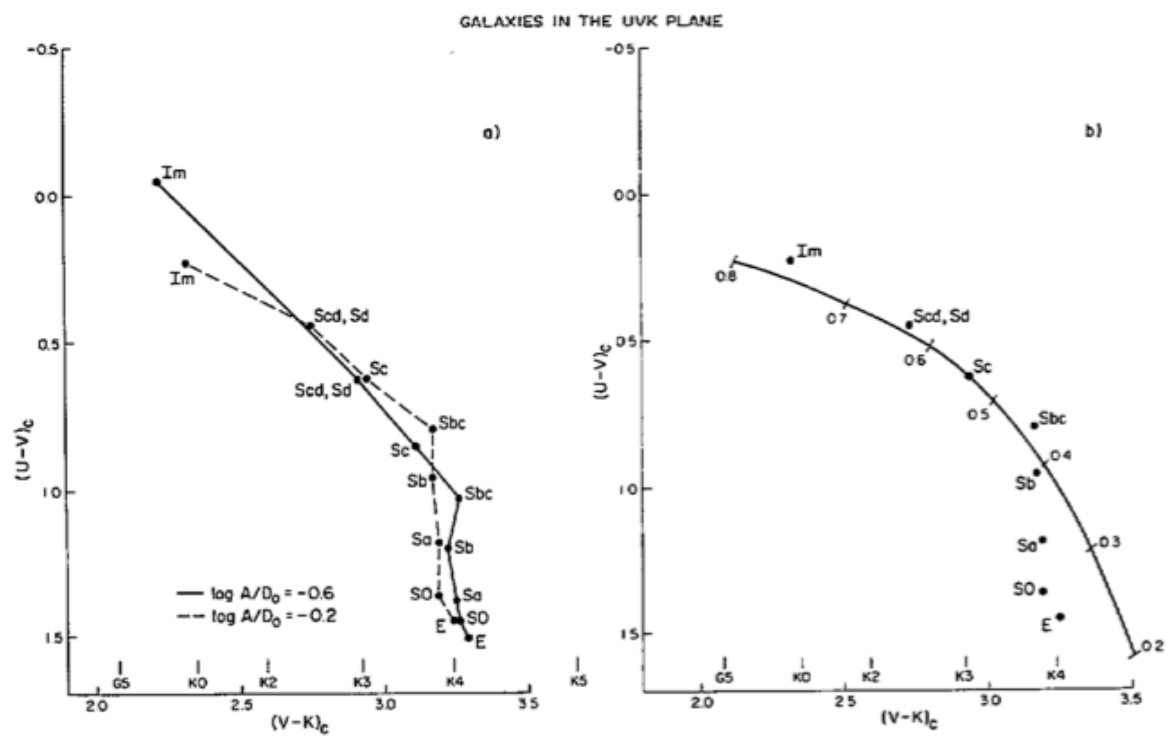


FIG. 2a

- Pickles 1985 (ApJ, 296, 340)

Simple population synthesis: the UVK plane

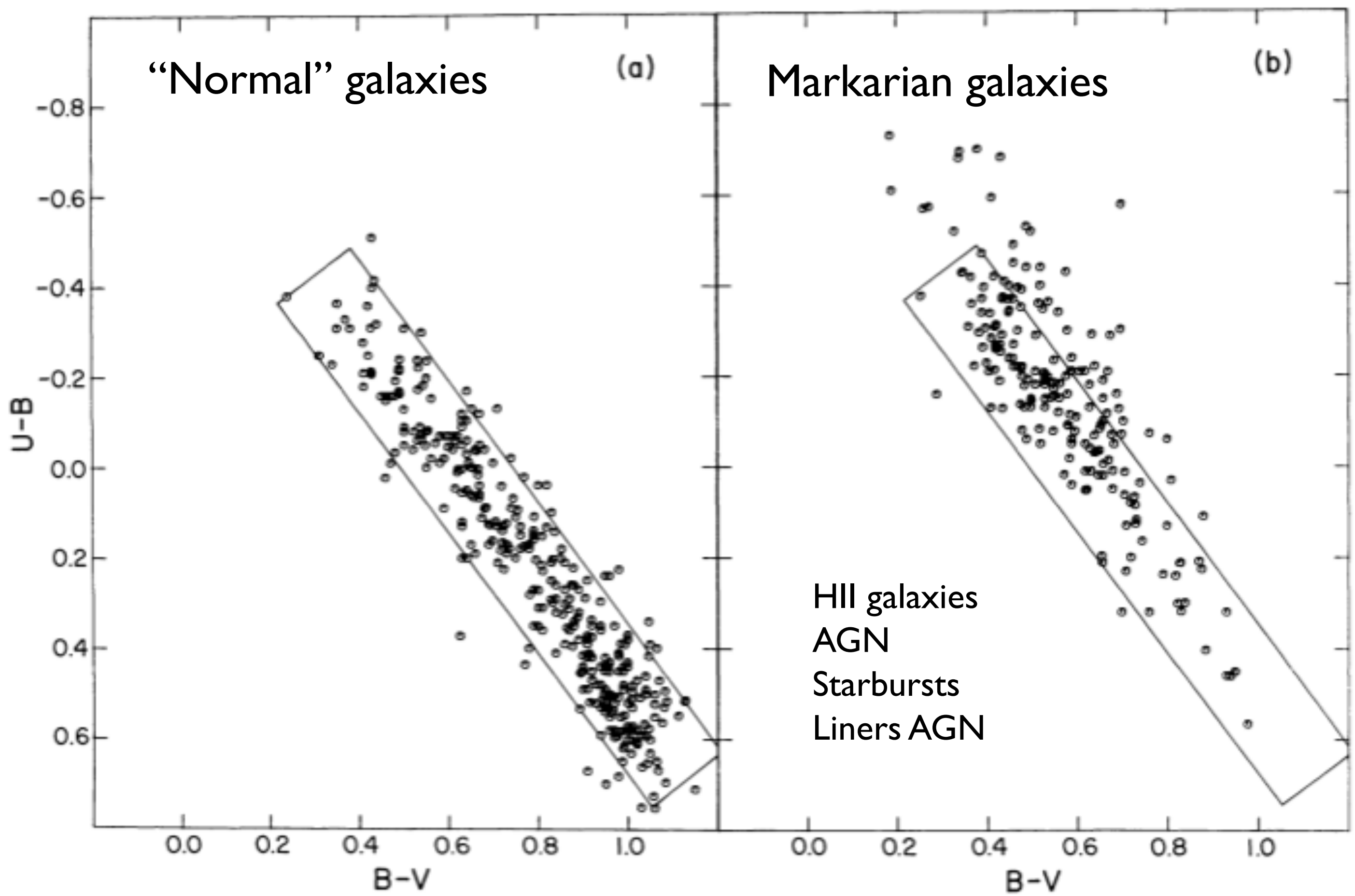


U: 370 nm
V: 550 nm
K: 2200 nm

Galaxies can be well-modeled by an admixture of A0V and M0III in U-V vs V-K

- Aaronson 1980 ApJ, 221, L103

Galaxies in the UBV plane



Markarian:
Russian astronomer

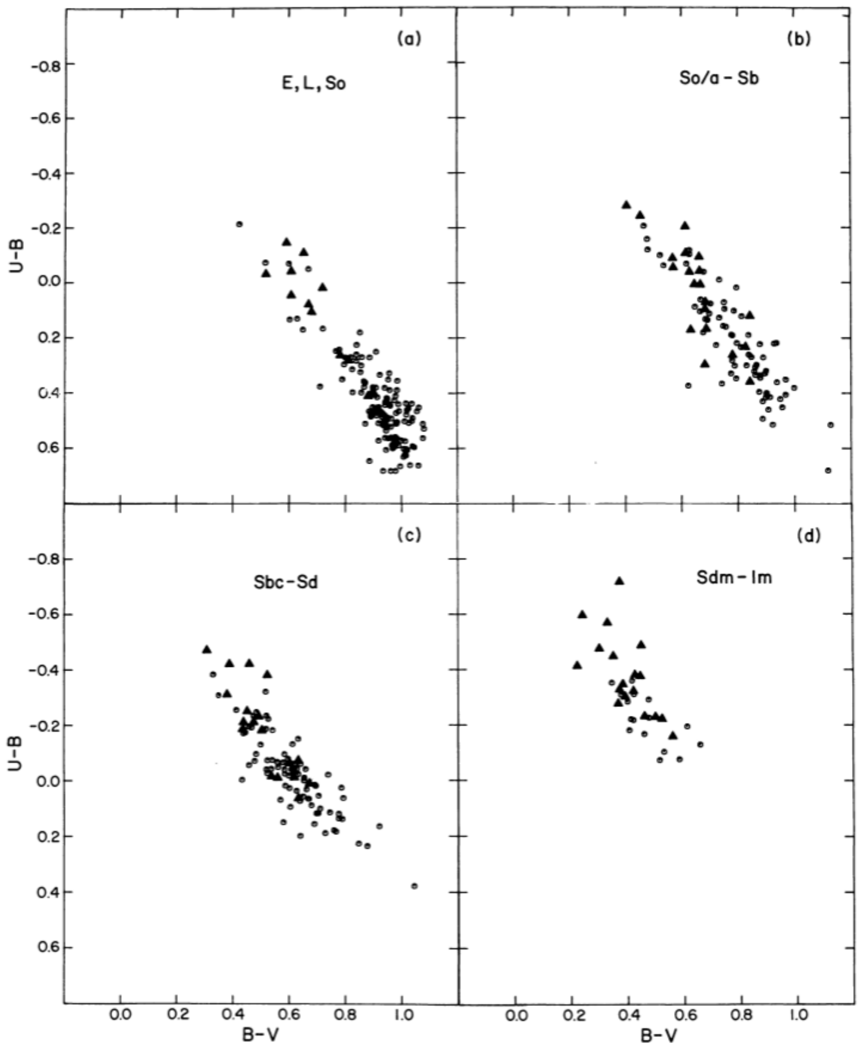
U: 370 nm
B: 440 nm
V: 550 nm

What's the color of an A0V?

What does this tell us about Aaronson's simplification of A0V+M0III for the UVK plane?

- Huchra 1977, ApJS, 35, 171

Galaxies in the UBV plane by Type



U: 370 nm
B: 440 nm
V: 550 nm

What's the color of an A0V?

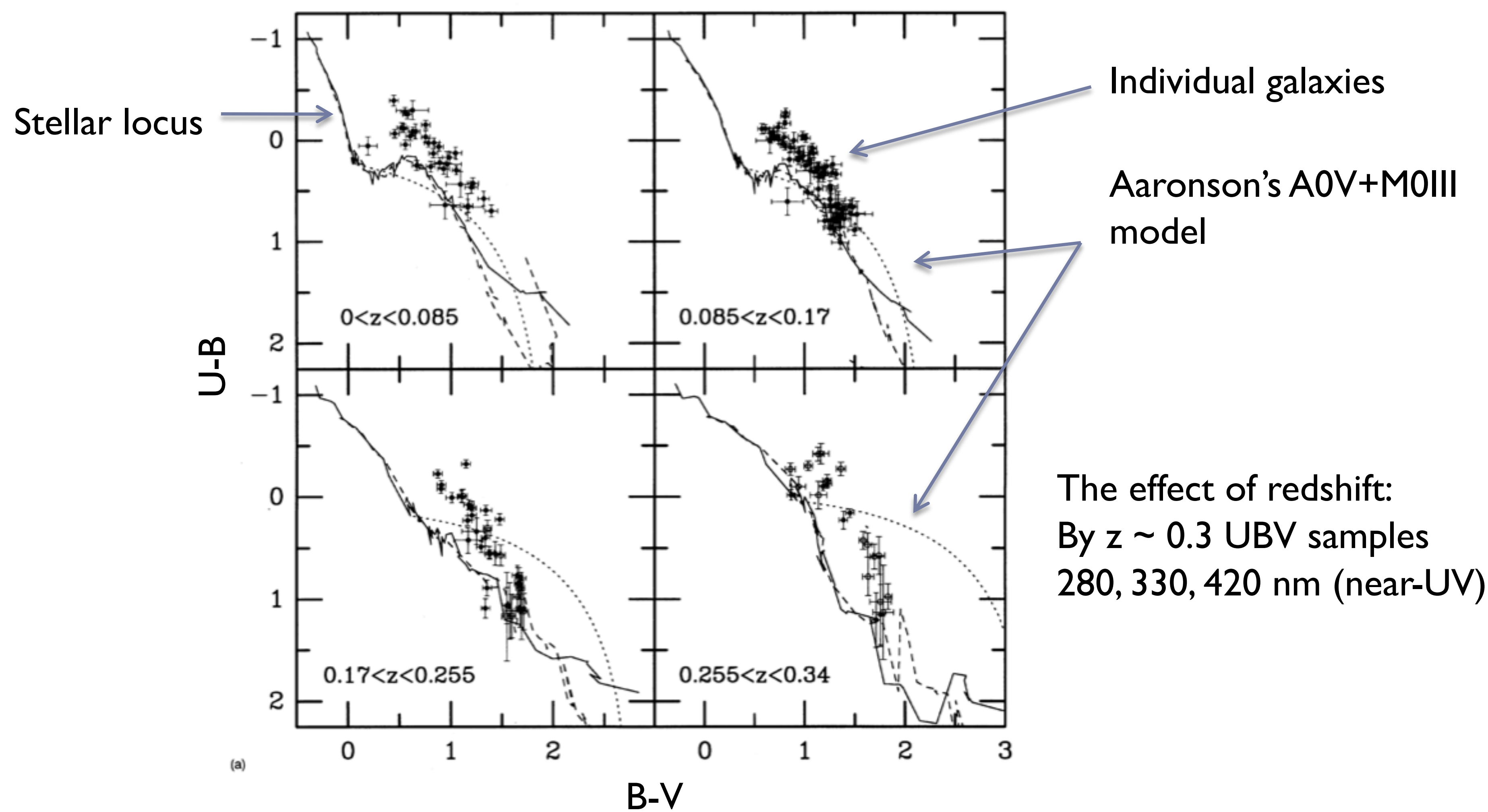
What does this tell us about Aaronson's simplification of A0V+M0III for the UVK plane?

Why is it more complicated when you look in more detail in the blue? (U-V ➔ U-B,B-V)

What are the implications for spectra?

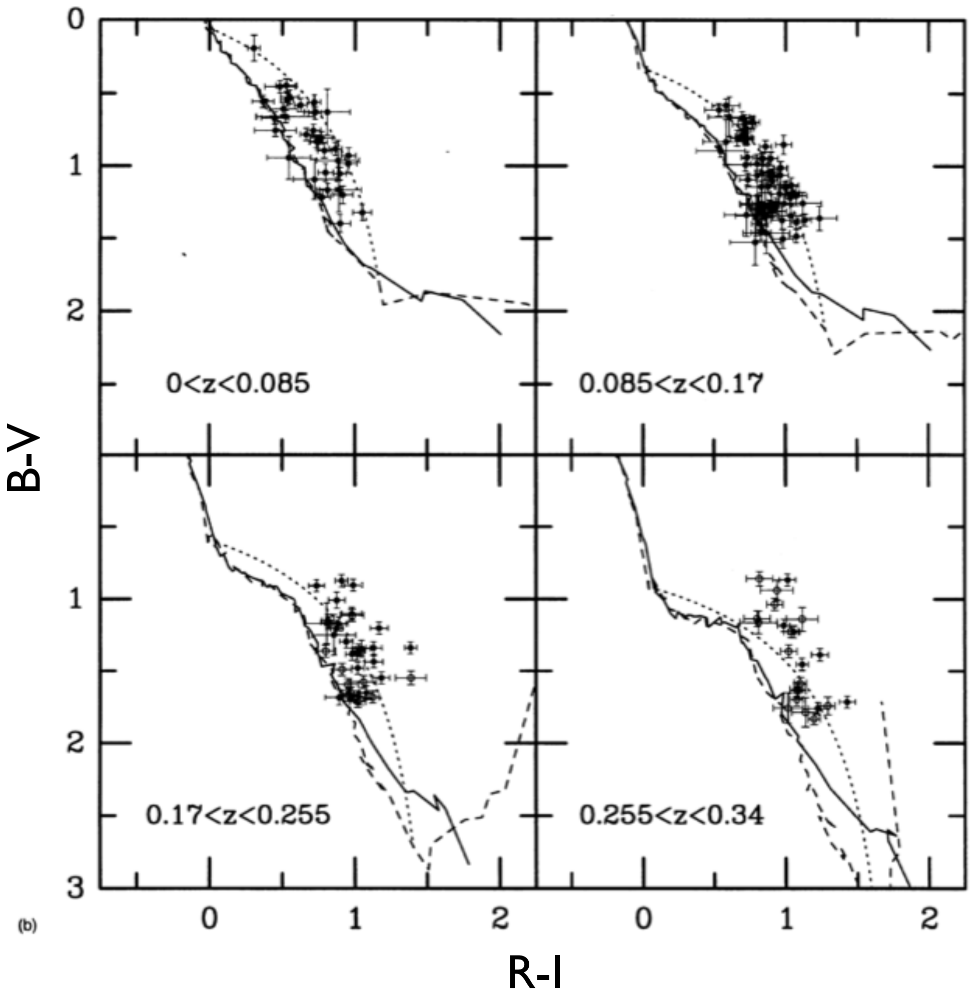
- Huchra 1977, ApJS, 35, 171

Galaxies: UBVRIK multi-colors



- Bershady 1995, AJ, 109, 97

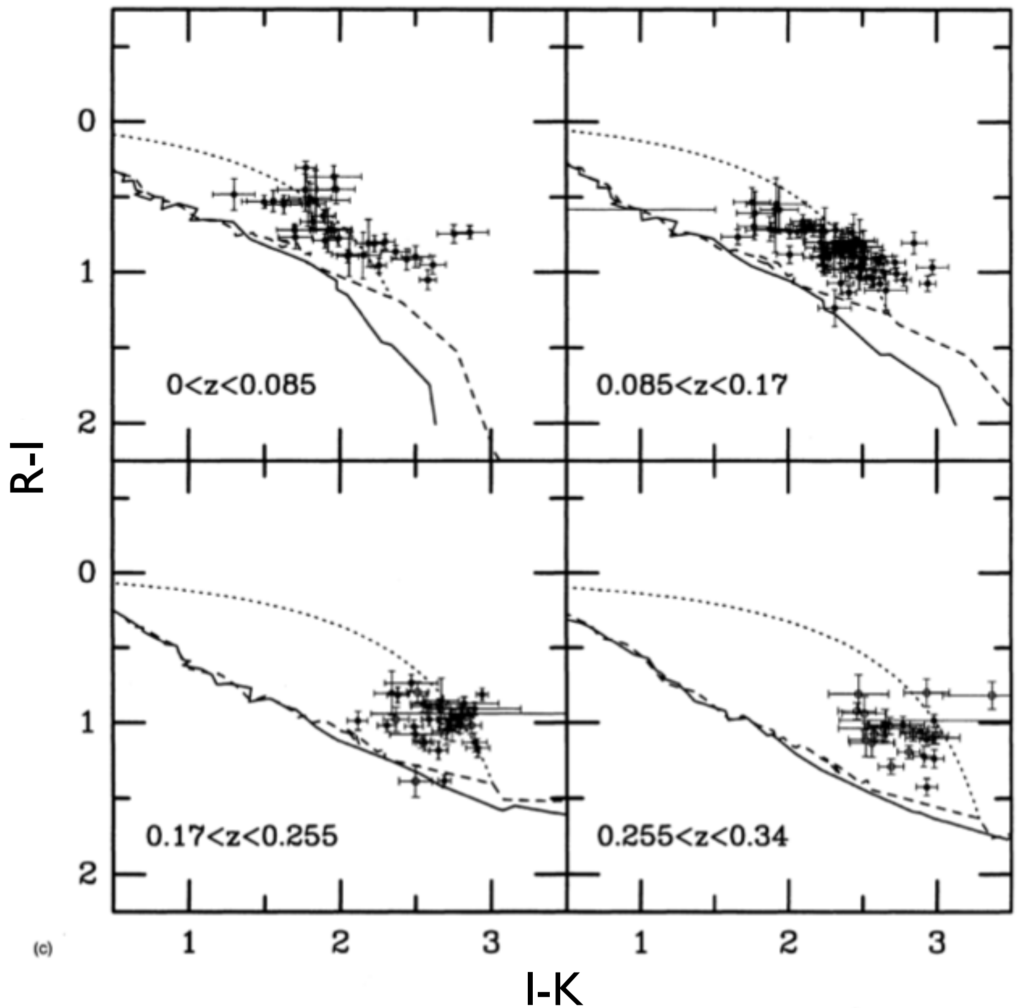
Galaxies: UBVRIK multi-colors



R: 650 nm
I: 800 nm

B95

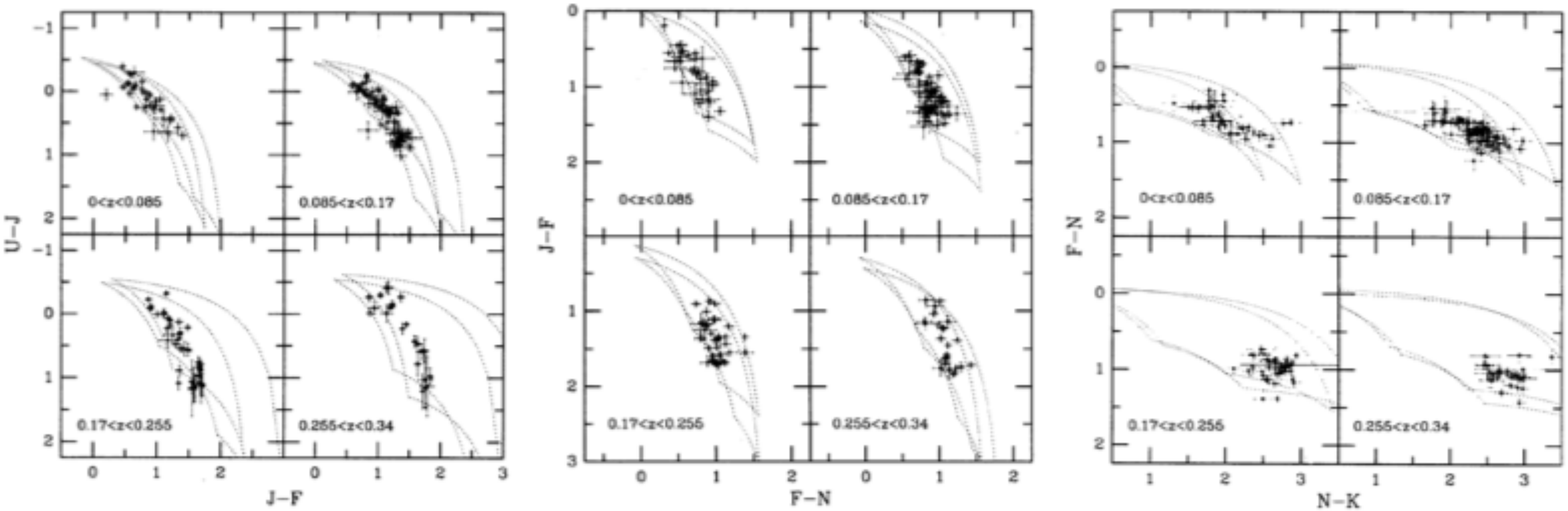
Galaxies: UBRIK multi-colors



- B95

Simple model: 4 stars in UBRIK

Linear combinations of B V, G V, K III, M III

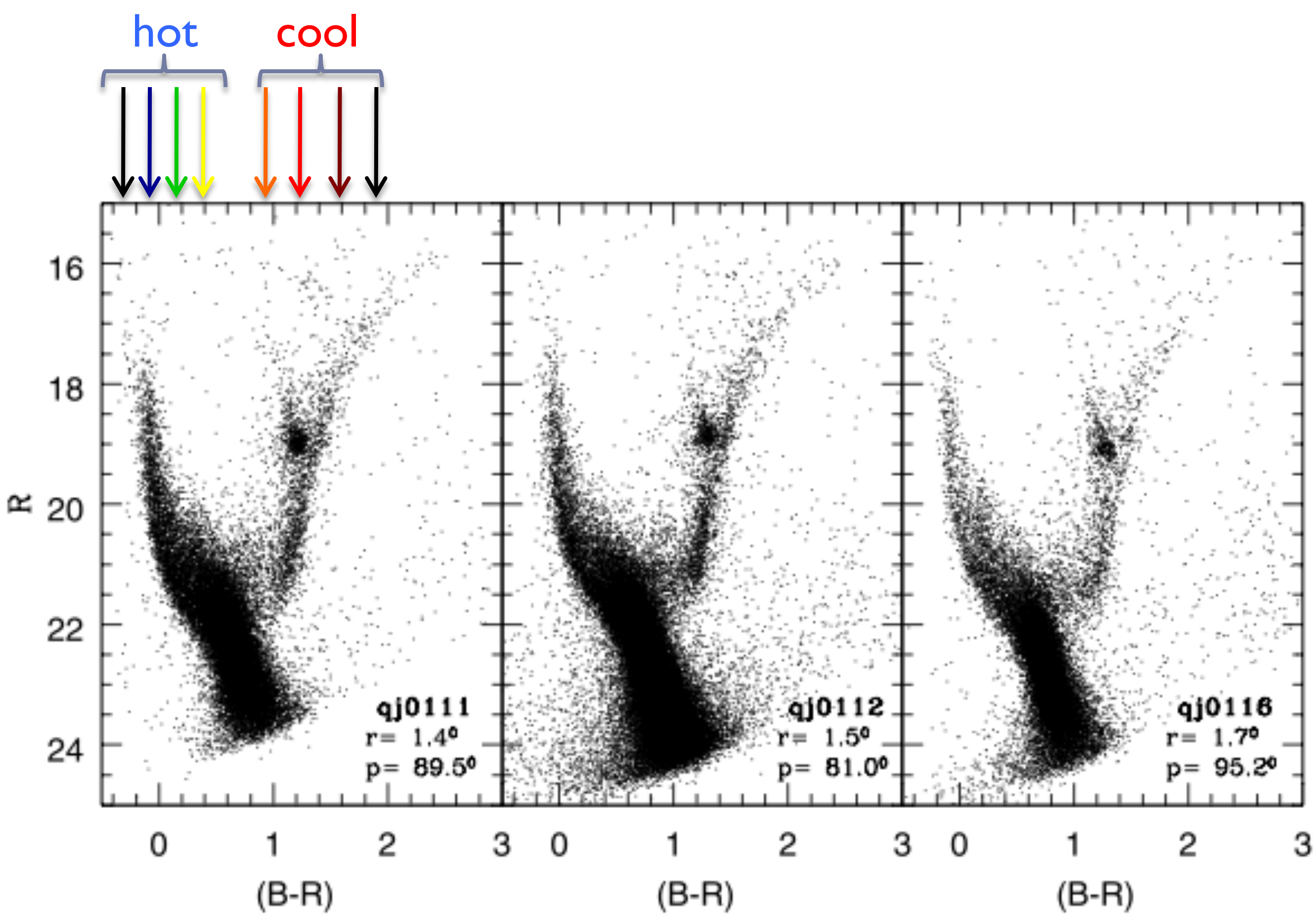


Alternatively, use linear combinations of 2 stars, but don't fix type:

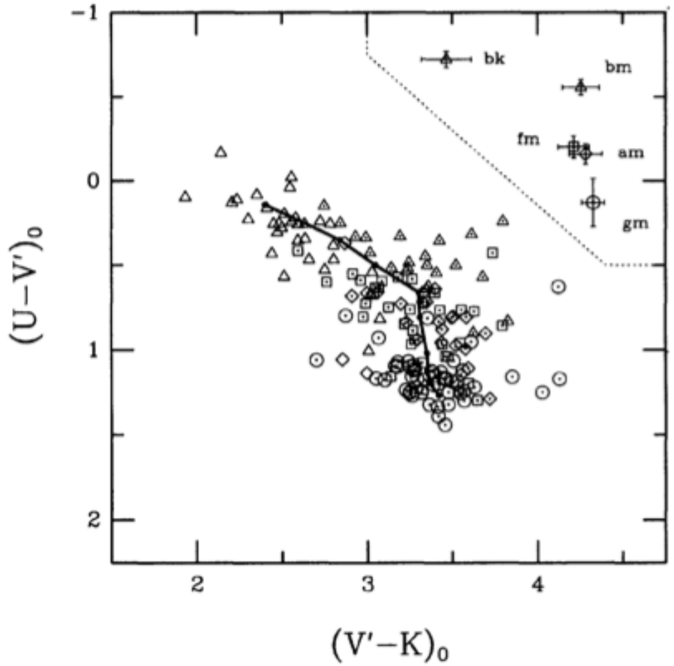
- One star is hot (ranging from B to G) – assume luminosity class V
- The second star is cool (ranging from G to M) – assume luminosity class III

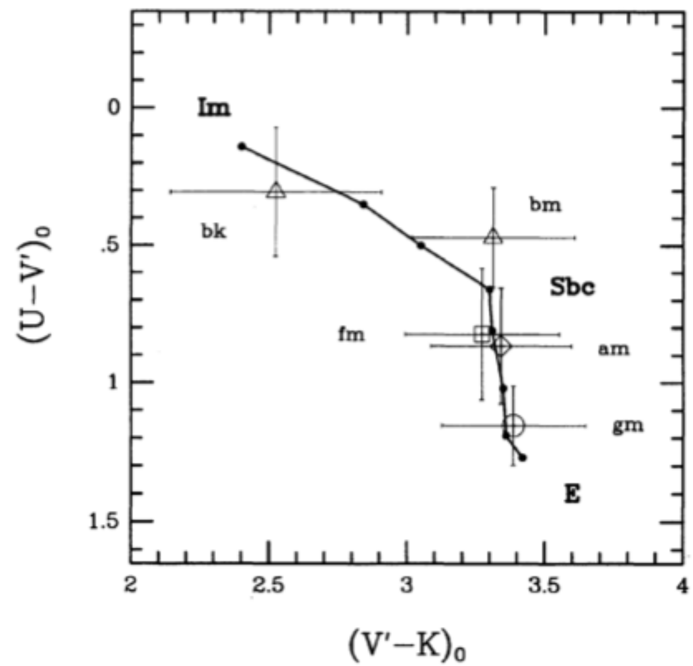
Thinking in terms of CMDs, why does this make sense?

CMD for the SMC at 60 kpc OMG



UVK plane revisited



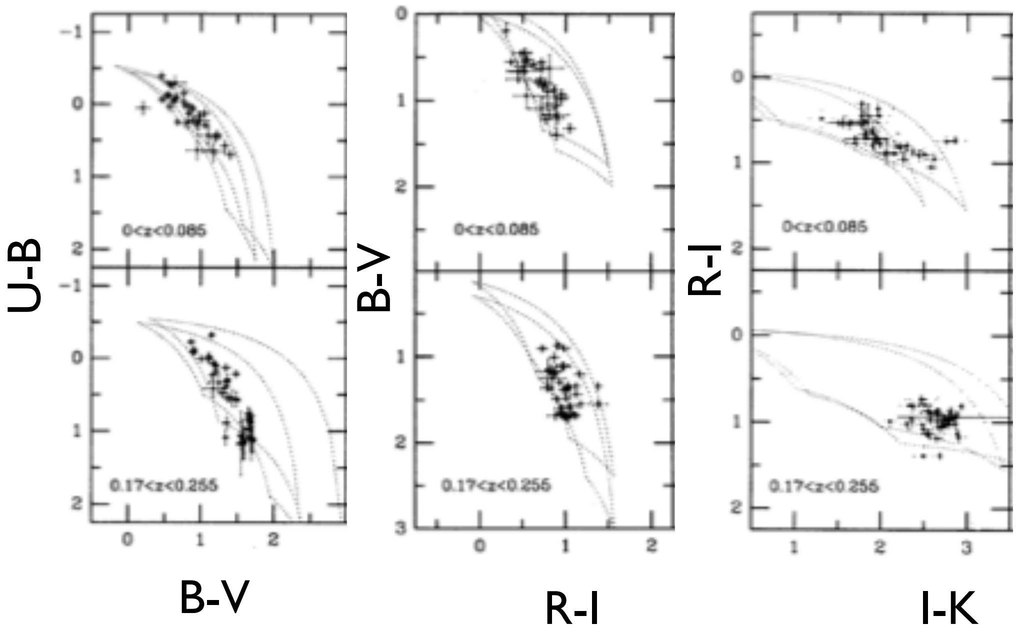


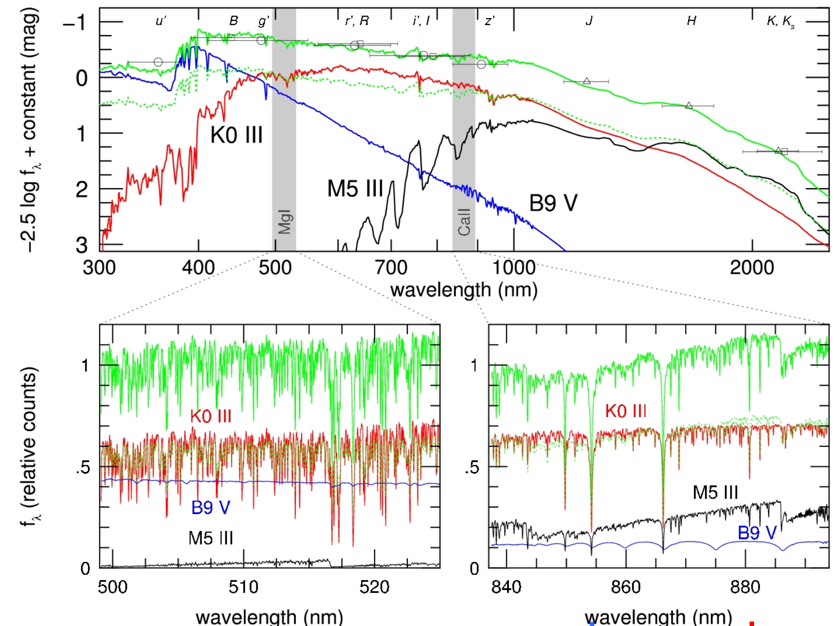
- Galaxies classified by two-star models required to fit UBVRIK multicolors
- Reminiscent of Morgan spectral-types, extended to red and NIR

Simple SPS: Linear combinations of 3-4 stars

(e.g., B V, G V, K III, M III) works from 0.35-2.2 microns

Integrated colors of galaxie….to detailed SEDs:



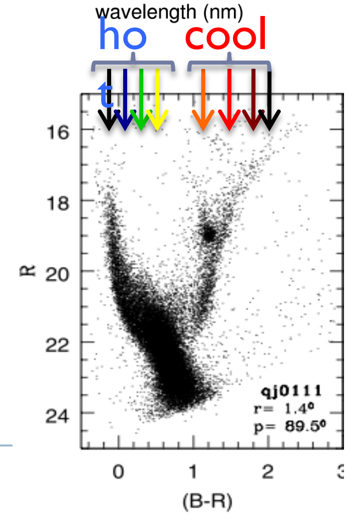


Why do it?

Whenever you know there are systematic uncertainties in complex models (e.g., SPS tracks, libraries) fall back to minimal empirical constraints. (a) This is what any complex model must reproduce. (b) You know which stars (what physics) are most important to get right in your complex models.

Why it works:

Think in terms of CMDs:

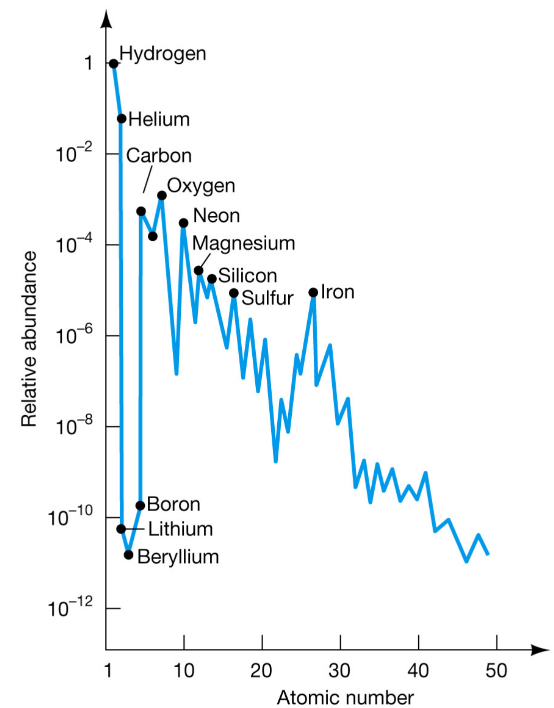


Nucleosynthesis

- Hydrogen Burning (main sequence)
  - P-P chain:
    - H + H ➔ $^{2}D + e^{+} + \nu$ + 0.42 MeV
    - ^{2}D + H ➔ $^{3}He + \gamma$
    - $^{3}He + {}^{3}He$ ➔ ^{4}He + 2H + 12.86 MeV
    - Or step through ^{8}Be (only 14% of the time)
  - CNO bi-cycle (if T > 20 million K)
    - ^{12}C+ H ➔ $^{13}N + \gamma$ ….
    - ^{14}N + H ➔ ^{15}O…..^{17}O + H ➔ $^{14}N + {}^{4}He$
    - N can be brought to surface via dredge-up; majority of ^{14}N is produced this way ➔ "secondary" product
- Giant Branch (T ~ 10^{8} K)
  - 2α➔ ^{8}Be; $^{8}Be + \alpha$ ➔^{12}C
  - Causes core expansion for $M > 2M_{\odot}$

Nucleosynthesis – later stages

- Higher mass stars ➔ past He burning
  - $^{12}C + \alpha \rightarrow {}^{16}O$ + energy ($M < 8M_\odot$)
  - $^{16}O + \alpha \rightarrow {}^{20}Ne$ + energy ($M > 8M_\odot$)
  - $^{20}Ne + \alpha \rightarrow {}^{24}Mg$ + energy
- More complex reactions:
  - $^{14}N \xrightarrow{\alpha} {}^{18}F \xrightarrow{\alpha} {}^{18}O \xrightarrow{\alpha} {}^{22}Ne \xrightarrow{\alpha} {}^{25}Mg + n$ (α reactions)
  - $^{12}C + {}^{12}C \rightarrow {}^{23}Mg + n$
    - *Free neutrons!*
- Highest mass stars
  - $^{24}Mg + \alpha \rightarrow {}^{28}Si$
  - $^{16}O + {}^{16}O \rightarrow {}^{32}S$
  - Leads to Fe peak ➔ Type-II SNe (core collapse, bounce)



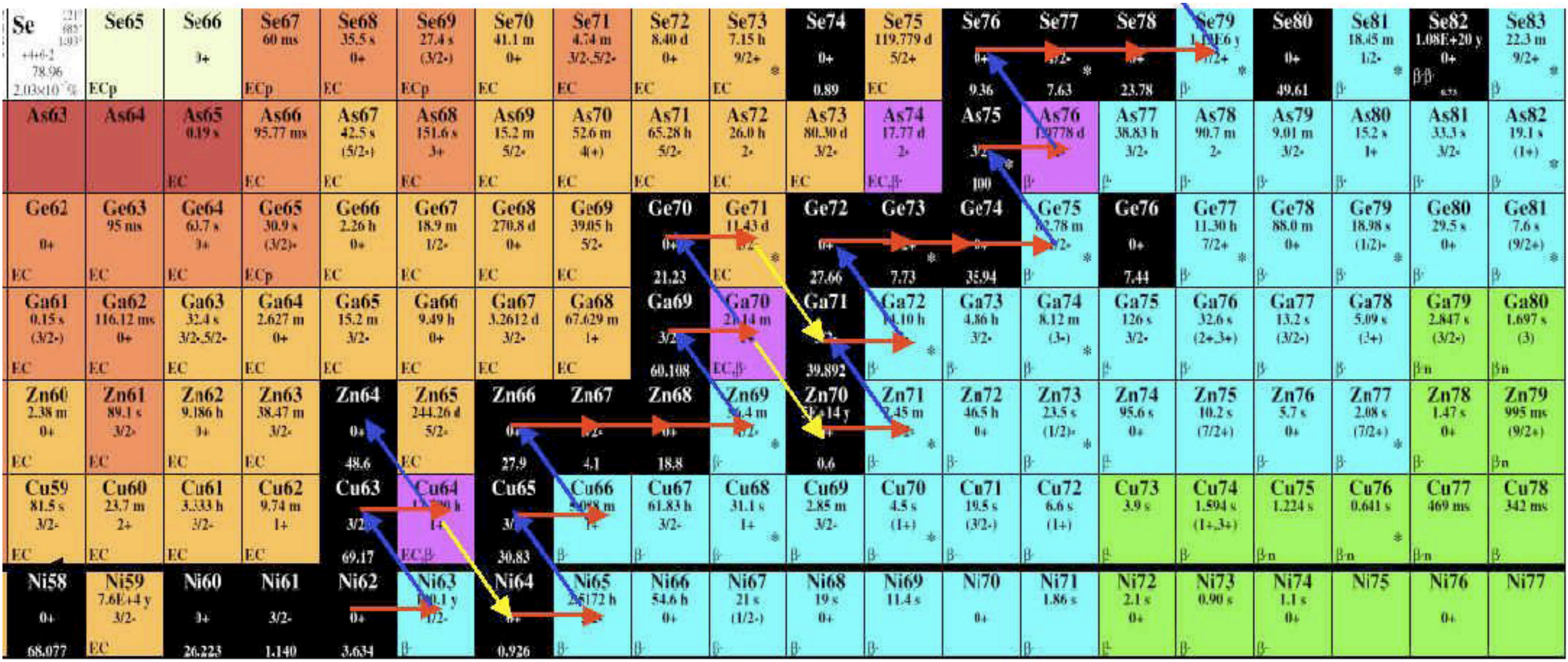
Dispersing the Elements

- Intermediate mass stars
  - $M < 2.5\ M_\odot$ ➔ CO degenerate core, PN, some He output
  - $2.5\ M_\odot < M < 8\ M_\odot$
    - Convective overshoot ➔ dredge-up of CNO cycle products (e.g., ^{14}N)
    - Dredge-up can reach He-burning products on AGB ➔ C, O
    - Pulses drive mass loss (10^{-7} to $10^{-5}\ M_\odot yr^{-1}$)
      - PN enriched in C,O,N, "s-process"
      - AGB shells good place to form molecules (CO)
- High mass stars ($M < 8\ M_\odot$)
  - Dispersal via SNe
  - Primary products are α elements
  - Some "r-process"

Neutron Capture Elements

- Certain elements are rich in neutrons
- Formation can't be explained by standard nucleosynthesis
- Neutron capture
  - $(t_{1/2})^{-1} \sim \sigma\Phi$ (cross section x neutron flux)
  - (Z,A) + n ➔ (Z,A+1); is this stable?
    - Yes: sits around and waits for another n
    - No: decays to (Z+1,A+1); is this stable?
  - Stable isotopes have higher abundances
- "Valley of Stability"

s-Process Valley of Stablity



Slow Neutron Capture

- "s-process"
  - Neutron densities ~ $10^5 cm^{-3}$
  - Neutrons originate in minor He-burning reactions
    - $^{13}C + \alpha \rightarrow {}^{16}O + n$
    - $^{22}Ne + \alpha \rightarrow {}^{25}Mg + n$
  - Where?
    - H, He shells where burning takes place
  - Example elements (Tc, Ba, La, Zr)
    - Tc is the lightest element with no stable isotopes; lifetime < stellar lifetime so presence of Tc implies in situ production and confirmation of s-process
- Nice review: Busso et al 2001, ApJ, 557, 802

Rapid Neutron Capture

- "r-process"
  - Neutron capture rate > β-decay rate (hours)
  - Neutron densities ~ $10^{23} cm^{-3}$ → only see this in SNe
  - Same fundamental process → n capture to stable nuclei
  - Example products: Eu, Ur, etc

- Mixed origins
  - Rb, Pr, Nd → 50/50 s/r
  - Ba, La, Ce → 85/15 s/r
  - Eu → 3/97 s/r

Type Ia Supernovae (SN Ia)

- CO white dwarf + companion
- Companion fills Roche lobe, dumps matter onto WD until electron degeneracy is overwhelmed:
  - Chandrasekhar mass = 1.4 $M_{\odot}$
- Collapse and deflagration:
  - Explosive nucleosynthesis → whole thing goes
- Produces burning up to iron:
  - Mg, Si, Cr, Ni, Fe (main production of Fe)

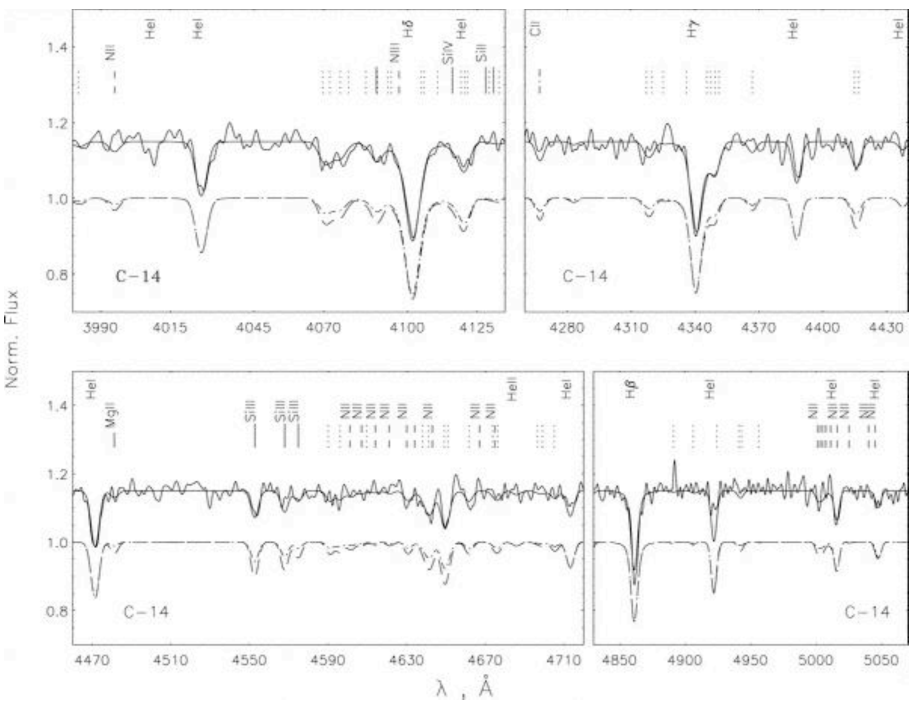
Abundance patterns in galaxies

- SFH reflected in abundances…
- Stellar lifetimes
  - $M > 20\ M_\odot$ ➔ $t < 10$ Myr
  - $1.5M_\odot < M < 5M_\odot$ ➔ $1.4 > t > 0.1$ Gyr
  - $M > 1.5\ M_\odot$ ➔ $t > 1.4$ Gyr
- Single massive stars produce
  - Little Fe (it's locked up)
  - Lots of α-elements, r-process elements
    - $40\ M_\odot$ star produces $7\ M_\odot$ of O
- Intermediate mass stars produce
  - O,C,N, plus s-process elements
    - $0.1\ M_\odot$ of N

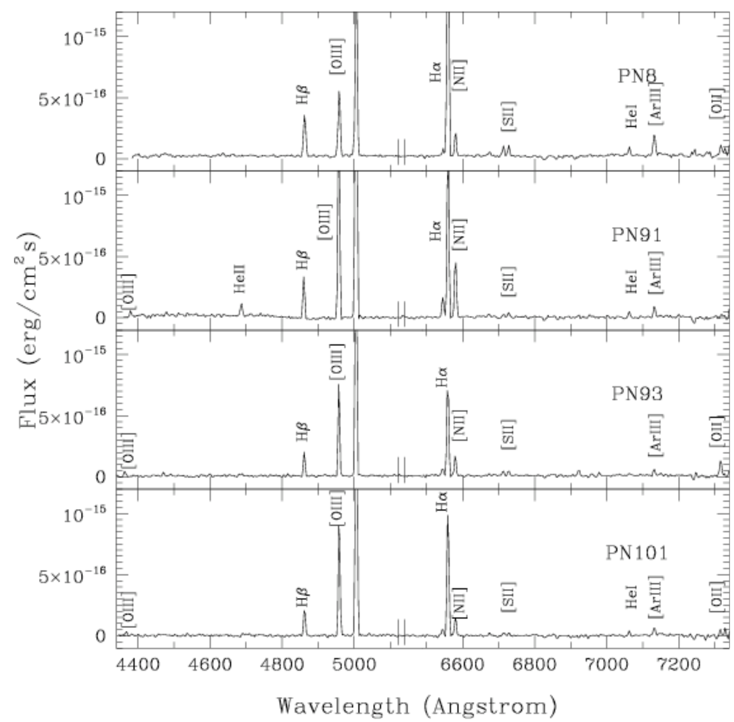
What are the implications for the SFH for finding stars and gas that is α-element rich?

Measurement Techniques

- (a) Stellar spectra: bright stars
- (b) Emission line spectra: HII regions and Planetary Nebulae (PN)
- (c) QSO absorption lines



(a) NGC 300



(b) M33 PN

Extragalactic Abundances: Definitions

- Relative Abundances
  - $[X/H] = \log_{10}(n(X)/n(H)) - \log_{10}(n(X)/n(H))_{\odot}$
    - where X is any element
  - Doesn't have to be H
    - $[O/Fe] = \log_{10}(n(O)/n(Fe)) - \log_{10}(n(O)/n(Fe))_{\odot}$
- Absolute abundances
  - $12 + \log_{10}(O/H)$ (small numbers!)

Solar/Orion Context

- Sun
  - $\log_{10}$(He/H) = -1.0
  - $\log_{10}$ (O/H) = -3.1
  - $\log_{10}$ (C/H) = -3.4
  - $\log_{10}$ (Fe/H) = -4.5
  - $\log_{10}$ (Ne/H) = -3.9
  - $\log_{10}$ (N/H) = -4.0
  - $\log_{10}$ (Z/H) = -8.5
- Orion
  - $\log_{10}$ (O/H) = -3.3
  - $\log_{10}$ (C/H) = -3.5
  - $\log_{10}$ (Fe/H) = -4.52

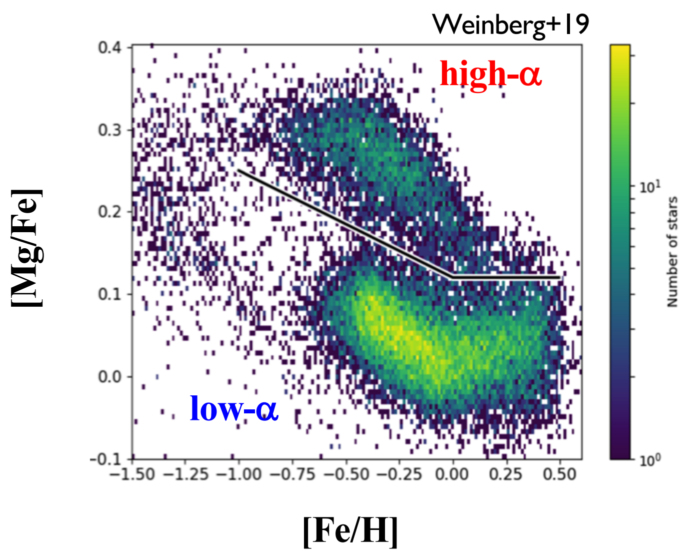
- Sun is slightly more metal rich than Orion!
  - (remember the local bubble?)
- LMC is 50-70% solar
  - [O/H] = -0.3 to -0.15
- SMC ~ 20-25% solar
  - [O/H] = -0.7 to -0.65

Abundance Patterns in the Milky Way

- Solar neighborhood
  - [Fe/H]-age relationship
  - [O/Fe] vs [Fe/H] correlation
    - Decreases with [Fe/H]
    - Similar for Mg, Si (α process)
  - [Ni/Fe], [Ba/Fe] flat with [Fe/H]
  - [s-process/Fe] correlates with [Fe/H]
    - e.g., [Ni/Fe], [Ba/Fe]
    - Why?
- Halo stars generally metal poor
  - [Fe/H] ~ -1.6 → -2.4
  - [α/H] ~ 0.25-0.30
  - [Fe/H] decreases with R (0.07 dex kpc^{-1})
- Thick disk
  - [O/Fe], [Mg/Fe] enhanced
  - Eu enhanced
  - [α/Fe] enhancement decreases with [Fe/H]
  - Looks like metal-poor halo, but kinematics of a disk

Classical MW Chemical Cartography:

Assembly and enrichment of stellar populations in our Galaxy



Striking chemical duality: Typical of other (MW-mass) galaxies?

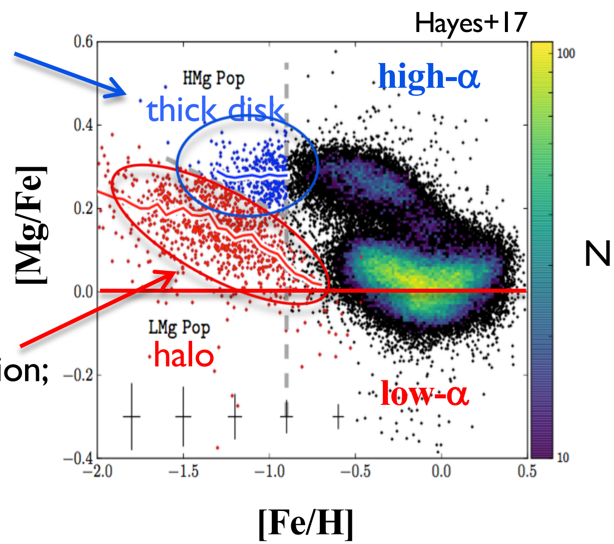
APOGEE Surveys: SDSS-III/IV

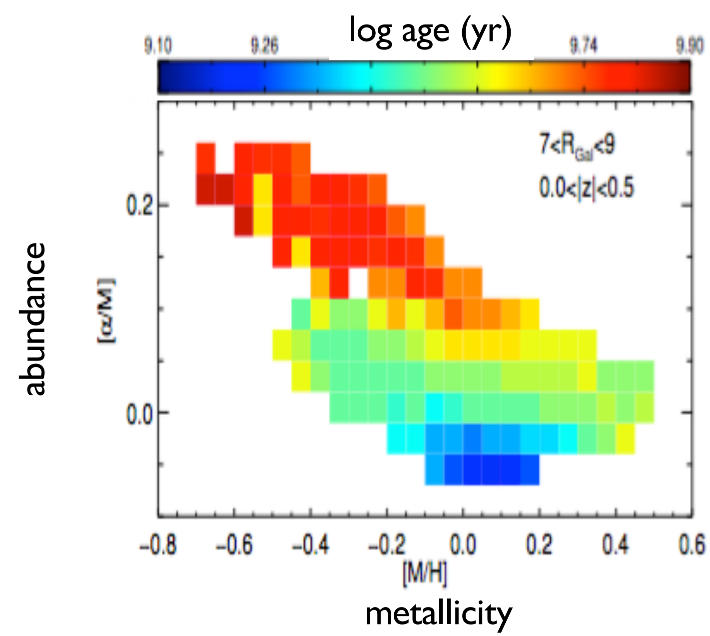
Classical MW Chemical Cartography:

In-situ vs accreted populations

Rotating population; in-situ formation thick disk

Non-rotating population; accreted halo





Feuillet+19

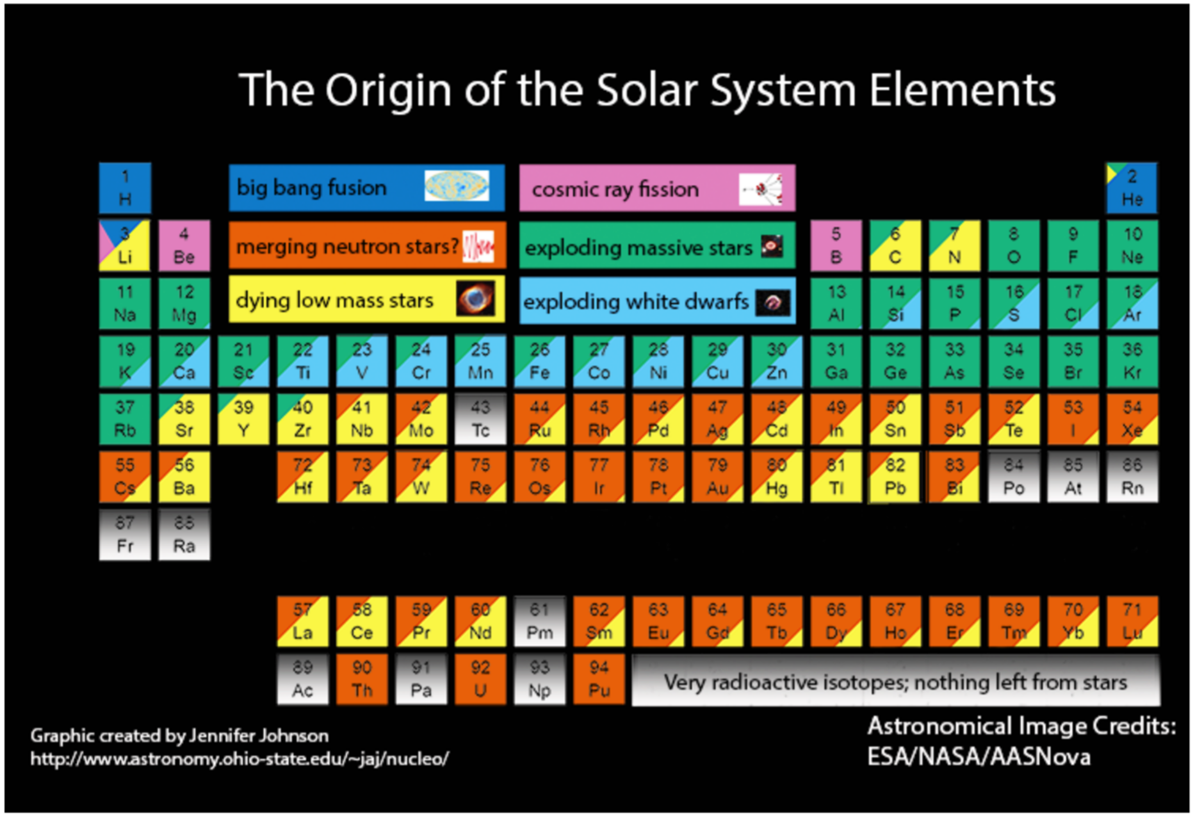
- Similar results for MW globular clusters

Hayes+17, Fernandez-Alvar+17, Darrington+19

Ages from Gaia distances and isochrone fitting

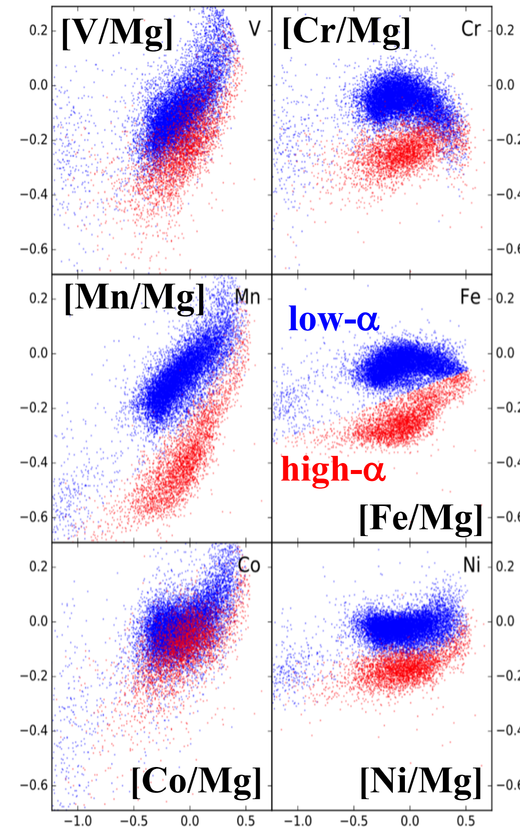
Classical MW Chemical Cartography:

Multi-element abundance ratios



Iron peak

odd even



[Mg/H]

Weinberg et al. 2019

- CCSN yields?
- Non-LTE systemtatics?

Abundance Patterns in the Milky Way

APOGEE Surveys: chemical cartography

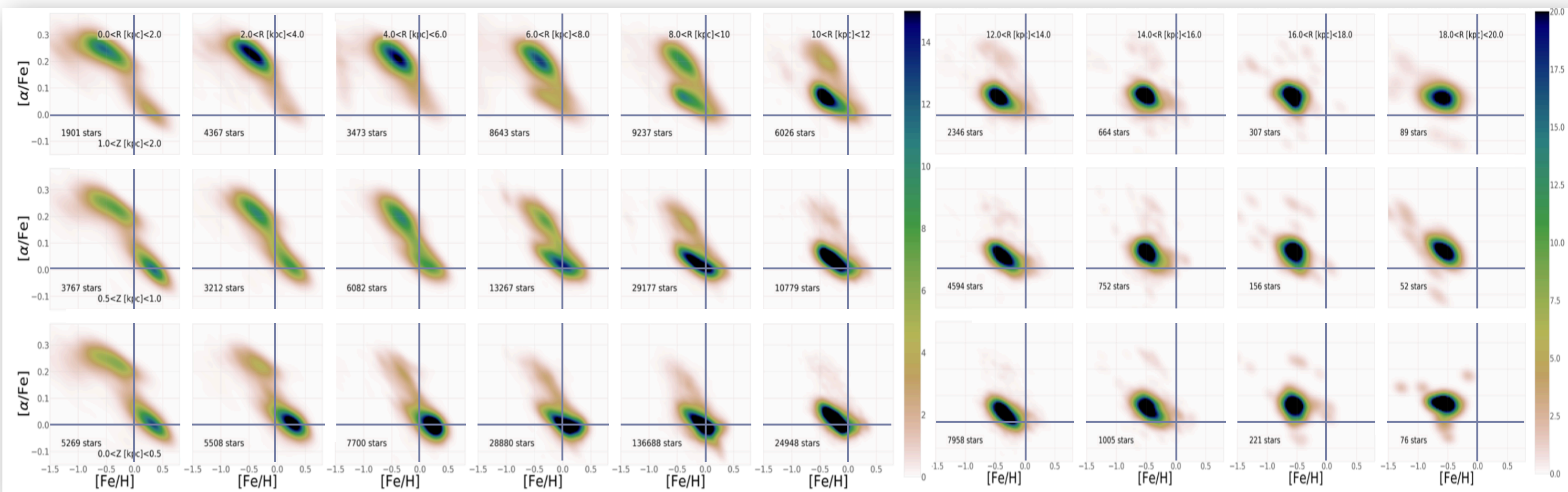
"striking chemical duality in the innermost regions of the disk, now clearly extending to the inner bulge "

Hayden+15 Queiroz+2020 Abudurro'uf+2022

2kpc

height

abundance



0

metallicity

0

radius

20kpc!

APOGEE-2: abundances *throughout* the galaxy

Abundance Patterns in the Milky Way

APOGEE Surveys: chemical cartography

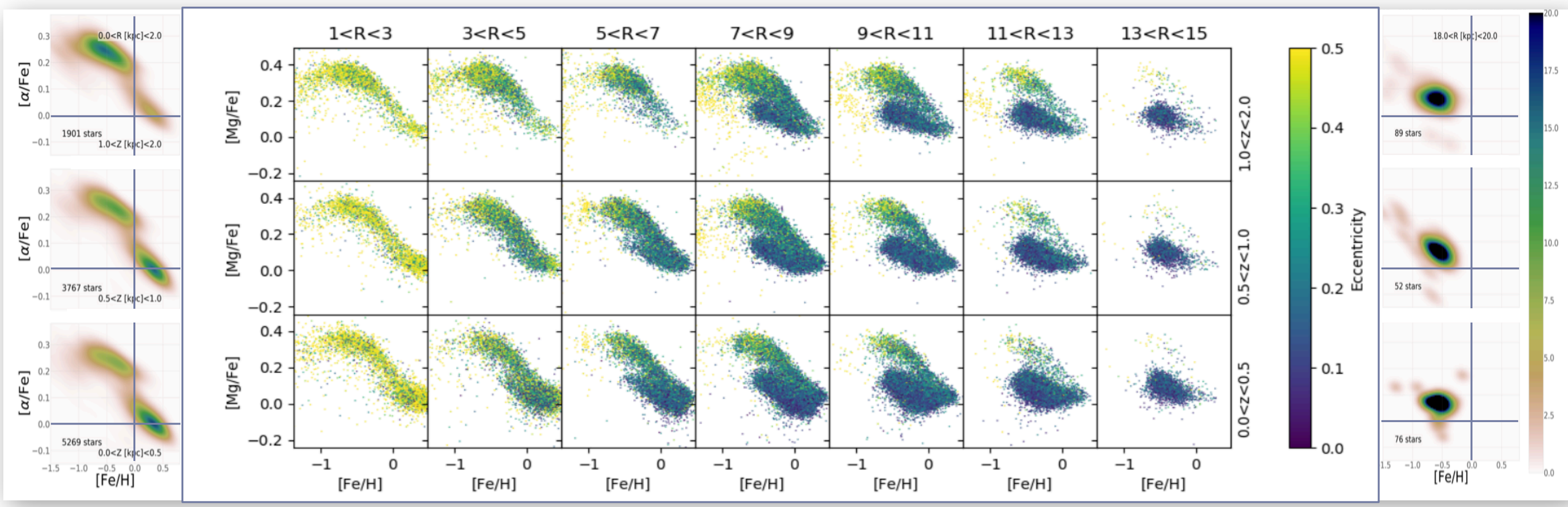
"striking chemical duality in the innermost regions of the disk, now clearly extending to the inner bulge "

Hayden+15 Queiroz+2020 Abudurro'uf+2022

2kpc

height

abundance



0

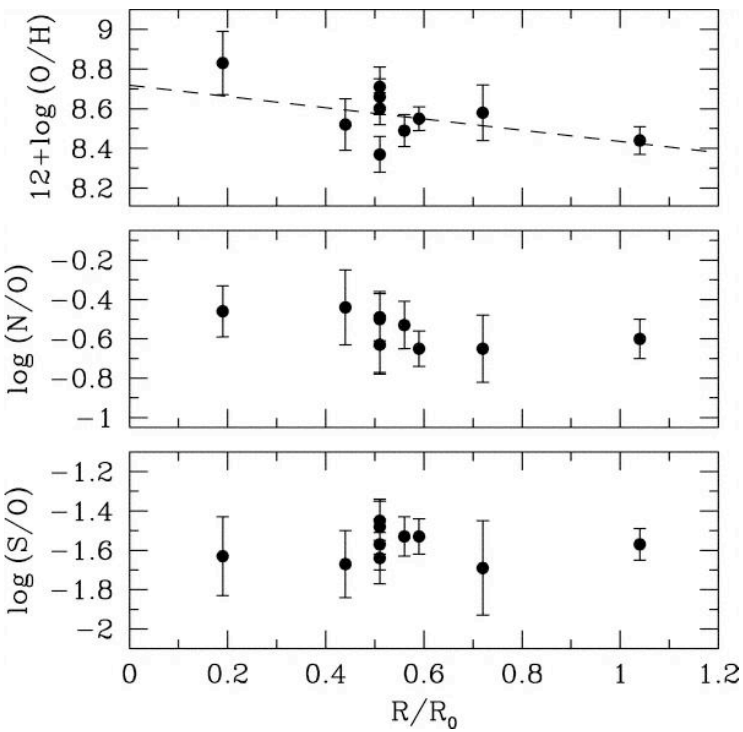
metallicity

0 radius *20kpc!*

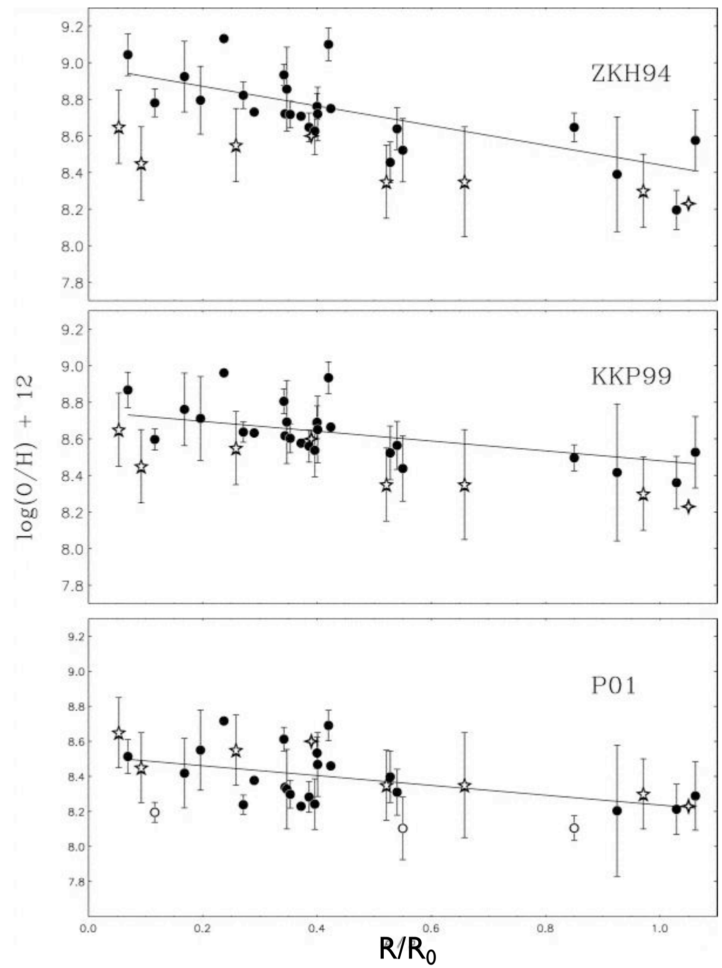
APOGEE-2: abundances *throughout* the galaxy

Abundance Gradients in Disk Galaxies

- HII regions in M51



- HII regions in N300



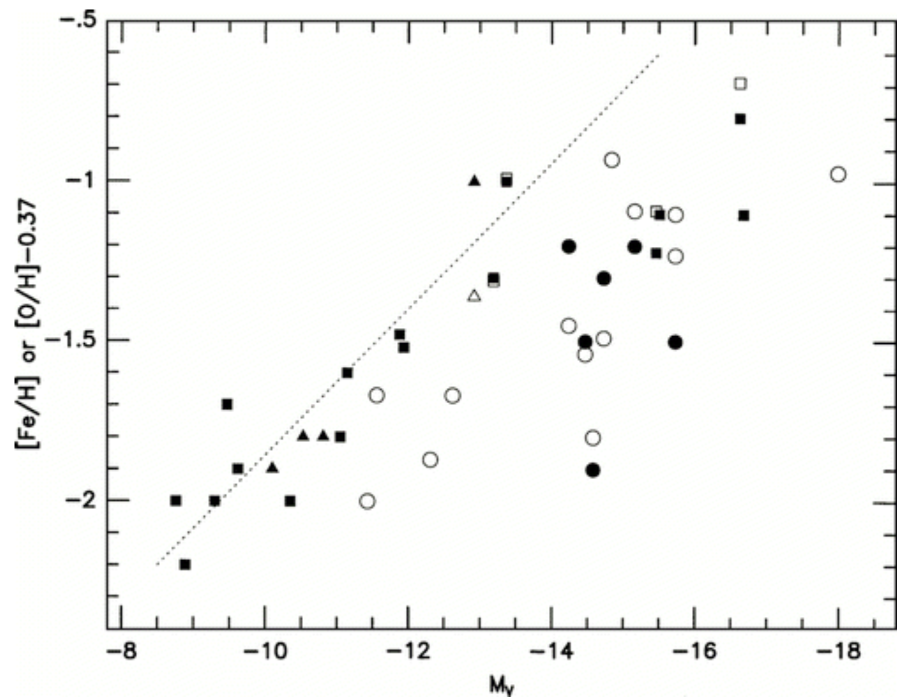
$\log(O/H)_\odot = -3.1 \rightarrow$
$12 + \log(O/H)_\odot = 8.9$

Disk Gradients (continued)

- General characteristics
  - 12 + log(O/H)+12 = 8.58 - 0.32 R/R_0
  - Generally: -0.04 to -0.07 dex/kpc
  - Flatter in late-types, steep in barred galaxies
- Why are there gradients?
  - Radial dependence on SFR/SFH?
  - Radial gas flows?
  - Radial dependence on yield?
  - Radial dependence on infalling gas?
- Why aren't there larger gradients?
  - Radial migration?

Extragalactic Abundances: Dwarfs

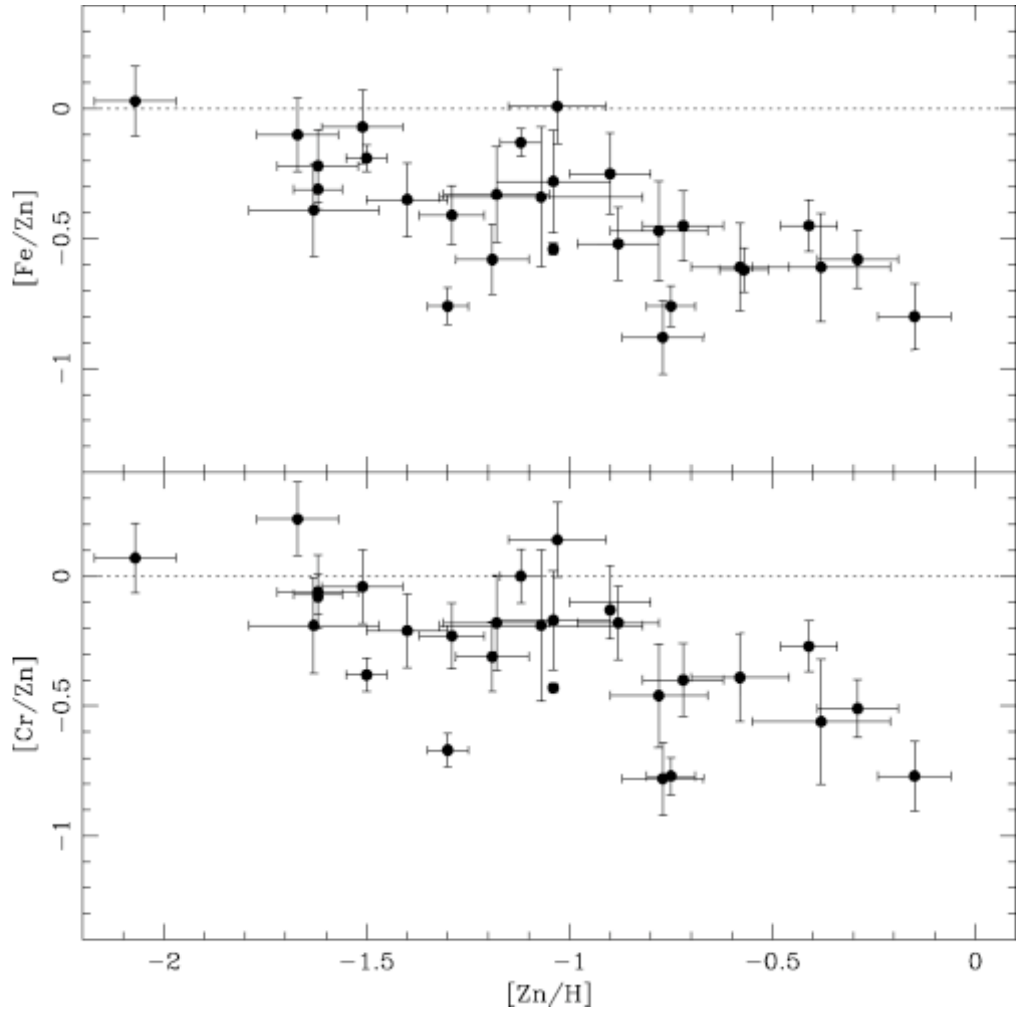
- LMC is 50-70% solar
  - [O/H] = -0.3 to -0.15
- SMC ~ 20-25% solar
  - [O/H] = -0.7 to -0.65
- Some dwarfs extremely metal poor (1/10 solar)
- Why?



Decreasing luminosity

QSO Absorption Lines

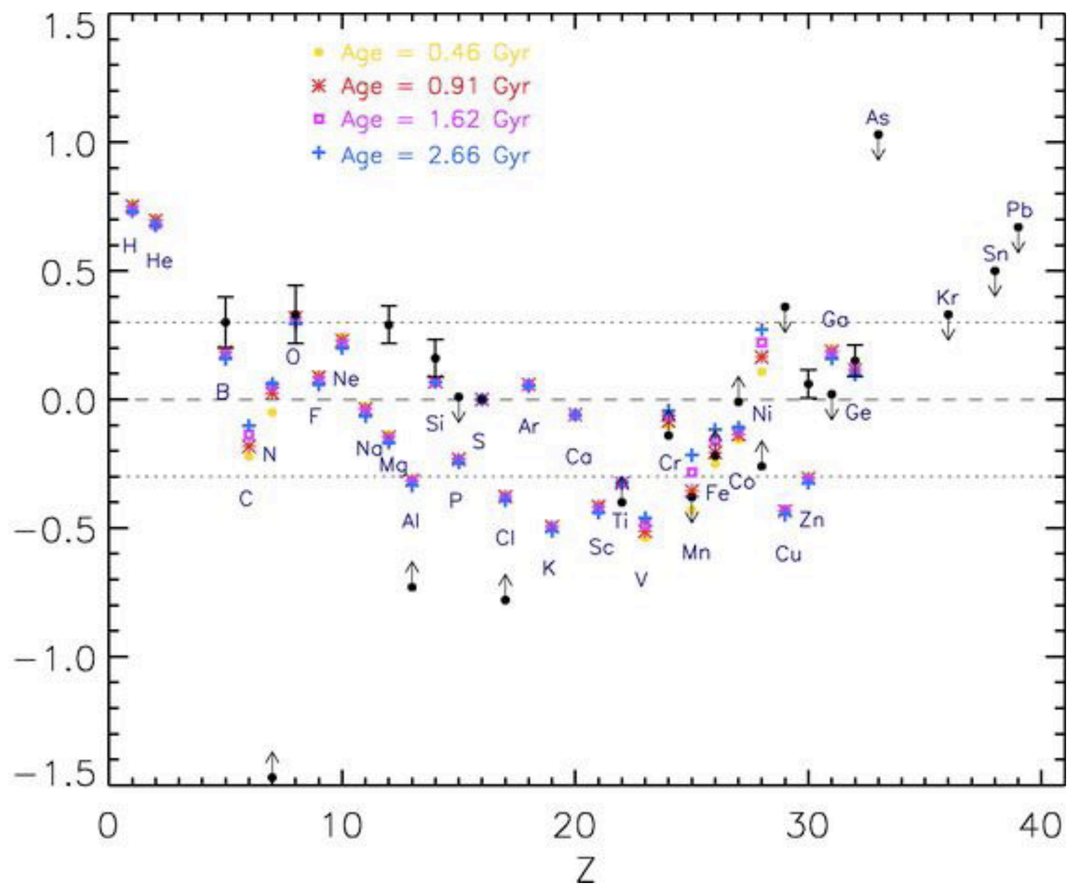
- Absorption line systems detected against background quasars
- Gas phase abundances can be measured via absorption lines
- Most metal-poor gas systems ever found
- Enrichment histories vary from solar



Lanfranchi & Friaca 2003

QSO Absorption Lines

- Damped Ly-α systems have high column, high velocities ➔ correlated with galaxies
- Thought to be progenitors of today's massive galaxies
- Consistent with:
  - young ages
  - 1/3 solar
  - Enrichment dominated by massive stars
    - few Type Ia Sne



Fenner, Prochaska, & Gibson 2004 ApJ

Chemical Evolution of Galaxies

- Simple models
  - $M_g(t)$ = gas mass
  - $M_r(t)$ = remnant mass
  - M_s= mass in stars
  - $M_h(t)$ = mass in heavy elements
  - $Z(t) = M_h/M_g$= metallicity
  - ΔM = change in mass
  - p = fractional yield of heavy elements

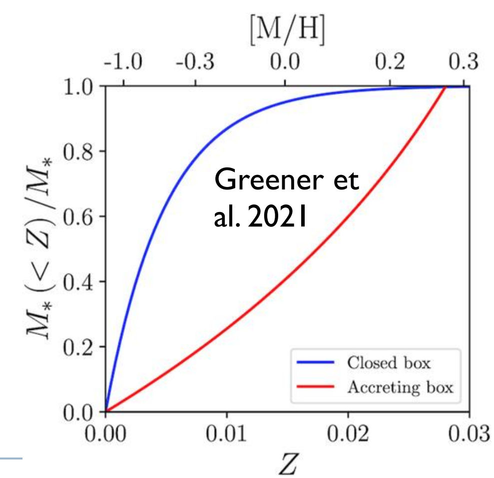
➔

$$\Delta M_h = p\Delta M_s - Z\Delta M_s = (p-Z)\Delta M_s$$

$$\Delta Z = \Delta(M_h/M_g) = [p\Delta M_s - Z(\Delta M_s+\Delta M_g)]/M_g$$

See S&G 4.3.2

- In a closed box $\Delta M_s+\Delta M_g=0$…..
  - $Z(t) = p \ln [M_g(t)/M_g(0)]$
  - Implies gas-rich things should have lower Z
  - Also: $M_s(<Z(t))=M_g(0)[1-e^{-Z(t)/p}]$ ➔

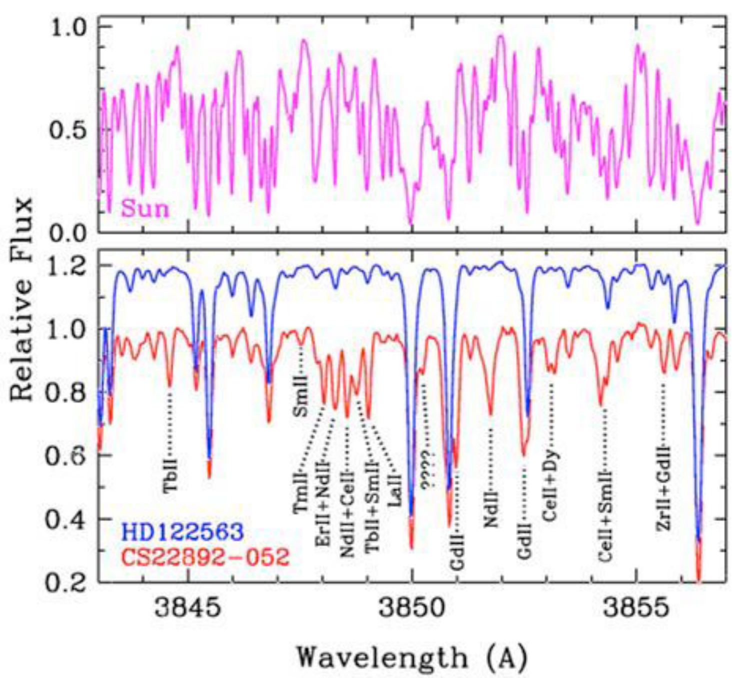


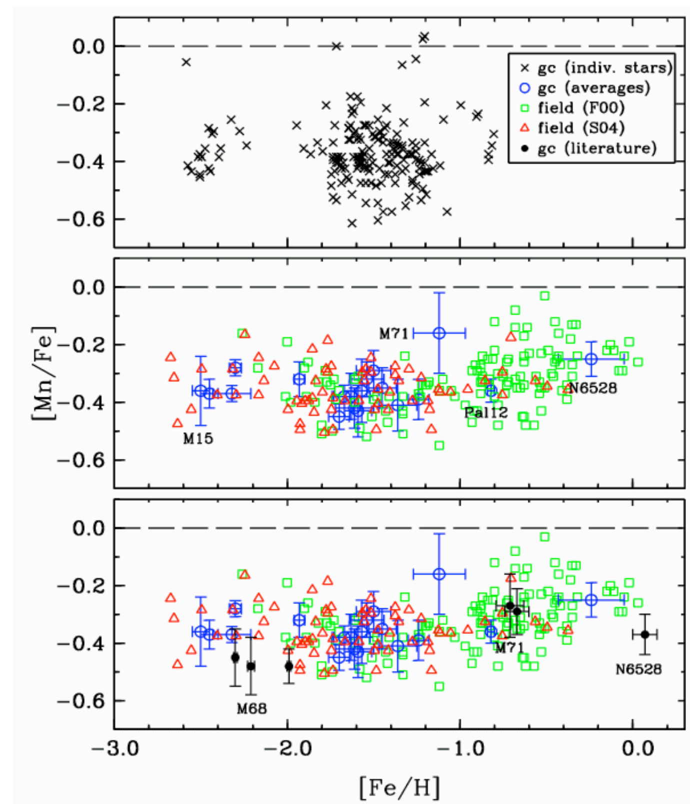
- We should see lots of really low metallicity G stars
- Something like 50% of G dwarfs should have $z < 0.25Z_\odot$!
- But we don't: closer to 25% for Fe and <1% for O
- ➔ so-called G-dwarf problem

van den Bergh 1962
Binney & Merrifield, 1998 (5.3.1)
Pagel 2009

Summary: Chemical Evolution

- What is the correlation between these observed absorption lines and the star formation history of this stellar system? *Alt:* What are the constraints on how and when stars form based on their chemical abundances?





Summary: Chemical Evolution

- Other themes:
  - Disk gradients
  - Trends with galaxy luminosity
  - Abundance patterns in QSO absorbers
  - The G-dwarf problems