Outline

- Review & a little more on reionization
- Stellar Classification
  - Photometry/classification
- Stellar Evolution
- Interpreting H-R diagrams
- Reading: “Old Main Sequence Turnoff Photometry in the Small Magellanic Clouds” Noël et al. (2007, AJ, 133, 2037)
  - What is the data they use?
  - Compare Figures 3 and 7 to some of the CMDs in the lecture notes – what are the similarities and differences?
Review: Big Bang / Creation of Matter

- Expansion & evolution: GR and Friedman equations: $R = 1/(1+z)$, $R,R$
- Early Universe
  - Inflation ($10^{-34}$ sec)
  - Particle genesis ($10^{-15}$ to 1 sec)
  - BBNS (3 minutes) $\Rightarrow$ Cosmic He abundances
  - Recombination ($4 \times 10^5$ yr) $\Rightarrow$ CMBR
- Dark Ages (?)
- Reionization and onward
  - When the first stars and AGN formed ($z=12$?)
  - Galaxy formation
  - Evolution of galaxies, their stars and planets

Structure grows via gravity in matter dominated era

precision cosmology & first glimpse of structure
Structure starts growing here

Afterglow Light Pattern 380,000 yrs.

Inflation

Quantum Fluctuations

reionization: 1st Stars about 400 million yrs.

Dark Ages

Development of Galaxies, Planets, etc.

Dark Energy Accelerated Expansion

WMAP

Big Bang Expansion 13.7 billion years
Epoch of Reionization

- Somehow, somewhere stars formed…
- …and ionized the surrounding IGM and the Universe emerged out of the “Dark Ages”
- WMAP says somewhere near $z \sim 12$…
  - But possibly two phases, one early ($z > 12$, and incomplete)
- When did the 1\textsuperscript{st} stars/galaxies form?
  - Gunn-Peterson trough in quasar absorption
  - Directly observing 1\textsuperscript{st} stars (NGST, TMT)
  - 21 cm line absorption/redshifted emission (SKA)
  - High redshift objects (VLA, GMRT, SKA)
  - Primordial, high redshift black holes (SKA)
21 cm Observations: Emission

$z = 12.1$  \quad $z = 9.2$  \quad $z = 7.6$

10 Mpc comoving
$\Delta \nu = 0.1$ Mhz

Furlanetto et al. 2004
Large scale structure: simulated

- Fly-through of the Cosmic Web
Large Scale Structure: observed

- Filaments and voids
  - Great Attractor
  - Characteristic scales: 40-120 Mpc
Large scale structure of the Universe

- Structure and Galaxy Formation
  - elliptical

![Image of elliptical and spiral structures]
The WHIM: Warm-Hot Intergalactic Medium

density

Dark matter

T/10^6 K

WHIM
Physical Processes in the Cosmic Web

- Large scale shocks as baryons accrete onto collapsing structures
- Gas is shock-heated to $10^5$-$10^7$ K
  - WHIM origins, or AGN and star-formation too?
- Shock accelerate particles (cosmic ray ions) to $10^{18}$–$10^{19}$ eV
- Inter-cluster B-fields: $10^{-7}$–$10^{-12}$ G
  - Origin and amplification?
Mapping the Cosmic Web

- Galaxies are only the high density islands in the web
- Most of the web is in the form of diffuse WHIM
  - Detected primarily via QSO absorption sightlines
  - Fraction of kinetic power converted to radiative energy
- Diffuse emission should be detectable in the optical (nebular line emission, e.g., redshifted Lyα) but suitable instrumentation has yet to be built.
- Diffuse synchotron emission (radio) another possibility
  - Parameters:
    - Infall velocity
    - Density of in-falling baryonic gas
    - Magnetic field strength
    - Efficiency of shock acceleration
    - Fraction of kinetic power converted to radiative energy

Furlanetto et al. 2003: Ly α surface-brightness

![Ly α surface-brightness images](image-url)
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
Digression & Review: Flux Units

- **Flux ($f_\nu$):** measured in Janskys
  - $1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} = 10^{-23} \text{ erg sec}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$

- **Flux ($f_\lambda$):** measured in ergs s$^{-1}$ cm$^{-2}$ A$^{-1}$ (cgs units)

- **Photon flux ($f_\gamma$) is useful for calculating signal-to-noise (counting statistics):**
  - Define *neper* $= \Delta \lambda / \lambda = \Delta \nu / \nu = \Delta \ln \nu$
  - The photon flux is:
    - photons sec$^{-1}$ cm$^{-2}$ neper$^{-1} = f_\nu / h$
    - where $h = 6.6256 \times 10^{-27} \text{ erg sec}$
  - Useful identify:
    - $1 \text{ microJy} = \mu\text{Jy} = 15.1 \text{ photons sec}^{-1} \text{ m}^{-2} \text{ neper}^{-1}$
Apparent magnitudes

\[ m_1 - m_2 = -2.5 \log_{10} \left( \frac{f_1}{f_2} \right) = -a \ln \left( \frac{f_1}{f_2} \right) \]

\[ a = 2.5 \log_{10} e = 1.08574 \]

\[ m = -2.5 \log_{10} \left( \frac{f_1}{f_0} \right) + m_0 \]

\[ f = f_0 \exp \left[ -0.4(m - m_0) \right] \]
Absolute Magnitudes

\[ m_\lambda - M_\lambda = 5 \log_{10} d - 5 + A_\lambda \]

\[ \therefore \quad \frac{f_1}{f_2} = \left( \frac{d_2}{d_1} \right)^2 \]

- Absolute magnitude is the apparent magnitude that would be observed if the object were at a distance, \( d \), of 10 pc.
- \( A_\lambda \) is the total extinction due to interstellar dust, in magnitudes, typically take to be only the Galactic foreground screen (Burstein & Heiles 1982, AJ, 87, 1165; Schlegel et al. 1998, ApJ, 500, 525):
  - \( f = f_0 \exp(-\tau_\lambda) \),
  - \( A_\lambda = 1.086 \tau_\lambda = -2.5 \log( f/f_0) \)

See nedwww.ipac.caltech.edu/help/extinction_law_calc.html
Absolute Magnitudes

- For extragalactic observers: $d$ in Mpc, plus the so-called $k$-correction, $\kappa$, which accounts for effects of the cosmological expansion
  1) effects of redshifting the rest-frame spectrum in the observed band-pass; and
  2) photon dilution.

$$m_\lambda - M_\lambda = 5 \log_{10} d + 25 + A_\lambda + \kappa_\lambda$$

### Astronomical Magnitude Systems

Table 3.1: Fluxes for m = 0

<table>
<thead>
<tr>
<th>Band</th>
<th>(\lambda_c (\mu))</th>
<th>(\Delta\lambda/\lambda)</th>
<th>Jy</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>0.36</td>
<td>0.15</td>
<td>1810</td>
<td>Bessell (1979)</td>
</tr>
<tr>
<td>B</td>
<td>0.44</td>
<td>0.22</td>
<td>4260</td>
<td>&quot;</td>
</tr>
<tr>
<td>V</td>
<td>0.55</td>
<td>0.16</td>
<td>3640</td>
<td>&quot;</td>
</tr>
<tr>
<td>R</td>
<td>0.64</td>
<td>0.23</td>
<td>3080</td>
<td>&quot;</td>
</tr>
<tr>
<td>I</td>
<td>0.79</td>
<td>0.19</td>
<td>2550</td>
<td>&quot;</td>
</tr>
<tr>
<td>J</td>
<td>1.26</td>
<td>0.16</td>
<td>1600</td>
<td>Campins, Rieke &amp; Lebofsky (1985)</td>
</tr>
<tr>
<td>H</td>
<td>1.60</td>
<td>0.23</td>
<td>1080</td>
<td>&quot;</td>
</tr>
<tr>
<td>K</td>
<td>2.22</td>
<td>0.23</td>
<td>670</td>
<td>&quot;</td>
</tr>
<tr>
<td>g</td>
<td>0.52</td>
<td>0.14</td>
<td>3730</td>
<td>Schneider, Gunn &amp; Hoessel (1983)</td>
</tr>
<tr>
<td>r</td>
<td>0.67</td>
<td>0.14</td>
<td>4490</td>
<td>&quot;</td>
</tr>
<tr>
<td>i</td>
<td>0.79</td>
<td>0.16</td>
<td>4760</td>
<td>&quot;</td>
</tr>
<tr>
<td>z</td>
<td>0.91</td>
<td>0.13</td>
<td>4810</td>
<td>&quot;</td>
</tr>
<tr>
<td>u'</td>
<td>0.35</td>
<td>0.18</td>
<td>3631</td>
<td>Fukugita et al. (1996)</td>
</tr>
<tr>
<td>g'</td>
<td>0.48</td>
<td>0.29</td>
<td>3631</td>
<td>&quot;</td>
</tr>
<tr>
<td>r'</td>
<td>0.63</td>
<td>0.22</td>
<td>3631</td>
<td>&quot;</td>
</tr>
<tr>
<td>i'</td>
<td>0.77</td>
<td>0.29</td>
<td>3631</td>
<td>&quot;</td>
</tr>
<tr>
<td>z'</td>
<td>0.91</td>
<td>0.16</td>
<td>3631</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

How are these determined?

Note uniformity in \(\Delta\lambda/\lambda\)
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 OBAGFKM classification
  - Further sub-classification is the luminosity class

Nicolet (1980)
Bessell & Brett (1988)
### Basic Properties of Stars (chapter 1.1)

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>Absorption Lines</th>
<th>$T_{\text{eff}}$ (K)</th>
<th>$M_V$ (V, I)</th>
<th>(B-V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>He II, C III</td>
<td>40-50,000</td>
<td>-6.8, -8</td>
<td>&lt;-0.33</td>
</tr>
<tr>
<td>B</td>
<td>He I, S III, H</td>
<td>12-30,000</td>
<td>-1.5, -7</td>
<td>-0.2</td>
</tr>
<tr>
<td>A</td>
<td>H, Mg II</td>
<td>7-9,000</td>
<td>1.0, -7</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>Ca II</td>
<td>6-7,000</td>
<td>3.0, -7</td>
<td>0.4</td>
</tr>
<tr>
<td>G</td>
<td>Ca II, CH</td>
<td>5.5-6,000</td>
<td>5.0, -7</td>
<td>0.6</td>
</tr>
<tr>
<td>K</td>
<td>CH, CN</td>
<td>4-5,500</td>
<td>6.0, -7</td>
<td>1.2</td>
</tr>
<tr>
<td>M</td>
<td>TiO</td>
<td>2.5-4000</td>
<td>9.0, -7</td>
<td>1.6</td>
</tr>
</tbody>
</table>

**Luminosity class**

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

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 $\alpha$-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 ($T_{\text{eff}}$)
  - $T_{\text{eff}}$ set by mass on the main sequence:
  - more mass burns brighter and hotter

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

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

- RGB to Horizontal Branch (HB)
  - Core contraction/core mass increases
  - $T \sim 10^8 \text{ K}, \rho \sim 10^4 \text{ g cm}^{-3}$ get He burning
    - $2\alpha \rightarrow ^8\text{Be}, ^8\text{Be} + \alpha \rightarrow ^{12}\text{C}$
    - In stars w/ $M > 2M_\odot$, it’s not degenerate and we get core expansion
    - Essentially a He-burning main sequence
    - In more massive stars get $^{12}\text{C} + \alpha \rightarrow ^{16}\text{O}$; for stars with $M$ up to $8M_\odot$ we’re left with a degenerate CO core (white dwarf)
  - He-burning lifetime $\sim 10^8$ years
- Evolution to Asymptotic Giant Branch ($M > 8M_\odot$)
- 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
Further Burning Stages

- $^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + \alpha$
- $^{16}\text{O} + ^{16}\text{O} \rightarrow ^{28}\text{Si} + \alpha$
- $^{20}\text{Ne} + ^{4}\text{He} \rightarrow ^{24}\text{Mg} + \gamma$

Leads ultimately to the production of $^{56}\text{Fe}$, core collapse, and supernova explosion (Type II SNe)

- Can also get n production via, e.g., $^{12}\text{C} + ^{12}\text{C} \rightarrow ^{23}\text{Na} + n$
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
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

ZAMS = zero-age main sequence
H-R Diagram continued

- Tracing evolution of a stellar population
- $(B-V) \rightarrow$ temperature
- $V \rightarrow$ luminosity

Globular cluster 47 Tuc
(Edmonds et al. 2002)
H-R Diagram

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

\[ dN = N_0 \xi(M) dM \]

\[ N_0 \int dM M \xi(M) = \text{total mass of burst/episode} \]

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 \( M_\odot \)
Stellar Populations

- **Integrated Colors**
  - Population I – “Disk Population” – open clusters, circular orbits, confined to a disk, “blue”
  - 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
Interpretting CMDs

- Density of any locale on a CMD is a function of IMF, SFR, mass, and age
  - \( C(M_V, V-I) = \iint \xi(\log m, t) \times \text{SFR}(t) \ dt \ d\log m \)
    - Small mass bin (i.e. single mass)
    - Constant IMF \((\xi)\)
    - 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)