Important things to know:

- Derive the Virial Theorem
- Schecter function
- Sersic relation
- deVouceleurs
- Fundamental Plane
- Tully Fisher relation
- Kormendy relation
- isophotes: boxy vs. disky
- inner SB profiles: cuspy vs. core

I History

1. 1700's: Messier objects, 39 of which are actually galaxies (total of 110 in the final catalogue).
2. 1864: GC, 1888: NGC (William Herschel and son John)
3. 1920's: 'Great Debate' between Curtis and Shapley on whether or not galaxies were located within the MW. Resolved by Hubbles discovery of Cepheids in M31.
4. 1980's: Importance of environment recognized: **morphology/density relation**; 'Nature vs. Nurture'.
5. 1990's: Techniques for finding and confirming high redshift galaxies (z¿2): **Lyman break galaxies**:
   - Lyman limit
   - Rydberg formula: $\frac{1}{\lambda} = R\left(\frac{1}{n_u^2} - \frac{1}{n_l^2}\right)$

   First large scale surveys, both nearby and at medium redshift. HST imaging of distant galaxies. N-body (dark matter) simulations.
6. 2000's:Precision Cosmology and LCDM, outside optical wavelengths: IR (Spitzer) and sub-mm (JCMT).
7. 2010's: Extended gas halos in galaxies. Possibly detection of DM and dark energy.

II Approaches

Multifaceted approach to studying galaxy formation and evolution:

Galaxy "archaeology"

Study nearby galaxies in detail, attempt to understand processes that led to their current appearence.

- Advantages: can resolve structure, individual stars in nearest galaxies, high S/N observations
- Disadvantages: some information may be erased by physical processes (e.g. merging), degeneracies in integrated light

Distant galaxies

look at galaxy samples at different lookback times, study distribution of properties (galaxy population) as a function of time.

- Advantages: direct probe of different stages. Relationship between lookback time and redshift.
- Disadvantages: brightness/selection effects, lack of detail, difficulty in associating objects at one redshift to those at another.

Physics of galaxy formation

- Advantages: some physics (e.g. gravity) is well understood
- Disadvantages: some physics (e.g. star formation) is not. Dyanamic range of the problem is huge.
  - Dynamic range in distances, from stellar scales to largest scale structure.
  - Dynamic range in mass, from stellar scales (1 $M_\odot$ to largest scale structure ($10^6 - 10^{15} M_\odot$)

III Overview of galaxies and galaxy formation

Components:

- Dark Matter: usually non-baryonic, but some baryonic matter can be hard to see, such as brown dwarfs. Dominates mass of galaxies.
- Stars: observed properties depend primarily on mass, age, and composition. Variety leads to multiple luminosities and colors in galaxies.
- ISM: molecular, atomic, and ionized gas phases; dust; mass of ISM varies widely between galaxies.
- Central black holes

Processes

- Gravitational collapse (of dark matter, and later, baryons) in cosmological framework.
  - How big are initial lumps at different size scales?
  - How much angular momentum?
  - How fast do lumps grow?
- Condensation of gas and cooling
  - "hot" vs. "cold" accretion
- Star Formation (not well understood)
  - Under what conditions do stars form?
  - What types (masses) of stars form?
  - Drives chemical evolution, which may impact cooling and future star formation
- Black hole formation
  - Primordial formation vs. formation from early stars
  - How common?
- Feedback/mass loss
  - How much energy? Does mass escape or just delay accretion?
  - What objects generate it? Winds, supernovae, galactic nucleii? How?
- Continued accretion from IGM
  - How much?
  - What mode?
  - What composition?
- Merging: Gas-rich vs. gas-poor
- Cluster (group?) environment: ram pressure, tides
- Dynamical evolution
  - Dynamical instabilities
  - Migration
  - Internal vs. external triggers

These processes have characteristic timescales, and the relation between them may influence how galaxies form, evolve, and appear.

Example

Overly simple, but illustrates the consequences of this scenrio (what scenerio???)). Galaxies range size from 10^{11} - $10^{12} M_{\odot}$. Self-gravitating cloud has two timescales:

1. dynamical, or free-fall:
$$t_{dyn} \sim (G\rho)^{-1/2}$$
2. cooling time:
$$t_{cool} \sim nkT_g/n^2\Lambda(T)$$
where Λ is the cooling function

If $t_{cool} > t_{dyn}$, then a cloud can be in quasi-static equilibrium, i.e. cooling is unimportant. If $t_{cool} < t_{dyn}$ the cloud cools, kinetic energy is converted to radiation, and the cloud collapses. Given a cooling curve for primordial composition, one can calculate the relevant timescales, and find that collapse is unlikely to occur for $M > 10^{12} M_{\odot}$. This implies that *dissipation* is important, at least for objects we observe as galaxies (e.g. luminous objects).

This argument is really only a suggestion, for a number of reasons: halos are not uniform density, so there's no such thing as a single cooling time for the entire halo.

More Questions: Add these to the ones above, and keep them in mind while studying. Read with a question in mind, connect old information to new information. Add main bullets first, then go through and add details, depending on how much time you have.

Questions

- When do each of these steps happen and what are their relative importances?
- What sets the masses of galaxies? Sizes? $(10^6 - 10^{12} M_{\odot})$ Luminosities?
- What sets the distributions of numbers of galaxies as a function of mass/luminosity?
- Does the ratio of baryonic mass/total mass change for different galaxies?
- What triggers star formation in galaxies?
- What is responsible for the rango of galaxy morphology?
- How much of present structure is determined by initial conditions, e.g. initial overdensity, angular momentum (and what are those initial conditions)?
- How much does present appearance depend on basic physics within galaxies, e.g. dynamics and chemical evolution?
- How much depends on environment, e.g. mergers and interactions, background radiation?
- Does the relative importance of these effects (initial conditions, internal evolution, environment) vary for different galaxies?

Morphological classification

Historical influence

Galaxies were considered in terms of their morphology, i.e. the Hubble sequence. However, it is not totally clear to what extent morphological classification traces underlying physics, and descriptive morphology may be biased by things that may not be fundamental. Still, it is widely used, so important to understand a bit.

Morphological systems

Hubble classification

- ellipticals: E0 (sphere) $\rightarrow$ E7 (skinny) $n = 10(\frac{1-b}{a})$ No distinction between dwarf ellipticals and dwarf spheroidals
- spirals: barred or unbarred (SBa,SBb,SBc; or Sa,Sb,Sc; respectively) where a,b,c denote size of bulge (bulge-to-disk ratio: B/D) in decreasing order. Also classified according to tightness of arms and the degree to which arms are resolved into HII regions. Later, have SA (normal spirals), SB (barred), and SAB (transition)
- SOs (aka lenticulars, or disks): intermediate, no spiral structure, split into $S0_1$, $S0_2$, $S0_3$, depending on the amount of dust.
- Irregulars: Irr I (Magellenic irregulars with lots of distinct HII regions) and Irr II (lack the resolution into distinct HII regions).
- Some pictorial examples

deVaucouleurs/RC3 classification

See also here.

- extends Hubble to later…
- …
- …
- …
- …
- …
- …

III.1 Note

morphological classification often depends on multiple characteristics…

III.2 Wavelength dependence

K Correction: correction to magnitude (or flux) due to redshift (need to be careful at high z).

Global Characteristics

Hubble class. of Ellipticals probably not fundamental… more meaningful to use isophotal shape (Kormendy and Bender classification), or kinematically by v/σ.

Spirals

correlation between luminosity, surface brightness, rotational velocity and gas fraction and Hubble type… lots of overlap.

Subjective

More quantitative classification schemes (i.e. less subjective):

- Bulge-to-disk ratio (B/D)
- Global profile fit, e.g. Sersic index
- Concentration, e.g. SDSS r_{90}/r_{50}, r_{80}/r_{20}, using circular apertures.

Non-symmetric galaxies

- Asymmetry
- Clumpiness
- Gini coefficient
- M20

Basic observational properties of galaxies

Surface Brightness

Surface Brightness (SB) is the basic measured property for imaging of a *resolved* object. Units:

- erg cm^{-2} s^{-1} sterradian^{-1}
- mag arcsec^{-2}

Magnitudes are often used, but if *summing* multiple SBs, flux units must be used. If you're adding and subtracting magnitudes, you're probably doing something wrong. ☺

SB is independent of distance until geometry of the universe becomes important:

$$SB \sim (1+z)^{-4}$$

In general, flux is a function of wavelength, so SB is measured in different bandpasses, e.g. UBVRI or SDSS (ugriz).

The *ratio* of the flux of the same object in different bandpasses gives an estimate of the *spectral slope* between bandpasses; often expressed as a difference in magnitudes, or *color index*, such as U-R.

Relevance of SB distribution: when investigating how stars are distributed in galaxies, be aware that *mass* in stars doesn't necessarily track *light* in stars (nor does it trace mass in other components).

In principle, SB is measured directly from a 2D detector as an arbitrary function of location. Galaxies are relatively faint: the SB of the central region of a typical galaxy is:

- Spiral: $V \sim 20 - 21$ mag arcsec^{-2} (not much brighter than typical dark sky)
- Elliptical: $V \sim 16 - 17$ mag arcsec^{-2}

More than half the light from galaxies comes from regions with $SB < SB_{\rm sky}$ so S/N is difficult to obtain.

Problems of seeing and sky determination for SB distribution in center and outer parts of galaxies. Sky problems are worse with small detectors and/or large galaxies.

Since SB is the key observable, there can be strong *selection effects* against low SB objects. If all galaxies had the same SB profile (they don't) then low SB galaxies are *strongly* biased against in either magnitude-limited or size-limited catalogs (apparent "size" of a galaxy will depend on its SB).

Most galaxies are symmetric at a significant level; isophotes are often well represented by ellipses. Elliptical contours fit spirals and ellipticals for different reasons:

- Spiral: viewing angle/disk thickness
- Elliptical: intrinsic ellipticity

(NGC1226, NGC1316).

Some basics of techniques for ellipse fitting: (insert links!)

In reality, galaxies have more complex features, e.g. asymmetries, departures from elliptical isophtoes, bars, spiral arms, jets, etc. (See below).

For a purely axisymmetric object, SB distribution reduces to a 1D SB profile. SB profiles are often parameterized, with distributions of the form of a **Sersic Law**:

$$\Sigma(r) = \Sigma_e \exp\left(-b_n\left[\left(\frac{r}{r_e}\right)^{1/n} - 1\right]\right)$$

where r_e is the half-light radius (the radius that encloses half the total light if the model is extrapolated to infinity), Σ_e is the SB at the *effective* radius ($\Sigma_0 \sim 2000\Sigma_e$), $b_n \approx 2n - 0.324$ and is determined from the definition of r_e, and n depends on the type of galaxy ($n = 4$ for ellipticals and $n = 1$ for disks).

- Disks: well represented *on average* by an exponential:

$$\Sigma(r) = \Sigma_s \exp\left(-\frac{r}{r_s}\right)$$

$$m(r) = m_s + kr$$

- Spherioids: historically characterized by **deVaucouleurs profile**, otherwise known as the '$r^{1/4}$' law:

$$\Sigma(r) = \Sigma_e \exp\left(-7.67\left[\left(\frac{r}{r_e}\right)^{1/4} - 1\right]\right)$$

$$m = m_0 + kr^{1/4}$$

There are other forms that can be used.

Sizes of galaxies: ...

Integrated Brightness

Spectral Energy Distribution

- luminus components
- velocities via Doppler shift: $\nabla\lambda/\lambda = v/c$

Distances

need this to get properties like luminosities and linear sizes.

$$m_M = 5\log d - 5$$

Various techniques:

- Variable stars
- Geometric techniques
- SB fluctuations: requires objects with a 'standard' population
- Planetary nebulae luminosity function
- **Scaling relations between velocity and luminosity**
  - Spirals: **Tully-Fisher relation** between maximum rotational velocity and luminosity

- Ellipticals: fundamental plane relation between velocity dispersion, surface brightness, and physical size ($D_n - \sigma$) relation

- Redshift
  - At low $z, z \approx v/c$
  - At $z \geq 0.1$

Statistical properties

Luminosity Function

Number density as a function of luminosity [lum or mag]

- $\Phi(L)$ - number density of galaxies per unit volumne with luminosity between L and $L + dL$

- $\Phi(M)$ - number of galaxies per unit volume with absolute mag between M and $M + dM$

- Integrate given number density of galaxies

First step toward understanding a fundamental question of galaxy formation: What sets the *range* of galaxy luminosities and the relative *numbers* of objects at different luminosities (though mass may be a more fundamental characteristic). Also an important cosmological probe for evolution of the galaxy population.

- LFs usually well characterized by a **Schecter Function**

$$\phi(L) = \frac{\phi_*}{L_*}(\frac{L}{L_*})^{\alpha} exp(-\frac{L}{L_*}) \tag{1}$$

$$\phi(M) \propto 10^{-0.4(\alpha+1)(M-M^*)} exp(-10^{0.4(M^*-M)} \tag{2}$$

  where $\phi(L)$ is the number of galxies with luminosity between L and $L + dL$, α is the faint-end slope, and ϕ_* and L_* are parameters. Typical 'local' parameters (e.g. SDSS at $z \sim 0.1$ are $\phi^* \sim 0.015 h^3 Mpc^{-3}$, $M_B^* \sim -19.5$, $M_R^* \sim -20.5$, and $\alpha = -1$ to -1.5.

  - Integrate Schecter function to get total luminosity density:

$$j = \phi_* L_* \Gamma(\alpha + 2) \tag{3}$$

  - Significant discussian over detailed shape and normalization of LF. Observational issues (e.g. selection functions) and astrophysical ones (e.g. large scale structure, "cosmic variance").

LF evolution → galaxy evolution

- Possibilities:
- LF shows evolution (Faber et al. 2007), all galaxy samples show evolution as well, but red galaxies show number density evolution.

Colors of galaxies

- Consider distribution of spectral energy distributions of galaxies, to first order represented by their color
- Bimodality (Strateva et al., AJ 122, 1861 (2001))
  - Red and Blue sequences (with 'green valley' in between).
  - Red sequence is tighter than blue sequence, so latter is sometimes called the 'blue cloud'.
  - Red sequence extends to higher luminosities, blue to lower luminosities, though significant overlap.
  - Cause of bimodality: ellipticals and early-type spirals don't have much SF and appear red, and later-type spirals with current SF appear blue, although dust, bulges, and metallicity all play a role. The correspondance with morphology is supported by correlation with structural parameters, e.g. multidimensional correlations (Blanton and Moustakis ARAA 2009).
- Easily observed and quantified
- Given likely differences in stellar populations, luminosity-stellar mass relation is probably different for the two different sequences. At a rough level, the color allows one to estimate the stellar mass from the luminosity. Some colors have more information about this than others, and some bandpasses for luminosity are more affected by differences in the stellar populations.
- Relation shifts when expressed in therms of stellar mass (Baldry et al. 2006), and there appears to be a transistion mass around 10^{10} $M_\odot$ between the two sequences.

Elliptical/Spheroidal galaxies

- Elliptical galaxies are not simple collections of
- SB profiles
  - Ellipticals better fit by Sersic profiles than by deVaucouleurs (Caon et al. 1993).

    * correlation of Sersic indices with other parameters suggests that there is something physical going on, but there are degeneracies.
    * Spiral bulges, low luminosity Ellipticals may be better represented by exponentials.
    * Slope of SB profile (Sersic?) appears to be corelated with Luminosity
    * SB vs L turns over at intermediate luminosity: two families of shperoidal systems? $\rightarrow$ **Cuspy and Core**
    * Ellipticals exist over wide range of sizes/luminosities/SBs
  - other profiles
    * King model (truncated Gaussian for velocity distribution)
    * Hubble profile

$$\Sigma(r) = \frac{\Sigma_s}{(1 + \frac{r}{r_s})^2}$$

    where $\Sigma_s = 0.25\Sigma_o$

  None are perfect matches to data over all scales (Burkert 1993 - comparison with deVaucouleurs law).

- Inner regions of spheroidals deviate from Sersic profiles fit to outer regions. Inner regions are of particular interest because they may reflect dissipational collapse of low angular momentum material... initially seemed like galaxies had cores, though this is partly an effect of seeing. Higher spatial resolution (HST) shows that galaxies have both flat and steep (cuspy) inner profiles. Inner profiles seem to be roughly bimodal.
  - Parametric fits to account for these become more complex, e.g. the 'nuker law':

$$I(r) = I_b 2^{(\beta-\gamma)/\alpha)} \left(\frac{r_b}{r}\right)^{\gamma} \left[1 + \left(\frac{r_b}{r}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$$

    where γ is the slope of the inner power law, β is the slope of the outer power law, and α is the sharpness of the break between them.
  - Profile type is correlated with luminosity. Luminous ellipticals ten to have 'cuspy' cores with a break radius and shallower central density profile. Lower luminosity ellipticals have power laws all the way in.
  - Galaixes with cusps...

- outer regions

- Intrinsic (3D) shapes of ellipticals: oblate (2 long axes) vs. prolate (1 long axis) vs. triaxial (all axes different length). Determine true shape by looking at distribution of ellipticals.
  - distribution function is different for fainter and brighter ellipticals
  - For bright giant E's, distribution is inconsistent with either prolate or oblate itrinsic shapes: not enough circular galaxies (Tremblay and Merritt Fig 3).

  - For fainter E's, distribution is *consistent* with oblate, prolate, or triaxial.
  - Triaxiality is also inferred for some giant E's from observation of isophotal twisting, which you cant get from oblate or prolate shape (de Zeeuw, Fig 1).

- Non-axisymmetric features in galaxies

  - Often described by amplitudes of Fourier moments of intensity distribution as a function of radius, e.g. α_1, α_2, α_4

$$I(r, \theta) = \Sigma c_m \cos(m\theta) + \Sigma s_m \sin(m\theta)$$

$$\alpha_m = \frac{\sqrt{c_m^2 + s_m^2}}{I_o}$$

    "First even term above ellipses is α_4 term:" (WTF???)

    * "boxy" isophotes: $\alpha_4 < 0$; bright, slow, central cores, strong radio and x-ray.
    * "disky" isophotes: $\alpha_4 > 0$; faint, significant rotation-flattening, little radio or x-ray emission, steep cusp.

  - Deviations
  - Possibly
  - also possible
  - some ellipticals

- Kinematics

  - key kinematic quantity is **velocity dispersion**; galaxies can be characterized by central velocity dispersion, but σ does vary with radius.
  - Some ellipticals have some rotation, mostly in lower luminosity systems.
  - Relative importance of organized over random motion can be characterized by v_{rot}/σ.
  - Shapes are expected to be influenced by rotation: for an oblate model with isotropic velocity distribution which is flattened by rotation: $v_{rot}/\sigma = \sqrt{\epsilon/(1-\epsilon)}$
  - Giant ellipticals have less rotation than this, implying anisotropic velocity dispersions to account for their shape (required for triaxial systems).
  - Low/medium luminosity (high SB) ellipticals may be isotropic with flattening caused by rotation.
  - Low SB ellipticals appear to have anisotropic velocity dispersion, i.e. more eccentric than expected from rotation; "measured in LG ellipticals 185 (factor of three low in v_{rot}/σ, 147, factor of 10 low)." seriously, wtf.
  - Significant fraction of ellipticals may have dynamical subcomponents, e.g. velocity and dispersion for some interesting cases.

- Relations between different parameters and different families of ellipticals

- Photometric parameters: SB with size, SB with luminosity ("Kormendy relations"), SB *shape* (e.g. Sersic index) with luminosity.
- kinematics vs. luminosity
  * More luminous galaxies have higher velocity dispersions (**Faber-Jackson relation**: roughly $L \sim \sigma^4$, but lots of scatter).
  * More luminous galaxies have less rotation.
- Faber-Jackson relations and the Kormendy relation (between SB and luminosity/size) are manifestations of the **Fundamental Plane of elliptical galaxies**:
  * Correlation between residuals in the Faber-Jackson relation and SB.
  * Galaxies do not populate the entire 3D space of I, r, and σ, but instead populate only a *plane* in this space.
  * relation between the **three fundamental global observables**: SB (or luminosity), size, and velocity dispersion (Dressler et al. 1987; Djorgovski and Davis 1987; Bender, Burstein and Faber 199x)
    - observed relation given by Virgo ellipticals:

$$r_c \propto (\sigma_o^2)^{0.7} I_c^{-0.85} \tag{4}$$

    - Origin of relation? Three assumptions would have to be true: Ellipticals are in virial equilibrium, M/L varies systematically with luminosity, and ellipticals form a "homologous" family, all, e.g. with deVaucouleurs profiles. In this case, one expects:

$$L = c_1 I_c r_c^2$$
$$M = c_2 \frac{\sigma_o^2 r_e}{G}$$

      where the first is a definition and the second is related to the *virial theorem*, which applies to the mean potention energy and mean kinetic energy per unit mass, averaged over the entire system. The constants are related to the shapes and other details (not necessarily constant among the variety of ellipticals).
    - Combining these, we get

$$r_e = \frac{c_2}{c_1} \left(\frac{M}{L} \right)^{-1} \sigma_o^2 I_c^{-1} \tag{5}$$

      If one has $M/L \propto L^{\,0.2}$, one then recovers the observed fundamental plane; could arise from stellar populations or from variations in baryon to total mass. Alterm=natively, one could have constant M/L with a structure which varies relative to one or more of the fundamental variables (which we know it does, e.g., systematic variations of Sersic n with luminosity, but not clear if this is entire "explanation").

        - Need to understand origin of assumptions; why should parameters, e.g. mass-to-light (mass includes dark matter) vary smoothly with luminosity? If ellipticals have dark matter halos, they don't require luminous inner parts to be in virial equilibrium.
        - There is relatively little scatter around the fundamental plane, implying that the assumptions are reasonably valid over a large range of elliptical properties, which implies some significant regularities in the galaxy formation process.
    * Galaxies do not fully populate the entire plane defined by our relation.
        - Consequently,when the plane is projected onto the other two axes, one can see a correlation.
        - In the luminosity(size)-σ plane, one finds that $L \propto \sigma^4$, which is known as the **Faber-Jackson relation**. However, since the locus of ellipticals isn't perfectly linear and the plane defied by the ellipticals isn't perpendicular to this dimension, the scatter around F-J is larger than the scatter around the fundamental plane. One can define a new radius which incorporates SB, such that the new radius vs σ views the fundamental plane edge-on; such a size measurement is called D_n, the isophotal *diameter* of the B=20.75 isophote. This $D_N - \sigma$ relation provides a very useful distance estimator - if the fundamental plane really is fundamental.
        - In the SB-size plane, one sees a relation in which smaller galaxies have higher SB for normal ellipticals; the diffuse ellipticals have different behavior where smaller galaxies have low SB. These are sometimes known as the **Kormendy relations** and are one of the main bases for separating these two types of objects.
        - SB-σ plane - presumably related to underlying physical parameters: density and virial temperature. In this plane, one can only form galaxies where cooling is effective, i.e. at larger densities and hotter temperatures. This restricts the area in the space in which we can find galaxies.
        - Additional features of the galaxy formation process may introduce additional restrictions into allowed locations of galaxies on the fundamental plane. Most luminous ellipticals are located along one line (with some scatter) in the fundamental plane, and most diffuse ellipticals are located along another.
    * Isophotal deviations vs. luminosity and kinematics
    * Several types of ellipticals??

- Spectral energy distributions
  - **Typical Features**: stellar absorption lines (4000 A break, Mg, Fe, etc.)
  - Generally red in color.
  - Color-luminosity relation:
  - Mg line strenth-luminosity relation:

  - Some ellipticals have signatures of a younger population:
  - Stellar populations within ellipticals:

- Interstellar matter in ellipticals
  - Ellipticals have significant interstellar gas, seen in X-ray emission (hot!), from stellar evolution or the environment.
  - Also evidence of colder gas and dust; 50% of ellipticals show evidence for dust their cores (Lauer et al. 2005) typically small components by mass.

IV Spiral/Disk galaxies

- SB profiles
- Size-luminosity/SB-luminosity relations
- Vertical distributions
- Non-axisymmetric features in disk galaxies: bars and spiral arms
- Kinematics: spirals are kinematically cold, meaning the random motion of stars is small compared to the organized motion (rotation), though there is some dispersion of velocities.
- **Tully-Fisher relation**: kinematics(maximum rotational velocity)-luminosity relation.
- Spectra
- Gas and Dust

V To sum up: Galaxy parameter (scaling) relations

- Structural: luminosity-SB
  - ellipticals: isophotal shape-luminosity relation (boxy vs. disky).
- Kinematic: Faber-Jackson, Tully-Fisher
  - ellipticals: luminosity-rotation relation
- structural/kinematic: Fundamental Plane
- Stellar populations
- Gas
- Black holes

VI Environments of galaxies: clusters and cluster galaxies

- Galaxies are not homogeneously distributed in space... Correlation function
- Groups and Clusters
- Abell cluster
- Galaxies in galaxy clusters (Boselli and Gaazzi, PASP 118, 517, 2006)
- Distributed hot gas in clusters, with mass comparable to that found in galaxies (one individual galaxy?)
  - X-ray observations
  - temperatures are 10^7 - 10^8 K
  - intracluster gas is enriched in heavy elements
  - X-ray observations useful for probing cluster masses, under assumption of hydrostatic equilibrium.
    * Need measurement of density and temperature profiles of X-ray gas
    * Estimates can be made from X-ray luminosity and/or temperature (better): the $M - kT$ relation
    * typical masses are 10^{14} - $10^{15} M_\odot$; a typical cluster mass function (Wen et al. 2010).
- Shapes of clusters, inhomogeneities: not all clusters are in equilibrium

VII Some galaxies to be familiar with

- stuff

VIII The building blocks of galaxies

Stars and Stellar populations

Relating observables to intrinsic population characteristics

- **Population characteristics:** distribution of masses, compositions and ages (star formation history).
- **Observe spectral energy distributions (or colors) of stars:** individual stars in very nearby galaxies, interated starlight for most galaxies.

Stellar evolution

- Internal structure of stars: determined by mass, chemical composition, and age (Russell-Vogt theorem). Exclues non-spherical symmetric effects, e.g. rotation, magnetic fields, binarity, etc.
- Luminosity (radius) and effective temperature derived from equations of stellar structure: mass conservation, hydrostatic equilibrium, energy equation, energy transport, along with auxiliary relations: equation of state, opacity, nuclear reaction rates.
- Main stages of stellar evolution:
  - Hydrogen core burning: main sequence (MS)
  - Hydrogen shell burning: giant branch (for lower mass stars)
  - Helium core burning: horizontal branch, red clump, blue core helium burners. Note key transition around 2 solar masses (depends on metallicity): shift to helium flash at lower masses.
  - Helium shell burning: Asymtotic Giant Branch (AGB)
  - Other nuclear burning for high mass stars
  - White dwarf or supernova
- Model tracks (evolution as a function of time for a given mass); for spherical symmetry, calculations are 1D.
- **Isochrones**: cross-section of poroperties at a fixed time across a range of masses. Some well-known groups that calculate evolutionary tracks/isochrones:
  - Padova
  - BASTI (Teramo)
  - Dartmouth
  - Yale-Yonsei
  - Victoria-Regina
  - Geneva
- Uncertainties that lead to some differences between different calculated isochrones: convective overshoot, diffusion, convection, helium abundance, mass loss, etc. Generally, Uncertainties are larger for later stages of evolution. Additionally, there may be missing physics, e.g. rotation and magnetic fields, that would require a full 3D treatment.
- Given effective temperature, surface gravity (from mass and radius), and composition, stellar atmospheres give observables: spectral energy distribution/colors. Some model atmospheres (need links!):
  - Kurucz
  - MARCS
- Theoretical Color-Magnitude Diagrams (CMDs) $\rightarrow$ observed; need distance and reddening/extinction
- Age effects (model isochrones) from Yi et al 2001.
- Metallicity effects: internal (opacity) and atmosphere (line blanketing) effect combine in the same direction to make more metal-rich populations redder: CMDs

  - Metallicity terminology: often given as mass fractions of hydrogen (X), helium (Y), and heavier elements (Z).
  - solar abundance: X=0.7, Y=0.28, Z=0.019 (roughly)
  - also given by

$$\left[\frac{\mathrm{Fe}}{\mathrm{H}}\right] = \log\left[\frac{(\mathrm{Fe/H})}{(\mathrm{Fe/H})_\odot}\right]$$

  - Be aware that this is an oversimplification, as Z contains lots of different elements. More later.

- Main sequence (MS)
  - Very rough scaling relation between luminosity and mass: $L \propto M^{3.5}$
  - Main sequence shifts with metallicity: redder for higher metallicity
  - Location also depends on helium abundance

- Red Giant Branch (RGB)
  - note that because of more rapid evolution after MS, RGB stars all have roughly the same mass.
  - temperature of RGB depends on age/mass: younger and more massive stars are hotter. Temperature also depends on metallicity: latter is dominant effect in older populations (greater than 5 Gyr).
  - At lower masses/larger ages, tip of RGB is close to constant bolometric luminosity regradless of age or metallicity. In observed plane, leads to roughly fixed tip luminosity *if* observing at long wavelengths (e.g. I band): basis for Tip of Red Giant Brance (TRGB) distance indicator.
  - RGB bump (RGBB from Bono et al 2001), location of which depends on mass/age and metallicity; arises when H burning shell crosses chemical discontinuity.

- Horizontal Branch (HB), aka. Red Clump (RC) or more generally He core burning sequence
  - High mass stars form blue He core-burning branch (also note red plume)
  - Intermediate mass stars form red clump.
  - Low mass stars form horizontal branch. Variable mass loss on RGB and at He flash gives a range of masses.
  - Horizontal branch morphology depends on metallicity: more metal-poor populations have bluer HB.
  - However, there is something else that also affects HB morphology, leading to the so-called second-parameter problem (e.g. M3/M13, from Rey et al 2001). Possibilities: Age? He abundance? Heavy element abundances? Density? Rotation?
  - RR Lyrae stars: in instability strip (caused by doubly ionized He, also includes Cepheids, delta Scuti stars, etc.) RR Lyrae stars are indicators of old metal-poor population. Periods of 0.5 days, but multiple groups (Oosterhoff classes) depending on stellar parameters...

- Asymtotic Giant Branch (AGB)
  - For intermediate masses/ages, AGB is significantly more luminous than the TRGB, hence of potential critical importance to studies of integrated light.

- For lower masses (older populations), AGB tip comparable to TRGB and AGB asymtotically approaches RGB (hence its name).

- Potential importance of binaries/interactions
  - unresolved (but otherwise non-interacting) binaries: broaden sequences, depending on mass ratios: equal masses give the appearence of a star 0.75 mag brighter.
  - interacting binary stars
  - blue stragglers: possible stellar merger/interaction products? M3 example from Sandage 1953.
  - supernovae type SNIa: arise from binaries, produce different heavy element abundances than core collapse SNe. (e?)
- End stages of stellar evolution: WDs, neutron stars, black holes, and supernovae
  - projenitor-final mass relation (from Binney and Merrifield)
  - White dwarf cooling sequence (from Hansen et al 2007: potential for age dating).
  - Supernovae: generate significant fraction of heavy elements (but not all). Significant energy input, thermal and mechanical.
- Galactic globular clusters: cornerstone of understanding stellar evolution historically, as apparent examples of a "simple stellar population (SSP)", with all stars of the same age and abundance.
  - However, it's not recognized that not all GCs are so simple.
  - Some CMDs show clear evidence of multiple components, e.g. NGC2808.
  - Long history of evidence of abundance variations between different stars, typified by the Na-O anticorrelation; demonstrated through observations of main sequence stars that this is not a mixing effect.
  - Two phenomena have recently been coupled, but not yet a clear understanding of how the multiple populations arise.

More information in a CMD than is represented by isochrones

one can also consider relative numbers of stars at different locations: CMDs that incorporate number of stars are reffered to as Hess diagrams (e.g. Fornax from Battaglia et al., 2006).

- For a simple stellar population (SSP, a population with a single age and metllicity), the relative number of stars at each stage is determined by the initial mass function (IMF) and the age.
- IMF determinations and parameterizations:
  - "classical" Salpeter IMF (power law with $dN/dM \propto M^{-2.35}$) and others (from Pagel). Note power law form: $dN/dM \propto M^{\alpha}$, or alternatively, $dN/d\log M \propto M^{\Gamma} \propto M^{\alpha+1}$
  - Widely used determination of local IMF is by Droupa Tout, and Gilmore 1993, who find

$$dN/dM \propto M^{-2.7} \text{ for } M > 1M_{\odot}$$

$$dN/dM \propto M^{-2.2} \text{ for } 0.5 < M < 1M_{\odot}$$

$$dN/dM \propto M^{-1.3} \text{ for } M < 0.5M_\odot$$

– Chabrier IMF: log-normal form, $dN/dM \propto \exp(\log M - \log M_o)^2$
– Empirically, no strong evidence for variations of the IMF as functions of, e.g., metallicity.
– No well-established theory for predicting the IMF

Star Formation Histories (SFHs) from resolved stellar populations

- In general, galaxies are not SSPs, i.e. their CMDs don't look like those of a cluster. Can fit Hess diagrams of resolved stellar populations with combinations of SSPs to derive constraints on SFH, e.g. simulated galaxies (from Tolstoy et al).
- Generally speaking, we want the star formation history: $SFH(t, Z, M)$ gives the number of stars (or stellar mass) at all combinations of age, metallicity, and mass; because of lack of observed IMF variation, usually IMF is separated out:

$$SFH(t, Z, M) = \xi(M)\psi(t, Z)$$

where ξ is the IMF.
- MW neighbors resolved down to oldest MS turnoff ($M \sim 5$), because typical distances give distance modulii $\lesssim 20$.
- M31 and neighbors somewhat shallower ($m - M \sim 24.5$) without large investment of telescope time.
- Results for MW:
  – solar neighborhood Hipparcos sample: roughly constant SFH, but be aware of dynamical effects and limited volume bias nearby sample to younger populations. When corrected for, star formation history in solar neighborhood likely to have significantly declined (see, e.g. Aumer & Binney 2009).
  – Age of oldest stars can be studied by WD sequence, gives $t_{\rm oldest} > 8$ Gyr. Also note presence of disk RR Lyrae stars ($t > 10$ Gyr??)
  – Might consider studying age distribution of clusters, as they are simpler populations, but note problems with disruption of clusters that would lead to a bias to younger clusters.
  – Bulge can also be studied, but note foreground population and extinction issues. Predominantly old population, e.g. bulge CMD, and luminosity function (from Ortolani et al 1995).
  – Halo (as defined kinematically/spatially) also prdominantly old, both from field population and from globular cluster population.
  – Historically, distinction between disk stars/open clusters (population I) and halo stars/globular clusters (population II), with pop I being younger and more metal rich. Note, however, the pop II association with low metallicity is now recognized not to be fundamental; inner halo/bulge significantly more metal rich.
  – For metallicities, note that there is a significant puzzle in that there is *not* a strong age-metallicity relation in the solar neighborhood (e.g. Orion has roughly solar metallicity, but is nearly 5 billion years younger): radial migration, inhomogeneous ISM, inflow ...?

- Results for Local Group (LG) dwarf galaxies
  - Carina dSph: striking evidence of episodic star formation, but this is NOT characteristic.
  - Others (from Tolstoy et al); note range of SFHs.
  - LG dIrrs compilation (from Dolphin et al 2005)
  - LG dSphs (from Dolphin et al 2005); possible similarity to dIrrs apart from lack of recent SF?
  - Many dwarfs show population gradients, e.g. from RGB/HB morphology (e.g., Harbeck et al 2001), likely metallicity gradients: some show evidence of age gradients, with younger population in center.
- Results for M33 (from Holtzman et al 2011); note significant age gradient, and significant component of younger stars.
- M31 halo (from Brown et al 2006); significantly different from MW bulge, with more of an intermediate-old population?
- Can do more distant galaxies if information from advanced stages (RC, HB) is reliable; (e.g. local volume SFH (from Williams et al, in prep), dwarf SFH (from Weisz et al 2011)).
- Even farther if info from AGB is reliable.
- General conclusions:
  - galaxies are not SSPs.
  - galaxies have gradients in their stellar populations
  - significant population of old stars in nearby galaxies?
  - more massive galaxies formed stars earlier??

Integrated light from *un*resolved stellar populations

- What stars contribute the most light?
  - Along the MS, use combination of M-L relation and IMF:

    $$L \propto (M^{-2.35} M^{3.5}) \propto M^{1.15}$$

    Massive stars dominate light.
  - Compare MSTO with evolved population: RGB has almost same mass as MSTO, but significantly more luminous: relative contributions depend on relative number of starsalong the giant branch compared with MSTO stars, but one finds that the luminous evolved populations dominate (Renzini fig 1.5).
  - Since post-MS evolution is fast compared to MS evolution for all masses, it is true that at any given time when the most luminous stars are the most evolved stars, the luminosity is given predominantly by stars of (nearly) a single mass (true for all except youngest ages, see Renzini 1.1) and luminosity vs. lifetime plots.
- Integrated brightness: do SSPs get brighter or fainter as they age?
  - At younger ages, have MS "peel-off" effect, but also supergiants! (WTF...)
  - At older ages, have competing effects of IMF and rate of evolution.

    * To determine the luminosity of a stellar population, consider the number of stars evolving off the MS, or equivalently, dying, which is given by the *evolutionary flux*:

      $$b(t) = \psi(M_{\rm TO})|\dot{M}| \text{ [stars yr}^{-1}]$$

      where TO stands for turnoff, ψ is the IMF, and $|\dot{M}|$ is the time derivative of the turnoff mass, e.g. Renzini 1.1. The key point is that lower mass stars evolve more slowly.
    * The IMF is important, along with age, in determining the luminosity evolution of a galaxy.
    * Once one reaches an age where most massive stars have died, all stars of lower mass reach comparable luminosity (tip of RGB), hence luminosity of population depends on number of red giants.
    * For a typical IMF number of stars increases slower toward lower mass than rate of generation of turnoff stars decreases.
    * Luminosity of the turnoff also has some smaller effect.
  - Do integrated colors depend on the IMF?
    * Need to know the relative contributions of each stage of evolution, i.e., from stars of different masses.
    * Number of stars in each post-MS stage is determined predominatnly by the time spend in each stage:

      $$N_j = b(t)t_j$$

      because all post-MS stars have nearly the same mass. So although the total flux is sensitive to the IMF, the relative contributions of each stage are not, at least for older populations (Renzini fig 1.5).
    * For all except the youngest population, the later stages of evolution provide a majority of the light. Evolved stages are nearly all the same mass.
    * Consequently, the integrated spectrum and the relative contributions of various evolutionary stages are nearly independent of the IMF. They *do* depend on the age and metallicity.
  - Dependence of color and luminosity on time (from Bruzual and Charlot 199?) for a SSP (single burst) normalized to one solar mass.
    * luminosity variation is a combination of IMF plus rate of evolution for lower masses.
    * color evolution comes from changing mix of stellar population, but this is just for a single (solar) metallicity.
    * note RSG phase, then subsequent dimming and reddening.
    * note this is bandpass dependent, with less dimming (at older ages where the RGB is dominant) at longer wavelengths.
  - Implication: if range of ages is present, integrated light is (significantly) weighted toward younger populations.
- What stars contribute the most *mass*?
  - For all measured

- relative stellar M/L ratios
- Can you estimate stellar mass from integrated light?
  - Consider the
  - For individual stars
  - Absolute value of
  - stellar M/L ratio depends on
  - So, it is possible
    - Variety of different
    - Some uncertainties
    - Larger
    - if IMF were to be variable
- Star formation histories from integrated colors
  - Issue: intgrated colors are affected by combination of age distribution, metallicty distribution, and reddening distribution.
  - color variations with age:
  - situation somewhat improved
  - Even if age-metallicity
- Given age-metallicty degeneracy from colors,
- Spectral evolution (BC fig 4) for a variety of SFRs
- Dependence of contributor on wavelength
- Potential problems with synthetic integrated spectra:
- What about spectral features?
  - For populations
  - For older populations
  - typical optical spectra
- Even with
- Main area of application

Chemical evolution

- Understanding
- Start with some initial conditions, then add star formation history: (IMF + SFR). This results in chemical enrichment for stars as a function of mass and metallicity. Also consider input and output of gas from any particular region, with either primordial or modified composition.
  - ICs: No heavy elements and pure gas (no stars).
  - SFH: birthrate function $\psi(m, t)$ gives number of stars formed with mass m per unit volume, usually split into separable function:

    $$B(m, t) = \xi(M)\psi(t)$$

    where $\xi(M)$ is the IMF and $\psi(t)$ is the SFR. This implicityly assumes an IMF which is constant in time, which may or may not be true, but so far, there is no strong observational evidence against it (although note pop III issues).

- For any particular star, use stellar evolution to compute the amount and composition of mass returned to the ISM vs. amount locked up in stellar remnants (Pagel fig 2, from Maeder 1992). Note that the *rate* of return depends on stellar mass, especially for the case of SnIa, which also depends on the binary fraction.
- nucleosynthesis: main element groups and their sources:
  * light elements: Big Bang Nucleosynthesis (BBN) plus subsequent destruction (?)
  * α elements (even Z from O up…???): massive stars (core collapse SN)
  * Fe-peak elements: type Ia SN and core collapse SN
  * s and r process (neutron capture, plux beta decay) elements: core collapse SN, AGB stars… (need neutron capture diagram here)
- Note that infall might arise from primordial clouds, or from processed material, e.g. mass-loss from halo stars. Outflow might come from SN winds, and in this case, it's possible that the composition of outflow material might be more enriched than the typical composition at any given time. So things can get complicated.

• Basic equations of chemical evolution
  - Allowing for
  - Consider a total (galaxy) mass M, split into a gas mass g and stellar mass s. For a simple model, consider the gas at any time to be well mixed. At any given time, we wish to know the fraction abundance (Z_i) of element i. Consider an inflow rate into the system, F and outflow (ejection) rate, E. Then we have:

$$M = g + s$$

$$\frac{dM}{dt} = F - E$$

$$\frac{dg}{dt} = F - E + e - \psi' t$$

where ψ' is the SFR in units of mass per time,

$$\psi' = \psi \int \xi \mathrm{d}m$$

(so ξ is normalized to a total of one), and e is the ejection rate of mass from stars,

$$e = \int_{m_t}^{m_U} (m - m_{\mathrm{rem}})\, \psi\, (t - \tau(m))\, \xi\, (m)\, \mathrm{d}m$$

which is a sum over all stellar masses of the product of the SFR at the time of formation of each mass with the mass returned to the ISM, weighted by the IMF. The lower limit of integration is at the stellar mass which is dying at time t; lower mass stars don't contribute because they haven't ejected any mass yet. We also have

$$\frac{ds}{dt} = \psi' - e$$

wince the mass in stars increases by te number of stars formed, but decreases by the amount of mass lost back to the ISM from the previous generation of stars. For the elements, we have

$$\frac{d(gZ_i)}{dt} = e_Z(i) - Z_i\psi + Z_F F - Z_E E$$

(Z_i is the mass fraction of element i; hereafter we'll drop the subscript for simplicity). The mass in each element *increases* by:

- amount of mass released by previous generations
- amount of mass added by inflow

but *decreases* by:

- amount of mass locked up in new stars
- amount of mass lost to outflow

The term e_Z is given by:

$$\psi(t-\tau(m))\xi(m)\mathrm{d}m$$

where q_Z represents the fractional mass of element Z synthesized and ejected during stellar evolution (so left term in brackets gives material which returns unprocessed and right term gives newly synthesized contribution). In a simple model, the synthesized masses are independent of the metallicity of the population (although we know this is not true for some elements, more on this later).

– To simplify, consider an approximation to these formulae called the *instantaneous recycling approximation* which assumes that all elements are returned instantaneously - good for products of massive stars, but less good for products from lower mass stars, e.g. iron. Then we have

$$e = \psi \int (m - m_{\mathrm{rem}})\xi(m)\mathrm{d}m \equiv (1-\alpha)\psi$$

where α is the *lock-up fraction*: the fraction of mass "locked up" in stars and remnants.

...

...

and finally,

$$g\frac{dZ}{ds} = \frac{d(gZ)}{ds} - Z\frac{dg}{ds} = p + (Z_F - Z)\frac{F}{\alpha\psi}$$

This is a basic equation of chemical synthesis.

– The *simplest* model for chemical evolution assumes no inflow or outflow, a homogeneous system without any spatial differentiation of metallicity, zero initial metallicity, and yields which are independent of composition. This is known as the Simple, one-zone model.
In the simple model, we have

$$\frac{dg}{dt} = -\frac{ds}{dt}$$

$$g\frac{dZ}{ds} = -g\frac{dZ}{dg} = p$$

Solving for $Z(g)$, we get

$$Z$$

Abundances as function of time

Relative abundances of different elements

Gas

Dust

Central black holes

Galaxy spectral energy distributions

Dark matter and galaxy masses