Contents

1 | 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.

2 | Approaches

Multifaceted approach to studying galaxy formation and evolution:

2.1 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

2.2 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.

2.3 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 ($10^6 - 10^{15} M_\odot$)

3 | Overview of galaxies and galaxy formation

Components:

Dark Matter (DM); usually non-baryonic, though even some baryonic matter can be hard to see, such as brown dwarfs. DM 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 (supermassive) black holes

Why do galaxies appear as they do? Important processes (not necessarily in chronological order):

- 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.[*]

3.1) Example

Overly simple, but illustrates the consequences of this scenerio[†].

- Galaxies appear to have a maximum size of order 10^{11} - $10^{12} M_\odot$, even though there are larger agglomerations of matter, e.g. clusters.
- Can be crudely explained by understanding of dissipation
- Self-gravitating cloud has two timescales:
  1. dynamical, or free-fall:

  $$t_{dyn} \sim (G\rho)^{-1/2}$$

  2. cooling time:

  $$t_{cool} \sim \frac{nkT_g}{n^2 \Lambda(T)}$$

  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.

3.2) Questions

- When do each of these steps happen and what are their relative importances?

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[*]see Mo et al.
[†]Rees 1995

- 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?

4 | Observing galaxies

4.1 | Imaging

Surface Brightness (SB) is the basic measured property for imaging of a *resolved* object. SB is independent of distance until geometry of the universe becomes important:

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

Units:

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

For adding multiple SBs, flux units must be used. If you're adding and subtracting magnitude units, you're probably doing something wrong. ☺Differences in magnitudes correspond to *ratios* in fluxes:

$$m_1 - m_2 = -2.5 \log \frac{F_1}{F_2}$$

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 *color index*, the difference in magnitude between the two bandpasses, such as U-R.

Relevance of SB distribution: How are stars 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. However, galaxies are relatively faint. Typical values in galactic centers are:

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 $SB < SB_{\mathrm{sky}}$ so S/N is difficult to obtain.

Problems of seeing and sky determination for determination of SB distribution in center and outer parts of galaxies. Sky problems are worse with small detectors/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. The apparent "size" of a galaxy will depend on its SB.

Most galaxies are symmetric at a significant level; **isophotes** (contours of constant SB) are often

well represented by ellipses. Elliptical contours fit spirals and ellipticals for different reasons: *

Spiral	viewing angle/disk thickness
Elliptical	intrinsic ellipticity

In reality, galaxies have more complex features, e.g. asymmetries, departures from elliptical isophotes, 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 in the form of a **Sersic Law**[†] (though there are other forms that can be used as well):

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

- Σ_r = SB at radius r
- r_e = *effective* radius (aka. half-light radius), the radius enclosing half the total light if the model is extrapolated to infinity.
- Σ_e = SB at r_e ($\Sigma_0 \sim 2000\Sigma_e$) at galaxy center?
- $b_n \approx 2n - 0.324$ and is determined from the definition of r_e (I assume this is talking about where that particular expression came from, including the constants.)
- n depends on the type of galaxy ($n = 4$ for ellipticals and $n = 1$ for disks).

4.1.1 SB profile for disk galaxies

Disks are usually well represented *on average* by an exponential:

$$\Sigma(r) = \Sigma_s \exp\left(-\frac{r}{r_s}\right) \quad \text{[flux units]}$$

$$m(r) = m_s + kr \quad \text{[magnitudes]}$$

4.1.2 SB profile for spheroids

Spheroids are historically characterized by **deVaucouleurs profile**, otherwise known as the "$r^{1/4}$" law:

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

$$m = m_0 + kr^{1/4} \quad \text{[magnitudes]}$$

4.1.3 Sizes of galaxies

Generally, galaxies do not appear to have sharp edges (although SB can drop sharply in some disk galaxies).

- Isophotal (D_{25} ??? in RC (rotation curve?) is B=25.0): Beware for low SB galaxies ???

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*Some basics of techniques for ellipse fitting: Kent, ApJ 266, 562 (1983); Lauer, ApJ 311, 34
[†]plot from MacArthur et al. (2003)

- Half-light radii (e.g. R_e)
- Petrosian radius: radius at which the *local* SB at that radius drops to some fraction of the *mean* SB within that radius. (in an annulus, SDSS used $0.8r$ - $1.25r$, with a fraction of 0.2)

Typical angular sizes: arcminutes for nearby galaxies, arcseconds for distant galaxies. Can get linear sizes with distance estimate (which depends on cosmology). Typical physical size (of the luminous component) is $\sim$ 1-30 kpc.

4.1.4 Integrated brightness

Issue: galaxies don't have edges. Types of mags:

Metric:	brightness within an aperture of fixed angular or physical size. Be careful if galaxies have a range of sizes.
Isophotal:	brightness within a specified SB contour, e.g. Holmberg mags, which is the brightness within $\mu_{pg} = 26.5$. wtf is μ_{pg}?? Be careful if galaxies have a range of SB profiles.
Model:	require assumption about outer SB profile
Petrosian:	mag within some fixed number of Petrosian radii (SDSS uses 2). Advantages with regard to SB (distance) and seeing effects. Note relation of Petrosian mag to model mag depends on SB profile. *

Typical integrated brightnesses of galaxies, and star-galaxy separation and crossover in number counts (. . . yes?)

Other issues in getting luminosities of galaxies:

- Foreground extinction, which depends strongly on Galactic latitude [†]
- Internal extinction/inclination, which can be significant (up to 1.5 mag in RC3 prescription (???))
- If looking at a population, be sure to compare luminosities in the same bandpass. This is an issue if looking over a range of redshifts; a fixed observed wavelength range corresponds to a different rest frame wavelength range at different redshifts. **K-corrections** are used to account for this at some level[‡]. These require knowledge/assumptions about the spectral energy distribution of galaxies. Alternatively, measure at different observed wavelengths.

4.2 Spectroscopy

The SED of a galaxy is the other fundamental observable; obviously, the most fundamental is spectral energy SB, but spectra are often obtained over some aperture, or long slit. Note increasing use of integral field spectroscopy (e.g. SDSS MaNGA).

The overall shape and features in SEDs (see also here) provide important information about the

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[*] http://classic.sdss.org/dr5/algorithms/photometry.html#mag_petro
[†] Burstein & Heiles, ApJS 54,33 (1984); Schlegel, Finkbeiner, & Davis, ApJ 500,525 (1998)
[‡] Hogg et al. astro-ph/0210394; Kinney et al. ApJ 467.38 (1996); Coleman, Wu, Weedman, ApJS 43,393 (1980)

nature of the luminous components, i.e. physical properties of the stellar population and the gas component As we'll discuss later, these can be challenging to sort out. The composite spectrum of a galaxy is the sum of different types of stars, weighted by relative numbers and luminosities, plus emission from gas and dust.

Spectra also allow the study of velocities via the Doppler shift:

$$\frac{\nabla \lambda}{\lambda} = \frac{v}{c}$$

which measures both the bulk velocity of the galaxy and the distribution of stellar velocities within the galaxy.

Bulk velocities

- Mean velocities of galaxies indicate that they are receding, with velocity proportional to distance $\rightarrow$ expansion of the universe.
- There is a dispersion of velocities around the mean relation; the deviation is called the **peculiar velocity**. In the field, typical peculiar velocities are a few hundred km s^{-1}. In clusters, they can be a thousand km s^{-1}.

Internal velocities

Internal velocities can be organized (rotation in disks), or they can be random, leading to broader lines that represent the velocity distribution of stars within a galaxy. This broadening would be the same at all points in the galaxy.

$$F(\lambda) \propto \int F(v_{los}) S\left(\lambda - \frac{v_{los}\lambda}{c}\right) dv_{los}$$

- S = spectrum of an individual star
- F = fractional distribution of stars at different line-of-sight velocities.

Lines are usually fairly well represented by a Gaussian velocity profile, characterized by the mean velocity:

$$\int v_{los} F(v_{los}) dv_{los}$$

and the velocity dispersion:

$$\int (v_{los} - \overline{v}_{los}) F(v_{los}) dv_{los}$$

e.g., central velocity dispersion or, more generally, the velocity dispersion profile.

Deviations from a Gaussian can be measured, and are usually characterized by higher order moments: *skew* (h_3) and *kurtosis* (h_4):

$$F(v_{los}) \propto \exp \frac{-\omega^2}{2} \left[1 + \sum h_k H_k(\omega)\right]$$

where $\omega \equiv (v_{los} - \overline{v})/\sigma$ and H_k are Gauss-Hermite functions. Some examples of velocity data.

Relevance: Internal velocities can be used to probe mass distribution within galaxies (assuming that gravity drives the motions). For a rotationally supported system:

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

For a collisionless system of (independent) particles, the distribution of velocities at any given location characterized by the velocity ellipsoid, and Jeans equation leads to:

$$\frac{\mathrm{d}\rho\sigma^2}{\rho\mathrm{d}r} + \frac{2\beta\sigma^2}{r} = -g(r)$$

where β is the **velocity anisotropy**:

$$\beta \equiv \left(1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2}\right)$$

though β is not generally known.

4.3 Distances to galaxies

Some properties of galaxies, such as luminosity and linear size, require knowledge of distances to galaxies:

$$m - M = 5\log d_L - 5$$

- d_L = distance [pc] $L = ?$
- M = absolute magnitude (or SB)
- m = apparent magnitude

Various techniques for getting distances[*]:

Variable stars Cepheids/RR Lyrae stars through period-luminosity (period-luminosity-color/metallicity) relation.

Geometric techniques • masers (proper motion compared with radial velocity in central disks)
  • exclipsing binaries

SB fluctuations from imprint of Poisson statistics: requires objects with a "standard" population (i.e. stellar luminosity function).

Planetary nebulae luminosity function

More luminous standard candles: type-Ia supernova ("standardizable")

Scaling relations between velocity and luminosity for relatively nearby galaxies
  • Spirals: **Tully-Fisher relation** between maximum rotational velocity and luminosity
  • Ellipticals: fundamental plane relation between velocity dispersion, SB, and physical size $(D_n - \sigma)$ relation.

Redshift (see next section)

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[*]see Freedman & Madore, ARAA review

4.3.1 Distances from redshift

Galaxies expand with everything else in the cosmic flow.

$$\frac{\Delta\lambda}{\lambda} = z; \quad 1 + z = \frac{lambda_{obs}}{\lambda_{emit}}$$

At *low z*, $z \approx v/c, v = Hd$. At *high z*, need knowledge of cosmological parameters to get distance from redshift (i.e. redshift-distance relation.[*])

Galaxies also move around relative to the uniform expansion because of local gravitational attraction from concentrations of mass. As mentioned above, the deviation of the velocity from the smooth flow is called the *peculiar velocity*. Typical peculiar velocities are on the order of several hundred km s^{-1}, but depend on environment; c.f., ?? Milky Way and galaxy clusters; if these are ignored, introduces spurious features in distance maps ("fingers of God", redshift space distortions).

At $z \gtrsim 0.1$, peculiar velocities lead to relatively small distance errors. At lower redshifts, might estimate distances using model of mass distribution and velocity field, but this is likely not well determined.

Spectroscopic redshift

Determining redshift spectroscopically for distant (faint) galaxies is observationally time-consuming. Accurate positions of individual lines require reasonable S/N; emission line galaxies are significantly easier. It is possible to get good redshifts from low S/N observations by taking advantage of multiple spectral features, e.g., by cross-correlation of spectrum against a template in $\log\lambda$ space.

Photometric redshift

Lower accuracy distances are possible from so-called *photometric redshifts* (though can't disperse light.) Use low resolution spectral information, i.e. multiband photometry to constrain redshift.[†] The different intrinsic SEDs of galaxies, internal reddening, and redshift need to be separated. Accuracy of results obviously depends on quality of photometry and number of bandpasses. Typical accuracies (checked against spectroscopic redshifts) give

$$\frac{\Delta z}{(1+z)} \sim 0.1$$

(sometimes better); note typical $\sim$ 10% outlier fraction (varies for different types of galaxies).

4.4 Morphological classification

Historically, 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.

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[*]see, e.g. Hogg, Distance Measures in Cosmology
[†]e.g. plot (from Niemack et al 2009, ApJ)

4.4.1   Morphological systems

Good reference: Sandage in Galaxies and the Universe, 1975. Some pictures:

- ellipticals
- S0s, also known as lenticulars
- spirals
- Tuning fork diagram

4.4.2   Hubble classification

- **ellipticals:** given as En, where

$$n = 10(\frac{1-b}{a})$$

  E.g., E0 (sphere) → E7 (skinny). 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 (note that the latter two are essentially impossible to judge for edge-ons). Later, have SA (normal spirals), SB (barred), and SAB (transition)
- **SOs (aka lenticulars, or disks):** intermediate, no spiral structure but have disk system, 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)
  - Irr II (lack the resolution into distinct HII regions).
- Some pictorial examples

4.4.3   deVaucouleurs/RC3 classification

diagram. See also here.

- Extends Hubble to later spiral types Sd, Sm, and finally Im.
- Extra classes around $S0$ ($S0^-, S0^+$)
- Allows for intermediate between barred and unbarred:
  - SA: normal spirals
  - SB: barred spirals
  - SAB: transition
- Adds extra distinction for *ring* vs. *s* shaped.
- Note that location along spiral dequence may not be the same as in "Hubble classification" (more based on B/D).
- Some pictorial examples
- Numerical galaxy types (T)

Note that morphological classification often depends on multiple characteristics, and therefore it can be somewhat subjective. Quantitative classification schemes have been worked on (see § 4.4.5), but are not widely used for nearby galaxies.

4.4.4 Wavelength dependence

Morphology depends on wavelength (e.g. O'Connell 9609101). Be careful about morphological classification at higher redshift (or at least a direct comparison with lower redshift galaxies) because you may be looking at morphology at a different wavelength (morphological **K Correction:** correction to magnitude (or flux) due to redshift).

Based on global characteristics, the Hubble morphological classification of ellipticals is probably not fundamental. It may be more meaningful to classify by *isophotal shape* ((Kormendy and Bender classification)) or kinematically by v/σ.

For the spiral sequence, there are correlations of luminosity, surface brightness, rotational velocity and gas fraction with Hubble type. However, each category has a broad range of global observables, and the categories overlap significantly.[*]:

- Considering mean or median values, there is little trend in radius, L_B (Bolometric luminosity?), and total mass for S0-Sc, but later types tend to be smaller, less massive, and less luminous (RH figure 2). However, note that LSB (Low Surface Brightness?) galaxies tend to be later types, and since these are not included, there may be a bias here.
- Typical SB may be lower for latest types, even without inclusion of LSB galaxies; CSB(?????) much higher for large ellipticals than spirals. Mass surface density appears to decrease monotonically with morphological class in spirals (RH figure 3).
- Cold gas is absent in ellipticals, and neutral hydrogen (HI) content appears to increase monotonically with type for spirals. It is possible that molecular gas content decreases with type, but not certain. (RH figure 4).

4.4.5 Quantitative classification schemes

As stated above, all of the aforementioned classification schemes are subjective at some level. Some of the more quantitative schemes that have been proposed, both parametric and non-parametric, are:

- **Bulge-to-disk ratio**, using B/D decomposition[†]. Issues: covariance between parameters, 1D vs. 2D, and validity of models.
- **Global profile fit**, e.g. Sersic index
- **Concentration**, e.g. SDSS r_{90}/r_{50}, r_{80}/r_{20}, using circular apertures. Elliptical apertures can also be considered, e.g. based on *second order moments*. Related to B/D. Sensitivity to seeing/distance.

4.4.6 Non-symmetric galaxies

Many of the schemes used for nearby galaxies fail for non-symmetric galaxies, for which other indicators have been suggested:

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[*]Some representative data from Roberts and Haynes review (ARAA 1994)
[†]MacArthur, Courteau, & Holtzman, ApJ 582, 689 (2003)

- **Asymmetry:**[*] Rotate about center, self-subtract,

$$A = \frac{0.5|\text{subtracted}|}{\text{total}}$$

Possible indicator of mergers.
- **Clumpiness:**[†] e.g. S. Subtract smoothed version of image from original image, ratio of flux in subtracted image to flux in original images gives S. Possible indicator of star formation.
- **Gini coefficient:**[‡] Applied to sorted list of pixel values. May be more stable at low resolution, S/N.
- **M20:** second order moment of brightest 20% of galaxy light [§] May be more stable at low resolution, S/N.

[*]Abraham et al, ApJS 107, 1, 1996
[†]Conselice ApJS 147, 1 (2003)
[‡]Abraham et al, ApJ 588, 218 (2003)
[§]Lotz et al., AJ 128, 163 (2004)

5 | Statistical properties of galaxies

Consider relative number of galaxies with different parameters, e.g. color or luminosity.

5.1 Luminosity Function

The luminosity function (LF) gives the number density of galaxies as a function of luminosity, which can be expressed either in luminosity or absolute magnitude units.

$\Phi(L)$ = number density of galaxies with luminosity between L and $L + \mathrm{d}L$
$\Phi(M)$ = number density of galaxies with absolute mag between M and $M + \mathrm{d}M$

The integral over the LF gives the total number density of galaxies (at all luminosities). The LF is the 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). It is also an important cosmological probe for evolution of the galaxy population (more later).

5.1.1 Measuring the LF

Obviously, distance measurements are required to get luminosity. Measurement critically depends on knowledge of the **selection function**. For magnitude limited samples, more luminous objects will be overrepresented. This is called the Malmquist bias[*]

The simplest idea for correction is to weigh counts by V_{max}, the largest volume to which the galaxy could have been observed given the selection function. However, the issue here is large-scale structure. $\rightarrow \dfrac{V}{V_{max}}$ test for uniformity and understanding of selection function[†].

Also may need to be careful about systematic biases arising from uncertainties in measured magnitudes and distances, if population is not uniform in underlying distribution of absolute mags and distances sampled (which it isn't). The LF rises toward fainter magnitudes, so more galaxies are scattered bright than are scattered faint (WTF??). In distance, more galaxies are located farther than nearer because of volume element (seriously, WTF), so more galaxies scattered into sample (with corresponding error in absolute magnitude) than scattered out of it.

Note that many biases are possible aside from a simple magnitude cut, e.g. color bias, SB bias, etc. In general, need to be *very* careful about understanding selection effects; model (and verify) them.

5.1.2 Observed LF

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[*]Be aware that this name is sometimes used to refer to different things.
[†]Significantly more sophisticated methods have been developed; see, e.g. Binggelli et al (ARAA 26, 26, 1988) for more details

- Absolute magnitudes (M_V) range from -22 to -8.
- Nomenclature: "dwarf" galaxies vs. "normal" galaxies.
- What objects dominate by number? What objects dominate the total luminosity?
- Different types have clearly different LFs
- Since proportion of a given type depends on environment, so must the general LF.

5.1.3 Functional fits to the observed LF and parameters of the LF

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

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

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

where $\phi(L)$ is the number of galxies with luminosity between L and $L + dL$. ϕ_*, L_*, and α (the faint-end slope) are the three parameters. The Schecter function is only an approximation, and is purely empirical.

A possibly useful feature of the Schecter function is that it can be integrated to get total luminosity density:

$$j = \phi_* L_* \Gamma (\alpha + 2)$$

Typical "local" parameters (e.g. SDSS at $z \sim 0.1$) are:

- $\phi^* \sim 0.015 h^3$ Mpc^{-3}
- $M_B^* \sim -19.5$
- $M_R^* \sim -20.5$
- $\alpha = -1$ to -1.5

As noted above, there is a dependence on type. So what is the implied luminosity density? And (getting ahead of ourselves) the implied stellar mass density, c.f. cosmological.

There has been significant discussian over detailed shape and normalization of LF. There are probably both observational issues (e.g. selection functions) and astrophysical ones (e.g. large scale structure, "cosmic variance").

5.1.4 Evolution of the LF

LF evolution contains a lot of information about galaxy evolution. Some possibilities:

- No evolution: distribution of galaxiy luminosities is unchanging.
- Passive evolution: number and internal (stellar) makeup of galaxies is unchanging (no star formation), but luminosity evolves as stars evolve.
- Luminosity evolution: stellar makeup of galaxies changes with time (star *formation*, leading to luminosity changes).
- Number (density) evolution: number of galaxies changes with time. Galaxies may be either created (formed) or destroyed (e.g. mergers) as a function of luminosity.

There is a large amount of work on this, but certainly the LF shows evolution[*]. All samples show luminosity evolution, but red galaxies show number density evolution. Schecter parameters (link?)

5.2 Colors of galaxies

Consider the distribution of SEDs of galaxies, to first order represented by their color. There is a striking bimodality in color[†]:

- Widley used terminology of 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 there is significant overlap.

At some level, this bimodality is nothing more than the bimodality between ellipticals/early-type spirals without much current star formation (red) and later-type spirals with current star formation (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[‡].

The key point is that color is easily observed and quantified. Given likely differences in stellar populations, the relation between luminosity and stellar mass is probably different for the two different sequences. At a rough level, the color allows one to estimate the stellar mass from the luminosity, though some colors certainly have more information about this than others, and some bandpasses for luminosity are more affected by differences in the stellar populations (more later).

Note that the relation shifts when expressed in terms of stellar mass[§], and that there appears to be a transistion mass around 10^{10} M$_\odot$ between the two sequences.

6 | Elliptical/Spheroidal galaxies

Elliptical galaxies are not simple collections of stars that are all similar to one another. They exist over a wide range in luminosity and other quantities.

6.1 SB profiles

Ellipticals better fit by Sersic profiles than by deVaucouleurs[¶].

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[*] Faber et al. (2007)
[†] quantified from SDSS by (Strateva et al., AJ 122, 1861 (2001))
[‡] Blanton and Moustakis ARAA 2009
[§] Baldry et al. 2006
[¶] Caon et al. 1993

- Correlation of Sersic indices with other parameters suggests that there is something physical going on, but be aware that there may be fit degeneracies.
- Spiral bulges, low luminosity Es may be better represented by exponentials.
- Slope of SB profile (Sersic n) appears to be correlated with luminosity
- SB vs L "turns over" (?) at intermediate luminosity: two families of shperoidal systems? → **Cuspy and Core**
- Ellipticals exist over wide range of sizes, luminosities, and SBs.

Other profiles that have been used:

- King model (truncated Gaussian for velocity distribution)
- Hubble profile:

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

where $\Sigma_s = 0.25\Sigma_o$

None are perfect matches to data over all scales[*].

Inner regions of spheroidals deviate from Sersic profiles fit to outer regions, (though outer regions can also deviate from Sersic profiles, especially notable in central cluster (cD) galaxies). Inner regions are of particular interest because they may reflect dissipational collapse of low angular momentum material[†]. Initially, it seemed like galaxies had cores, but 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 (though this bimodality is currently under debate).

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 may have "extra light", perhaps related to an accretion event; note that at least some of these show distinct kinematic signature in their cores.

6.2) Intrinsic (3D) shapes of ellipticals

- oblate (2 long axes)

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[*]see Burkert 1993 for comparison with deVaucouleurs law
[†]See, e.g. NGC 4472
[‡]e.g. NGC720 vs. NGC4621

- prolate (1 long axis)
- triaxial (all axes different length).

True shapes are determined by by looking at distribution of ellipticiites

- Distribution function is different for fainter and brighter Es.
- For bright giant Es, distribution is *inconsistent* with either prolate or oblate itrinsic shapes: not enough circular galaxies[*].
- For fainter Es, distribution is *consistent* with oblate, prolate, or triaxial.
- Triaxiality is also inferred for some giant Es from observation of isophotal twisting, which you cant get from oblate or prolate shape[†].

6.3 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

$$I\left(r,\theta\right) = \sum c_m \cos\left(m\theta\right) + \sum s_m \sin\left(m\theta\right)$$

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

"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 from elliptical fits are seen in slliptical/spheroidal systems, e.g. NGC 821 v. NGC 2300. It is possible that isophotal deviations form a continuous sequence[‡]:

$$S \to S0 \to disky\ Es \to true\ Es \to boxy\ Es.$$

It is also possible that true Es are just disky Es viewed edge-on[§], and that there are two distinct classes of Es. Some Es also show non-symmetric deviations from smooth SB distributions, e.g. ripples, shells, and streams, especially in outer regions.

6.4 Kinematics

Elliptical galaxies are kinematically *hot*. The random motions of stars is generally large compared to the organized motion (but this is not to say that there is *no* rotation).

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[*] Tremblay and Merritt Fig 3
[†] de Zeeuw, Fig 1
[‡] e.g. Kormendy and Bender classification
[§] Kormendy and Bender, figure 3

The key kinematic quantity is **velocity dispersion**, σ. Galaxies can be characterized by *central* σ, but σ does vary with radius.

Some ellipticals do have some rotation, mostly in lower luminosity systems. The relative importance of *organized* motion 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 that is flattened by rotation:

$$\frac{v_{rot}}{\sigma} = \sqrt{\frac{\epsilon}{(1 - \epsilon)}}$$

Giant ellipticals have less rotation than this, implying anisotropic velocity dispersions to account for their shape (required for triaxial systems in any case). Low/medium luminosity (high SB) Es, however, *may* be isotropic with flattening caused by rotation[*]. Low SB Es appear to have anisotropic σ, i.e. more eccentric than expected from rotation; "measured in LG Es 185 (factor of three low in v_{rot}/σ, 147, factor of 10 low)." seriously, wtf. Significant fraction of Es may have dynamical subcomponents, e.g. velocity and dispersion for some interesting cases.

6.5 Relations between different parameters and different families

6.5.1 Photometric parameters

SB-size relation, between SB and SB-luminosity relations ("Kormendy relations")???. Also, profile *shape* (e.g. Sersic index) with luminosity.

6.5.2 Kinematics vs. luminosity

More luminous galaxies have less rotation, but higher velocity dispersions (**Faber-Jackson relation**, which is roughly $L \sim \sigma^4$, but lots of scatter).

6.5.3 The Fundamental Plane

Faber-Jackson relations and the Kormendy relation (between SB and L/size) are manifestations of the **Fundamental Plane of elliptical galaxies**; there is a correlation between residuals in the Faber-Jackson emphrelation and SB. Galaxies do not populate the entire 3D space of I, r, and σ, but instead populate only a *plane* in this space. There is a relation between the **three fundamental global observables**: SB (or luminosity), size, and velocity dispersion[†]. The observed relation given by Virgo ellipticals is:

$$r_c \propto \left(\sigma_0^2\right)^{0.7} I_c^{-0.85}$$

What is the origin of relation? Three assumptions would have to be true:

1. Es are in virial equilibrium
2. M/L varies systematically with luminosity

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[*]de Zeeuw, figure 3
[†]original refs: Dressler et al. 1987; Djorgovski and Davis 1987; Bender, Burstein and Faber 199x

3. Es 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** (though this applies to the mean potential 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 Es).

Combining these, we get

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

If $M/L \propto L^{0.2}$, then the observed fundamental plane is recovered; could arise from stellar populations or from variations in baryon to total mass. Alternatively, if M/L is constant with a structure that 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").

However, we still need to understand origin of assumptions; why should parameters, e.g. mass-to-light vary smoothly with luminosity? Recall that this ratio includes dark matter. If ellipticals have dark matter halos, the luminous inner parts are not required 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, there is a correlation[*].

Luminosity (size) — σ plane:

Luminosity is proportional to velocity dispersion as $L \propto \sigma^4$, which is known as the **Faber-Jackson relation**. However, since the locus of Es isn't perfectly linear and the plane defied by the ellipticals isn't perpendicular to this dimension, the scatter around the Faber-Jackson relation is larger than the scatter around the fundamental plane. A new radius can be defined that 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).

SB — size plane:
Relation for *smaller* galaxies:

- *higher* SB for *normal* small Es

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[*]Djorgovski figure 2

- *lower* SB for *diffuse* small Es

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 two underlying physical parameters:

1. density
2. 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.

6.5.4 Isophotal deviations vs. luminosity and kinematics

Deviations from elliptical shape is correlated with dynamics, such that slower rotators are more likely to be "boxy", and faster rotators are more likely to be "disky" *.

There appears to be two kinds of "boxiness", one found in giant Es and one found in bulges, which in fact are relatively rapid rotators. It is likely that these come from different origins: plausibly, mergers in the case of giant Es and bars/disk evolution in the case of bulges.

The core properties are correlated with the global shapes and dynamics: cuspy core galaxies are boxy and anisotropic, cuspy galaxies are disky and rotating.

6.5.5 Several types of ellipticals??

Normal and low luminosity Es:

- significant rotation
- nearly isotropic
- oblate spheroids
- cusps (no cores)
- disky isophotes

Giant Es:

- non-rotating
- anisotropic (triaxial)
- less flattened
- cuspy cores

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*Kormendy and Bender, figure 2

- boxy isophotes

Dwarf spheroidals (diffuse ellipticals?):

- lower SB
- off the fundamental plane
- anisotropic (slow rotators for their ellipticity)

Bulges: multiple types? As an aside: globular clusters, which are likely to be significantly different.

6.6 Spectral energy distributions

Note typical features in ellipticals: stellar absorption lines (4000Å break, Mg, Fe, etc.) Es are generally red: implications are predominantly old population. Relations:

- Color-luminosity: more luminous Es are redder. However, as wel'll see, variations of color at this level can come from either metallicity or age, so interpretation isn't trivial.
- Mg line strenth-luminosity: more luminous Es have stronger lines. This correlation is even tighter when considering relation between central velocity dispersion and line strength (The Mg-σ relation), over large range of σ. As we'll see, this variation could arise from variations in age or metallicity, or different heavy element abundance ratios. Of equal interest to the Mg-σ relation is the quite small scatter around the relation.

Some Es have signatures of a younger population: E+A (or k+a) galaxies: galaxies with strong Balmer lines. These are relatively rare, but likely are indicative of post-starburst galaxies with significant star formation 1 Gyr ago. These are not associated with a cluster environment. Some show morphological signs of recent interactions.

Stellar populations within ellipticals: Es have gradients in color/line strength, i.e. tend to be redder toward the center (but again, there is some degeneracy between age and metallicity as possible reasons for this).

6.7 Interstellar matter in ellipticals

It is now known that Es have significant interstellar gas, seen not in optical, but in X-ray emission → hot gas. This makes sense since some gas is expected from stellar evolution, although there is also the possibility of gas from the environment.

Some Es aso show evidence of colder gas and dust. A surprisingly large fraction ($\sim 50\%$) show some evidence for dust their cores[*] These are typically small components by mass.

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[*]Lauer et al. 2005

7 | Spiral/Disk galaxies

(7.1) SB profiles

(7.2) Size-L/SB-L relations

(7.3) Vertical distributions in disk galaxies

(7.4) Non-axisymmetric features in disk galaxies: bars and spiral arms

(7.5) 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.

7.5.1 Tully-Fisher relation

: kinematics(maximum rotational velocity)-luminosity relation.

(7.6) Typical spectra

(7.7) Gas and dust

8 | Galaxy parameter (scaling) relations

Structural luminosity-SB
  • isophotal shape-luminosity relation for Es (boxy vs. disky).
Kinematic Faber-Jackson, Tully-Fisher
  • ellipticals luminosity-rotation relation. The Faber-Jackson relation also applies to

ellipticals, but this is the relation between luminosity and velocity dispersion, not rotational velocity. . . ?

Structural/kinematic Fundamental Plane

- A global generalization to all galaxies: the fundamental manifold*, with an assumption about how to combine rotation and velocity dispersion to get a characteristic "velocity", all galaxies appear to lie in a plane.

Stellar populations color-magnitude, Mg-σ for Es (stronger for more luminous Es)

Gas HI-SB, L-metallicity

Black holes M_{BH}-σ

- Central black hold seems to be ubiquitious in galaxies
- BH masses can be estimated (with difficulty; see later). More luminous (spheroid) galaxies appear to have more massive black holes.
- Tighter relation exists with velocity dispersion:M_{BH}-σ relation (or $M_{spheroid}$)[†]. Note that black hole mass seems to be more linked to spheroid than to total galaxy mass (although claims to the contrary have been made).

9 | 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

10 | Some galaxies to be familiar with

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[*]Zaritsky et al. (2008)
[†]Kormendy and Bender, 2001

Part II: The building blocks of galaxies

11 | Stars and Stellar populations

How to relate 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.

11.1 Review: 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 redden-
  ing/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
  $$\left[\frac{\text{Fe}}{\text{H}}\right] = \log\left[\frac{(\text{Fe/H})}{(\text{Fe/H})_\odot}\right]$$
  - 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.

11.2 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

11.3 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 $t_{\mathrm{oldest}} > 8$ 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??

11.4 Integrated light from unresolved 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*:

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

    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

11.5 Chemical evolution

Understanding chemical evolution provides another clue about the formation history of galaxies. Since stars generate this evolution, one can in principle learn something about star formation histories by looking at the distribution of compositions. The more handle we have on metal-licites, the better we can contstrain ages. The *distribution* of metallicities within galaxies (recall gradients) potentially provide important information about mode of galaxy formation. We'd like self- consistency between SFH and chemical abundances. Potential information about gas entering and leaving system. Relative abundances of different elements also may provide clues about formation history.

The basic picture of chemical evolution starts with some initial conditions, then add SFH: (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 a separable function:

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

  where $\xi(M)$ is the IMF and $\psi(t)$ is the SFR. This implicitly 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 all sorts of realistic effects makes it difficult to make very simple predictions for the evolution of abundances. However, under some simplifying assumptions, it is possible to do so. A simple chemical evolution model serves as a useful baseline against which observations can be compared to determine where the assumptions may break down. In addition, understanding a simple model allows us to introduce and become aquainted with terminology that is in widespread use.

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:

$$M = g + s$$

$$\frac{\mathrm{d}M}{\mathrm{d}t} = F - E$$

$$\frac{\mathrm{d}g}{\mathrm{d}t} = F - E + e - \psi' t$$

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

$$\frac{\mathrm{d}s}{\mathrm{d}t} = \psi' - e$$

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

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

(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:

$$e_Z = \int_{m_\tau}^{m_U} \left[(m - m_{rem})Z(t - \tau(m)) + mq_Z \right] \psi(t - \tau(m))\xi(m)\mathrm{d}m$$

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.

$$\alpha = 1 - \int_{m_\tau}^{m_U} m'\xi(m')\mathrm{d}m' + \int_{m_\tau}^{m_U} m_{\mathrm{rem}}(m)\xi(m)\mathrm{d}m$$

where the second term is the total mass in stars that have died, and the third term is the mass from those stars that have been locked up in remnants.

Alternatively, one can think of the *Return fraction*, $R = 1 - \alpha$. This gives us

$$\frac{\mathrm{d}g}{\mathrm{d}t} = F - E + (1 - \alpha)\psi - \psi = F - E - \alpha\psi$$

We also have

We define the stellar *yield*, p_Z to be

so the yield gives the fraction of the remnant population synthesized and released in each element. This gives

where the RHS terms are recycled material, new production, lock-up in new stars, inflow, and outflow. Simplifying, we have

Using mass locked up in stars, s, as the independent variable

so we get

If we make a further assumption of a uniform wind, $Z_E = Z$, then

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

where μ is the gas fraction

The average abundance in stars is

which tends to p as μ becomes small, i.e. the gas fraction becomes small. For larger gas fractions, the mean $< Z >$ will be lower than the yield. Note that this is the mean metallicity weighted by stellar mass, not by stellar luminosity or by number (but these could easily be derived).

11.6 Measuring stellar abundances

Stellar abundances in individual stars measured from absorption features. Hot stars only allow measurements of very few elements, while cool stars (T<3500 K) are complicated due to very large numbers of lines and prominence of molecular features. When lines are well-separated, abundance determination is possible from measurements of the *equivalent width*. When lines are more crowded, usually approached by spectral synthesis.

In all cases, to measure abundances, need to know: style

atmospheric parameters   • Temperatures (T_e) may be derived from colors (unless reddening is an issue); also often derived from excitation equilibrium: require lines of different excitation potential to give the same abundance (e.g. FeI lines)
  • Surface gravity ($\log g$) can be derived from luminosities, temperatures and masses, hence distances are required. Alternatively, use ionization equilibrium: require lines of different ionization states to give the same abundance (e.g., FeI vs. FeII).
  • microturbulence

atomic parameters   • Astrophysical gf values: Atomic parameters are determined from lab experiments, but not always available at high quality. gf values are derived from measurements of stars in which abundance is presumed to be known from other measurements.

Abundances in unresolved populations are challenging, for the reasons previously discussed (age-metallicity degeneracy, blending of different features, etc.) Present day abundances in galaxies best measured through gas abundances (to be discussed).

Units for measuring abundances:

- Stellar abundances: usually measured relative to the sun $[X/Y]$:

$$\log \left[\frac{(X/Y)}{(X/Y)_\odot} \right]$$

- Z_i: mass fraction of element i
- $\log(X/Y)$: log of ratio of mass fractions
- $12 + \log(Z_i/H)$: log of ratio of mass fraction to hydrogen, with 12 added (to keep the numbers positive?)

Abundances as function of time

The simple model predicts an increase of the metallicity with time. The rate of increase depends on the SFR. For example, if we *assume* that the SFR is proportional to the gas mass, $ds/dt = \omega g$, where $\omega = constant$, we get:

$$z = \omega t$$

and the abundance is expected to increase linearly with time.

Relative abundances of different elements

Simple model predicts that, at any time, elements will be found in relative abundances given by the ratio of their yields. This is true to some extent for α elments, e.g. in the solar neighborhood[*]. Most other elements go in lockstep with O (Fig. 11)

This is not true for Fe. This is plausibly explained for by a significant fraction of Fe coming from SnIa, which has a time delay, and so the simple model with instantaneous recycling doesn't hold. This is important to realize, because many direct "metallicity" determinations are make from Fe liens. If SnIa is the right explanation, one would expect to a constant ratio of Fe/O for systems in which star formation proceeded rapidly (i.e. finished before SnIa go off), but in systems with more extended start formation, Fe/O would increase at higher O abundance (Page I figure 10).

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[*]from Bensby et al. 2003

Note that α/Fe traces timescales of extended star formation, which is not necessarily the same as age (you could have a short epoch of star formation at a late time to give alpha-enhancement even at younger ages). However, very old populations would be expected to have alpha-enhanced populations, e.g. as observed in globular clusters. With the SnIa interpretation, α/Fe provides a clock. Unfortunately, the calibration of the clock is not extremely well known because of the unknown precise nature of SNIa projenitors. It is usually considered to be of order 1 Gyr but there is very plausibly a range of SNIa ages.

The constancy of element abundance ratio holds for *primary* elements i.e. those that are produced from primordial abundance. In addition some elements are secondary which means that some element must previously exist in order for the secondary element to be created. An example is N, which is produced during the CNO cycle in greater abundance with a larger initial abundance of C. This is observed (Fig. 12)

More generally, the constancy of element abundance ratios could fail if the yields are themselves a function of metallicity. This may be expected to occur, e.g. for elements that are significantly contributed by mass loss, since mass loss may increase with increasing metallicity.

In reality, lots of different elements appear *not* to go in lockstep with one another, presumably because of the origin of different elements from different processes and in different types of stars. These variations may hold important clues for tracing the origin of stellar systems. α/Fe traces duration of star formation (relative to SnIa timescale). Other element ratios may trace variations in the IMF, since different mass stars contribute different fractions of heavy elements, or stochastic effects from a given IMF for star formation occurring in small parcels (e.g. clusters). Gives rise to the idea of *chemical tagging* ???. Example: Local Group dwarf galaxies and the Galactic halo*. Could the halo come to be built up by dwarfs? Caution: just because *present-day* dwarfs don't match doesn't mean previously existing ones don't. Note SDSS-III APOGEE survey.

Mass-metallicity relation here? http://arxiv.org/abs/1211.3418

12 | Gas

Intrinsic gas characteristics:

- temperature
- density
- composition
- ionization field
- total gas mass

Gas in galaxies exists in multiple phases:

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*from Tolstoy et al. 2009

phase	temperature
molecular clouds	$\lesssim 100$ K
cold, neutral (atmic) medium (CNM)	$\lesssim 100$ K
warm, neutral (atmic) medium (WNM)	$\lesssim 8000$ K
warm, ionized medium (WIM/DIG)	~ 8000 K
hot, ionized medium (HIM)	$> 10^5$ K

Also denser ionized gas in HII regions, SN remnants, PNe. CNM/WNM/WIM/HIM perhaps roughly in pressure equilibrium, but note other support mechanisms such as turbulence, magnetic fields, etc. If they are in pressure equilibrium, higher temperature components have correspondingly lower densities.

12.1 Observing and characterizing the gas

Two general methods:

Emission
Atomic lines

- Permitted: In low temperature gas (T = 10000 K $\sim$ 1eV), the energy difference to excited states is typically too high for excitations to occur from collisions. An exception is H lines from recombination; these exist from UV through radio wavelengths.
- "Forbidden": Low transition probabilites; important in low density gas because collisions are less frequent, allowing time for radiative transitions to occur before collisional de-excitation. Wavelengths are typically in the optical and UV regimes. Note that many of these are doublets because of multiple angular momentum levels. Most prominent in optical: [OIII], [NII], [SII], [OII], [OI]
- Fine-structure lines, transitions ivolving spin alignment with orbital alignment. Typically FIR wavelengths
- Hyperfine-structure lines, transitions involving electron spin alignment with nuclear spin. Radio wavelengths.

Molecular lines

- Vibrational transitions, typically IR wavelengths
- Rotational transitions, typically mm wavelengths. However, rotational transitions only strong for non-symmetric molecules that have a dipole moment (not H_2, although it can have some IR features if shock heated). CO emission is most prominent.

Emission in many cases is proportional to ρ^2. If the excitation mechanism is collisional (i.e., requires two particles), the observational quantity is the *emission measure*: $\propto \int n_e^2 \mathrm{d}\ell$.

12.1.1 Absorption

Atomic lines
- Typically from ground state, e.g. H Lyman transitions, Na 5890, CaII
- Most prominent in optical

Molecular lines
- Mostly UV, e.g. H_2 absorption

Absorption is generally more sensitive, but it does require a bright background source, e.g. UV light from quasars. Absorption is linearly proportional to density. The observational quantity is *column density*: $\propto \int n \mathrm{d}\ell$

12.2 Heating and cooling

What determines temperature?

12.2.1 Heating

- Radiative heating (both via ionization and heating through dust)
- Mechanical heating (shocks, jets, etc.)
- Gravitational heating
- Cosmic rays

12.2.2 Cooling

- Bremsstrahlung (free-free)
- Line emission from heavier elements
- Molecules
- Cooling curves and contributions (Sutherland & Dopita 1983)

12.3 HI measurements: 21 cm line

- Traces neutral medium
- From spin-flip transition: very rare (10 Myr) but H is very numerous. Relative number in two energy states set by collisional equilibrium and proportional to statistical weights of two levels (3:1); upper levels are populated from (microwave background photons, collisional saturation?)
- HI flux at a given location gives column density (atoms/surface area):

$$n_{HI}[\mathrm{cm}^{-2}] \approx 1.82 \times 10^{18} \int \left[\frac{T_b(\nu)}{\mathrm{K}} \right] \mathrm{d} \left[\frac{v}{\mathrm{km\ s}^{-1}} \right]$$

Typical column densities in galaxies $\sim 10^{20}$ cm^{-2}

- Total HI flux (integrated over entire galaxy), along with distance, gives total HI mass:

$$\frac{M_{HI}}{M_\odot} = 2.36 \times 10^5 \left(\frac{D}{\mathrm{Mpc}}\right)^2 F_{HI}$$

  for F_{HI} in Jy km s^{-1}.
- 21-cm single dish observations have low spatial resolution. Higher resolution possibly with interferometric observations (e.g. VLA) but information on smooth distribution/total mass can be lost.
- HI can be observed to very low column densities ($\sim 10^{13}$ cm^2) in absorption, but only for the Lyman series. Primary tool for studying the IGM: Lyman alpha clouds, epoch of reionization, quasar absorption line systems. . .
- Typical column densities are. . . Total mass in HI can be a significant fraction of total stellar mass, increasingly important in lower luminosity galaxies.
- Temperature might be inferred from width of line, but need to be careful about turbulence, cloud structure, etc. Estimate can also be made by comparing emission flux with absorption if you have a background source (radio galaxy).

12.4   Molecular gas

12.5   Warm ionized gas

12.6   Hot gas

If "very" hot, detectable in X rays: thermal Bremsstrahlung (free-free) cutoff frequency decreases with increasing temperature. At lower temps (T $\sim 10^5$ K), very hard to detect. Soft X rays are absorbed by neutral hydrogen. Detectalbe in absorption by high ionized metals, e.g. OVI, CIV, NV. Very hard to determine total mass, but mass may be very significant, just from cosmological baryon fraction ???

12.7   Denser ionized gas

Easiest gas to observe in galaxies.

12.8   Chemical evolution and abundances from gas

12.9   Distribution of gas within spirals

Neutral gas primarily observed in blue sequence galaxies. HI distribution usually extends beyond optical distribution of starlight, while molecular is more centrally concentrated. In some galaxies,

CO traces Hα well, but not in others. Hot gas is observed in most galaxies.

12.10 Gas as a kinematic tracer

Measuring galaxy rotation - both optically and using HI (both spatially resolved, e.g. VLA, and unresolved data).

- Swaters et al. 2002
- Velocity-coded color (from NRAO)
- Spider diagrams
- PV diagrams: note spread of velocity at any given position; location of peak velocity may not give the *maximum* velocity at that position

Rotation is often characterized by v_{max}: maximum of rotation curve (sometimes hard to measure). From unresolved HI profiles, rotation is characterized by line widths, e.g. W_{50}, W_{20} (width at 50% and 20% of the peak line flux, respectively).

12.11 Interaction between stars and gas

12.11.1 supernovae and mass loss from stars

13 | Dust

13.1) General importance of dust

- Can obscure light from stars/gas: affects inferences on populations, abundances, etc.
- Emits radiation which can be observed (mostly IR) to probue obscured emission.
- Important for ehemistry of ISM, e.g. created of H_2.
- Important for heating and cooling of ISM
- Probably *not* important as a significant mass component; likely only a fraction of a percent of ISM by mass

13.2) Extinction

Foreground and internal. Extinction laws and their variation.

Extinction of light is characterized by an **extinction curve**, which gives the relative amount of light lost as a function of wavelength. Note that extinction curves are often in magnitudes (logarithmic). Generally, shorter wavelengths are attenuated more, leading to the phenomenon of reddening. This implies that the dust grain sizes are comparable to the wavelength of the light. Existence of the 2200Å bump. The total amount of extinction is proportional to the amount of reddening, e.g. $R_V \equiv A_V/E(B-V)$. More generally, $R_\lambda \equiv A_\lambda/E(B-V)$.

Variations in the extinction curve exist, both within the Milky Way and in nearby galaxies[*]. This variation is more significant in the UV. Cardelli, Clayton, and Mathis suggest that extinction curves can be parameterized by a single parameter R_V. Probably related to dust properties, e.g. grain size.

Extinction has both scattering and absorption components. Scattering leads to, e.g., reflection nebula and diffuse light. Measuring scattering suggests optical albedo ~ 0.5, so roughly equal amounts of scattering and absorption. Absorption leads to heating and re-emission.

Discussions of extinction curves refer to the extinction of background light by foreground dust (i.e. a foreground screen). Integrated galaxy light likely does not fall into this scenario (apart from foreground Milky Way extinction). Remember Burstein & Heiles and Sclegel, Fink beiner & Davis for MW maps. Scattering is significant and leads to "saturation"[†].

13.2.1 Amount of gas, dust-to-gas ratio, and transparency of galaxies

The amount of extinction seems to be well correlated with the amount of neutral H

$$N(H) = 5.8 \times 10^{21} E(B-V) \quad \left[\mathrm{cm^{-2}\ mag^{-1}}\right]$$

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[*]Gordon et al. 2003
[†]Witt & Gordon, 2003

$$A_V = 5.3 \times 10^{-22} N_H \quad \left[\mathrm{mag\ cm^2}\right]$$

This suggests that dense (inner) regions of ISM are likely to be optically thick, but not low density ones. Confirmed by observations of "overlapping" galaxies.

13.3 Emission from dust

- Predominant heating is from starlight (some collisional heating in dense clouds)
- Amount of energy absorbed depends on flux, size, and albedo. Amount of energy radiated depends on temperature, size, and emissivity.
- Dust particles are not ideal blackbodies. In addition, they may not be in temperature equilibrium, especially small particles.
- MW dust
- Dust emits in far IR, e.g. MW emission and models. Note sharper emission features from PAHs around 10 microns.
- Dust emission traces star formation; luminous IR galaxies (LIRGs, ULIRGs, 10 to 100x IR emission than typical galaxy).
- Implications for higher redshift: sub-mm observations and the negative K-correction

13.4 Composition

- Solids have broad or non-existent absorption features, so abundances from absorption are difficult or impossible.
- Some inferences from interstellar gas abundances: if stellar abundance ratios are assumed, than observed gas abundances show depletion (from Draine), e.g. of C, Mg, Si, Fe at a level greater than 50%.
- Still can't identify uniquely what molecules the dust is in. Possibilities:
  - silicates
  - oxides
  - carbon solids
  - hydrocarbons, e.g. PAHs (polycyclic aromatic hydrocarbons)
  - carbides
  - metallic Fe
- Some absorption features are observed:
  - 2200Å feature: originally thought to be graphite, now perhaps PAHs
  - 9.7 and 18 microns: silicates? (from Draine)
  - diffuese interstellar bands (DIBs) (from Draine)
- As stated above, emission features are observed in IR from PAHs

Overall, plausible to expect that the **dust-to-gas ratio might be a function of metallicity**.

13.5 Creation/destruction

Dust is apparently difficult to create in the ISM. It is thought to be created in envelopes of cool stars → **the amount of dust may also be a function of star formation.**

14 | Central black holes

(some references: Peterson, "An Introduction to Active Galactic Nuclei", Ferrarese & Ford (2005)).

Galaxies harbor central supermassive black holes: how do we know?

14.1 AGN as indicators of central black holes

Some fraction nearby galaxies who "active" nuclei:

- Optical emission lines
- Power-law continua spanning most of the EM spectrum.
- Radio sources, often with jets
- AGN review[*][†]
    - Seyfert galaxies: Optical emission lines. Types 1 (broad lines) and 2 (narrow lines). Distinguishable from HII regions, etc. from **emission line ratios**.
    - LINERS: weaker lines, lower ionization
    - BL Lac objects
    - Quasars and QSOs
    - Radio galaxies, e.g. Cen A, M87. Emission is from synchrotron emission. Energy source may be the same, but don't generally directly see nuclear activity. Fanaroff-Riley (FR) types 1 (low radio luminosity, edge-darkened) and 2 (high radio luminosity, edge-brightened).
    - See tables in section 4b of Whittle notes with some spectra.
- Frequency of Seyfert phenomenon 1-2% but LINERS much more common; perhaps tens of percents of local galaxies show activity at some level.

Generally considered to be powered by accretion onto a nuclear black hole. Arguments for the existence of black holes:

- Luminosity: can be as high as $\sim 10^{45-58}$ erg s^{-1} for some AGN. **Eddington Luminosity:**

$$L_e = \frac{4\pi G M m_p c}{\sigma_T} = 1.3 \times 10^{46} \frac{M}{10^8 M_\odot} \left[\text{erg s}^{-1} \right]$$

- Non-stellar continua
- Timing arguments. AGN show rapid variability with timescales of days (optical/radio) to hours (X-ray): implies small objects (small fraction of a pc).

Overall physical picture: different active nucleii phenomena all arise from a common physical scenario. Some *intrinsic* differences give rise to different phenomena, whereas some differences arise from viewing angle.

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[*] see book by Peterson, 1997
[†] see Whittle (UVa) lecture notes

- Unified model: several main regions:
  - Accretion disk
  - Broad line region (BLR)
  - Narrow line regions (NLR)
  - Dust torus
- Alternative model[*]
- Viewing angle differences: Unified model (and another)
- Some possible intrinsic causes of variation between types
  - Accretion rates and accretion rate differences
  - Differences from variations in gas suppy (quantity and/or efficiency of infall)
  - Differences from different black hole masses?

14.2 Black holes in non-active galaxies

It appears that most galaxies, even inactive ones, harbor central supermassive black holes. This is expected at some level from number density of quasars at higher redshift. Detection of SMBHs[†‡]:

- **Sphere of influence** (region where velocity generated by central mass is comparable to or larger than velocity determined from overall galaxy potential) is very small:

$$r_h \sim \frac{GM_{BH}}{\sigma^2} \sim 11.2 \frac{M_{BH}}{10^8 M_\odot} \left(\frac{\sigma}{200 \text{km s}^{-1}} \right)^{-2} \quad [\text{pc}]$$

- MW galactic center (e.g. UCLA group video)
- Other galaxies: BHs inferred but strictly speaking, not absolutley required[§].

If they have BHs, why aren't they active? Gas supply? Advection dominated accretion flow (ADAF)?

14.3 Measuring black hole masses

- Proper motions
- Stellar and gas kinematics
- Gas kinematics
- Broad Fe Kα (6.4 KeV X-ray line)
- Reverberation mapping

BH masses have now been made for several dozen galaxies. Initially, correlation seen between BH mass and galaxy luminosity. Relation between BH mass and central velocity dispersion significantly tighter. Origin not well understood. $M_{BH} - \sigma$ relation (or $M_{spheroid}$).

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[*]Elvis (2000)
[†]Ferrarese & Ford
[‡]Whittle (UVa) lecture
[§]Ferrarese & Ford 2005

14.4 Importance of central black holes

15 | Galaxy spectral energy distributions

16 | Dark matter and galaxy masses

Dark matter dominates mass in the universe. How much is there? How is it distributed, both among and within galaxies? To what extent does it regulate galaxy properties?

Note from cosmology: we expect

- $\Omega_m \sim 0.27$
- $\Omega_b \sim 0.047$

16.1 Observations of dark matter in galaxies

The amount of dark matter in a galaxy is often characterized by the mass-to-light ratio (M/L). **Note that there is a distinction between stellar M/L and total M/L.**

16.1.1 Galaxy rotation curves

Rotation curves (RCs) probe dark matter content and profile. The general observation of flat profiles (sometimes reffered to as "isothermal" profiles) implies that $M \propto r$ and $\rho \propto r^{-2}$.

Recall that the shape of the rotation curve is moderately well-correlated with the luminosity, in the sense that one gets steeper RCs for lower L galaxies[*]. However there is significant variation at each luminosity. Note that not all RCs are flat; there is a variety of shapes.

Comparison of the luminosity profile with the rotation profile shows that the *luminous* mass alone is unable to produce the rotation profile, therefore dark matter is required. The fraction of "dark mass" increases with radius, and also increases with fixed radius with decreasing luminosity.

Dark matter in disk galaxies

Given the luminosity profile, the shape of the RC shows that DM has to be present, because there's no way to get high enough stellar mass-to-light ratios in the outer region. However, determining the amount of dark matter in disk galaxies requires knowledge of the M/L of the stellar population, which is unknown (recall that M/L depends on the SFH, especially the IMF). The stellar M/L can't be derived from the RC because the density distribution of the DM is unknown. It's possible that the presence of dust makes this more challenging to infer.

A common assumption is the **"maximum-disk hypothesis"**, in which the innermost parts of the RC are assumed to be driven by the luminous mass alone. These regions then give a M/L, which is assumed to be constant as a function of radius. Combined with the outer roation curve, mass profiles for the luminous and dark components are derived. However, data is often degenerate in different ratios of disk to DM[†]. The applicability of this hypothesis is debateable.

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[*]Persic and Salucci, figure 4
[†]see van der Kruit example, from van der Kruit Galaxy Masses 2009 talk

For example, for an exponential disk:

$$V_{max} \propto \sqrt{\frac{M}{r_d}}$$

so we might expect a trend at fixed L (if we extrapolate from M to L) with scale length: not observed in Tully-Fisher relation.

The *total* M/L in disk galaxies has been found to be $\sim$ 10-50 in regions probed by RCs.

Dark matter in LSB galaxies

The RCs for LSB galaxies confirm a high M/L. Compare two galaxies at identical positions in TF relation and see that the LSB galaxy is much more DM dominated[*]. This suggests that RCs are correlated not only with luminosity, but also with surface brightness.

LSB RCs are of particular interest because they may provide the most direct probes of DM distribution. The shapes of their RCs are currently under active debate as to what they imply for DM distribution. Numerical DM simulations predict a "cuspy" distribution of DM, with $\rho_{DM} \propto r^{-1}$ in the inner regions, e.g. the Navarro-Frenk-White (NFW) profile:

$$\rho = \frac{\rho_0}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

family of profiles characterized by the concentration r_{200}/r_s.

However, there may also be an effect of baryons on DM (adiabatic compression, or expansion?), since in inner regions, gravity from baryons may not be negligible. Some observations[†] suggest more of a core. The interpretation of relatively low velocities in LSB centers can be complicated by a variety of effects, such as projection, beam smearing, non-circular velocities, etc. The "core vs. cusp" debate is still active.

DM halos are expected to extend far beyond what we can see from physical tracers (even HI gas) within the galaxy embedded in their centers. Typical virial radii (from simulations) are expected to be several hundred kpc. So total masses are not well probed by rotation curves.

Dark matter in ellipticals

Theoretically, the presnece of DM in ellipticals is exptected. However, it is harder to observe than in spirals because of the lack of an "easy" dynamical tracer, like a rotating component. THey also have higher SB, so there is a larger contribution by baryones to kinematics[‡].

For non-rotating components, the velocity dispersion profiel is insufficient to measure masses without knowledge of *velosity ellipsoid*, parameterized by *velocity anisotropy*:

$$\beta \equiv 1 - \frac{<v_\theta^2>}{<v_r^2>}$$

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[*]from de Blok & McGaugh
[†]Swaters et al 2003
[‡]see review by Gerhard 2006

Or more generally, distribution of orbits[*]. Inclination/projection also plays a role...

Potential tracers:

- Velocity distribution of stars (integrated light). Need to use line profile shapes, 2D distributions (integral field)
- Planetary nebulae
- Globular clusters
- Gas disks (rare, but do exist)

Note that even for non-rotating systems, distribution of mass often described by the *circular velocity*:

$$v_c \equiv \sqrt{\frac{GM(r)}{r}}$$

From stellar velocity distributions, most ellipticals show evidence of flat circular velocity curves, indicating the presence of DM in the inner regions, but not always a lot.

Modelling suggests that a simple estimate[†]

$$M/L \sim 5\frac{\sigma_e^2 r_e}{GL}$$

gives a reasonable rough estimate; c.f virial relation (???) and relation for central velocity dispersion, e.g. for isothermal sphere. There has been some debate about PN observations at larger radii, with some observations gsuggesting declining circular velocities. However, understanding of velocity anisotropy is important to the conclusion.

Indpendent mass estimate proveded by X-ray halos under the sasumption of hydrostatic equilibrium (requires measuring densities and temperatures), which, when they exist, generally indicate the presence of dark matter halos[‡]

$$M(r) = -\frac{k_B T(r) r}{\mu m_p G}\left[\frac{d \ln \rho}{d \ln r} + \frac{d \ln T}{d \ln r}\right]$$

Bottom line: ellipcals probably have dark matter.

16.1.2   Gravitational lensing

Another way of probing mass. There is a distinction between *strong* and *weak* lensing[§]. Weak lensing is measured statistically.

16.2) Total masses of galaxies

16.3) Halo abundance matching

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[*]e.g. velocity dispersion profiles, from van der Marel (1994)
[†]Cappellari et al. (2006)
[‡]from Sato et al. 2000
[§]both from Treu talk at Galaxy Masses 2009