

# ASTR 3830: Astrophysics 2 – Galactic and Extragalactic Final Exam Review Guide

The Students of ASTR 3830

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# Chapter 1

## Exam 1 Content

### 1.1 The Milky Way (C&O Chapter 24)

#### 1.1.1 Determining Morphology of the Milky Way

##### Magnitudes

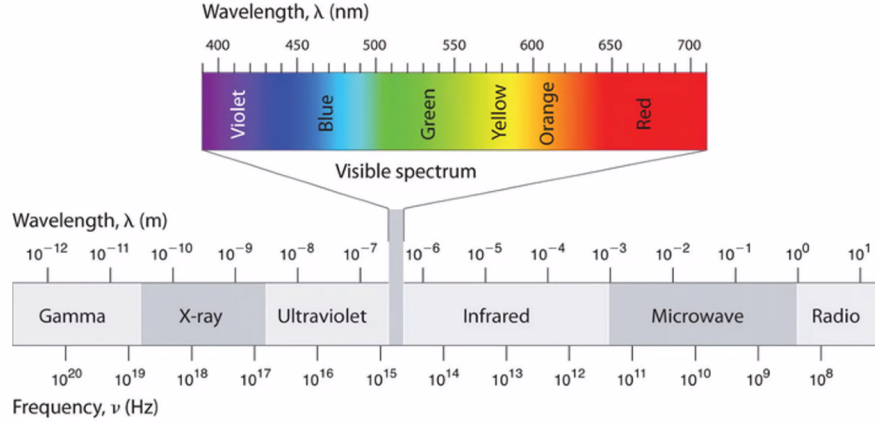
- M: Absolute magnitude, magnitude as seen at 10 pc?
- m: Apparent magnitude, magnitude as seen at observer's distance
- Small magnitude = brighter
- Big mag = dimmer
- It's backwards
- Pro tip: when looking at a plot, take your time to orient yourself (which is left, which is right, up, down, brighter, dimmer, more massive, less massive, etc) because astronomers are out of their minds and don't make graphs like normal people.

The Milky Way is a SBb-SBc bar spiral.

#### 1.1.2 Filter Systems

- F(####) - filter (centered at) note to watch out for inferred numbers
  - Example: U365
- Standard UBV System (Johnson system):
  - U - ultraviolet centered at 365 nm
  - B - blue centered at 440 nm
  - V - visual centered at 550 nm
- Extension: UBVRI
  - R - red
  - I - Infrared

Memorize this:



### 1.1.3 Differential Star Count

- Counts the number of stars with an absolute magnitude between  $M$  and  $M + dM$  that are found within a solid angle  $\Omega$  and have apparent magnitudes in the range between  $m$  and  $m + dm$ :

$$A_M(M, S, \Omega, m) dM dm \equiv \frac{d\bar{N}_M(M, S, \Omega, m)}{dm} dM dm \quad (\text{C\&O 24.4})$$

- In special case where we assume no interstellar extinction ( $A = 0$ ) and infinite universe of uniform stellar density (i.e.  $n_M(M, S, \Omega, r) = n_M(M, S) = \text{constant}$ ),

$$\begin{aligned} A_M(M, S, \Omega, m) &= \frac{d\bar{N}_m(M, S, \Omega, m)}{dm} \\ &= \frac{\ln 10}{5} \Omega n_m(M, S) 10^{3(m-M+5)/5} \\ &= \frac{3 \ln 10}{5} \bar{N}_M(M, S, \Omega, r) \end{aligned} \quad (\text{C\&O 24.5})$$

### 1.1.4 Integrated Star Count

- Counts the total number of stars with absolute magnitudes in the range  $M$  to  $M + dM$  that appear brighter than the limiting magnitude,  $m$  (replaces the limiting distance  $r$  - see C\&O 24.1):

$$n(S, \Omega, r) = \int_{-\infty}^{\infty} n_M(M, S, \Omega, r) dM \quad (\text{C\&O 24.2})$$

where  $n_M(M, S, \Omega, r) dM$  is the number density of stars with attribute  $S$  that lie within a solid angle  $\Omega$  in a specific direction.

- In the special case where we assume no interstellar extinction ( $A = 0$ ) and infinite universe of uniform stellar density (i.e.  $n_M(M, S, \Omega, r) = n_M(M, S) = \text{constant}$ ),

$$\begin{aligned} \bar{N}_M(M, S, \Omega, m) &= \frac{\Omega}{3} n_M(M, S) 10^{3(m-M+5)/5} \\ &= \frac{\Omega}{3} n_M(M, S) \exp\left(\ln 10^{3(m-M+5)/5}\right) \\ &= \frac{\Omega}{3} n_M(M, S) e^{[3(m-M+5)/5] \ln 10} \end{aligned}$$

### 1.1.5 Obscuration

- Use distance to solve for extinction  $A_\lambda$ :

$$d = 10^{(m_\lambda - M_\lambda - A_\lambda + 5)/5} \implies A_\lambda = m_\lambda - M_\lambda + 5 - 5 \log_{10} d \quad (\text{C\&O 24.1})$$

- Observe using infrared (longer wavelengths) to penetrate dust

### 1.1.6 Milky Way Components

**TABLE 24.1** Approximate Values for Various Parameters Associated with the Components of the Milky Way Galaxy. Definitions and details are discussed in the text.

Disks			
	Neutral Gas	Thin Disk	Thick Disk
$M$ ( $10^{10} M_\odot$ )	$0.5^a$	6	0.2 to 0.4
$L_B$ ( $10^{10} L_\odot$ ) <sup>b</sup>	—	1.8	0.02
$M/L_B$ ( $M_\odot/L_\odot$ )	—	3	—
Radius (kpc)	25	25	25
Form	$e^{-z/h_z}$	$e^{-z/h_z}$	$e^{-z/h_z}$
Scale height (kpc)	< 0.1	0.35	1
$\sigma_w$ ( $\text{km s}^{-1}$ )	5	16	35
[Fe/H]	> +0.1	−0.5 to +0.3	−2.2 to −0.5
Age (Gyr)	$\lesssim 10$	$8^c$	$10^d$
Spheroids			
	Central Bulge <sup>e</sup>	Stellar Halo	Dark-Matter Halo
$M$ ( $10^{10} M_\odot$ )	1	0.3	$190_{-170}^{+360}$ <sup>f</sup>
$L_B$ ( $10^{10} L_\odot$ ) <sup>b</sup>	0.3	0.1	0
$M/L_B$ ( $M_\odot/L_\odot$ )	3	$\sim 1$	—
Radius (kpc)	4	> 100	> 230
Form	boxy with bar	$r^{-3.5}$	$(r/a)^{-1} (1 + r/a)^{-2}$
Scale height (kpc)	0.1 to 0.5 <sup>g</sup>	3	170
$\sigma_w$ ( $\text{km s}^{-1}$ )	55 to 130 <sup>h</sup>	95	—
[Fe/H]	−2 to 0.5	< −5.4 to −0.5	—
Age (Gyr)	< 0.2 to 10	11 to 13	$\sim 13.5$

<sup>a</sup>  $M_{\text{dust}}/M_{\text{gas}} \simeq 0.007$ .

<sup>b</sup> The total luminosity of the Galaxy is  $L_{B,\text{tot}} = 2.3 \pm 0.6 \times 10^{10} L_\odot$ ,  
 $L_{\text{bol,tot}} = 3.6 \times 10^{10} L_\odot$  ( $\sim 30\%$  in IR).

<sup>c</sup> Some open clusters associated with the thin disk may exceed 10 Gyr.

<sup>d</sup> Major star formation in the thick disk may have occurred 7–8 Gyr ago.

<sup>e</sup> The mass of the black hole in Sgr A\* is  $M_{\text{bh}} = 3.7 \pm 0.2 \times 10^6 M_\odot$ .

<sup>f</sup>  $M = 5.4_{-3.6}^{+0.2} \times 10^{11} M_\odot$  within 50 kpc of the center.

<sup>g</sup> Bulge scale heights depend on age of stars: 100 pc for young stars, 500 pc for old stars.

<sup>h</sup> Dispersions increase from 55  $\text{km s}^{-1}$  at 5 pc to 130  $\text{km s}^{-1}$  at 200 pc.

### 1.1.7 Milky Way Kinematics

- Does not follow Keplerian model, Flat velocity curve

- Density wave theory: explains the winding problem and how stars move in and out of the spiral arms, the spiral arms originate from quasi-static density waves – traffic build up example. Each star has its tilted stellar orbits
- Perigalacticon/Apogalacticon calculation

### 1.1.8 Galaxy Rotation Curves

- Doesn't follow Keplerian model
- Flattens out at higher radii, follows Keplerian at smaller radii
- Rotation curve is determined by the mass enclosed (light matter and dark matter)
- Inner region (up to  $\sim 5 \text{ kpc}$ ), density of stars goes as  $\sim 1/r$ , velocity goes as  $\sim \sqrt{2}$
- Outer region, need density go as  $\sim 1/r^2$  to create flat rotation curve, velocity goes as  $\sim 1/\sqrt{r}$ 
  - $M_r$  becomes constant

### 1.1.9 Evidence for Dark Matter

- It is not gas. Hot gas would have emission lines, cold gas would have absorption lines
- It is not asteroids, rocks or dust: there isn't enough
- Flat rotation curves
- Mass-to-light ratio: the ratio between the measured luminosity and the estimated mass. It does not account for the rotation of the stars.
- Gravitational lensing

### 1.1.10 MACHOs, WIMPs

- MACHO: massive compact halo objects: brown dwarfs, white dwarfs, neutron stars, black holes, etc.
- WIMPs: weakly interacting massive particles (neutrinos)
- Both possible explanations for dark matter
- Does not explain all the mass expected

### 1.1.11 NFW Profile

- NFW density profile

$$\rho_{NFW}(r) = \frac{\rho_0}{(r/a)(1+r/a)^2} \quad (\text{C\&O 24.52})$$

- Averages out to be  $1/r^2$  over much of the halo to explain that velocity = constant on the rotation curves
- Shallow near the center ( $\sim 1/r$ ) near the center
- Steeper ( $\sim 1/r^3$ ) near the edge of the halo
- Total mass contained within NFW profile is still not bound (like problem 4 in homework)
- For galaxies,  $a \sim 10 - 30 \text{ kpc}$  (scale radius)



### 1.1.12 Galactic Center Observations

- 1 m wavelength  $\Rightarrow$  radio
- Adaptive optics: Keck Telescope using adaptive optics (AO) to observe *Sgr A\**

### 1.1.13 Evidence for a SMBH in the Galactic Center

- Rotation of S2 and other stars around the center of the galaxy. (Seen through the microwave)
- No other explanation besides a SMBH.
- X-ray emission.
- Used orbits of stars to calculate mass of center =  $3.7 \pm 0.2 \times 10^6 M_\odot$

### 1.1.14 Virial Theorem

$$\langle E \rangle = \langle K \rangle + \langle U \rangle$$

- See Lecture 3, Section 2.4 of C&O
- $-2\langle K \rangle = \langle U \rangle$ 
  - Note: This form applies to special case where galaxy is in equilibrium and gravitationally bound

### 1.1.15 Sgr A\* Luminosity Function

- Luminosity comes from accretion
- Using the virial theorem:  $\langle E \rangle = \frac{1}{2}\langle U \rangle$
- Luminosity is  $dE/dt$

## 1.2 The Nature of Galaxies (C&O Chapter 25)

### 1.2.1 The Great Debate Over Spiral Nebulae

- Side 1) The mysterious “spiral nebulae” are nebulae within our own galaxy
- Side 2) They are outside our galaxy - “island universes”
- Shapley: supported idea of nebulae being in our Galaxy - argued using apparent magnitudes of novae - argued that if the disk of Andromeda were as large as the Milky Way, then its angular size in the sky would imply a distance to the nebula so large that luminosities of novae would be greater than those found in Milky Way. Also argued the points of Maanen: proper-motion measurements of M101 suggest angular rotation of  $0.02'' \text{ yr}^{-1}$ , if diameter similar to Milky Way then why rotational speed not larger?
- Curtis: supported the idea of spiral nebulae Being outside our Galaxy - argued that the novae observed must be at least 150kpc away in order to have intrinsic brightnesses comparable to those in the Milky Way. Also argued that the large radial velocities measured for spiral nebulae indicated they could not remain gravitationally bound within a Kapteyn-model Milky Way. (Lecture 1)

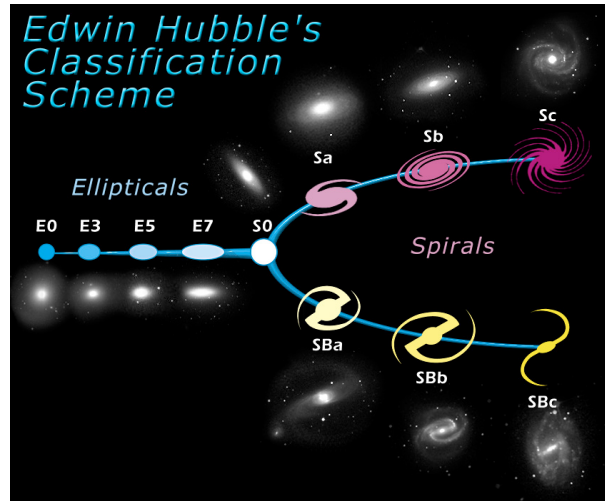
Curtis was proven correct when Hubble detected Cepheid variable stars in M31. Using apparent magnitudes to determine absolute magnitudes, and then using the period-luminosity relation:

$$M_{\langle V \rangle} = -2.81 \log_{10}(P_d) - 1.43 \quad (\text{C\&O 14.1})$$

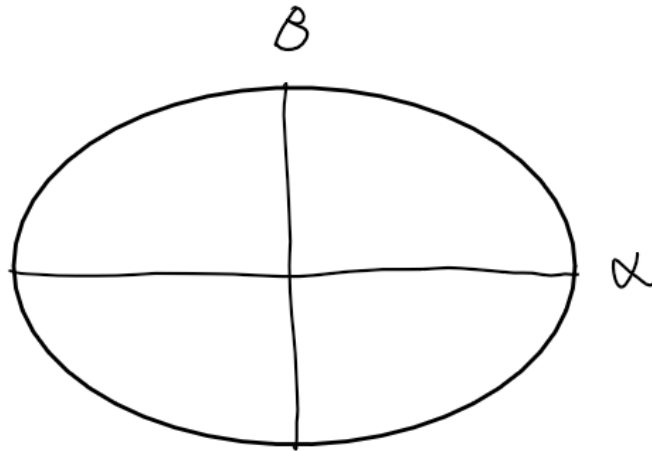
where  $M_{\langle V \rangle}$  is the average absolute  $V$  magnitude and  $P_d$  is the pulsation period in units of days.

Hubble was able to approximately calculate the distance to Andromeda to be outside the Milky Way Galaxy.

### 1.2.2 Galaxy Morphologies, Hubble Classification Scheme



- 3 types: ellipticals, spirals, irregulars
- E0  $\rightarrow$  E7: greater ellipticity
- S0: disk, bulge, no arms
- Sa  $\rightarrow$  Sc: lower bulge-to-disk size and luminosity ratios, spiral arms less tightly wound
- NOT an evolutionary sequence
- Observed ellipticity:  $\epsilon = 1 - \beta/\alpha$



### 1.2.3 Galaxy Surface Brightness, Sérsic Profile

- A galaxy's surface brightness  $\mu$  is the amount of flux from the galaxy per square arcsecond on the sky
- Calculate luminosity, then total flux from all stars
- Surface brightness is unrelated to distance
- Observer units:  $\mu$  units:  $\text{mag arcsec}^{-2}$
- Theorist units:  $I$  units:  $L_{\odot} \text{ pc}^{-2}$

- K-correction: de-redshifted
- de Vaucouleurs Profile: surface brightness  $I \sim r^{1/4}$  for spiral galaxy bulges and elliptical galaxies:

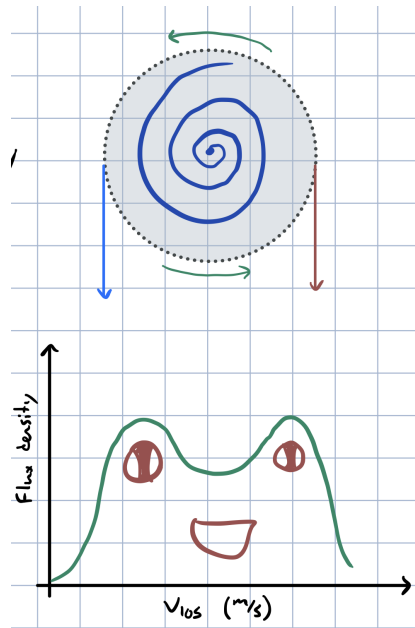
$$\log_{10} \left[ \frac{I(r)}{I_e} \right] = -3.3307 \left[ \left( \frac{r}{r_e} \right)^{1/4} - 1 \right] \quad (\text{C\&O 24.13})$$

where  $I$  is the surface brightness measured in units of  $L_{\odot} \text{ pc}^{-2}$ ,  $r_e$  is a reference radius (called the effective radius), and  $I_e$  is the surface brightness at  $r_e$ .  $r_e$  is defined to be that radius within which one-half of the bulge's light is emitted.

- **Note:** the equation above uses  $I$  as the surface brightness which is consistent with C&O, but in class we have used  $\mu$  as the surface brightness.

### 1.2.4 How to Measure Rotation in Other Galaxies

- Neutral H in the interstellar medium
- The spin flip transition of HI emits photons of wavelength 21 cm



(Art courtesy of James l'Artiste.) Find  $v_{max}$  with right peak - middle or left peak + middle

### 1.2.5 Tully-Fisher Relation

- Tully and Fisher studied 21-cm emission lines in spiral galaxies and found that the absolute magnitude is related to the rotation
- $v_{max}$  is easiest to find, so measure  $v_{max}$ , use Tully-Fisher to get  $M$  (absolute magnitude), and then distance - you also need  $m$  (apparent magnitude)

$$M_B = -9.95 \log_{10} V_{\max} + 3.15 \quad (\text{Sa}), \quad (25.5)$$

$$M_B = -10.2 \log_{10} V_{\max} + 2.71 \quad (\text{Sb}), \quad (25.6)$$

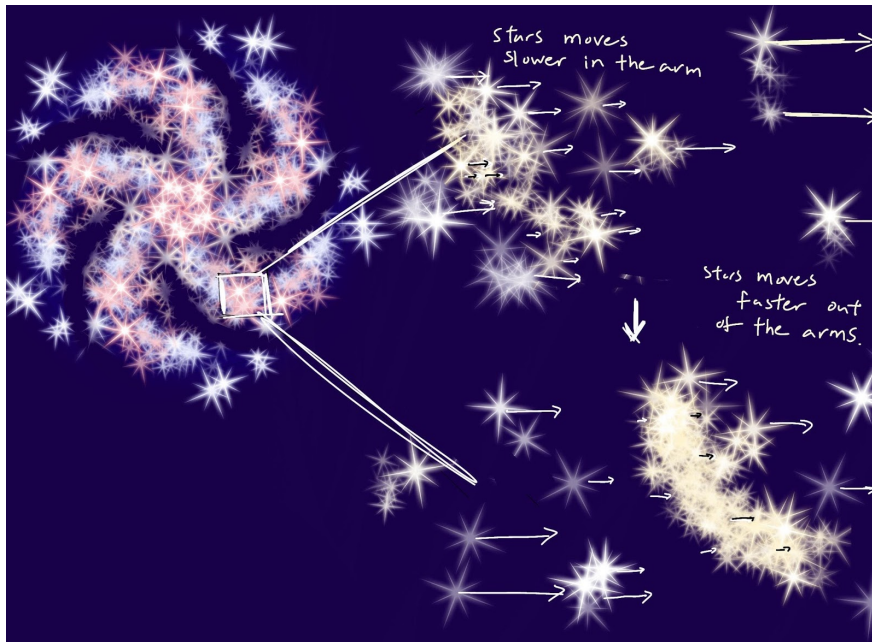
$$M_B = -11.0 \log_{10} V_{\max} + 3.31 \quad (\text{Sc}). \quad (25.7)$$

### 1.2.6 Types of Spiral Arms

- Grand-design spiral: 2 large arms - 10% of the spiral galaxy
- Multiple-arm: > 2 large arms - 60% of the spiral galaxy
- Flocculent spiral: Not well defined arms - 30%

### 1.2.7 Winding Problem, Density Wave Theory

- Traffic jam produced by slow moving truck (density wave) while cars (stars) slow down while moving around the truck.
- If we assume that all the stars in the galaxy stay together as they orbit, the spiral arms would wind up until we eventually have no spiral arms.
- This assumption is wrong, instead the stars constantly speed up or slow down as they enter and exit the spiral arms.



# Chapter 2

## Exam 2 Content

### 2.1 The Nature of Galaxies

#### 2.1.1 Spiral Galaxies versus Elliptical Galaxies: Major Differences

##### Spiral Galaxies

- Late-type in Hubble classification scheme
- Blue (which means less star formation!)
- Generally less luminous than ellipticals
- More abundant in the field
- Mass:  $10^9$  to  $10^{12} M_{\odot}$  (less massive on average)

##### Elliptical Galaxies

- Early-type in Hubble classification scheme
- “Red and dead” (not forming new stars)
- Generally more luminous (brighter)
- More abundant in clusters
- Mass:  $10^9$  to  $10^{14} M_{\odot}$  (more massive on average)

##### Bonus: Irrigular Galaxies!

- Sort of in between
- Usually the result of mergers

#### 2.1.2 Stellar Velocity Dispersion

- “Statistical dispersion of stellar velocities around the mean stellar velocity in a galaxy”
- Derived from the Virial Theorem to derive mass:  $-2\langle K \rangle - \langle U \rangle$ 
  - Assuming spherical distribution,  $\langle v_r^2 \rangle = \sigma_r^2$  where  $\sigma_r$  is the “radial velocity dispersion”
- Side note: **virial mass**  $M \approx 5R\sigma_r^2/G$  can be used to calculate the total mass of an elliptical galaxy or the bulge of a spiral galaxy but not the whole spiral galaxy

- Measure stellar absorption lines, add them all up to make a galaxy spectrum and measure the velocity dispersion to get the total mass of a galaxy. The wider the absorption line, the more massive the galaxy.

### 2.1.3 Faber-Jackson Relation

- Correlation between central velocity dispersion and luminosity
- Derived from the virial theorem
- For elliptical galaxies and spiral bulges (note: Tully-Fisher was for spiral galaxies)
- Brighter galaxies have larger velocity dispersions
- $L \propto \sigma^4 \propto L_{\odot} 10^{M_{\odot}/2.5} 10^{-M/2.5}$  where  $\sigma$  is the velocity dispersion and  $L$  is the luminosity
- $\log(\sigma_r) \propto -M$

### 2.1.4 The Fundamental Plane

- $\sigma$ , luminosity, and size are the fundamental parameters of an elliptical galaxy or spherical bulge
- We often see 2D projections of the fundamental plane (i.e. Faber-Jackson relation)

### 2.1.5 Galaxy Luminosity Function

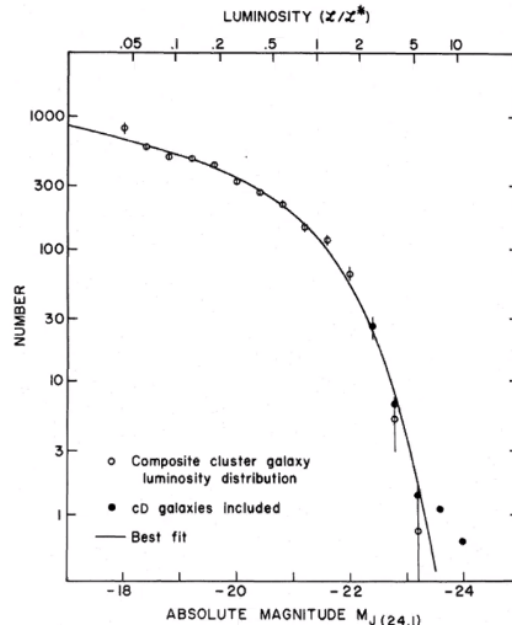
- Relative number of galaxies at each luminosity
- Number density of galaxies in a particular sample that have luminosities between  $L$  and  $L + dL$ :

$$\Phi(L) dL = \frac{\sigma^*}{L^*} \left( \frac{L}{L^*} \right)^{\alpha} e^{-L/L^*} dL$$

- When  $L \ll L^*$ ,  $L \rightarrow 0$
- In magnitudes:

$$\Phi(M) dM \approx 10^{0.4(\alpha+1)M} \exp\left(-10^{0.4(m^*-M)}\right) dM$$

- The “knee” is the turnover point where  $\alpha = 1$
- To measure the luminosity function:
  1. Measure the apparent magnitudes for all galaxies in the sample
  2. Convert to absolute magnitudes
  3. Calculate K-correction
  4. Count the number of galaxies in each K-corrected absolute magnitude bin, then divide the number of galaxies by the volume surveyed.



### 2.1.6 The K-Correction

- De-redshift
- K-correction “corrects” for the fact that sources observed at different redshifts are compared with each other at different rest wavelength bands
- Calculating the absolute magnitude of galaxies requires making corrections to their observed apparent magnitudes if we are to properly account for the effect of extinction, both within the Milky Way and within the target galaxy.

## 2.2 Galactic Evolution

### 2.2.1 Major versus Minor Galaxy Mergers

- Major merger: mass ratio of merging galaxies is between 3:1 and 1:1
- Minor merger: mass ratio of merging galaxies is below 3:1

### 2.2.2 Tidal Stripping and Tidal Tails

- Tidal stripping:

$$F = \frac{2GMmR}{r^3}$$

where  $F$  is the tidal force on the galaxy of mass  $m$ , has radius  $R$ , and is a distance  $r$  from a galaxy with mass  $M$ .

- Tidal tails are a result of tidal stripping as the tidal forces unbind gas and stars from galaxies
- The Milky Way is currently stripping material from the Large and Small Magellanic Clouds!

### 2.2.3 Dynamical Friction

- As an object of mass  $M$  moves through a galaxy, a high-density “wake” forms behind it. This wake exerts net gravitational force on  $M$  that opposes its forward motion, slowing it down.
  - This is the reason for mergers, otherwise objects would just pass through each other.
- Force due to dynamical friction is given by

$$F_d = -4\pi \ln(\Lambda) \left( \frac{G^2 M^2 \rho}{v^2} \right)$$

where  $\Lambda = b_{max}/m_{min}$  (depends on the material/density of material the galaxy is moving through) and  $\rho = nm$

- In class, we assumed the density of the dark matter halo to be

$$\rho(r) = \frac{v^2}{4\pi G r^2}$$

### 2.2.4 Initial Mass Function

- Only gives distribution of stellar masses immediately after stars are born (doesn't give mass distribution of, for example, stars in the Milky Way today).
- 

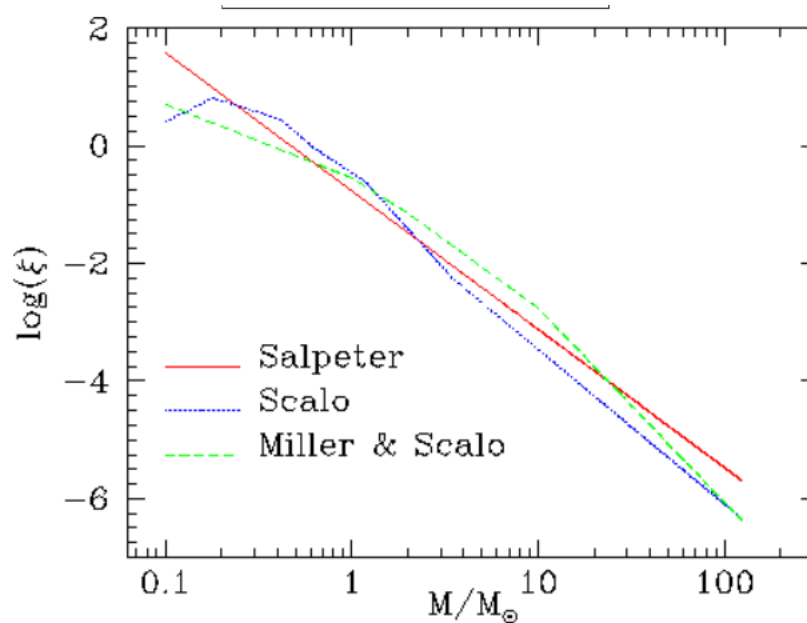
$$\xi(M) = \frac{dN}{dM} = CM^{-(1+x)}$$

where  $N$  is the number of stars,  $M$  is the mass of the stars, and  $C$  is a normalization constant. For stars with masses in the range  $7M_\odot < M < 35M_\odot$ ,  $x = 1.8$ .

- The above leads directly to

$$N = \int_0^\infty \xi(M) dM$$

for *all* masses (change bounds for given range).





### 2.2.5 Eggen, Lynden-Bell, and Sandage Collapse Model

- Galaxy forms all at once from direct collapse of a proto-galactic nebula
- “Top-down” model

### 2.2.6 Hierarchical Merger Model

- Stars in the stellar halo were a part of stellar clusters in initial proto-galaxies (some clusters survived to become globular clusters)
- Proto-galactic gas clouds collided and settled toward the center, forming a thick disk
- Gas continued to settle onto the midplane, forming a thin disk
- Stripped gas from satellite galaxies in recent mergers settled toward the galactic center accounting for the young stars in the bulge
- “Bottom-up” model: small galaxies merge to larger galaxies
- Future gas for bulge: tidal stripping of LMC and SMC

### Galaxy Structure

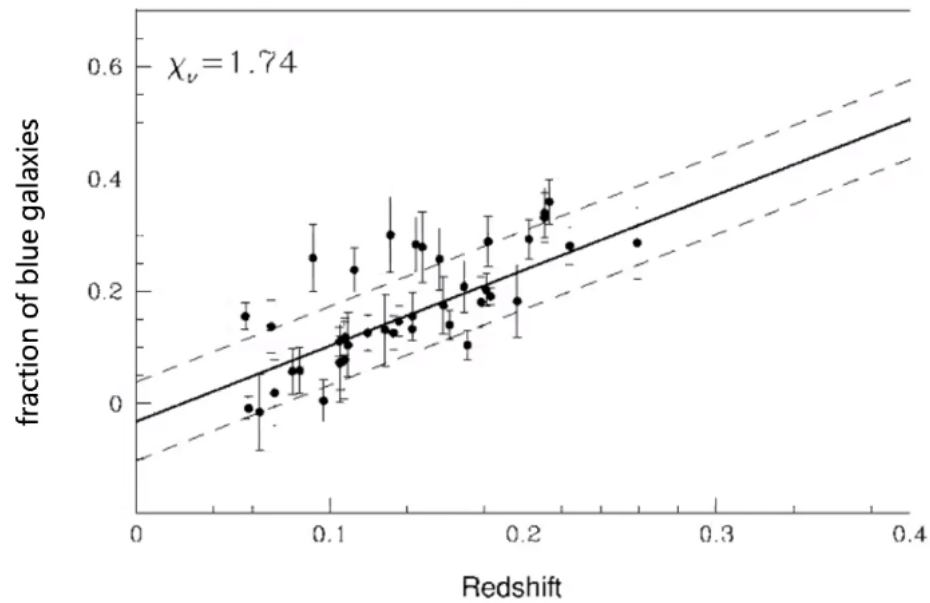
1. **Globular Clusters and Stellar Halos:** stellar clusters formed in proto-galaxies and merged to form galaxies. Some stars tidally got stripped away to become stars of stellar halo and some stellar clusters survived to become globular clusters.
2. **Thick Disk:** proto-galactic gas clouds collided and settled towards the center of the galaxy and then cooled to form new stars
3. **Thin Disk:** After the thick disk formation, gas continued to settle onto a galactic midplane and formed new stars
4. **Young Stars in the Bulge:** recent mergers with satellite galaxies stripped gas and settled towards the galactic center
5. **Future Gas for the Bulge:** tidal stripping of LMC and SMC

### Morphology-Density Relation

Due to more mergers occurring in dense environments (clusters) and the transformation of spirals into ellipticals during mergers, elliptical galaxies are more abundant in clusters.

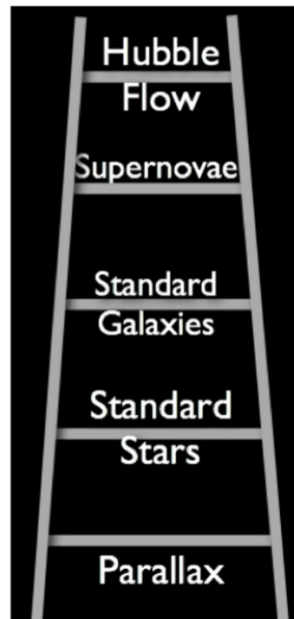
### Butcher-Oemler Effect

- Galaxies becoming redder over time
- If a  $z = 0$  galaxy cluster has 40% ellipticals, a  $z = 2$  galaxy cluster has  $< 40\%$  ellipticals and more blue spirals. Note: redshift of 2 corresponds to most merger events



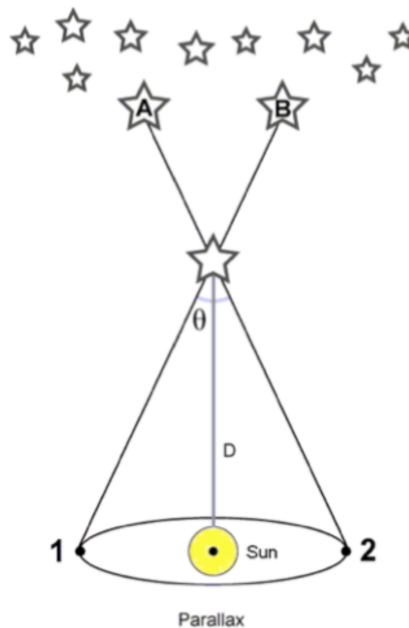
## 2.3 The Structure of the Universe

### 2.3.1 The Cosmological Distance Ladder



#### Parallax

- Only out to one kiloparsec



### Cepheid Variable Stars

- Out to 30 Mpc
- Cepheids pulsate rapidly and we can measure the period of pulsations
- Period-luminosity relationship for Cepheids:

$$M_V = -3.53 \log(P_d) - 2.13 + 2.13(B - V)$$

where  $M_V$  is the absolute visual magnitude,  $P_d$  is the period in days, and  $B - V$  is the color index.

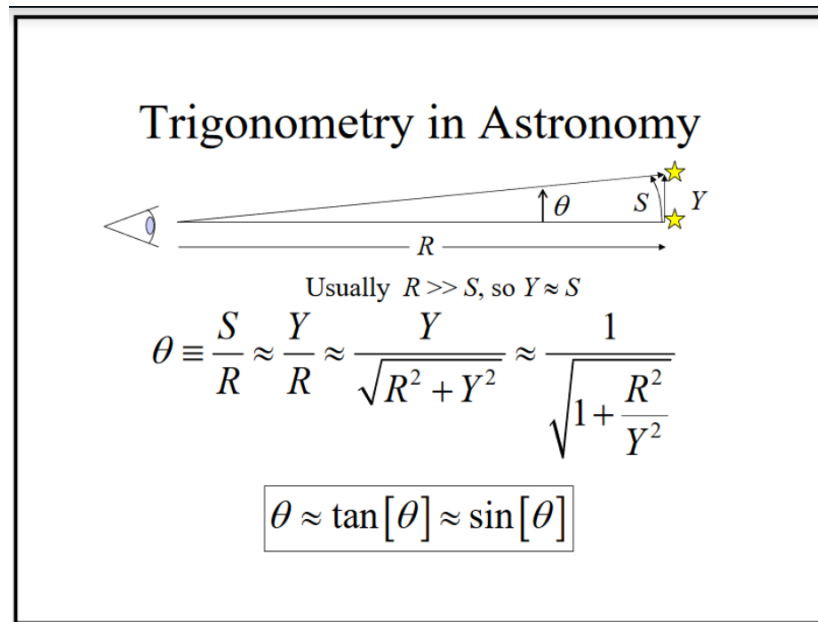
- What can we find?
  - Observe  $P_d$  and  $B - V$ , infer  $M_V$
  - Observe  $m_V$ , use  $M_V$  from above to get distance ( $d = 10^{(m-M+5)/5}$  parsecs)
- Notes: Blue Cepheids are brighter, longer period means brighter

### Tully-Fisher Relation

- Out to 100 Mpc
- Only works for spiral galaxies
- What can we find?
  - Observe  $v_{max}$  (distance between center and peak of graph), infer  $M_B$
  - Observe  $m_B$ , infer distance

### Supernovae

- Out to  $> 1000 Mpc$
- Measure the size of a nearby supernova's photosphere



- Type Ia light curves:
  - The maximum brightness of a supernova is inversely correlated with the rate of light curve decline (bright supernovae decline more slowly)
  - What can we find?
    - \* Observe rate of decline, infer  $M$
    - \* Observe  $m$ , combine with peak  $M$  to get distance

### Hubble Flow

- Most galaxies exhibit redshifts in their spectra:  $v = cs$  for  $v \ll c$ .
  - Farther galaxy means larger redshift means moving faster means “Hubble flow”
- Hubble’s Law:  $v = H_0 d$  where  $v$  is the galaxy’s velocity along the line of sight,  $d$  is the distance to the galaxy in Mpc, and  $H_0$  is Hubble’s constant (current value of 71 km/sec/Mpc - controversial)
- Highest rung on the distance ladder - most galaxies

Method	Uncertainty for Single Galaxy (mag)	Distance to Virgo Cluster (Mpc)	Range (Mpc)
Cepheids	0.16	15 – 25	29
Novae	0.4	21.1 ± 3.9	20
Planetary nebula luminosity function	0.3	15.4 ± 1.1	50
Globular cluster luminosity function	0.4	18.8 ± 3.8	50
Surface brightness fluctuations	0.3	15.9 ± 0.9	50
Tully–Fisher relation	0.4	15.8 ± 1.5	> 100
$D$ – $\sigma$ relation	0.5	16.8 ± 2.4	> 100
Type Ia supernovae	0.10	19.4 ± 5.0	> 1000

### 2.3.2 Expanding Universe, Hubble’s Law

- The further a galaxy is from Earth, the fast it is moving away and the larger its redshift  $z$
- For non-relativistic motion:

$$z = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}} = \frac{v}{c}$$

- For relativistic motion:

$$z = \sqrt{\frac{1 + v/c}{1 - v/c}} - 1 \rightarrow \frac{v}{c} = \frac{(z + 1)^2 - 1}{(z + 1)^2 + 1}$$

- Hubble’s Law  $v = H_0 d$  where  $H_0$  is the Hubble constant.  $H_0 = 100h$  km/s/Mpc
- Most galaxies are red-shifted and moving away, but some are blue-shifted, for example, Andromeda (M31)

### 2.3.3 Peculiar Velocity

- A galaxy’s own velocity through space (as opposed to recessional velocity which is the velocity of the expanding universe carrying the galaxy along)
- If the recessional velocity is less than the peculiar velocity, the object is coming towards you!

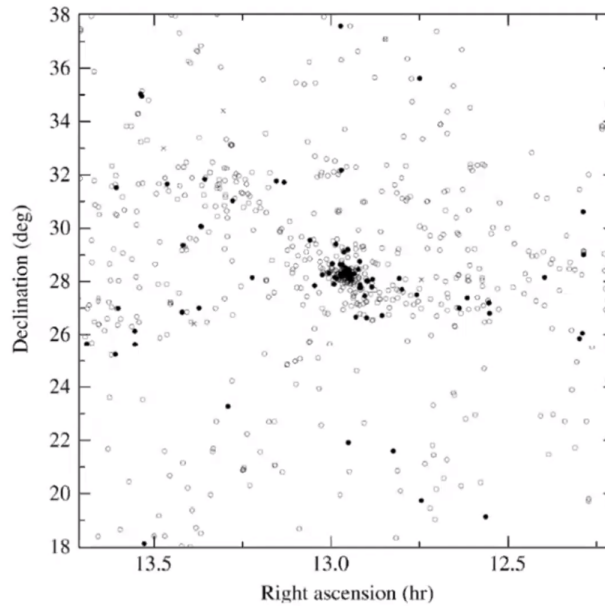
### 2.3.4 The Age of the Universe

- Assume constant rate of expansion
- $t = d/v = d/(H_0 \times d) = 1/H_0$
- Gives estimate of around 13 billion years which isn’t too far off!

### 2.3.5 Distribution of Galaxies in the Universe

- More ellipticals near center of galaxy cluster due to being more dense and more likely for galaxies to merge and form ellipticals
- More likely for spiral galaxies to be on outer edge where mergers less likely

- Spirals more abundant in field, ellipticals more abundant in clusters



### 2.3.6 Groups and Cluster

- Most galaxies are found in groups or clusters: gravitationally bound associations of galaxies
- Groups have less than 50 members, diameter  $1.4h^{-1}$  Mpc, velocity dispersion 150 km/s, and mass  $2 \times 10^{13}h^{-1}M_{\odot}$ .
- Clusters have between 50 and 1000 members (poor to rich, respectively) with diameter  $6h^{-1}$  Mpc, velocity dispersion between 800 and 1000 km/s, and mass  $10^{15}M_{\odot}$ .

	Groups	Clusters
Number of members	<50	50 – 1000s (poor to rich)
Diameter ( $h^{-1}$ Mpc)	1.4	6

- Local Group: Milky Way and Andromeda, M33, and Pinwheel galaxy
- Nearest galaxy clusters:
  - Virgo Cluster: 16 Mpc away, 250 larger galaxies, 2000 smaller galaxies, diameter 3 Mpc
  - Coma Cluster: 90 Mpc away, roughly 10000 member galaxies, diameter 6 Mpc
- There are more elliptical galaxies at the center of a galaxy cluster
- Virial Mass for a galaxy cluster (lecture 12 boardwork):

$$M = \frac{5R\sigma^2}{G}$$

### 2.3.7 Evidence for Dark Matter from Cluster Masses

- Fritz “Nuclear Goblins Guy” Zwicky measured the velocity dispersion and estimated the cluster mass
- Compared to the total mass of galaxies in the cluster
- Total mass of galaxies did not account for all the mass in the cluster
- “Missing mass” turned out to be dark matter and hot intracluster gas

### 2.3.8 Intracluster Gas

- Roughly 90% of the baryonic mass of a galaxy cluster is in the form of ionized gas
- Gas radiates via thermal bremsstrahlung: free-free emission of x-ray photons
- Using ideal gas law and HSE, can derive galaxy cluster mass as a function of  $r$  entirely from hot intracluster gas quantities:

$$M_r = -\frac{kTr}{\mu m_H G} \left( \frac{\partial \ln \rho}{\partial \ln r} + \frac{\partial \ln T}{\partial \ln r} \right)$$

where  $\mu$  is a constant.

- To find the total mass, evaluate  $M_r(r = R)$ .
- The hotter the gas, the more massive the cluster.





## Chapter 3

# Final Exam Content



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