Galaxies

- **Goals:**
  - To determine the types and distributions of galaxies?
  - How do we measure the mass of galaxies and what comprises this mass?
  - How do we measure distances to galaxies and what does this tell us about their formation?
- **Nebulae and Galaxies**
  - In 1845 Parsons discovered that many nebulae had spiral structures.
    - Most astronomers believed that the nebulae were local phenomenon (in our Galaxy).
    - In 1920 there was the “Great Debate” between Shapley (believed spiral nebulae were local) and Curtis (believed they were external galaxies).
    - Hubble solved the issue using Cepheids to measure the distances of galaxies.

• Galaxy Types

– The Hubble Classification Scheme

Figure 26-10

- **Four basic types of galaxies, <u>Elliptical</u>, <u>Spiral</u>, <u>Barred Spiral</u> and <u>Irregular</u>.**
- **Each type of galaxy reflect their differences in shape, star formation and dynamical histories.**
- **The sequence of galaxy types is called the "Hubble tuning fork".**
- **In general elliptical galaxies contain an old (cool and red) population of stars while spirals contain old (in the nucleus) and young (in the spiral arms).**

– Spiral Galaxies

Figure 26-5

- **Spiral galaxies are further subdivided according to the relative size of the central bulge and the winding of the spiral arms.**

  Sa: Large nucleus (bulge), small disk

  Sb: Smaller nucleus, tight spiral arms

  Sc: Almost no nucleus, wide spiral arms

– Spiral Galaxies

- **Disk is supported by rotational velocity.**
- **Light profile in spirals falls off exponentially with distance from the center of the galaxy.**

$$I(r) = B_o e^{-r/D}$$

- **I(r): surface brightness (flux arcsec^{-2})**
  B_o: Central surface brightness
  r: distance from center of galaxy
  D: scale length
- **The scale length defines how rapidly the light falls off with distance (measure of the size of a galaxy).**

– Barred Spirals

Figure 26-6

- **Barred spirals (SB) have the same subclasses as non-barred, Sba, SBb, SBc.**
- **The bar refers to the nucleus or bulge of a spiral galaxy. Spiral arms originate from the bar rather than the nucleus itself.**
- **It is believed the bar is brought about by the gravitational forces that the stars exert on one another as they orbit the nucleus.**
- **In the local Universe the ratio of barred to non-barred spirals is 2:1.**

– Elliptical Galaxies

Figure 26-7

- Elliptical shape with no spiral arms
- Classification is based on their ellipticity (E0-E7). E0: round, E7: highly elongated.
- Dominated by an old stellar population (red) with little new star formation or dust (Population II stars).
- Distribution of velocities is Gaussian (the stars are not rotating about the nucleus).
- The light profile of an elliptical galaxy follows an "$r^{1/4}$ law".

$$I(r) = I_e e^{-7.67\left[\left(r/r_e\right)^{1/4} - 1\right]}$$

- $I(r)$: Surface brightness (flux arcsec^{-2})
  I_e: Surface brightness at r_e
  r_e: Half light radius
  r: Distance from nucleus center
- The "$r^{1/4}$ law" profile holds for bulges of spirals as well.
- Number of giant ellipticals is rare but the dwarf (10^6 $M_\odot$) ellipticals are common.

– Most galaxy profiles are a mixture of an elliptical and spiral profile.

• Galaxy Masses

Figure 25-17

- Rotational velocities of spiral galaxies.
  - We can trace the distribution of the gas in a spiral galaxy using the HI 21 cm line.
  - Regions of a galaxy moving away from us are redshifted by the Doppler shift and those regions moving towards us are blueshifted relative to the galaxy.
  - Measuring these Doppler shifts we can map out the rotation of the spiral galaxy (rotation curve).
- Kepler's and the Mass of Galaxies
  - Kepler's law relates the mass and the velocity of rotation through,

$$P^2 = \frac{4\pi^2 r^3}{G(M + M_o)}$$

  - M_o: mass of the test particle (zero)
    M: mass interior to radius r.

$$P = \frac{2\pi\pi}{v}$$

  - v: velocity of rotation at radius r
  - Combing these equations

$$v = \left(\frac{GM}{r}\right)^{1/2}$$

– Rotation curves of spiral galaxies

- If the density of mass within a galaxy traced the light the the rotation velocity will increase out to the size of the galaxy.

$$M(r) = \frac{4\pi}{3} r^3 \rho$$

- r: radius
  ρ: average density

$$v(r) \propto r$$

- v(r): rotation velocity as a function of r
- For radii greater than the size of the galaxy the mass of the galaxy will not increase with radius

$$v(r) = \frac{1}{r^{1/2}}$$

- Rotational velocity should increase out to the edge of the galaxy and then decrease with radius.
- <u>PROBLEM:</u> Rotation curves at radii greater than the size of a galaxy are <u>flat.</u> There must be more mass in a galaxy than the visible light would imply.
- This is evidence for dark matter.

– Flat rotation curves

- If the rotation curve is flat v(r) is constant then the density of the mass must decrease as

$$\rho \propto \frac{1}{r^2}$$

- To explain the dark matter we can look to the distribution of low mass stars (MACHOS: massive compact halo objects) or more exotic particles such as weakly interacting massive particles (WIMPs).
- The dark matter is believed to reside in a halo (at the center of which is the gas and stars that we see as the galaxy).
- 90% of the mass of the galaxy is in the form of <u>dark matter</u>. The ration of the dark to luminous matter is called the mass-to-light ratio. For galaxies it is measured to be approximately 10:1.

Distances to Galaxies

– Cepheid variables

- Hubble first noticed that variable stars in local galaxies matched the variable stars we see in our own Galaxy.
- Cepheids have a relation between their period of variability and their absolute magnitude.
- If we can measure their variability we can estimate their distance using the distance modulus equation

$$m - M = 5\log_{10}(d) - 5$$

- m: apparent magnitude
  M: absolute magnitude (at 10pc)
  d: distance (parsecs)
- Cepheids are called standard candles (we know or can infer their absolute luminosity)
- Cepheids are bright ($2 \times 10^4\ L_\odot$) the HST can measure their period out to 20 Mpc.
- This extends the "distance ladder" out to nearby galaxies.

– Galaxy Redshifts

Figure 26-15

- By comparing spectra (identifying particular emission and absorption lines) we can measure the redshift of a galaxy.
- For old stellar populations (galaxies with substantial numbers of G and K stars) the most common features used are the Ca H and K lines.
- For young stellar populations (O and B stars) the ionizing radiation produces a lot of emission lines (e.g. Hα).
- Comparing the restframe (redshift zero) wavelengths of these lines with the observed spectrum we can derive the redshift of the galaxy.

$$z = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta\lambda}{\lambda}$$

- λ: observed wavelength
  λ_o: restframe wavelength
  z: redshift
- The redshift of a galaxy gives its recession velocity.

- # Hubble's Law
  - ## Redshift vs Distance
    - Hubble discovered that redshift was proportional to its distance measured from the Cepheids (for local galaxies).

$$cz = H_0 d$$

- c: speed of light
  z: redshift
  H_o: Hubble's constant (km s^{-1} Mpc^{-1})
  d: distance (Mpc)
- This is commonly written as

$$v = H_0 d$$

- v: recession velocity
- This relation is important because we can now measure the redshifts of galaxies (easy) and directly infer their distance.
- Because all galaxies tend to have positive redshift this means that they are all expanding away from us (and each other) - the Universe is expanding.
- Galaxies further away from us have larger recessional velocities - uniform expansion.
- For very large distances/redshifts the linear relation no longer holds.

– Hubble's Constant

- We compare Hubble's law with the distance-time relation for motion at constant speed.

$$d = v\,t$$

- d: distance moved
  t: time of motion
  v: velocity
- The Hubble constant H_o is therefore a measure of 1/time.

$$H_o = \frac{1}{t}$$

- The time "t" in terms of the Hubble constant is the "age" of the Universe (Hubble time).
- If $H_o = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$

$$t = \frac{1}{50 \text{ km s}^{-1} \text{ Mpc}^{-1}} \text{ x} \left(10^6 \text{ pc/Mpc}\right) \text{x} \left(3\text{x}10^{13} \text{ km/pc}\right)$$

$$= 6\text{x}10^{17} \text{ s}$$

$$= 2\text{x}10^{10} \text{ yrs}$$

- This does not give the exact age of the Universe as it does not account for deceleration.
- H_o is a fundamental parameter.

– Measuring Hubble's Constant

- Hubbles constant is in principle simple to measure. We plot distance vs redshift for a large number of galaxies and calculate the gradient of the plot.
- Current measurements vary from H_o= 50-80 km s^{-1} Mpc^{-1}. "Best" value is now 70 km s^{-1} Mpc^{-1}.
- Cepheid periods can only be measured for nearby galaxies.
- When we measure the redshift of a galaxy it is made up of the expansion velocity of the Universe (Hubble expansion) plus the velocity due to the gravitational pull of near by structures (peculiar velocity).

$$cz = H_o d + v_{pec}$$

- v_{pec}: velocity due to gravity.
- For nearby galaxies (<20 Mpc) the peculiar velocity can be a large component of the redshift (v_{pec}~300 km s^{-1}).
- To move to higher redshifts (where peculiar velocities have a smaller fractional effect) we must find new standard candles. These are secondary distance indicators (they are indirect).

– The Tully-Fisher Law of Spirals

- Brent Tully and Richard Fisher found that there was acorrelation between the absolute magnitude of a galaxy and its rotational velocity (the peak of the rotation curve).
- The larger the rotational velocity the more luminous the galaxy. This means more mass gives more light.
- From the rotational velocities of galaxies.

$$v^2 \propto \frac{M}{R}$$

- If we assume that all spirals have the same surface brightness.

$$SB = \frac{L}{R^2} = \text{constant}$$

- SB: surface brightness (flux arcsec^{-2}) L: Luminosity$\rightarrow$ $L^{1/2} \propto R$.
- If the mass of a galaxy traces the luminosity (mass to light ratio is constant, $M \propto L$).

$$L \propto v^4$$

- As we measure luminosity in magnitudes then we expect the a plot of magnitude vs velocity to have a slope of 10.

$$m \propto -2.5\log\left(v^4\right)$$
$$\propto -10\log(v)$$

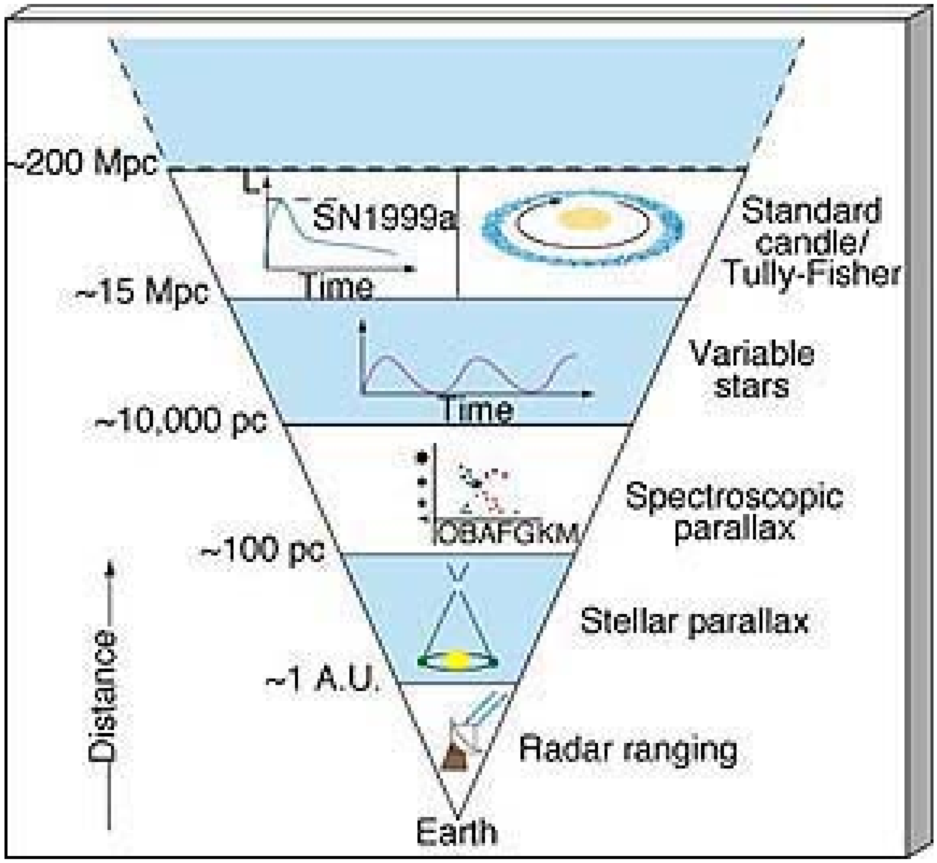
– Faber-Jackson relation for ellipticals

- Discovered by Faber and Jackson, We can compare the velocity dispersion of stars in elliptical galaxies with their luminosity (analogous to the Tully-Fisher relation).

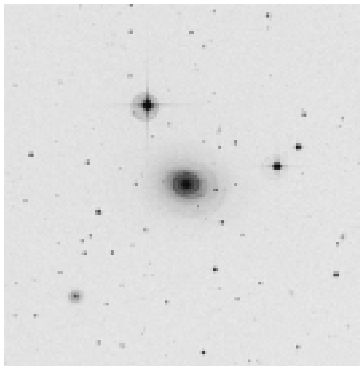
$$L \propto v^4$$

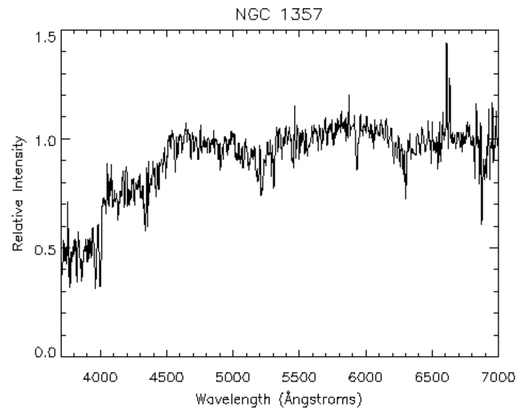
- If we measure the rotational velocity (spirals) or velocity dispersion (ellipticals) of a galaxy from spectroscopic observations we have a measure of its absolute/intrinsic magnitude.
- Tully-Fisher and Faber-Jackson provide a way of measuring standard candles for galaxies out to large distances.
- We can measure the relation out to distances >100 Mpc.
- All the secondary distance indicators have a substantial scatter in their relation. The distances we estimate using them are not exact - we need to understand the errors.
- To move from nearby stars and galaxies to distant galaxies we need to use different techniques for measuring distance. We need a "distance ladder".

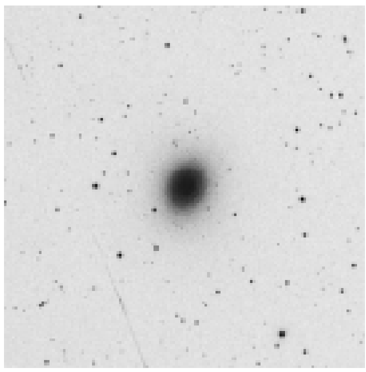
- **The Distance Ladder**

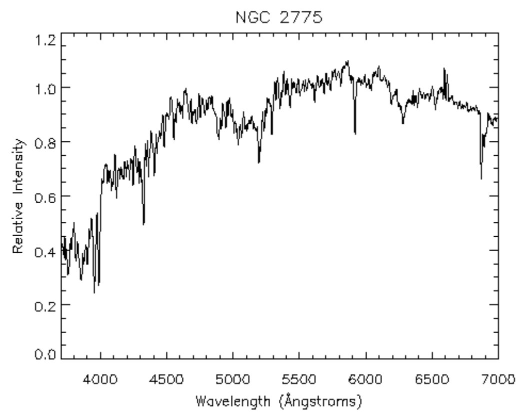


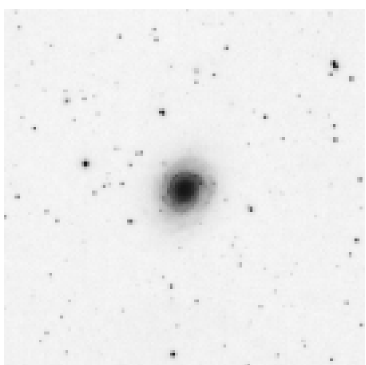
  - To measure distances to galaxies we need to employ different techniques.
  - Stepping from one technique to the next requires bootstrapping.

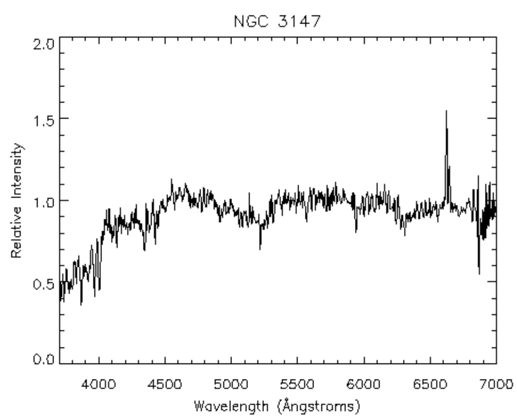



NGC 1357
Relative Intensity
0.0 0.5 1.0 1.5
4000 4500 5000 5500 6000 6500 7000
Wavelength (Ångstroms)




NGC 2775
Relative Intensity
0.0 0.2 0.4 0.6 0.8 1.0 1.2
4000 4500 5000 5500 6000 6500 7000
Wavelength (Ångstroms)




NGC 3147
Relative Intensity
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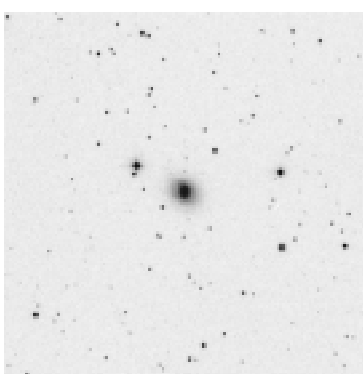
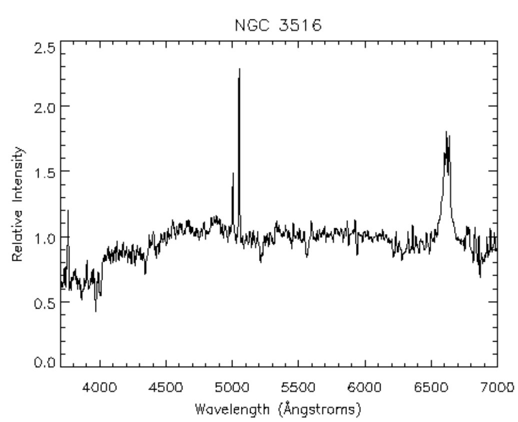
4000 4500 5000 5500 6000 6500 7000
Wavelength (Ångstroms)




NGC 3516
Relative Intensity
0.0 0.5 1.0 1.5 2.0 2.5
4000 4500 5000 5500 6000 6500 7000
Wavelength (Ångstroms)

• Luminosity Function of Galaxies

– The distribution of galaxy lumiosity

- **Galaxies come in a range of luminosities (for spirals 10^8-10^{10} $L_\odot$) from dwarf to giant galaxies.**
- **The number density (number per Mpc^3) of galaxies is called the <u>luminosity function</u>.**
- **The luminosity function is well fitted by a functional form called the <u>Schechter function</u>.**

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

- **L: luminosity of a galaxy**
  $\Phi(L)$: Number of galaxies of luminosity L per cubic Mpc.
  α:slope of luminosity function for $L<L^*$
  L^*: Characteristic luminosity of a galaxy
- **The luminosity function shows that there are typically more faint galaxies than brighter ones (i.e. $L>L^*$).**
- **For galaxies the characteristic density is Φ^*=0.005 Mpc^3.**
- **The characteristic luminosity (in magnitudes) in the blue bands is -21.5 magnitudes.**

- **Galaxy Formation**
  - **Merging sub components**
    - It is believed that galaxies are built up by merging smaller components.
    - As we look back in redshift (and time) the spiral and elliptical galaxies we see in the local Universe are no longer present.
    - High redshift galaxies are amorphous.
    - Collisions between galaxies can induce shock waves that lead to star formation in the merging component.
    - Merging galaxies that produce large amounts of star formation are called "<u>starburst</u>" galaxies.
    - Our own galaxy shows streams of stars that suggest the Large Magellanic Cloud, Small Magellanic Cloud (SMC) and our Galaxy have had many encounters.
    - These merging events can disrupt the disks of galaxies.
    - If the angular momentum can be lost from the system and the gas dissipated we can be left with an elliptical galaxy.

- # Clusters of Galaxies
  - ## Galaxies are clustered through gravity
    - Distribution of galaxies on the sky is not random. Gravitational potentials cause clusters of galaxies to form.
    - Typically clusters have more elliptical galaxies than spirals (as merging of galaxies is more prevalent in clusters).
    - A typical crossing time for a galaxy in a cluster is about
  - ## Velocity dispersion of clusters
    - Using the virial theorem we can estimate the mass of a cluster if we can measure the velocities of individual galaxies.
    - Virial theorem states that for a stable spherical distribution of objects - kinetic energy equals 1/2 the potential energy.

$$\mathrm{K.E.} = \sum \frac{1}{2} M_i V_i^2$$

$$= \frac{1}{2} M_{tot} \left\langle V^2 \right\rangle$$

    - M_{tot}: total mass of cluster
      $\langle v \rangle$: mean velocity of cluster
    - We only see the radial component of the velocity - $\langle v_{rad}^2 \rangle = \langle v^2 \rangle / 3$.

– Velocity dispersions of clusters

- **The gravitational potential can be approximated by**

$$\mathrm{P.E.} = \frac{GM_{tot}^2}{R_{tot}}$$

- **R_{tot}: Cluster radius**
- **The relation between mass and mean velocity (velocity dispersion) is given by**

$$M_{tot} = \frac{3\langle V_{rad}^2 \rangle R_{tot}}{G}$$

- **If we measure the velocity dispersion of a cluster we have a measure of the mass (as with rotation curves).**
- **The velocity dispersions of clusters of galaxies are typically 600-1000 km s^{-1}.**
- **To derive the velocity dispersion from redshift measurements we must first subtract the mean redshift of the cluster.**
- **Comparing the mass associated with the galaxies in a cluster with the mass of the cluster we get a mass-to-light ratio**

$$\frac{M_{tot}}{L} \approx 200 \frac{M_O}{L_O}$$

- **Clusters have substantially more dark matter in them than galaxies.**

- **Lensing by clusters of galaxies**
  - **Clusters are massive systems**
    - **The gravitational potential of a cluster is sufficient to bend light (from General Relativity). The cluster behaves as a lens.**
    - **The deflection of the light depends on the mass of the cluster.**

$$\alpha = 4\frac{GM}{c^2}$$

    - **α: Deflection angle**
    - **The lensing effect can cause arcs, rings, crosses, multiple images and arclets. The distortion depends on where the background galaxy lies relative to the mass of the cluster.**
    - **Objects that are lensed maintain their surface brightness but are elongated.**
    - **This results in an amplification of magnification of their total light.**
    - **As the lensing depends on the mass of the cluster we can use the effect to <u>measure</u> cluster masses directly.**
    - **Measuring the mass of clusters gives an estimate of the mass of the Universe.**

- Large scale structure
  - Clusters and superclusters
    - Galaxies and clusters of galaxies are themselves clustered.
    - Redshift surveys of the local Universe show that galaxies lie in great walls and sheets extending over 100's Mpc (superclusters).
    - The picture of clustering on scales small (galaxies) to large (superclusters) is known as <u>hierarchical structure formation</u>.
    - It is believed these sheets and filaments form a "cosmic web" where clusters form at the intersection of the filaments.
    - Between these structures lie great voids.
    - The most common theories for structure formation assume that most of the Universe is made up of dark matter and that galaxies form in only the most overdense regions.
    - We do not know what comprises this dark matter (searches are underway to detect WIMPS and MACHOs).