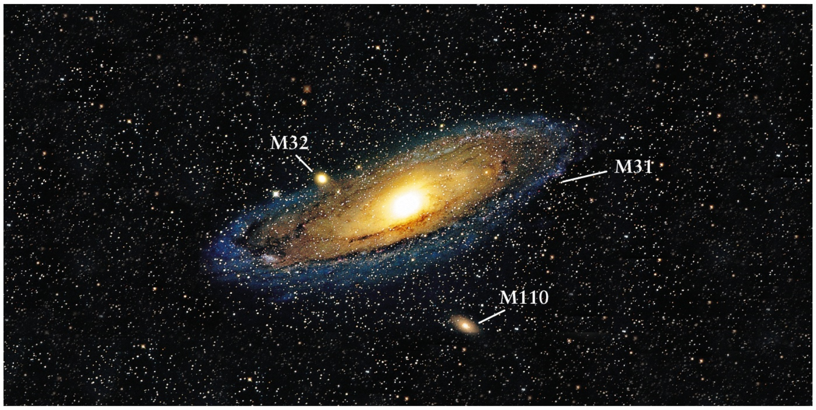
Galaxies

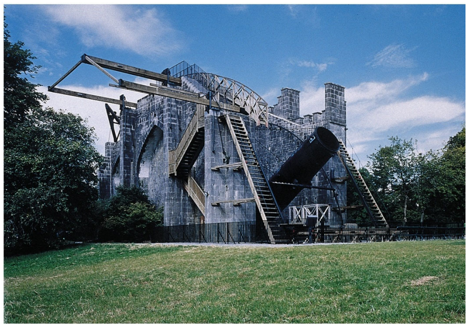


First Observations

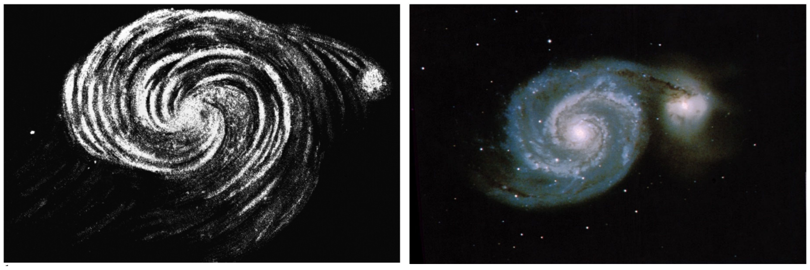
To the naked eye and even through a small telescope, galaxies appear as diffuse objects. They were originally thought to be another type of nebulae.

Earl of Rosse

The first person to have had a large enough telescope to study these objects was the third Earl of Rosse in Ireland. In 1845 he built a gigantic telescope with a 6-foot diameter mirror. He examined many of these nebulae that had initially been discovered and cataloged by William Herschel. Lacking photographic equipment, he had to make sketches of his visual observations.



Sketch & Photograph of M51



Island Universes?

Are these nebulae “island universes” outside of our Galaxy or are they just one more component, like the globular clusters? Throughout the nineteenth century, astronomers were very divided on this issue.

In 1920, there was a “debate” given at the National Academy of Sciences.

1) Harlow Shapley, who had recently determined the size of the Galaxy and the location of the Sun in the Galaxy by using globular clusters, thought the nebulae were relatively **small, nearby objects**.

2) Opposing him was **Heber Curtis**, who argued that each spiral nebulae was a rotating system of stars **much like our own Galaxy**.

This is known as the Curtis-Shapley debate.

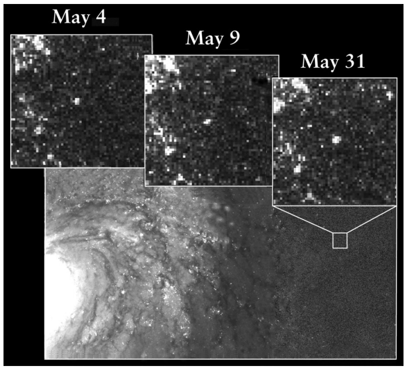
Who Won?

Reviewers of the Curtis-Shapley debate note that Shapley had “bad” data from another astronomer that indicated the nebulae have a proper motion; hence, they must be nearby. Shapley made the correct arguments using that data. Curtis, on the other hand, did not have any data to support his case, but (as was ultimately shown) he did have the correct answer.

What was needed was a definitive determination of the distance to the spiral nebulae. This was accomplished by Edwin Hubble.

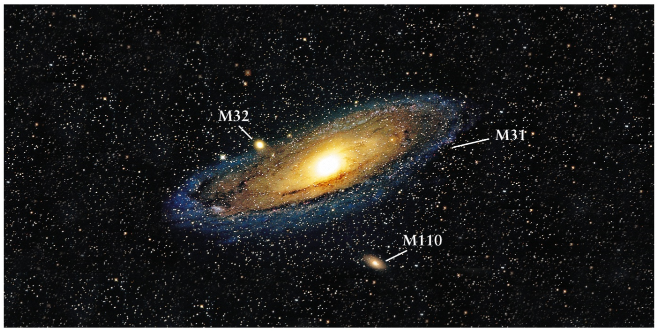
Distance to Andromeda

Hubble began taking photographs of the Andromeda “Nebula”. When examining his plates, he thought he had detected a nova. After taking more plates and reviewing previously acquired ones, he realized it was a Cepheid variable star. Several more Cepheids were detected. After a few months of observations, he established their periods and deduced their luminosities, using Henrietta Leavitt’s Period-Luminosity relationship.



Wendy Freedman, Carnegie Institution of Washington, and NASA

Distance to Andromeda



Science Source

Now, in combination with the apparent magnitudes of the Cepheids, Hubble computed a distance. The modern result is 750,000 pc or 2.5 million light years. Based on its angular size, the Andromeda Galaxy has a diameter of 70 kpc (the Milky Way is 50 kpc across).

Hubble Classification

Hubble spent his career observing, cataloging, and classifying galaxies.
He classified galaxies into four broad categories based on their appearance.

Spirals (S)
Barred Spirals (SB)
Ellipticals (E)
Irregulars (Irr)

Spiral Galaxies

Spiral galaxies consist of a nucleus, a disk, a halo, and spiral arms.

Interstellar material is usually spread throughout the disk.

Bright emission lines are present, and absorption of light by dust is often apparent.

NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STScI-PRC01-07

Spiral Galaxies

Open star clusters can be seen in the arms of nearby spirals, as well as globular clusters in the halos.

Both young and old stars are in these galaxies.

All spirals rotate in the sense that their arms trail.


Whirlpool Galaxy • M51

NASA and The Hubble Heritage Team (STScI/AURA)
Hubble Space Telescope WFPC2 • STScI-PRC01-07

Barred Spiral Galaxies

Spiral Galaxies

The normal Spirals are indicated with an “S”, whereas the Barred Spirals are “SB”.

For both, there is a gradual transition of types. Lower-case letters “a”, “b”, and “c” are added to indicate the **size of the nucleus** AND the **tightness with which the spiral arms are coiled**.

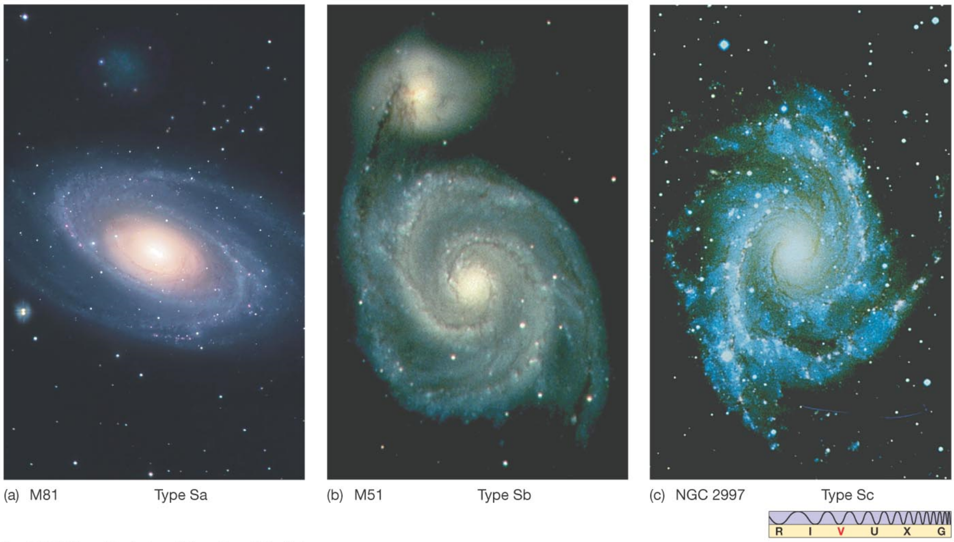
At one extreme (“**a**”), the nuclear bulge is **large** and luminous, the arms are faint and **tightly coiled**, and bright emission nebulae and supergiants are not seen.

At the other extreme (“**c**”) are spirals in which the nuclear bulges are **small** – almost lacking – and the arms are **loosely wound**, or even wide open. In these latter galaxies, there is a high degree of resolution of the arms into luminous stars, star clusters, and emission nebulae.

An Sa Spiral – NGC 1357

An Sb Spiral – M81

An Sc Spiral – NGC 4321

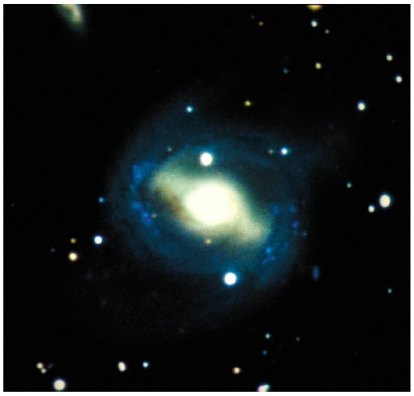


(a) M81 Type Sa

(b) M51 Type Sb

(c) NGC 2997 Type Sc

An SBa Barred Spiral – NGC 4650



An SBb Barred Spiral – M83

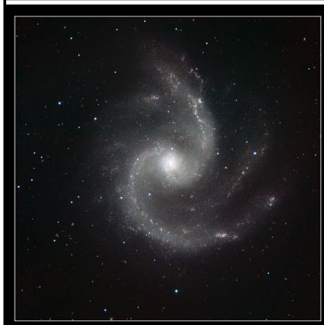
An SBc Barred Spiral – NGC 1365

2. Barred Spiral Galaxies


M58: SBa galaxy


M83: SBb galaxy


NGC 1365: SBc galaxy


NGC 5427

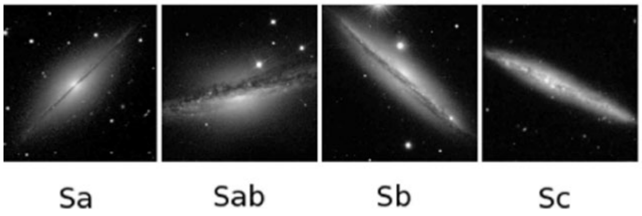

Messier 100 (NGC 4321)

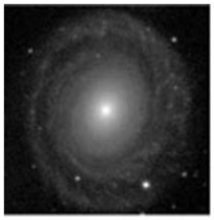

NGC 1300

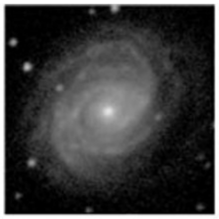

NGC 4030

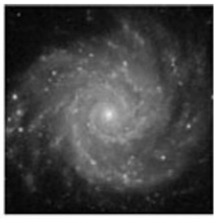

NGC 2997

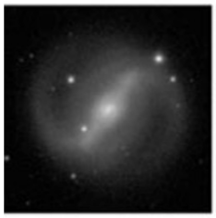

NGC 1232

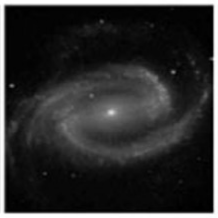


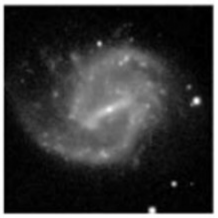

Sa


Sb


Sc


SBa


SBb


SBc

Why Different Types?

The differences between Sa, Sb, and Sc galaxies may be related to the relative amounts of gas and dust they contain. IR observations show that about 4% of the mass of an Sa galaxy is in the form of gas and dust. This percentage is 8% for Sb galaxies and 25% for Sc galaxies.

Why Bars?

Barred spiral galaxies outnumber ordinary spirals by about two to one. Why don't all spiral galaxies have bars?

Calculations indicate that a bar will **not** develop if a galaxy is surrounded by a sufficiently **massive halo of Dark Matter**.

The difference between barred spirals and ordinary spirals may thus lie in the amount of Dark Matter the galaxy possesses.

Spiral Galaxies

Spiral galaxies range in diameter from about 6000 to more than 70,000 pc, and the hydrogen gas in the disks often extends to far greater diameters.

From the limited observational data we have, their masses are estimated to range from 10^9 to 10^{12} times the mass of the Sun.

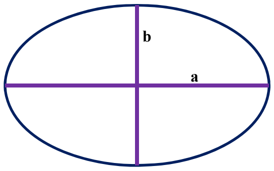
Elliptical Galaxies

These are spherical or ellipsoidal systems that consist almost entirely of old stars. They contain no trace of spiral arms. Their light is dominated by red stars (Population II), and in this respect, ellipticals resemble the nuclear bulge and halo components of spiral galaxies.

Dust and emission nebulae are not conspicuous in elliptical galaxies, but ellipticals are not devoid of interstellar matter. Many contain narrow lanes of absorbing dust, and X-ray data indicate that 1 to 2 percent of the total mass of ellipticals may be in the form of gas at a temperature that exceeds a million degrees. In the larger, nearby ellipticals, many globular clusters can be seen.

Classification Schemes

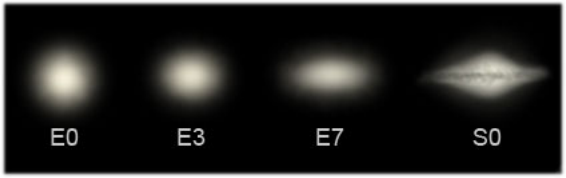
The ellipticals are classified according to their degree of flattening (or ellipticity), from E0 to E7 [10(a-b)/a].

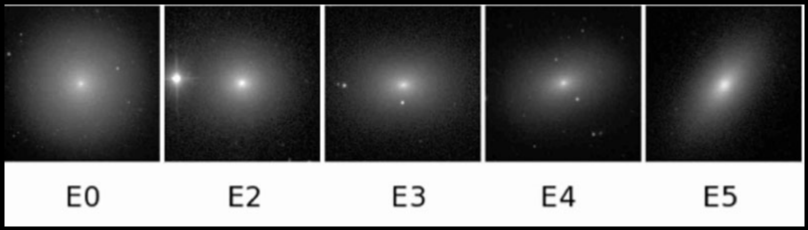


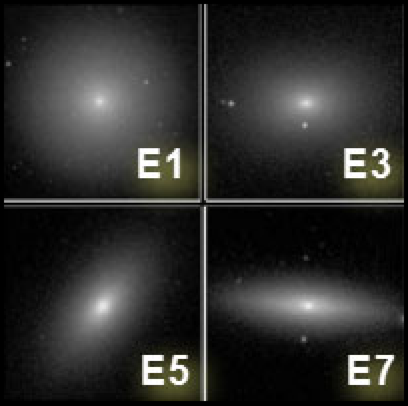
An E0 Elliptical – M87

An E2 Elliptical – M32

An E5 Elliptical – M59


E0
E3
E7
S0


E0
E2
E3
E4
E5


E1
E3
E5
E7

True Shapes

Hubble's classification of elliptical galaxies is based on the **appearance** of their images, not upon their **true** shapes.

An E7 galaxy, for example, must really be a relatively flat elliptical galaxy seen nearly edge on, but an E0 galaxy could be of any ellipticity, that just happens to be seen face on.

Analyses indicate that some elliptical galaxies are oblate (like a pumpkin), others are prolate (like a football), and still others are triaxial (where all three axes are unequal).

Elliptical Galaxies

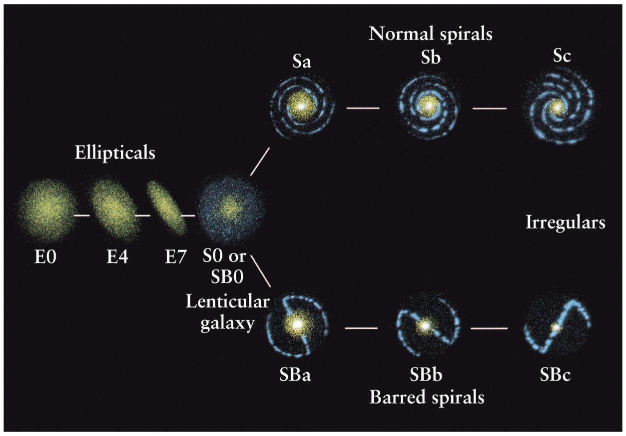
The rare giant ellipticals are as bright as 10^{11} solar luminosity. The mass of giant ellipticals is at least 10^{12} times the mass of the Sun. These diameters extend over many hundred thousand light years and are larger than those of the largest spirals.

As a class, the Elliptical galaxies have the largest and smallest members, both in mass and luminosity.

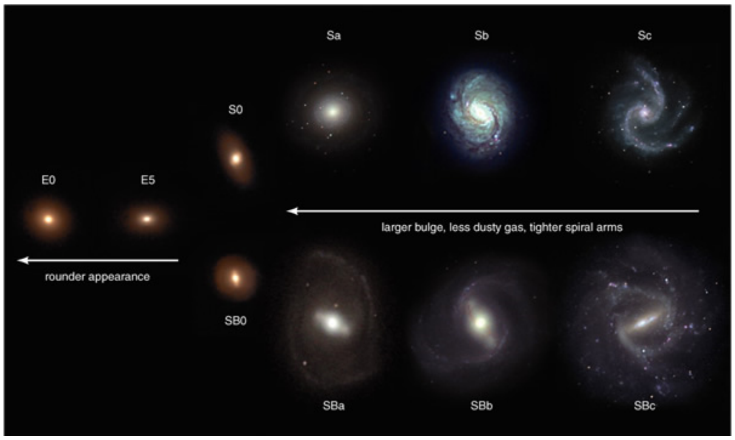
Lenticular Galaxies

A few galaxies are observed to have the disk shape of spirals but no trace of spiral arms. Hubble regarded these as galaxies of a type intermediate between spirals and ellipticals, sometimes referred to as "lenticular" galaxies, and he classified them as S0.

Tuning Fork Diagram



Tuning Fork Diagram



Irregular Galaxies

As many as 25% of all galaxies fall into the class of Irregular galaxies. They show no trace of circular symmetry but have an irregular or chaotic appearance.

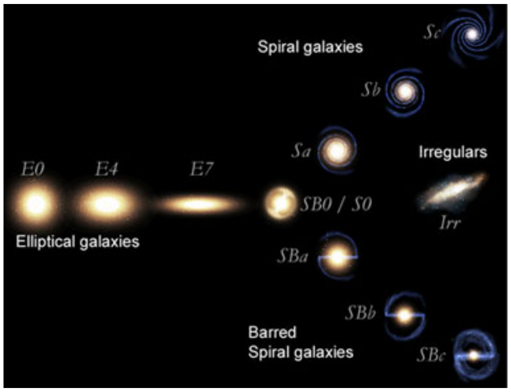
Many appear to be undergoing relatively intense star formation activity, with bright, young star clusters and clouds of ionized gas. These luminous regions dominate the appearance of the galaxies.

In contrast, 21-cm observations of hydrogen reveal an underlying symmetry, based on a rotating disk of gas similar to that in spiral galaxies. Irregular galaxies have stars of both Population I and II.

Large Magellanic Cloud

Small Magellanic Cloud

Tuning Fork Diagram



Hubble Telescope Images of Galaxies

Table of Properties

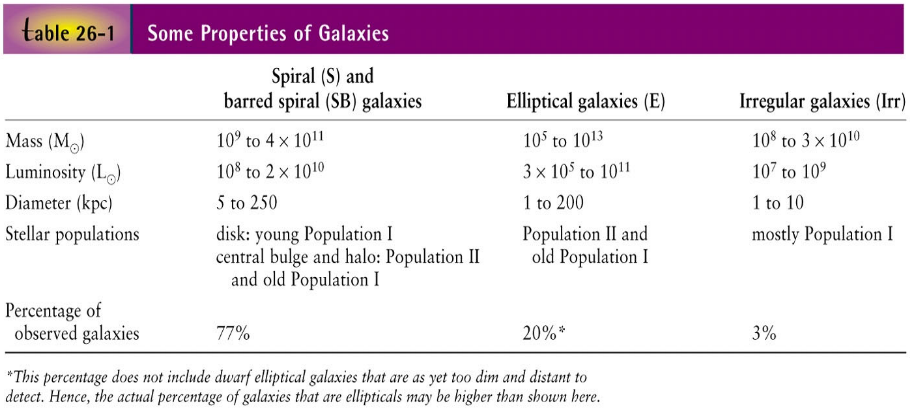


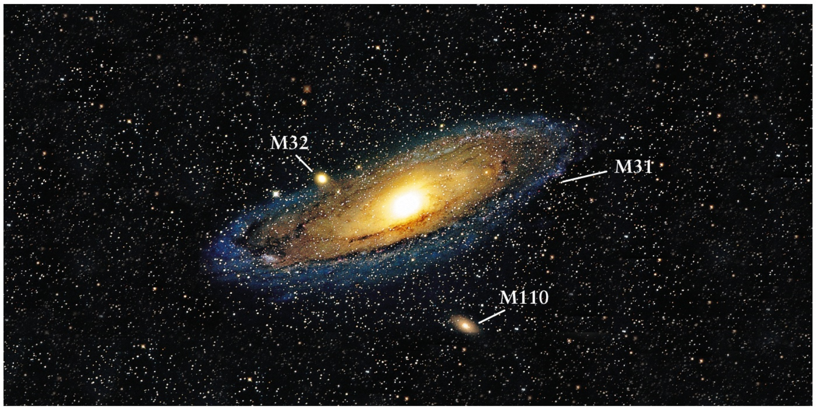
table 26-1 Some Properties of Galaxies

	Spiral (S) and barred spiral (SB) galaxies	Elliptical galaxies (E)	Irregular galaxies (Irr)
Mass ($M_\odot$)	10^9 to 4×10^{11}	10^5 to 10^{13}	10^8 to 3×10^{10}
Luminosity ($L_\odot$)	10^8 to 2×10^{10}	3×10^5 to 10^{11}	10^7 to 10^9
Diameter (kpc)	5 to 250	1 to 200	1 to 10
Stellar populations	disk: young Population I central bulge and halo: Population II and old Population I	Population II and old Population I	mostly Population I
Percentage of observed galaxies	77%	20%*	3%

This percentage does not include dwarf elliptical galaxies that are as yet too dim and distant to detect. Hence, the actual percentage of galaxies that are ellipticals may be higher than shown here.

Universe by Freedman, Geller, and Kaufmann

Distances to Galaxies



Distances to Galaxies

Galaxies are too far to show parallaxes or proper motions. A multi-step process is needed.

(1) First, we derive distances to individual nearby stars in our Galaxy by measuring parallaxes and proper motions.

$$d = 1 / p''$$

(2) With knowledge of the absolute magnitudes, we then can determine distances to those clusters that contain stars similar to those with known absolute magnitudes.

$$m - M = 5 \log(d/10)$$

Distances to Galaxies

(3) Once we measure the distance to a cluster, we derive the absolute magnitude of every star within the cluster. Fortunately, clusters contain some stars, including Cepheid variables, that are much more luminous than any of the nearby stars. These stars are so luminous that ones just like them can be detected in other galaxies.

This calibrates the HR Diagram.

(4) By measuring the apparent magnitudes of stars in nearby galaxies and combining this data with their known/assumed absolute magnitudes, the distance to the galaxy is derived.

Standard Candles

The challenge is to find **standard candles** that are luminous enough to be seen across tremendous distances to even further galaxies. Standard candles should have the following properties:

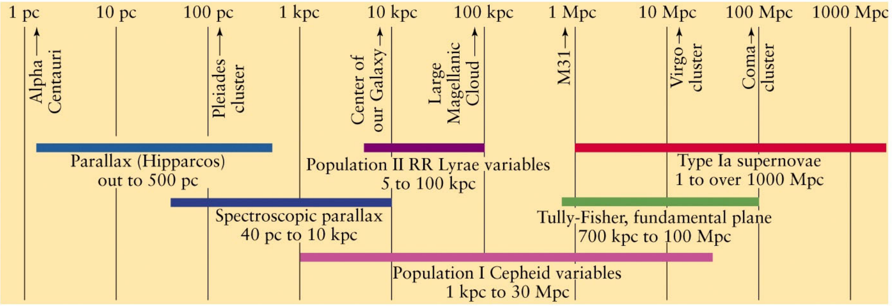
1. They should be luminous, so we can see them out to great distances.
2. We should be fairly certain about their luminosities.
3. They should be easily identifiable.
4. They should be relatively common.

Examples of Standard Candles

Individual stars can be detected only in relatively nearby galaxies. At larger distances, we must use objects that are even brighter than “normal” stars.

1. Cepheids
2. Brightest Stars (Supergiants)
3. Planetary Nebulae
4. Novae
5. Globular Clusters
6. Type Ia Supernovae
7. 21-cm Line Width (Tully-Fisher relation)
8. Total Light of Galaxies

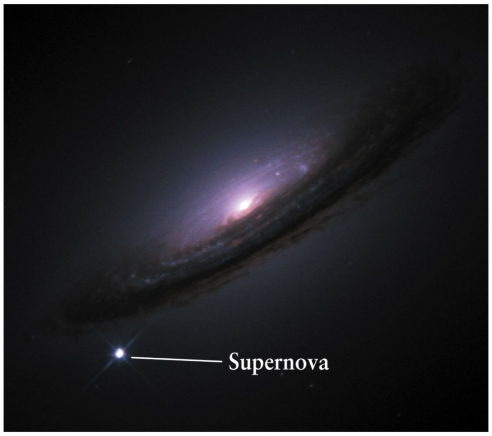
Distances of Standard Candles



Universe by Freedman, Geller, and Kaufmann

$$\mathbf{m - M = 5 \log (d / 10)}$$

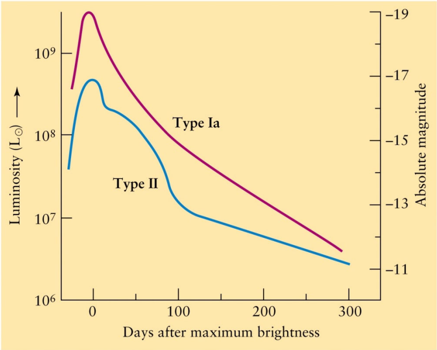
Supernova in a Galaxy



Supernovae Light Curves

Observational studies indicate there are two kinds of supernovae.

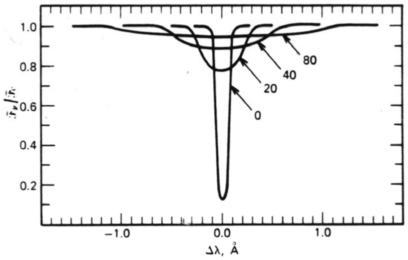
Type Ia are thought to occur in binary systems that contain a white dwarf and a nearby companion. Mass transfer causes the mass of the white dwarf to exceed 1.4 solar masses. The star collapses, heats up, nuclear reactions begin, and the energy released disrupts the star.



Universe by Freedman, Geller, and Kaufmann

Tully-Fisher Relation

One method for determining distances does not make use of standard candles. In the 1970's, Brent Tully and Richard Fisher found that the width of the hydrogen 21-cm line of a spiral galaxy is related to the galaxy's luminosity.

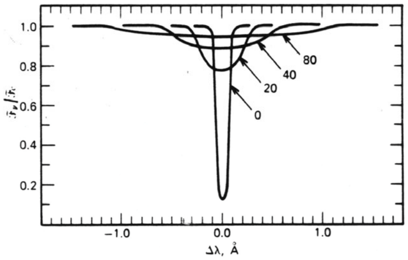


Tully-Fisher Relation

(a) The broader the line, the faster it is rotating.

(b) It is rotating faster because it is more massive.

(c) Because it is more massive, it must be more luminous.



Tully-Fisher Relation

The relationship exists because light from the approaching side of a rotating galaxy is blueshifted while that from the galaxy's receding side is redshifted.

How the T-F Relation Works

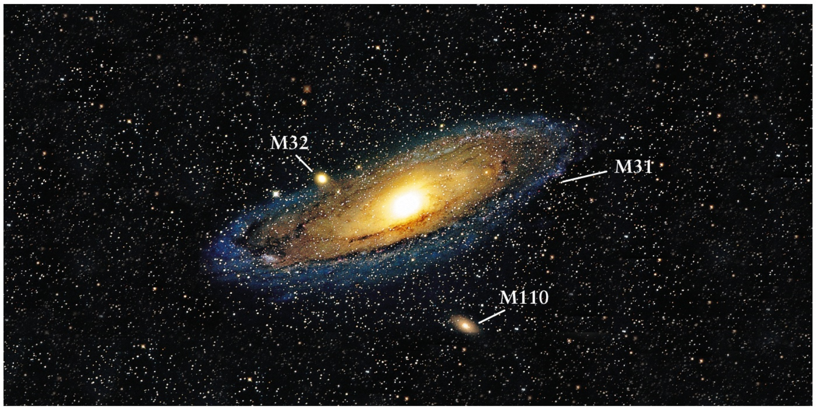
1. The 21-cm line is Doppler broadened by an amount directly related to how fast a galaxy is rotating.

2. Rotation speed is related to the galaxy's mass.

3. The more massive a galaxy, the more stars it contains and thus the brighter it is.

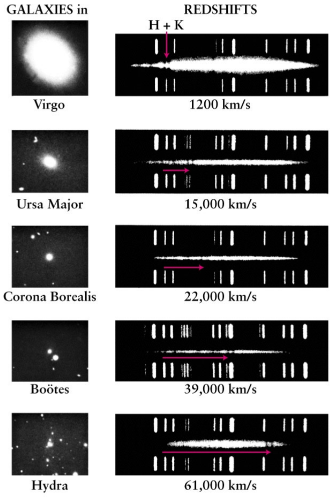
4. Therefore the width of the 21-cm line is directly related to its luminosity.

Spectra of Galaxies



An Expanding Universe

The universe is **expanding**. For over 20 years, beginning in 1914, Vesto Slipher obtained spectra of more than 40 galaxies. Only a few, now known to be very near-by and recognized as members of our Local Group, are approaching us. Slipher found the majority to be receding at speeds as large as 1800 km/s.



Carnegie Observatories

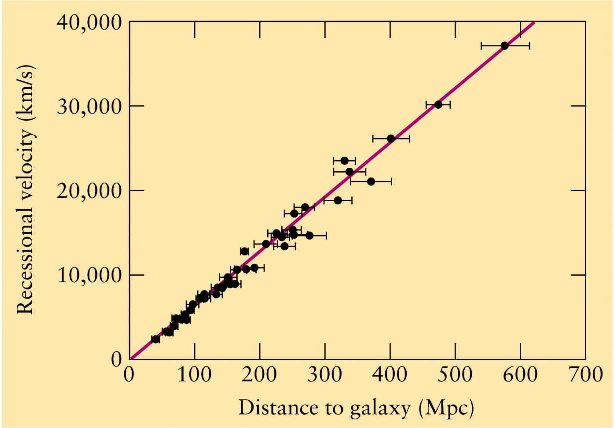
The Hubble Law

Edwin Hubble and Milton Humason determined distances to those galaxies previously observed by Slipher. In 1931 they compared distances and velocities of remote galaxies moving away from us at speeds as high as 20,000 km/s. Their law of redshifts, now known as the **Hubble Law**, established that the velocities of recession of galaxies are proportional to their distances from us. Written as an equation, the Hubble Law is

$$\mathbf{v = H_o\, d,}$$

where v is the recession speed (km/s), d is the distance (Mpc), and H_o is a number called the **Hubble constant** (km/s/Mpc).

Hubble Law Diagram



Universe by Freedman, Geller, and Kaufmann

The Hubble Constant H_o is the slope of the line.

The Hubble Law

The distances to clusters of galaxies are fairly well known and the Hubble Law seems to hold for them, too. Estimates of the value of the Hubble constant **have been in the range of 50 to 100 km/s per million parsecs**. The most recent work appears to be converging on a value near

72 km/s /Mpc.

Velocity-Distance Relation

The fact that galaxies obey the Hubble Law shows that the Universe is expanding uniformly. A uniformly expanding Universe requires that we and all other observers within it, *no matter where they are located*, observe a proportionality between the velocities and distances of remote galaxies.

The velocities of recession or redshifts are given by:

$$\mathbf{z} = (\lambda - \lambda_o) / \lambda_o = \Delta\lambda / \lambda_o \qquad = (v / c)$$

In other words, **z** is the ratio of the amount by which the wavelength of a line is shifted ($\Delta\lambda$) to the laboratory or rest wavelength (λ_o) of that line.

Redshift Distance

$z = v / c = (\lambda_{obs} - \lambda_o)/ \lambda_o$ and $v = H_o d$

$\mathbf{d = z c / H_o}$

Example: Hα line $\lambda_{obs} = 690.5$ nm; $\lambda_o = 656.3$ nm

$z = (690.5 - 656.3) / 656.3 = 0.052$

$d = (0.052) (3 \times 10^5 \text{ km/s}) / (75 \text{ km/s /Mpc})$

$= 208$ Mpc $= 680$ million light years

Example Problem

3a. A galaxy's spectral line has been redshifted to 700 nm. Given that the rest wavelength is 500 nm, calculate z.

a. 0.1
b. 0.2
c. 0.3
d. 0.4

3b. Using $H_o = 100$ km/s/Mpc, calculate the distance to the galaxy.

a. 1000 Mpc
b. 1200 Mpc
c. 1500 Mpc
d. 2000 Mpc

$d = ((700 - 500) / 500) (3 \times 10^5 \text{ km/s/Mpc}) / 100 \text{ km/s/Mpc} = 1200$ Mpc

Re-Cap of Characteristics

1. Shapes are Classified as
   Spiral (S), Barred Spiral (SB), Elliptical (E),
   Lenticulars (S0), and Irregular (Irr).
2. Shapes are related by the Hubble Tuning Fork Diagram.
3. Distances are determined by using
   Standard Candles and
   The Hubble Law

$$\mathbf{d = z\,c\ /\ H_o}$$