Guiding Questions

• How did astronomers first discover other galaxies?
• How did astronomers first determine the distances to galaxies?
• Do all galaxies have spiral arms, like the Milky Way?
• How do modern astronomers tell how far away galaxies are?
• How do the spectra of galaxies tell astronomers that the universe is expanding?
• Are galaxies isolated in space, or are they found near other galaxies?
• What happens when galaxies collide with each other?
• Is dark matter found in galaxies beyond the Milky Way?
• How do astronomers think galaxies formed?
When galaxies were first discovered, it was not clear that they lie far beyond the Milky Way.

Rosse’s “Leviathan of Parsonstown”
M51 as viewed through the “Leviathan”
This is NOT a true color image
At the beginning of the 20th century, what we now call spiral galaxies were referred to as “spiral nebulae” and most astronomers believed them to be clouds of gas and stars associated with our own Milky Way. The breakthrough came in 1924 when Edwin Hubble was able to measure the distance to the “Great Nebula in Andromeda” (M 31) and found its distance to be much larger than the diameter of the Milky Way. This meant that M 31, and by extension other spiral nebulae, were galaxies in their own right, comparable to or even larger than the Milky Way.

Edwin P. Hubble (1889-1953)
M31 - The Great Spiral Galaxy in Andromeda

This nearby galaxy in the Local Group of galaxies, of which the Milky Way is a member, is 2.9 million light years away.
The Nuclear Bulge of M31

Note that you find young stars along the spiral arms. M32 and NGC 205, both dwarf elliptical galaxies, are in the bottom center and upper right.

(NOAO/AURA Photos)
The Outer Disk of M31

(NOAO/AURA Photos)
Hubble demonstrated that the spiral nebulae are far beyond the Milky Way

- Edwin Hubble used Cepheid variables to show that spiral nebulae were actually immense star systems far beyond our Milky Way Galaxy
Spiral galaxies are so-named because of the graceful shapes of arms emanating from a bright central nucleus. Spirals are classified according to how tightly or loosely wound the arms are, and it turns out that the brightness of the central nucleus is correlated to the tightness of the arm. The galaxies M 104 (below) and M 51 (right) respectively show tightly and loosely wound. Notice the effects of dust in both galaxies.

(NOAO/AURA Photos)
Barred Spiral Galaxies

The spiral galaxies M 91 (left) and M 109 (right) have bars across their nuclei from which spiral arms unwind. In virtually all spirals (barred or not) the galaxies rotate such that the spiral arms trail behind in the rotation. The Milky Way is known to be a barred spiral galaxy. (NOAO/AURA Photos)
Elliptical galaxies lack spiral arms and dust and contain stars that are generally identified as being old. The elliptical galaxies M 32 (below) and M 110 (right) show varying degrees of ellipticity. (NOAO/AURA Photos)
Irregular galaxies lack any specific form and contain stars, gas and dust generally associated with youth. The irregular galaxy at top right is the Large Magellanic Cloud, a satellite of the Milky Way located about 170,000 light years from the Sun. It is about 60,000 light years across. The bright reddish feature in the upper right is a region of star formation. The galaxy at the bottom is an irregular galaxy in Sagittarius.

(NOAO/AURA Photo)
Galaxies were classified according to their appearance by Hubble and placed in a diagram.
Galaxies can be grouped into four major categories: spirals, barred spirals, ellipticals, and irregulars. Lenticular (SB0) galaxies are intermediate between spiral and elliptical galaxies. From this table, consider which galaxies are the most and least massive, most and least luminous, and largest and smallest in size.
The disks of spiral and barred spiral galaxies are sites of active star formation.
Elliptical galaxies are nearly devoid of interstellar gas and dust, and so star formation is severely inhibited.

(a) E0 (M105)  
(b) E3 (NGC 4365)  
(c) E6 (NGC 3377)
Irregular galaxies have ill-defined, asymmetrical shapes. They are often found associated with other galaxies.
Astronomers use various techniques to determine the distances to remote galaxies.

Standard candles, such as Cepheid variables and the most luminous supergiants, globular clusters, H II regions, and supernovae in a galaxy, are used in estimating intergalactic distances.
The Tully-Fisher relation, which correlates the width of the 21-cm line of hydrogen in a spiral galaxy with its luminosity, can also be used for determining distance.

A method that can be used for elliptical galaxies is the fundamental plane, which relates the galaxy’s size to its surface brightness distribution and to the motions of its stars.
Masers

1. As a distant galaxy rotates, the maser shown by the red dots recedes from us.

2. Microwaves from the receding maser are Doppler shifted to longer wavelengths. The amount of Doppler shift tells us the speed of this maser’s motion.

3. As the galaxy rotates, the maser shown by the blue dots approaches us.

4. Microwaves from the approaching maser are Doppler shifted to shorter wavelengths: The amount of Doppler shift tells us the speed of this maser’s motion.

5. As the galaxy rotates, the maser shown by the green dots appears to move through this angle.

6. By relating the true speed of the masers shown in red and blue to the apparent speed of the maser shown in green, we can calculate the distance to this galaxy using the small-angle formula.

• One distance-measuring technique that has broken free of the distance ladder uses observations of molecular clouds called **masers**

• “Maser” is an acronym for “microwave amplification by stimulated emission of radiation”
The Hubble law relates the redshifts of remote galaxies to their distances from the Earth.

There is a simple linear relationship between the distance from the Earth to a remote galaxy and the redshift of that galaxy (which is a measure of the speed with which it is receding from us).

The more distant the galaxy... ...the greater its redshift and the more rapidly it is receding from us.
The Hubble law is \( v = H_0 d \)

The value of the Hubble constant, \( H_0 \), is not known with certainty but is close to 71 km/s/Mpc.
Galaxies are grouped into clusters and superclusters.

The 2dF galaxy survey

Galaxies are grouped into clusters rather than being scattered randomly throughout the universe.
Fields of view in the 2dF survey
Clusters of Galaxies

Rather than occurring individually in space, galaxies are grouped in clusters ranging in size from a few dozens to thousands of galaxies. The Coma Cluster, shown at right, is 300 million light years from the Milky Way and contains more than 1,000 (and possibly as many as 10,000) galaxies. The Milky Way is a member of a small cluster called the Local Group which contains about 40 galaxies. The two largest members of the Local Group are M 31 and the Milky Way.
A rich cluster contains hundreds or even thousands of galaxies.

A poor cluster, often called a group, may contain only a few dozen galaxies.

A regular cluster has a nearly spherical shape with a central concentration of galaxies.

In an irregular cluster, galaxies are distributed asymmetrically.
Our Galaxy is a member of a poor, irregular cluster called the Local Group.
• Rich, regular clusters contain mostly elliptical and lenticular galaxies
• Irregular clusters contain spiral, barred spiral, and irregular galaxies along with ellipticals
• Giant elliptical galaxies are often found near the centers of rich clusters
Stream of material left by the Canis Major Dwarf (shown in red)

Sun

Canis Major Dwarf

Milky Way Galaxy (shown in blue)
(a) An X-ray image of Abell 2029 shows emission from hot gas.

(b) A visible-light image of Abell 2029 shows the cluster’s galaxies.
Colliding galaxies produce starbursts, spiral arms, and other spectacular phenomena.

When two galaxies collide, their stars pass each other, but their interstellar media collide violently, either stripping the gas and dust from the galaxies or triggering prolific star formation.
M82

Large star clusters

Dust blown around by powerful stellar winds
The gravitational effects during a galactic collision can throw stars out of their galaxies into intergalactic space.
Interaction between the galaxies has produced new, blue stars

Galaxies with material flowing between them

“Tail” of stars and gas pulled out of the interacting galaxies
The Doppler Effect permits us to measure the speed of material orbiting around the center of a galaxy. Photographs of galaxies show that luminous material appears to be concentrated towards the center and drops off with increasing distance. If matter were really concentrated in this fashion, we would see “rotation curves” following the “expected” path in the diagram at right. What is invariably observed instead is that rotation curves tend to remain high as far out as they can be measured. This implies the existence of massive halos of dark matter in galaxies. The nature of the material comprising this dark matter is not precisely known, making this one of the greatest problems of contemporary astronomy.
Most of the matter is dark matter.

- The luminous mass of a cluster of galaxies is not large enough to account for the observed motions of the galaxies; a large amount of unobserved mass must also be present.
- This situation is called the dark-matter problem.
• Hot intergalactic gases in rich clusters account for a small part of the unobserved mass
• These gases are detected by their X-ray emission
• The remaining unobserved mass is probably in the form of dark-matter halos that surround the galaxies in these clusters
Gravitational lensing of remote galaxies by a foreground cluster enables astronomers to glean information about the distribution of dark matter in the foreground cluster.
Two images of the same distant object are caused by lensing from this elliptical galaxy.

This bluish arc is a distorted image of a distant galaxy produced by lensing from this red galaxy.

A blurred image of a distant galaxy is lensed by four red galaxies.
All of these blue arcs are images of the same distant galaxy.
Galaxies formed from the merger of smaller objects

• Observations indicate that galaxies arose from mergers of several smaller gas clouds
• A large galaxy in a rich cluster may tend to grow steadily through galactic cannibalism, perhaps producing in the process a giant elliptical galaxy
Closeup images of the numbered objects in (a)
Whether a protogalaxy evolves into a spiral galaxy or an elliptical galaxy depends on its initial rate of star formation.

In an elliptical galaxy, there is a brief, intense burst of star formation, when the galaxy is young.

In an spiral galaxy, star formation continues at a more leisurely pace that extends over billions of years.

The stellar birthrate in galaxies
1. Stars form gradually within a protogalaxy.

2. Gas not involved in star formation collapses to form a disk.

3. A spiral galaxy results.

Formation of a spiral galaxy
Formation of an elliptical galaxy

1. Stars form rapidly within a protogalaxy.
2. Gas is quickly consumed to make stars.
3. A elliptical galaxy results.
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