Chapter 6
Galaxies

Introduction

Left to right: Antlia dwarf galaxy, (top) Hercules galaxy cluster, (bottom) Large Magellanic Cloud, M83 (spiral galaxy in Hydra), Hanny's Verwoop

Before 1920, astronomers conceived of the Universe as being filled with stars. In 1917, Shapley showed that the stars of the Milky Way peter out beyond about 100.000 light-years, beyond which seemed to lie nothing but emptiness. Then Hubble discovered (1) that the region beyond is filled with millions of "island universes" or galaxies like our own Milky Way, and (2), that the Universe of galaxies is expanding. We live in a Universe filled with galaxies. Why that is so is one of the biggest questions in astronomy today.

3 KINDS OF GALAXIES: ELLIPTICAL, SPIRAL, AND IRREGULAR

Hubble spent the rest of his career studying the galaxies. The first thing a scientist does when encountering a new phenomenon is to classify the different forms he sees. Hubble classified the galaxies into two major types, **elliptical** and **spiral,** with a third type, **irregular** galaxies, serving as a catch-all to include all the galaxies that didn't fall neatly into one of the other of the two main types.

Elliptical galaxies

Elliptical galaxies are round galaxies. They are round in three dimensions, like a melon. Some are spherical, like a cantaloupe, while others are elongated like a watermelon. He used the symbol "E0" to describe a cantaloupe-shaped galaxy, and "E5" to describe a watermelon-shaped galaxy. E7 looks like a cigar! Types E1, E2, E3, and E4 specify intermediate shapes. An **ellipse,** by the way, is a flattened circle. Planet orbits are ellipses. Stars that orbit about one another also move in ellipses. The frequent occurrance of ellipses in astronomy accounts for the use of the terem “elliptical” to describe this class of galaxies.

Elliptical galaxies showed no evidence of structure. They contain stars and little else. They vary considerably in size: the largest have *trillions* of stars; the smallest only a few *million* stars. The small galaxies are called **dwarf elliptical** or **dwarf spheroidal** galaxies. These small galaxies are by far the most abundant in the universe, but because they are small and faint, you don’t see them much in photographs of galaxy clusters. At the other extreme, **giant elliptical** galaxies, containing trillions of stars, are the largest galaxies of all, but are rare.

Elliptical galaxies have little gas or dust out of which new stars can be made; consequently, the stars that they contain are all old. Hot, bluish stars, as we shall see later, don’t live long, so they aren’t found in elliptical galaxies. The old stars that are found in them tend to be yellowish in color, so the galaxies as a whole are yellowish in color.

Examples of elliptical galaxies. Left to right: IC1101, (top) M49, (bottom) M110, M32 (satellite of the Andromeda Galaxy), M87 in Virgo

Spiral galaxies

Spiral galaxies are disk galaxies: they are flat as a pancake. The disk contains the **spiral arms** that give these galaxies their awe-inspiring beauty. In the center of the galaxies is a thicker, roundish region rather like a small elliptical galaxy. This is the **central bulge.**

Spiral galaxies vary in the shape of their spiral arms and the size of their central bulges. Hubble gave the label “Sa” to galaxies with large bulges and tightly-wound spiral arms. “Sc” galaxies have small central bulges and open, well-defined spiral arms. Type Sb is intermediate.

Like elliptical galaxies, spiral galaxies come in different sizes, containing from billions of stars to trillions of stars. Unlike elliptical galaxies, there are no dwarf spiral galaxies. It seems you need at least a few billion stars to make a spiral galaxy.

Examples of spiral galaxies. Left to right: the Great Andromeda Galaxy (M31), (top) M74 in Pisces, (bottom) M101 in Ursa Major, NGC3370, NGC5866.

The central bulge of a spiral galaxy is like a little elliptical galaxy in that it contains little gas or dust and has little star formation. The spiral arms, on the other hand, are rich in gas and dust, which continually form new star clusters. Some of the new stars that form in the arms are massive, hot, stars that blaze in blue light. As a result, spiral arms are bluish in color. In color photographs, you see pinkish regions strung out along the spiral arms; these are **nebulae,** gas clouds illuminated by hot stars. You will also see many dark **dust lanes** lining the insides of the arms**.** If the galaxy is seen edge-on, the dust forms a dark band going straight through the galaxy. These are the signs of active star formation.

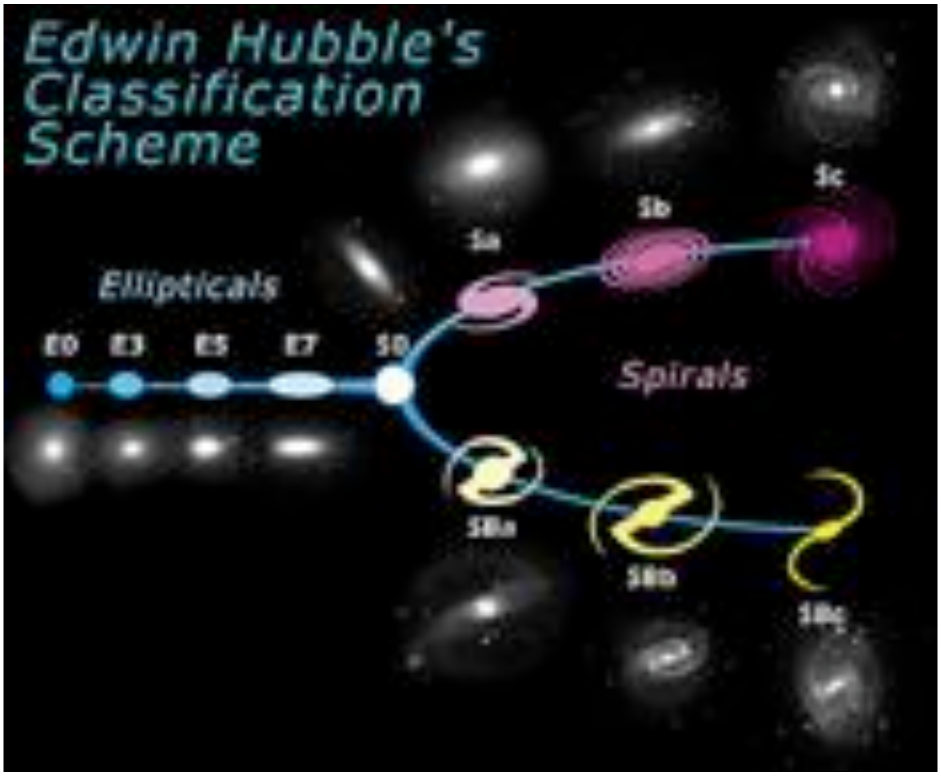
About a third of the spiral galaxies have a straight section going through the central bulge called simply a **bar.** These galaxies are therefore called **barred spiral** galaxies. A surprising discovery of the last twenty years was that our own galaxy is a barred spiral galaxy. Hubble assigned types SBa, SBb, and SBc. The Milky Way galaxy, if we could see it from the outside, might be classified SBb.

Barred spiral galaxy NGC7424

A special kind of galaxy is the **lenticular** galaxy. ("Lenticular" means lens-shaped.) This is a cross between a spiral galaxy and an elliptical galaxy. A lenticular galaxy (type S0) looks like an elliptical galaxy that has somehow acquired a large disk without spiral arms. One of the most familiar galaxies to amateurs, the Sombrero Galaxy (M104) is an excellent example of this kind.

The Sombrero Galaxy (M104) in Virgo

After classifying the galaxies as elliptical, normal spiral, and barred spiral, he arranged his types into a pattern known as the **Hubble sequence,** shown in the famous "tuning fork" diagram**.** Hubble imagined that this was an evolutionary sequcnce; that is to say, galaxies started out as elliptical galaxies and "grew up" to become spiral or barred spiral galaxies. We now know that this idea was mistaken. We now know that spiral galaxies are born that way. The reason some galaxies became elliptical and some become spiral is that spiral galaxies start out with more rotation motion (angular momentum).



The "Tuning Fork" Diagram of Edwin Hubble.

Irregular Galaxies

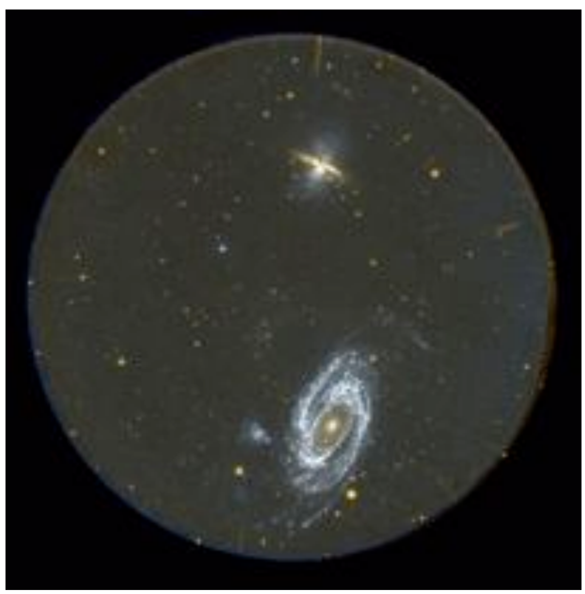
Many galaxies resemble neither spiral galaxies nor elliptical galaxies. Not knowing what else to do, Hubble simply called them **irregular** galaxies. Today we realize they fall into two groups, **dwarf** galaxies and colliding galaxies.

"Dwarf" means small. (In fairy tales, a dwarf is a little person, The most famous is the story of "Snow White and the Seven Dwarves.) English-speaking astronomers got into the habit of using this word to describe small stars; so it was natural to start calling small galaxies dwarf galaxies. (Incidentally, in fairy tales, two of them are "dwarves," but astronomers always say "dwarfs.")

Dwarf irregular galaxies are galaxies that probably started out as dwarf ellipticals but came too close to a giant spiral or elliptical galaxy. The gravity of the giant galaxy distorts the dwarf galaxie and often triggers a wave of star formation. Many dwarf irregular galaxies show large star formation regions. Galaxy clusters are rich in dwarf galaxies, so this kind of interaction is frequent.

NGC6822 in Sagittarius, a dwarf irregular in the Local Group.

Large galaxies can distort each other if they come close enough together. A famous example is the pair M81 and M82 in Ursa Major. The gravity of M82 has bent the spiral arms of M82 out of shape, while the gravity of M81 has caused a burst of star formation on M82. Frequent supernovas have expelled high-speed gasses from M82 that make it resemble an exploding cigar. Such a galaxy is called a **starburst** galaxy.



M81 (bottom) and M82 (top) in Ursa Major, seen in ultraviolet light. (GALLEX.)

Galaxies in clusters are close enough together that they frequently collide with other galaxies during their lifetime. When they do so, the individual galaxies become wildly distorted, with long streamers of stars drawn out of the galaxies, as seen in the famous **Antennae** galaxies. Ultimately, the galaxies will merge to form a giant elliptical galaxy.

The Antennae galaxies

GALAXY CLUSTERS

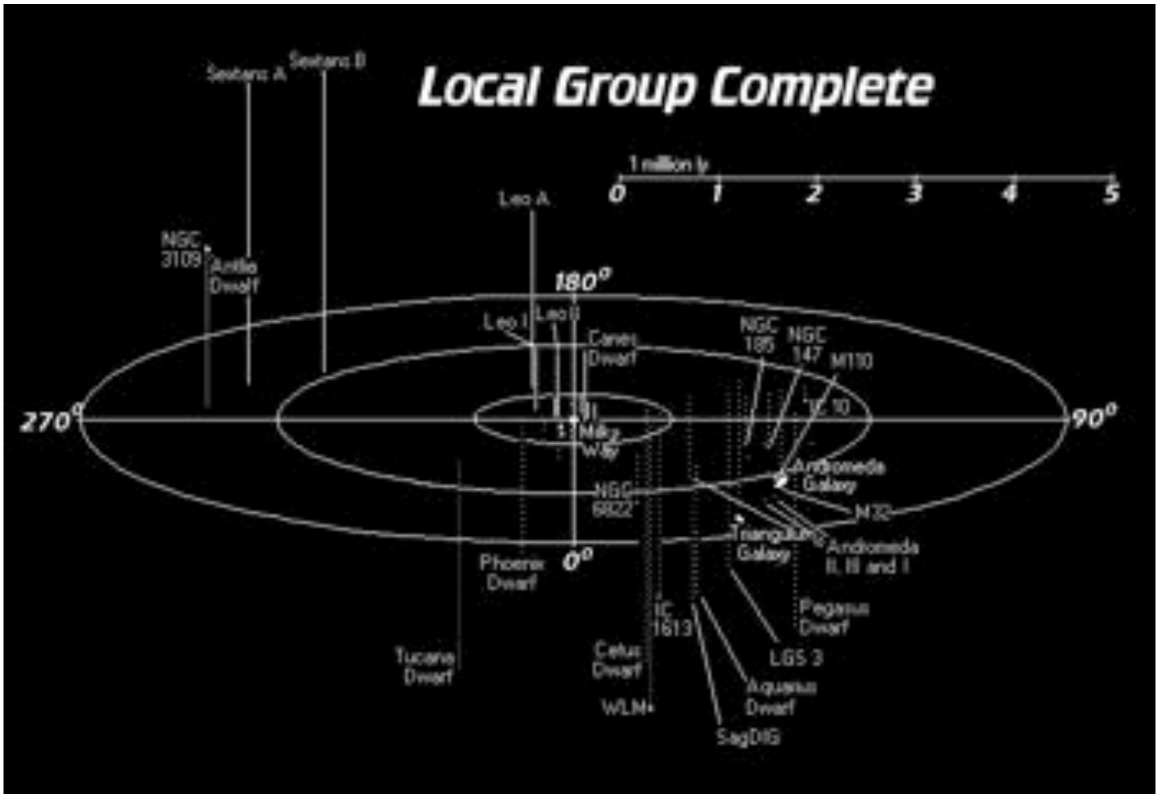
Galaxies seldom occur alone; most are found in galaxy clusters. Some galaxy clusters are small, having only a few members, whilst others are quite large, the largest containing *thousands* of individual galaxies, each having billions of stars. A typical galaxy cluster has a mix of spiral and elliptical galaxies, both outnumbered by the numerous dwarf galaxies. A hot thin gas fills the space between the galaxies. This gas is so hot that it gives off X-rays. Since X-rays don't penetrate the Earth's atmosphere, astronomers weren't aware of this gas until the space age. Now we know that it most clusters there is more matter in the form of gas than there is in the form of galaxies and stars. Even more mass is in the form of the mysterious **dark matter,** about which more later.

The nearest rich cluster is the **Virgo galaxy cluster**, located about 50 million light-years away in the direction of the constellations Virgo and Coma Berenices. It contains about 2500 galaxies. Since the cluster is relatively close, many of its members can be seen in small amateur telescopes. The month of May finds amateurs spending entire evenings hopping from one galaxy to another in the Virgo cluster. About four times father away is a much richer cluster, the **Coma cluster,** containg at least 10.000 galaxies. By chance, it lies in the constellation Coma Berenices, adjacent to Virgo.

Part (a small part!) of the Virgo galaxy cluster. (Canada-France-Hawaii Telescope)

The Local Group

The Milky Way galaxy, the Andromeda galaxy, and about 30 smaller galaxies compose a small cluster called simply the **Local Group.** It's not very impressive as galaxy clusters go, but it's home! The Local Group naturally divides into two sub-groups, one centered on the Andromeda Galaxy and the other centered on the Milky Way. The Andromeda group includes a medium-sized spiral galaxy, **M33** in the constellation Triangulum. There are no large elliptical galaxies in the Local Group, but there are several medium-sized ellipticals, all satellites of the Andromeda Galaxy, M31. These include **M32,** a fine elliptical containing a few billions stars that appears as a fuzzy "star" in photographs of M31.



The Local Group (astronomy.org)

After M33. the next largest galaxy in the Local Group is the **Large Magellanic Cloud (LMC).** It and the **Small Magellanic Cloud (SMC)** are satellites of the Milky Way. The LMC is located about 150,000 light-years from the Sun, while the SMC is about 1 ½ times as far. The LMC has a straight section in the middle; it appears to be a barred spiral galaxy that got too close to the Milky Way, which tore its spiral arms away. Both the LMC and the SMC are close to the South Celestial Pole as seen from Earth. so neither can be seen from most of the U.S. The got their name because they first came to the attention of European astronomers when they were seen by the crew of Magellan's ship as it was sailing around Africa. in 1520.

The Magellanic Clouds

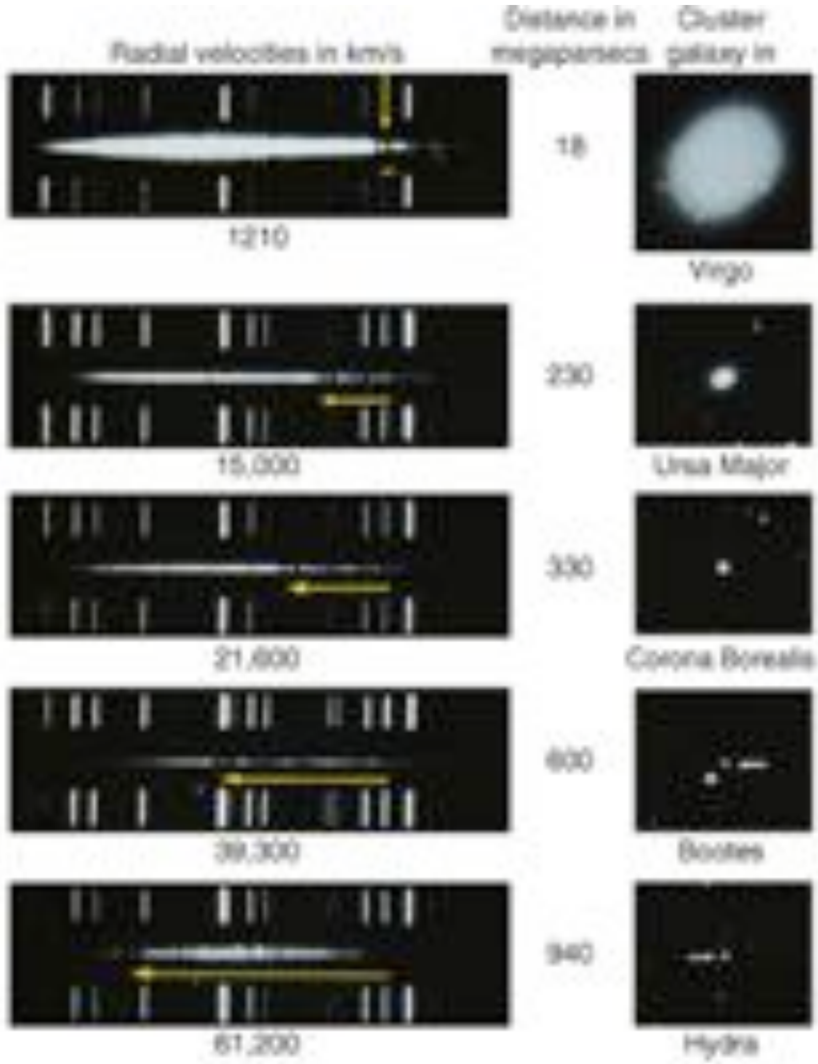
HUBBLE'S LAW

As we saw in Chapter 4, Hubble discovered that the Universe is expanding, causing the other galaxies to move away from ours. Actually, we should speak of whole galaxy clusters, since the expansion of space does not disrupt galaxy clusters or the galaxies themselves, which can hold themselves together by gravity. Galaxy clusters, however, are only weakly attracted to other galaxy clusters, and the continual expansion of space inevitably drags them apart.

Hubble's Law says that *the farther away a galaxy, the faster it is receding from us.* Mathematically,

$$v = H_o(\text{distance})$$

where v is the speed of recession. H_o is Hubble's constant. It is a number that says how fast space is expanding at the present time. (The expansion rate changes with time, so Hubble's constant is not really constant!) H_o is the slope of the straight line in Hubble's diagram of speed vs. distance. It is obtained by measuring the recession speed and the distance of many galaxies.



The spectra of five galaxies, showing Hubble's Law. The middle band of light is the spectrum; the white lines are comparison lines produced in the telescope. Note the two dark lines in the spectrum, the H and K lines of calcium. In the more distant galaxies, these lines are shifted far to the red end of the spectrum.

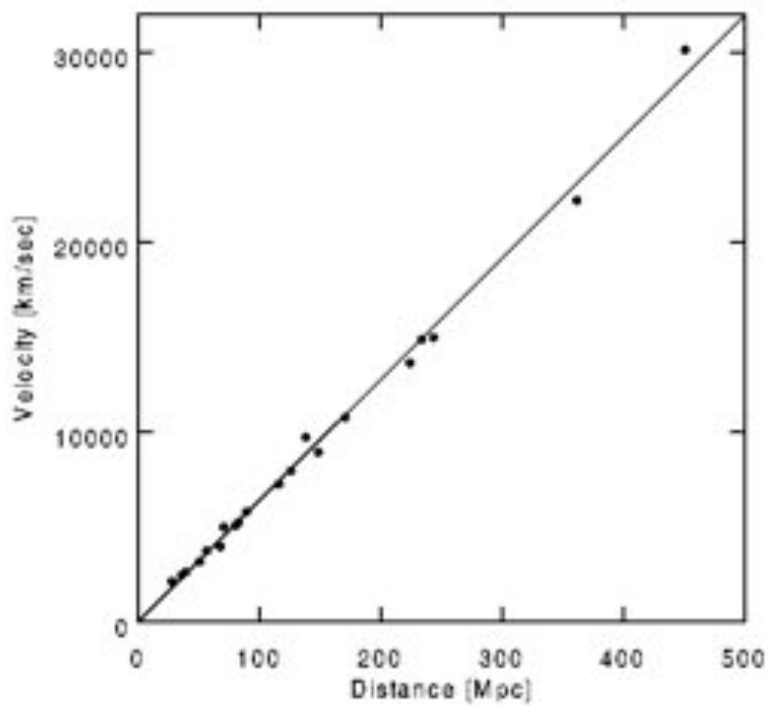
The recession speed v is measured using the Doppler effect. First, the astronomer measures the redshift of the galaxy:

$$z = (\text{change in wavelength})/(\text{original wavelength})$$

Why the letter z is used for this quantity is anyone's guess; perhaps all the other letters were used up. Whatever the reason, z is the letter that astronomers always use to denote the redshift. The redshift, according to the Doppler effect, is the speed of recession of the galaxy measured as a fraction of the speed of light, so that the speed is just:

$$v = zc$$

where c = 300,000 km/s, the speed of light.



Hubble's Law: velocity vs. distance is a straight-line relation: velocity increases with distance. Mpc = megaparsec.

Determining the distance to the galaxy is the difficult part. In general, one must find a standard candle in the galaxy and then apply the inverse square law to calculate the distance. Once this is done for a good sample of galaxies going out to a fair distance, then the slope of Hubble's line can be calculated. This is H_o. Once H_o is known, then the distance to other galaxies—galaxies so distance that standard candles cannot be seen in them—can be calculated by using Hubble's Law backwards:

$$(\text{distance}) = v/H_o$$

Using this method, the distance to millions of remote galaxies has been measured.

SUPERCLUSTERS, WALLS, AND VOIDS

Even a casual glance at a star atlas shows that the galaxies and galaxy clusters are not spread uniformly over the sky. By the 1970s it was realized that galaxy clusters themselves group into larger clusters called **superclusters.** During the 1980s and 90s, as astronomers systematically surveyed space out to greater and greater distances (redshifts), an astonishing pattern was revealed: the galaxy clusters are strung out along lines or walls hundreds of millions of light-years long. In between the strings and walls are vast regions containing few galaxies: these are the **voids.** One of the challenges of theoretical astronomy today is to explain how the Universe went from the smooth hot gas of the Big Bang to the clumpy structure of walls and voids that we see today.

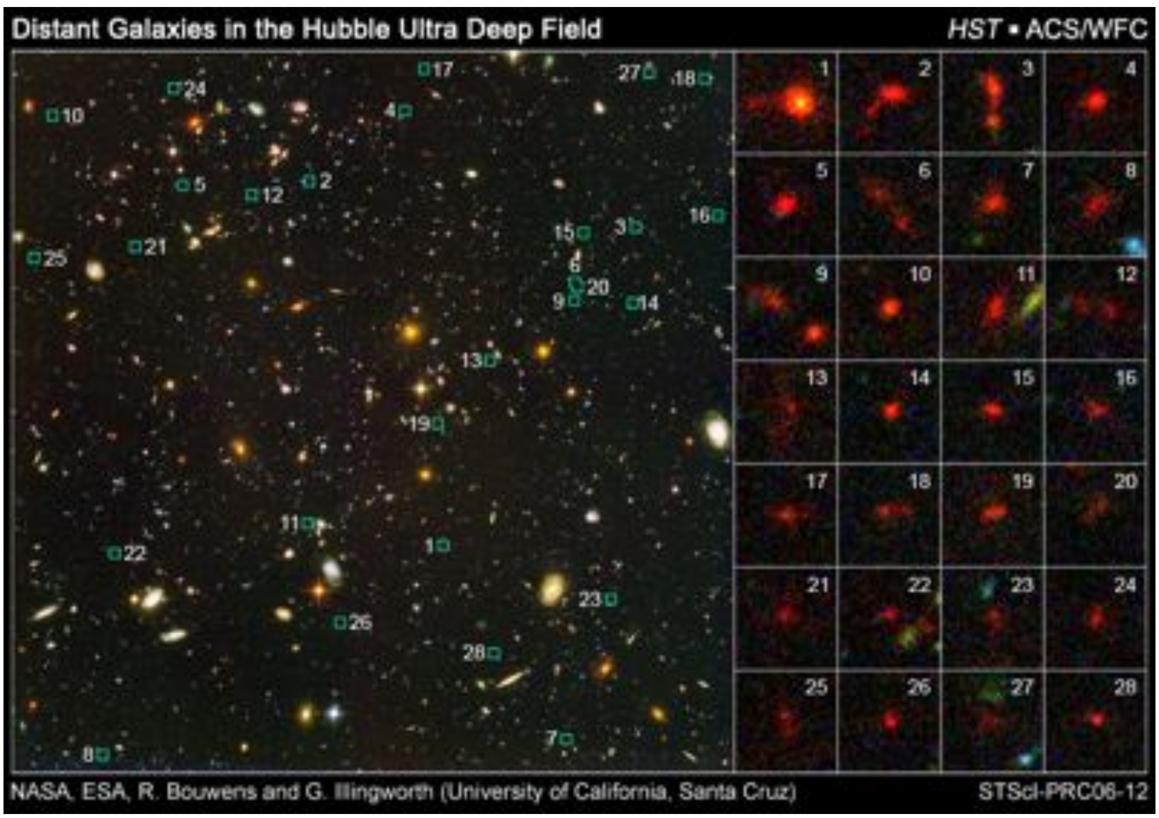
Galaxy formation

Galaxies are the creations of the force of gravity. As we have seen, when the Universe was a half million years old and was just cooling to the point that hydrogen atoms formed, space was a hot, smooth gas. And yet the hydrogen was in a sense a minor constituent of the Universe, for most of the matter then (as now) was the dark matter, whose precise nature we do not know. Evidently, however, gravity was able to start clumps in the dark matter, regions of space with slightly more dark matter than average, while other regions had slightly less dark matter. The hydrogen (and helium) was in turn attracted to the dense clumps of dark matter, so it started to clump as well. It was the case of the rich getting richer and the poor getting poorer: as time went by the dentse clumps became denser and denser, while the thin regions became thinner and thinner.

The next few hundred million years are known as the **Dark Ages,** for the hydrogen gas was now too cool to give off visible light, while there were no stars yet to create light. During this period the Universe was truly dark. But important events were taking shape. The dense clumps grew and became denser and denser until a threshold was crossed and some clumps became dense enough to form stars.

The details of the formation of the first stars and galaxies are a topic of much current research. Astronomers have got good results from massive computer calculations which show the smooth Universe of the Big Bang transforming into the superclusters and voids that we see today. The big thing holding us back today is our ignorance of the dark matter. To this day, the dark matter has not been directly detected, so its properties cannot be measured. Believe it or not, but astronomers infer the properties of the dark matter by adjusting the dark matter in their models so that the Universe comes out looking like what we see today.

One of the reasons for building the Hubble Space Telescope (HST) was to see galaxies when the Universe was young. The HST has succeeded spectacularly in doing so. It has shown us that the earliest galaxies were small and irregular in shape, nothing like the giant galaxies we see today. The light from these galaxies has been shifted far into the red and even the infrared by the expansion of space. To see even farther back in time, it will be necessary to look at rather long infrared wavelengths, beyond the capability of the HST. This is the main reason for building the Webb Space Telescope (WST). The WST (if it ever gets off the ground) will, we hope, enable astronomers to peer back in time to the era when the first stars began to shine. It should help answer the question, how did the galaxies form?



Early galaxies seen by the Hubble Space Telescope. These galaxies are seen as they were during the first billion years or so of the Universe. They appear small and irregular in shape, unlike the great spiral and elliptical galaxies we see today in the Universe. The light from these galaxies has been highly redshifted by the cosmic expansion.