CHAPTER VI

GALAXY AND COSMOLOGY

Outline:

- ⊙ *Types of Galaxy*

- ⊙ *Milky Way*
  - *Basic structure and dimension*

- ⊙ *Big Bang Model*
  - *Cosmic microwave background*
  - *Hubble law*

VI.1 Types of Galaxy

Our study of the Milky Way has been aided greatly by studies of other galaxies. However, for a long time it wasn’t clear that the spiral nebulae we see in the sky are really other galaxies. From their appearance, it might just be assumed that these nebulae are small nearby objects, just as HII (hydrogen which is ionized) regions are part of our galaxy.

The issues were crystallized in 1920 in a debate between *Harlow Shapley* and *Heber D. Curtis*. Curtis argued that spiral nebulae were really other galaxies. His argument was based on some erroneous assumptions. First, he confused novae in our galaxy with supernovae in other galaxies. Shapley thought the spiral nebulae were part of our own galaxy, partly based on an erroneous report of a measurable proper motion for some nebulae. The issue was settled in 1924 by the observational astronomer *Edwin Hubble* (after whom the Space Telescope is named). Hubble studied Cepheids in three spiral nebulae (including the Andromeda Galaxy), and clearly established their distance as being large compared with the size of the Milky Way.

In his studies Hubble realized immediately that not all spiral galaxies have the same appearance. Furthermore, he found galaxies that do not have a spiral structure. Hubble classified the galaxies he studied according to their basic appearance. It was originally thought that the different types of galaxies represented different stages of galactic evolution (similarly, some astronomers thought that different spectral type stars along the main sequence were evolutionary states of the same star). We now know that this is not the case. However, Hubble’s classification scheme, depicted in **Figure 6.1**, is still quite useful.

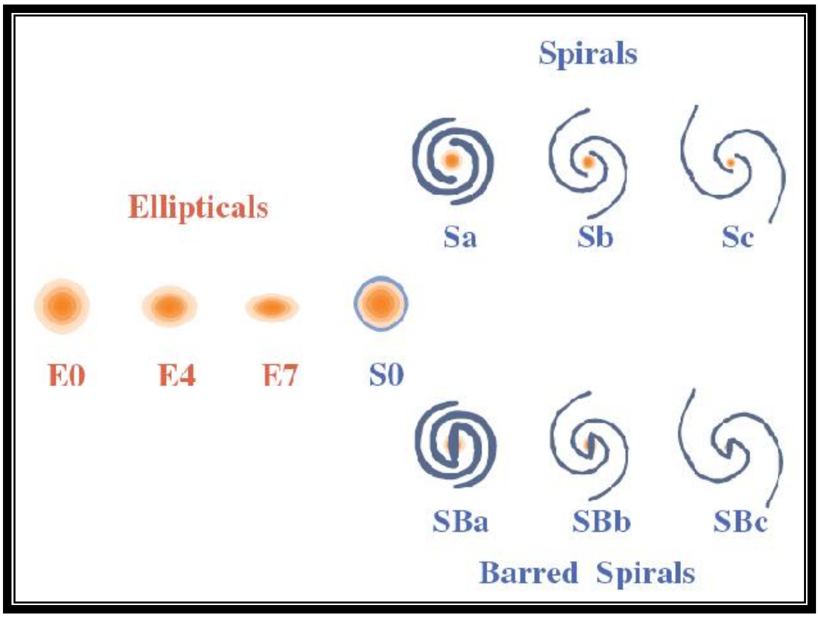

Figure 6.1 Hubble classification of galaxies. Ellipticals range from E0 (round) to E7 (the most oblate).The regular spirals are divided according to the relative size of the nucleus and the disk, and the tightness of the spiral arms.The Sa have the largest nuclei and the most open arms.The barred spirals, SB, follow the same classification as the normal spirals. S0 galaxies have nuclei and small disks but no spiral arms.

Elliptical galaxies have, as their name suggests, simple elliptical appearances. An example of elliptical galaxy is shown in **Figure 6.2**. The ellipticals are classified according to their degree of eccentricity. The ones that look spherical (zero eccentricity) are called E0, and the most eccentric are called E7. The most common type of elliptical galaxies are called *dwarf ellipticals*, since they are also the smallest. Their sizes are typically a few kiloparsecs and their masses are a few million solar masses. More spectacular are the *giant ellipticals*, with extents up to 100 kpc and masses of about 10^{12} M⊙, with some with masses up to a factor of ten higher.

Figure 6.2 Elliptical galaxies. M87, in Virgo, which is a giant elliptical, type E0.The fuzzy patches visible near the edge of the galaxy are globular star clusters.The inset shows a blow-up of the center.

The gas content (as a stellar formation material) of ellipticals is low. Ellipticals generally contain an evolved stellar population, with no O or B stars. However, their metal abundances are not low. Giant ellipticals have metal abundances that are quite high, about twice the solar value.

Spirals make up about two-thirds of all bright galaxies. They are subdivided into classes Sa, Sb and Sc. The two important features of the classification are (1) *the openness or tightness of the winding of the spiral pattern*, and (2) *the relative importance of the central bulge and the disk of the galaxy*. Sa galaxies have the largest bulges and the most tightly wound arms. Sc galaxies have the smallest bulges and the most open arms. We think that the Milky Way is between Sb and Sc. Different types of spirals are shown in **Figure 6.3**.

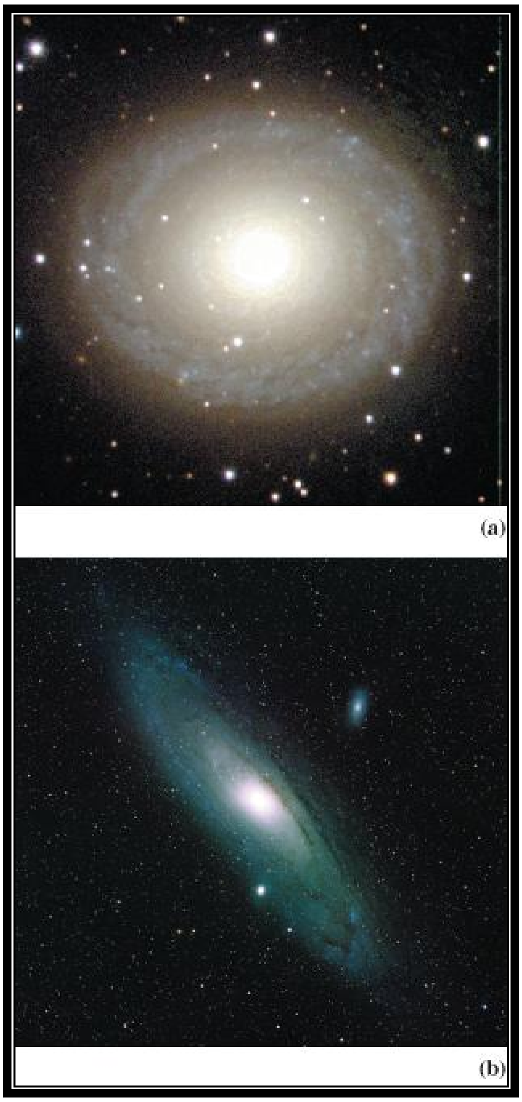

Figure 6.3 Various types of spiral galaxies. (a) NGC 7217, an Sa galaxy. (b) The Andromeda Galaxy (M31), type Sb, one of our nearest neighbors. It is at a distance of about 700 kpc, and is more than 20 kpc across. Notice the two companions, including M32.We think that it is very similar to our own Milky Way.

Some spirals have a bright bar running through their center, out to the point where the arms appear to start. These are called *barred spirals*. An example is shown in **Figure 6.4**. The barred spirals are also subclassified into SBa, SBb and SBc, according to the same criteria as Sa, Sb and Sc. In general, the spiral pattern in barred spirals is quite well defined.

Figure 6.4 NGC 1365, in Fornax, type SBc. [ESO–European Southern Observatory]

An important feature of spirals is the obvious presence of an interstellar medium (gas and dust). Even when a spiral is seen edge-on, we can tell that it is a spiral by the presence of a lane of obscuring dust in the disk of the galaxy. The light from spirals contains an important contribution from a relatively small number of young blue stars, suggesting that star formation is still taking place in spirals.

There is an additional type of galaxy that has certain features in common with spirals, but does not show spiral arms. This type is called *S0* ('Szero') (see **Figure 6.5**). The bulge in an S0 is almost as large as the rest of the disk, giving the galaxy an almost spherical appearance. Some S0 galaxies also contain gas and dust, suggesting that they belong in the spiral classification. However, most S0 galaxies have no detectable gas. The role of S0 galaxies is still not well understood.

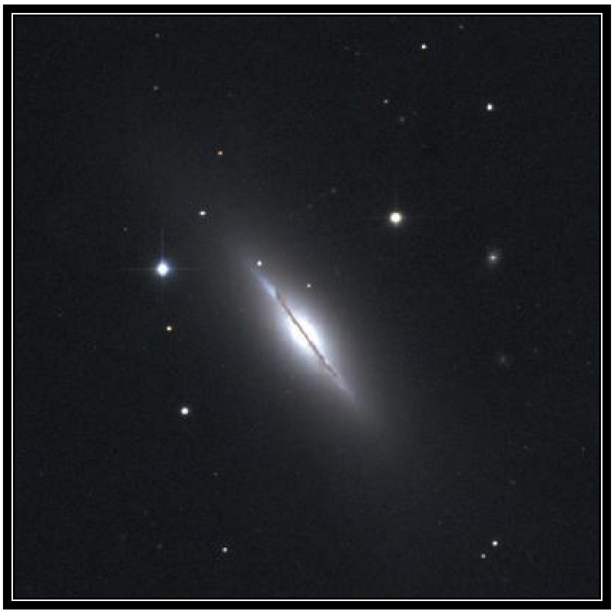

Figure 6.5 M102, type S0. [NOAO/AURA/NSF]

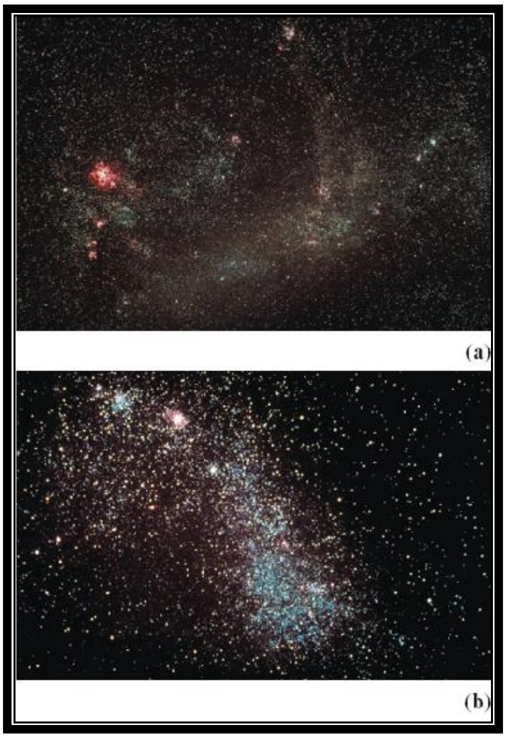

Figure 6.6 The Magellanic Clouds. (a) The Large Magellanic Cloud (LMC) is 50 kpc from us. (b) The Small Magellanic Cloud, which is 65 kpc from us. [NOAO/AURA]

Some galaxies have no regular pattern in their appearance. These are called *irregular galaxies*. The Magellanic Clouds, shown in **Figure 6.6**, are irregular companions to our own galaxy. Irregulars make up a few percent of all galaxies. We distinguish between two types of irregulars: Irr I galaxies are resolved into stars and nebulae; Irr II galaxies just have a general amorphous appearance. *Lenticular galaxies* have an irregular elongated structure. *Ring galaxies* have prominent bright rings around their centers.

VI.2 Milky Way: Basic Structure and Dimension

Milky Way, the large, disk-shaped aggregation of stars, or galaxy, that includes the Sun and its solar system. In addition to the Sun, the Milky Way contains about 400 billion other stars. There are hundreds of billions of other galaxies in the universe, some of which are much larger and contain many more stars than the Milky Way.

Astronomers classify the Milky Way as a large spiral or possibly a barred spiral galaxy, with several spiral arms coiling around a central bulge about 10,000 light-years thick. Spiral galaxies contain both old and young stars as well as numerous clouds of dust and gas from which new stars are born. There are three basic structures on spiral galaxy, those are *bulge*, *disk* and *halo* (see **Figure 6.7**). Stars in the central bulge are close together, while those in the arms are farther apart. The arms also contain clouds of interstellar dust and gas. The disk is about 100,000 light-years in diameter and is surrounded by a larger cloud of hydrogen gas. Surrounding this cloud in turn is a spherical halo that contains many separate globular clusters of stars mainly lying above or below the disk. This halo may be more than twice as wide as the disk itself. In addition, studies of galactic movements suggest that the Milky Way system contains far more matter than is accounted for by the visible disk and attendant clusters – up to 2,000 billion times more mass than the Sun contains. Astronomers have therefore speculated that the known Milky Way system is in turn surrounded by a much larger ring or halo of undetected matter known as *dark matter*.

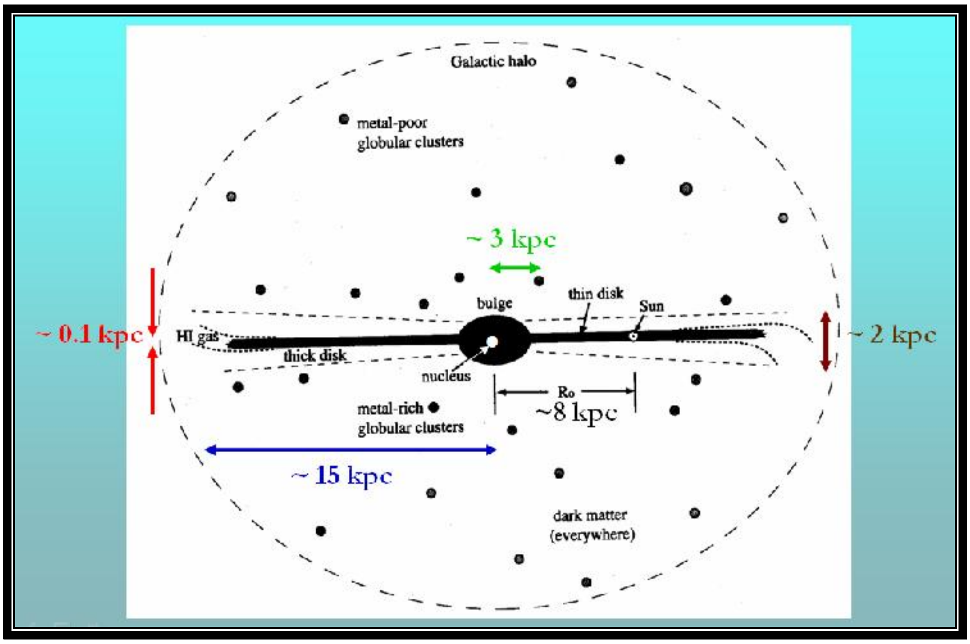

Figure 6.7 Basic structure and dimension of Milky Way. [L.S. Sparke, J.S. Gallagher]

The distribution of mass in galaxies is a crucial quantity, both for cosmology and for theories of the origin and evolution of galaxies. Observationally it is determined from the velocities of the stars and interstellar gas. Total masses of galaxies can also be derived from their motions in clusters of galaxies.

The mass of Milky Way and also other spiral galaxies are obtained from their *rotation curve v(R)*, which gives the variation of their rotational velocity with radius. Assuming that most of the mass is in the almost spherical bulge, the mass within radius *R*, *M(R)*, can be estimated from Kepler's third law:

$$\mathbf{M(R)=\frac{Rv^2(R)}{G}} \quad \text{……….(6.1)}$$

Some typical rotation curves are shown in **Figure 6.8**. In the outer parts of many spirals, *v(R)* does not depend on *R*. This means that *M(R)* is directly proportional to the radius – the further out one goes, the larger the interior mass is.

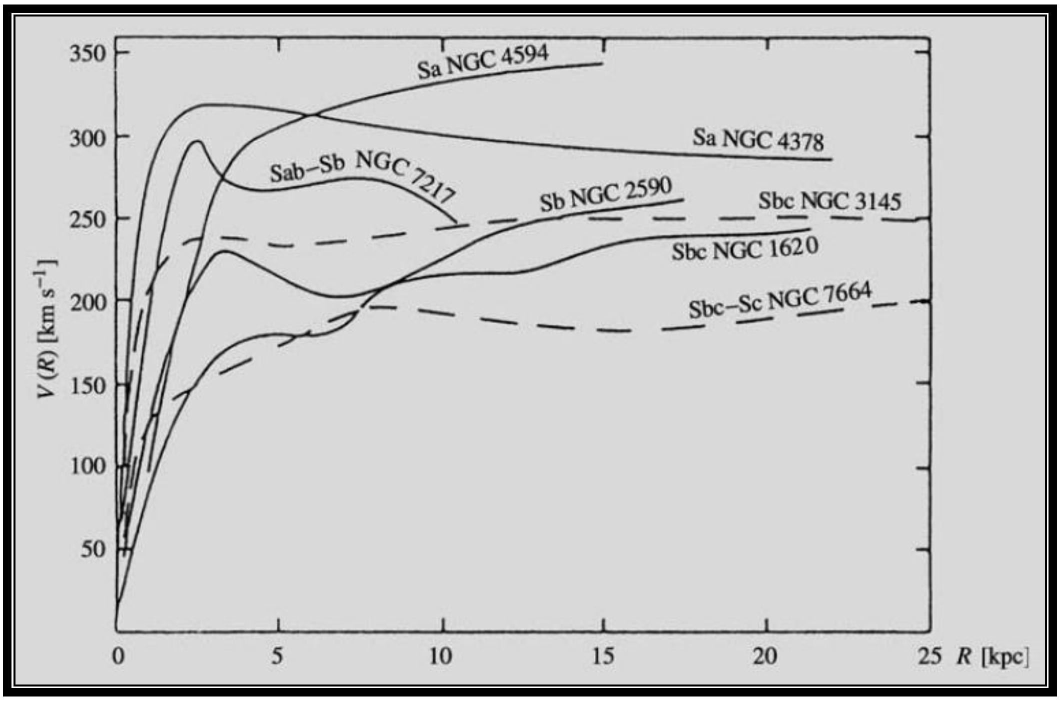

Figure 6.8 Rotation curves for seven spiral galaxies. [Rubin, V.C., Ford, W.K., Thonnard, N. (1978)]

All of the material in the galaxy orbits the galactic center. If the galaxy were a rigid body, all of the gas and dust would orbit with the same period. However, material closer to the galactic center orbits with a shorter period than material farther out. This is not an unusual situation. After all, the planets in the Solar System exhibit the same behavior: Mercury takes less time to orbit the Sun than does the Earth, and so on. When the orbital period depends on the distance from the center, we say that the material is exhibiting *differential rotation*.

The differential galactic rotation produces Doppler shifts in spectral lines that we observe from gas at different distances from the galactic center than the Sun. This is illustrated in **Figure 6.9**. In **Figure 6.9(a)**, we look at five test particles at different distances along the line of sight. In each case the Doppler shift depends on the relative radial velocity (component of velocity in the line of sight) of the test particle and the Sun. That is, we take the line of sight component of the particle's motion and subtract the line of sight component of the Sun's motion.

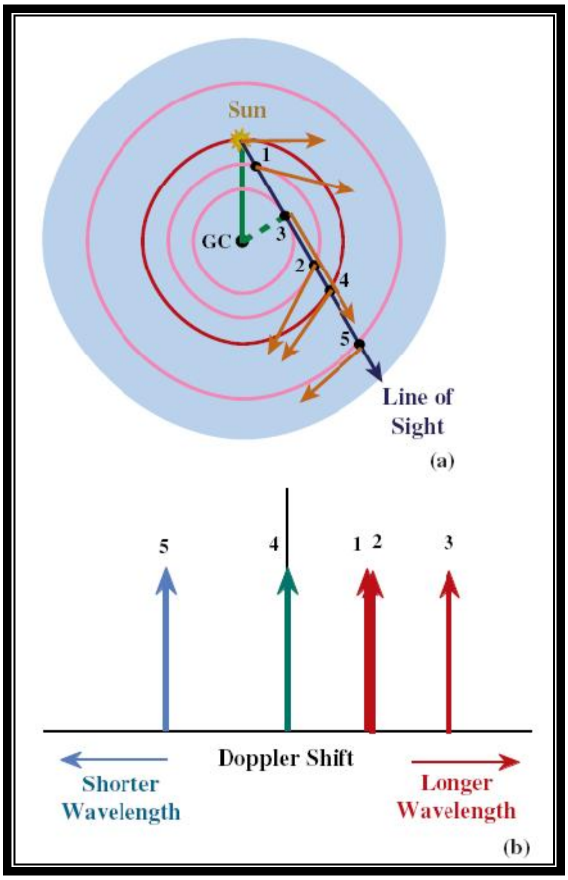

Figure 6.9 Doppler shift produced by galactic differential rotation by material at different locations along a given line of sight. (a) The locations of five test particles in an overhead view.Arrows for each particle indicate the velocity (magnitude and direction). For each particle the Doppler shift will depend on the relative radial velocity of that particle and the Sun. (b) For each particle, the position of the arrow shows the amount of Doppler shift.

In **Figure 6.9(b)** we look at the Doppler shifts for each test particle. Point 1 is slightly closer to the center than the Sun. It is moving slightly faster than we are, so there will be a small Doppler shift. It is moving away from us so that the shift will be to longer wavelength (redshift). Point 2 is where our line of sight crosses the same circle. The speed is the same as at point 1, and the angle with the line of sight is the negative of that at point 1. Since the line of sight component depends on the cosine of that angle, that component is the same. The Doppler shift for point 2 is therefore the same as for point 1. Point 3 is where the line of sight passes closest to the center. Material is moving fastest around that circle. It is also moving directly away from us, so that point has the largest Doppler shift to the red. Point 4 is in the same orbit as the Sun. Our distance from that object is constant, so our relative radial velocity must be zero, meaning that the Doppler shift is zero. Point 5 is farther from the center than the Sun, and is moving slower than us. We are therefore overtaking it, so there is a Doppler shift to shorter wavelength (blueshift).

The quantity R_0, our distance from the galactic center, is determined from studies of the distribution of globular clusters, and more recently from the studies of clusters of masers near the galactic center. For approximately 20 years prior to 1985, the generally accepted value was 10.0 kpc. However, data accumulated by 1985 suggest a smaller value. As of 1985, the International Astronomical Union started recommending the value $R_0 = 8.5$ kpc.

By using an agreed upon value, astronomers can be sure that they are using the same values when they compare their studies of various aspects of galactic structure. Prior to 1985, the adopted value for v_0, the orbital speed about the galactic center, was 250 $\mathrm{kms^{-1}}$. The value recommended in 1985, to go with the new R_0, is $v_0 = 220\ \mathrm{kms^{-1}}$.

Example:

Problem *For the values of the galactic rotation constants, find the time it takes the Sun to orbit the galactic center and the mass interior to the Sun's orbit.*

Answer *The time for the Sun to orbit is simply the circumference, $2\pi R_0$, divided by the speed v_0:*

$$\mathbf{t = \frac{(2\pi)\left(8.5\times10^{3}pc\right)\left(3.1\times10^{13}kmpc^{-1}\right)}{\left(220kms^{-1}\right)}}$$

$$\mathbf{t = 7.5\times10^{15}s = 2.4\times10^{8}years}$$

We find the mass interior to R_0 from equation (6.1):

$$\mathbf{M = \frac{\left(2.2\times10^{5}ms^{-1}\right)^{2}\left(8.5\times10^{3}pc\right)\left(3.1\times10^{16}mpc^{-1}\right)}{\left(6.67\times10^{-11}Nm^{2}kg^{-2}\right)}}$$

$$\mathbf{M = 2.0\times10^{41}kg = 1.0\times10^{11}M\odot}$$

VI.3 Big Bang Model

Georges Édouard Lemaître (1894–1966), Belgian cosmologist, in 1927 proposed that the expansion of the universe was started by an initial explosion, then there must have been an era in the past when it was much denser than it is now. This hot, dense early era was named the *big bang* by Fred Hoyle, a steady-state cosmologist, in an attempt to ridicule the theory. The theory survived the ridicule, the name remained, and we now refer to all cosmological models with an evolving universe as 'big-bang cosmologies'.

VI.3.1 Cosmic microwave background

Following the idea that the universe was very hot and dense, *George Gamow* suggested, in 1946, that when the universe was less than about 200 seconds old, the temperature was greater than one billion kelvin, hot enough for nuclear reactions to take place rapidly. In 1948, *Ralph Alpher, Hans Bethe* and Gamow showed (in a paper often referred to as the alpha/beta/gamma (for the names of the authors) paper) that these nuclear reactions might be able to explain the current abundance of helium in the universe. In a more thorough analysis of the problem, Alpher and *Robert Herman*, in a classic paper published in 1948, found that the early universe should have been filled with radiation, and that the remnant of that radiation should still be detectable as a low intensity background of microwaves.

When the universe was young enough to have its temperature higher than 3,000 K, the atoms were all ionized. The universe was a plasma of nuclei and electrons. The free electrons are particularly efficient at scattering radiation. They provided a continuum opacity for any radiation present. This means that radiation would not travel very far before getting scattered; the universe was opaque. The radiation therefore stayed in equilibrium with the matter. The spectrum of the radiation was that of a blackbody at the temperature of the matter. As the universe expanded, the density decreased, and the temperature decreased. As the matter cooled, the radiation also cooled. Then the point was reached at which the temperature dropped below 3,000 K. At the lower temperature, the electrons and nuclei (mostly protons, or helium) combined to make atoms. This is called the *era* *of recombination*. The neutral atoms are very inefficient at absorbing radiation, except at a few narrow ranges of wavelengths corresponding to spectral lines. For all practical purposes, the universe became transparent to the radiation. Since the radiation and matter no longer interacted significantly, we say that they were *decoupled*. In the early universe, the energy density of radiation was greater than that of matter. We say that the universe was *radiation-dominated* at that time. Now the opposite is true; we live in a *matter-dominated* universe.

At the instant before the electrons and protons recombine, making the universe transparent, matter at all points is emitting photons in all directions. Since the matter becomes transparent, the photons continue running around in all directions on the surface of our expanding sphere. We see a steady stream of photons, not a brief flash as might be expected if we were looking at a localized explosion. The fact that the radiation is moving in all directions means that we see it coming from all directions. The radiation should appear isotropic. Also, cosmic background photons reaching us today are coming from one light day farther away than those that reached us yesterday.

Alpher and Herman (in 1948) gave an equation to calculate the temperature of the background radiation. Since most of the radiation would be expected in the radio part of the spectrum, Alpher and Herman talked to radio astronomers, but the radio astronomers saw many difficulties. First, the signals would be very weak. Also, radio observations are easiest when you can compare the radiation in one direction with that in another direction. Since the background radiation would be the same everywhere, this basic technique could not be used. Also, at the time, there was a general feeling that the steadystate theory is correct, so there was not much motivation to carry out this difficult experiment.

Two physicists at the Bell Telephone Laboratories, *Arno Penzias* and *Robert Wilson* (**Figure 6.10**), accidentally detected this radiation and reported their observations in 1965. Penzias and Wilson were unaware of the work of Alpher and Herman. They were using a very accurate radio telescope for both communications and radio astronomy. To have accurately calibrated results, they had to understand all sources of noise (interference) in their system. They found an unaccounted–for source of noise at a very low level. The noise seemed to be coming either from their system, or from everywhere in the sky. After carefully analyzing their system (including disassembling and reassembling certain parts, and even cleaning out bird droppings), they were confident that the noise was coming from everywhere in the sky. They only had a measurement at one wavelength, so they could not confirm the shape of the spectrum. However, they found that the intensity corresponds to a blackbody at a temperature of about 3 K.

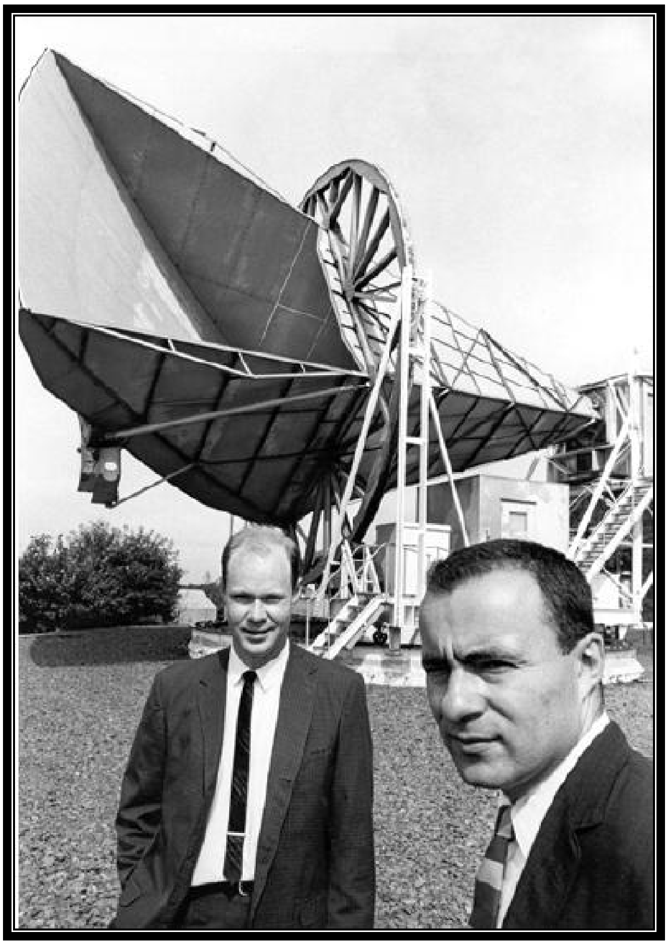

Figure 6.10 Arno A. Penzias and Robert W.Wilson, who discovered the cosmic background radiation in 1967, in front of the telescope they used, at Bell Laboratories in New Jersey. [Reprinted with permission from Lucent Technologies' Bell Labs]

It was clear that Penzias and Wilson had found the cosmic background radiation. That confirmation came when the Princeton group carried out their observations at a different wavelength, and found that the radiation is present and that the spectrum is consistent with that of a blackbody. For their painstaking work in detecting this important signal, Penzias and Wilson were awarded the Nobel Prize for Physics in 1977.

VI.3.2 Hubble law

In the late 1920's, Hubble discovered that the spectral lines of galaxies were shifted towards the red by an amount proportional to their distances. If the redshift is due to the Doppler effect, this means that the galaxies move away from each other with velocities proportional to their separations, i. e. that the universe is expanding as a whole.

In terms of the redshift $z = (\lambda - \lambda_0)/\lambda_0$, Hubble's law can be written as

$$\mathbf{z} = \left(\frac{\mathbf{H}}{\mathbf{c}}\right)\mathbf{r} \ldots\ldots\ldots(6.2)$$

where c is the speed of light, H is the *Hubble constant* and r the distance of the galaxy. For small velocities ($V << c$) the Doppler redshift $z = V/c$, and hence

$$\mathbf{V} = \mathbf{Hr} \ldots\ldots\ldots(6.3)$$

which is the most commonly used form of Hubble's law. If the Universe is expanding, the galaxies were once much nearer to each other. If the rate of expansion had been unchanging, the inverse of the Hubble constant, $T = H^{-1}$, would represent the age of the Universe. If the expansion is gradually slowing down, the inverse Hubble constant gives an upper limit on the age of the universe. According to present estimates, $60\ \mathrm{kms^{-1}Mpc^{-1}} < H < 80\ \mathrm{kms^{-1}Mpc^{-1}}$, corresponding to 11 giga years $< T <$ 17 giga years.

THE HUBBLE LAW:
Redshift – Distance Relation

Procedure:

You are going to use software from CLEA Project: Hubble Redshift to do this laboratory activity.

1. When you have access to telescope, observe two galaxies in each cluster (i.e., in each field). Use the "Change Field" menu to move the telescope to a new cluster.

   Use **stop/resume count** to check the signal-to-noise. A signal-to-noise of 10 is good.

   For each, record the apparent magnitude from the monitor screen, and measure (with the mouse) and record the observed wavelengths of the H and K calcium lines. (Click on the line center and read the wavelength off the screen).

2. Use your data to make a Hubble plot.

   For one of the calculations, you will need to know the absolute magnitudes (M) of the galaxies that you observed. Since they all seem to be the same type of galaxy and we don't know the true M, we'll assume M= –22 for all of them.

   Please have the six columns be:
   First column: galaxy name
   Second column: apparent magnitude
   Third column: calculated distance (pc)
   Fourth column: distance (Mpc)
   Fifth column: measured wavelength of H line
   Sixth column: measured wavelength of K line

3. Find the Hubble constant from your plot.

Lab Skills and Objectives

- **Be able to measure Doppler shift**
- **See how Hubble plot is constructed**
- **Understand the relationship between redshifts of galaxy spectra and the expansion rate of the universe**