CHAPTER ONE

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OBSERVING THE FARTHEST THINGS IN THE UNIVERSE

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When we look out into space at night, we see the Moon, the planets, and the stars. The Moon is so close, only about 380 000 kilometers (240 000 miles) that we can send humans out to walk on it, as we did in the brief glorious period from 1969 to 1972. Even the planets are close enough that we can send spacecraft out to them, notably the Voyager spacecraft, one of which has passed Neptune. Whereas light and radio signals from spacecraft take only about a second to reach us from the Moon, the radio signals from Voyager 2 at Neptune took several hours to travel to waiting radio telescopes on Earth. We say that the distance to the Moon is 1 light-second and the distance to Neptune is several light-hours.

Aside from our Sun, the nearest star at 8 light-minutes away, the distances to the stars are measured in light-years. The nearest star system is Alpha Centauri, visible only in the southern sky, and the single nearest star is known as Proxima Centauri, about 4.2 light-years away. We know so little about the stars that new evidence in 1993 indicates that Proxima Centauri might not be a member of a triple-star system along with the other parts of alpha Centauri, as has long been thought. The speeds at which those stars are moving through space may be sufficiently different that Proxima is only temporarily near Alpha's components.

MEASURING DISTANCES IN THE UNIVERSE

Only for the nearest stars, those within about 100 light-years of our Earth and Sun, can we find their distances by a fairly direct method. This method depends on the concept of parallax, in which objects seem to shift with

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respect to a background when we look at them from different point of view. The easiest way to demonstrate parallax is to hold out your arm and to look at your thumb with first only your left eye and then only your right. You will notice that your thumb seems to jump with respect to the distant wall as you alternately blink your eyes. If you hold your thumb closer, the parallax from eye to eye is greater. This parallax effect also shows up in automobile speedometers, as the needle looks to be in slightly different places when seen from the point of view of the driver and of the passenger.

Parallaxes for stars have only been measured since 1838, since they are so small. We measure them from different points of view, just as we do with left eye/right eye, but for stars the different points of view are the Earth's orbit at intervals of several months. The points of view are thus, at best, twice the distance to the Sun, which is twice 150 million kilometers (93 million miles). Except for Alpha Centauri and Proxima, the parallaxes we measure are all less than 1 second of arc. One second of arc is a tiny angle, 1/60 of a minute of arc and 1/3600 of a degree of arc. Since the Moon is only half a degree, or about 30 minutes of arc, across, one second of arc is about 1/20 of one per cent of the apparent diameter of the Moon. Our unaided eyes can distinguish angles of about 1 minute of arc, so it take a telescope to measure the parallax to even the nearest stars.

A European spacecraft has been in orbit for the last few years measuring parallaxes to unprecedented precision. This Hipparcos spacecraft (for High Precision Parallax Collecting Spacecraft, a pun on the name of the Greek astronomer Hipparchus who measured star brightnesses two thousand years ago) didn't go into the proper orbit, but scientists and engineers have nonetheless been able to get enough good data from it to calculate parallaxes for over 100 000 stars. Since the smaller the parallax shift, the larger the distance, these newly precise values give us more-or-less accurate values for the distances to these stars. But even so, these values are for stars measured only in 10s of light-years.

Our galaxy, the Milky Way Galaxy, is an assortment of stars, gas, and dust containing about a trillion (1 000 000 000 000) times the mass of the Sun; we say that it contains 'a trillion solar masses.' (To keep track of large numbers without having to count zeroes all the time, we commonly put the number of zeroes as a superscript to the number 10: 1 trillion is 10^{12}. The system works even with small values for the exponent, since we define 10^0 as 1. Thus 10^1 is 10, 10^2 is 100, and so on.) Our Sun is located in a spiral arm of our galaxy, about 30 000 light-years from its center. Thus stars far from us in our galaxy are much too far away for us to measure their distances using parallaxes.

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Instead, we often determine what types of stars they are by looking at their spectra or at the distribution of the amount of light they give off in different colors. Since we know how bright standard stars are with those properties, and we can measure how bright the star we are examining is, we figure out how far away the star has to be to appear as bright as it does. The concept is like figuring out how far away a lamppost is on a dark night by how bright it looks. Brightness goes down with the square of the distance. Thus a star that is twice as far away as another star of the same intrinsic brightness appears one-half squared, or one-fourth, as bright.

The nearest galaxies are a pair of small satellite galaxies to our Milky Way. Since they were brought to the attention of European astronomers by the crew of Magellan's ship, who noticed them when they got sufficiently far south, they are known as the Magellanic Clouds. They are only about 400 000 light-years away. Astronomy got a big boost and lots of excitement in 1987 when a star exploded in the Large Magellanic Cloud. This supernova became bright enough to be seen on Earth with the naked eye; since it is in another galaxy, we can calculate that it had to be extremely bright, about as bright as all the rest of the stars in that galaxy put together. Supernova 1987A, as it is known, is still being monitored, though it has faded enough so that it can be observed only with telescopes.

The next galaxy like our own, moving outward from us, is the Great Galaxy in Andromeda (Fig. 1.1). It is known as M31, from its position as the 31st object in a catalogue of non-stellar objects compiled by Charles Messier in France over two hundred years ago. Messier was compiling a list of objects to avoid confusing them with the comets he was searching for, but his list turns out to contain about 100 of the most interesting objects of the sky. Whenever an object has a Messier number, we usually use it, and it broadcasts that 'here is an object pretty bright and easy to observe.' The Andromeda Galaxy is a spiral galaxy some 2.2 million light-years away and is perhaps the farthest object we can see with the unaided eye. Another spiral galaxy, M33 in the constellation Triangulum, is slightly farther away and can also be seen by some people with unaided eye.

How do we tell distances to these galaxies, which are all much too far away for us to measure parallaxes? Indeed the problem plagued astronomy for a long time, especially since in the early years of this century a distinguished astronomer reported that he had measured some motion in M31, akin to a small parallax as an indicator that something is very close by. The matter was resolved only in the 1920s by Edwin Hubble, a Rhodes scholar and lawyer turned astronomer, who used the then largest telescope in the

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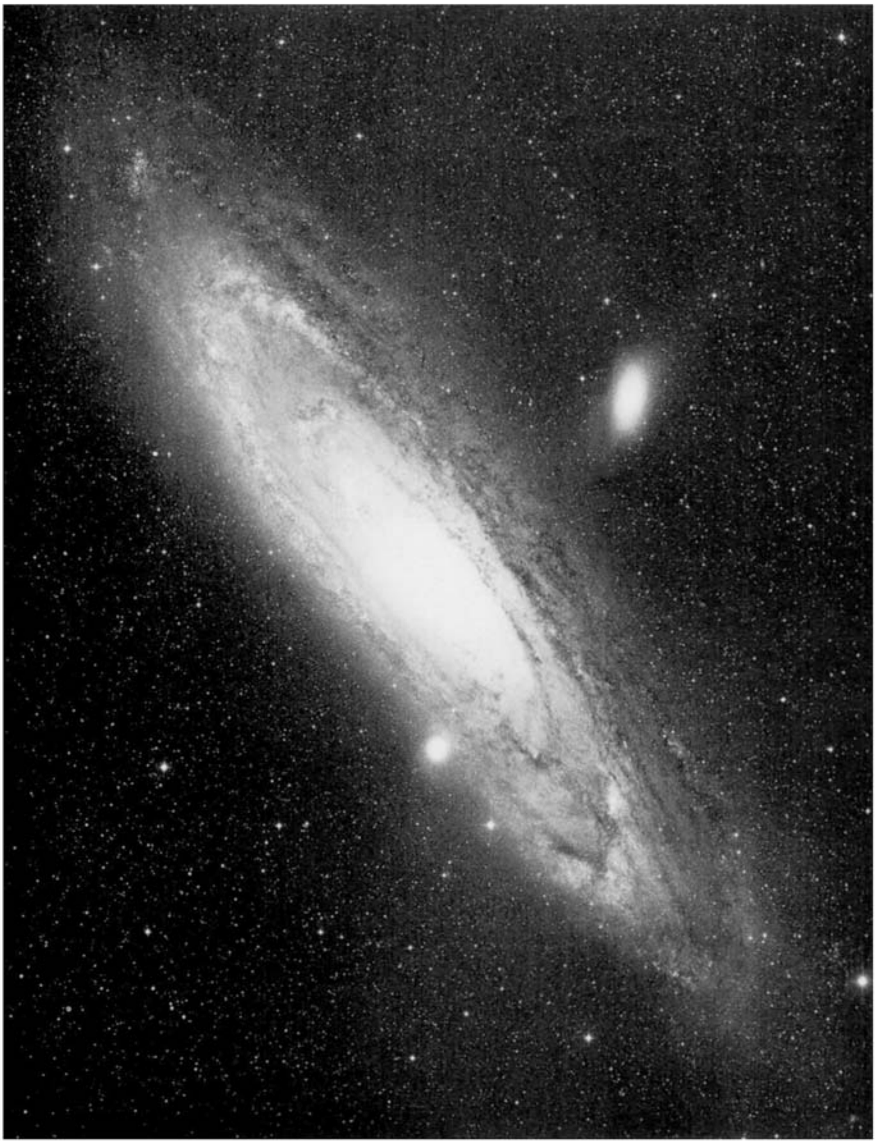

Fig. 1.1. The Great Galaxy in Adromeda, M31, a spiral galaxy containing a trillion times the mass of the Sun. It is seen obliquely. (Palomar Observatory photograph)

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world, the 2.5-m (100-inch) reflector on Mt. Wilson in California, to measure the brightnesses of several variable stars in M31, the Andromeda Galaxy. (Of course, there are really thousands of galaxies we can detect with a large telescope in the constellation Andromeda, but 'the Andromeda Galaxy' is generally understood to mean M31.)

Earlier, Henrietta Leavitt at the Harvard College Observatory had found the key in observing a type of variable star known as Cepheid. They got their name from their prototype, the star delta Cephei (that is, the fourth brightest star in the constellation Cepheus), which gets brighter and fainter by a small factor with a period of a few days. Leavitt discovered that the longer the period, the brighter the star. So by simply following how long a Cepheid

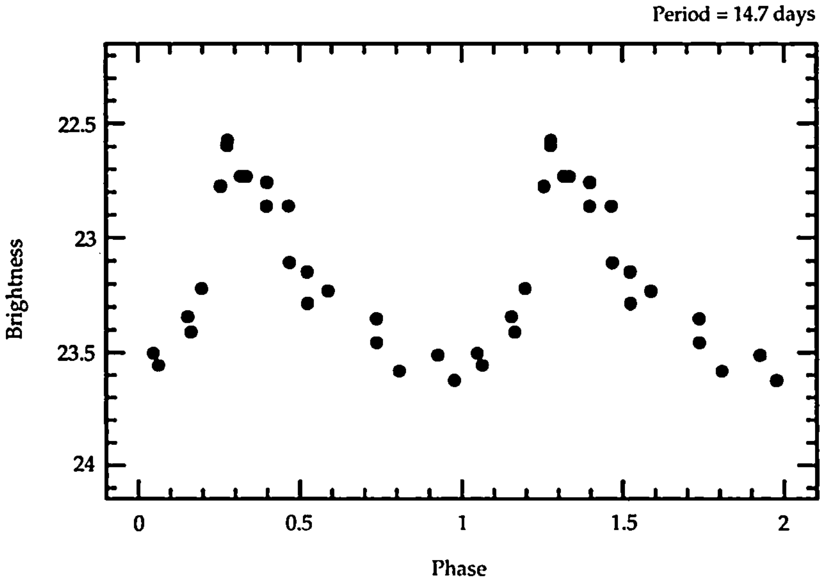

Fig. 1.2. A light curve for one of the 31 Cepheids studied in the galaxy M81 as part of one of the Key Projects of the Hubble Space Telescope. The horizontal axis shows the phase of the 14.7-day cycle (a cycle is repeated here) while the vertical axis shows the magnitude (brightness) in the spectral band known as V, a yellow band that corresponds to the visible part of the spectrum best seen with the eye; 23rd magnitude is very faint, fainter than ground-based telescopes can observe at such high accuracy. (Wendy L. Freedman, Carnegie Observatories; Shaun M. Hughes, Barry F. Madore, and Jeremy R. Mould, Caltech; Myung Gyoon Lee, Carnegie Observatories; Peter B. Stetson, Dominion Astrophysical Observatory; Robert C. Kennicutt and Anne Turner, Steward Observatory; Laura Ferrarese and Holland Ford, Space Telescope Science Institute; and John A. Graham, Carnegie Institution of Washington)

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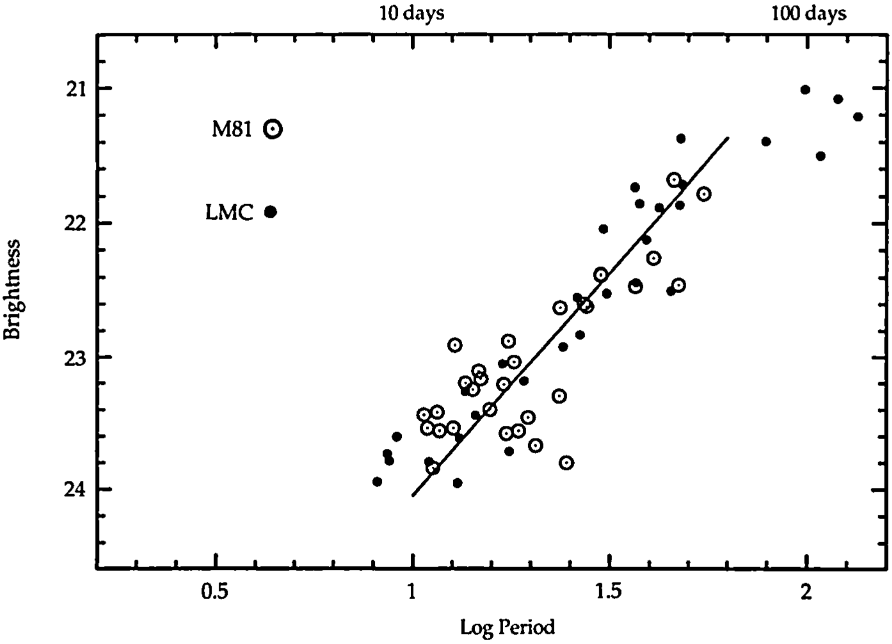

Fig. 1.3. The period–luminosity diagram, graphing the period in days vs. the (V) magnitude of the stars (on a logarithmic scale of period, with 1=10 days, 1.5=32 days, and 2=100 days). Open circles show the Hubble Space Telescope measurements of the galaxy M81, while filled circles show Cepheids in the Large Magellanic Cloud (LMC) shifted by an amount that corresponds to the difference in distances of the two galaxies from us (9.09 magnitudes). (Freedman, *et al.*, as in previous figure)

variable star takes to go through a cycle of brightness, we can know how bright it is intrinsically. Then we can use the standard method of comparing how bright it really is with how bright it looks to find out how far away it is. Leavitt worked out her method for a nearby galaxy, the Large Magellanic Cloud, and Hubble's extension of the method to the Andromeda Galaxy gave us the distance to unprecedented accuracy. It was this observation that showed, indeed, that M31 was a distant galaxy like our own and not merely a spiral cloud of gas in our own galaxy.

The method is still our best way of finding distances to objects reasonably far away. One of the major goals of the Hubble Space Telescope is to use its unique capabilities to detect Cepheid variables in galaxies as far away as possible, as part of the accurate determination of the cosmic distance scale. The first step in that important task was reported in 1993 with the determination of the distance to the spiral galaxy M81 from studies of 30 newly discovered

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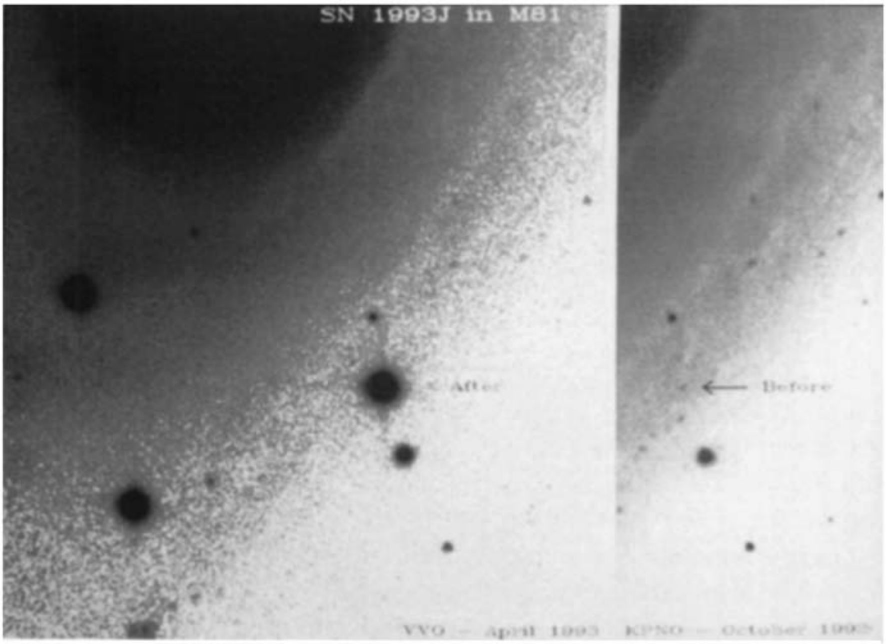

Fig. 1.4. The spiral galaxy M81 in Ursa Major, both before and after its March 28, 1993, eruption of Supernova 1993J. (John Salzer, Wesleyan University)

Cepheids in it with periods from 10 days to 55 days (Figs. 1.2, 1.3). M81 turns out to be 11 million light-years away, a distance determined through this method by the Hubble Space Telescope to plus or minus 10 per cent, a much lower uncertainty than previous measurements had. The work was carried out by Wendy Freedman of the Observatories of the Carnegie Institution of Washington (which formerly ran the Mt. Wilson Observatory and worked jointly with the Palomar Observatory, but which now concentrates on observations with its own telescope in Chile and on other astronomical research) and colleagues from many institutions.

The determination of the distance to M81 had immediate applicability, since a supernova was discovered in it. This supernova (Fig. 1.4) erupted on March 28, 1993, and grew to be the brightest supernova visible from Earth's northern hemisphere observatories since 1937, over 50 years. Since the intrinsic brightness of an object can be determined by measuring its apparent brightness and then scaling with the inverse-square law for its distance, the analysis gave us a more accurate brightness for this type of supernova than we previously had. Since supernovae are much brighter than Cepheid variables, knowing more about supernovae enables us to find distances to more distant galaxies in which supernovae are discovered. If Supernova 1993J in M81 had turned out to be the kind of supernova that comes from the incineration of a white dwarf star when it reached the maximum mass that such stars can have, we would then have found the 'standard candle' that astronomers want to measure distances throughout the Universe. But Supernova 1993J seems to come, instead, from the collapse of a massive star. These stars collapse and reach a wide variety of brightnesses, so they can help determine distances but not as accurately.

THE EXPANSION OF THE UNIVERSE

Hubble, also in the 1920s, analyzed the spectra of dozens of galaxies. The farther away the galaxy, the longer the exposure he had to take on film, even with the world's largest telescopes. Some of his exposures were 16 hours long or longer; he would have to shut the telescope down at the end of the night and resume the next night. We shall see later on, that such exposures can now be obtained in minutes, using today's electronic detectors.

In any case, when Hubble examined the galaxy spectra, he saw that there was a tendency for the farther galaxies to have their spectra shifted to longer wavelengths by a greater factor than nearer galaxies (Fig. 1.5). Thus the particular traces of calcium in the spectrum of the galaxy, a feature that is particularly strong and easy to notice, appeared not quite as far into the

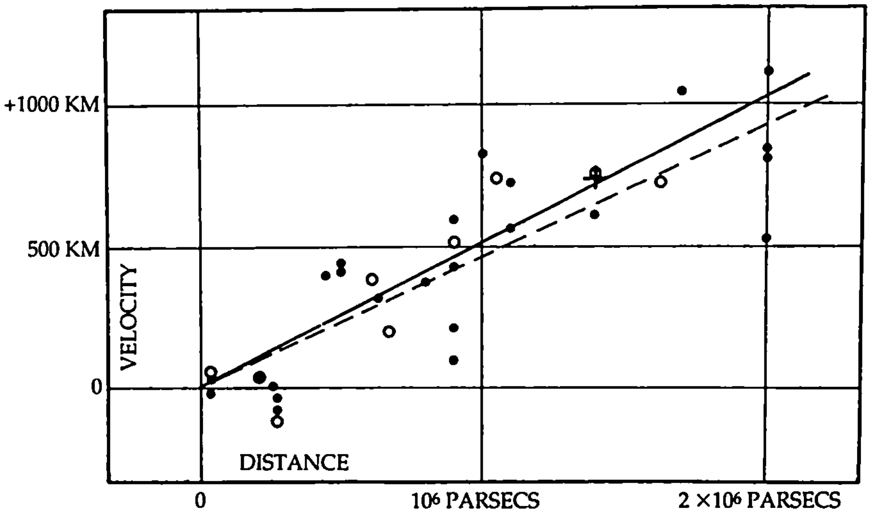

Fig. 1.5. The 1929 Hubble-law diagram compiled by Hubble. (National Academy of Sciences)

ultraviolet as they did on Earth. Since they were slightly moved to a direction toward the red from the ultraviolet, they are 'redshifted,' even though they don't actually turn red. Hubble made the leap of genius and suggested that there was a direct link between the amount of redshift and the distance of the galaxy. In future years, he worked with Milton Humason at Mt. Wilson to push the data farther out into the Universe, and his extrapolation proved correct. The relation between distance and redshift was a straight-line proportionality as far as he could determine. Indeed, the relation still seems true, and we even now argue and debate about a possible tiny curvature at the top end of the straight line.

This Hubble law of expansion, the law linking redshift and distance, is the main way we determine distances to the most distant galaxies. But it is based on observations for nearer objects, in which we can determine the distance in some other way. We try now to measure as many of these distances to as high an accuracy as possible.

The conundrum that astronomy has had for decades is that different groups of people measure different values for the Hubble constant, the constant of proportionality linking velocity and distance: $v=H_0d$, where v is velocity, d is distance, and H_0 is the Hubble constant (or 'Hubble's constant'), with the subscript zero indicating that the Hubble constant is measured at some beginning time. The traditional value measured for some decades by Allan Sandage, Hubble's heir at the Mt. Wilson and Palomar Observatories, and his colleague Gustav Tammann, is some 50 kilometers per second per megaparsec. Some other scientists found 100. But other groups are now often finding a value closer to 80. The debate is still going on hot and heavy. We look for the Hubble Space Telescope and some of the new generation of ground-based telescopes to resolve the controversy. The first results from the repaired Hubble Space Telescope for Cepheid variables in several galaxies in the Virgo Cluster of galaxies give values of about 80 kilometers per second per megaparsec for the Hubble constant. These galaxies are far enough away that we think their velocities of recession show the actual average expansion velocity of the Universe.

What do the strange units of Hubble's constant mean? A parsec is a way that astronomers use to measure distance, since it is easily computed by taking one over the measured parallax angle. If you are at a distant star and look back at the radius of the Earth's orbit, it takes up ('subtends') a certain angle in the sky. If you go far enough back, it takes up about a degree; if you go about 60 times farther back, it takes up a minute of arc; and if you go another 60 times farther back, it takes up a second of arc. At this distance, you are one

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parsec from Earth. The distance works out to be about 3.3 light-years. Now we can analyze Hubble's constant. For each million parsecs (megaparsec, or Mpc) you go away, the speed at which a galaxy is receding increases by 50 kilometers per second or 100 kilometers per second, depending on which group is correct. Thus at a distance of one million parsecs (taking the first number), a galaxy is receding at 50 kilometers a second; at two million parsecs, a galaxy is receding at 100 kilometers a second; at three million parsecs, a galaxy is receding at 150 kilometers a second, and so on. Actually, for the nearer galaxies like Andromeda, which is only 2.2 million light-years and thus less than one parsec away, the galaxy has its own motion to and fro, called 'peculiar motion,' which adds to or subtracts from the velocity from Hubble's law. So one has to go to more distant galaxies to apply Hubble's law properly.

Fig. 1.6. The expanding Universe is often likened to a rising raisin cake, with the galaxies corresponding to the raisins. An individual galaxy, like an individual raisin, is not expanding. If you were sitting on any raisin, though, you would see all the raisins receding from you. You need not be at the center of the cake to have this feeling. The Universe, indeed, may be infinite and have no center. (Jay M. Pasachoff photograph)