33–5 The Expanding Universe: Redshift and Hubble's Law

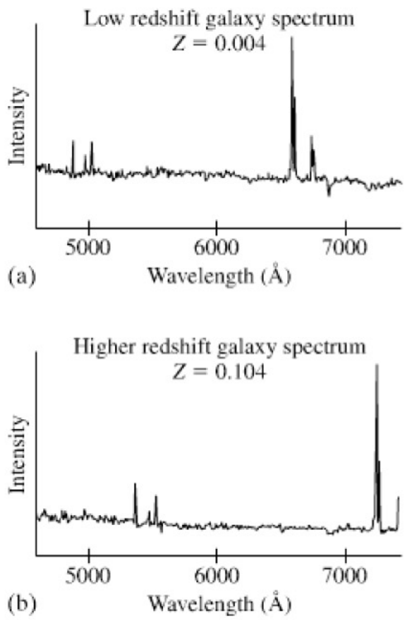

FIGURE 33–19 Atoms and molecules emit and absorb light of particular frequencies depending on the spacing of their energy levels, as we saw in Chapters 27, 28, and 29. (a) The spectrum of light received from a relatively slow-moving galaxy, where $Z = (\lambda - \lambda_0)/\lambda_0$. (b) Spectrum of a galaxy moving away from us at a much higher speed. Note how the peaks (or lines) in the spectrum have moved to longer wavelengths (the redshift).

We discussed in Section 33–2 how individual stars evolve from their birth to their death as white dwarfs, neutron stars, and black holes. But what about the universe as a whole: is it static, or does it change? One of the most important scientific results of the twentieth century was that distant galaxies are racing away from us, and that the farther they are from us, the faster they are moving away. How astronomers arrived at this astonishing idea, and what it means for the past history of the universe as well as its future, will occupy us for the remainder of the book.

That the universe is expanding was first put forth by Edwin Hubble in 1929. This idea was based on distance measurements of galaxies (Section 33–3), and determination of their velocities by the Doppler shift of spectra lines in the light received from them (Fig. 33–19). In Chapter 12 we saw how the frequency and wavelength of sound are altered if the source is moving toward or away from an observer. If the source moves toward us, the frequency is higher and the wavelength is shorter. If the source moves away from us, the frequency is lower and the wavelength is longer. The **Doppler effect** occurs also for light, but the shifted wavelength or frequency is given by a formula slightly different† from that for sound. According to special relativity, the Doppler shift is given by

$$\lambda = \lambda_0\sqrt{\frac{1 + v/c}{1 - v/c}}, \qquad \left[\begin{array}{l}\text{source and observer moving}\\ \text{away from each other}\end{array}\right] \qquad \textbf{(33–3)}$$

where λ_0 is the emitted wavelength as seen in a reference frame at rest with respect to the source, and λ is the wavelength measured in a frame moving with velocity v away from the source along the line of sight. (For relative motion *toward* each other, $v < 0$ in this formula.) When a distant source emits light of a particular wavelength, and the source is moving away from us, the wavelength appears longer to us: the color of the light (if it is visible) is shifted toward the red end of the visible spectrum, an effect known as a **redshift**. (If the source moves toward us, the color shifts toward the blue or shorter wavelength.) The amount of a redshift is specified by the *redshift parameter*, z, defined as

Redshift parameter (defined)

$$z = \frac{\lambda}{\lambda_0} - 1 = \frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta\lambda}{\lambda_0}. \qquad \textbf{(33–4)}$$

We can combine Eqs. 33–4 and 33–3 to obtain‡

$$z = \sqrt{\frac{1 + v/c}{1 - v/c}} - 1. \qquad \textbf{(33–5a)}$$

For speeds not too close to the speed of light, it is easy to show (Problem 29) that z is proportional to the speed of the source to or away from us (as was the case for sound):

$$z = \frac{\lambda - \lambda_0}{\lambda_0} \approx \frac{v}{c}. \qquad [v \ll c] \quad \textbf{(33–5b)}$$

But redshifts are not always small, in which case the approximation of Eq. 33–5b would not be valid. Modern telescopes regularly observe galaxies with $z \approx 5$.

†For light there is no medium and we can make no distinction between motion of the source and motion of the observer (special relativity), as we did for sound which travels in a medium (Chapter 12).

‡Equation 33–5a for z is not precisely correct because, strictly speaking, the redshift is due to the expansion of space, not motion through space (Doppler effect, Eq. 33–3).