6
Observational Cosmology

Giordano Bruno was burned at the stake for his heretical ideas in 1600. He believed that the stars are like our Sun and appear to be dimmer only because of their great distance from us. This was an inspired guess, but how can we verify that it is actually true? How far away are the stars? And what are they made of?

These questions bedeviled Isaac Newton. He thought there was a distinction between the "lucid matter" of the stars and the "opaque matter" of the Earth and the planets. In a letter to Richard Bentley, where he discussed the creation of the Solar System amongst other things, Newton wrote: "But how the matter should divide itself into two sorts, and that part of it which is to compose a shining body should fall down into one mass and make a sun and the rest which is fit to compose an opaque body should coalesce, not into one great body, like the shining matter, but into many little ones; or if the sun at first were an opaque body like the planets or the planets lucid bodies like the sun, how he alone should be changed into a shining body whilst all they continue opaque, or all they be changed into opaque ones whilst he remains unchanged, I do not think explicable by mere natural causes, but am forced to ascribe it to the counsel and contrivance of a voluntary Agent."

While Newton resorted to divine intervention to explain the separation of the Solar System into the lucid Sun, and opaque planets, spectroscopic experiments in the mid 1800s revealed that the Sun and the stars are actually made

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of the same chemical elements as the Earth and planets.[1] In this chapter we will study how spectroscopy allows us to identify chemical elements; even those in distant stars. We will also learn how the Doppler effect is used to measure velocities of cosmic bodies, and how astronomical distances are determined.

6.1 Fingerprints of the Elements

Light coming to us from the stars brings a treasure-trove of information. We learned in Chap. 3 that light consists of electromagnetic waves that can have a wide range of wavelengths (or frequencies). For visible light, different wavelengths correspond to different colors. When a beam of white light is shone through a prism, it emerges on the other side having a continuum of colors, like a rainbow (see Fig. 6.1a). This *continuum spectrum* shows that white light is composed of many colors, ranging from red to violet.

Light emitted from a hot gas that is incident on a prism displays an *emission* line spectrum—a pattern of bright lines with particular wavelengths can be seen on a black background (Fig. 6.1b). Another interesting phenomenon occurs when a beam of white light is passed through cool gas before it gets to the prism. The gas absorbs waves having some specific wavelengths, and a pattern of black lines, called *absorption lines*, appears in the spectrum (Fig. 6.1c). The pattern of both emission and absorption lines depends on the composition of the gas. Atoms of a given chemical element can emit and absorb light only at a particular set of wavelengths,[2] so the emission or absorption line spectrum provides a unique "fingerprint" for each element.

Light that emanates from the hot inner parts of a star has a continuum spectrum[3] that develops absorption lines as it passes through the cooler stellar atmosphere. Astronomers measure the spectra of stars, and by comparing with the absorption lines of gases measured in the laboratory, they can identify whether elements such as hydrogen, helium, carbon, etc., are present in the star. In fact, helium was discovered on the Sun in 1868, well before it was found on the Earth in 1895. Stellar spectroscopy has indisputably determined that stars are indeed made of the same "stuff" as the Earth.

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[1]The development of nuclear physics has led to a detailed understanding of how "opaque matter" can become "lucid matter" under the right conditions. Even more astonishing is that most of the elements from which we are made were actually produced in the stars themselves (as we will discuss later).

[2]This fact was already known in the mid-1800s, but was explained only much later by quantum mechanics.

[3]Although light emitted by atoms has a discrete line spectrum, in stellar interiors atoms are broken up into electrons and nuclei which scatter off one another, producing a continuous spectrum.

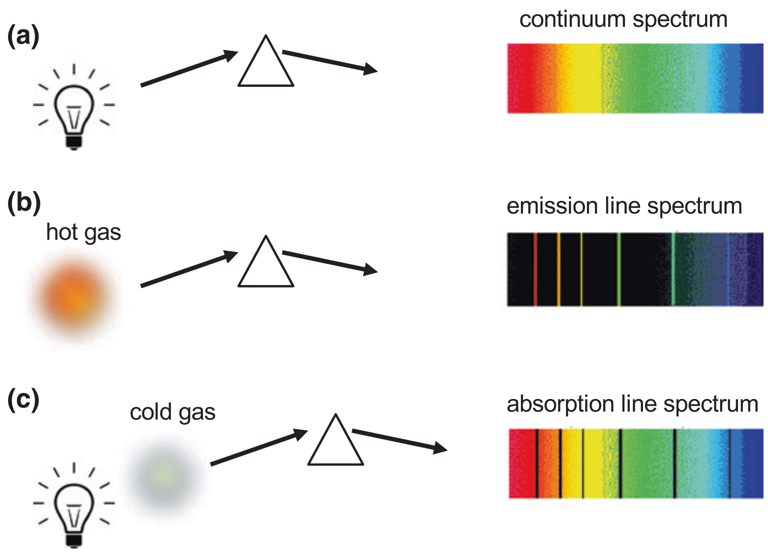

Fig. 6.1 **a** When white light passes through a prism, it spreads into a continuum of colors. **b** A hot gas emits specific wavelengths that show up as bright lines on a black background. **c** A cold gas absorbs specific wavelengths that are then absent from the continuum spectrum. Notice that the emission lines have the same wavelengths as the absorption lines (as long as the hot and cold gas are of the same type)

6.2 Measuring Velocities

For nearby stars, like Barnard's star, we can directly calculate how fast the star is moving in a direction orthogonal to the line of sight. We do so by measuring the star's displacement on photographic plates taken some time apart. However, more distant stars are so far away that it is impossible to detect their motion and measure their velocities using this method. So how do we measure the velocity of astronomical objects? (Fig. 6.2).

The observed wavelength (color) of light depends on the relative motion of the source and the observer. If a source of light is moving towards us, the observed wavelength gets shorter—that is, it shifts towards the blue end of the spectrum. Conversely, if a source is moving away from us, the observed wavelength will get longer, shifting towards the red end of the spectrum. We say the source is blue- or redshifted. This phenomenon, known as the *Doppler effect*, occurs for all kinds of waves, including sound waves and ripples on the surface of water. You have probably experienced it when a siren has passed by: an approaching siren has a higher pitch (shorter wavelength) than a receding one. As illustrated in Fig. 6.3, the wave crests pile up in

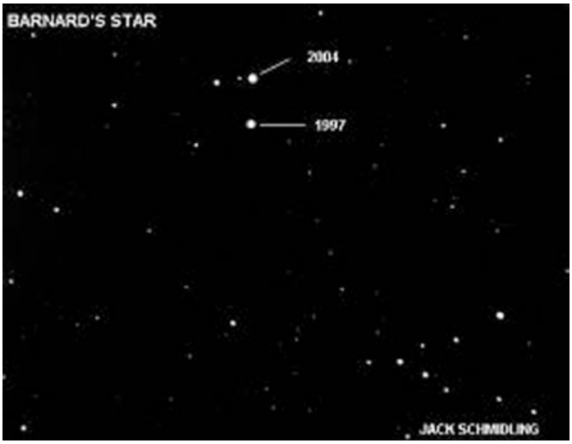

Fig. 6.2 Barnard's star, shown here at two different times, is about 6 light years away. *Credit* © Schmidling Productions "Barnard's star" (Encyclopædia Britannica Online. Web. 24 Dec. 2016)

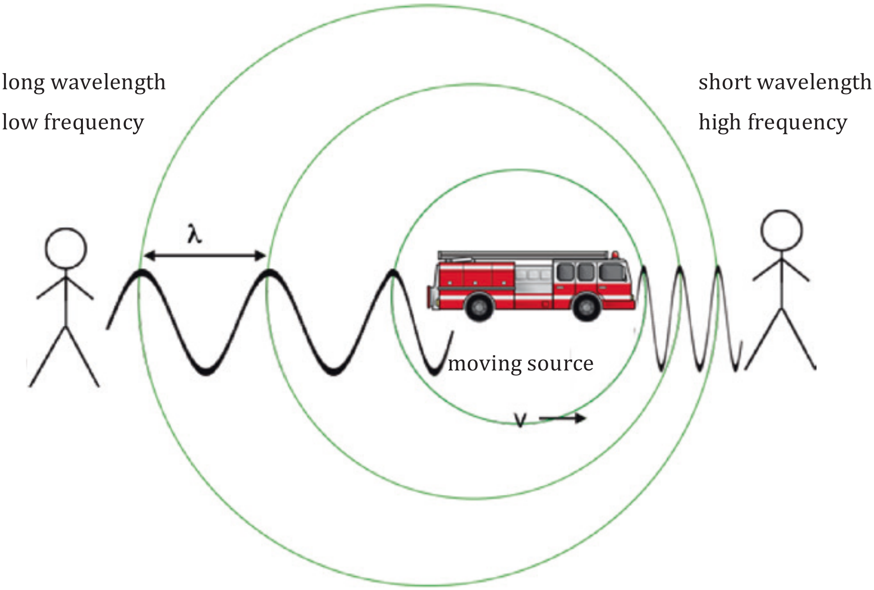

Fig. 6.3 Doppler effect for sound. Approaching sirens have a higher pitch than receding ones *Credit* NASA's Imagine the Universe

front of a moving source and spread out in its wake. Remembering that the wavelength is the distance between the crests, it is easy to see that the wavelength gets shorter in front and longer in the wake of the source.

Quantitatively, the Doppler effect for light can be expressed by a simple formula:

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c} \tag{6.1}$$

where λ is the wavelength, v is the relative velocity of the source and observer, and c is the speed of light. As before, the symbol Δ stands for "change", so $\Delta\lambda$ is the change in the wavelength λ. The velocity v is assumed to be small compared to c (nonrelativistic motion), and it is taken to be negative if the source is approaching and positive if it is receding. (Note: λ is the emitted wavelength, and $\Delta\lambda = \lambda_o - \lambda$, where λ_o is the wavelength measured by the observer.) The *redshift* z is defined as

$$z \equiv \frac{\Delta\lambda}{\lambda}. \tag{6.2}$$

Thus, using Eq. (6.1), we note that for nonrelativistic motion, $z = v/c$.

For a moving star, the entire spectrum gets blue- or redshifted, including the black absorption lines. Astronomers identify line patterns of different elements and measure how much these patterns are shifted relative to a sample at rest in the laboratory. Equation (6.1) can then be used to determine the velocity of the star.[4] It is hard to overstate the crucial role spectroscopy and the Doppler effect play in our endeavor to understand the universe.

6.3 Measuring Distances

The determination of distances to astronomical objects is notoriously difficult and has dominated much of twentieth century astronomy. Today astronomers use a variety of techniques to measure distances—each one is most useful within a given range. Distances to nearby stars can be found by measuring their *parallax*, which is the apparent movement of the star relative to the background sky as the Earth rotates around the Sun (see Fig. 6.4). Demonstrating the effect of parallax is so simple that anyone can do it—you don't even need a telescope! If you stretch out your arm, hold up

[4]Note that Doppler effect can be used only to measure velocities along the line of sight, that is, towards or away from us. Transverse velocities in the orthogonal directions cannot be measured in this way.

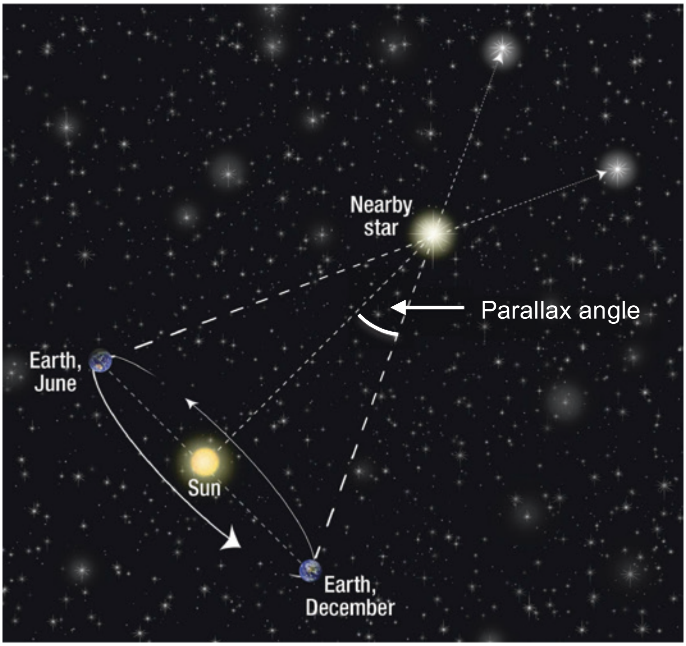

Fig. 6.4 The apparent shift in position of a nearby star relative to very distant background stars allows us to determine the nearby star's distance. The Earth's orbital diameter can be used as a baseline if we view the star at the beginning and end of a 6 month period. In reality (unlike the figure) the distance to the stars is much greater than the Earth's orbit, so the parallax angle is very small *Credit* NASA, ESA, and A. Feild (STScI)

your thumb, and alternately close your right and left eyes, you will see that your thumb appears to alternate between two different positions relative to the back of the room. From some simple geometry, knowing the distance between your eyes (the "baseline"), and the angular shift of your thumb (twice the parallax angle), you can determine the distance to your thumb.

The parallax is used to define an astronomical unit of distance, called a *parsec* (pc). One parsec is the distance at which a star would have a parallax of $1''$;[5] it is equal to about 3.3 light years. In this book we will usually express distances in light years, and not parsecs. Since parallactic angles are very small, it becomes extremely hard to measure them for objects that are more than about 100 light years away.

[5]An arc second is a measure of angle. There are 360° in a full circle, $60'$ in a degree, and $60''$ in an arc minute. An arc second is a tiny angular measure (it is about the angle subtended by a dime placed 4 km away).

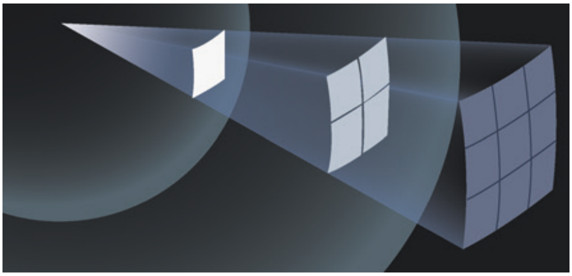

Fig. 6.5 The energy emitted by the source is spread over a *spherical* surface, whose area grows like the *square* of the distance from the source

While 100 light years seems like a large distance, our nearby neighbor, the Andromeda galaxy, is 2.5 million light years away. So parallax measurements can be seen as a first rung in what we call the cosmic distance ladder. Astronomers use a variety of so called *standard candles* to extend the reach of our distance measurements. Although none of them is perfect, they all work on the following premise: if we know how intrinsically luminous a light source is, and we measure how bright it appears, we can figure out how far away it is. The key relation is that the brightness of a light source decreases with the square of its distance,

$$b = \frac{L}{4\pi d^2} \tag{6.3}$$

The luminosity L is the energy of light emitted by the source per second. As the light travels a distance d from the source, this energy gets spread over a sphere of area $4\pi d^2$, and the apparent brightness b decreases accordingly (see Fig. 6.5).

Pulsating stars, called Cepheids, are particularly useful standard candles. Their brightness varies periodically, with periods ranging from days to months. A remarkable property of Cepheids, discovered in 1912 by Henrietta Leavitt of Harvard College Observatory, is that they display a tight relationship between their period of variation (which is easy to measure) and their luminosity, as shown in Fig. 6.7. Thus by measuring the period, we can deduce the luminosity L. We can also measure the apparent brightness b, and once we know L and b, we can use Eq. (6.3) to determine the distance to the star. Cepheids can be used to measure distances up to about 10 million light years (Fig. 6.6).

Today astronomers use extremely powerful stellar explosions, called *supernovae*, as standard candles. Although there are many kinds of supernovae, with differing properties, *Type 1a supernovae* have very uniform luminosities and

Fig. 6.6 Henrietta Swan Leavitt (1868–1921) received an excellent education from Radcliff College, but being a woman she was unable to work as an official academic. Instead she found work as a "human computer" (with many other women) at Harvard College Observatory, where she earned the equivalent pay of a servant. She was a quiet, hard working woman, whose seminal discovery of the period-luminosity relationship for Cepheid stars made it possible for astronomers to measure the Universe. Despite the importance of her discovery, Leavitt received almost no credit in her lifetime. A member of the Swedish Academy of Sciences tried to nominate her for the Nobel Prize in 1924, only to discover that she had died of cancer three years earlier, at the age of 53

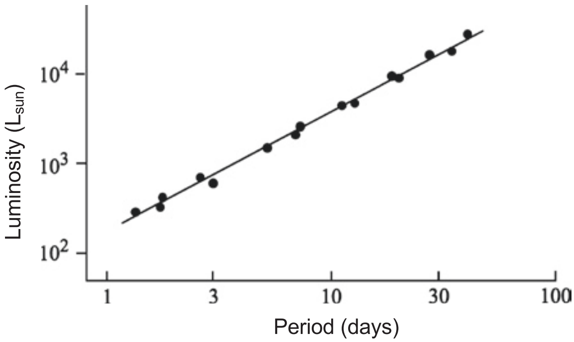

Fig. 6.7 A sketch of the period-luminosity relation for Cepheid variable stars *Credit* Mark Whittle

are thus excellent standard candles. The physics of Type 1a supernovae is not yet fully understood, but the most plausible cause is a thermonuclear explosion of a white dwarf star.[6] There appear to be two mechanisms to trigger the explosion. Firstly, if a white dwarf has a companion star, from which it can

[6]When an ordinary star (with a mass similar to the Sun's) depletes its nuclear fuel, it becomes a very dense compact white dwarf star. The pull of gravity in a white dwarf is balanced by the pressure of the material within the star.

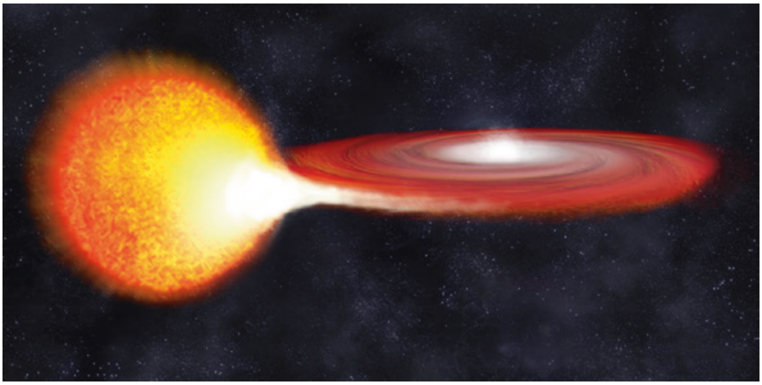

Fig. 6.8 Artist's impression of a white dwarf star accreting matter from a binary companion. When the star reaches a certain mass threshold it explodes, becoming a supernova *Credit* NASA/CXC/M.Weiss

accrete material, it may gain so much mass that gravity overwhelms the pressure forces, and the white dwarf starts to collapse. This ignites a runaway thermonuclear reaction, and the white dwarf star is completely blown away. An alternative scenario is a collision of two white dwarfs. When the two stars merge, their combined mass exceeds the stability threshold, and once again this leads to collapse. Whatever the mechanism, there is strong observational evidence that Type 1a supernovae have nearly the same peak luminosity. By measuring the apparent brightness of such supernovae and knowing the luminosity, the distance to the host galaxy can be determined. These powerful beacons have allowed astronomers to chart the universe out to billions of light years (Fig. 6.8).

6.4 The Birth of Extragalactic Astronomy

By the turn of the 20th century, astronomers had identified two types of objects outside our Solar System—point-like stars and faint, fuzzy extended objects called *nebulae*. The great question of the day was "*What is the nature of the nebulae?*" There were two rival theories. The first theory advocated that there was nothing but empty space beyond our Galaxy. Nebulae were considered to be objects within the Galaxy, probably sites of star formation. The opposing view held that nebulae were distant "island universes" in their own right, similar to our Galaxy. This contentious question resulted in "The Great Debate" between Harlow Shapley and Heber Curtis, held in 1920 at the Museum of Natural History in Washington. The debate ended inconclusively,

Fig. 6.9 Stars and nebulae *Credit* NASA

but the issue was definitively resolved in 1923, when Edwin Hubble established that the nebulae were other island universes, completely separate from our Galaxy (Fig. 6.9).

Hubble identified Cepheid variable stars in Andromeda and several other nebulae. Using Leavitt's period-luminosity relation, he was then able to determine the distances to these nebulae. Today we know that Andromeda is about 2.5 million light years away—roughly 50 times the radius of the Milky Way. Hubble's initial estimate of 1.5 million light years was significantly lower. However, it was still large enough to show that the nebulae must include billions of stars; and that they are indeed "island universes" similar to our own Galaxy. We now call them galaxies (Fig. 6.10).

Summary

Each chemical element displays a characteristic pattern of spectral lines. By analyzing the spectra of light coming from stars and galaxies we can determine their chemical composition. Furthermore, the spectral lines may be shifted relative to a laboratory sample here on Earth. From this shift we can determine velocities using the Doppler effect. Distances to nearby stars can be found using stellar parallax, while for more distant objects astronomers use a variety of "standard candles" like Cepheid stars and supernovae. In par-

Fig. 6.10 Pinwheel galaxy *Credit* ESA and NASA

ticular, Edwin Hubble used Cepheids to establish that the then mysterious spiral nebulae were not part of our Galaxy, but were separate distant galaxies.

Questions

1. What are emission and absorption line spectra?
2. Does red light have a longer or shorter wavelength than blue light? Does it have a higher or lower frequency than blue light?
3. If an object is approaching us, will its spectral lines be blue or red shifted? Explain.
4. An unshifted (laboratory) emission line spectrum of pure hydrogen (top), and an emission line spectrum from a moving object are shown in Fig. 6.11. Using the Doppler formula Eq. (6.1), calculate the velocity of the moving object. Is it moving toward or away from the observer?
5. The distances to nearby stars are found by measuring their parallax. If the parallax angle of star A is twice that of star B, which of the two stars is closer to us? By how much?
6. What is a "standard candle" and how do astronomers use them to measure distances?
7. Imagine that you have measured the distance to a galaxy using a standard candle. After you publish your results, it comes to light that your standard candle is twice as luminous as you had thought. How is the distance to the galaxy modified?

Fig. 6.11 Hydrogen emission line spectra. (Wavelengths are measured in nanometers.)

8. A 50 W light bulb is placed at a distance 10 m away, and a 100 W bulb is placed at a distance 20 m away. Which of the two bulbs appears brighter? By how much?
9. How can we use Cepheid variable stars to measure distances?