CHAPTER 7

A QUICK TOUR OF THE COSMOS

The distribution of matter in the universe is not uniform. Matter comes in clumps: we live on a planet circling a star, and there is not much matter between these two objects. The planets and star we call the solar system is part of a much larger clump called a galaxy, and our particular galaxy of about 100,000,000,000 stars is called the Milky Way. In turn, our galaxy is part of a small cluster of galaxies called the Local Group. This chapter provides a very quick tour through the distance scales of the galactic clumps, and gives a short introduction to the techniques used to determine interstellar distances.

7.A Planets, Stars, Galaxies and all that

Planet Earth, on which we reside, is very small on the cosmic distance scale: the radius of the Earth is only 6.4×10^3 km, or about 1% of the radius of the Sun (7.0×10^5 km). However, even the size of stars is miniscule compared to the distances between stars and planets. The distance from the Sun to the Earth is 1.5×10^8 km, or almost 500 times the radius of the Sun, while the distance from the Sun to Pluto is 5.9×10^9 km. There is increasing observational evidence that other stars have planetary systems as well. Thus far, only planets with masses comparable to Jupiter can be inferred from observation, and such planets appear to have orbital radii not grossly different from those of the solar system. Beyond our planets, the distance to the star nearest our solar system, Proxima Centauri, is 4.0×10^{13} km.

These distance scales are summarized in Table 7.1. One can see that even the distance to the closest star is immense by terrestrial standards, with the clerical consequence that the standard terrestrial distance unit of a kilometer is not useful for interstellar road maps. It is more convenient to use the much larger unit of a light-year, or ly, that is 9.46 x 10^{12} km. Another useful unit of length is the parsec (pc), which is equal to 3.26 ly. The historical origin of the pc is discussed in Sec. 7.B.

Not only do other stars appear to have planets, a significant fraction of stars have companion stars that orbit each other as a *binary* pair. Stars themselves are not uniformly distributed throughout space, but are usually found in swarms in the form of galaxies. Our own galaxy, the Milky Way, consists of roughly 100,000,000,000 or 10^{11} stars. The Milky Way is about 50,000 ly in radius, and our solar system lies some 30,000 ly from its centre, orbiting the centre with a period of about 200 million years. A useful comparison of this time scale is that dinosaurs became extinct around 65 million years ago. A section of the Milky Way is shown in Fig. 7.1.

Galaxies other than the Milky Way are clearly visible from Earth and are visually well-defined. The 50,000 ly radius of our galaxy appears to be a typical galactic size. The galaxies also appear to be clustered, although the number of galaxies in our Local Group of galaxies is more like 30 than the cluster of 10^{11} stars in the Milky Way. The nearest members of the Local Group, the Magellenic Clouds, are about 170,000 ly away, which is about triple the radius of the Milky Way.

Table 7.1 Cosmic distances, given in km and light-years (1 ly = 9.46 x 10^{12} km).

Quantity	km	ly
radius of Earth	6.4 x 10^{3}	6.8 x 10^{-10}
radius of Sun	7.0 x 10^{5}	7.4 x 10^{-8}
distance from Sun to Earth	1.50 x 10^{8}	1.59 x 10^{-5}
distance from Sun to Pluto	5.9 x 10^{9}	6.3 x 10^{-4}
distance to nearest star	4.0 x 10^{13}	4.27
Sun to centre of Milky Way	2.8 x 10^{17}	30,000
radius of Milky Way	4.7 x 10^{17}	50,000
distance to nearest galaxy	1.6 x 10^{18}	170,000
distance to galaxies in Hydra	4 x 10^{22}	4,000,000,000
furthest object detected	> 10^{23}	>10,000,000,000

Fig. 7.1 A section of the Milky Way, looking from Earth through the galactic plane. The copyright to this colour image is held by the Anglo-Australian Observatory, and cannot be reproduced without permission.

Although the galactic sizes are about 10^{14} times the radius of the Earth, they are still small compared to the size of the visible universe as a whole. Many clusters of galaxies have been observed in the universe, and they can be seen up to *billions* of light years from the Earth. For example, one of the clusters in the constellation Hydra is 4-6 x 10^9 ly away. The furthest objects detected are more than 10^{10} ly or 10^{19} Earth radii away. It's a small world.

7.B Parallax

How do we know the distance scales ascribed to stars and galaxies in Sec. 7.A? The radius of the Earth's orbit around the Sun can be determined from a variety of phenomena, including the gravitational force that the Sun exerts on the Earth. Knowing the radius of the Earth's orbit, distances to nearby stars can be found through parallax, which is used to interpret the apparent motion of stars resulting from the motion of the Earth in its orbit.

The technique was first used in 1838 by Freidrich Wilhelm Bessel (1784-1846) to deduce that the star 61 Cygni lies about 10 ly from Earth (from Hoyle, 1975).

Consider the greatly exaggerated situation in Fig. 7.2. The Earth is shown in its orbit at two extreme positions 6 months apart, labelled by the letters A and B, and a nearby star is at position S. An observer on Earth, views S with respect to the “fixed” stars a very long distance away, and the direction towards a distant fixed reference star is indicated by the two lines with arrows at their tips. At position A, the star S appears to lie to the right of the fixed background by an angle $\theta /2$. Six months later, owing to the orbital motion of the Earth, the star appears to lie to the left of the fixed background by $\theta /2$. That is, the star has apparently moved through an angle θ with respect to the fixed background in six months. The angle $\theta /2$ is referred to as the parallax of the star.

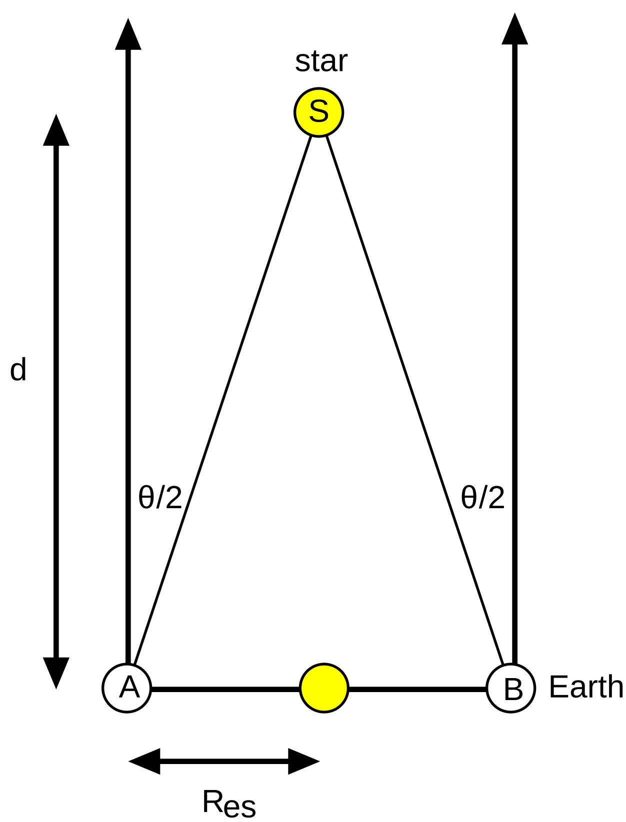


Fig. 7.2 Change in apparent position of a star at S as seen from the Earth over a period of six months. The star is a distance d from the orbit of the Earth, the orbit itself having a radius of R_{es}.

From trigonometry, we know that

$$\tan(\theta/2) = R_{es} / d, \qquad (7.1)$$

where R_{es} is the radius of the Earth-Sun orbit and d is the perpendicular distance of the star from the orbital diameter. Note that the star need not be perpendicular to the plane of the Earth-Sun orbit; the maximum apparent change in the remote star's position will be described by Fig. 7.1 irrespective of the tilt in the Earth's orbit with respect to the star's position.

Now, in practice, the distances d are very large compared to R_{es}. In Table 7.1, the distance from Earth to the nearest star is about 100,000 times R_{es} indicating that θ is tiny. Using the small angle approximation for the tangent function,

$$\tan(\theta) \rightarrow \theta \qquad \text{as } \theta \rightarrow 0, \qquad (7.2)$$

we find that

$$d = 2R_{es} / \theta, \qquad (7.3)$$

where θ is quoted in radians. Of course, the use of trigonometric functions can be avoided entirely if one starts with small angles and defines θ as an angle subtending an arc of length $2R_{es}$ on a circle of radius d.

Astronomical measurements of parallax may be quoted in terms of arc seconds, rather than radians. An arc second is 1/60 of an arc minute, which in turn is 1/60 of a degree. If there are 180 degrees for every π radians, then

$$648000 \text{ arc seconds} = \pi \text{ radians}. \qquad (7.4)$$

The value of d corresponding to $\theta/2$ of exactly 1 arc second is called the parsec (from parallax second), and is equal to 3.26 ly.

Current technology permits the measurement of angular differences of well under 0.1 arc seconds. However, there is a lower limit to the minimum angular difference that can be detected, and this places an upper limit on how far away a star's position can be deduced using parallax. Currently, parallax is useful as a technique only for stars within about 300 ly of Earth.

7.C The Luminosities and Distances of Stars

The temperature on the surface of the Earth averages around 300 ^oK. We know by the warmth given to our planet by the Sun, that the surface temperature of the Sun is considerably warmer - about 5,800 ^oK. Light emitted from a hot object has a distribution of wavelengths that is specific to the object's temperature. For example, while the Sun emits an abundance of light throughout the visible spectrum, a heating element on a stove is more likely to appear red even at its hottest. The surface temperatures of distant stars can be determined by examining the wavelength distribution of their emitted light, and it is found that most stars have surface temperatures in the 2,500 to 30,000 ^oK range.

One cannot equate the surface temperature of stars to their interior temperature. Energy is constantly produced in the interior of stars, and is finally emitted from the stellar surface in the form of light and other radiation. This energy, as we discuss in Chap. 11, originates in nuclear reactions that proceed at temperatures much higher than 10^4 ^oK. It is estimated from simulations of the generation and transport of energy in the Sun that its interior temperature is in the 15 x 10^6 ^oK range, or about 2000 times the surface temperature. Massive stars, particularly near the end of their lifetimes, may have interior temperatures an order of magnitude or more higher than the Sun.

The total energy emitted from the surface of a star per unit time, or the total power of the star, is referred to as its *luminosity* L. The luminosity of the Sun, for example, is 3.9 x 10^{26} J/s or watts. The amount of energy from the Sun that reaches a particular planet depends on the distance of the planet from the Sun, since solar energy is emitted in all directions and spreads throughout space. By the time the solar radiation reaches a distance d from the Sun, it has been spread over an area of $4\pi d^2$, as illustrated in Fig. 7.3. The amount of energy per unit time crossing an element of area facing the Sun, but a distance d away from it, is referred to as the flux f.

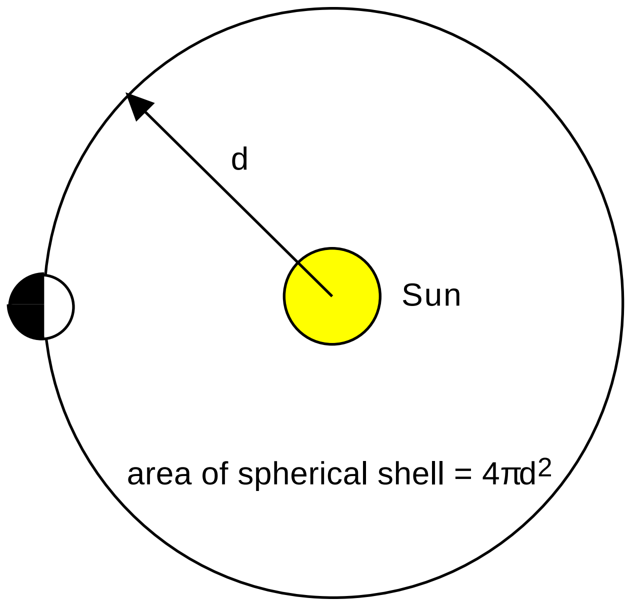


Fig. 7.3 Radiant energy from the Sun is spread over an area of $4\pi d^2$ by the time the radiation is a distance *d* from the Sun.

Clearly, the flux is given by

$$f = L \;/\; 4\pi d^2 \qquad (7.5)$$

and has units of energy per unit area per unit time. Further, there is nothing special about the Sun in this equation, it applies to all stars.

Example 7.1: *If the solar luminosity is 3.9 x 10^{26} J/s, what is the flux from the Sun as seen on the Earth, a distance of 1.5 x 10^{11} m away?*

From the given values of *L* and *d*, the flux is

$$f = L \;/\; 4\pi d^2 = 3.9 \times 10^{26} \;/\; (4\pi\,[1.5 \times 10^{11}]^2)$$

$$= 1400 \text{ J/ s-m}^2.$$

Changing units somewhat, the flux is 1.4 kilowatts per square meter. It takes about 1 kilowatt to power a kettle, so the energy needs of a typical household could be met if *most* of the power could be collected from several square meters of area directly facing the Sun.

The luminosities of nearby stars can be determined accurately since their positions are known from parallax. From such studies, it was discovered that the luminosity of young stars increases steadily with their temperature. Hence, the luminosity of a distant young star can be established if its surface temperature is known, for example, through the spectrum of its emitted light. Once the luminosity of the star is determined, then the distance to the star can be deduced by measuring the flux from the star. That is, we extract L from the temperature, measure f on Earth, and use Eq. (7.5) to solve for d.

The problem with this approach, of course, is that dust and gas between Earth and the star in question tend to reduce f and give a calculated distance that is longer than the true distance. There are ways to overcome these obstacles with careful observation, however, and the flux/luminosity method is used extensively to determine the distances to stars that are beyond the distance for which the parallax method works.

A special set of stars called Cepheid variables are used for evaluating the distance to moderately remote objects. Cepheids are stars whose luminosity oscillates with periods of roughly 1 to 50 days. Earlier this century, astronomer Henrietta Leavitt established that Cepheid luminosity is a unique function of the oscillation period, through her studies of nearby Cepheids with well-determined distances. By measuring the oscillation period of a remote Cepheid, one can obtain its true luminosity, and then find its position using Eq. (7.5). The Cepheid variables are members of what astronomers refer to as *standard candles*, used to determine the distance to remote objects that show no measurable parallax.

Summary

The distance scales in the universe span a very broad range, including

- distance from Sun to Pluto = 6.3×10^{-4} ly
- distance to nearest star = 4.27 ly
- distance to centre of Milky Way = 30,000 ly
- radius of Milky Way = 50,000 ly
- distance to nearest galaxy = 170,000 ly
- distance to galaxies in Hydra = 4,000,000,000 ly,

where 1 ly = 1 light-year = 9.46×10^{12} km.

The distances to nearby stars can be determined using parallax, which is the apparent motion of stars caused by the motion of the Earth in its orbit around the Sun. The apparent position changes by an angle which is given by Eq. (7.3) as

$$\theta = 2R_{es} / d,$$

where R_{es} is the radius of the Earth-Sun orbit, d is the distance to the star, and θ is the maximum angular change in position over six months, quoted in radians. A star that is a *parsec* away from Earth shows a parallax θ /2 of 1 arc second (or 3.26 ly).

The luminosity of a star L is the amount of energy it emits per unit time. The amount of energy per unit time reaching an element of area directly facing the star is called the flux, f, which is given by Eq. (7.5)

$$f = L \ / \ 4\pi d^2,$$

where d is the distance from the star to the observer. This relationship can be used to determine the distance of a star from Earth, if the luminosity of the star can be established, and the flux of its radiant energy on Earth can be measured. The luminosity of young stars is strongly related to their surface temperature. In Cepheid variables, the luminosity oscillates and is a function of the oscillation period.

Further Reading

J. Gribben, *In Search of the Big Bang* (Bantam, New Yrok, 1986), Chap. 2.

F. Hoyle, *Astronomy and Cosmology* (Freeman, San Francisco, 1975), Chaps. 1-3, 8.

W. J. Kaufmann III, *Galaxies and Quasars* (Freeman, San Francisco, 1979), Chaps. 1-2.

Problems

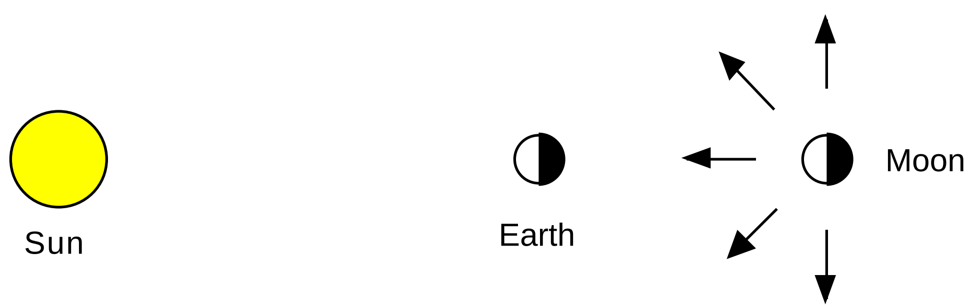
1. Show that 2 arc seconds of apparent motion (θ) corresponds to 3.26 ly of distance (a parsec) in Eq. (7.3).

2. Find the angular change θ for a star 10 ly from Earth.

3. The apparent position of a star is observed to change by a maximum of 0.3 arc seconds in six months. How far away is the star?

4. It has been known for about four centuries that the cube of the radius of a circular planetary orbit is proportional to the square of its period (that is, the proportionality constant is the same for all planetary orbits around the Sun). Using the radius of the Earth's orbit from Appendix C, calculate the orbital radii for Mercury and Venus if they take 88 and 225 days, respectively, to circle the Sun. Compare your results with the known orbital radii.

5. During the full moon, the Sun, Earth and Moon are in the relative positions indicated:



Suppose that the surface of the Moon reflects all of the light striking it from the Sun equally over the hemisphere indicated by the arrows in the diagram. How much reflected energy from the Moon would be received per unit time in a m^2 of area on the Earth directly facing the Moon? Compare this with the power received per m^2 of area on the Earth directly facing the Sun.

6. The nearest pair of co-orbiting neutron stars lies 1,600 ly from Earth. It has been estimated that they could release 10^{45} J of energy if they collide with each other. How much of this energy would reach a m^2 of area on the Earth's surface directly facing the neutron stars? Over what time period would the energy have to arrive to "outshine" the Sun?