Introduction to Astronomy and Cosmology

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University of Manchester, UK

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To the memory of my father, Archibald, who inspired my love of astronomy, to Bernard Lovell who made it possible for me to pursue that love and to my wife, Judy, with love.

Contents

Preface

This textbook arose out of the lecture course that the author developed for first year physics and astronomy undergraduates at the University of Manchester. When it was proposed that all the students should undertake the course, not just those who had come to study astrophysics, several of the physics staff felt that it would not be appropriate for the physics students. But this view was countered with the fact that astronomy is a wonderful showcase for physics and this text covers aspects of physics ranging through Newton's and Einstein's theories of gravity, particle and nuclear physics and even quantum mechanics.

Not all of the material covered by the course was examinable; in particular the descriptions of the planets in our solar system and the background to some of the key discoveries of the last century. However, the author believes that this helps to give life to the subject and so these parts of the course have not been left out. Wherever possible, calculations have been included to illustrate all aspects of the book's material, but the level of mathematics required is not high and should be well within the capabilities of first year undergraduates. The questions with each chapter have come from course examination papers and tutorial exercises and should thus be representative of the type of questions that might be asked of students studying an astronomy course based on this book.

Some textbooks are rightly described as "worthy but dull". It is the author's earnest hope that this book would not fit this description and that, as well a conveying the basics of astronomy in an accessible way, it will be enjoyable to read. If, perhaps, the book could inspire some who have used it to continue their study of astronomy so that, in time, they might themselves contribute to our understanding of the universe, then it would have achieved all that its author could possibly hope for.

Acknowledgements

The author would like to thank those who have helped this book to become a reality: the students who tested the questions and commented on the course material, my colleagues Phillipa Browning, Neil Jackson, Michael Peel and Peter Millington who carefully read through drafts of the text and the team at Wiley; Zoe Mills, Gemma Valler, Wendy Harvey, Andy Slade and Richard Davies who have provided help and encouragement during its writing and production.

No matter how hard we have all tried, the text may well contain some mistakes – for which the author takes full responsibility! To help eradicate them, should there be future editions, he would be most grateful if you could send comments and corrections via the website: http://www.jb.man.ac.uk/public/im/astronomy.html

This will provide additional supporting material for the book and a (hopefully small) list of corrections.

Author's Biography

Ian Morison began his love of astronomy when, at the age of 12, he made a telescope out of lenses given to him by his optician. He went on to study Physics, Mathematics and Astronomy at Oxford and in 1970 was appointed to the staff of the University of Manchester where he now teaches astronomy, computing and electronics.

He is a past president of the Society for Popular Astronomy, one of the UK's largest astronomical societies. He remains on the society's council and holds the post of instrument advisor helping members with their choice and use of Telescopes.

He lectures widely on astronomy, has co-authored books for amateur astronomers and writes regularly for the two UK astronomy magazines. He also writes a monthly sky guide for the Jodrell Bank Observatory's web site and produces an audio version as part of the Jodrell Bank Podcast. He has contributed to many television programmes and is a regular astronomy commentator on local and national radio. Another activity he greatly enjoys is to take amateur astronomers on observing trips such as those to Lapland to see the Aurora Borealis and on expeditions to Turkey and China to observe total eclipses of the Sun.

In 2003 the Minor Planets Committee of the International Astronomical Union named asteroid 15,727 in his honour, citing his work with MERLIN, the world's largest linked array of radio telescopes, and that in searching for intelligent life beyond our Solar System in Project Phoenix. In 2007 he was appointed to the post of Gresham Professor of Astronomy. Dating from 1597, this is the oldest astronomy professorship in the world and was once held by Christopher Wren.

Chapter 1

Astronomy, an Observational Science

1.1 Introduction

Astronomy is probably the oldest of all the sciences. It differs from virtually all other science disciplines in that it is not possible to carry out experimental tests in the laboratory. Instead, the astronomer can only observe what he sees in the Universe and see if his observations fit the theories that have been put forward. Astronomers do, however, have one great advantage: in the Universe, there exist extreme states of matter which would be impossible to create here on Earth. This allows astronomers to make tests of key theories, such as Albert Einstein's General Theory of Relativity. In this first chapter, we will see how two precise sets of observations, made with very simple instruments in the sixteenth century, were able to lead to a significant understanding of our Solar System. In turn, these helped in the formulation of Newton's Theory of Gravity and subsequently Einstein's General Theory of Relativity – a theory of gravity which underpins the whole of modern cosmology. In order that these observations may be understood, some of the basics of observational astronomy are also discussed.

1.2 Galileo Galilei's proof of the Copernican theory of the solar system

One of the first triumphs of observational astronomy was Galileo's series of observations of Venus which showed that the Sun, not the Earth, was at the centre of the Solar System so proving that the Copernican, rather than the Ptolemaic, model was correct (Figure 1.1).

In the Ptolemaic model of the Solar System (which is more subtle than is often acknowledged), the planets move around circular 'epicycles' whose centres move around the Earth in larger circles, called deferents, as shown in Figure 1.2. This enables it to account for the 'retrograde' motion of planets like Mars and Jupiter when they appear to move backwards in the sky. It also models the motion of Mercury and Venus. In their case, the deferents, and hence the centre of their

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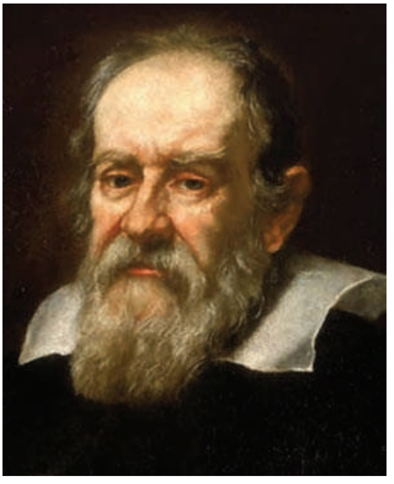

Figure 1.1 Galileo Galilei: a portrait by Guisto Sustermans. Image: Wikipeda Commons.

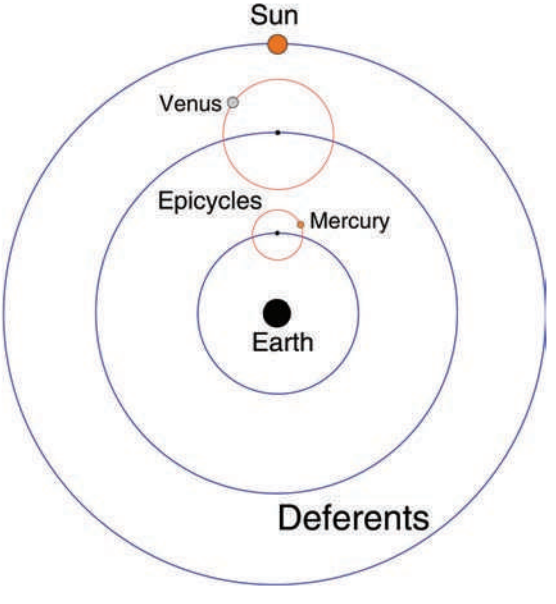

Figure 1.2 The centre points of the epicycles for Mercury and Venus move round the Earth with the same angular speed as the Sun.

epicycles, move around the Earth at the same rate as the Sun. The two planets thus move around in circular orbits, whose centres lie on the line joining the Earth and the Sun, being seen either before dawn or after sunset. Note that, as Mercury stays closer to the Sun than Venus, its deferent and epicycle are closer than that of Venus – in the Ptolemaic model, Mercury is the closest planet to the Earth!

In the Ptolemaic model, Venus lies between the Earth and the Sun and hence it must always be lit from behind, so could only show crescent phases whilst its angular size would not alter greatly. In contrast, in the Copernican model Venus orbits the Sun. When on the nearside of the Sun, it would show crescent phases whilst, when on its far side but still visible, it would show almost full phases. As its distance from us would change significantly, its angular size (the angle subtended by the planet as seen from the Earth) would likewise show a large change.

Figure 1.3 shows a set of drawings of Venus made by Galileo with his simple refracting telescope. They are shown in parallel with a set of modern photographs which illustrate not only that Galileo showed the phases, but that he also drew the changing angular size correctly. These drawings showed precisely what the Copernican model predicts: almost full phases when Venus is on the far side of the Sun and a small angular size coupled with thin crescent phases, having a significantly larger angular size, when it is closest to the Earth.

Galileo's observations, made with the simplest possible astronomical instrument, were able to show which of the two competing models of the Solar System was correct. In just the same way, but using vastly more sophisticated instruments, astronomers have been able to choose between competing theories of the Universe – a story that will be told in Chapter 9.

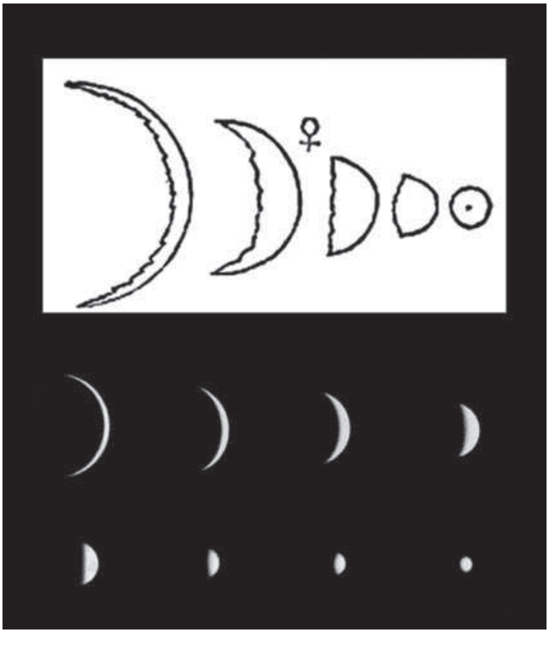

Figure 1.3 Galileo's drawings of Venus (top) compared with photographs taken from Earth (bottom).

1.3 The celestial sphere and stellar magnitudes

Looking up at the heavens on a clear night, we can imagine that the stars are located on the inside of a sphere, called the celestial sphere, whose centre is the centre of the Earth.

1.3.1 *The constellations*

As an aid to remembering the stars in the night sky, the ancient astronomers grouped them into constellations; representing men and women such as Orion, the Hunter, and Cassiopeia, mother of Andromeda, animals and birds such as Taurus the Bull and Cygnus the Swan and inanimate objects such as Lyra, the Lyre. There is no real significance in these stellar groupings – stars are essentially seen in random locations in the sky – though some patterns of bright stars, such as the stars of the 'Plough' (or 'Big Dipper') in Ursa Major, the Great Bear, result from their birth together in a single cloud of dust and gas.

The chart in Figure 1.4 shows the brighter stars that make up the constellation of Ursa Major. The brightest stars in the constellation (linked by thicker lines) form what in the UK is called 'The Plough' and in the USA 'The Big Dipper', so called after the ladle used by farmers' wives to give soup to the farmhands at lunchtime. On star charts the brighter stars are delineated by using larger diameter circles

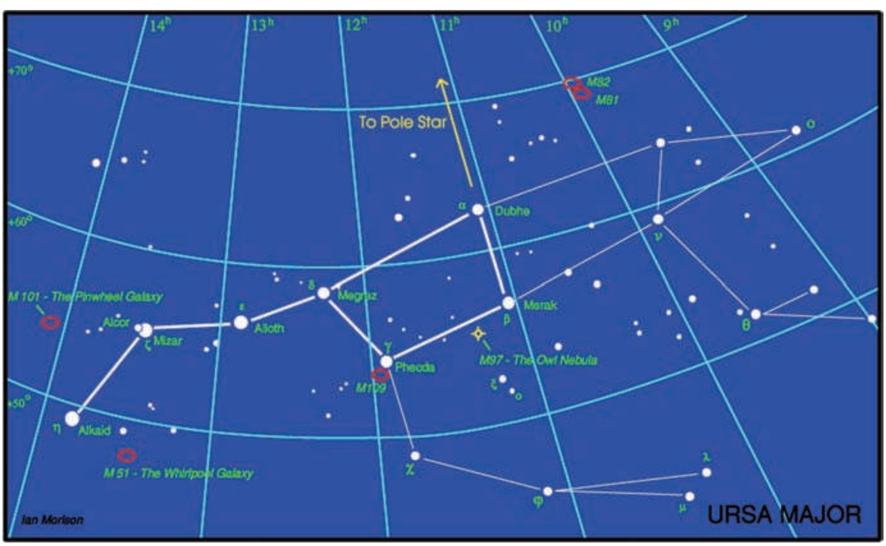

Figure 1.4 The constellation of Ursa Major – the Great Bear.

which approximates to how stars appear on photographic images. The grid lines define the positions of the stars on the celestial sphere as will be described below.

1.3.2 *Stellar magnitudes*

The early astronomers recorded the positions of the stars on the celestial sphere and their observed brightness. The first known catalogue of stars was made by the Greek astronomer Hipparchos in about 130–160 BC. The stars in his catalogue were added to by Ptolomy and published in 150 AD in a famous work called the Almagest whose catalogue listed 1028 stars. Hipparchos had grouped the stars visible with the unaided eye into six magnitude groups with the brightest termed 1st magnitude and the faintest, 6th magnitude. When accurate measurements of stellar brightness were made in the nineteenth century it became apparent that, on average, the stars of a given magnitude were approximately 2.5 times brighter than those of the next fainter magnitude and that 1st magnitude stars were about 100 times brighter than the 6th magnitude stars. (The fact that each magnitude difference showed the same brightness ratio is indicative of the fact that the human eye has a logarithmic rather than linear response to light.)

In 1854, Norman Pogson at Oxford put the magnitude scale on a quantitative basis by defining a five magnitude difference (i.e., between 1st and 6th magnitudes) to be a brightness ratio of precisely 100. If we define the brightness ratio of one magnitude difference as R, then a 5th magnitude star will be R times brighter than a 6th magnitude star. It follows that a 4th magnitude star will be $R \times R$ times brighter than a 6th magnitude star and a 1st magnitude star will be $R \times R \times R \times R \times R$ brighter than a 6th magnitude star. However, by Pogson's definition, this must equal 100 so R must be the 5th root of 100 which is 2.512.

The brightness ratio between two stars whose apparent magnitude differs by one magnitude is 2.512.

Having defined the scale, it was necessary to give it a reference point. He initially used Polaris as the reference star, but this was later found to be a variable star and so Vega became the reference point with its magnitude defined to be zero. (Today, a more complex method is used to define the reference point.)

1.3.3 *Apparent magnitudes*

It should be noted that the observed magnitude of a star tells us nothing about its intrinsic brightness. A star that appears bright in the sky could either be a faint star that happens to be very close to our Sun or a far brighter star at a greater distance. As a result, these magnitudes are termed **apparent magnitudes**. The nominal apparent magnitudes relate to the brightness as observed with instruments having the same wavelength response as the human eye. As we shall see in Chapter 6, one can also measure the apparent magnitudes as observed in specific wavebands, such as red or blue, and such measurements can tell us about the colour of a star.

Some stars and other celestial bodies, such as the Sun, Moon and planets are much brighter than Vega and so can have negative apparent magnitudes. Magnitudes can also have fractional parts as, for example, Sirius which has a magnitude of −1.5. Figure 1.5 gives the apparent magnitudes of a range of celestial bodies from the brightest, the Sun, to the faint dwarf planet, Pluto.

1.3.4 *Magnitude calculations*

From the logarithmic definition of the magnitude scale two formulae arise.

The first gives the brightness ratio, R, of two objects whose apparent magnitude differs by a known value Δm:

$$R = 2.512^{\Delta m} \tag{1.1}$$

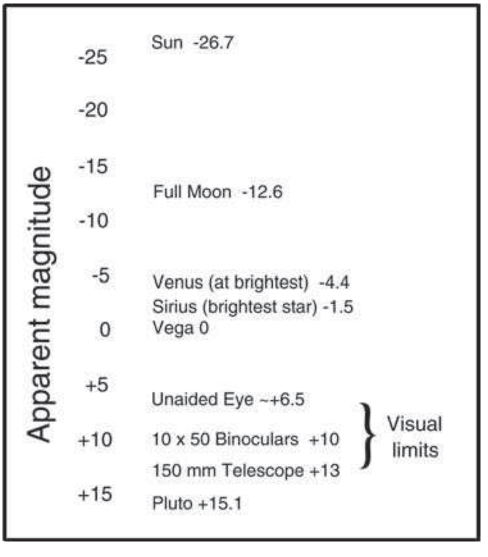

Figure 1.5 Some examples of apparent magnitudes.

The second gives the magnitude difference between two objects whose brightness ratio is known. We can derive this from the first as follows:

Taking logarithms to the base 10 of both sides of Equation (1.1) gives:

$$\begin{aligned} \mathrm{Log}_{10} R &= \mathrm{Log}_{10}(2.512) \times \Delta m \\ \mathrm{Log}_{10} R &= 0.4 \times \Delta m \\ \Delta m &= \mathrm{Log}_{10} R / 0.4 \\ \Delta m &= 2.5 \times \log_{10} R \end{aligned}$$

As an example, using values from Figure 1.5, let us calculate how much brighter the Sun is than the Moon.

The difference in magnitudes is $26.7 - 12.6 = 14.1$, so

$$\begin{aligned} R &= 2.512^{14.1} \\ &= 436\,800 \end{aligned}$$

The Sun is ~440 000 times brighter than the full Moon.

This perhaps emphasizes the fact that the eye can cope with an incredibly wide range in brightness: we can see a surprising amount with the light of the full Moon and yet can cope with the light on a bright sunny beach.

Consider a second example: a star has a brightness which is 10 000 times less than Vega (magnitude 0). What is the magnitude of the star?

There is a quick way to do this: 10 000 is 100×100. However, a ratio of 100 in brightness is 5 magnitudes so this star must be 10 magnitudes fainter than Vega and will thus be 10th magnitude.

Using the formula:

$$\begin{aligned} \Delta m &= 2.5 \times \log_{10}(10\,000) \\ &= 2.5 \times 4 \\ &= 10 \end{aligned}$$

gives the same result.

1.4 The celestial coordinate system

The early star catalogues located the positions of the stars on the celestial sphere using a slightly different coordinate system than we do now. The modern coordinate system is analogous to the way in which we define positions on the surface of the Earth and uses the orientation of the Earth in space as its basis. The Earth's rotation axis is extended up and down to the points where it reaches our imaginary celestial sphere. The point where the axis meets the sphere directly above the North Pole is called the **North Celestial Pole** and that below the South Pole is the **South Celestial Pole.** If the Earth's equator is extended outwards it will cut the celestial sphere into two – into the northern and southern hemispheres – forming the **Celestial Equator** (see Figure 1.6).

There is one path around the celestial sphere that is of great importance: that of our Sun. If the Earth's rotation axis was at right angles to the plane of its orbit around the Sun, the Sun's path would trace out the Celestial Equator but, as the axis of the Earth's rotation is inclined to its orbital plane by an angle of 23.5°, the path of the Sun is a great circle, called the **ecliptic,** which is inclined by 23.5° to the Celestial Equator. The Sun spends half the year in the southern half of the celestial sphere and the other half in the northern. Its path thus crosses the Celestial Equator twice every year: once at the **vernal equinox,** on March 20 or 21, as it comes into the northern hemisphere and 6 months later when, at the **autumnal equinox** on September 22 or 23, it returns to the southern hemisphere.

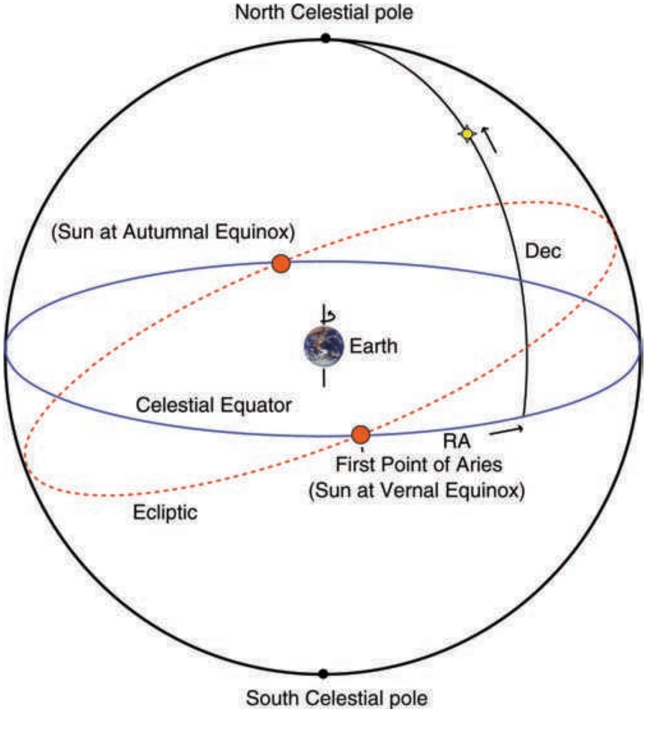

Figure 1.6 The celestial sphere.

Just as a location on the Earth's surface has a 'latitude', defined as its angular distance from the equator towards the poles, so a star has a '**declination**'" (Dec) given as an angle which is either positive (in the northern hemisphere) or negative (in the southern hemisphere). The 'Pole Star' in the northern sky is close to the North Celestial Pole at close to +90 declination and the region at the South Celestial Pole (where there is no bright star) is at −90 declination.

The second coordinate proves to be rather more difficult. On the Earth we define the position of a location round the Earth by its longitude. However, there has to be some arbitrary zero of longitude. It was sensible that the zero of longitude, called the **Prime Meridian**, should pass through a major observatory and that honour finally fell to the Royal Greenwich Observatory in London.

As referred to above, the path of the Sun gives two defined points along the Celestial Equator that might sensibly be used as the zero of **Right Ascension** (RA) – the points where the ecliptic crosses the Celestial Equator at the vernal and autumnal equinoxes. The point where the Sun moves into the northern hemisphere was chosen and was given the name **'The first point of Aries'** as this was the constellation in which it lay. Star positions are measured eastwards around the celestial sphere from the first point in Aries to give the star's RA.

However, for reasons that will become apparent when we describe how star positions are measured, RA is not measured in degrees but in time, with 24 h equivalent to 360°. Hence, the celestial sphere is split into 24 segments each of 1 h and equivalent to 15° around the Celestial Equator.

Angular measure

A great circle measures 360° in angular extent.
Each degree is divided into 60 arcmin.
Each arcminute is divided into 60 arcsec.
There are then 3600 arcsec in 1°.
(Arcseconds and arcminutes can also be written as seconds of arc and minutes of arc, respectively.)

1.5 Precession

Should you locate the point where the Sun crosses the ecliptic at the vernal equinox on a star chart (with position: RA = 0:00 h, Dec = 0.0°), you might be surprised to find that it is not in Aries, but in the adjacent constellation Pisces. This is the result of the precession of the Earth's rotation axis in just the same way that the axis of rotation of a spinning top or gyroscope is seen to precess. The precession rate is slow; one rotation every ~26 000 years, but its effect over the centuries is to change the positions of stars as measured with the co-ordinate system described above, which is fixed to the Earth. Consequently, a star chart is only valid for one specific date. Current star charts show the positions of stars as they were at the start of the millennium and will state 'Epoch 2000' in their titles. One result of precession is that the Pole Star is only close to the North Celestial Pole at this particular moment in time in the precession cycle (Figure 1.7). In ~12 000 years, the bright star Vega will be near the North Celestial Pole instead (though by no means as close). It also means that constellations currently not observable from the UK will become visible above the southern horizon.

Interestingly, it is stars in the part of the sky that was visible to ancient astronomers and which were thus included in the constellations that enable us to estimate not only the time but also the latitude from which the constellations were delineated and named.

A region of about 36° radius in the southern sky did not contain any of the original 48 constellations implying that this region was invisible to those who

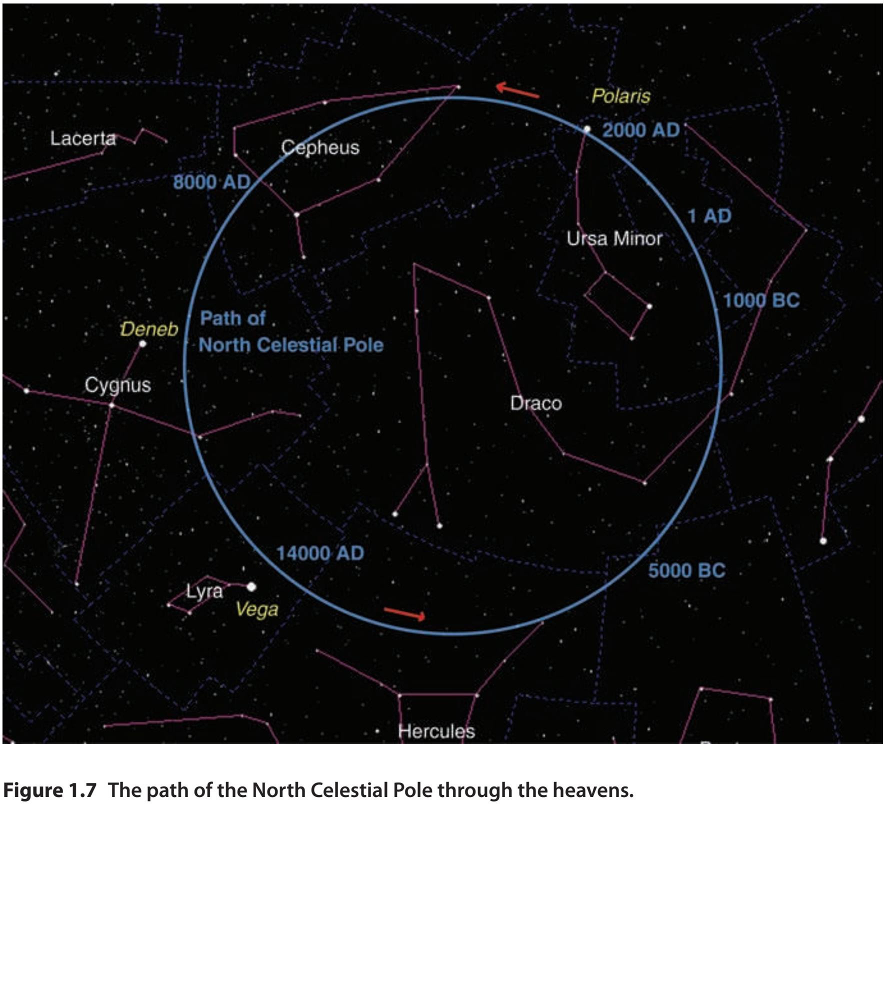

Figure 1.7 The path of the North Celestial Pole through the heavens.