Cambridge University Press
978-0-521-82196-4 - Astronomy: A Physical Perspective
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Excerpt
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Chapter 1

Introduction

1.1 An understandable universe

Our curiosity about the world around us is most naturally manifested when we look up at the night sky. We don't need any special instruments to tell us something interesting is going on. However, only with the scrutiny afforded by a variety of instruments can these patches of light, and the dark regions between them, offer clues about their nature. We have to be clever to collect those clues, and just as clever to interpret them. It is the total of these studies that we call *astronomy*.

We are fortunate to live in an era of extraordinary astronomical discovery. Some have even called this the 'Golden Era of Astronomy'. For centuries astronomers were restricted to making visual observations from the surface of the Earth. We can now detect virtually any type of radiation given off by an astronomical object, from radio waves to gamma rays. Where necessary, we can put observatories in space. For the Solar System, we can even visit the objects we are studying.

For all of these capabilities, there is a major drawback. We cannot do traditional experiments on remote astronomical objects. We cannot change their environment and see how they respond. We must passively study the radiation that they give off. For this reason, we refer to astronomy as an *observational* science rather than an *experimental* one. It is because of this difference that we must be clever in using the information that we do receive. In this book, we will see what information we can obtain and how the clues are processed. We will see that, in exchange for the remoteness of astronomical objects, we get to study a large number of objects under a variety of conditions.

One of the most fascinating aspects of astronomy is that many phenomena can be understood in terms of relatively simple physics. This does not mean that we can explain every detail. However, we can explain the basic phenomena. In this book, we emphasize the application of a few physical principles to a variety of situations. For this purpose, some background in physics is needed. We assume that the reader has had an introductory course in classical physics (mechanics, electricity and magnetism, thermodynamics). We also use quite a bit of modern physics (relativity, atomic and nuclear physics). The modern physics will be developed as we need it. In addition, a familiarity with the concepts of calculus is assumed. While most of the material can be mastered without actually taking derivatives and working out integrals, the concepts of derivatives as representing changes and integrals as representing sums are used. The reader may also note a variation in the mathematical level from subject to subject. This is because the goal in writing this book is to present each astronomical subject at the simplest level that still provides for a reasonable understanding.

In organizing an astronomy text, one important question is where to put the material on the Solar System. The traditional approach has been to place the Solar System first. This allows the student to start with familiar, nearby objects first and work out from there. The disadvantage is that we use techniques to study the Solar System that we cannot use on more distant objects. In this book we place the Solar System last. This allows the student to form a better idea of how astronomy is done on remote objects. We can also use the physics that we develop in studying stars and other astronomical objects to give us a better appreciation for how the Solar System works. Finally, putting the Solar System at the end allows for a discussion of the formation of the Solar System, utilizing things that we learn about star formation.

We start with stars, those points of light in the night sky. This allows us to develop physical ideas (radiation, gravity, etc.) that we will use throughout the book. We will see how we obtain information about the basic properties of stars: temperatures, sizes, masses, compositions. The Sun will then be looked at as an example of a typical star. We will then put these stellar properties together, and describe a theoretical picture of how stars work. In Part II we will develop the special and general theories of relativity, to allow us to understand better the unusual states that are reached when stars die. We will discuss the normal lifetime of stars and stellar old age and death in Part III. In stellar death, we will encounter a variety of exotic objects, including neutron stars and black holes.

In Part IV, we will look at the contents of our own galaxy, the Milky Way. We will start by looking at the interstellar medium and then at how stars are formed. Finally, we will look at how stars, gas and dust are organized into a galaxy.

In Part V, we will look at the overall structure of the universe, including the arrangement of galaxies and their motions. We will start by looking at other galaxies. We will also study active galaxies, which give off much more energy than our own. We will follow the trail of active galaxies from starburst galaxies to quasars. The early history of the universe (the big bang) will be described, and we will see can how we look for clues about the past and its ultimate fate. In talking about the early universe, we will encounter one of the most fascinating recent developments, the merging of physics on the largest and smallest scales. This involves blending theories on the ultimate structure of matter with theories of the overall structure of the universe.

In the final part, Part VI, we will study the Solar System. We will see how the formation of the Solar System can be fit into ideas already developed about star formation. We will encounter a variety of surfaces, atmospheres and rings that can be explained by using the physical ideas already developed. We will also look at the origin of life on the Earth and the search for life elsewhere in the Solar System and in our galaxy.

Although the organization of the book is around astronomical objects, the presentation of the topics emphasizes the application of the underlying physics. Almost all of the physical tools will apply to several topics. A great strength of physical theories is the great range of their applicability. For example, orbital mechanics can tell us about the masses of binary stars or help us plan a probe to Mars. Radiative transfer helps us understand the appearance of the Sun, the physical conditions in interstellar clouds or the temperatures of planetary atmospheres. Tidal effects help us explain the appearance of certain galaxies, rings around some planets and the internal heating of Io, one of Jupiter's moons.

Though understanding how astronomical objects work is our goal, astronomy's foundation is observation. We will see how observations often define a problem – the discovery of new phenomena. Observations usually provide a check on theories that are developed. In this book, we will therefore emphasize the interplay between observation and understanding the physics. We will see how some observations yield numbers with great precision, while others only give order of magnitude estimates, but both types can be equally important for deciding between theories.

With the current pace of astronomical discovery, there is an important caution to keep in mind. When you read an introductory text on classical physics, you are reading about theories that were worked out and tested over a century ago. No question is raised about the correctness of these theories. In astronomy, new ideas or new observations are constantly changing the thinking about various problems. Many of the topics discussed in this book are far from being settled. Sometimes, more than one explanation is presented for a given phenomenon. This is done either because we don't know which is correct, or to show how one theory was eliminated in favor of another. Just because this is a "text" it doesn't mean that it has the final word. If you understand where the problems lie, and the reasoning behind the explanations, then you will be able to follow future developments as they appear in scientific magazines or journals.

This, then, is the plan. As you study the material that follows, see how far you can go with a little bit of physics and a lot of curiosity and ingenuity.

1.2 The scale of the universe

The objects that we encounter in astronomy are, for the most part, so large or distant that it is hard to comprehend their size or distance. We will take a brief look at the distances involved when we study different astronomical objects. We will talk about these sizes in more detail when we encounter the objects in the rest of the book. In Fig. 1.1, we show a selection of objects on the various scales.

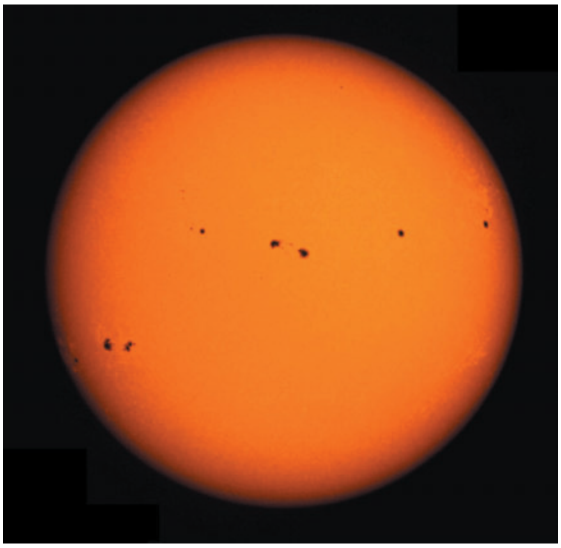
We start by looking at the Earth and Moon (Fig. 1.1a). Earth has a radius of about 6000 km. Its mass is about 6×10^{27} grams. The Moon is about 4×10^{5} km from the Earth. It takes about one second for light to travel from the Moon to the Earth.

We next look at the Sun (Fig. 1.1b). It is 1.5×10^{8} km from the Earth, meaning it takes light over eight minutes to get here from the Sun. We call this distance the Astronomical Unit. Its mass is 2×10^{33} g. This turns out to be average for a star, and we even use it as a convenient measure. The Sun's radius is 6×10^{5} km.

We see how far out the planets are by looking at Pluto (Fig. 1.1c). It is almost 40 astronomical units from the Sun, meaning it takes light almost six hours to reach us from Pluto.

By the time we reach the nearest stars, they are so far away that it takes light years to reach us. So we measure their distance in light years

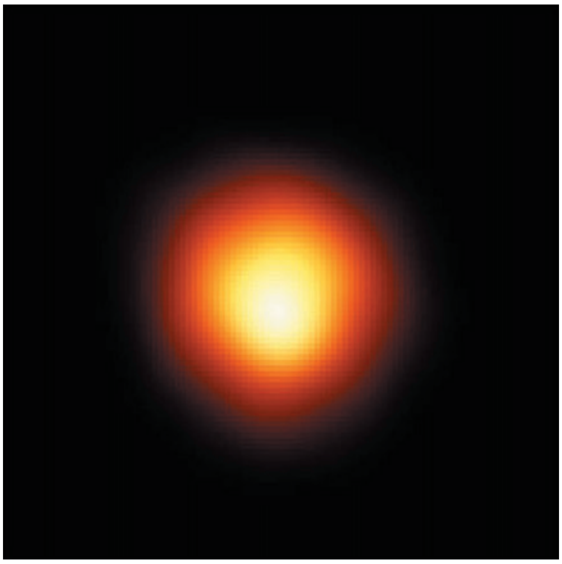
(a)



(b)

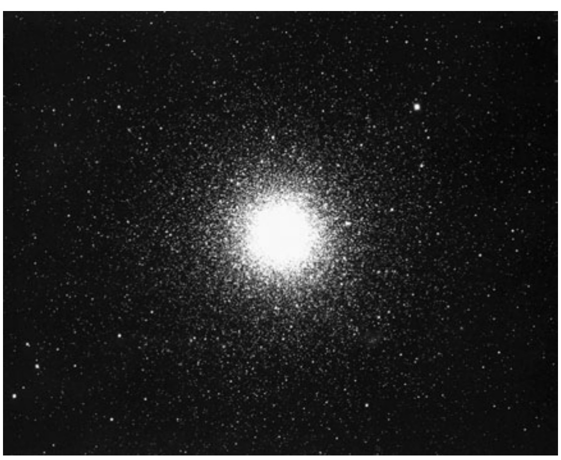
(c)

Fig 1.1. Photographs to show different astronomical scales. (a) The Earth and Moon from space. [NASA] (b) The Sun. [NOAO/AURA/NSF] (c) Pluto and its moon, Charon. [STScI/NASA]

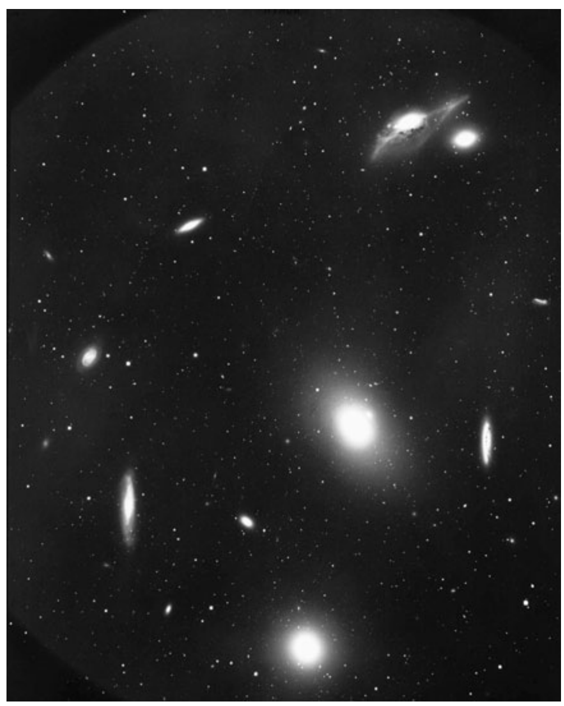


(d)

(f)



(e)



(g)

Fig 1.1. (*Continued*) (d) Betelgeuse. [STScI/NASA] (e) A globular cluster. [NOAO/AURA/NSF] (f) The Andromeda Galaxy. [NOAO/AURA/NSF] (g) A cluster of galaxies. [NOAO/AURA/NSF]

(almost 10^{13} km) or parsecs (one parsec is about three light years). Fig. 1.1(d) shows a star about as far away as we can take direct picture of its disk. It is the giant star Betelgeuse in the constellation of Orion, some 500 parsecs away, meaning it took the light for that image about 1500 years to reach us.

The next largest scale are groupings of stars called clusters, such as the globular cluster in Fig. 1.1(e). These objects may contain 10^5 stars, and have extents of tens of parsecs. Because of their collective brightness, we can see them far away, even on the other side of our galaxy. In fact, they tell us that we are 8500 parsecs from our galactic center. That means it takes light from the galactic center 25 000 years to reach us.

In Fig. 1.1(f), we leave the Milky Way Galaxy and look at one of our neighbors, the Andromeda Galaxy, which we think looks a lot like our galaxy would look if we could view it from outside. It is so far away that we measure its distance in thousands of parsecs, kiloparsecs. It is 700 kiloparsecs away, meaning it takes light about 2.1 million years to reach us. It is about 20 kiloparsecs across. It has a mass equal to more than 10^{11} Suns. When we look at larger scales, we will see that galaxies are like the molecules of the universe.

Our final step is to a cluster of galaxies, such as the Virgo Cluster, which is shown in Fig. 1.1(g). These clusters are groupings of thousands of galaxies, and are typically millions of parsecs across. We detect some clusters so far away that their light has taken a significant fraction of the age of the universe (which we think is about 14×10^9 yr) to reach us.

As we have said, this description is just to give you a flavor of the sizes involved. The individual objects will be discussed in detail throughout this book.

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Part I

Properties of ordinary stars

Chapter 2

Continuous radiation from stars

2.1 Brightness of starlight

When we look at the sky, we note that some stars appear brighter than others. At this point we are not concerned with what causes these brightness differences. (They may result from stars actually having different power outputs, or from stars being at different distances.) All we know at first glance is that stars *appear* to have different brightnesses.

We would like to have some way of quantifying the observed brightnesses of stars. When we speak loosely of brightness, we are really talking about the *energy flux*, f, which is the energy per unit area per unit time received from the star. This can be measured with current instruments (as we will discuss in Chapter 4). However, the study of stellar brightness started long before such instruments, or even telescopes, were available. Ancient astronomers made naked eye estimates of brightness. Hipparchus, the Greek astronomer, and later Ptolemy, a Greek living in Alexandria, Egypt, around 150 AD, divided stars into six classes of brightness. These classes were called *magnitudes*. This was an ordinal arrangement, with first-magnitude stars being the brightest and sixth-magnitude stars being the faintest.

When quantitative measurements were made, it was found that each jump of one magnitude corresponded to a fixed *flux ratio*, not a flux difference. Because of this, the magnitude scale is essentially a logarithmic one. This is not too surprising, since the eye is approximately logarithmic in its response to light. This type of response allows us to see in very low and very high light levels. (We say that the eye has a large dynamic range; this range is achieved at a sacrifice in our ability to discriminate small brightness differences.)

The next step was to make the scale continuous, so that, for example, we could accurately describe the brightness of a star that is between second and third magnitude. In addition we would like to extend the scale, so that the brightnesses of stars that we can see only through telescopes can be included. It was found that a difference of five magnitudes corresponds to a factor of 100 in brightness. In setting up the magnitude scale, this relation is defined to be exact.

Let b_1 and b_2 be the observed brightnesses of two stars, and let m_1 and m_2 be the corresponding magnitudes. The statement that a five-magnitude difference gives a flux ratio of 100 corresponds to

$$b_1/b_2 = 100^{(m_2 - m_1)/5} \tag{2.1}$$

We can see that this equation guarantees that each time $m_2 - m_1$ increases by five, b_1/b_2 decreases by a factor of 100. Remember, *increasing* the brightness *decreases* the magnitude. This point sometimes confuses even professional astronomers. That is why you will often hear astronomers talking about being so many magnitudes "brighter" or "fainter" than something else, without worrying about whether that makes m larger or smaller.

Equation (2.1) gives brightness ratios in powers of 100, but we usually work in powers of ten. To convert this we write 100 as 10^2, so equation (2.1) becomes

$$b_1/b_2 = 10^{(m_2 - m_1)/2.5} \tag{2.2}$$

This equation can be used to calculate the brightness ratio for a given magnitude difference. If we want to calculate a magnitude difference for a given brightness ratio, we take the logarithm (base 10) of both sides, giving

$$m_2 - m_1 = 2.5 \log_{10}(b_1/b_2) \tag{2.3}$$

To see how this works, let's look at a few simple examples. On the original scale, the magnitude range for stars visible to the naked eye is 1 to 6 mag. This corresponds to a brightness ratio

$$b_1/b_2 = 10^{(6-1)/2.5} = 10^2$$

The largest ground-based telescopes extend our range from 6 to 26 mag. This corresponds to an additional brightness ratio

$$b_1/b_2 = 10^{(26-6)/2.5} = 10^8$$

We can also find the magnitude difference, Δm, corresponding to a factor of 10^6 in brightness:

$$\Delta m = 2.5 \log_{10}(10^6) = (2.6)(6) \text{ mag} = 15 \text{ mag}$$

So, we have taken the original six magnitude groups and come up with a continuous scale that can be extended to fainter or brighter objects. Objects brighter than magnitude 1 can have magnitude 0 or even negative magnitudes.

2.2 The electromagnetic spectrum

Thomas Young first demonstrated interference effects in light, showing that light is a wave phenomenon. If we pass light through a prism (Fig. 2.1), we can see that the light is spread out into

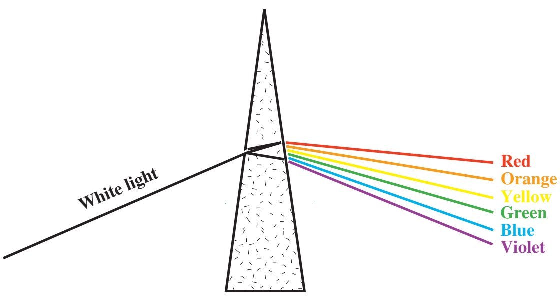

Fig 2.1. The colors of visible light. When light passes through a prism, the rays of different colors are deflected by different amounts. The colors are listed, from top to bottom, in order of decreasing wavelength.

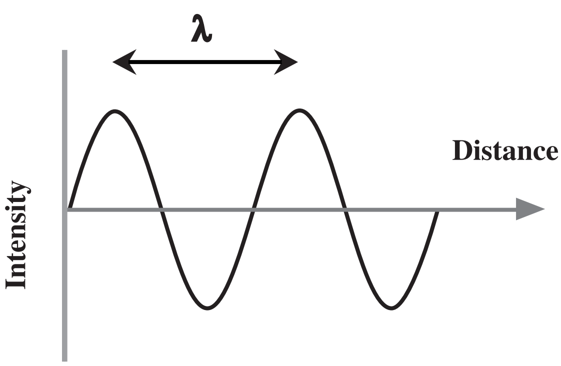

Fig 2.2. The wavelength λ is the distance between the corresponding points of a wave in successive cycles. For example, it can be from peak to peak.

different colors. We call this range of colors the *visible spectrum*. These colors have different wavelengths (Fig. 2.2). For example, the red light has a wavelength around 650 nm ($= 650 \times 10^{-9}$ m $= 6.5 \times 10^{-7}$ m $= 6.5 \times 10^{-5}$ cm). (We used to express this in terms of angstrom units, after the Swedish physicist A. J. Ångstrom, but this is not part of the official metric system. The angstrom was a convenient unit, since it is about the size of a typical atom.) At the opposite end of the visible spectrum from red is violet, with a wavelength of about 400 nm.

In a vacuum, all wavelengths of light travel at the same speed $c = 3.0 \times 10^{10}$ cm/s (3.0×10^8 m/s, 3.0×10^5 km/s). At this speed light can travel a distance equal to the Earth's circumference 7.5 times per second. A light pulse take 1.3 s to reach the Moon. The speed of light is so large that measuring it requires the accurate measurement of time over short intervals, or the passage of light over long distances. Until late in the 19th century, the large distances between astronomical objects were used to provide reasonably long travel times. More recently, accurate timing devices have made laboratory measurements feasible.

All waves have a frequency associated with them. The frequency tells us the number of oscillations per second, or the number of crests that pass per second. The product of the wavelength λ and the frequency ν gives the speed of the wave. That is,

$$\lambda \nu = c \tag{2.4}$$