1

Seeing through the fog

Prelude

What is the farthest you can see with the naked eye? This is a familiar trick question and the answer, of course, is an astronomical one. If your eyesight is good, and the sky is dark, you can see as far as the Andromeda galaxy, two million light years away. Huge though this distance seems, it is a tiny fraction of the size of the known Universe, which we now believe to be some ten to twenty thousand million light years in extent. One of the purposes of this book is to show, in outline, how it is possible to arrive at such results and to give some idea as to how reliable they are.

Because the Universe is so vast, it is impossible to grasp its scale expressed in kilometres, or even in light years, so it is useful to think of the Universe as a hierarchy, building up gradually from human scales to astronomical ones, always relating the next distance to the previous one. One way of doing this is shown in Table 1.1, which starts with an hour's train journey. A hierarchy is also a useful way of thinking about both the structure and the contents of the Universe (Appendix 1). On the smallest scale there is our solar system and many double and multiple star systems. On larger scales, stars are often found in clusters of from a few hundred up to a million stars. These clusters, together with individual stars, form the building blocks of galaxies, which themselves are grouped into clusters and superclusters on scales up to the size of the observable Universe. As we move up in scale, the units of distance used on Earth become inconveniently small, and astronomers introduce new ones: the astronomical unit, the light year and the parsec.

The *astronomical unit* (AU) is the semi-major axis of the Earth's orbit around the Sun, and is approximately 150 million kilometres. It is commonly used as the unit for describing distances within the solar system, and also for those in binary star systems. The solar system has a diameter of

Table 1.1. *Some astronomical distances and sizes. Note that* $R_*/R_\odot \gg AU/R_E \gg R_A/R_G$. *That is, stellar separations are relatively larger than any other astronomical distance. In the entry for* R_V, $h = H_0/100\,km\,s^{-1}\,Mpc^{-1}$ *where* H_0 = *Hubble's constant (Chapter 15)*

Distance or size	Symbol	Value	Relative value
London to Brighton	R_L		80 km
Earth radius	R_E	6371 km	80 R_L
Earth to Moon (nearest neighbour)	R_M	384,000 km	60 R_E
Solar radius	$R_\odot$	696,000 km	100 R_E
Earth to Sun (astronomical unit)	AU	149.6×10^6 km	400 R_M ($2 \times 10^4\, R_E$)
Solar system radius	R_S	5.9×10^9 km	40 AU
One parsec	pc	3.0856×10^{16} m	206265 AU
Nearest star	R_*	1.275 pc	7000 R_S ($7 \times 10^7\, R_\odot$)
Sun to Galactic Centre	R_G	10 kpc (10^4 pc)	8000 R_*
Andromeda galaxy (radius of Local Group)	R_A	670 kpc	70 R_G
Nearest cluster of galaxies (Virgo)	R_V	$11\,h^{-1}$ Mpc	30 R_A
Radius of observable Universe	R	3000 Mpc	300 R_V

about 100 AU and typical binary star separations are tens or hundreds of AU.

Interstellar distances are usually expressed in *light years* or in *parsecs.* Although they differ numerically only by a factor of about 3, they are conceptually quite different. A light year is the distance travelled by light in one year, and is about 10 million million kilometres. A parsec is defined geometrically (see Chapter 7) as the distance at which 1 AU subtends an angle of 1 arcsecond, and is about 30 million million kilometres. Because 1 radian = 206 265 arcseconds, a parsec can also be expressed as 206 265 AU (Chapter 7). Stellar separations are typically a few parsecs. A galaxy has a typical size of about 100 kiloparsecs (kpc) and galactic separations are typically a few megaparsecs (Mpc). The size of the observable Universe is about 3000 Mpc. More precise values of these new units are given in Table 1.2.

We will look at the different scales in the Universe in different detail, jumping straight from the top of the Earth's atmosphere to the nearest stars without pausing in the solar system. We will spend most of our time among

Table 1.2. *Units of distance in astronomy* (see text)

1 astronomical unit (AU) = 149.6×10^6 km
1 light year (ly) = 9.460×10^{12} km $\simeq 6 \times 10^4$ AU
1 parsec (pc) = 206 265 AU ($\simeq 2 \times 10^5$ AU) = 3.086×10^{13} km $\simeq 3\frac{1}{4}$ ly

the stars, but will also discuss the general properties of galaxies, those great collections of stars, dust and gas of which Andromeda and our own Milky Way are local examples. At the end of the book we will extend our grasp to the whole Universe and reach back in time to the origins of the universal microwave background – the last whisper of the Big Bang which astronomers believe began the Universe.

Throughout, the emphasis will be on what can be, and is, observed, so I will spend the first half of the book discussing how astronomers observe the Universe. This is not, however, a practical handbook for observers, either amateur or professional – it is a theoretician's view of observational astronomy, in which I will concentrate on the principles involved rather than on all the practical details.

1.1 The naked-eye sky

If you are lucky enough to live far from city lights, and look up into a clear, dark sky, your first impression will be of a myriad points of light: the stars. As your eyes become accustomed to the dark, you will notice that some of them are concentrated into a band across the sky, faint in the northern hemisphere but quite marked in the southern hemisphere. This is the Milky Way, our own local galaxy, whose bright central regions are in the southern sky. Some brighter 'stars' will gradually reveal themselves by their motion against the star background as planets (from the Greek word *planetes*, meaning 'wanderers'). Very occasionally one of the points will display a fuzzy tail that shows it to be a comet. Much more commonly, fuzzy patches will turn out to be star clusters or gas clouds (such as the nebula in the sword of Orion).†

On moonlit nights, the Moon itself is the dominant object; because scattered moonlight makes the background sky much brighter, we can then

† The eighteenth-century French comet-hunter Messier found so many fuzzy objects that weren't comets that he compiled a list of about 100 of them, as objects for comet-seekers to avoid! The Messier catalogue contains many of the brightest gas clouds, star clusters and galaxies, and the names are still used; the Orion nebula is M42.

only see the brightest stars and planets, especially in regions of the sky close to the Moon. In the daytime sky, all the stars disappear: the Sun is so bright that only the Sun (and the Moon when up) are normally visible, although Venus can be seen if you know where to look. This is not only because the Sun is bright but (as for the Moon) because the sky itself is bright: scattered sunlight causes it to appear blue (or grey on a cloudy day); I will explain this in Section 1.3.

If you look at the sky for long enough, you will find that it is constantly changing, on many timescales, and the changes reveal new objects and phenomena. 'Shooting stars' or *meteors* streak across the sky in a few seconds; these are the debris of dead comets, and other interplanetary dust particles, burning up as they enter the atmosphere. Typically, you might see about six per hour; occasional rich showers may display one a minute or more. Frequently you will see a more slowly moving point of light: an artificial satellite, crossing the sky in 15–20 minutes.

After a few hours, you will become aware of the rotation of the Earth: at night, the whole pattern of stars will move westward across the sky at a rate of about 15°/hour (15°corresponds to about the width of two fists held together at arm's length); the Sun shows the same motion during the day, as does the Moon when visible. But the Moon has its own motion against the star background, which accounts for the fact that it sometimes appears in daytime and sometimes at night: it moves eastward at a rate of about 13°/day, rising nearly an hour later each day.

The planets, comets and the Sun itself also have their own motions relative to the stars, but they are much slower and become apparent only after weeks or months. The planets and comets move at comparable rates against the stars, from about 30°/week for Mercury to 1°/month for Saturn. The Sun, because of its annual motion around the Earth, has a motion of about 1°/day, or 30°/month. I will discuss the Sun's motion in more detail in Section 7.3.

1.2 Absorption in the Earth's atmosphere

All these qualitative features can be discovered by simple naked-eye observations, and have been known for thousands of years. To learn more about the Universe, we must begin to make more quantitative measurements. A fundamental constraint on the observational astronomer is then imposed by the Earth's atmosphere, which absorbs all radiation from space except in two narrow windows in the visual and radio regions (Fig. 1.1). Of course, rockets and satellites now allow observation from above the atmosphere over the

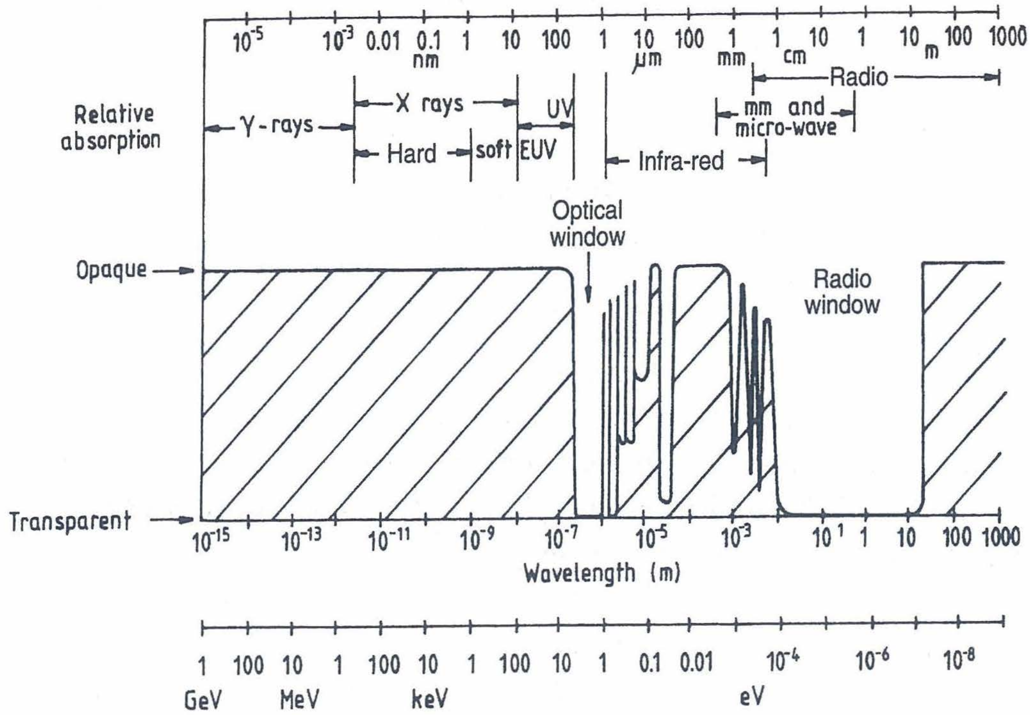

Fig. 1.1. The electromagnetic spectrum, showing the absorption by the Earth's atmosphere. At the Earth's surface only radiation in the radio, infrared and optical windows can be detected. The divisions between the various named wavebands are somewhat arbitrary, and there is some overlap in usage. The wavelength scale is shown at the top of the diagram in the units normally employed in the wavebands shown below them. At the very shortest wavelengths it is more common to describe photons by their energies, shown on the lowermost scale. Even above the atmosphere, the interstellar medium in our Galaxy effectively cuts out radiation in the EUV and soft X-ray region, and is also opaque to the very lowest energy radio waves and the very highest energy gamma-rays.

whole range of the electromagnetic spectrum, and many of the most exciting developments in astronomy in the last 20 years have come from gamma-ray, X-ray, ultraviolet and infrared observations (see Chapter 6). However, space research remains very expensive and the bulk of astronomical observations are still made using ground-based telescopes. I will therefore concentrate in this book on visual and radio techniques, and will start by discussing the effects of the Earth's atmosphere.

Radiation is absorbed in the Earth's atmosphere by a number of atomic and molecular processes. Absorption at particular frequencies – line or band absorption – arises from excitation of molecules and atoms, while the more drastic ionization or molecular dissociation processes give rise to continuous absorption at all frequencies above the threshold energy needed to knock the atom or molecule apart. The extinction is total, except in the visual and radio windows (Fig. 1.1).

The visual window extends from about 300 nm (3000 Å) to about 1.4 μm. The cut-off in the ultraviolet is caused by a thin layer of ozone molecules (O_3) at a height of about 25 km – the now infamous ozone layer. In the infrared, the cut-off is more gradual, with a series of narrow windows extending up to about 24 μm between bands of absorption caused mainly by water vapour (H_2O) and carbon dioxide (CO_2). Infrared astronomers take full advantage of these windows (see Chapters 5 and 8).

The radio window extends from about 8 mm to about 15 m, although the screening by water vapour and oxygen (O_2) molecules starts to decrease at wavelengths longer than about 300 μm. The long wavelength cut-off is caused by critical reflection in the ionosphere, a region in the atmosphere above about 100 km which has a high density of free electrons and ions. Long-wavelength radio waves cannot penetrate this 'plasma' because their wave frequency is too low to excite oscillations at the natural vibrational frequency (the 'plasma frequency') of the ionosphere. It is this phenomenon, frustrating to radio astronomers, that allows communication round the Earth by bouncing long-wavelength radio waves off the ionosphere; however, long-wave radio is seriously affected by variations in solar activity, which alter the level of ionization in the upper atmosphere, and satellite communications are now more reliable.

Not only photons are absorbed in the atmosphere. The Earth is also being bombarded by a steady flux of high-energy charged particles ('cosmic rays'), mainly protons and electrons. Despite their high energies (10^{10}–10^{20} eV), most primary cosmic ray particles are completely stopped by collisions with air molecules. These collisions often produce many secondary particles ('air showers') that can be detected directly, but both primary and secondary cosmic rays can also be detected by radiation from fluorescing air molecules along the tracks of the particles. Particles with enough energy may be travelling through the atmosphere at speeds in excess of the local speed of light ($= c/n$, where c is the speed of light in a vacuum and n is the refractive index of the atmosphere; $n > 1$, so this does not violate the relativistic upper limit of c for the propagation of information) and can be detected by the resulting blueish Čerenkov radiation. Some fraction of the primary and secondary particles reach the ground, though with much reduced energies (the atmosphere has an absorbing power equivalent to about one metre of lead), and can even be detected in deep mines.

Although our own atmosphere is the major source of absorption for astronomers, it is not the only one. Even satellite observations are handicapped by absorption, either by dust and charged particles within the solar system (a fairly small effect) or by dust and gas in the interstellar medium in our own and other galaxies. As we will see later, absorption by interstellar dust is important enough in the visual and ultraviolet to prevent our seeing the centre of our Galaxy. In the extreme ultraviolet (EUV) and soft X-ray regions, the photons have just the right energies to ionize the neutral hydrogen which pervades almost all the space between the stars, and the extinction is almost total in directions where the hydrogen is dense; the ROSAT X-ray satellite launched in 1990 was the first one to make observations in the EUV and to reveal that there were more gaps in the hydrogen distribution than had been expected.

1.3 Bouguer's method of allowing for absorption

Even in the 'windows' in the spectrum, the atmosphere is not completely transparent, and it is important to understand the effects of absorption on what we observe and to be able to allow for them.

There are two different effects. *Absorption* by atoms or molecules reduces the observed brightness of a source, because photons are actually destroyed. *Scattering* of photons by molecules or dust degrades the image of an extended source, and may change the wavelength distribution of the radiation, but it has little effect on the net flux of photons reaching the ground, although of course it gives an effective absorption *in the direction of the source*.

The properties of scattering depend on the relative sizes of the scattering particles and the wavelength λ of the radiation:

1. *Particle size $\gg$ wavelength.* The scattering is independent of wavelength, e.g. (in the visual) clouds, mist or fog. This explains why the sky is grey on a cloudy day: the scattered sunlight is scattered equally at all (visual) wavelengths.
2. *Particle size $\simeq$ wavelength.* The scattering depends strongly both on wavelength and on the actual particle size. In the visual, the relative change in brightness caused by dust varies roughly as $1/\lambda$, so blue light is scattered more than red. Interstellar dust (Chapters 11 and 12) produces a similar reddening.
3. *Particle size $\ll$ wavelength.* The scattering depends very strongly on wavelength, with the scattered intensity varying as $1/\lambda^4$ (Rayleigh scattering). In the visual, the blueness of the sky, and of distant horizons (an effect well known to landscape painters), is caused by the Rayleigh scattering of sunlight by air molecules: blue light reaches us from all directions in which there are air molecules, and the blue is more intense in directions in which there are many molecules. Because

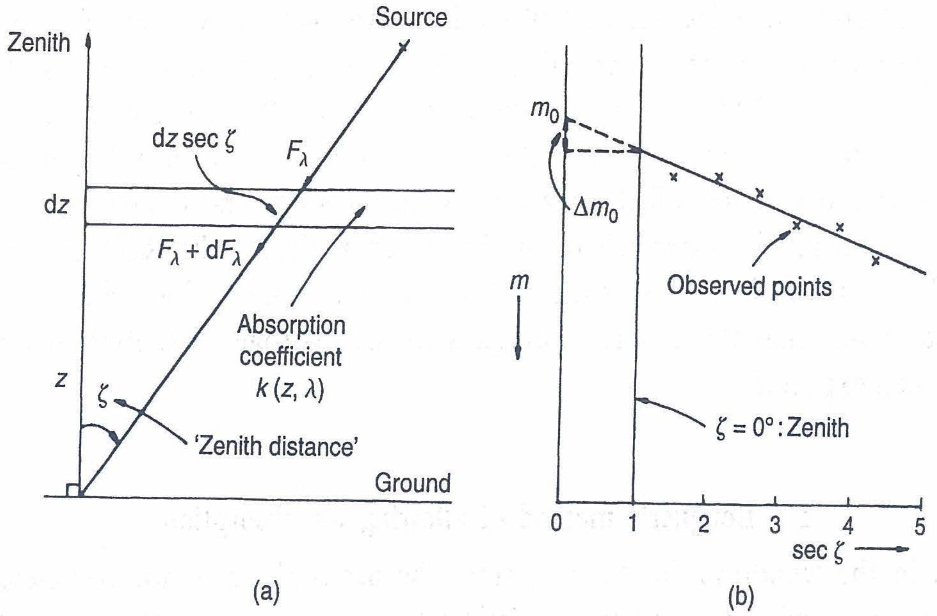

Fig. 1.2. (a) The Earth's atmosphere, represented as a series of plane parallel layers of thickness dz at height z. Neglecting refraction, light from an astronomical source passes in a straight line through these layers, being progressively attenuated by the amount given in equation (1.1). (b) The apparent magnitude of a star plotted as a function of zenith distance (equation (1.6)) and extrapolated to the value above the atmosphere.

the blue light has been scattered out of the direct beam, the Sun itself appears reddened, especially when seen near sunset or sunrise through a long path-length in the atmosphere.

The third case is the only one of interest at radio wavelengths.

It is clear that the amount of absorption by the atmosphere depends on whether we are looking directly overhead, through a minimum thickness of atmosphere, or along a long path-length to the horizon. The variation of absorption with the altitude of the source (its height above the horizon – see Chapter 7) can be used to estimate the total absorption, using a method due to Bouguer.

If we neglect refraction and the curvature of the atmosphere, we may picture the atmosphere as made up of a series of plane parallel layers whose properties depend on their height z above the ground (Fig. 1.2(a)). Suppose radiation of wavelength λ passes through a thin layer, thickness dz, at an angle ζ to the vertical (ζ is known as the 'zenith distance'). If the incident flux is F_λ then the decrease in flux dF_λ is clearly proportional to F_λ and to the path-length through the layer:

$$dF_\lambda = -kF_\lambda \sec\zeta \mid dz \mid, \qquad (1.1)$$

where k, which is a function $k(z, \lambda)$ of the zenith distance and wavelength, is the *absorption coefficient* in the layer (this equation is really a definition of k). If F_0 is the flux outside the atmosphere, then by integrating equation (1.1) with respect to z we find at ground level ($z = 0$):

$$F_\lambda(\zeta) = F_0 \exp(-\sec\zeta \int_0^\infty k\,\mathrm{d}z). \tag{1.2}$$

The unknown integral can be eliminated in terms of the flux at the zenith ($\zeta = 0$):

$$F_\lambda(0) = F_0 \exp(-\int_0^\infty k\,\mathrm{d}z), \tag{1.3}$$

giving

$$\log_{10} F_\lambda(\zeta) = \log_{10} F_0 + \sec\zeta \log_{10} \frac{F_\lambda(0)}{F_0}. \tag{1.4}$$

As we will see in Chapters 2 and 8, astronomers conventionally express visual fluxes in magnitudes, a logarithmic scale defined by:

$$m_\lambda = -2.5 \log_{10} F_\lambda + \text{ constant}. \tag{1.5}$$

(The same convention is sometimes used for radio magnitudes as well.) Then equation (1.4) can be written as:

$$m_\lambda = m_0 + \Delta m_0 \sec\zeta \tag{1.6}$$

where m_λ is the magnitude that is observed from the ground, m_0 is the magnitude that would be observed from outside the atmosphere and Δm_0 ($= -2.5 \log_{10}(F_\lambda(0)/F_0)$) is the total absorption in magnitudes at the zenith ($\zeta = 0$, $\sec\zeta = 1$). Since this expression is linear in $\sec\zeta$, m_0 and Δm_0 can easily be estimated by observing m_λ at various zenith distances, plotting these values against $\sec\zeta$, fitting a straight line to the observations and extrapolating to $\sec\zeta = 0$ (Fig. 1.2(b)). Since Δm_0 depends quite strongly on λ, observations need to be made in carefully defined wavebands.

For zenith distances exceeding about 60°, we cannot neglect refraction or the Earth's curvature. However, we can use an exactly analogous method, simply replacing equation (1.6) by

$$m_\lambda = m_0 + \Delta m_0 M(\zeta) \tag{1.7}$$

where $M(\zeta)$ is the *air mass* – a measure of the absorption along the curved light-path. The air mass is determined empirically from balloon observations of pressure and temperature, and tables are available of air mass as a function of zenith distance (for small zenith distances, the air mass reduces to $\sec\zeta$). Then $M(\zeta)$ can be treated as a known function, and extrapolation to zero air mass again gives m_0 and Δm_0. Because the atmospheric structure is not static, the tables give a mean value, so estimates of absorption are less satisfactory for objects near the horizon. For this reason, and because the total absorption is less, astronomers try to observe objects when they are as close to the zenith as possible, that is, when they are on the observer's meridian (Chapter 7).

1.4 Scintillation and 'seeing'

In the last section I tacitly assumed the atmosphere to be static and horizontally stratified. Neither assumption is true – the real atmosphere is in constant motion on many spatial and time scales, from the slow, large-scale air motions involved in weather fronts to the rapid, small-scale turbulence present in winds. These restless changes cause *scintillation.* There are two effects: variations in air mass along the line of sight cause fluctuations in intensity, while variations in the refractive index along the line of sight cause variations in the position of the image. Small-scale turbulence in the atmosphere causes a stellar image, for example, to 'dance' rapidly and randomly with time on a scale of a few arcseconds – a point source is smeared out into a 'seeing disc', unless observed with very high time resolution. Extended sources, with images much larger than an arcsecond in diameter, are less affected; thus stars 'twinkle', but the major planets, with diameters of 10–30 arcseconds, do not unless the air is extremely turbulent.

Rapid scintillation is a major limitation for ground-based optical telescopes, affecting both the maximum resolving power and the faintest detectable sources (see Chapter 2). Optical telescopes are therefore often said to be 'seeing-limited'. The effects are largest near the horizon, which is another reason why astronomers try to observe as near to the zenith as possible.

At radio wavelengths, very-small-scale turbulence has less effect and scintillation arising from the Earth's atmosphere is less important. In particular, the maximum resolving power is set by diffraction, not seeing (Chapter 4) and radio telescopes are said to be 'diffraction-limited'. However, radio telescopes are significantly affected by scintillation arising in the interplanetary and interstellar medium. High-time-resolution observations, planned by Hewish in the late 1960s to use scintillation to study the properties of the interstellar medium, led incidentally to the discovery of pulsars (see Chapter 9).