# 1

# Light

Electromagnetic radiation is the primary source of astronomical information. In particular, until the early 1930s all astronomy was based on the use of telescopes that extended the power of the human eye but were restricted to the collection of visible light. Then the advent of radio astronomy marked the beginning of a revolution, which later bloomed when the space age, starting in the late 1950s, made it possible to observe the sky from devices operating outside the atmosphere of our planet. This and the development of new technological tools soon allowed us to exploit wider and wider intervals of the entire spectrum of the electromagnetic radiation as a way to probe the properties of the universe. In general, the sources of astronomical electromagnetic radiation and other sources of astronomical information (see Chapter 5) are what we call visible matter.

The purpose of this chapter is to introduce some key concepts and notation that characterize light and the collection of light for astronomical purposes. We will also briefly outline some obvious complications that affect the acquisition of observational data, some of which are intrinsic to electromagnetic radiation, others to the telescopes and instruments that are used, and, for observations from the ground, the complications related to the presence of the atmosphere. We will then proceed to a brief description of the main types of information that we may extract from the observations, by means of imaging and spectroscopy. We will recall the difference between apparent and intrinsic properties of the astronomical sources, which is at the basis of probably the most important problem in astronomy, that is, the measurement of the distance to a given source. We will then comment on the fact that the light from distant sources is often a mixture of photons from different stars or different components. This will serve as an excuse for a quick introduction to important concepts, such as stellar populations, mass-to-light ratios, mean motions, and velocity dispersions.

In closing the chapter, we will describe a method to measure the distance to a stellar system based on the application of a very simple dynamical model to a suitable set of observations.

## 1.1 The Electromagnetic Spectrum, Imaging, and Spectroscopy

### 1.1.1 Types of Radiation and Wavebands

The electromagnetic spectrum is divided into broad regions (defined in terms of photon energy $E$ or, equivalently, of photon wavelength $\lambda$ or frequency $\nu$). We recall that from the relation $E = h\nu = hc/\lambda$, where $h = 6.6261 \times 10^{-27}$ erg s is the Planck constant and $c = 2.9979 \times 10^{10}$ cm s$^{-1}$ is the speed of light in vacuum, the wavelength associated with 1 eV = $1.6022 \times 10^{-12}$ erg is $1.2398 \times 10^{-4}$ cm = 1.2398 $\mu$ = $1.2398 \times 10^4$ Å = $1.2398 \times 10^3$ nm. This also sets the relation between the often used units micron ($\mu$), angstrom (Å), and nanometer (nm).

The gamma ray domain refers to photon energies greater than 1 MeV and wavelengths of 1 Å or smaller. X-rays have lower energies, down to energies ≈ 1 keV (i.e., wavelengths from 1 to 100 Å); soft X-rays are those with lower energies, below ≈ 10 keV, and hard X-rays have higher energies. The ultraviolet (UV) part of the spectrum extends from wavelengths in the range 100 Å to ≈ 4000 Å. Visible light covers the wavelength interval of 4000–7000 Å. Then infrared radiation is characterized by wavelengths below 100 $\mu = 10^{-1}$ mm; in particular, near-infrared photons have wavelengths of one or few microns, whereas at longer wavelengths astronomers talk about far-infrared radiation. Finally, radio waves are those with wavelengths of millimeters or larger (in particular, those with wavelength up to 1 m are often called microwaves).

Observations in one of the above-defined broad regions of the electromagnetic spectrum are often subdivided into finer regions, called wavebands. In particular, visible light, which is the focus of all observations before the advent of modern astronomy, is often divided into bands, such as B, V, R, I, whereas in more modern near-infrared observations we distinguish between J, H, K bands in the order of increasing wavelength. These subdivisions often reflect commonly used filters in astronomical observations and may correspond to specific transparency windows in the atmospheric transmission.

### 1.1.2 Atmospheric Transparency

The atmosphere is basically transparent to visible light and to radio waves with wavelengths larger than 1 cm up to 10 m. It is basically opaque to high-energy

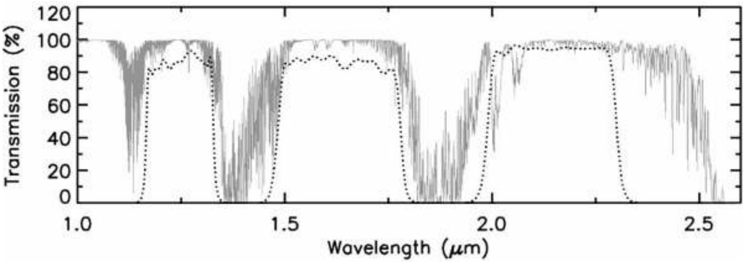


Figure 1.1 From left to right, J, H, and K filter profiles (dotted lines) superposed on the atmospheric transmission at Mauna Kea (From: Tokunaga, A. T., Simons, D. A., Vacca, W. D., "The Mauna Kea Observatories near-infrared filter set: II. Specifications for a new JHKL'M' filter set for infrared astronomy," 2002. *Publ. Astron. Soc. Pacific*, **114**, 180; © The Astronomical Society of the Pacific. Reproduced by permission of IOP Publishing. All rights reserved.).

incoming radiation, from the UV to gamma rays. In the astrophysically interesting domain of the near-infrared and millimetric radiation, there are several excellent transmission windows, which are best exploited by telescopes located at high altitudes. This is one important reason that explains why many observatories have been built at relatively high altitudes.

The atmospheric transparency is often illustrated quantitatively by plotting, as a function of the radiation wavelength, the altitude at which the intensity of the radiation coming from an astronomical source is reduced by a factor of 2. Alternatively, at a given astronomical site, we may plot the transmission as a function of wavelength, with the standard definition that the transmission is taken to be unity if the intensity of the incoming radiation is unaffected (see Fig. 1.1).

### 1.1.3 Hydrogen Lines

The fact that most of the visible matter in the universe is made of hydrogen suggests that a large fraction of what we can extract from astronomical observations derives from the identification of hydrogen lines, produced either in emission or in absorption by transitions involving different energy levels of the hydrogen atom. In particular, it is well known that the lines of the Lyman series, that is, of transitions from various excited levels to the ground level, fall in the UV part of the spectrum and that the Balmer series, associated with the transition from higher levels to the first excited level, fall in the visible, whereas the Paschen and Brackett series fall in the infrared. In the ultraviolet, a special role is played by the Ly$\alpha$ line connecting the first excited level to the ground level, with wavelength 1216 Å. In the visible, part of the Balmer series, important lines are H$\alpha$ at 6563 Å and H$\beta$ at 4861 Å.

Of course, the above information refers to the source. Because of the cosmological redshift, the Ly$\alpha$ emission of distant sources can be brought into the visible part of the spectrum of the observer, whereas the Balmer lines may be moved to the near-infrared.

In Chapter 3, we will see that a major development occurred in radio astronomy when, first theoretically, and then observationally, it was discovered that a hyperfine transition related to the spin alignment of the electron and the proton in atomic hydrogen is associated with a line at 21.106 cm (1420.4 MHz), often referred to as the 21-cm line.

### 1.1.4 Telescopes

Larger and larger telescopes have been built and are being planned, with the goal of studying the sky in better and better detail and of gathering information on fainter and fainter sources. This technological progress is accompanied by major developments in the creation of light and optimally performing materials for the construction of the telescope parts, in the construction of instruments, and in data storage and analysis. For a long time the largest optical telescopes were the 5-m (200-inch) Hale telescope, located at Palomar mountain in California and operative since 1949, and the 6-m (20-ft) telescope at the Special Astrophysical Observatory, in the Russian Caucasus mountains, operative since 1975. The specifications 5 m and 6 m denote the diameter of the so-called primary mirror; they are often referred to as aperture of the telescope. It is commonly perceived that large telescopes are built because larger telescopes have better angular resolution. However, this is only partly true.

### 1.1.5 Angular Resolution and Sensitivity

The angular resolution of an imaging device can be defined as the minimum angular distance between two point sources that can be effectively separated or distinguished by an observation. It can be shown that an ideal system, characterized by an effective aperture $D$, dealing with electromagnetic radiation of wavelength $\lambda$, has an angular resolution $\theta \approx \lambda/D$, which is often called the diffraction limit. Real devices have poorer angular resolution.

The human eye has an angular resolution of $\approx$ 1 arcmin. The star Mizar in the constellation Ursa Major has a closeby star, Alcor, which can be easily resolved with the naked eye (it is at an angular distance of $\approx$ 12 arcmin from Mizar).

As another example of angular scales, we may mention the Galilean satellites, the four brightest moons of planet Jupiter, that are typically located at an angular distance of 2 to 10 arcmin from Jupiter and easily visible with normal binoculars. Io's angular diameter is ≈ 1 arcsec.

Sensitivity describes the measure of the faintest signal that can be detected. For a telescope it scales as the square of its aperture $D^2$, that is, of its collecting area in relation to the incoming photons. Of course, another parameter that is involved in determining the sensitivity of an observation is the exposure time. With a given telescope deeper images, that is, images that reveal fainter details, are generally obtained by taking longer exposures.

In terms of sensitivity, under very good conditions the human eye is able to see stars ≈ 100 times fainter than the brightest star of the constellation Leo, the blue star Regulus.

### 1.1.6 Seeing and Point Spread Function

A primary factor that severely limits optical observations from the ground is the turbulence present in the atmosphere, that is, in the air through which incoming photons pass before reaching the telescope. The main properties of the atmospheric turbulence in relation to astronomical observations are the relevant cell size of the air clumps (at visible wavelengths, ≈ 10 to 20 cm) and the typical time scale over which the cell optical properties change ($\approx 10^{-2}$ s or below). Astronomers generally describe the phenomenon by saying that observations from the ground are affected by seeing. Broadly speaking, seeing is the angular diameter (full width at half maximum) of a disk into which a point source is imaged in a relatively long exposure as a result of the blurring effect of atmospheric turbulence. It has been realized that much of the effect is due to the state of the air in the vicinity of the telescope; because of this, modern telescopes are built with special care, especially in relation to the thermal properties of the hosting domes. In practice, a good astronomical seeing is of the order of 1 arcsec. Under exceptional conditions, the seeing at the best observatories can be as low as 0.3 arcsec. For large optical telescopes, this is generally much worse than the diffraction limit. Therefore, the construction of large optical telescopes is mainly justified by their better sensitivity, and only to a lesser extent by their resolving power. However, we will see in the next subsections that astronomers have found ways to bypass, in large part, this limitation to observations.

A simple phenomenon, experienced by the human eye, that is related to the blurring effect of turbulence on visible light is the twinkling of the stars (which are effectively point sources), as opposed to the steady light from the brightest planets (which are angularly small, but finite-size extended sources).

Note that the apparent diameters of planets Venus, Mars, Jupiter, and Saturn are, ≈ 10 to 65, ≈ 4 to 25, ≈ 30 to 50, and ≈ 15 to 20 arcsec, respectively. We recall that the Moon's angular diameter is ≈ 30 to 35 arcmin.

Even in the absence of effects of turbulence in the atmosphere, a given optical device, because of technical limitations and other factors, reduces the image of a point source to a distorted finite-size spot. Astronomers quantify this general effect by defining the Point Spread Function (PSF), which describes how a point is blurred in the observation. The observed image of an extended source is the convolution of the source signal with such PSF.

### 1.1.7 Active and Adaptive Optics

Modern telescopes are capable of effectively controlling the surface collecting the light from astronomical sources, so as to overcome some of the effects that would spoil the results of the observations with respect to those that could be obtained under ideal conditions. The process is performed by means of a combination of mechanical tools (actuators in the case of active optics) and electronic tools.

Active optics (starting in the 1980s) generally refers to actions taking place on the time scale of seconds, to compensate for relatively large amplitude mechanical and thermal stresses that may be induced by the geometric configuration of the telescope with respect to gravity and winds.

Adaptive optics (starting in the 1990s) refers to smaller-amplitude actions taking place on the time scale of $10^{-2}$ s and below, aimed at overcoming the effects of seeing. In its simplest form, the general strategy is to take advantage of a sufficiently bright point source in the field of view (a guide star), during observations, and thus to read off from its distortion the relevant PSF that can be applied to reconstruct the desired seeing-free image. In the most recent versions of adaptive optics, when a sufficiently bright point source is not available in the desired direction, an artificial guide star in the field of view can be created by shining a suitable laser beam toward the sky.

### 1.1.8 Interferometry

Another way to improve angular resolution is to make use of interferometric techniques. The general idea is to acquire the signal from incoming electromagnetic waves with a set of separate telescopes placed at different locations and to coherently superpose the signals in such a way that the separate telescopes behave as parts of a single detecting device. The largest distance between two telescopes of an interferometric configuration is the largest baseline; if we call it $D$, the ideal angular resolution achievable by the interferometer is $\approx \lambda/D$. Of course, even if angular resolution can be greatly improved by interferometry, the sensitivity remains limited by the total collecting area of the array of telescopes, which is generally much smaller than $D^2$.

The technique was developed successfully very soon at long wavelengths, in radio astronomy, starting in the 1940s. It is routinely used with continental and intercontinental baselines of thousands of kilometers (VLBI).

At shorter wavelengths, in the infrared and in the visible, major technological advances are required, and interferometry was developed mainly at the end of the last century. As a notable example, we should mention the Very Large Telescope Interferometer (VLTI), in which the large 8.2-m telescopes of VLT on Cerro Paranal in Chile can be used in interferometric mode together with smaller and mobile 1.8-m auxiliary telescopes, achieving $\approx$ 200 m as the largest baseline.

### 1.1.9 Imaging and Spectroscopy

There are two main modes of astronomical observation, imaging and spectroscopy.

Typically, images are intensity maps, in a given waveband, that provide us with morphological details of the selected field of view. For certain sources, such as nearby globular clusters, images give a picture of the way stars crowd up in the central regions. For other, more distant, extended sources, such as galaxies, images give us information about the overall shapes that characterize the sources. Clearly, images are two-dimensional maps (they cover a small solid angle in the sky) for which the intrinsic physical size (length scales) can be set only if we can measure the distance to the source. The problem of inferring the three-dimensional structure of an observed source or field is one of the key open problems of astronomical observations; a related open problem, for an extended source characterized by some internal symmetry, is to determine its inclination with respect to the line of sight.

We tend to interpret the observed morphology in terms of internal structure of the source. However, if we define structure as mass distribution, it is obvious that images in certain wavebands may give us misleading information about the source structure, either because of absorption of the photons in their path from source to detector or, more simply, because the waveband that we are using does not correspond to the source component that best traces the mass distribution. In this respect, for the purpose of studying the structure of galaxies, it has been realized that the best representative images are those obtained in the near-infrared, because this type of radiation is least affected by extinction by interstellar dust and because this emission best traces the evolved red giant stars that are thought to make the bulk of the mass of the stellar component of galaxies; in contrast, images in the visible exhibit morphological details that are best representative of the interstellar medium and newly born stars. In a completely different context, in the visible the intergalactic space in clusters of galaxies appears to be practically empty, whereas we now know from X-ray observations (see Chapter 4) that it contains very large amounts of matter in the form of a diffuse plasma.

Spectroscopy studies the incoming flux distribution as a function of wavelength and is especially valuable when certain lines, either in absorption or in emission, can be identified and analyzed. Spectroscopy is the key tool to make us understand the nature of the mechanism of electromagnetic emission operating in a given source. It provides important information on the physical state of the source (e.g., on its temperature) and on its chemical composition.

One important role of spectroscopic observations is their diagnostic power in relation to kinematics. For those sources for which spectral lines can be identified and analyzed, the Doppler effect provides us with the opportunity to extract information on the velocity of the source relative to the observer along the line of sight. For an observed nearby stellar system at known distance, such as a globular cluster, images give information on two spatial coordinates (in the plane of the sky), and spectroscopy gives information on the velocity component of stars along the line of sight; in other words, the combined use of imaging and spectroscopy gives us information on three out of six of the coordinates that define the relevant phase space.

## 1.2 Apparent and Intrinsic Quantities, Standard Rods, and Standard Candles

If we do not know the distance to a given source, observations give us only incomplete information about the system that we are studying. In practice, we can measure its apparent size (e.g., if we are observing an extended source, its apparent diameter) and its apparent luminosity (in a given waveband, from the flux that we receive with our telescopes). A given observed source can be rather small and faint, near to us, or, alternatively, it can be huge and powerful, if it turns out to be very far away.

This general theme has set long-lasting landmark controversies about the nature of certain sources that were eventually resolved by a convincing distance determination. Notable examples are the nature of the nebulae and the discovery of galaxies and, in more modern times, the nature of Gamma Ray Bursts and the discovery that they originate in systems located at cosmological distances. The high-energy phenomenon of Gamma Ray Bursts, as will be briefly described in Chapter 4, demonstrates another important aspect that connects apparent and intrinsic luminosity, that is, whether the source is emitting in a beamed way or isotropically over the whole sky.

### 1.2.1 Magnitudes and Parallaxes

In general, astronomers measure apparent and absolute luminosities in magnitudes and lengths in parsecs or kiloparsecs.

Without facing the task of providing complete and exact definitions, we would only like to mention here that, with respect to the standard units used in physics to measure luminosities, magnitudes correspond to taking the operation $-2.5\log$, where the logarithm is meant to be to base 10. Therefore, if we compare two sources, the first of which is 100 times brighter than the second, their magnitudes differ by 5, and the fainter source has larger magnitude.

The brightest stars in the sky have apparent magnitudes around zero. The brightest, Sirius, shines at $m_V \approx -1.47$ mag in the V band, and, being located at a distance of $\approx 2.64$ pc from us, it is characterized by absolute magnitude $M_V \approx 1.42$ mag; that is, this would be its luminosity in magnitudes if Sirius were located at a distance of 10 pc. For comparison, the Sun's apparent magnitude is $\approx -26.7$, whereas its absolute magnitude is $\approx 4.83$; in more standard units the Sun's absolute luminosity is $1\ L_\odot \approx 3.83 \times 10^{33}$ erg s$^{-1}$. At its brightest, Venus shines at $\approx -4.9$ mag.

The unit of length that is used most frequently is the parsec, $1$ pc $\approx 3.09 \times 10^{18}$ cm $\approx 3.26$ light-years. The origin of the parsec, and its precise definition, is traced to a process of triangulation, in which the parsec is defined as the distance at which 1 AU $\approx 1.5 \times 10^{13}$ cm (the Astronomical Unit is the distance between the Earth and the Sun) subtends an angle of 1 arcsec. The very small change of position in the sky of a nearby star, in a frame of reference given by much more distant stars, when the observation is made at different times during the Earth's orbit around the Sun, is called parallax. Distance measurements are also sometimes called parallaxes, even when the distance measurement does not involve triangulation.

In closing this subsection, we record some dimensional relations that turn out to be useful in the course of many astronomical calculations. For angles, note that 1 radian is $180^\circ/\pi \approx 57.2958^\circ \approx 206265''$. For times, 1 yr $\approx \pi \times 10^7$ s. For velocities, 1 km s$^{-1} \times 10^6$ yr $\approx 1.02$ pc.

### 1.2.2 Line-of-Sight Velocities and Proper Motions

The Doppler effect is at the basis of velocity measurements in astronomy. Typically, the measurement consists in identifying a certain line (or certain lines) in the light coming from a given source. For relatively small speeds, the line-of-sight velocity $v_{los}$ between the source and the observer is obtained by measuring the wavelength displacement $\Delta\lambda$, that is, the difference between the observed wavelength and the wavelength $\lambda$ at emission, and by applying the relation $\Delta\lambda/\lambda \approx v_{los}/c$, where $c$ is the speed of light. If the source is receding from the observer, the observed wavelength is longer, that is, it is redshifted. This gives a direct measurement of $v_{los}$, which is obviously distance independent.

For stars belonging to our Galaxy or nearby galaxies, measurements of this kind give velocities of up to few hundreds of kilometers per second; for stars in the solar neighborhood, that is, within a few hundred parsecs from us, the relative velocity $v_{los}$ of individual stars is often of the order of 30 km s$^{-1}$. In the nearby universe, that is, for galaxies a few hundred megaparsecs away, the Doppler shift $z = \Delta\lambda/\lambda$ is always a redshift and is (approximately) directly proportional to the distance $d$ of the source, corresponding to the Hubble law $v = H_0 d$. The quantity $H_0 \approx 70$ km s$^{-1}$ Mpc$^{-1}$ is called the Hubble constant and measures the expansion rate of the universe in our cosmological vicinity. The quantity $H_0^{-1}$ is of the order of $10^{10}$ yr and thus is the basic time scale that sets the age of the universe (the time that has passed since the Big Bang took place). Astronomers now observe galaxies characterized by redshift greater than unity; of course, a simple interpretation of these data in terms of recession speeds along the line of sight is less significant, and a cosmological interpretation well beyond the simple concept of the Doppler shift is required.

Going back to the motion of nearby stars, it is clear that, depending on their distance and on the value of the velocity component transverse to the line of sight, by taking observations at significantly different epochs, several years apart from one another, we may be able to detect the motion of a star in the sky, with respect to a frame of reference provided by much more distant stars. The associated velocity that can be extracted from a set of measurements of this type is called proper motion and is typically given as an angular velocity vector $\omega$, which is only an apparent quantity. Recall that the position of a star in the sky is given by two angles [e.g., astronomers often refer to equatorial coordinates defined by the pair of angular coordinates $(\alpha, \delta)$, called right ascension and declination; note that, because of the geometry of spherical coordinates, the angular velocity is related to the time derivatives of the two angles by the relation $\omega = (\dot{\alpha}\cos\delta, \dot{\delta})$]. If we know the distance $d$ to the star of which we have measured the proper motion, we can thus reconstruct the intrinsic transverse velocity $v_\perp = \omega d$ relative to us. In practice, the angular displacements are always