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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 λ or frequency ν). 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 = 1.6022×10^{-12} erg is 1.2398×10^{-4} cm = 1.2398 μ = 1.2398×10^{4} Å = 1.2398×10^{3} nm. This also sets the relation between the often used units micron (μ), 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 $\approx$ 1 keV (i.e., wavelengths from 1 to 100 Å); soft X-rays are those with lower energies, below $\approx$ 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 $\approx$ 4000 Å. Visible light covers the wavelength interval of 4000−7000 Å. Then infrared radiation is characterized by wavelengths below 100 μ = 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

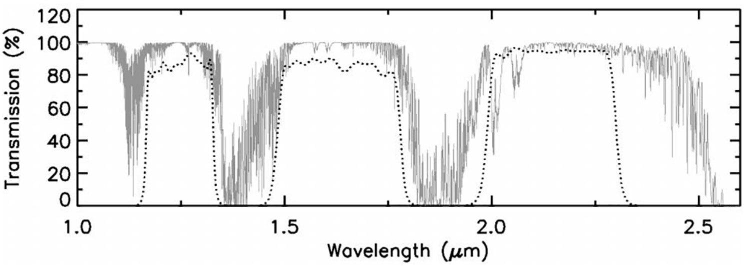

Figure 1.1 From left to right, J, H, and K filter profiles (dotted lines) superposed on the atmospheric transmission at Mauna Kea (From: Tokunaga, A. T., Simons, D. A., Vacca, W. D., "The Mauna Kea Observatories near-infrared filter set: II. Specifications for a new JHKL'M' filter set for infrared astronomy," 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

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is played by the Lyα 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 Hα at 6563 Å and Hβ at 4861 Å.

Of course, the above information refers to the source. Because of the cosmological redshift, the Lyα 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 λ, 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

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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 ≈ 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 ≈ -26.7, whereas its absolute magnitude is ≈ 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 ≈ -4.9 mag.

The unit of length that is used most frequently is the parsec, 1 pc $\approx 3.09 \times 10^{18}$ cm ≈ 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 $180°/\pi \approx 57.2958° \approx 206265''$. For times, 1 yr $\approx \pi \times 10^7$ s. For velocities, 1 km s$^{-1} \times 10^6$ yr ≈ 1.02 pc.

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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 λ 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 ω, 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 (α, δ), 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

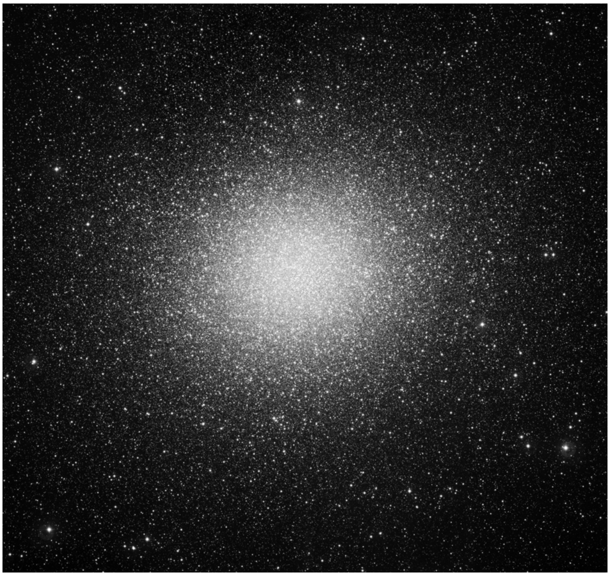

Figure 1.2 The globular cluster NGC 5139 (ω Cen) in an image taken with a field of view of approximately 30 × 30 arcmin from ESO's La Silla Observatory. The image shows only the central part of the cluster. North is up, east is to the left; it is a composite of B, V, and I filtered images (credit: European Southern Observatory "CC BY 4.0."). Currently, globular clusters are believed to contain only small amounts of dark matter, although they are likely to host significant amounts of dark remnants (see Section 3.3). A color version of this figure is available at www.cambridge.org/bertin

very small. Measurements of proper motions generally require long periods of observations with telescopes characterized by the capability of measuring positions with extreme accuracy (astrometric precision). Yet, the development of new telescopes and instruments (e.g., see Chapter 2) and patient analysis combined with a nontrivial discussion of the problem of the relevant frames of reference has already made it possible to measure proper motions and intrinsic transverse velocities for thousands of stars in globular clusters such as ω Cen (see Fig. 1.2).

1.2.3 Standard Rods, Standard Candles, and Distance Measurements

As we mentioned earlier in this section, the simplest distance measurement for stars can be made by triangulation, by taking advantage of the motion of the

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Earth around the Sun. But, until recently, this measurement has been possible only for the nearest stars (but see Section 2.3). When triangulation is not feasible, a distance measurement is typically based on the identification of a suitable "standard rod" or "standard candle." With these terms we indicate astronomical objects of which we have independent convincing evidence for either their intrinsic linear size or their intrinsic luminosity; in modern astronomy, an example of a standard candle is a special type of supernova (type Ia), for which astronomers have gathered convincing evidence for considering its intrinsic luminosity well established. By observing the apparent size for an extended object of which we know independently its intrinsic size, we measure its distance d (the scaling is with d in the nearby universe, from Euclidean geometry). By observing the apparent luminosity for an object of which we know independently its intrinsic luminosity, we also measure its distance (for isotropic sources, the scaling is with d^2 in the nearby universe, from the fact that the emitted power spreads out to the sphere of surface $4\pi d^2$). Of course, a number of effects may require the adoption of suitable corrections in order to make the final measurements; for example, the light from the source may suffer from absorption due to intervening material or magnification due to an intervening gravitational lens.

In practice, astronomers often make use of certain empirical scaling laws as an equivalent of standard rods or standard candles. An example of a scaling law equivalent to a standard candle is that of the empirical period–luminosity relation for the variable stars Cepheids, which allowed Hubble to measure the distance to nearby galaxies, such as M31. From a relatively easy measurement of the pulsation period (of the order of days) of a given Cepheid, by application of the period–luminosity relation we obtain a measurement of its intrinsic luminosity, which, compared to the observed apparent luminosity, yields the desired distance determination. Naturally, if we can identify in a nearby galaxy many Cepheids and carry out the measurement for each of them, we make an improved distance measurement, because, to some extent, we can limit the effects related to the fact that the period–luminosity relation is not a mathematical equation but, rather, a correlation between physical quantities with finite dispersion. A more modern example of a scaling law equivalent to a standard candle is the so-called Tully–Fisher relation for spiral galaxies, which states that

$$L = aV^4, \tag{1.1}$$

where L is the intrinsic luminosity produced by the stars of the galaxy and V its characteristic rotation speed. The quantity V can be measured by spectroscopic methods in a distance-independent way. The Tully–Fisher relation allows us to determine the intrinsic luminosity L of the galaxy and then, from the observed apparent luminosity, its distance.

As an example of standard rod we can refer to the fundamental plane relation, which applies to elliptical galaxies. Empirically it has been established that

$$\log R_e = \alpha \log \sigma_0 + \beta SB_e + \gamma, \tag{1.2}$$

where R_e is the effective radius, that is, the radius of the disk from which we receive half of the total luminosity of the elliptical galaxy (if the galaxy does not appear to us as circular but is truly elliptical, the quantity R_e can be suitably defined), σ_0 is the central velocity dispersion (a measure of the random motions of the stars in a small region close to the galaxy center), and SB_e is the mean surface brightness (in magnitudes per square arcsecond) of the galaxy inside the disk of radius R_e. Note that in the nearby universe, because for given apparent properties the intrinsic luminosity scales as d^2 and the intrinsic size scales as d, the surface brightness is distance independent. The parameters α, β, and γ are numerical coefficients that have been determined empirically. Therefore, for a given elliptical galaxy from a spectroscopic measurement of σ_0 and a photometric measurement of SB_e, the fundamental plane relation allows us to measure the intrinsic size R_e, which, compared to the apparent angular size, allows us to measure the distance to the galaxy.

Extending the concepts developed in this subsection to the study of sources at cosmological distances, that is, at finite redshifts, requires some nontrivial discussions. Quantitatively, the relevant results generally depend on the specific cosmological model that we are considering. Probably the most striking point is that the distance based on the comparison between intrinsic and apparent size is different from the distance based on the comparison between intrinsic and apparent luminosity (then we distinguish between angular-diameter distances and luminosity distances).[1] Another important effect to keep in mind is that in this context surface brightness is not distance independent, because it suffers from the so-called cosmological dimming (which depends on redshift). Another quantity related to distance that we may consider is the time passed from the emission of the photons coming from a given source to the collection of the photons by the observer. This leads to the concept of look-back time. In a monotonic way, sources at larger and larger redshifts sample conditions of the universe at larger and larger look-back times, that is, closer and closer to when the Big Bang occurred.

In this respect, a curious effect should be noted. Galaxies come in different sizes, so they should not be confused with standard rods. Yet, we may say that 10 kpc is a linear size that can be typically associated with a galaxy (e.g., the distance from the Sun to the center of our Galaxy is ≈ 8 kpc). If we plot the apparent angular size corresponding to 10 kpc as a function of redshift z (to draw such a curve we have to set the values of the main parameters that characterize the adopted cosmological model; we will briefly address the main properties of cosmological models in Section 2.2 and in Chapter 10), we find the surprising result that after a rapid Euclidean decline for $z \ll 1$ the curve reaches a minimum of ≈ 1 arcsec at $z \approx 1$, and then it is characterized by positive derivative. There are then two important surprises. The first is that beyond a certain lookback time (already reached by modern telescopes, because we observe galaxies with $z > 1$), galaxies should appear to become larger and larger. The second is that galaxies are always observed as extended sources, no matter how far they are from us.

1.3 Emission from Complex Sources and Mass-to-Light Ratios

When we observe extended sources, especially when they are far away, so that we cannot resolve their individual components, the photons that we collect are a blend of radiation emitted from a variety of sources by means of many different mechanisms. For example, the optical light from galaxies is dominated by the light emitted by stars of many different types, but also comprises light from the interstellar medium (especially in spiral galaxies, which generally host HII regions, i.e., regions of ionized hydrogen). In turn, the 21-cm observations of spiral galaxies collect the emission from a turbulent medium, made of clouds characterized by different sizes and different thermal properties, which are generally not resolved by the radiotelescope.

1.3.1 Stellar Populations

If we then refer to the stellar component of a galaxy, a small region of an image is generally associated with the emission from many many stars, including main-sequence stars, white dwarfs, neutron stars, and so on. In the visible, stars such as white dwarfs and neutron stars would contribute very little to the observed image. Much of the light may be contributed by relatively few young stars, such as O and B stars, if present, but other individually fainter stars may contribute significantly if they happen to be much more numerous. Astronomers refer to stellar populations as a term to indicate a stellar mixture with well-defined age and chemical characteristics. For spiral galaxies, Population I objects refer to the younger component, which is usually associated with

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a relatively thin disk. Population II objects are typically older and related to a thicker disk density distribution. In broad terms, we may think of a stellar population as a gas of stars made of stars of different types in given proportions, much like ordinary air is largely made of nitrogen, but contains other elements, such as oxygen, in given amounts.

1.3.2 Mass-to-Light Ratios

The brief digression of the previous subsection is meant to be the basis for a natural question that arises when we analyze astronomical images. At the source, how much mass corresponds to the light collected by our telescopes? In particular, for optical images of galaxies that we know are dominated by the light emitted by stars, how can we convert an observed surface brightness into a surface (projected along the line of sight) density distribution of the stars present? The key factor of conversion is called the relevant mass-to-light ratio, often denoted by M/L, for which a specification should be added to indicate for which waveband the factor is meant to be applied. Obviously, for wavebands in the visible part of the spectrum, in solar units ($M_\odot/L_\odot$) the mass-to-light ratio is expected to be of order unity, just because the Sun is not a special star. We recall that the solar mass is $1M_\odot = 1.989 \times 10^{33}$ g.

In principle, based on a number of assumptions related to the star formation rates expected in a given system, the major formation events occurred in the past (i.e., the star formation history), combined with a detailed knowledge of the results of stellar evolution, astronomers can devise population synthesis evolutionary models that may be able to predict how much mass corresponds to a given amount of emitted light by a stellar population observed at a given epoch. Color and spectral analysis of the observed light can then lead to justified estimates of the relevant mass-to-light ratio. In practice, mass-to-light ratios are best measured by means of dynamical studies (see Part II of this book).

In its simplest form, the mass-to-light ratio is a local concept. Different parts of a given galaxy may be associated with different mass-to-light ratios, because the properties of the underlying stellar populations may change from place to place. In reality, for a given galaxy or for other stellar systems, such as globular clusters, an observed homogeneity of colors and spectral features may justify the use of a constant mass-to-light ratio within the system, as a reasonable first approximation.

As we will discuss in detail in Part II, the issue of the measurement of mass-to-light ratios is strictly connected to the problem of the amount and distribution of dark matter. Especially for the cases in which we have evidence for the presence of dark matter, the concept can be defined in the sense of a cumulative quantity (by considering the ratio of the mass to the emitted light in relation to larger and larger volumes), and eventually it can be used as a global quantity; however, as we will discuss in Part II, the spatial extent of dark halos is not easy to determine empirically.

For nearby globular clusters, we can easily resolve most of their brightest stars. In these cases, we have a rather direct determination of the properties of the stellar populations that are involved. But even here the task of determining the mass-to-light ratio in a cluster and how it may change in different parts of the cluster (in particular, from the central regions to the periphery) is made difficult by the fact that white dwarfs, neutron stars, and black holes (the so-called dark remnants) are difficult to detect.

1.3.3 Doppler Shift and Doppler Broadening

If we now consider spectroscopic observations of emission from complex sources, we should be aware that the information contained in the data may be not as easy to extract as we may naively imagine. In particular, if we take spectroscopic data for a part of a galaxy (as an example, refer to the case of an elliptical galaxy), with light coming primarily from a large number of unresolved stars, we should consider the following effects. The light that we are receiving from a given piece of the galaxy comes from stars located at very different distances from the galaxy center because of projection along the line of sight (note that the star number densities and the star sizes are so small that, unless there is significant absorption from interstellar medium, the light from the most distant stars along a given line of sight proceeds directly to our telescopes, because it is not intercepted by the stars that are closer to us). Therefore, not only is the set of stars that we sample characterized by a blend of stars and star motions because we are collectively considering entire stellar populations, but the populations that contribute to the signal occupy very different regions in the galaxy that we are studying.

From the point of view of diagnosing the kinematics of the observed system, from a given small region of the galaxy we will observe an overall Doppler shift and an overall Doppler broadening of the relevant spectral lines. In general, we may argue that Doppler shifts are to be associated with mean motions present in the stellar system, whereas Doppler broadenings are to be associated largely with random motions (velocity dispersions) and gradients of mean motions present in the small region of the galaxy that we are studying. In practice, the interpretation of these data requires the specification of a suitable model. In the simplest case, by suitable model we mean a specification of the six-dimensional distribution function $f(\vec{x}, \vec{v})$, that is, the probability of finding a star at a given vector position $\vec{x}$, with given vector velocity $\vec{v}$. The direct problem of deriving, from an adopted model f, the expected Doppler shifts and Doppler broadenings at a given position in the sky, by projection of the Doppler effects along the line of sight, may be technically difficult but is conceptually straightforward. In turn, the inverse problem of extracting from the observed Doppler shifts and Doppler broadenings information on the underlying model f is a difficult and generally ill-posed problem. In principle, best results could be obtained if we could measure the entire line profiles, but such measurements are extremely difficult to make. Another point that should be kept in mind and that complicates the analysis further is the fact that the effects on the line profiles are weighted by the luminosity of the individual stars that contribute to the observed emission.

For atomic hydrogen (HI) 21-cm observations of spiral galaxies, we face similar problems, which may be partly eased if the gas is distributed in a regular and symmetric thin disk. In this case, the extraction of information about the overall rotation (the rotation curve) can be made with good confidence from the observed shifts, whereas the broadening of the 21-cm line reflects the turbulent motions of the gas. In practice, a number of effects, such as the presence of noncircular motions, spiral structure, warps, asymmetries, and extra-planar gas, complicate the issue in nontrivial ways.

1.4 Dynamical Measurement of the Distance to a Globular Cluster

In this short section, we wish to introduce an interesting example of astronomical measurement based on dynamics. We have no intention to develop here realistic models of globular clusters, which would require more advanced methods and would bring us well outside the main scope of this book. To some extent, we may take the example described here as a kind of thought experiment. In reality, for some clusters for which good models are available measurements substantially similar to the one described here have already been performed.

1.4.1 The Maxwell–Boltzmann Distribution Function

From the kinetic theory of gases, we know that the particles of which a simple one-component system is made should be described by the Maxwell–Boltzmann distribution function in the six-dimensional phase space

$$f = Ae^{-\frac{E}{kT}}, \tag{1.3}$$

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if the system is thermodynamically relaxed. Here E is the single-particle energy, k is Boltzmann's constant, and T the temperature of the gas. For particles of mass m, the single-particle kinetic energy is $mv^2/2$. Therefore, with respect to the velocity space, the distribution function is an isotropic Gaussian

$$f = \hat{A} e^{-av^2}, \tag{1.4}$$

where $a = m/(2kT)$. Note that $1/\sqrt{a}$ is a typical velocity that characterizes the random motions of the particles that make the gas. Mathematically, it gives a measure of the width of the Gaussian, so that a cold (hot) gas is characterized by a small (large) velocity dispersion. For a real gas, thermodynamical relaxation is ensured by the frequent collisions among the gas molecules.

1.4.2 Dynamical Distance to a Globular Cluster

It has long been debated, as briefly already described by Henri Poincaré in his essay *Science et Méthode* (1908), whether globular clusters can be considered as relaxed gases of stars. Progress in stellar dynamics and observations has led to the picture that many globular clusters should indeed be regarded, at least in their central regions, as relaxed stellar systems and thus should be characterized by a distribution function similar to that of Eq. (1.3). Without entering the issues related to the justification of this statement, let us follow here a simple consequence of astronomical interest.

Consider a relaxed globular cluster for which, in the central regions, we have collected the line-of-sight velocity measurements $\{v_{los}^{(n)}\}$ for a large number N of individual stars ($n = 1, 2, \ldots, N$) and proper motions $\{\omega^{(m)}\}$ for a large number M of individual stars ($m = 1, 2, \ldots, M$). The two sets of stars for which the data have been collected need not coincide.

The average values of these quantities will give us an estimate of the velocity vector that describes the three-dimensional motion of the cluster as a whole.

The dispersions around the average, σ_{los} and σ_ω, can then be measured. We recall that the intrinsic velocity dispersion $\sigma_\perp$ is related to the apparent proper motion dispersion σ_ω by the relation $\sigma_\perp = d\sigma_\omega$, where d is the distance to the cluster. From the model assumption that the velocity dispersion is isotropic, if we identify the two velocity dispersions we then obtain a measurement of the distance d. This is a dynamical measurement, because it is based on a dynamical argument. For more complex dynamical models, a dynamical measurement of the distance d can be made on the basis of the data mentioned in this simplified example.

Note

1 Distinguishing the concepts associated with the different distance definitions is quite subtle. In particular, for a given cosmological model and a given redshift, the various distances can be very different from one another. The concepts are well described in cosmology books; see also Hogg, D. W. 2000. https://arxiv.org/pdf/astro-ph/9905116.pdf. For quantitative purposes, one useful "distance calculator" is available, for example, at www.astro.ucla.edu/wright/CosmoCalc.html.

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