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1

Introduction

Astrophysics is the branch of physics that studies, loosely speaking, phenomena on large scales—the Sun, the planets, stars, galaxies, and the Universe as a whole. But this definition is clearly incomplete; much of astronomy[1] also deals, e.g., with phenomena at the atomic and nuclear levels. We could attempt to define astrophysics as the physics of distant objects and phenomena, but astrophysics also includes the formation of the Earth, and the effects of astronomical events on the emergence and evolution of life on Earth. This semantic difficulty perhaps simply reflects the huge variety of physical phenomena encompassed by astrophysics. Indeed, as we will see, practically all the subjects encountered in a standard undergraduate physical science curriculum—classical mechanics, electromagnetism, thermodynamics, quantum mechanics, statistical mechanics, relativity, and chemistry, to name just some—play a prominent role in astronomical phenomena. Seeing all of them in action is one of the exciting aspects of studying astrophysics.

Like other branches of physics, astronomy involves an interplay between experiment and theory. Theoretical astrophysics is carried out with the same tools and approaches used by other theoretical branches of physics. Experimental astrophysics, however, is somewhat different from other experimental disciplines, in the sense that astronomers cannot carry out controlled experiments,[2] but can only perform **observations** of the various phenomena provided by nature. With this in mind, there is little difference, in practice, between the design and the execution of an experiment in some field of physics, on the one hand, and the design and the execution of an astronomical observation, on the other. There is certainly no particular distinction between the methods of data analysis in either case. Since everything we discuss in this book will ultimately be based on observations, let us begin with a brief overview of how observations are used to make astrophysical measurements.

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[1] We will use the words "astrophysics" and "astronomy" interchangeably, as they mean the same thing nowadays. For example, the four leading journals in which astrophysics research is published are named the *Astrophysical Journal*, the *Astronomical Journal*, *Astronomy and Astrophysics*, and *Monthly Notices of the Royal Astronomical Society*, but their subject content is the same.

[2] An exception is the field of laboratory astrophysics, in which some particular properties of astronomical conditions are simulated in the lab.

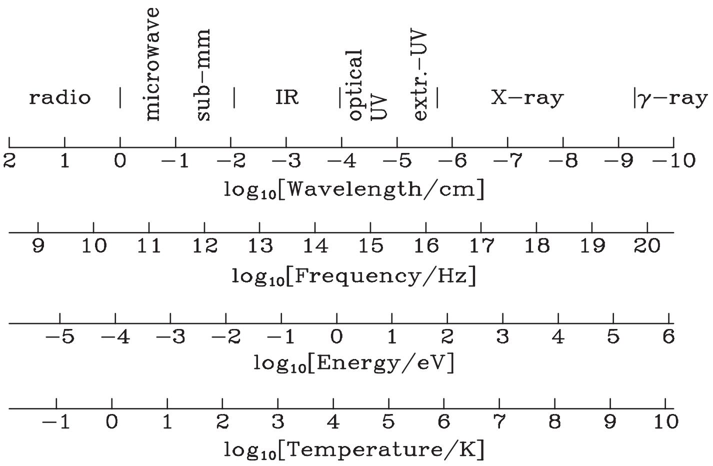

Figure 1.1 The various spectral regions of electromagnetic radiation, their common astronomical nomenclature, and their approximate borders in terms of wavelength, frequency, energy, and temperature. Temperature is here associated with photon energy E via the relation $E = kT$, where k is Boltzmann's constant.

1.1 Observational Techniques

With several exceptions, astronomical phenomena are almost always observed by detecting and measuring electromagnetic (EM) radiation from distant sources. (The exceptions are in the fields of cosmic-ray astronomy, neutrino astronomy, and gravitational wave astronomy.) Figure 1.1 shows the various, roughly defined, regions of the EM spectrum. To record and characterize EM radiation, one needs, at least, a camera that will focus the approximately plane EM waves arriving from a distant source and a detector at the focal plane of the camera, which will record the signal. A "telescope" is just another name for a camera that is specialized for viewing distant objects. The most basic such camera–detector combination is the human eye, which consists (among other things) of a lens (the camera) that focuses images on the retina (the detector). Light-sensitive cells on the retina then translate the light intensity of the images into nerve signals that are transmitted to the brain. Figure 1.2 sketches the optical principles of the eye and of two telescope configurations.

Until the introduction of telescope use to astronomy by Galileo in 1609, observational astronomy was carried out solely using human eyes. However, the eye as an astronomical tool has several disadvantages. The **aperture** of a dark-adapted pupil is <1 cm in diameter, providing limited **light-gathering area** and limited **angular resolution**. The light-gathering capability of a camera is set by the area of its aperture (e.g., of the objective lens, or of the primary mirror in a reflecting telescope). The larger the aperture, the more photons, per unit time, can be detected, and hence fainter sources of light can be observed. For example, the largest visible-light telescopes in operation today have 10-meter primary mirrors, i.e., more than a million times the light gathering area of a human eye.

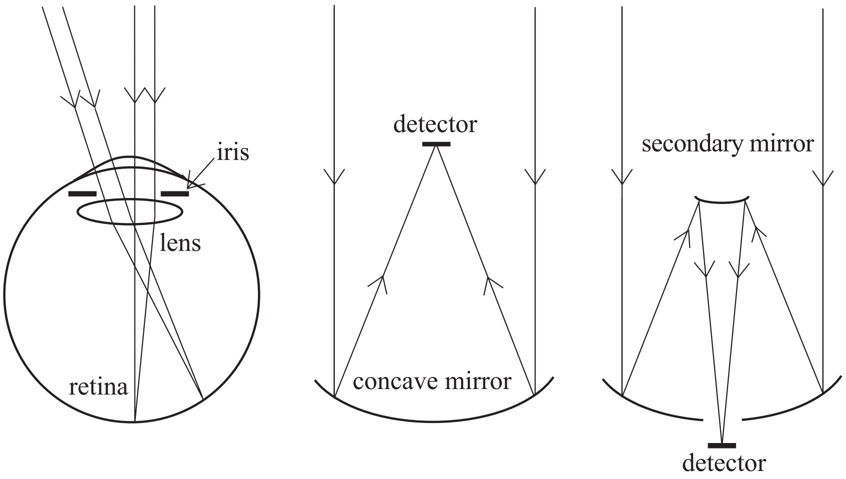

Figure 1.2 Optical sketches of three different examples of camera–detector combinations. *Left:* Human eye, shown with parallel rays from two distant sources, one source on the optical axis of the lens and one at an angle to the optical axis. The lens, which serves as the camera in this case, focuses the light onto the retina (the detector), on which two point images are formed. *Center:* A reflecting telescope with a detector at its *prime focus.* Plotted are parallel rays from a distant source on the optical axis of the telescope. The concave mirror focuses the rays onto the detector at the mirror's focal plane, where a point image is formed. *Right:* Reflecting telescope, but with a secondary, convex mirror, which folds the beam back down and through a hole in the primary concave mirror, to form an image on the detector at the so-called *Cassegrain focus.*

The angular resolution of a camera or a telescope is the smallest angle on the sky between two sources of light that can be discerned as separate sources with that camera. From wave optics, a plane wave of wavelength λ passing through a circular aperture of diameter D, when focused onto a detector, will produce a diffraction pattern of concentric rings, centered on the position expected from geometrical optics, with a central spot having an angular radius (in radians) of

$$\theta = 1.22\frac{\lambda}{D}. \tag{1.1}$$

Consider, for example, the image of a field of stars obtained through some camera, and having also a bandpass filter that lets through light within only a narrow range of wavelengths. The image will consist of a set of such diffraction patterns, one at the position of each star (see Fig. 1.3). Actually seeing these diffraction patterns requires that blurring of the image not be introduced, either by imperfectly built optics or by other elements, e.g., Earth's atmosphere. The central spots from the diffraction patterns of two adjacent sources on the sky will overlap, and will therefore be hard to distinguish from each other, when their angular separation is less than about λ/D. Similarly, a source of light with an intrinsic angular size smaller than this **diffraction limit** will produce an image that is *unresolved,* i.e., indistinguishable from the image produced by a **point source** of zero angular extent. Thus, in principle, a 10-meter telescope working at the same visual wavelengths as the eye can have an angular resolution that is 1000 times better than that of the eye.

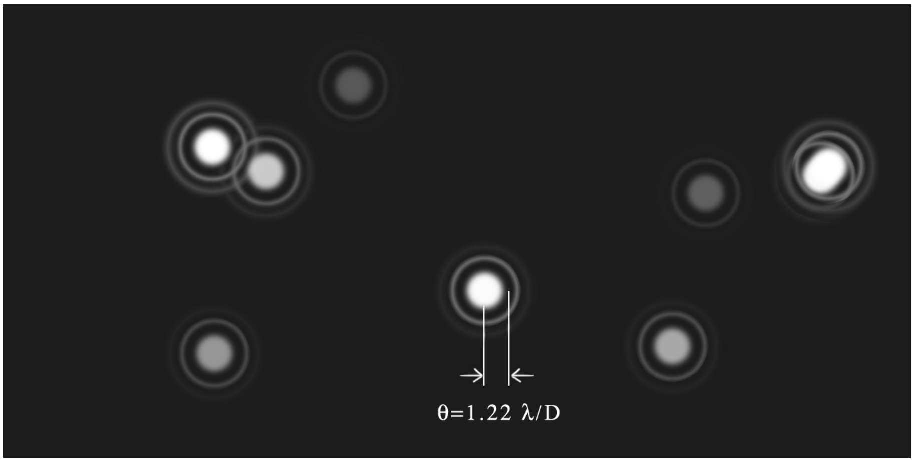

Figure 1.3 Simulated diffraction-limited image of a field of stars, with the characteristic diffraction pattern due to the telescope's finite circular aperture at the position of every star. Pairs of stars separated on the sky by an angle $\theta < \lambda/D$ (e.g., on the right-hand side of the image) are hard to distinguish from single stars. Real conditions are always worse than the diffraction limit, due to, e.g., imperfect optics and atmospheric blurring.

In practice, it is difficult to achieve diffraction-limited performance with ground-based *optical* telescopes, due to the constantly changing, blurring effect of the atmosphere. (The **optical** wavelength range of EM radiation is roughly defined as 0.32–1 μm.) However, observations with angular resolutions at the diffraction limit are routine in radio and infrared astronomy, and much progress in this field has been achieved recently in the optical range as well.[3] Angular resolution is important not only for discerning the fine details of astronomical sources (e.g., seeing the moons and surface features of Jupiter, the constituents of a star-forming region, or subtle details in a galaxy), but also for detecting faint unresolved sources against the background of emission from the Earth's atmosphere, i.e., the "sky." The night sky shines due to scattered light from the stars, from the Moon, if it is up, and from artificial light sources, but also due to fluorescence of atoms and molecules in the atmosphere. The better the angular resolution of a telescope, the smaller the solid angle over which the light from, say, a star, will be spread out, and hence the higher the contrast of that star's image over the statistical fluctuations of the sky background (see

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[3] In the technique of **adaptive optics** that is used in the near-infrared, the light from the region being observed is reflected off a deformable mirror in the light path to the detector. Some of the light from the field of view, which needs to include a bright source, e.g., a star, is diverted to a *wavefront sensor*. Based on the distorted image of the bright source in a brief exposure, the wavefront sensor determines the shape of the deformable mirror that is required to correct the atmospheric distortion and convert the distorted wavefront back to a plane-wave shape. Once the mirror is properly deformed, a new image of the bright source is obtained and analyzed, and so on. This loop repeats at a rate of about 1 kHz, thus keeping up with the variations in wavefront distortions due to cells of air of different densities (and hence refraction indices) that drift across the telescope aperture. The bright source can be a bright star that happens to lie in the field of view being studied, or it can be an artificial *laser guide star*, produced by sending in reverse through the telescope optics a high-powered laser that scatters on, or excites, atoms high in the atmosphere, producing a small bright spot in the sky.

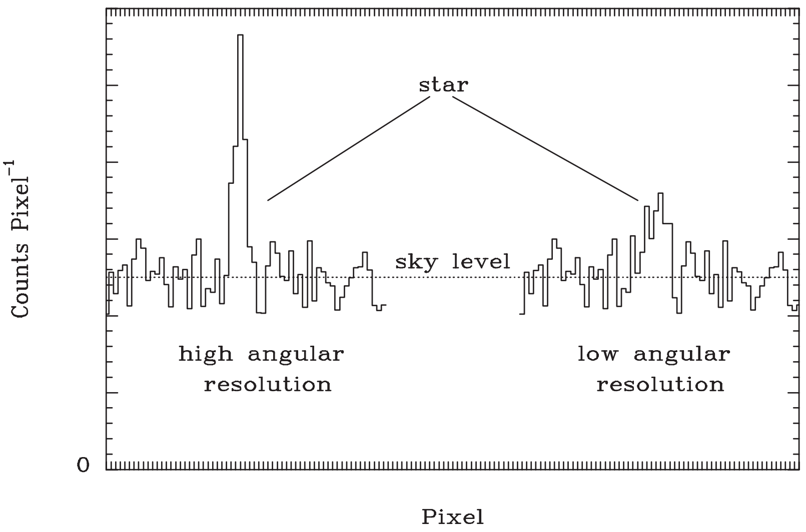

Figure 1.4 Cuts through the positions of a star in two different astronomical images, illustrating the effect of angular resolution on the detectability of faint sources on a high background. The vertical axis shows the counts registered in every pixel along the cut, as a result of the light intensity falling on that pixel. On the left, the narrow profile of the stellar image stands out clearly above the Poisson fluctuations in the sky background, the mean level of which is indicated by the dashed line. On the right, the counts from the same star are spread out in a profile that is twice as wide, and hence the contrast above the background noise is lower.

Fig. 1.4). A high sky background combined with limited angular resolution is among the reasons why it is difficult to see stars during daytime.

A third limitation of the human eye is its fixed integration time, of about 1/30 second. In astronomical observations, faint signals can be collected on a detector during arbitrarily long exposures (sometimes accumulating to months), permitting the detection of extremely faint sources. Another shortcoming of the human eye is that it is sensitive only to a narrow **visual** range of wavelengths of EM radiation (about 0.4–0.7 μm, i.e., within the optical range defined above), while astronomical information exists in all regions of the EM spectrum, from radio, through infrared, optical, ultraviolet, X-ray, and gamma-ray bands. Finally, a detector other than the eye allows keeping an objective record of the observation, which can then be examined, analyzed, and disseminated among other researchers. Astronomical data are almost always saved in some digital format, in which they are most readily later processed using computers. All telescopes used nowadays for professional astronomy are equipped with detectors that record the data (whether an image of a section of sky, or otherwise—see below). The popular perception of astronomers peering through the eyepieces of large telescopes is an anachronism.

The type of detector that is used in optical, near-ultraviolet, and X-ray astronomy is usually a **charge-coupled device** (CCD), the same type of detector that is found in many commercially available digital cameras. A CCD is a slab of silicon that is divided into

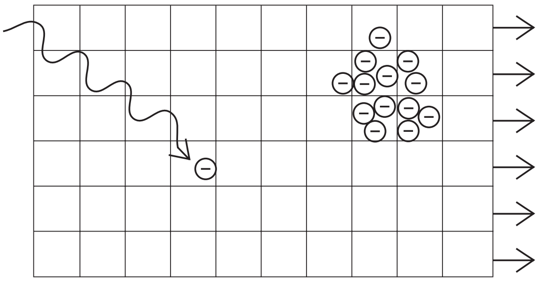

Figure 1.5 Schematic view (highly simplified) of a CCD detector. On the left, a photon is absorbed by the silicon in a particular pixel, releasing an electron, which is stored in the pixel until the CCD is read out. On the right are shown other photoelectrons that were previously liberated and stored in several pixels on which, e.g., the image of a star has been focused. At the end of the exposure, the accumulated charge is transferred horizontally from pixel to pixel by manipulating the voltages applied to the pixels, until it is read out on the right-hand side (arrows) and amplified.

numerous *pixels* by a combination of insulating buffers that are etched into the slab and the application of selected voltage differences along its area. Photons reaching the CCD liberate *photoelectrons* via the photoelectric effect. The photoelectrons accumulated in every pixel during an exposure period are then read out and amplified, and the measurement of the resulting current is proportional to the number of photons that reached the pixel. This allows forming a digital image of the region of the sky that was observed (see Fig. 1.5).

So far, we have discussed astronomical observations only in terms of producing an image of a section of sky by focusing it onto a detector. This technique is called *imaging*. However, an assortment of other measurements can be made. Every one of the parameters that characterize an EM wave can carry useful astronomical information. Different techniques have been designed to measure each of these parameters. To see how, consider a plane-parallel, monochromatic (i.e., having a single frequency), EM wave, with electric field vector described by

$$\mathbf{E} = \hat{\mathbf{e}} E(t) \cos(2\pi \nu t - \mathbf{k} \cdot \mathbf{r} + \phi). \tag{1.2}$$

The unit vector $\hat{\mathbf{e}}$ gives the direction of polarization of the electric field, $E(t)$ is the field's time-dependent (apart from the sinusoidal variation) amplitude, ν is the frequency, and $\mathbf{k}$ is the wave vector, having the direction of the wave propagation, and magnitude $|\mathbf{k}| = 2\pi/\lambda$. The wavelength λ and the frequency ν are related by the speed of light, c, through $\nu = c/\lambda$. The phase constant of the wave is ϕ.

Imaging involves determining the direction, on the sky, to a source of plane-parallel waves, and therefore implies a measurement of the direction of $\mathbf{k}$. From an image, one can also measure the strength of the signal produced by a source (e.g., in a photon-counting device such as a CCD, by counting the total number of photons collected from the source over an integration time). As discussed in more detail in chapter 2, the photon flux is related to the *intensity*, which is the time-averaged electric-field amplitude squared, $\langle E^2(t) \rangle$.

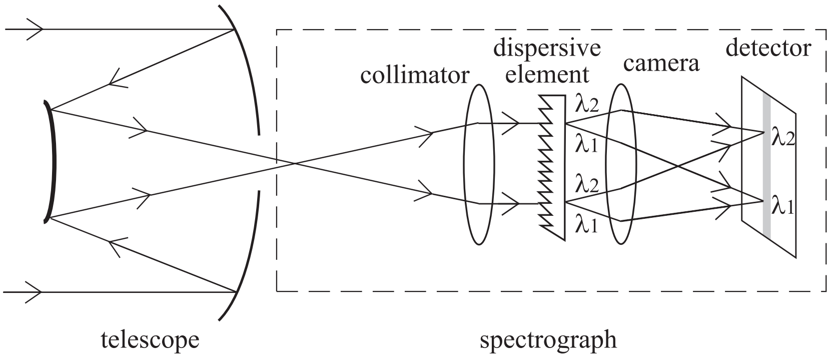

Figure 1.6 Schematic example of a spectrograph. Light from a distant point source converges at the Cassegrain focus of the telescope at the left. The beam is then allowed to diverge again and reaches a *collimator* lens sharing the same focus as the telescope, so that a parallel beam of light emerges. The beam is then transmitted through a dispersive element, e.g., a transmission grating, which deflects light of different wavelengths by different angles, in proportion to the wavelength. The paths of rays for two particular wavelengths, λ_1 and λ_2, are shown. A camera lens refocuses the light onto a detector at the camera's focal plane. The light from the source, rather than being imaged into a point, has been spread into a spectrum (gray vertical strip).

Measuring the photon flux from a source is called *photometry*. In time-resolved photometry, one can perform repeated photometric measurements as a function of time, and thus measure the long-term time dependence of $\langle E^2 \rangle$.

The wavelength of the light, λ (or equivalently, the frequency, ν), can be determined in several ways. A bandpass filter before the detector (or in the "receiver" in radio astronomy) will allow only EM radiation in a particular range of wavelengths to reach the detector, while blocking all others. Alternatively, the light can be reflected off, or transmitted through, a dispersing element, such as a prism or a diffraction grating, before reaching the detector. Light of different wavelengths will be deflected by different angles from the original beam, and hence will land on the detector at different positions. A single source of light will thus be spread into a **spectrum**, with the signal at each position along the spectrum proportional to the intensity at a different wavelength. This technique is called *spectroscopy*, and an example of a telescope–spectrograph combination is illustrated in Fig. 1.6.

The phase constant ϕ of the light wave arriving at the detector can reveal information on the precise direction to the source and on effects, such as scattering, that the wave underwent during its path from the source to the detector. The phase can be measured by combining the EM waves received from the same source by several different telescopes and forming an interference pattern. This is called *interferometry*. In interferometry, the *baseline* distance B between the two most widely spaced telescopes replaces the aperture in determining the angular resolution, λ/B. In radio astronomy, the signals from radio telescopes spread over the globe, and even in space, are often combined, providing baselines of order 10^4 km, and very high angular resolutions.

Finally, the amount of polarization (*unpolarized*, i.e., having random polarization direction, or *polarized* by a fraction between 0 and 100%), its type (linear, circular), and the orientation on the sky of the polarization vector $\hat{\mathbf{e}}$ can be determined. For example, in optical astronomy this can be achieved by placing polarizing filters in the light beam, allowing only a particular polarization component to reach the detector. Measurement of the polarization properties of a source is called *polarimetry*.

Ideally, one would like always to be able to characterize all of the parameters of the EM waves from a source, but this is rarely feasible in practice. Nevertheless, it is often possible to measure several characteristics simultaneously, and these techniques are then referred to by the appropriate names, e.g., spectro-photo-polarimetry, in which both the intensity and the polarization of light from a source are measured as a function of wavelength.

In the coming chapters, we study some of the main topics with which astrophysics deals, generally progressing from the near to the far. Most of the volume of this book is dedicated to the theoretical understanding of astronomical phenomena. However, it is important to remember that the discovery and quantification of those phenomena are the products of observations, using the techniques that we have just briefly reviewed.

Problems

1. a. Calculate the best angular resolution that can, in principle, be achieved with the human eye. Assume a pupil diameter of 0.5 cm and the wavelength of green light, $\sim 0.5\ \mu$m. Express your answer in arcminutes, where an arcminute is 1/60 of a degree. (In practice, the human eye does not achieve diffraction-limited performance, because of imperfections in the eye's optics and the coarse sampling of the retina by the light-sensitive *rod* and *cone* cells that line it.)

b. What is the angular resolution, in arcseconds (1/3600 of a degree), of the Hubble Space Telescope (with an aperture diameter of 2.4 m) at a wavelength of 0.5 μm?

c. What is the angular resolution, expressed as a fraction of an arcsecond, of the Very Long Baseline Interferometer (VLBI)? VLBI is an network of radio telescopes (wavelengths $\sim$1–100 cm), spread over the globe, that combine their signals to form one large interferometer.

d. From the table of Constants and Units, find the distances and physical sizes of the Sun, Jupiter, and a Sun-like star 10 light years away. Calculate their angular sizes, and compare to the angular resolutions you found above.

2. A CCD detector at the focal plane of a 1-m-diameter telescope records the image of a certain star. Due to the blurring effect of the atmosphere (this is called “seeing” by astronomers) the light from the star is spread over a circular area of radius R pixels. The total number of photoelectrons over this area, accumulated during the exposure, and due to the light of the star, is $N_{\rm star}$. Light from the sky produces $n_{\rm sky}$ photoelectrons per pixel in the same exposure.

a. Calculate the signal-to-noise ratio (S/N) of the photometric measurement of the star, i.e., the ratio of the counts from the star to the uncertainty in this measurement. Assume Poisson statistics, i.e., that the "noise" is the square root of the total counts, from all sources.

b. The same star is observed with the same exposure time, but with a 10-m-diameter telescope. This larger telescope naturally has a larger light gathering area, but also is at a site with a more stable atmosphere, and therefore has 3 times better "seeing" (i.e., the light from the stars is spread over an area of radius $R/3$). Find the S/N in this case.

c. Assuming that the star and the sky are not variable (i.e., photons arrive from them at a constant rate), find the functional dependence of S/N on exposure time, t, in two limiting cases: the counts from the star are much greater than the counts from the sky in the "seeing disk" (this is called the "source-limited" case); and vice versa (called the "background-limited" case).
Answer: S/N $\propto t^{1/2}$ in both cases.

d. Based on the results of (c), by what factor does the exposure time with the 1-m telescope need to be increased to reach the S/N obtained with the 10-m telescope, for each of the two limiting cases?
Answer: By a factor 100 in the first case, and 1000 in the second case.

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