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Chapter 1
Light

> Always the laws of light are the same, but the modes and degrees of seeing vary.
>
> – Henry David Thoreau, *A Week on the Concord and Merrimack Rivers*, 1849

Astronomy is not for the faint of heart. Almost everything it cares for is forbiddingly remote, tantalizingly untouchable, and invisible in the daytime, when most sensible people do their work. Nevertheless, many – including you, brave reader – have enough curiosity and courage to collect the flimsy evidence that trickles in from the universe outside our atmosphere and hope it may hold a message.

In this chapter we introduce you to astronomical evidence. Some is in the form of material, like meteorites, but most is in the form of light from faraway objects. Accordingly, we begin with three familiar theories describing the behavior of light: light as a wave, light as a quantum entity called a photon, and light as a geometrical ray. The ray picture is simplest, and we use it to introduce some basic ideas about measuring the brightness of a source. Most information in astronomy, however, comes from analyzing how brightness varies with wavelength, so we next introduce the important idea of spectroscopy. We end with a discussion of the astronomical magnitude system. We begin, however, with a few thoughts on the nature of astronomy as an intellectual enterprise.

1.1 The story

> . . . as I say, the world itself has changed. . .. For this is the great secret, which was known by all educated men in our day: that by what men think, we create the world around us, daily new.
>
> – Marion Zimmer Bradley, *The Mists of Avalon*, 1982

Astronomers are storytellers. They spin tales of the universe and of its important parts. Sometimes they envision landscapes of another place, like the roiling liquid-metal core of the planet Jupiter. Sometimes they describe another time, like the era before Earth when dense buds of gas first flowered into stars, and a darkening universe filled with the sudden blooms of galaxies. Often the stories

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solve mysteries or illuminate something commonplace or account for something monstrous: How is it that stars shine, age, or explode? Some of the best stories tread the same ground as myth: What threw up the mountains of the Moon? How did the skin of our Earth come to teem with life? Sometimes there are fantasies: What would happen if a comet hit the Earth? Sometimes there are prophecies: How will the universe end?

Like all stories, creation of astronomical tales demands imagination. Like all storytellers, astronomers are restricted in their creations by many conventions of language as well as by the characters and plots already in the literature. Astronomers are no less a product of their upbringing, heritage, and society than any other crafts people. Astronomers, however, think their stories are special, that they hold a larger dose of "truth" about the universe than any others. Clearly, the subject matter of astronomy – the universe and its important parts – does not belong only to astronomers. Many others speak with authority about just these things: theologians, philosophers, and poets, for example. Is there some characteristic of astronomers, besides arrogance, that sets them apart from these others? Which story about the origin of the Moon, for example, is the truer: the astronomical story about a collision 4500 million years ago between the proto-Earth and a somewhat smaller proto-planet, or the mythological story about the birth of the Sumerian/Babylonian deity Nanna-Sin (a rather formidable fellow who had a beard of lapis lazuli and rode a winged bull)?

This question of which is the "truer" story is not an idle one. Over the centuries, people have discovered (by being proved wrong) that it is very difficult to have a commonsense understanding of what the whole universe and its most important parts are like. Common sense just isn't up to the task. For that reason, as Morgan le Fay tells us in *The Mists of Avalon*, created stories about the universe themselves actually *create* the universe the listener lives in. The real universe (like most scientists, you and I behave as if there is one) is not silent, but whispers very softly to us humans. Many whispers go unheard, and the real universe is probably very different from the one you read about today in any book that claims to tell its story. People, nevertheless, must act. Most recognize that the bases for their actions are fallible stories, and they must therefore select the most trustworthy stories that they can find.

Most of you won't have to be convinced that it is better to talk about colliding planets than about Nanna-Sin if your aim is to understand the Moon or perhaps plan a visit. Still, it is useful to ask the question: what is it, if anything, that makes astronomical stories a more reliable basis for action, and in that sense more truthful or factual than any others? Only one thing, I think: *discipline*. Astronomers feel an obligation to tell their story with great care, following a rather strict, scientific, discipline.

Scientists, philosophers, and sociologists have written about what it is that makes science different from other human endeavors. There is much discussion and disagreement about the necessity of making scientific stories "broad and

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deep and simple," about the centrality of paradigms, the importance of predictions, the strength or relevance of motivations, and the inevitability of conformity to social norms and professional hierarchies.

But most agree on the perhaps obvious point that a scientist, in creating a story (scientists usually call them "theories" or "models") of, say, the Moon, must pay a great deal of attention to all the relevant evidence. A scientist, unlike a science-fiction writer, may only fashion a theory that never, ever, violates that evidence.

This is a book about how to collect and interpret relevant evidence in astronomy. Most of that evidence is in the form of light arriving from far, far away.

1.2 Models for the behavior of light

Some (not astronomers!) regard astronomy as applied physics. There is some justification for this, since astronomers, to help tell some astronomical story, persistently drag out theories proposed by physicists. Physics and astronomy differ partly because astronomers are interested in telling the story of an object, whereas physicists are interested in uncovering the most fundamental rules of the natural world. Astronomers tend to find physics useful but sterile; physicists tend to find astronomy messy and mired in detail. We now ponder the question: how does light behave? More specifically, what properties of light are important in making meaningful astronomical observations and predictions? Physics has the answers.

1.2.1 Electromagnetic waves

> . . . we may be allowed to infer, that homogeneous light, at certain equal distances in the direction of its motion, is possessed of opposite qualities, capable of neutralizing or destroying each other, and extinguishing the light, where they happen to be united; . . .
>
> – Thomas Young, *Philosophical Transactions, The Bakerian Lecture*, 1804

Electromagnetic waves are a model for the behavior of light. We know this model is incorrect (*incomplete* is perhaps a better term). Nevertheless, since the wave theory precisely describes so much of light's behavior, we need to review its claims. Christian Huygens,[1] in his 1678 book, *Traité de la Lumière*, made the first serious argument that visible light is best regarded as a *wave* phenomenon.

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[1] Huygens (1629–95), a Dutch natural philosopher and major figure in seventeenth-century science, had an early interest in lens grinding. He discovered the rings of Saturn and its large satellite, Titan, in 1655–56, with a refracting telescope of his manufacture. At about the same time, he invented the pendulum clock and formulated a theory of elastic bodies. He developed his wave theory of light later in his career, after he moved from The Hague to the more cosmopolitan environment of Paris. Near the end of his life, he wrote a treatise on the possibility of extraterrestrial life.

A ***wave*** is a disturbance that propagates through space. If some property of the environment (say, the level of the water in your bathtub) is disturbed at one place (perhaps by a splash), a wave is present if that disturbance moves continuously from place to place in the environment (ripples from one end of your bathtub to the other, for example). Material particles, like bullets or ping-pong balls, also propagate from place to place. Waves and particles share many characteristic behaviors – both can ***reflect*** (change directions at an interface), ***refract*** (change speed or direction in response to a change in the transmitting medium), and can carry energy from place to place.

However, waves exhibit two characteristic behaviors not shared by particles. ***Diffraction*** is the ability to bend around obstacles. A water wave entering a narrow opening, for example, will travel not only in the "shadow" of the opening but will spread in all directions on the far side. ***Interference*** is the ability to combine with other waves in predictable ways. Two water waves can, for example, destructively interfere if they combine so that the troughs of one always coincide with the peaks of the other – the same phenomenon that permits noise-cancelling earphones.

Although Huygens knew that light exhibited the properties of diffraction and interference, he unfortunately did not discuss them in his book. Isaac Newton, his younger contemporary, opposed Huygens' wave hypothesis and argued that light was composed of tiny solid particles. Newton's reputation was such that his view prevailed until the early part of the nineteenth century, when Thomas Young and Augustin Fresnel drew attention to diffraction and interference in light. Soon the evidence for "light waves" proved irresistible.

Well-behaved waves exhibit certain measurable qualities: amplitude, wavelength, frequency, and wave speed. Physicists in the generation following Fresnel were able to measure these quantities for visible light waves. Since light was a wave, and since waves are disturbances that propagate, it was natural to ask: "What 'stuff' does a light wave disturb?" In one of the major triumphs of nineteenth-century physics, James Clerk Maxwell proposed an answer in 1873.

Maxwell (1831–79), a Scot, is a major figure in the history of physics, comparable to Newton and Einstein. His doctoral thesis demonstrated that the rings of Saturn (discovered by Huygens) must be made of many small solid particles in order to be gravitationally stable. He conceived the kinetic theory of gases in 1866 (Ludwig Boltzmann did similar work independently) and transformed thermodynamics into a science based on statistics rather than determinism. His most important achievement was the mathematical formulation of the laws of electricity and magnetism in the form of four partial differential equations. Published in 1873, ***Maxwell's equations*** completely accounted for separate electric and magnetic phenomena and also demonstrated the connection between the two forces. Maxwell's work is the culmination of classical physics, and its limits led to both the theory of relativity and the theory of quantum mechanics.

Maxwell proposed that light is a propagating ***electric and magnetic*** disturbance. The following example illustrates his idea.

Consider a single, motionless electron, electron A, attached to the rest of an atom by means of a spring. (The spring is just a mechanical model for the electrostatic attraction that holds the electron to the nucleus.) This pair of charges, the negative electron and the positive ion, constitute a dipole. A second electron, electron B, is also attached to the rest of its atom by a spring, but this second dipole is at some distance from A. Electron A repels B, and B's stationary position in its atom is in part determined by the location of A. The two atoms are sketched in Figure 1.1. Now to make a wave: Set electron A vibrating on its spring. Electron B must respond to this vibration, since the force it feels is changing direction. It moves in a way that will echo the motion of A. The lower part of Figure 1.1 shows the changing electric force on B as A moves through a cycle of its vibration.

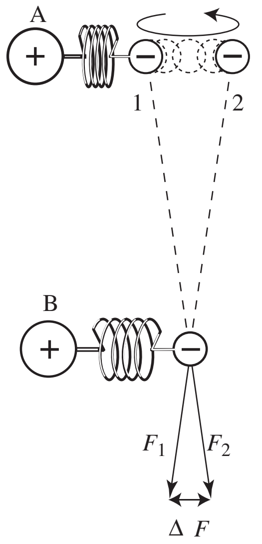

Fig. 1.1 Acceleration of an electron produces a wave. The electrons in initially undisturbed atoms are in stationary positions. Each electron is attached to the rest of the atom (the heavy, positively charged ion) by some force, which we represent as a spring. If the electron in the source atom (A) is disturbed so that it oscillates between positions (1) and (2), then the electron in the receiver (B) experiences a force that changes from F_1 to F_2 in the course of A's oscillation. The difference ΔF, sets the amplitude of the changing part of the electric force seen by B.

The disturbance of dipole A has propagated to B in a way that suggests a wave is operating. Electron B behaves like an object floating in your bathtub that moves in response to the rising and falling level of a water wave.

In trying to imagine the actual thing that a vibrating dipole disturbs, you might envision the water in a bathtub. Now imagine some stuff that fills space around the electrons, the way a fluid would, so a disturbance caused by moving one electron can propagate from place to place. The physicist Michael Faraday[2] supplied the very useful idea of a ***field*** – an abstract *entity* (not a material fluid at all) created by any charged particle. The field permeates space and gives other charged particles instructions about what force they should experience. In this conception, electron B consults the local field in order to decide how to move. You are probably familiar with understanding magnetic and gravitational forces as also arising from their corresponding fields. Shaking (accelerating) the electron at A distorts the field in its vicinity, and this distortion propagates to vast distances, just like the ripples from a rock dropped into a calm and infinite ocean.

The details of propagating a field disturbance turned out to be a little complicated. Hans Christian Oersted and André Marie Ampère in 1820 had shown experimentally that a changing electric field, such as the one generated by an accelerated electron, produces a magnetic field. Acting on his intuition of an underlying unity in physical forces, Faraday experimentally confirmed his guess

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[2] Michael Faraday (1791–1867), considered by many the greatest experimentalist in history, began his career as a bookbinder with minimal formal education. His amateur interest in chemistry led to a position in the laboratory of the renowned chemist, Sir Humphrey Davy, at the Royal Institution in London. Faraday continued work as a chemist for most of his productive life, but conducted an impressive series of experiments in electromagnetism in the period 1834–55. His ideas, although largely rejected by physicists on the Continent, eventually formed the empirical basis for Maxwell's theory of electromagnetism.

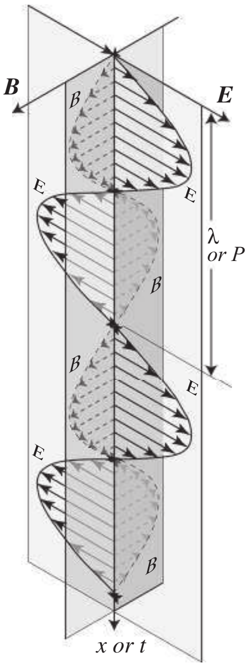

Fig. 1.2 A plane-polarized electromagnetic wave. The electric and magnetic field strengths are drawn as vectors that vary in both space and time. The illustrated waves are said to be plane-polarized because all electric vectors are confined to the *x*–*y* plane.

that a changing magnetic field must in turn generate an electric field. Maxwell had the genius to realize that his equations implied that the electric and magnetic field changes in a vibrating dipole would support one another and produce a wavelike self-propagating disturbance. Change the electric field and you thereby create a magnetic field, which then creates a different electric field, which creates a magnetic field, and so on, forever. Thus, it is proper to speak of the waves produced by an accelerated charged particle as ***electromagnetic***. Figure 1.2 shows a schematic version of an electromagnetic wave. The changes in the two fields, electric and magnetic, vary at right angles to one another and the direction of propagation is at right angles to both (a ***transverse wave***).

Thus, a disturbance in the electric field does indeed seem to produce a wave. Is this *electromagnetic* wave the same thing as the *light* wave we see with our eyes?

From his four equations – the laws of electric and magnetic force – Maxwell derived the speed of any electromagnetic wave, which, in a vacuum, turned out to depend only on constants

$$c = \sqrt{\varepsilon\mu} \tag{1.1}$$

Here ε and μ are well-known constants that describe the strengths of the electric and magnetic forces. (They are, respectively, the electric permittivity and magnetic permeability of the vacuum.) When he entered the experimental values for ε and μ in the above equation, Maxwell computed the electromagnetic wave speed, which turned out to be numerically identical to the speed of light, a quantity that had been experimentally measured with improving precision over the preceding century. This equality of predicted and experimentally measured speeds was a quite convincing argument that light waves and electromagnetic waves were the same thing. Maxwell had shown that three different entities, electricity, magnetism, and light, were really tightly related.

Other predictions based on Maxwell's theory further strengthened this view of the nature of light. For one thing, one can note that for any well-behaved wave the speed of the wave is the product of its frequency and wavelength:

$$c = \lambda\nu \tag{1.2}$$

There is only one speed that electromagnetic waves can have in a vacuum; therefore, there should be a one-dimensional classification of electromagnetic waves (the ***electromagnetic spectrum***). In this spectrum, each wave is characterized only by its particular wavelength (or frequency). A single light wave of a particular wavelength is usually represented as the harmonic function

$$E(x,t) = E_0 \sin\left\{\frac{2\pi}{\lambda}(x - ct)\right\} = E_0 \sin\{\phi\} \tag{1.3}$$

where E_0 and ϕ are, respectively, the ***amplitude*** and the ***phase*** of the wave. Table 1.1 gives the modern names for various portions or ***bands*** of the

Table 1.1 *The electromagnetic spectrum. Region boundaries are not well defined, so there is some overlap. Subdivisions are based in part on distinct detection methods.*

Band	Wavelength range	Frequency range	Subdivisions (long λ – short λ)
Radio	$>$ 1 mm	$<$ 300 GHz	VLF–AM–VHF–UHF
Microwave	0.1 mm–3 cm	100 MHz–3000 GHz	Millimeter–Submillimeter
Infrared	700 nm–1 mm	3×10^{11}–4×10^{14} Hz	Far–Middle–Near
Visible	300 nm–800 nm	4×10^{14}–1×10^{15} Hz	Red–Blue
Ultraviolet	10 nm–400 nm	7×10^{14}–3×10^{16} Hz	Near–Extreme
X-rays	0.001 nm–10 nm	3×10^{16}–3×10^{20} Hz	Soft–Hard
Gamma ray	$<$ 0.1 nm	$>3\times10^{18}$ Hz	Soft–Hard

electromagnetic spectrum. William Herschel and Johann Wilhelm Ritter had already discovered infrared and ultraviolet “light,” respectively, in 1800–01 – well before Maxwell’s theory. In 1888, Heinrich Hertz demonstrated the production of radio waves based on Maxwell’s principles. These experimental confirmations convinced physicists that Maxwell had discovered the secret of light. Humanity had made a tremendous leap in understanding reality. This leap to new heights, however, soon revealed that Maxwell had discovered only a part of the secret.

The wave theory of light very accurately describes the way light behaves in most macroscopic situations. In summary, the theory says:

1. Light exhibits all the properties of classical, well-behaved waves, namely: reflection at interfaces, refraction upon changes in the medium, diffraction around edges, interference with other light waves, and polarization in a particular direction (plane of vibration of the electric vector).
2. A light wave can have any positive wavelength. The range of possible wavelengths constitutes the electromagnetic spectrum. Frequency and wavelength are related by Equation (1.2).
3. In a vacuum, light waves travel in a straight line at speed c. Travel in other media is slower and subject to refraction and absorption.
4. A light wave carries energy whose magnitude depends on the squares of the amplitudes of the electric and magnetic waves.

1.2.2 Quantum mechanics and light

> It is very important to know that light behaves like particles, especially for those of you who have gone to school, where you were probably told something about light behaving like waves. I’m telling you the way it does behave – like particles.
>
> – Richard Feynman: *Q.E.D.*, 1985

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Toward the end of the nineteenth century, physicists realized that electromagnetic theory could not account for certain behaviors of light. The theory that eventually replaced it, ***quantum mechanics***, postulates that light possesses the properties of a particle as well as the wavelike properties described by Maxwell's theory. Quantum mechanics insists that there are situations in which we cannot think of light as a wave, but must think of it as a collection of particles, like bullets shot out of the source at the speed of light. These particles are termed ***photons***. Each photon "contains" a particular amount of energy, E, that depends on the frequency it possesses when it exhibits its wavelike properties:

$$E = h\nu = \frac{hc}{\lambda} \tag{1.4}$$

Here h is Planck's constant (6.626×10^{-34} J s) and ν is the frequency of the wave. Thus a single radio photon (low frequency) contains a small amount of energy, and a single gamma-ray photon (high frequency) contains a lot. A convenient unit for the energy of a photon is the ***electronvolt*** (1 eV = 1.602×10^{-19} J)

The quantum theory of light gives an elegant and successful picture of the interaction between light and matter on the microscopic scale. In this view, atoms no longer have electrons bound to nuclei by springs or (what is equivalent in classical physics) electric fields. Electrons in an atom, rather, have certain permitted energy states described by a wave function – in this theory, everything, including electrons, has a wave as well as a particle nature. An electron changing from one of these permitted states to another explains the generation or absorption of light by atoms. Energy is conserved: energy lost when an atom makes the transition from a higher to a lower state is exactly matched by the energy of the photon emitted. In summary, the quantum theory says:

1. Light exhibits all the properties described in the wave theory in situations where wave properties are measured.
2. Light behaves, in other circumstances, as if it were composed of massless particles called photons, each containing an amount of energy equal to its frequency times Planck's constant.
3. The interaction between light and matter involves creation and destruction of individual photons and the corresponding changes of energy states of charged particles (usually electrons).

We will make great use of the quantum theory in later chapters, but for now, our needs are more modest.

1.2.3 A geometric approximation: light rays

> By Light Rays I understand its least Parts . . . Mathematicians usually consider the Rays of Light to be Lines reaching from the luminous Body to the Body illuminated . . .
>
> – Isaac Newton, *Opticks,* 1704

Since the quantum picture of light is as close as we can get to the real nature of light, you might think quantum mechanics would be the only theory worth considering. However, except in simple situations, application of the theory demands complex and lengthy computation. Fortunately, it is often possible to ignore much of what we know about light and use a very rudimentary picture which pays attention only to those few properties of light necessary to understand much of the information brought to us by photons from out there. In this geometric approximation, we treat light as if it traveled in "rays" or streams that obey the laws of reflection and refraction as described by geometrical optics. It is helpful to imagine a ray as the path taken by a single photon of a particular wavelength.

We might then imagine a stream of photons, each tracing a ray from the source to an observer's detector. Sometimes it is essential to recognize the discrete nature of the particles. We might then think of astronomical measurements as acts of *counting* and classifying the individual photons as they hit our detector like sparse raindrops tapping on a tin roof.

Sometimes, we can ignore the lumpy nature of the photon stream and just assume it behaves like a smooth fluid that carries energy from source to detector along the rays. In this case, we think of astronomical measurements as recording smoothly varying quantities – like measuring the volume of rain that falls into a bucket in one day. We might be aware that the rain arrived as discrete drops, but it is safe to ignore the fact.

We will adopt this simplified ray picture for much of the discussion that follows, adjusting our awareness of the discrete nature of the photon stream or its wave properties as circumstances warrant. For the rest of this chapter, we use the ray picture to discuss two of the basic measurements important in astronomy: ***photometry,*** which measures the amount of energy arriving from a source, and ***spectrometry,*** which measures the distribution of this energy with wavelength. Incidentally, our use of the word "wavelength" does not mean we are going to think deeply about the wave theory just yet. It will be sufficient to think of wavelength as a property of a light ray that can be measured – by noting which ray a photon follows when sent through a spectrograph, for example.

Besides photometry and spectroscopy, the other general categories of measurement are ***imaging*** and ***astrometry***, which are concerned with the appearance and positions of objects in the sky, and ***polarimetry***, which is concerned with the polarization of light from the source.

1.3 Measurements of light rays

> Twinkle, twinkle, little star,
> Flux says just how bright you are.
> – Anonymous, *c.* 1980

1.3.1 Luminosity and brightness

Astronomers have to construct the story of a distant object using only the tiny whisper of electromagnetic radiation it sends us. We define the (electromagnetic) luminosity, L, as the total amount of energy that leaves the surface of the source per unit time in the form of photons. Energy per unit time is called power, so we can measure L in physicists' units for power (SI units), joules per second or watts. Alternatively, it might be useful to compare the object with the Sun, and we then might measure the luminosity in solar units:

$$L = \mathit{Luminosity} = \text{Energy per unit time emitted by the entire source}$$

$$L_{\odot} = \text{Luminosity of the sun} = 3.827 \times 10^{26}\,\text{W}.$$

The luminosity of a source is an important clue about its nature. One way to measure luminosity is to surround the source completely with a box or (since this is physics) sphere of perfectly energy-absorbing material, then use an "energy gauge" to measure the total amount of energy intercepted by this enclosure during some time interval. Figure 1.3 illustrates the method. Luminosity is the amount of energy absorbed divided by the time interval over which the energy accumulates. The astronomer, however, cannot measure luminosity in this way. She is too distant from the source to put it inside a sphere, even in the unlikely case she has one big enough. Fortunately, there is a quantity related to luminosity, called the ***apparent brightness*** of the source, which is much easier to measure.

Measuring apparent brightness is a local operation. The astronomer holds up a scrap of perfectly absorbing material of known area so that its surface is perpendicular to the line of sight to the source. She measures how much energy from the source accumulates in this material in a known time interval. Apparent brightness, F, is defined as the total energy per unit time per unit area that arrives from the source:

$$F = \frac{E}{tA} \tag{1.5}$$

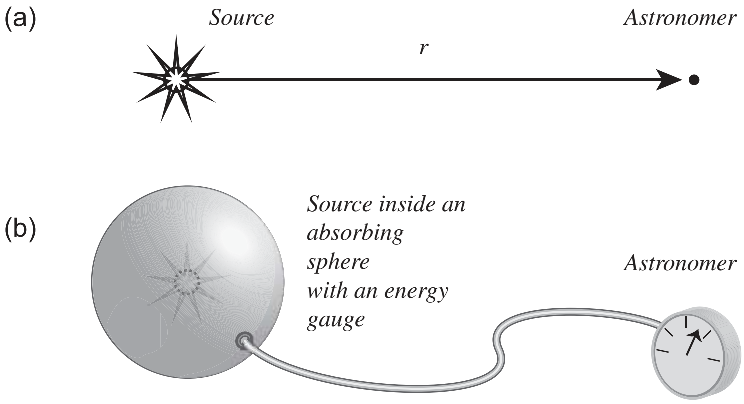

Fig. 1.3 Measuring luminosity by intercepting all the power from a source.