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Excerpt
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A Brief History of Planetary Photometry

If you've picked up this book, odds are that you are a scientist, engineer, amateur astronomer, or student who is interested in the study of planets using images acquired either with a telescope or spacecraft. Even in the modern era, the vast majority of what we know about objects in the solar system comes not from physical samples but from images. For centuries this was all we had, and our predecessors labored to learn as much as possible from subtle differences in brightness and color. As we noted in the preface, the sheer antiquity of the subject has left many parts of the field arcane, and so throughout this book we will, where possible, introduce concepts in historical context. In this chapter, we briefly introduce the historical backdrop and development of the field up to the beginning of the twentieth century, and we end with a recent example of its power and continuing applicability. But first, we must make it clear what it is we are talking about.

1.1 Photometry Defined

This book is about planetary photometry, but technically this is a misnomer. **Photometry** is defined as the science of the measurement of light in terms of how the human eye perceives it. But because human eyes differ in their sensitivity to colors and the intensity of perceived brightness, this is a subjective measurement that must be standardized. True photometry is used by lighting engineers to determine how best to light a room, street, or building. This is not what astronomers or planetary scientists mean by photometry.

The real subject of this book is **radiometry**, the measurement of light in standard physical units, independent of the perception of the human eye. However, early astronomy, including planetary science, was strictly a visual science and all of the early measurements of stellar and planetary brightness and color relied upon the human eye – it *was* photometry. Today, astronomers still use and publish *visual* magnitudes, or those determined after using a filter and light detector that approximates the wavelength range of the eye, but they have removed the physiological basis of measurement.

Despite these changes, the term photometry has persisted in planetary science. With *telescopic* observations, the term **photometric calibration** is used to mean the reduction of data using standard stars and color filter sets, such as the Johnson-Morgan UBV system (see Chapter 2). *Spacecraft* missions will often use the term **radiometric calibration** to mean that their images have been calibrated into standardized physical units, e.g. W m^{-2} sr^{-1} μm^{-1}. However, if a scattering model is used to correct those calibrated values to what would be observed under a standardized lighting and viewing geometry (e.g. looking straight down on a planet, the Sun 30° from zenith), the results are also sometimes said to have been photometrically calibrated.

To summarize, in common usage **planetary photometry** means the measurement and calibration of light from distant non-stellar objects using some system of standard references, and where possible, correction (or normalization) to common illumination and viewing circumstances.

1.2 The Nature of Vision and Light

1.2.1 Early Theories of Vision

Early theories of light and vision generally postulated one of two main ideas: light or an equivalent originated in the eyes and traveled outward where it interacted with objects, the **extromission theory**; and the opposing view that light or an equivalent left the objects and entered the eye, the **intromission theory**.

One of the earliest treatises on light and optics, called *Optics and Catoptrics*, is that of Euclid (circa 300 BCE), who is most famous for his book *The Elements* (of geometry). Like *The Elements*, *Optics* begins with axioms on the behavior of light and derives more complex ideas. Euclid subscribed to the extromission concept of vision (DiLaura, 2006). Like much of early Greek science, this work contained little or no experimentation to test or check concepts.

Ptolemy of Alexandria (90–168 CE), best known for his *Almagest* and the Earth-centered model of the solar system, wrote a treatise some four centuries after Euclid called *A Work on Optics*; it similarly assumed that vision originated in the eye. Unlike Euclid, however, Ptolemy's work included early experiments with refraction (DiLaura, 2006).

Perhaps the most influential book on optics in the Middle Ages, if sometimes indirectly, was the *Book of Optics* (Kitab al-Mazir) by the great Arabic scientist **Ibn al-Haytham** (aka **Alhazen**) (965–1040 CE). Alhazen subscribed to the intromission concept of vision, correctly arguing that, if the eyes were the source of some type of illuminating rays, we could see in the dark. He correctly separated the concept of light from vision, and experimentally demonstrated that light travels in straight lines, and that different sources of light do not interfere with each other, a phenomenon referred to as *immiscibility* (DiLaura, 2006; Falco and Weintz Allen, 2008).

Alhazen's work was inaccessible to many until the Archbishop of Canterbury and scholar **John Peckham** (1230–1292) wrote *Perspectiva communis* circa 1260. Lindberg (1981) notes that this book was not a presentation of new ideas, but primarily an orderly restatement of much of Alhazen's work, and where possible, other work in the field.

By the time of **Johannes Kepler** (1571–1630), the intromission concept was firmly entrenched, the eye was recognized as an optical device, and the mathematics of geometry was employed to study reflection and refraction. In his 1604 treatise *Ad Vitellionem Paralipomena Quibus Astronomiae pars Optica Traditur* (Supplement to Vitello on the Optical Part of Astronomy), Kepler advanced the modern conception of light rays and recognized, if not explicitly, the inverse square law for the attenuation of light over distance (Lindberg, 1981; DiLaura, 2006; Malet, 2010). The law would not be stated explicitly until 1634 by the French theologian and mathematician **Merin Mersenne** (1588–1648) (DiLaura, 2006).

1.2.2 Modern Concepts of Light

By the seventeenth century, there were two competing theories on the nature of light. In one corner, **Christiaan Huygens** (1629–1695), a Dutch physicist and astronomer, proposed in his 1690 *Treatise on Light* that light was a wave phenomenon like sound. As light traveled, it excited a new spherical wave at each point in its path; these waves add to give the wave front phenomenon we see (Huygens, 1900 [1690]). Today, these excited waves are often referred to as *Huygens wavelets*. This theory differed dramatically from the previous conception of light as a ray-like thing that traveled in straight lines, but was later found to be consistent with experimental evidence.

The competing theory, championed by **Isaac Newton** (1642–1726) and published in his 1704 *Opticks*, was that light was of a *corpuscular* nature – composed of particles that traveled in straight lines. Unlike Huygens's conception, this *was* consistent with the ray theory of optics. These corpuscles were thought to be objects of tiny size with a pure color, and Newton used this concept to explain why white light split into different colors as it traversed a prism (Newton, 1704; DiLaura, 2006).

By the late seventeenth century, it was known that the speed of light was finite, if rapid. The first indications of this came from observations of Jupiter's moon Io by the Danish astronomer **Ole Roemer** (1644–1710) in 1676 (Roemer, 1677). Roemer's method is quite ingenious. The inner moon Io orbits Jupiter every 42.46 h. If the distance between Earth and Jupiter were constant, an observer would see Io disappear behind Jupiter or reappear from the other side every 42.46 h. However, depending upon our relative orbital positions, the Earth may be approaching or receding from Jupiter. If approaching, the apparent orbital period appears to be less than 42.46 h; if receding from Jupiter, the apparent period is slightly longer. Roemer realized that the differences in apparent period were caused by the change in distance between Earth and Jupiter, and that light took a finite amount of time to traverse that change in distance (Mach, 1926). Although it is often reported that Roemer estimated the speed of light from this work, French (1990) states that, for whatever reason, Roemer did not, but Huygens did in 1690.

By 1800, other optical phenomena were garnering attention. A number of scientists had noted that the shadows cast by edges were not sharp, but consisted of alternating bright and dark bands. Similar bands were seen in the shadows cast when light passed through double slits. In 1804, **Thomas Young** (1773–1829) performed a series of classic experiments that demonstrated that these features were caused by an **interference effect**, analogous to the interference of ripples in water, and best explained if light were wavelike in nature (Young, 1804). Despite Newton's status in the worlds of physics and astronomy, the wave theory championed by Huygens became the standard model of light until the twentieth century because only it could easily explain these observations. Despite this, the ray theory still enjoyed (and currently enjoys) popularity, especially for modeling the behavior of light in systems of mirrors and lenses. The modern conception of light behaving as both wave and particle would not arise until the early twentieth century and quantum mechanics.

In 1819, the French physicist **Augustin-Jean Fresnel** (1788–1827) published a *Memoir on the Diffraction of Light* in which he adopted Huygens principle of wavelets to explain the experiments of Young, a phenomenon now referred to as **diffraction** (Fresnel, 1819). This marriage of ideas was extremely powerful and is still a useful way to think about diffraction. Fresnel later teamed up with **François Arago** (1786–1853), another French physicist, to show that polarized light did not always behave as expected in these diffraction experiments (Arago and Fresnel, 1819).

Polarized light had been discovered more than a century earlier when **Rasmus Bartholin** (1625–1698) passed a narrow beam of light through a crystal of Iceland spar, a form of calcite (Bartholin, 1670). After passing through the calcite, the point was split into two beams, a phenomenon referred to as **double refraction**. Materials with this property are called **birefringent**, and today we recognize it to be a consequence of an anisotropic refractive index. The two beams, often called the *ordinary* and *extraordinary rays*, are polarized in perpendicular directions. What Arago and Fresnel demonstrated was that, while rays of the same polarization interfered to produce fringes, perpendicularly polarized rays did not.

1.3 The Human Eye and Visual Magnitude

Early photometry relied exclusively on the only sensor available to measure brightness – the human eye, a remarkable organ sensitive to a narrow range of the electromagnetic spectrum. To understand why photometry developed the way it did, we need an understanding of how the eye works.

1.3.1 The Sun's Light and Planck's Law

The eye has evolved with its particular spectral sensitivity characteristics because of the circumstances of our place in the universe. We orbit an average star, classified as a G2-type (yellow, main-sequence) star, with a "surface" temperature of about 5,800 K.

All objects generate and radiate electromagnetic energy; how much and at what wavelength is principally determined by how hot they are. The physicist **Max Planck** (1858–1947) derived a formula, now known as the Planck Function, that allows us to predict how much energy is radiated from a **blackbody** (a perfectly efficient radiator or *emitter*) at any given temperature and wavelength of light:

$$L(\lambda, T) = \frac{2hc^2}{\lambda^5}\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]^{-1} \quad 1.1$$

Here L is the emitted spectral radiance[1] (power per unit area per wavelength interval in the normal direction per unit solid angle), h is Planck's constant

[1] We will define this quantity in Chapter 2. For now it is sufficient to note that it can be equated to "brightness."

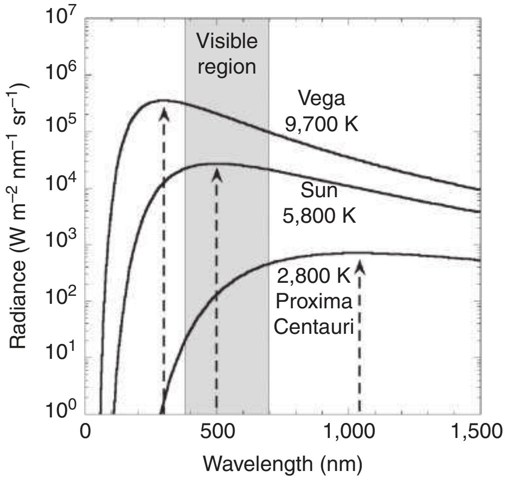

Figure 1.1. Blackbody curves for surfaces with temperatures equivalent to those of the Sun, Vega, and Proxima Centauri.
Credit: Michael K. Shepard.

(6.626×10^{-34} J s^{-1}), c is the speed of light (3×10^8 m s^{-1}), λ is the wavelength (m), k is the Boltzmann constant (1.381×10^{-23} J K^{-1}), and T is the temperature of the object (K).

Curves of this function for a given temperature are called **blackbody curves**. In Figure 1.1, note that for an object at the temperature of the Sun, the peak of the emitted radiation is at a wavelength of 500 nm, right in the part of the electromagnetic spectrum that our eyes see as yellow-green. Not coincidentally, this broad region is where our eyes are most sensitive to light. It evolved that way to take maximum advantage of the ambient solar lighting on Earth. If we had evolved around a star with a surface temperature of 9,700 K, such as Vega, our eyes would likely be most sensitive around 300 nm, deep within the ultraviolet region. Or if creatures with sight have evolved around the red dwarf Proxima Centauri, our nearest stellar neighbor, they are likely to be most sensitive to wavelengths around 1,040 nm, well within the near-infrared.

1.3.2 Physiology and Perception

The eye is sensitive to an incredible dynamic range of luminance, from high noon on Arctic ice to the midnight darkness of the wilderness, illuminated – if at all – only by starlight. There is more than a factor of a billion in the illumination between these environments (Kitchin, 2003). To deal with a range this large, the eye uses several mechanisms.

The pupil of the eye is a variable aperture that closes and opens in response to the amount of light available. Its aperture ranges from ~1 mm in daylight to about 7 mm when fully dark-adapted. Thus the possible change in total light incident on the retina is a factor of $\sim 7^2 = 49$; or alternatively, the daytime eye only lets in about 2% of the nighttime eye. If the only restriction on the light input to an electronic sensor was an aperture that could reduce the amount of incident light by 98%, those capable of measuring variations at night would tend to saturate or fail outright if used in the daytime. To prevent this and still remain sensitive to a wide range of incident light, the eye uses additional mechanisms.

First, we have two different light sensors, **rods** and **cones**. Cones require abundant light to activate and essentially work only in daylight or other well-lit areas. They are tightly packed in a ~1 mm wide region, called the **fovea**, in the center of the **retina**, the web of light-sensitive material that covers the back of the eye. Cones come in three different versions sensitive to different frequencies of light – roughly, blue (short wavelength or S-cones, peak sensitivity at ~430 nm), green (medium wavelength or M-cones, peak sensitivity at ~540 nm), and red (long wavelength or L-cones, peak sensitivity at 580 nm). Thus **photopic**, or cone-based, vision is the high-resolution color vision we experience when looking *directly* at something. Overall, the photopic eye is most sensitive to light around 550 nm because the M- and L-cones together dominate over the S-cones (Kitchin, 2003).

As light levels drop, cones lose their effectiveness, and rods, receptors about one hundred times more sensitive, take over (Kitchin, 2003). Vision based only on the rods is called **scotopic**. Rods are sparse in the fovea, but cover the rest of the retina. They are a broad-band, monochromatic sensor, so in low light, we see only in shades of gray. They are most sensitive to light in the blue-green region of the spectrum (peak around 500 nm), so at moderately low light levels, like dawn or dusk, there is a shift in perceived colors toward the blue as we use both rods and cones. This is called the **Purkinje effect**, after Czech scientist **Jan Purkyne** (1787–1869), and is known to affect visual estimates of stellar magnitudes when comparing stars of different colors (assuming the telescope intensifies the starlight enough to keep cones partially active; Rossotti, 1983).

In very low light, we also use a biological pigment called **rhodopsin**, or visual purple because of its purple tint. In bright light conditions, it is photobleached, or destroyed by light. In the absence of light, it regenerates, taking about 30–45 minutes to fully form and for the eye to become dark-adapted.

When a photon of light hits a rod coated in rhodopsin, it sets off a chemical cascade, triggering the nerve and greatly increasing the sensitivity of the rods to light. It is this dark adaptation that allows humans to see reasonably well in low-light conditions. However, because the dark adaptation is rod-based, the fovea is insensitive under these conditions. That is why those trying to detect faint objects will look slightly to the side of the suspected object to move it off the fovea and onto the rod-covered part of the retina.

For photometry, an important consideration is the contrast sensitivity of the eye. Given two adjacent sources of illumination, how different must they be for the observer to detect them as separate? In the mid-nineteenth century this type of work became the foundation of a branch of experimental psychology called psychophysics – the relationship between physical stimuli and their perception, or more loosely, the mind-body connection. It began when the German physician and experimental psychologist, **Ernst H. Weber** (1795–1878) conducted experiments that led to the empirical relationship now known as **Weber's law**. Weber found that when people are subjected to two sensory stimuli, there is a value called the **just-noticeable difference** that is required before the subject can distinguish between the two stimuli. For example, suppose a subject is holding masses of 100 g in each hand, and the mass in one hand is slowly increased. At some point, let us say 102 g, the subject will notice that the two weights are now different. The just-noticeable difference is 2 g. But if the weights are 1,000 g, a difference of 2 g will not be noticed. Weber found that one needed to add 20 g in that case for the difference to be noticed. Weber's law states that the *ratio* of the just-noticeable difference to the stimuli is a constant; in this case, a 2% difference in weight must be applied for it to be noticed (Weber, 1834).

This behavior was rediscovered and quantified by the German physicist and experimental psychologist **Gustav T. Fechner** (1801–1887) who recast it into a mathematical relationship called **Fechner's law** or the **Weber-Fechner law**. Over some range of magnitudes, there is often a logarithmic relationship between the physical intensity of a stimuli and its sensation

$$S = k \log I \qquad 1.2$$

where S is the perception of the stimuli in some arbitrary units, k is a constant that must be experimentally determined, and I is the physical intensity of the stimulus (Masin et al., 2009). As with anything involving perception, this "law" is only an approximation. It does, however, nicely coincide with our perception of brightness and the stellar magnitude scale.

Well before Fechner, Bouguer (1729) experimentally determined that the eye could just distinguish between light stimuli that differed by 1 part in 64, or

1.6% (Mach, 1926). Subsequent work finds that over a wide range of illumination intensities, a value of 1.8% is often more appropriate (Walsh, 1926).

1.3.3 Early Magnitude Systems

Early astronomers, beginning with Ptolemy, classified the stars in the sky according to their apparent brightness. The brightest stars were classified as being of the first **magnitude**. Here "first" refers to the highest or greatest. Slightly dimmer stars, roughly half as bright, were classified as second magnitude, and so on. The dimmest stars that could be perceived were classified as sixth magnitude. It is an unfortunate system because brighter stars have smaller magnitudes. There have been modern attempts to change the system, but the inertia of history has firmly entrenched it (Hearnshaw, 1996).

Originally, this classification scheme had little or no quantitative underpinning. This made stellar magnitudes a matter of judgement, and there was no way to include either the brighter objects, including the visible planets, Moon, or Sun, or fainter objects once the telescope was invented. These problems were finally tackled by astronomers in the late eighteenth and nineteenth centuries as they attempted to cast the system into a more quantitative framework. There were several issues that required attention.

The first major problem to be confronted was that the eye is not a linear detection system. The English astronomer **John Flamsteed** (1646–1719) noted that stars that differed by a magnitude by eye also differed by a magnitude even when made brighter by viewing through a telescope. The Swedish physicist and astronomer **Anders Celsius** (1701–1744) invented an early extinction photometer and found that stars that differed by a magnitude when viewed in a telescope also differed by a magnitude even when an absorbing plate was inserted into the optical train (Hearnshaw, 1996). Both observations reveal that the eye is not responding linearly, but geometrically to brightness – that it is the ***ratio*** of brightness differences that are detected, and stars that differ by a magnitude have some multiplicative difference in brightness, not an absolute difference. As we noted earlier, this was also experimentally demonstrated by Weber and Fechner in the mid-nineteenth century. The question was, what was the multiplicative factor? Hearnshaw (1996, in his table 3.1) lists more than a dozen values experimentally determined from 1829 to 1888; these factors range from a low of 2.241 by Fechner to a high of 2.8606 by **P. Ludwig Seidel** (1821–1896). This uncertainty in the true factor made it difficult to standardize stellar catalogs.

1.3.4 The Pogson Interval

In 1856, the English astronomer **Norman Pogson** (1829–1891) proposed that the factor be fixed by fiat, so that two stars with a brightness difference of one magnitude have a brightness ratio of 2.512, or

$$\frac{E_A}{E_B} = 2.512 \quad \text{if} \quad m_B - m_A = 1.0 \text{ mag} \qquad 1.3$$

Here, E is the brightness, or irradiance of incident starlight (the incident light is effectively collimated), and m is the apparent magnitude of the star. There were advantages of this odd ratio. It was a close average to the ratio measured by previous astronomers, and it was mathematically convenient; if two stars have a brightness ratio of 100, they differ by 5 magnitudes ($2.512^5 = 100$) so that a sixth magnitude star is 100 times fainter than a first magnitude star. Hearnshaw (1996) notes that none other than **Edmund Halley** (1656–1742) had presciently stated just this relationship in 1720.

By the late nineteenth century, Pogson's proposal had been adopted by most of the world's major observatories (Hearnshaw, 1996). It is now thought that the eye's response to brightness is better described by a power-law than a logarithm, but Pogson's proposal is now as deeply embedded in the definition of magnitude as is the reversed scale.

1.4 Early Principles of Photometry

Photometry developed along the lines that it did because the eye was the only instrument available to detect and qualify concepts like bright and dark, and as we have seen, there are caveats in its use as a quantitative instrument. In this section, we review the major contributors and concepts that enabled its development.

1.4.1 Concepts and Contributors

Perhaps the most important concepts for the development of modern photometry are those of the light ray and ray density. The ray is a helpful fiction, a way to describe the idea that something with energy travels linearly from point to point. The fact that light traveled only in straight lines had been known at least since Alhazen, who demonstrated this experimentally. However, there was widespread confusion over why light got weaker with distance. Throughout the Middle Ages, scholars thought that the rays themselves weakened with distance (DiLaura, 2001). However, a much better way of thinking about the