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Excerpt
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Light and Magnitude

1.1 Light

Except in extremely rare circumstances, minor planets are too faint to be seen with the naked eye. So to study a minor planet, you need a telescope. A telescope gathers and focuses light from the body, allowing objects too faint to be seen with the eye to be observed and studied. The telescope needs a detector to capture the light.

1.1.1 Electromagnetic Spectrum

Light usually refers to the visible portion of the electromagnetic spectrum that can be seen with the naked eye. All parts of the electromagnetic spectrum have been used to study asteroids; however, the visible is the one that is most often used since the radiation from the Sun peaks and the atmosphere is relatively transparent in this wavelength region. The light that allows us to see asteroids originated from the Sun. Light from the Sun is reflected by the asteroid and then detected by the observer.

The regions (Table 1.1 and Figure 1.1) of the electromagnetic spectrum (in order of decreasing wavelength) are radio, microwave, infrared, visible, ultraviolet, X-rays, and gamma rays. Visible light is usually broken up (in order of decreasing wavelength) into red, orange, yellow, green, blue, indigo, and violet. This sequence is often remembered as ROYGBIV. In a vacuum, light travels at a speed (c) of 299 792 458 m/s (usually written as 3×10^8 m/s).

Light can be characterized as both a wave and a particle. Particles of light are called photons and are massless with no charge. Since light also acts like a wave, its properties can also be characterized by both its frequency (ν) and wavelength (λ). The units of frequency are usually given as hertz (Hz) (cycles/second) while the units of wavelength vary [e.g., meters (m), microns (μm) (1×10^{-6} m), nanometers (nm) (1×10^{-9} m), angstroms (Å) (1×10^{-10} m)]. The frequency and wavelength of

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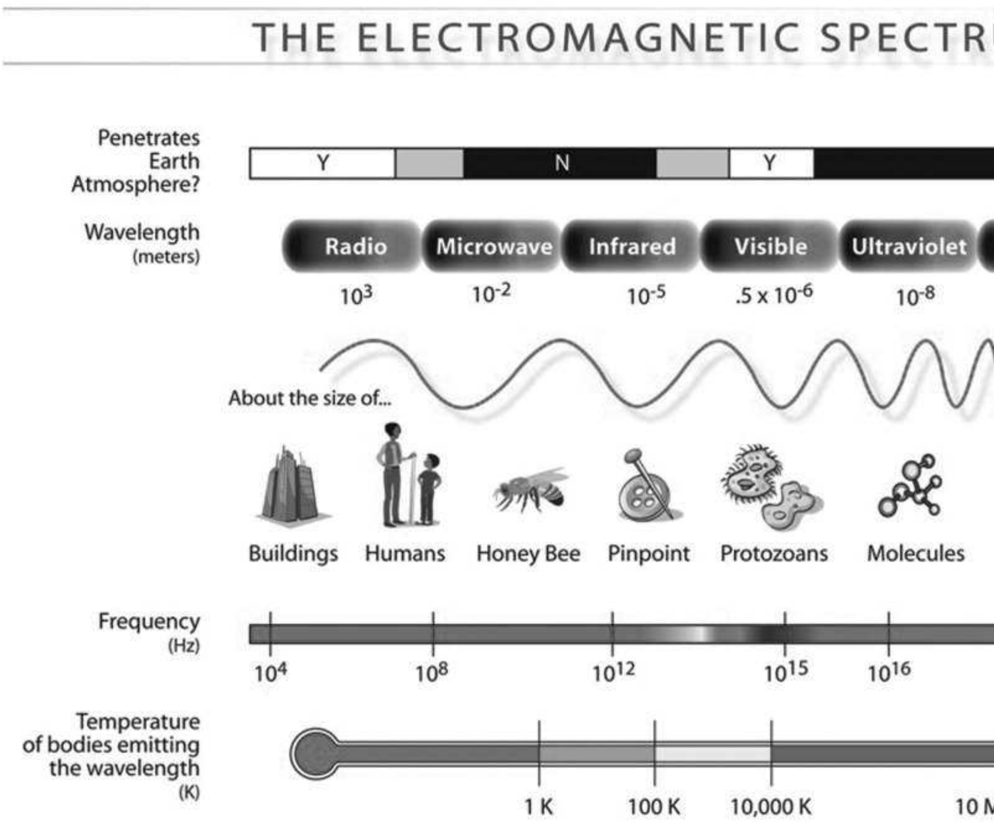

Figure 1.1 The wavelengths (m) and frequencies (Hz) of different regions of the electromag
length regions that penetrate the Earth's atmosphere, a list of different bodies with similar size
region, and the temperatures of different bodies emitting black body radiation primarily at that
(A black and white version of this figure will appear in some formats. For the color versio
section.)

Table 1.1 *The wavelength regions for different parts of the electromagnetic spectrum*

Region	Wavelength range (meters)
radio	> 1
microwave	$1 \times 10^{-3} - 1$
infrared	$7.0 \times 10^{-7} - 1 \times 10^{-3}$
visible	$4.0 \times 10^{-7} - 7.0 \times 10^{-7}$
ultraviolet	$1 \times 10^{-8} - 4.0 \times 10^{-7}$
X-ray	$1 \times 10^{-11} - 1 \times 10^{-8}$
gamma ray	$< 1 \times 10^{-11}$

a photon are inversely correlated and obey the formula $c = \nu\lambda$ in a perfect vacuum. The energy of a photon is $h\nu$ where h is Planck's constant (6.626×10^{-34} J s). Radio waves have extremely long wavelengths, small frequencies, and small energies while gamma-ray photons have extremely small wavelengths, large frequencies, and large energies.

The wavelength, frequency, and energy of a photon are all interrelated, and knowing one of these values allows you to calculate the other two quantities. If you know the wavelength of a photon, you can calculate its frequency and energy. If you know its frequency, you can calculate its wavelength and energy. And if you know its energy, you can calculate its wavelength and frequency. So knowing the value of either the wavelength, frequency, or energy of the light used to study an asteroid, you are able to uniquely define its characteristics.

1.1.2 Atmosphere

All radiation does not pass equally through the Earth's atmosphere. Visible light, short wavelength radio waves (including microwaves), and some infrared wavelengths pass relatively unimpeded through the atmosphere while X-rays, gamma rays, and some ultraviolet wavelengths are absorbed (Figure 1.2).

There is a large atmospheric window (Figure 1.2) in the far ultraviolet, visible, and near-infrared (~0.3 to ~2.4 μm) where most wavelengths of light can pass relatively easily through the atmosphere (Gupta, 2003). From ~2.4 to ~3.5 μm, H_2O, which is a relatively small constituent of the atmosphere, has a number of strong absorption bands that severely affect the transmission of these wavelengths of light through the atmosphere. Ultraviolet photons shortward of ~0.3 μm are significantly absorbed by the atmosphere (particularly by the ozone layer).

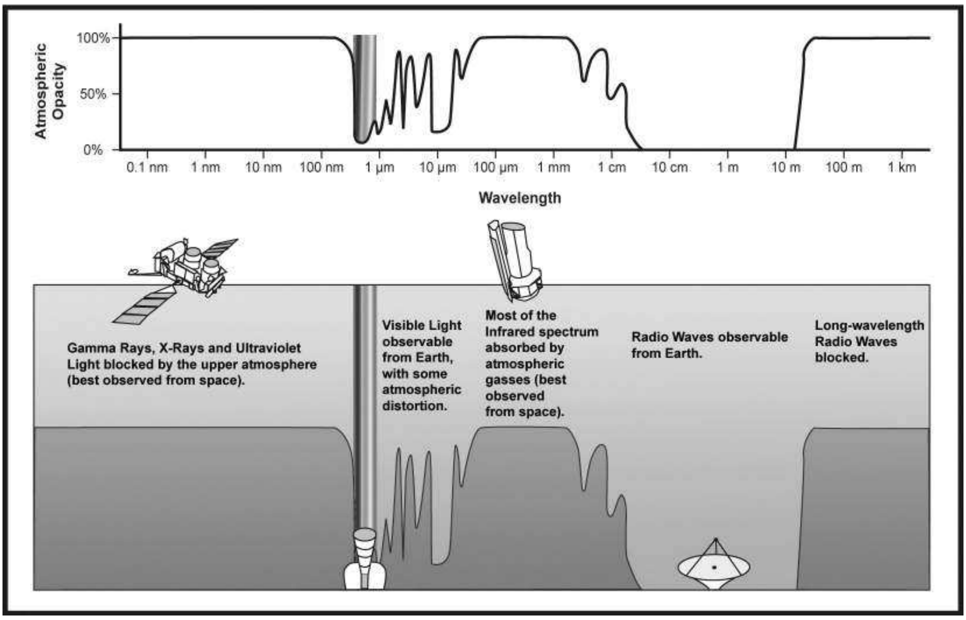

Figure 1.2 The transmittance of electromagnetic radiation through the atmosphere. Microwaves are included as part of the short wavelength radio waves. Atmospheric opacity is the amount of light absorbed by the atmosphere with 100% opacity indicating total absorption and 0% opacity indicating total transmission. Credit: NASA. (A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

1.2 Black Bodies

The Sun, the source of the asteroid's reflected light, is assumed to act like a black body. A black body is a theoretical object that absorbs all radiation that strikes it and emits radiation at all wavelengths. This emission is due to the thermal motion of charged particles in the material and is often called black body or thermal radiation.

Radiation from a star can be modeled as if the radiation was emitted from a black body. However, stars are not "perfect" black bodies. The temperature of a star will vary across its surface, so different regions will have different black body emission so the black body curve will not be the ideal black body curve for a body at one temperature. Also, atoms or ions in the atmosphere of the star absorb radiation being emitted. These absorption lines are apparent in measured stellar spectra (including the Sun) due to the absorption of light by different atoms.

Plots of the emitted intensity of radiation versus wavelength for theoretical black bodies have characteristic shapes that are just a function of temperature and wavelength (Figure 1.3). Using classical physics, the Rayleigh–Jeans law, proposed by Lord Rayleigh (1842–1919) and James Jeans (1877–1946), modeled black body

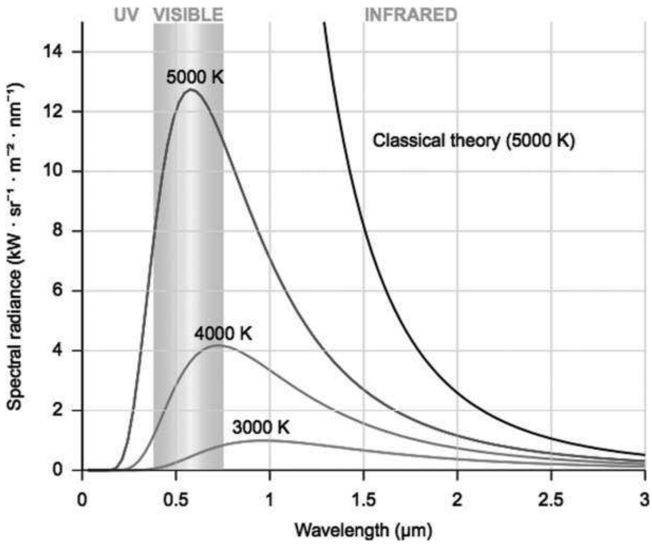

Figure 1.3 Black body curves for bodies at temperatures at 5000 K, 4000 K, and 3000 K plus the classical theory prediction for a body at 5000 K. Credit: Dark Kule. (A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.)

radiation as proportional to T/λ^4; however, this law inaccurately predicted that emitted radiation would continually increase with decreasing wavelength. The Planck function, proposed by Max Planck (1858–1947) using quantum theory, accurately predicts the spectral distribution of electromagnetic radiation from a black body and can be written as

$$B_\lambda(\lambda,T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1} \tag{1.1}$$

where the emitted intensity is given in terms of W m^{-3} sr^{-1} if the temperature is in kelvin (K) and the wavelength is in meters. The Boltzmann constant (k) is 1.381×10^{-23} J K^{-1}. The Boltzmann constant relates the kinetic energy and temperature of a molecule in an ideal gas. A solid angle is a measure of the fraction of the surface of a sphere that a body covers as seen from the center of the sphere. A solid angle is given in steradians (sr) with a sphere subtending 4π steradians.

If the radiation is emitted isotropically (independent of direction), the Planck function can also be written (Delbó and Harris, 2002) as

$$B(\lambda,T) = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1} \tag{1.2}$$

which has units of W m^{-3}. This formula gives the emitted flux from a black body. A flux is the flow of some quantity per unit area.

The radiant flux (F_e) (or total power per unit area) emitted by the black body is a function of the fourth power of the temperature (T). This equation is called the Stefan–Boltzmann law and can be written as

$$\frac{F_e}{4\pi R^2} = \sigma T^4. \tag{1.3}$$

The $4\pi R^2$ term is the total surface area of the body with a radius R. The Stefan–Boltzmann constant (σ) (5.67×10^{-8} W m^{-2} K^{-4}) is a constant of proportionality that relates the intensity of the emitted radiation per unit area to the fourth power of the temperature. As the temperature increases, the amount of energy emitted per second will dramatically increase. If you double the surface temperature of a body, the amount of energy emitted per second by the body will increase by a factor of 16 times.

Asteroids reflect and also emit radiation. However, gray bodies, such as asteroids, do not emit all the energy that strikes them. The Stefan–Boltzmann Law for gray bodies is written as

$$\frac{F_e}{4\pi R^2} = \varepsilon\sigma T^4. \tag{1.4}$$

The emissivity(ε) term is the efficiency with which a body radiates thermal radiation. The emissivity is 1 for a "perfect" black body but will be less than 1 for any type of gray body. For asteroids, the emissivity is often assumed to be 0.9.

The peak of the black body curve (where the object emits most of its light) is inversely proportional to temperature with cooler black bodies peaking at longer wavelengths than hotter bodies (Figure 1.1), which is called Wien's law. Wien's law is given by the equation

$$\lambda_{\max} = 2.898 \times 10^{-3} \frac{m\,K}{T}. \tag{1.5}$$

The calculated wavelength is in meters and the temperature is in kelvin. Radiation from the Sun peaks in the visible wavelength region while radiation from asteroids peaks in the infrared since they have much cooler surface temperatures.

Radiation detected from an asteroid is usually dominated by reflected light at wavelengths less than 2.5 μm while emitted thermal radiation usually dominates past 5 μm (Kim et al., 2003). The temperature of an asteroid will be primarily be a function of its distance from the Sun and how the dark the surface is. Objects further from the Sun are heated by less solar radiation than those that are closer and will have cooler surface temperatures. The flux of solar radiation striking an asteroid follows an inverse square law where the flux is proportional to the inverse of the distance squared from the Sun. Darker surfaces also tend to absorb more radiation than lighter surfaces. So darker asteroids will tend to be hotter than brighter surfaces at the same distance from the Sun.

For asteroids, the transition between reflected and thermal radiation usually occurs between 2.5 and 5 μm and is a function of the surface temperature of the body. The exception are dark near-Earth asteroids, which have "thermal tails" between ~2 and ~2.5 μm. These thermal tails are due to these bodies having a measurable blackbody flux in the ~2–2.5 μm wavelength region due to their relatively high surface temperatures.

1.3 Albedo

Albedo is a quantity that defines how light or how dark a surface is. Values for albedos tend to range from 0 (perfectly absorbing) to 1 (perfectly reflecting). Albedo is the fraction of radiation reflected from a surface. However, there are many different ways to define the albedo of a surface.

Bond albedo (A) is the fraction of all the total radiation at all wavelengths and at all solar phase angles that is scattered from a surface. The solar phase angle (Figure 1.4) is the angle between the light incident on a body from the Sun and the light reflected from the body and detected by an observer. Since the Bond albedo accounts for all scattered light, it varies from 0 to 1. The visual Bond albedo (A_v) only accounts for radiation scattered in the visible. The Bond albedo and the visual Bond albedo are often assumed to be similar in value since the Sun's flux peaks in the visible.

The geometric albedo (p) is the ratio of the brightness of a body at zero phase angle relative to a theoretical flat and fully reflecting disk with the same cross section that reflects light diffusively (scatters light equally in all directions). Objects with diffuse reflectance are said to have a Lambertian reflectance. The geometric albedo can be greater than 1 if light from the surface is preferentially reflected backwards towards the observer. The visual geometric albedo (p_v) is the geometric albedo that accounts for only visible light.

1.4 Temperature

The shape and intensity of the emitted radiation from an asteroid will be a function of its average surface temperature. This temperature is often called the effective temperature. The effective temperature of an asteroid can be estimated by assuming that it is a black body and then equating the emitted power and the absorbed power. The absorbed flux (F_a) in watts will be

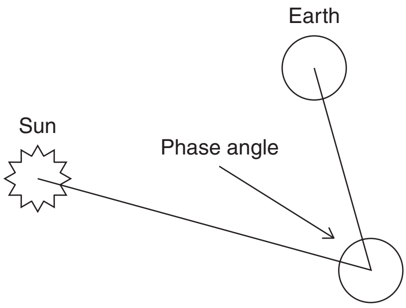

Figure 1.4 Illustration of the phase angle for an observer on the Earth observing a planet or a minor planet.

$$F_a = (1 - A)\pi R^2 \left[\frac{S_0}{\left(r^2 / AU^2\right)} \right] \tag{1.6}$$

where A is the Bond albedo, S_0 is the solar constant (~1366 W/m^2), and r is the heliocentric distance in AU. The solar constant is the average solar flux at the top of the Earth's atmosphere and is not actually a constant because it slightly varies over time. The $\frac{S_0}{\left(r^2 / AU^2\right)}$ term adjusts the solar flux for the asteroid's distance from the Sun according to the inverse square law. The πR^2 term is the cross-sectional area of the asteroid that is absorbing the radiation. One astronomical unit (AU) is approximately the mean of the average distance between the Earth and the Sun and is now defined by the IAU as 149 597 870 700 meters.

If you equate the emitted flux with the absorbed flux, the resulting formula will be

$$4\pi R^2 \varepsilon\sigma T^4 = (1 - A)\pi R^2 \frac{S_0}{\left[r^2 / (AU)^2\right]}. \tag{1.7}$$

Solving for T^4 produces the formula

$$T^4 = \frac{(1 - A)S_0}{4\varepsilon\sigma\left[r^2 / (AU)^2\right]}. \tag{1.8}$$

Then solving for the effective temperature produces the formula

$$T = \left(\frac{(1 - A)S_0}{4\varepsilon\sigma\left[r^2 / (AU)^2\right]} \right)^{1/4} \tag{1.9}$$

for the average temperature. So by increasing the albedo so there is less radiation absorbed, the average surface temperature of a body will decrease. Also if the distance from the Sun is increased for a body, its average surface temperature will become lower.

Example 1.1

A near-Earth asteroid has an effective surface temperature of ~270 K and was observed at a distance from the Sun of 1 AU. What is this object's Bond albedo?

Solving for the Bond albedo using *Equation 1.8* produces the formula

$$A = 1 - \frac{4\varepsilon\sigma T^4 \left[r^2 / (\mathrm{AU})^2 \right]}{S_0}. \tag{1.10}$$

The emissivity (ε) is assumed to be 0.9. Substituting the values in the equation then produces the formula

$$A = 1 - \frac{4(0.9)(5.67 \times 10^{-8})(270)^4}{(1366)} \tag{1.11}$$

with all the units cancelling. The calculated Bond albedo will then be 0.21.

1.5 Telescopes

Telescopes gather light from astronomical bodies and focus it to produce an image. Telescopes that just use lenses to produce an image are called refracting telescopes, while those that use mirrors are called reflecting telescopes. The first telescopes were refractors and were pioneered by Galileo Galilei (1564–1642) starting in 1609. The Galilean telescope has a convex primary lens that collects the parallel rays of light from an object and focuses it and a concave eyepice that intercepts the light from the lens and renders the rays parallel again. This design was updated by Johannes Kepler (1571–1630) who used a convex lens as the eyepiece. This design was called the Keplerian telescope. Refracting telescopes were the primary research telescopes until the early twentieth century.

The size of a telescope is given by its aperture size, which is the diameter of its main optical component (lens or mirror). The larger the aperture, the brighter and sharper the image tends to be since more photons tend to be collected and focused. However as the size of the lens increases for refracting telescopes, the focal length also tends to increase, which increases the size of the telescope tube. The weight of the lens also increases, which increases the weight of the counterweight needed to balance the telescope.

Telescopes that are used today for research are almost all reflecting telescopes. Reflecting telescopes use a curved mirror (called the primary mirror) or a series of curved mirrors to focus an image. Isaac Newton (1642–1727) built the first reflecting telescope in 1668. Besides having smaller sizes, reflecting telescopes have a number of other advantages compared to refracting telescopes. It is easier to make a high-quality mirror than a lens. Large lenses are much heavier than large mirrors. Lenses are also affected by chromatic aberration where all wavelengths of light cannot be focused to the same point reflecting telescopes are not affected by chromatic aberration. There are a number of different types of designs for reflecting telescopes.

Mirrors can be spherical and have a curved shape that is either convex or concave. However unless corrected for, simple spherical mirrors suffer from spherical aberration where light reflected from the edge of the mirror is focused at a slightly different point than light reflecting from the center of the mirror. Mirrors can be made with hyperbolic or parabolic shapes to eliminate spherical aberration since they focus all light to a single point. Hyperbolic mirrors tend to be more difficult and expensive to make than parabolic mirrors. However, the disadvantage of parabolic mirrors is that they can distort point sources, which is called a coma since it resembles the tail of a comet.

The commonest type of reflecting telescope is the Cassegrain reflector. Invented in the 1600s, a Cassegrain reflector uses two mirrors: a primary concave mirror and a secondary convex mirror. There is an opening in the primary that allows light to pass to the eyepiece. The classical Cassegrain design has a parabolic primary mirror and a hyperbolic secondary mirror.

The most commonly used type of Cassegrain reflector for research is the Ritchey–Chrétien Telescope (RCT), which was invented in the early twentieth century by George Ritchey (1864–1945) and Henri Chrétien (1879–1956). A Ritchey–Chrétien reflector has a hyperbolic primary mirror and a hyperbolic secondary mirror. The advantage of using hyperbolic mirrors is that the images are relatively free of coma and spherical aberration. The Hubble Space Telescopes and the Keck Telescope all are Ritchey–Chrétien telescopes.

Catadioptric telescopes use both refraction (lens) and reflection (mirror) in their optical systems. Schmidt telescopes (often called Schmidt cameras) have a spherical primary mirror and a aspherical correcting lens. This type of telescope was invented by Bernhard Schmidt (1879–1935) in 1930. The main advantage of a Schmidt telescope is that it has a relatively wide field of view.

1.6 Detectors

Detectors are used to record an image produced by a telescope. An image of an astronomical body allows you to determine the position of a body relative to the