

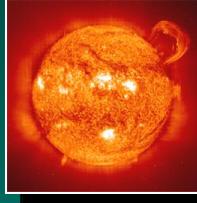
# Electromagnetic Radiation Principles



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Jensen, J. R., 2005, *Remote Sensing of Environment: An Earth Resource Perspective*,  
Upper Saddle River: Prentice-Hall, Inc., 2<sup>nd</sup>  
Edition, *in press*.

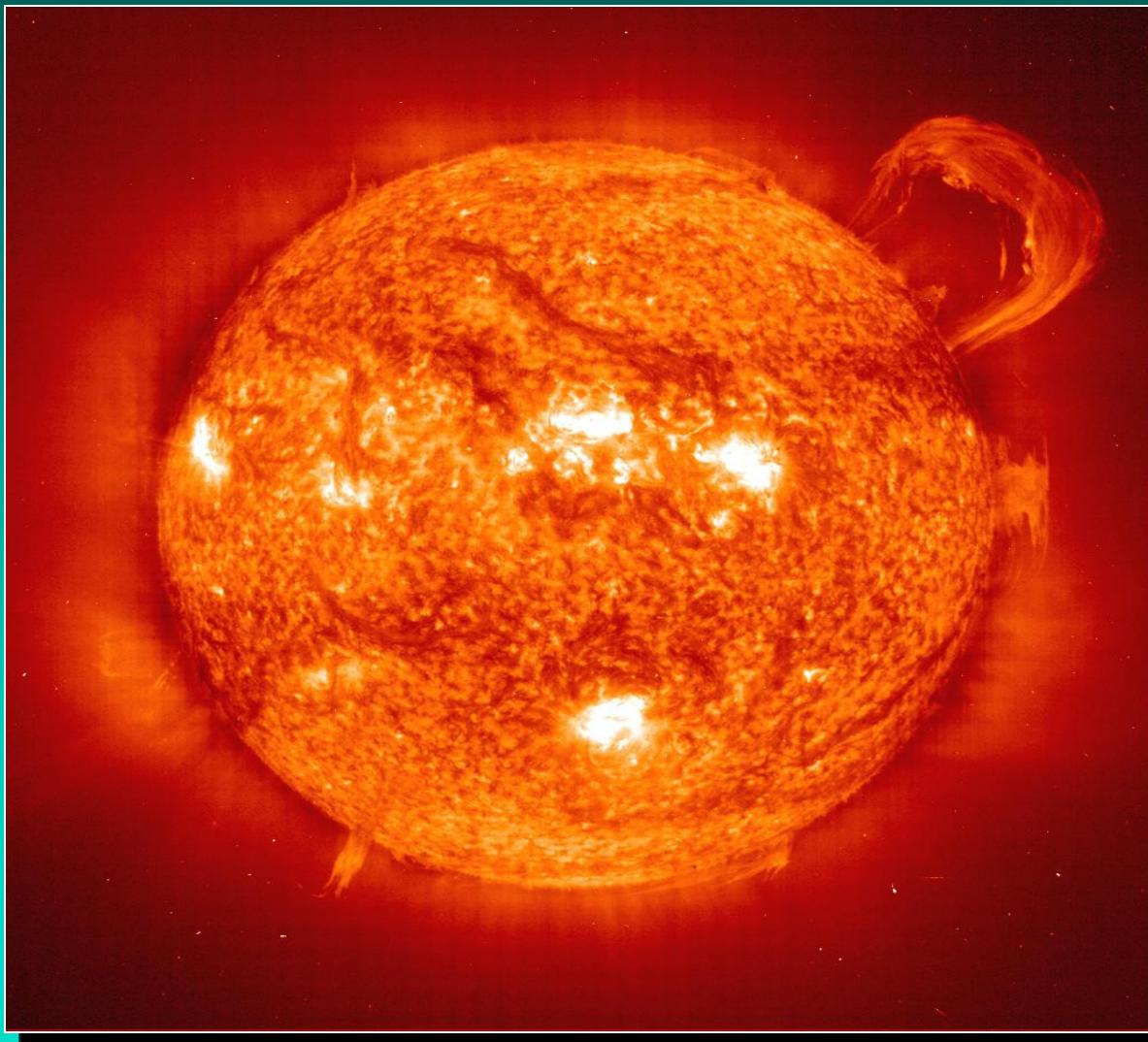


## Electromagnetic Energy Interactions

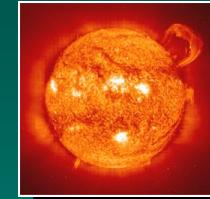
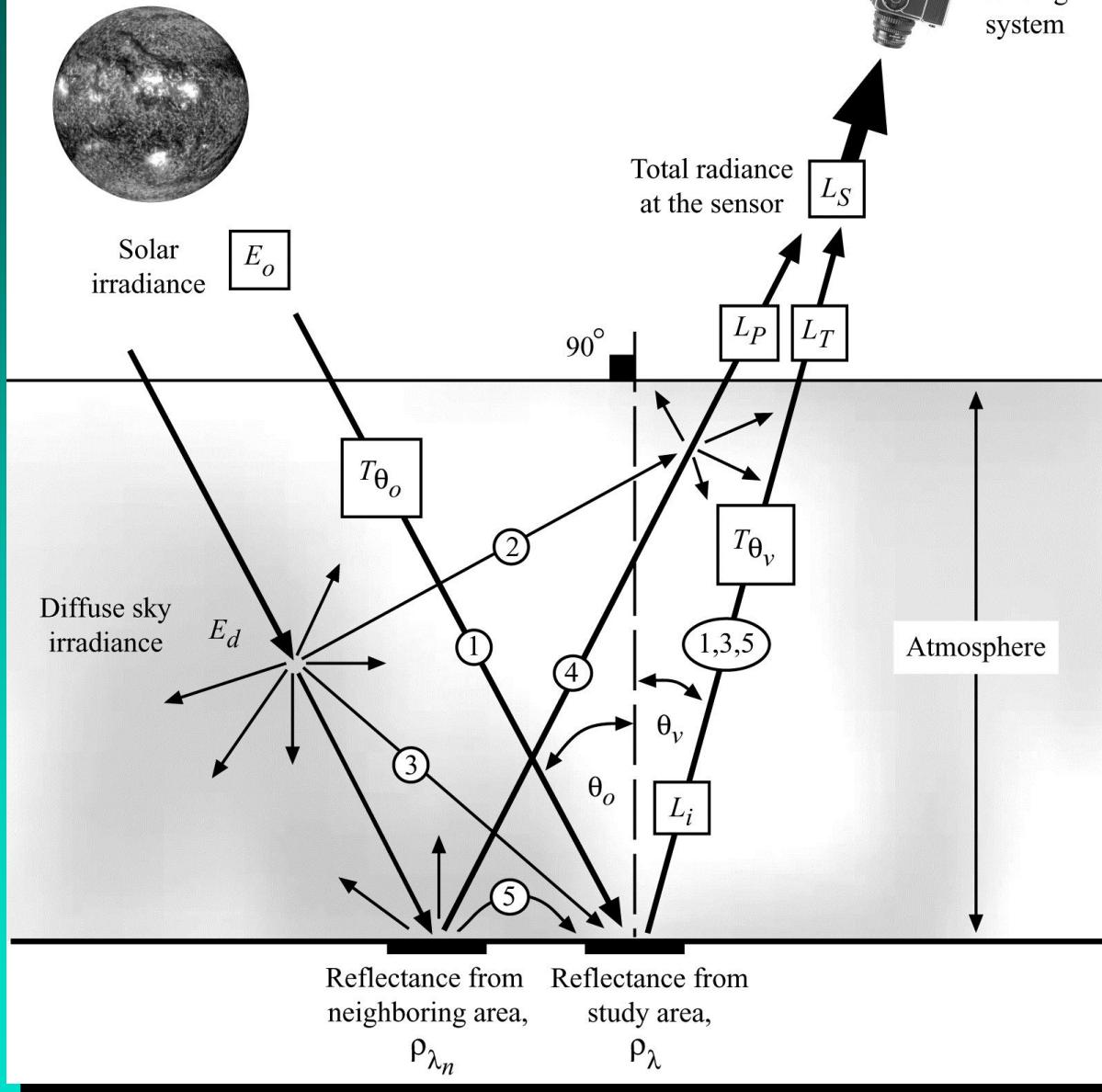
*Energy recorded by remote sensing systems undergoes fundamental interactions that should be understood to properly interpret the remotely sensed data. For example, if the energy being remotely sensed comes from the Sun, the energy:*

- is radiated by atomic particles at the source (the Sun),
- propagates through the vacuum of space at the speed of light,
- interacts with the Earth's atmosphere,
- interacts with the Earth's surface,
- interacts with the Earth's atmosphere once again, and
- finally reaches the remote sensor where it interacts with various optical systems, filters, emulsions, or detectors.

Solar and Heliospheric Observatory (SOHO)  
Image of the Sun Obtained on September 14, 1999



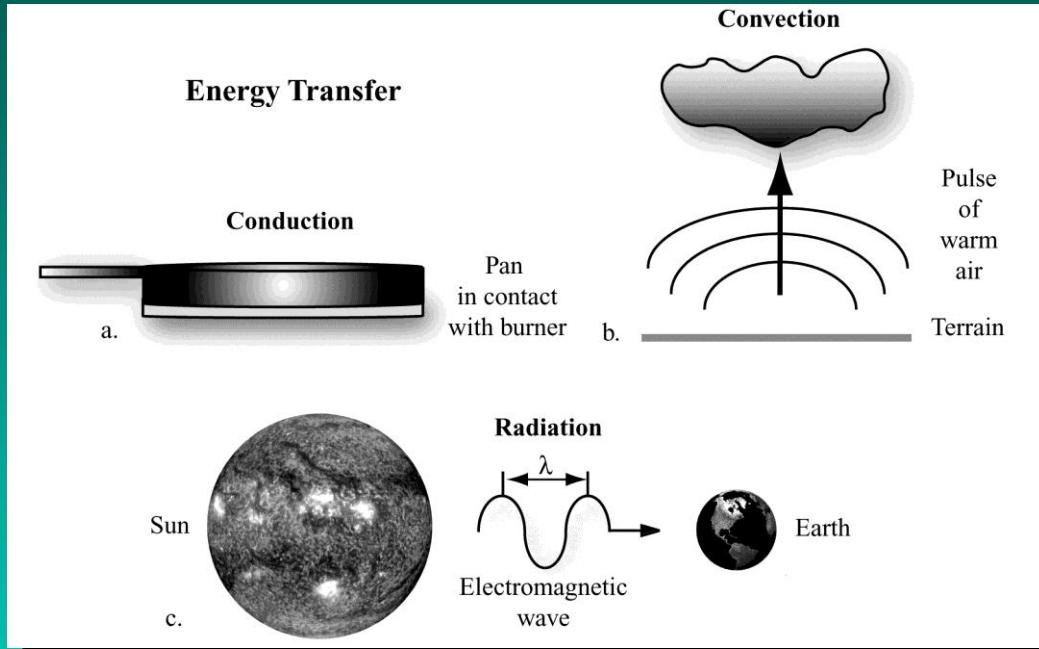
## Various Paths of Radiance Received by a Remote Sensing System



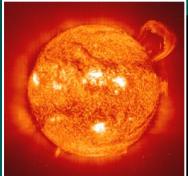
Energy-matter interactions in the atmosphere, at the study area, and at the remote sensor detector



# How is Energy Transferred?



Energy may be transferred three ways: *conduction*, *convection*, and *radiation*. a) Energy may be conducted directly from one object to another as when a pan is in direct physical contact with a hot burner. b) The Sun bathes the Earth's surface with radiant energy causing the air near the ground to increase in temperature. The less dense air rises, creating convectional currents in the atmosphere. c) Electromagnetic energy in the form of electromagnetic waves may be transmitted through the vacuum of space from the Sun to the Earth.

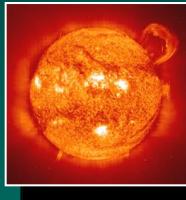


## Electromagnetic Radiation Models

To understand how electromagnetic radiation is created, how it propagates through space, and how it interacts with other matter, it is useful to describe the processes using two different models:

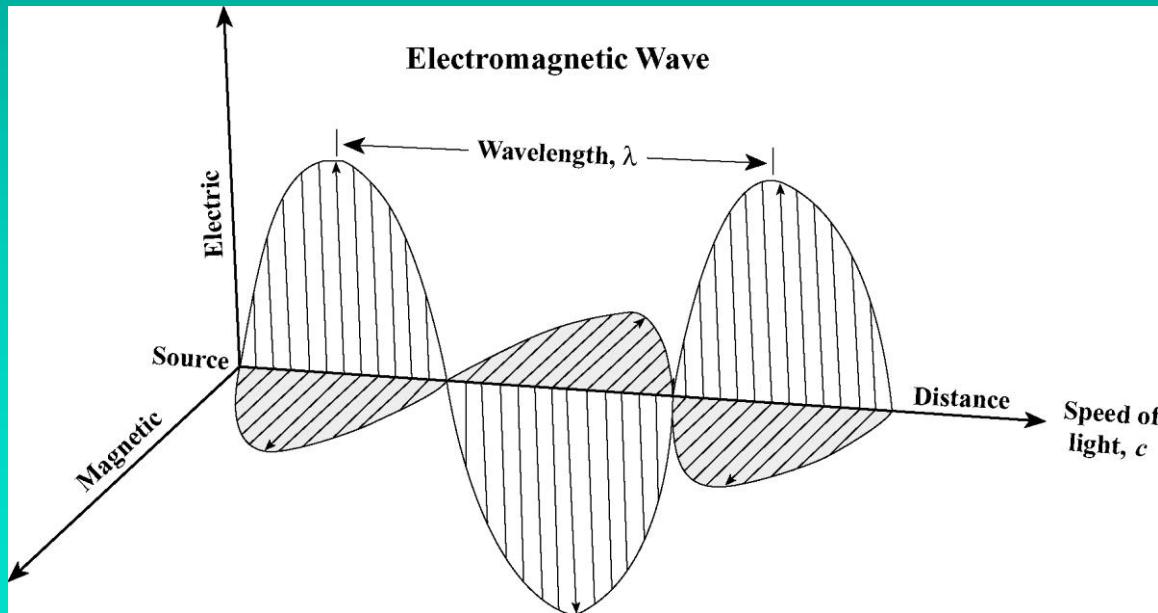
- the *wave* model, and
- the *particle* model.

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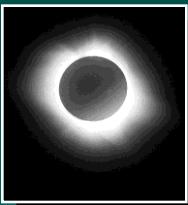


# Wave Model of Electromagnetic Radiation

In the 1860s, James Clerk Maxwell (1831–1879) conceptualized electromagnetic radiation (EMR) as an electromagnetic wave that travels through space at the speed of light,  $c$ , which is  $3 \times 10^8$  meters per second (hereafter referred to as  $\text{m s}^{-1}$ ) or  $186,282.03$  miles  $\text{s}^{-1}$ . A useful relation for quick calculations is that light travels about 1 ft per nanosecond ( $10^{-9}$  s). The *electromagnetic wave* consists of two fluctuating fields—one **electric** and the other **magnetic**. The two vectors are at right angles (orthogonal) to one another, and both are perpendicular to the direction of travel.



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## The Wave Model of Electromagnetic Energy

*Electromagnetic radiation* is generated when an electrical charge is accelerated.

- The *wavelength* of electromagnetic radiation ( $\lambda$ ) depends upon the length of time that the charged particle is accelerated and its frequency ( $v$ ) depends on the number of accelerations per second.
- *Wavelength* is formally defined as the mean distance between maximums (or minimums) of a roughly periodic pattern and is normally measured in micrometers ( $\mu\text{m}$ ) or nanometers (nm).
- *Frequency* is the number of wavelengths that pass a point per unit time. A wave that sends one crest by every second (completing one cycle) is said to have a frequency of one cycle per second or one hertz, abbreviated 1 Hz.



## Wave Model of Electromagnetic Energy

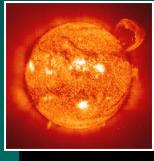
The relationship between the wavelength,  $\lambda$ , and frequency,  $v$ , of electromagnetic radiation is based on the following formula, where  $c$  is the speed of light:

$$c = \lambda \cdot v$$

$$v = \frac{c}{\lambda}$$

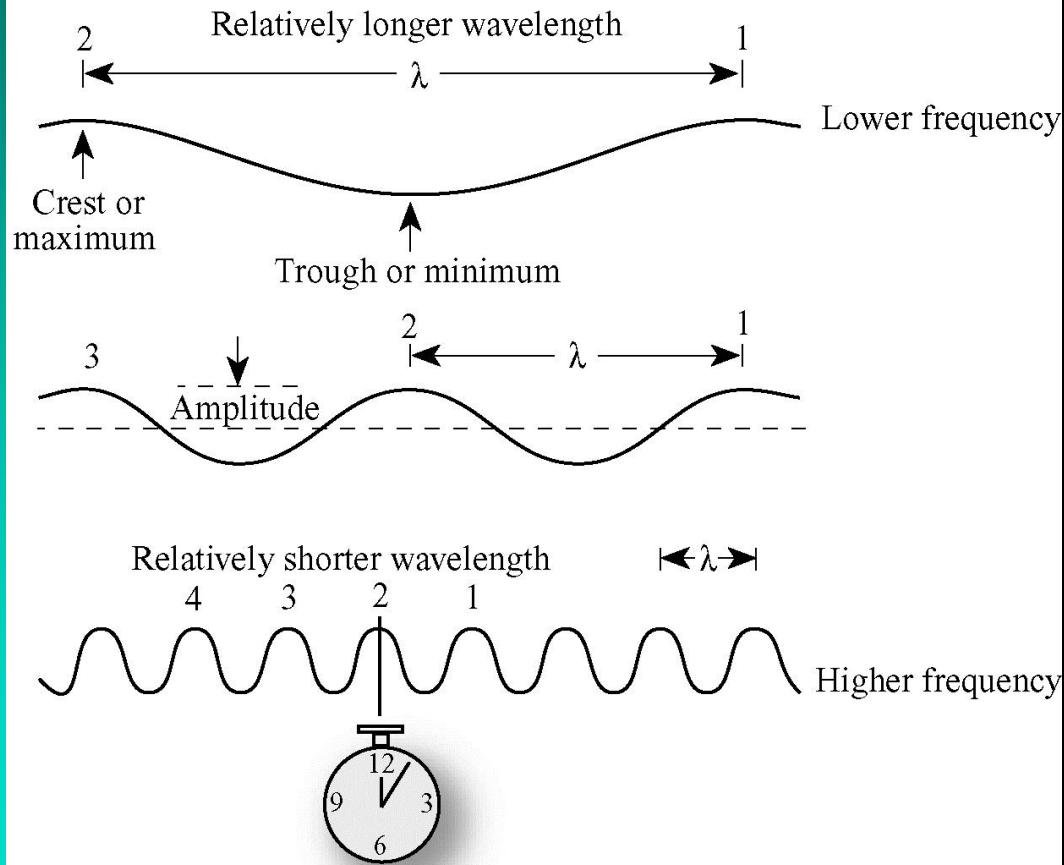
$$\lambda = \frac{c}{v}$$

Note that frequency,  $v$ , is inversely proportional to wavelength,  $\lambda$ . The longer the wavelength, the lower the frequency, and vice-versa.



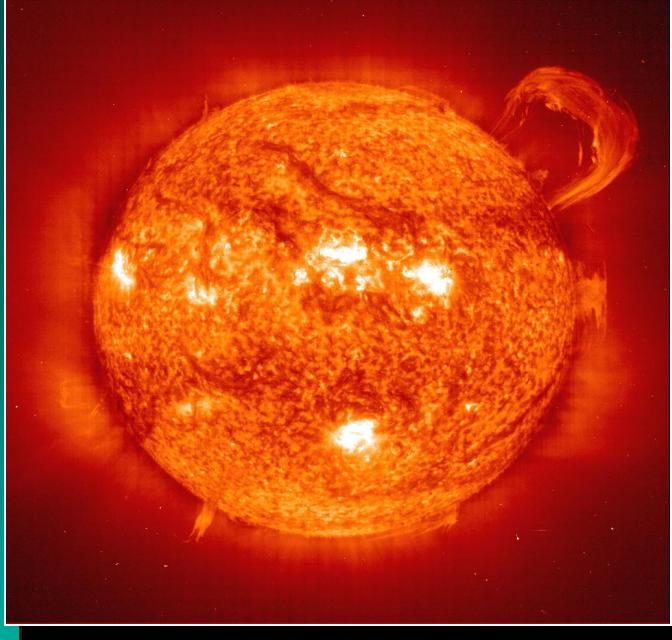
# Wave Model of Electromagnetic Energy

## Inverse Relationship between Wavelength and Frequency

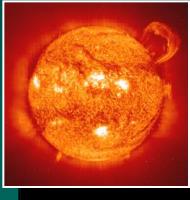


This cross-section of an electromagnetic wave illustrates the inverse relationship between *wavelength* ( $\lambda$ ) and *frequency* ( $\nu$ ). The longer the wavelength the lower the frequency; the shorter the wavelength, the higher the frequency. The amplitude of an electromagnetic wave is the height of the wave crest above the undisturbed position.

Successive wave crests are numbered 1, 2, 3, and 4. An observer at the position of the clock records the number of crests that pass by in a second. This frequency is measured in cycles per second, or hertz



- The electromagnetic energy from the Sun travels in eight minutes across the intervening 93 million miles (150 million km) of space to the Earth.
- The Sun produces a *continuous spectrum* of electromagnetic radiation ranging from very short, extremely high frequency gamma and cosmic waves to long, very low frequency radio waves
- The Earth approximates a 300 K (27 °C) blackbody and has a dominant wavelength at approximately 9.7 μm.

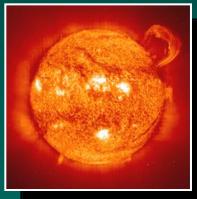


## Stephen Boltzmann Law

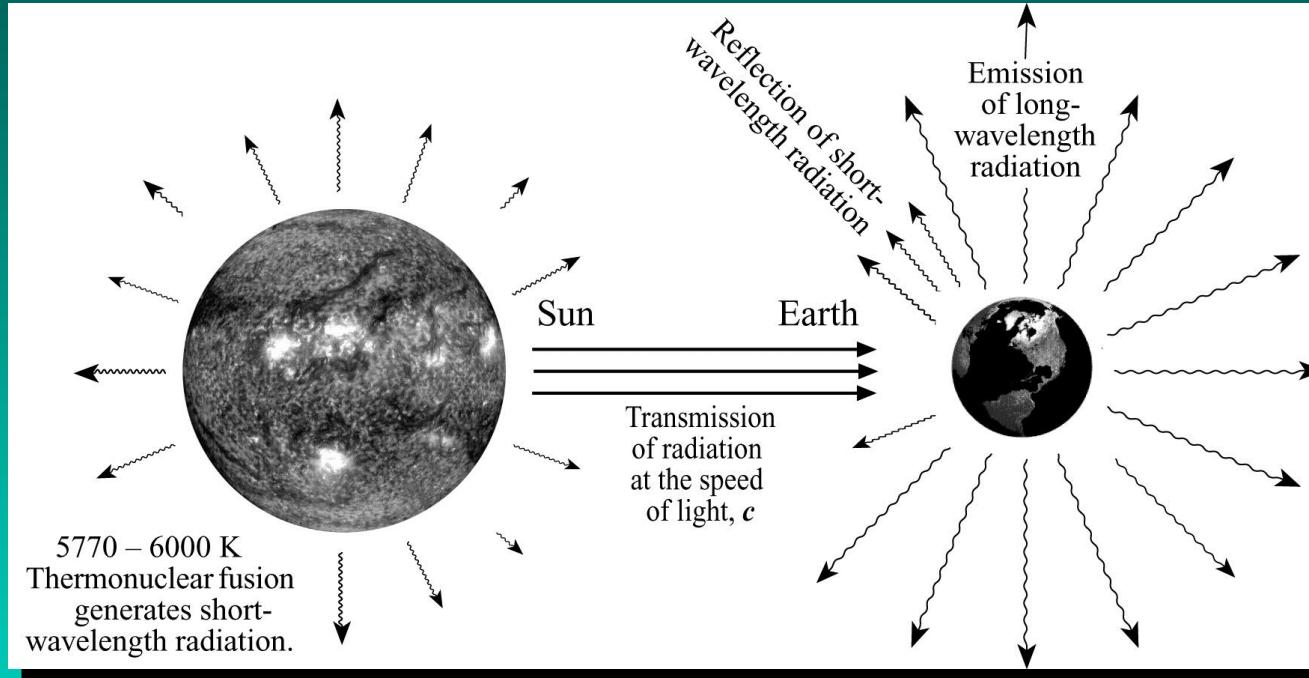
Using the *wave model*, it is possible to characterize the energy of the Sun which represents the initial source of most of the electromagnetic energy recorded by remote sensing systems (except radar). We may think of the Sun as a 6,000 K *blackbody* (a theoretical construct which radiates energy at the maximum possible rate per unit area at each wavelength for any given temperature). The *total emitted radiation* ( $M_\lambda$ ) from a blackbody is proportional to the fourth power of its absolute temperature. This is known as the *Stefan-Boltzmann law* and is expressed as:

$$M_\lambda = \sigma T^4$$

where  $\sigma$  is the Stefan-Boltzmann constant,  $5.6697 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ . Thus, the amount of energy emitted by an object such as the Sun or the Earth is a function of its temperature.

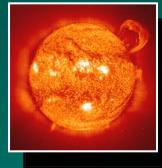
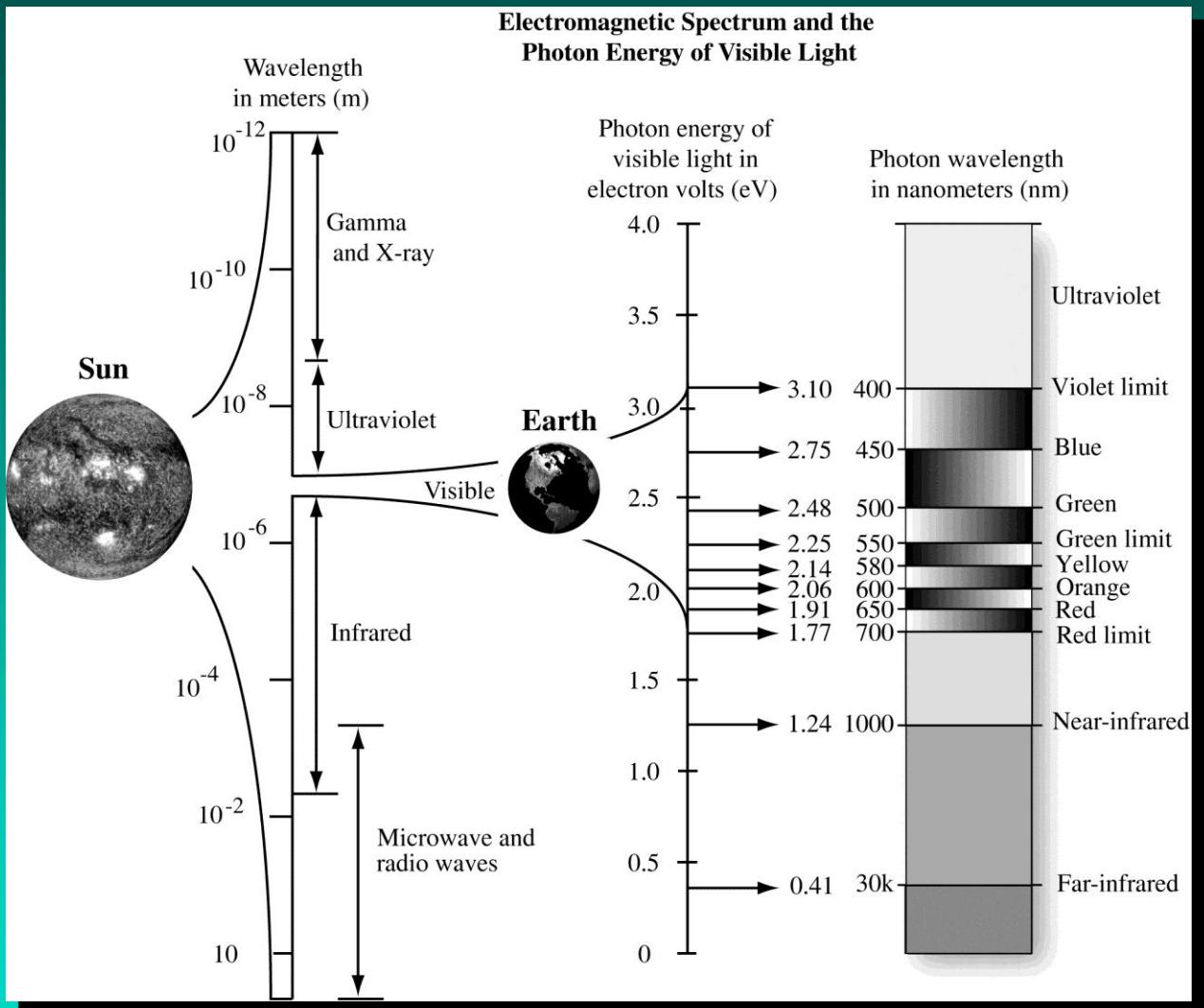


# Sources of Electromagnetic Energy



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Thermonuclear fusion taking place on the surface of the Sun yields a continuous spectrum of electromagnetic energy. The 5770 – 6000 kelvin (K) temperature of this process produces a large amount of relatively short wavelength energy that travels through the vacuum of space at the speed of light. Some of this energy is intercepted by the Earth, where it interacts with the atmosphere and surface materials. The Earth reflects some of the energy directly back out to space or it may absorb the short wavelength energy and then re-emit it at a longer wavelength.

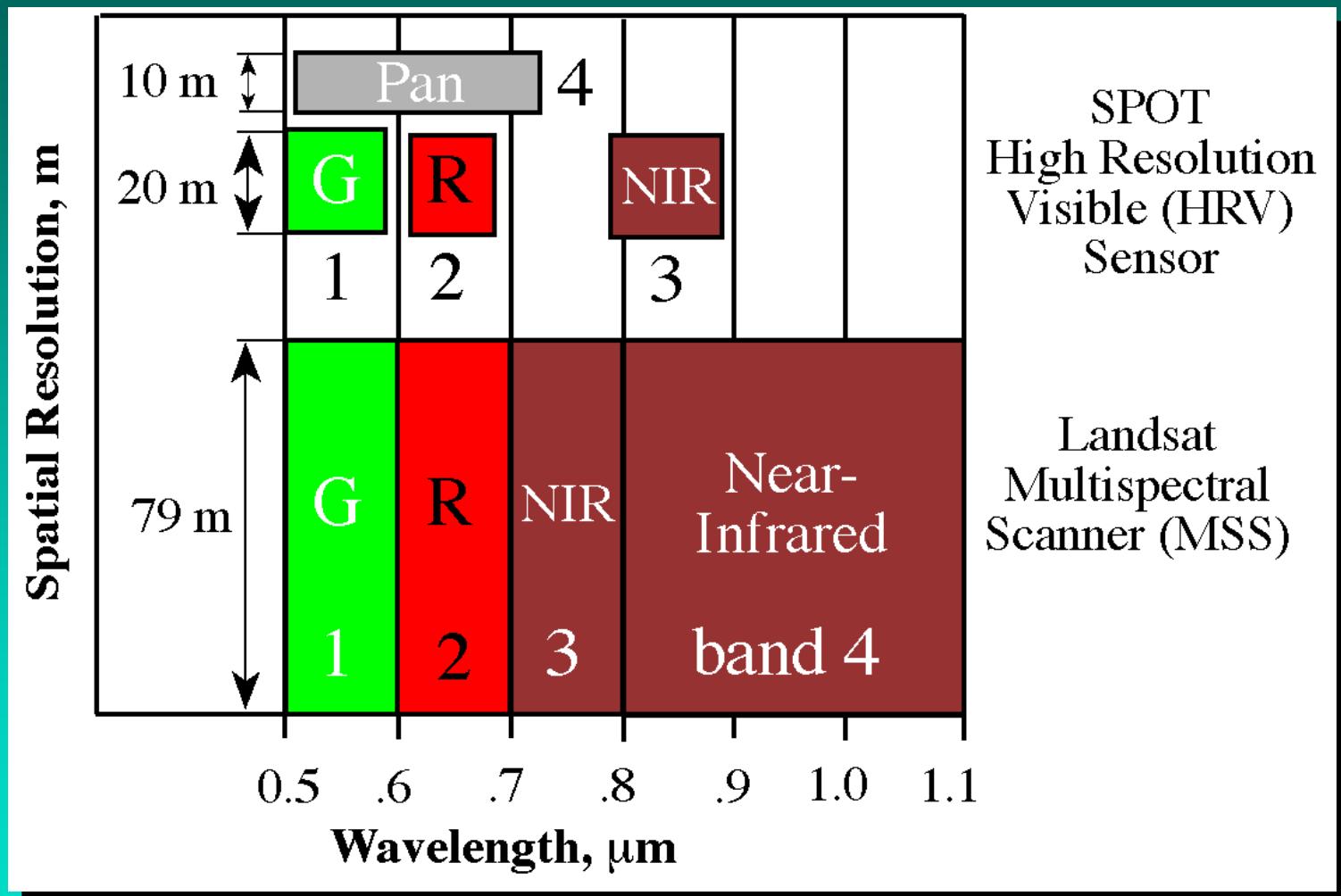


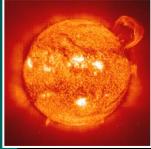
## Electromagnetic Spectrum

The Sun produces a *continuous spectrum* of energy from gamma rays to radio waves that continually bathe the Earth in energy. The visible portion of the spectrum may be measured using wavelength (measured in micrometers or nanometers, i.e.,  $\mu\text{m}$  or nm) or electron volts (eV). All units are interchangeable.



## Spectral Bandwidths of Landsat and SPOT Sensor Systems





## Wein's Displacement Law

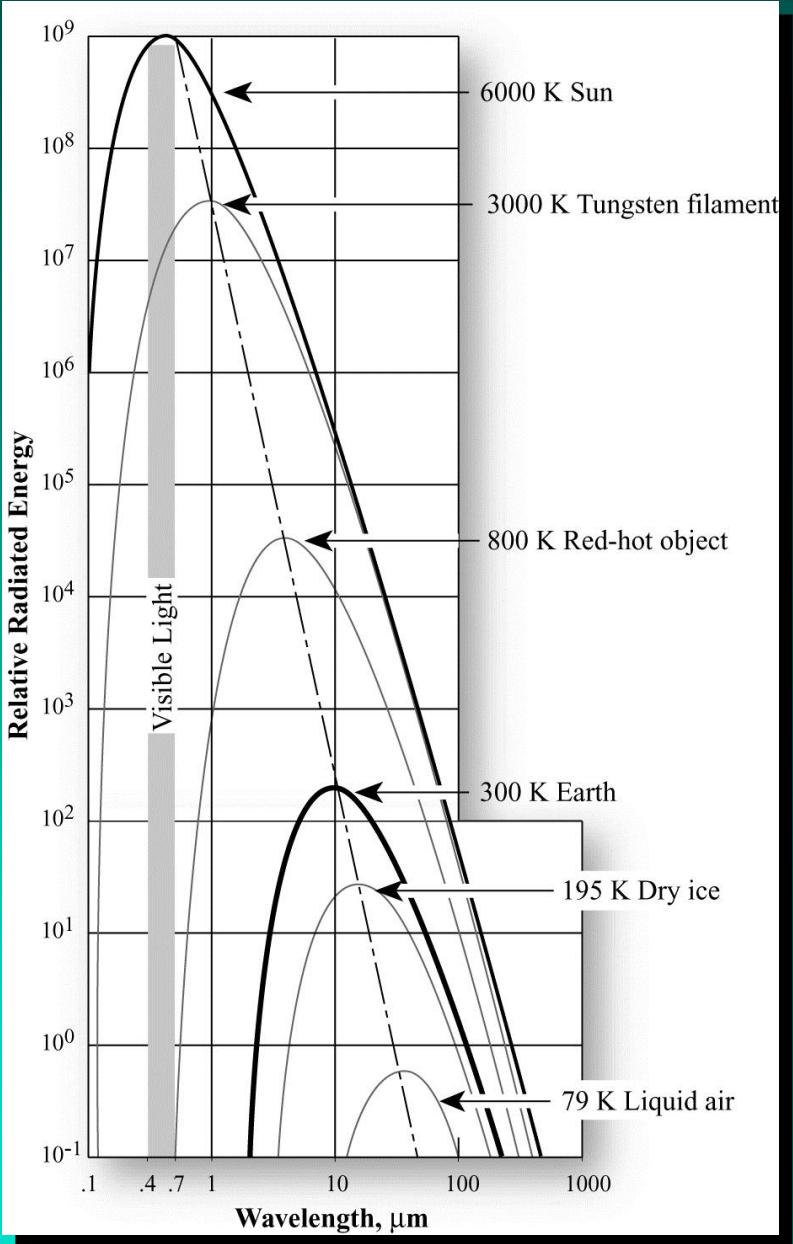
In addition to computing the total amount of energy exiting a theoretical blackbody such as the Sun, we can determine its dominant wavelength ( $\lambda_{max}$ ) based on *Wein's displacement law*:

$$\lambda_{max} = \frac{k}{T}$$

where  $k$  is a constant equaling  $2898 \text{ } \mu\text{m K}$ , and  $T$  is the absolute temperature in kelvin. Therefore, as the Sun approximates a  $6000 \text{ K}$  blackbody, its dominant wavelength ( $\lambda_{max}$ ) is  $0.48 \text{ } \mu\text{m}$ :

$$0.483 \text{ } \mu\text{m} = \frac{2898 \text{ } \mu\text{m K}}{6000 \text{ K}}$$

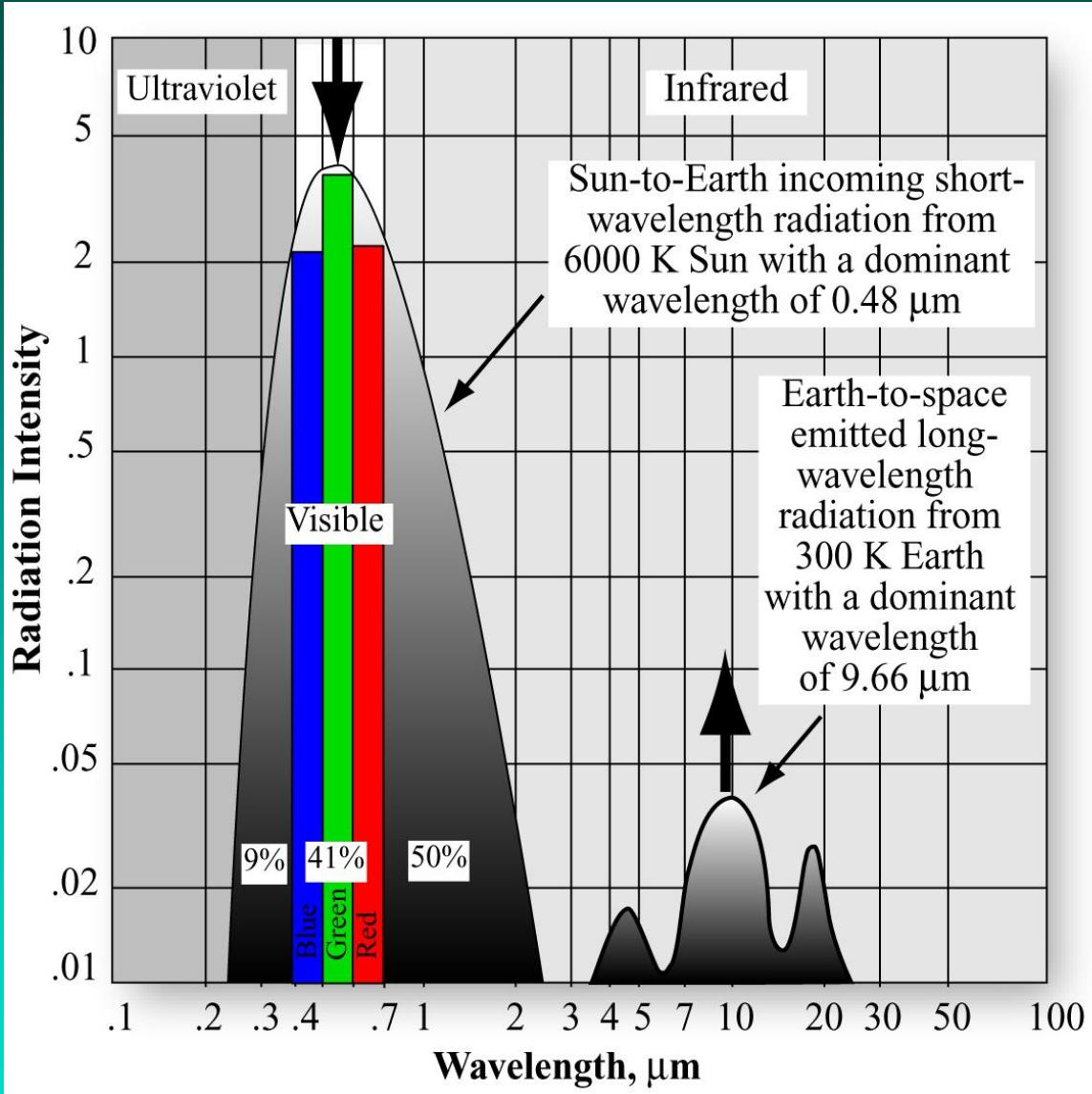
where  $\sigma$  is the Stefan-Boltzmann constant,  $5.66697 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ .

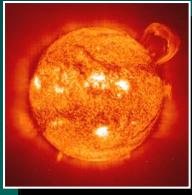


## Blackbody Radiation Curves

Blackbody radiation curves for several objects including the Sun and the Earth which approximate 6,000 K and 300 K blackbodies, respectively. The area under each curve may be summed to compute the total radiant energy ( $M_\lambda$ ) exiting each object. Thus, the Sun produces more radiant exitance than the Earth because its temperature is greater. As the temperature of an object increases, its dominant wavelength ( $\lambda_{\max}$ ) shifts toward the shorter wavelengths of the spectrum.

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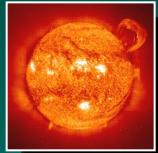




## Particle Model of Electromagnetic Energy

For a 100 years before 1905, light was thought of as a smooth and continuous wave as discussed. Then, Albert Einstein (1879-1955) found that when light interacts with electrons, it has a different character.

- He found that when light interacts with matter, it behaves as though it is composed of many individual bodies called *photons*, which carry such particle-like properties as energy and momentum. As a result, most physicists today would answer the question “*What is light?*” as “*Light is a particular kind of matter*”.
- Thus, we sometimes describe electromagnetic energy in terms of its wave-like properties. But, when the energy interacts with matter it is useful to describe it as discrete packets of energy, or *quanta*.

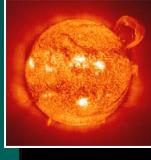


## Quantum Theory of EMR

Niels Bohr (1885–1962) and Max Planck recognized the discrete nature of exchanges of radiant energy and proposed the *quantum theory* of electromagnetic radiation. This theory states that energy is transferred in discrete packets called quanta or photons, as discussed. The relationship between the frequency of radiation expressed by wave theory and the quantum is:

$$Q = h \times v$$

where  $Q$  is the energy of a quantum measured in joules,  $h$  is the Planck constant ( $6.626 \times 10^{-34}$  J s), and  $v$  is the frequency of the radiation.



## Particle Model of Electromagnetic Energy

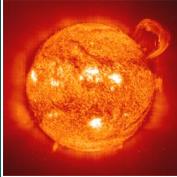
Referring to the previous formulas, we can multiply the equation by  $h/h$ , or 1, without changing its value:

$$\lambda = \frac{hc}{hv}$$

By substituting  $Q$  for  $h\nu$ , we can express the wavelength associated with a quantum of energy as:

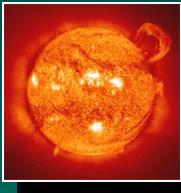
$$\lambda = \frac{hc}{Q} \quad \text{or} \quad Q = \frac{hc}{\lambda}$$

*Thus, the energy of a quantum is inversely proportional to its wavelength, i.e., the longer the wavelength involved, the lower its energy content.*



## Particle Model of Electromagnetic Energy

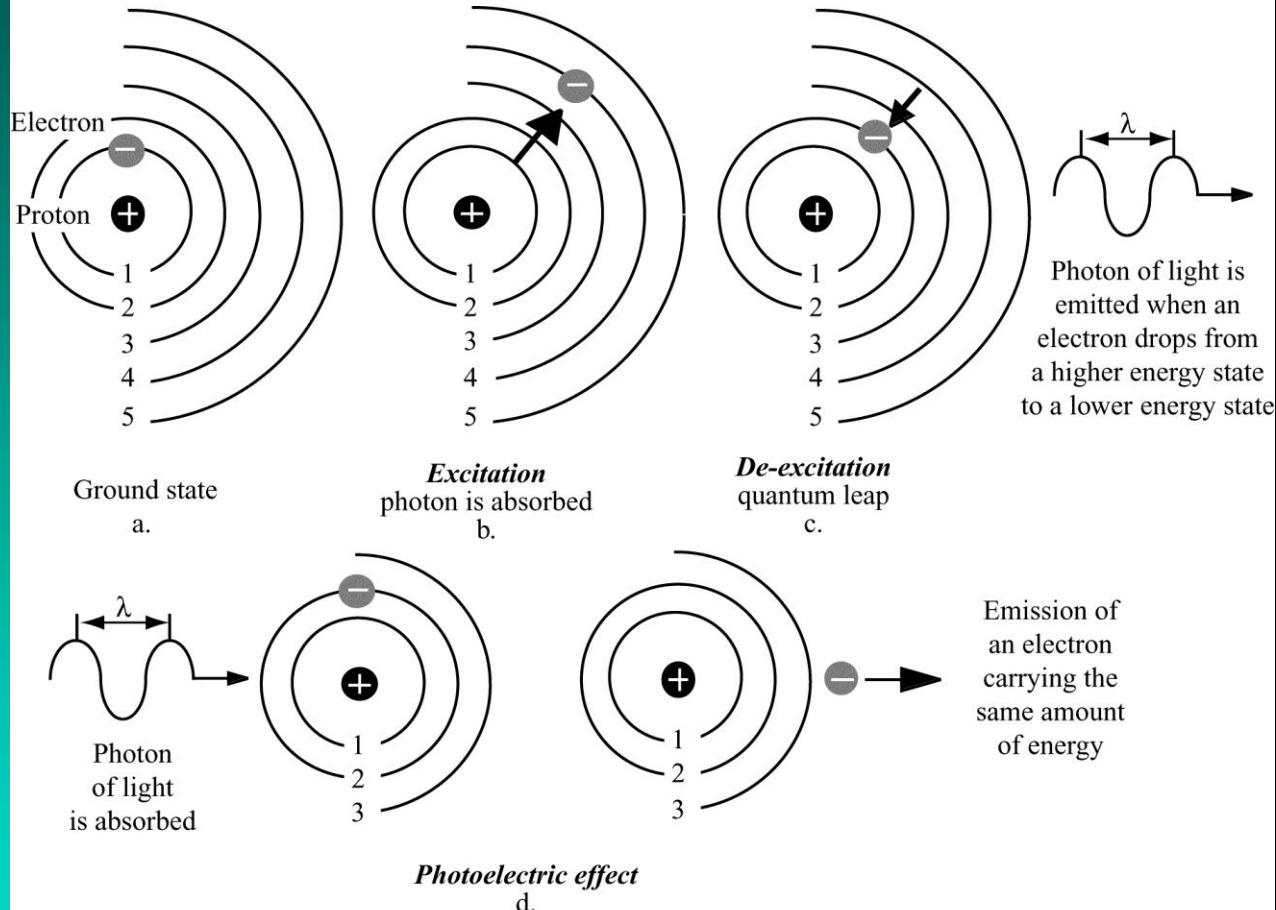
*Electrons* are the tiny negatively charged particles that move around the positively charged *nucleus* of an atom. Atoms of different substances are made up of varying numbers of electrons arranged in different ways. The interaction between the positively charged nucleus and the negatively charged electron keep the electron in orbit. While its orbit is not explicitly fixed, each electron's motion is restricted to a definite range from the nucleus. The allowable orbital paths of electrons about an atom might be thought of as *energy classes or levels*. In order for an electron to climb to a higher class, work must be performed. However, unless an amount of energy is available to move the electron up at least one energy level, it will accept no work. If a sufficient amount of energy is received, the electron will jump to a new level and the atom is said to be *excited*. Once an electron is in a higher orbit, it possesses *potential energy*. After about  $10^{-8}$  seconds, the electron falls back to the atom's lowest empty energy level or orbit and gives off radiation. *The wavelength of radiation given off is a function of the amount of work done on the atom, i.e., the quantum of energy it absorbed to cause the electron to be moved to a higher orbit.*



## Particle Model of Electromagnetic Energy

Matter can be heated to such high temperatures that electrons which normally move in captured non-radiating orbits are broken free. When this happens, the atom remains with a positive charge equal to the negatively charged electron which escaped. The electron becomes a free electron and the atom is called an ion. In the ultraviolet and visible (blue, green, and red) parts of the electromagnetic spectrum, radiation is produced by changes in the energy levels of the outer, *valence electrons*. The wavelengths of energy produced are a function of the particular orbital levels of the electrons involved in the excitation process. If the atoms absorb enough energy to become ionized and if a free electron drops in to fill the vacant energy level, then the radiation given off is ***unquantized*** and ***continuous spectrum*** is produced rather than a band or a series of bands. Every encounter of one of the free electrons with a positively charged nucleus causes rapidly changing electric and magnetic fields so that radiation at all wavelengths is produced. The hot surface of the Sun is largely a plasma in which radiation of all wavelengths is produced. The spectra of a plasma is a continuous spectrum.

## Creation of Light from Atomic Particles and the Photoelectric Effect

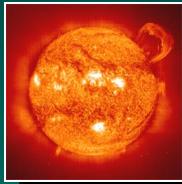


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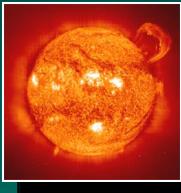
## Creation of Light from Atomic Particles

A **photon** of electromagnetic energy is emitted when an electron in an atom or molecule drops from a higher-energy state to a lower-energy state. The light emitted (i.e., its wavelength) is a function of the changes in the energy levels of the outer, valence electron. For example, yellow light may be produced from a sodium vapor lamp. Matter can also be subjected to such high temperatures that electrons, which normally move in captured, non-radiating orbits, are broken free. When this happens, the atom remains with a positive charge equal to the negatively charged electron that escaped. The electron becomes a free electron, and the atom is called an ion. If another free electron fills the vacant energy level created by the free electron, then radiation from all wavelengths is produced, i.e., a continuous spectrum of energy. The intense heat at the surface of the Sun produces a *continuous spectrum* in this manner.



## Particle Model of Electromagnetic Energy

*Electron orbits are like the rungs of a ladder.* Adding energy moves the electron up the energy ladder; emitting energy moves it down. The energy ladder differs from an ordinary ladder in that its rungs are unevenly spaced. This means that the energy an electron needs to absorb, or to give up, in order to jump from one orbit to the next may not be the same as the energy change needed for some other step. Also, an electron does not always use consecutive rungs. Instead, it follows what physicists call *selection rules*. In many cases, an electron uses one sequence of rungs as it climbs the ladder and another sequence as it descends. The energy that is left over when the electrically charged electron moves from an excited state to a de-excited state is *emitted* by the atom as a *packet of electromagnetic radiation*; a particle-like unit of light called a *photon*. *Every time an electron jumps from a higher to a lower energy level, a photon moves away at the speed of light.*

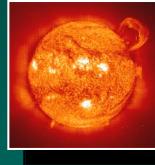
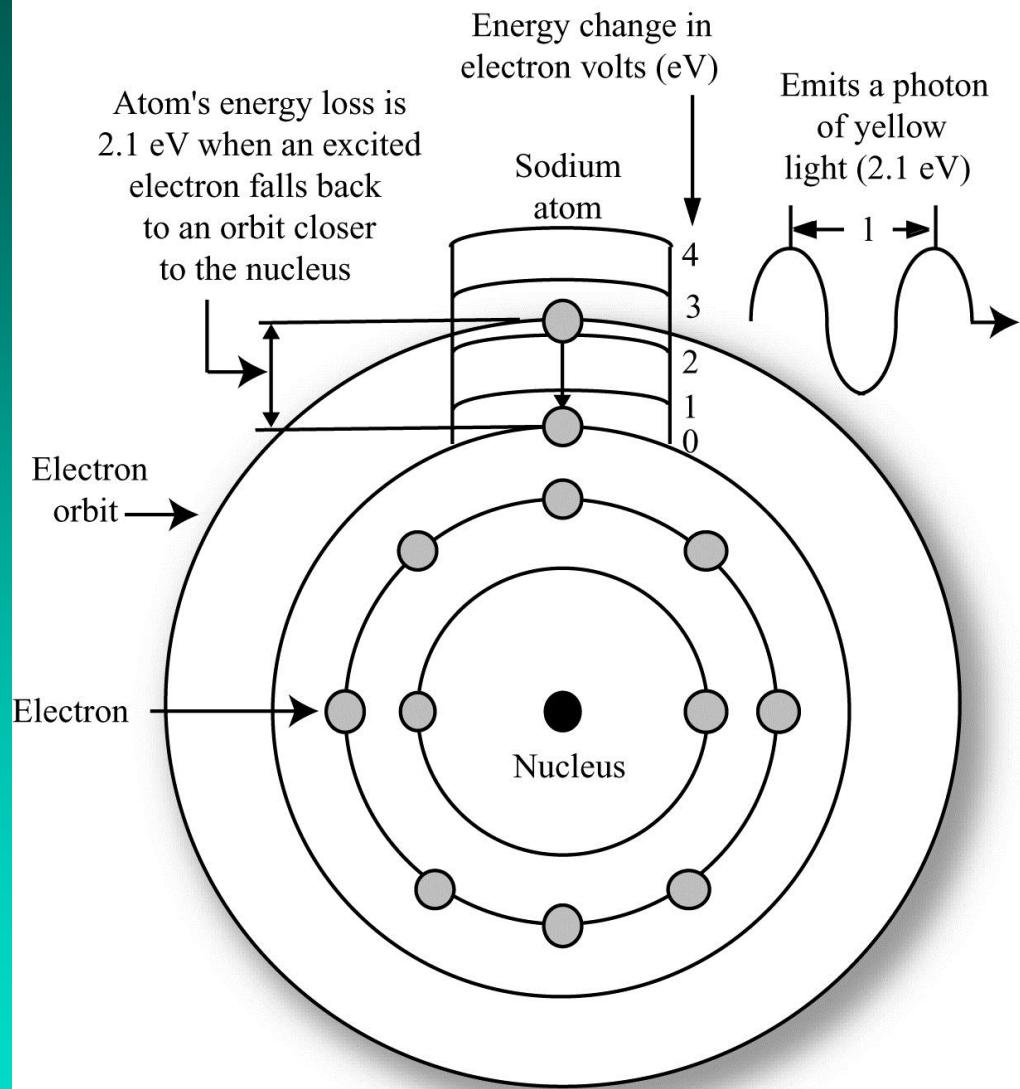


## Particle Model of Electromagnetic Energy

Substances have *color* because of *differences in their energy levels and the selection rules*.

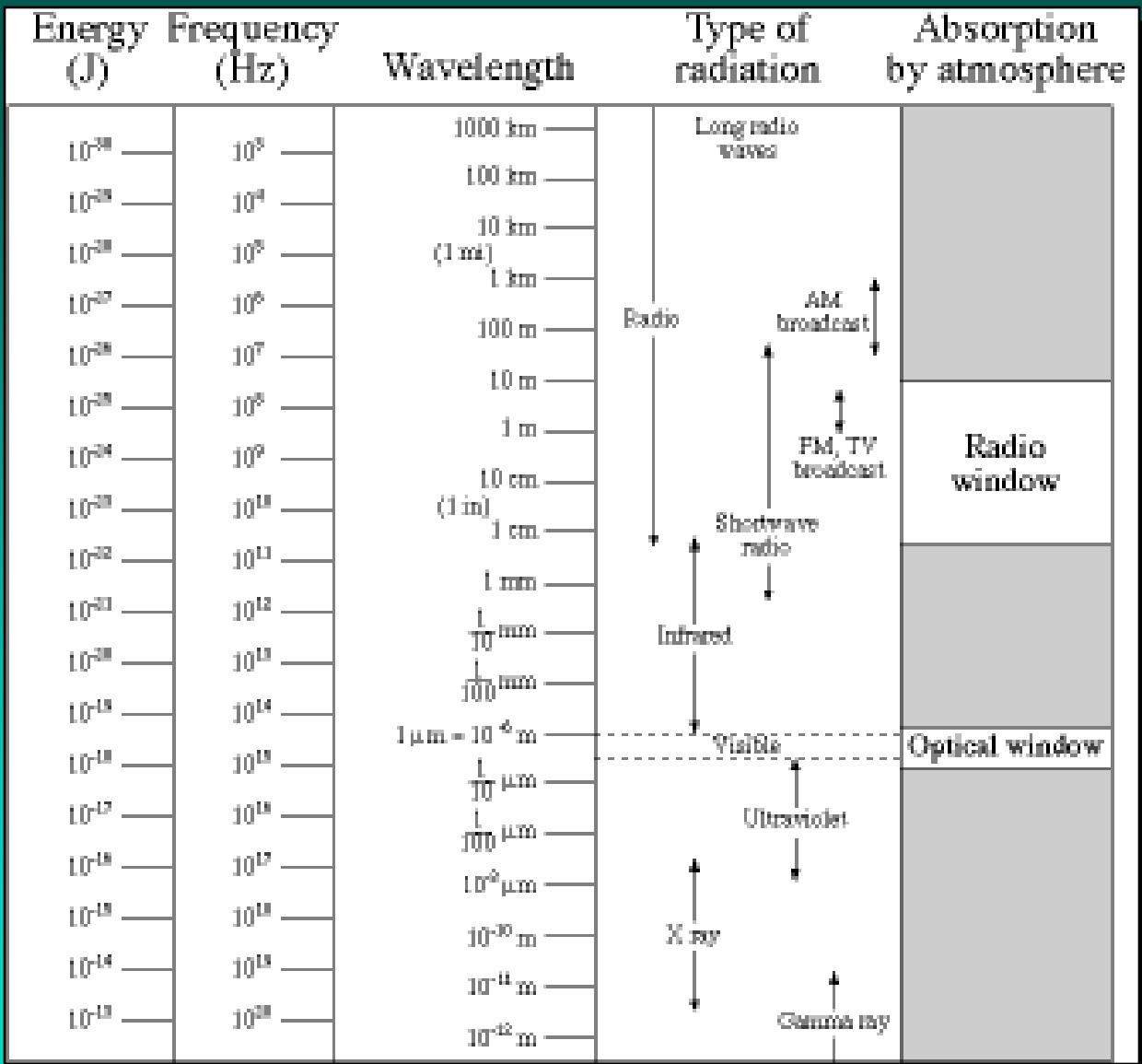
- For example, consider energized *sodium vapor* that produces a bright yellow light that is used in some street lamps. When a sodium-vapor lamp is turned on, several thousand volts of electricity energize the vapor. The outermost electron in each energized atom of sodium vapor climbs to a high rung on the energy ladder and then returns down the ladder in a certain sequence of rungs, the last two of which are 2.1 eV apart. The energy released in this last leap appears as a photon of yellow light with a wavelength of 0.58  $\mu\text{m}$  with 2.1 eV of energy.

## Creation of Light from Atomic Particles in a Sodium Vapor Lamp



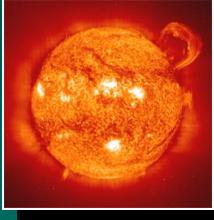
## Creation of Light

Creation of light from atomic particles in a sodium vapor lamp. After being energized by several thousand volts of electricity, the outermost electron in each energized atom of sodium vapor climbs to a high rung on the energy ladder and then returns down the ladder in a predictable fashion. The last two rungs in the descent are 2.1 eV apart. This produces a photon of **yellow** light, which has 2.1 eV of energy.



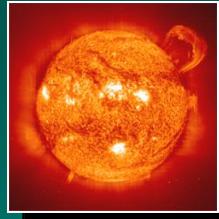
## Energy of Quanta (Photons)

The energy of quanta (photons) ranging from gamma rays to radio waves in the electromagnetic spectrum.



## Particle Model of Electromagnetic Energy

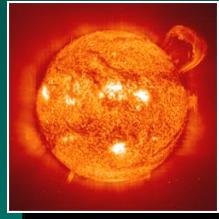
Somehow an electron might disappear from its original orbit and reappear in its destination orbit without ever having to traverse any of the positions in between. This process is called a *quantum leap* or *quantum jump*. If the electron leaps from its highest excited state to the ground state in a single leap it will emit a single photon of energy. It is also possible for the electron to leap from an excited orbit to the ground state in a series of jumps, e.g. from 4 to 2 to 1. If it takes two leaps to get to the ground state then each of these jumps will emit photons of somewhat less energy. The energies emitted in the two different jumps must sum to the total of the single large jump.



# Scattering

Once electromagnetic radiation is generated, it is propagated through the earth's atmosphere almost at the speed of light in a vacuum.

- Unlike a vacuum in which nothing happens, however, the atmosphere may affect not only the speed of radiation but also its wavelength, intensity, spectral distribution, and/or direction.

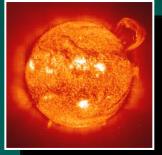
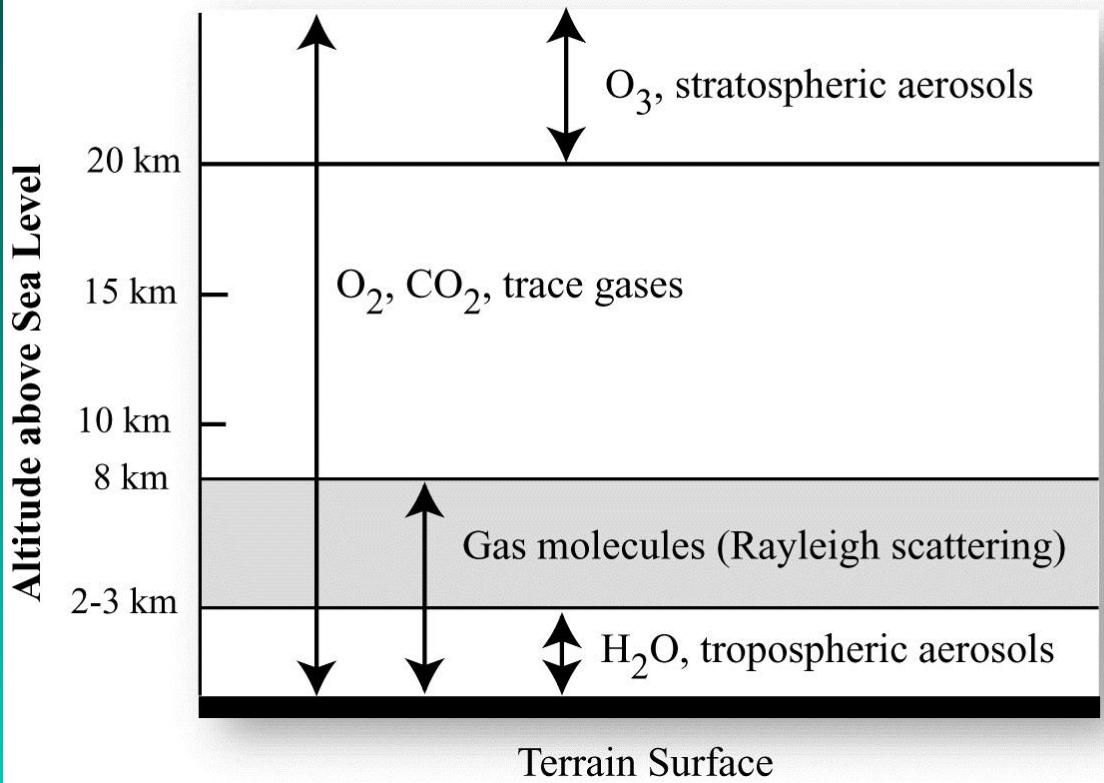


# Scattering

*Scatter* differs from *reflection* in that the direction associated with scattering is **unpredictable**, whereas the direction of reflection is predictable. There are essentially three types of scattering:

- Rayleigh,
- Mie, and
- Non-selective.

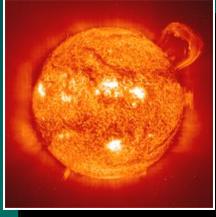
## Atmospheric Layers and Constituents



## Atmospheric Layers and Constituents

Major subdivisions of the atmosphere and the types of molecules and aerosols found in each layer.

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## Rayleigh Scattering

*Rayleigh scattering occurs when the diameter of the matter (usually air molecules) are many times smaller than the wavelength of the incident electromagnetic radiation.* This type of scattering is named after the English physicist who offered the first coherent explanation for it. All scattering is accomplished through absorption and re-emission of radiation by atoms or molecules in the manner described in the discussion on radiation from atomic structures. It is impossible to predict the direction in which a specific atom or molecule will emit a photon, hence scattering.

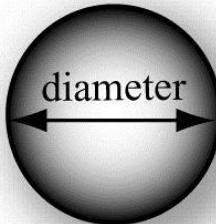
The energy required to excite an atom is associated with short-wavelength, high frequency radiation. *The amount of scattering is inversely related to the fourth power of the radiation's wavelength.* For example, blue light ( $0.4 \text{ } \mu\text{m}$ ) is scattered 16 times more than near-infrared light ( $0.8 \text{ } \mu\text{m}$ ).

# Atmospheric Scattering

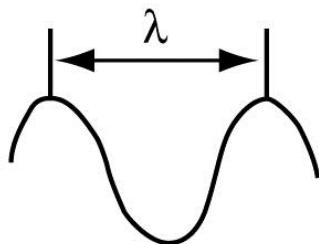
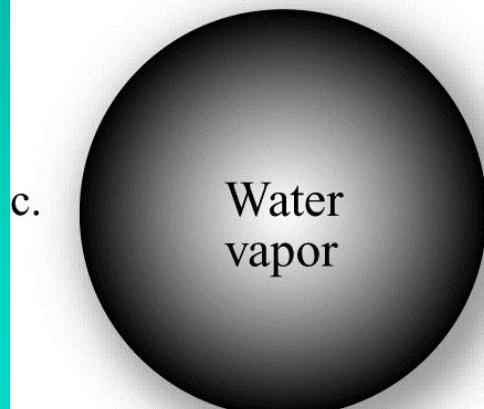
## Rayleigh Scattering

- a.  Gas molecule

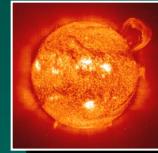
## Mie Scattering

- b.  Smoke, dust

## Nonselective Scattering



Photon of electromagnetic energy modeled as a wave

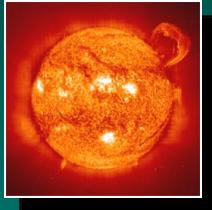
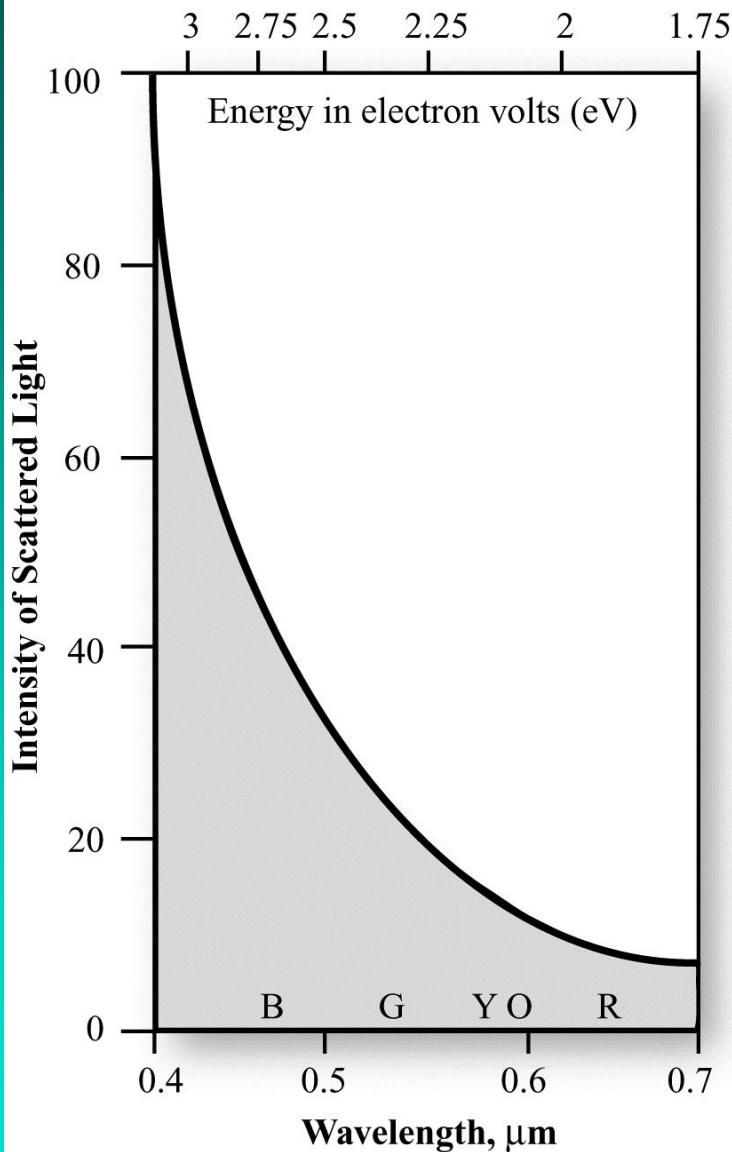


## Atmospheric Scattering

Type of scattering is a function of:

- 1) the wavelength of the incident radiant energy, and
- 1) the size of the gas molecule, dust particle, and/or water vapor droplet encountered.

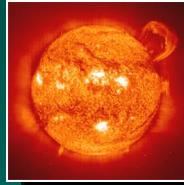
## Intensity of Rayleigh Scattering Varies Inversely with $\lambda^{-4}$



## Rayleigh Scattering

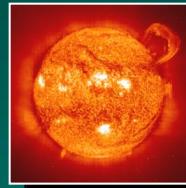
The intensity of Rayleigh scattering varies inversely with the fourth power of the wavelength ( $\lambda^{-4}$ ).

Jensen 2005



## Rayleigh Scattering

- *Rayleigh scattering is responsible for the blue sky.* The short violet and blue wavelengths are more efficiently scattered than the longer orange and red wavelengths. When we look up on cloudless day and admire the blue sky, we witness the preferential scattering of the short wavelength sunlight.
- *Rayleigh scattering is responsible for red sunsets.* Since the atmosphere is a thin shell of gravitationally bound gas surrounding the solid Earth, sunlight must pass through a longer slant path of air at sunset (or sunrise) than at noon. Since the violet and blue wavelengths are scattered even more during their now-longer path through the air than when the Sun is overhead, what we see when we look toward the Sun is the residue - the wavelengths of sunlight that are hardly scattered away at all, especially the oranges and reds (Sagan, 1994).

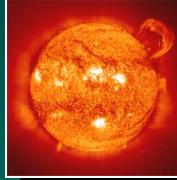


## Rayleigh Scattering

The approximate amount of Rayleigh scattering in the atmosphere in optical wavelengths (0.4 – 0.7 μm) may be computed using the *Rayleigh scattering cross-section* ( $\tau_m$ ) algorithm:

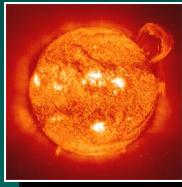
$$\tau_m = \frac{8\pi^3(n^2 - 1)^2}{(3N^2\lambda^4)}$$

where  $n$  = refractive index,  $N$  = number of air molecules per unit volume, and  $\lambda$  = wavelength. The amount of scattering is inversely related to the fourth power of the radiation's wavelength.



## Mie Scattering

- *Mie scattering* takes place when there are essentially *spherical* particles present in the atmosphere with *diameters approximately equal to the wavelength of radiation being considered*. For visible light, water vapor, dust, and other particles ranging from a few tenths of a micrometer to several micrometers in diameter are the main scattering agents. The amount of scatter is greater than Rayleigh scatter and the wavelengths scattered are longer.
- *Pollution* also contributes to beautiful *sunsets* and *sunrises*. The greater the amount of smoke and dust particles in the atmospheric column, the more violet and blue light will be scattered away and only the longer *orange* and *red* wavelength light will reach our eyes.



## Non-selective Scattering

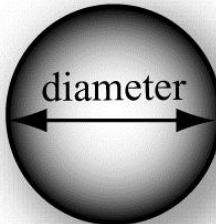
- *Non-selective scattering* is produced when there are particles in the atmosphere *several times the diameter of the radiation being transmitted*. This type of scattering is non-selective, i.e. all wavelengths of light are scattered, not just blue, green, or red. Thus, water droplets, which make up clouds and fog banks, scatter all wavelengths of visible light equally well, causing the cloud to appear white (a mixture of all colors of light in approximately equal quantities produces white).
- Scattering can severely reduce the information content of remotely sensed data to the point that the imagery loses contrast and it is difficult to differentiate one object from another.

# Atmospheric Scattering

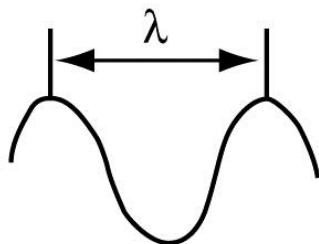
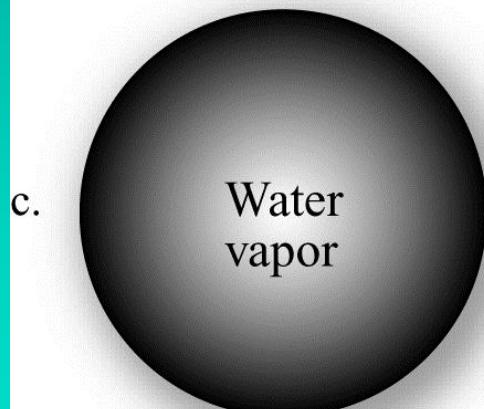
## Rayleigh Scattering

- a.  Gas molecule

## Mie Scattering

- b.  Smoke, dust

## Nonselective Scattering



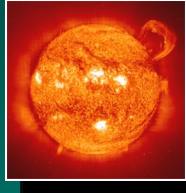
Photon of electromagnetic energy modeled as a wave



## Atmospheric Scattering

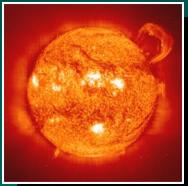
Type of scattering is a function of:

- 1) the wavelength of the incident radiant energy, and
- 1) the size of the gas molecule, dust particle, and/or water vapor droplet encountered.



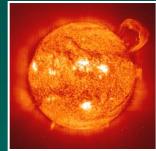
## Absorption

- *Absorption* is the process by which radiant energy is absorbed and converted into other forms of energy. An *absorption band* is a range of wavelengths (or frequencies) in the electromagnetic spectrum within which radiant energy is absorbed by substances such as water ( $H_2O$ ), carbon dioxide ( $CO_2$ ), oxygen ( $O_2$ ), ozone ( $O_3$ ), and nitrous oxide ( $N_2O$ ).
- The cumulative effect of the absorption by the various constituents can cause the atmosphere to *close down* in certain regions of the spectrum. This is bad for remote sensing because no energy is available to be sensed.

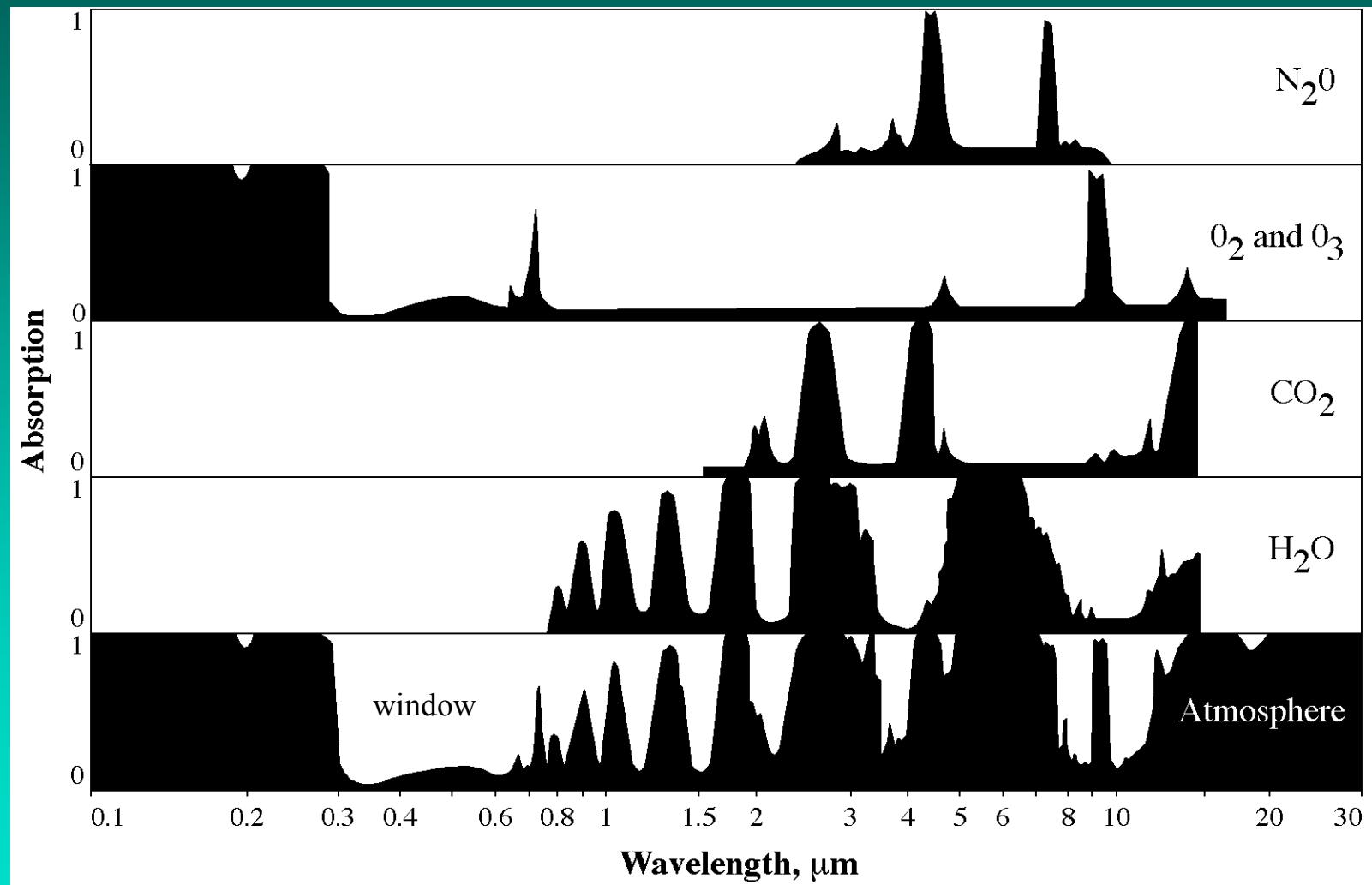


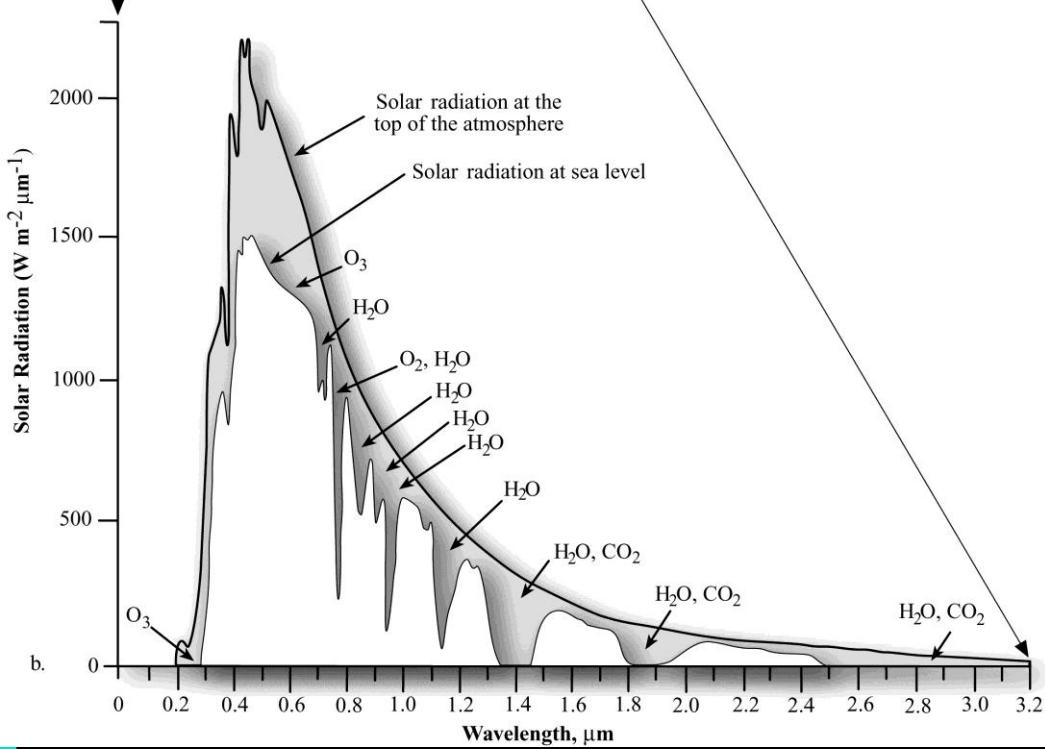
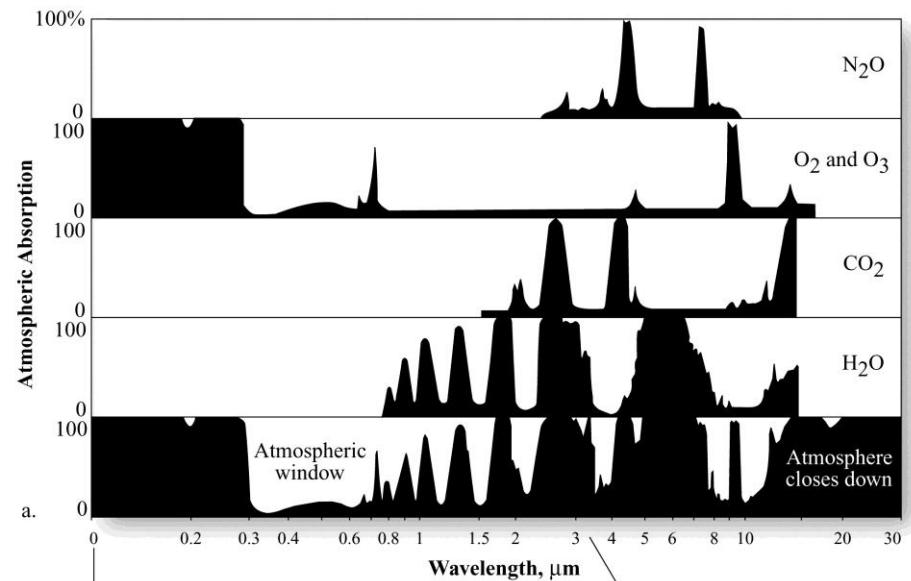
# Absorption

- In certain parts of the spectrum such as the visible region (0.4 - 0.7  $\mu\text{m}$ ), the atmosphere does not absorb all of the incident energy but transmits it effectively. Parts of the spectrum that transmit energy effectively are called “atmospheric windows”.
- *Absorption* occurs when energy of the same frequency as the resonant frequency of an atom or molecule is absorbed, producing an *excited state*. If, instead of re-radiating a photon of the same wavelength, the energy is transformed into heat motion and is reradiated at a longer wavelength, absorption occurs. When dealing with a medium like air, absorption and scattering are frequently combined into an *extinction coefficient*.
- *Transmission* is inversely related to the extinction coefficient times the thickness of the layer. Certain wavelengths of radiation are affected far more by absorption than by scattering. This is particularly true of infrared and wavelengths shorter than visible light.



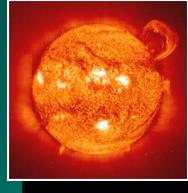
## Absorption of the Sun's Incident Electromagnetic Energy in the Region from 0.1 to 30 $\mu\text{m}$ by Various Atmospheric Gases





a) The *absorption* of the Sun's incident electromagnetic energy in the region from 0.1 to 30  $\mu\text{m}$  by various atmospheric gases. The first four graphs depict the absorption characteristics of N<sub>2</sub>O, O<sub>2</sub> and O<sub>3</sub>, CO<sub>2</sub>, and H<sub>2</sub>O, while the final graphic depicts the cumulative result of all these constituents being in the atmosphere at one time. The atmosphere essentially “closes down” in certain portions of the spectrum while “atmospheric windows” exist in other regions that transmit incident energy effectively to the ground. It is within these windows that remote sensing systems must function.

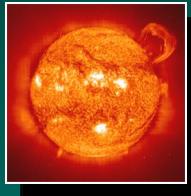
b) The combined effects of atmospheric absorption, scattering, and reflectance reduce the amount of solar irradiance reaching the Earth's surface at sea level.



## Reflectance

*Reflectance* is the process whereby radiation “bounces off” an object like a cloud or the terrain. Actually, the process is more complicated, involving re-radiation of photons in unison by atoms or molecules in a layer one-half wavelength deep.

- Reflection exhibits fundamental characteristics that are important in remote sensing. First, the incident radiation, the reflected radiation, and a vertical to the surface from which the angles of incidence and reflection are measured all lie in the same plane. Second, the angle of incidence and the angle of reflection are equal.

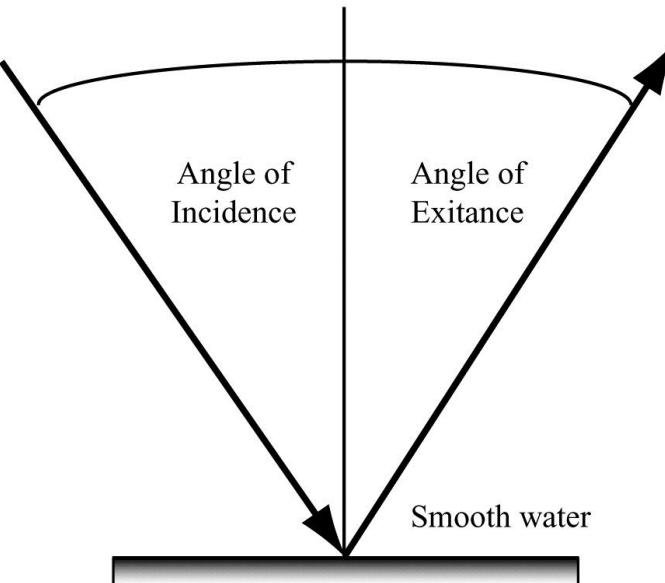


# Reflectance

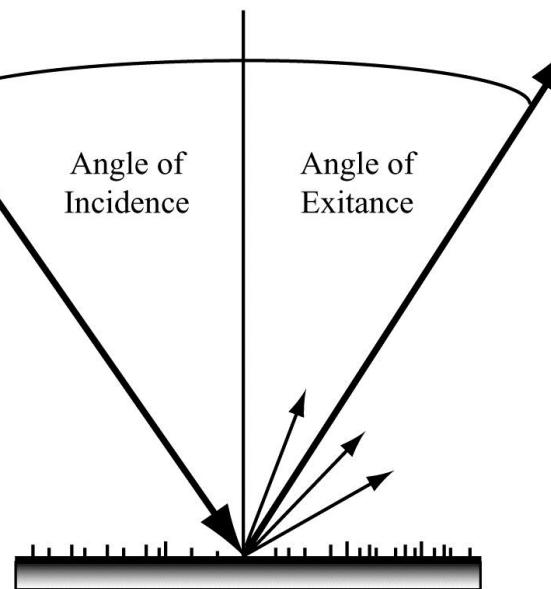
There are various types of reflecting surfaces:

- When *specular reflection* occurs, the surface from which the radiation is reflected is essentially smooth (i.e. the average surface profile is several times smaller than the wavelength of radiation striking the surface).
- If the surface is rough, the reflected rays go in many directions, depending on the orientation of the smaller reflecting surfaces. This diffuse reflection does not yield a mirror image, but instead produces *diffused radiation*. White paper, white powders and other materials reflect visible light in this diffuse manner.
- If the surface is so rough that there are no individual reflecting surfaces, then scattering may occur. Lambert defined a *perfectly diffuse surface*; hence the commonly designated *Lambertian surface* is one for which the radiant flux leaving the surface is constant for any angle of reflectance to the surface normal.

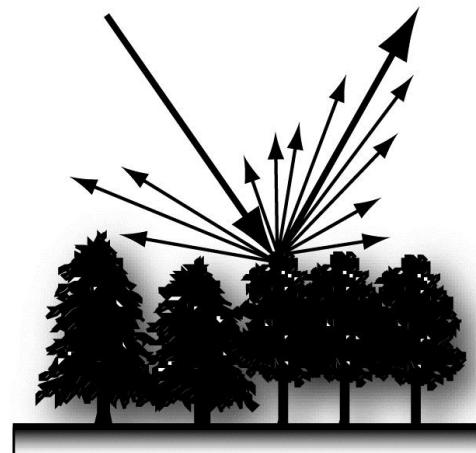
## Specular versus Diffuse Reflectance



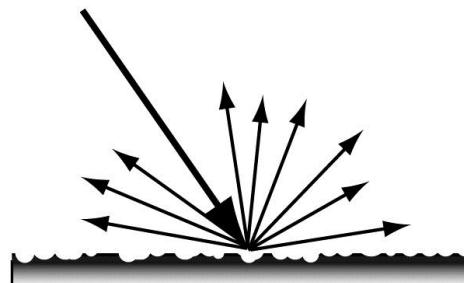
a. Perfect specular reflector.



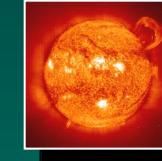
b. Near-perfect specular reflector.



c. Near-perfect diffuse reflector.

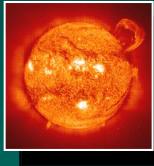


d. Perfect diffuse reflector, or Lambertian surface.



Reflectance

Jensen 2005



## Terrain Energy-Matter Interactions

Radiometric quantities have been identified that allow analysts to keep a careful record of the incident and exiting radiant flux. We begin with the simple *radiation budget equation*, which states that the total amount of radiant flux in specific wavelengths ( $\lambda$ ) incident to the terrain ( $\Phi_{i_\lambda}$ ) must be accounted for by evaluating the amount of radiant flux reflected from the surface ( $\Phi_{reflected\ \lambda}$ ), the amount of radiant flux absorbed by the surface ( $\Phi_{absorbed\lambda}$ ), and the amount of radiant flux transmitted through the surface ( $\Phi_{transmittal\ \lambda}$ ):

$$\Phi_{i_\lambda} = \Phi_{reflected\ \lambda} + \Phi_{absorbed\lambda} + \Phi_{transmittal\ \lambda}$$



## Terrain Energy-Matter Interactions

The time rate of flow of energy onto, off of, or through a surface is called *radiant flux* ( $\Phi$ ) and is measured in watts (W). The characteristics of the radiant flux and what happens to it as it interacts with the Earth's surface is of critical importance in remote sensing. In fact, this is the fundamental focus of much remote sensing research. By carefully monitoring the exact nature of the incoming (incident) radiant flux in selective wavelengths and how it interacts with the terrain, it is possible to learn important information about the terrain.



## Hemispherical Reflectance, Absorptance, and Transmittance

The *Hemispherical reflectance* ( $\rho_\lambda$ ) is defined as the dimensionless ratio of the radiant flux reflected from a surface to the radiant flux incident to it:

$$\rho_\lambda = \frac{\Phi_{reflected}}{\Phi_{i\lambda}}$$

*Hemispherical transmittance* ( $\tau_\lambda$ ) is defined as the dimensionless ratio of the radiant flux transmitted through a surface to the radiant flux incident to it:

$$\tau_\lambda = \frac{\Phi_{transmitted}}{\Phi_{i\lambda}}$$

*Hemispherical absorptance* ( $\alpha_\lambda$ ) is defined by the dimensionless relationship:

$$\alpha_\lambda = \frac{\Phi_{absorbed}}{\Phi_{i\lambda}}$$



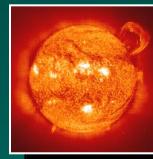
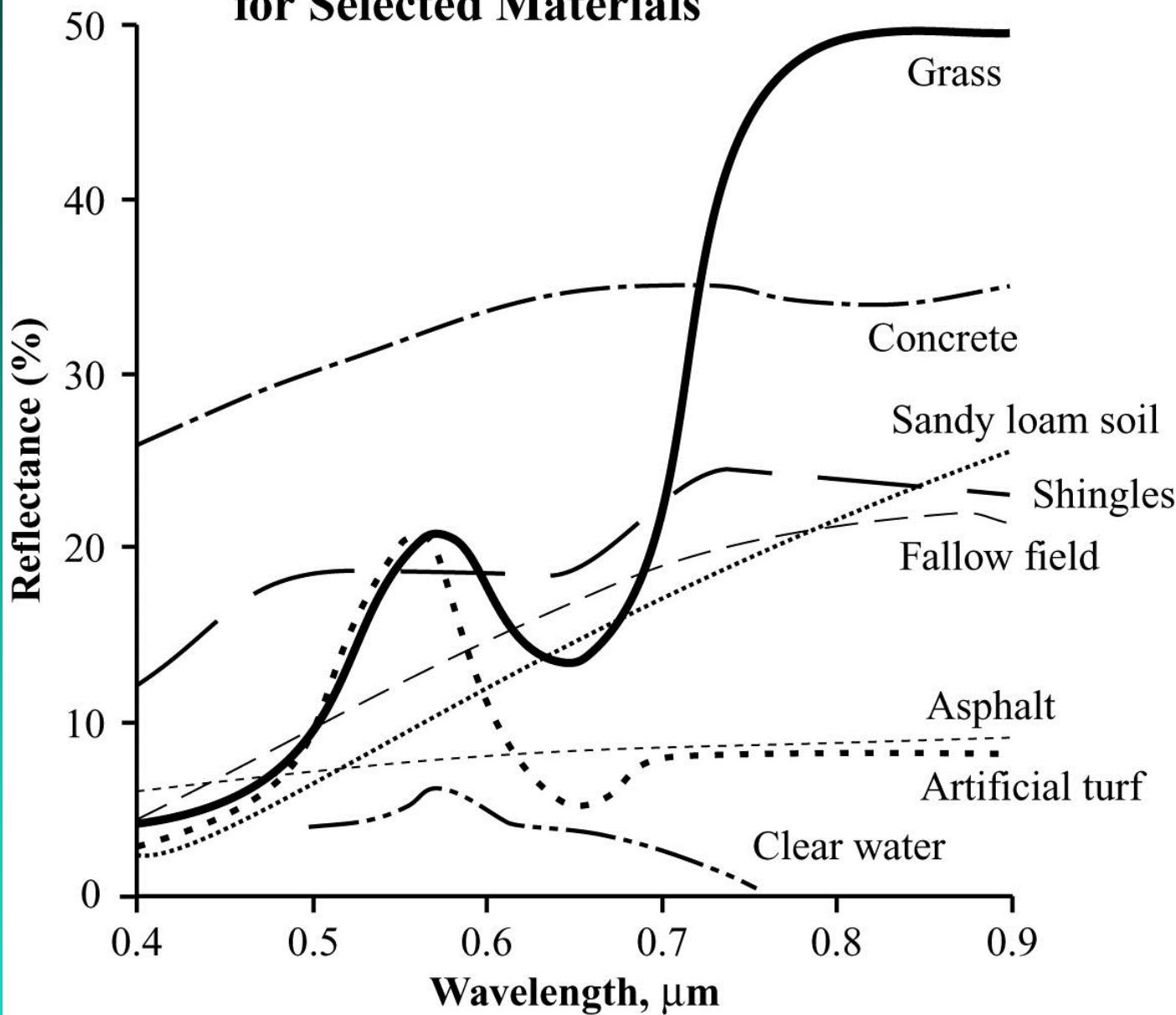
## Hemispherical Reflectance, Absorptance, and Transmittance

These radiometric quantities are useful for producing general statements about the spectral reflectance, absorptance, and transmittance characteristics of terrain features. In fact, if we take the simple hemispherical reflectance equation and multiply it by 100, we obtain an expression for percent reflectance ( $\rho_{\lambda\%}$ ):

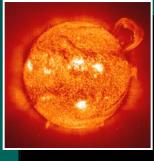
$$\rho_{\lambda\%} = \frac{\Phi_{reflected\lambda}}{\Phi_{i_\lambda}} \times 100$$

This quantity is used in remote sensing research to describe the general spectral reflectance characteristics of various phenomena.

# Spectral Reflectance Curves for Selected Materials



Typical spectral reflectance curves for urban–suburban phenomena in the region  $0.4 – 0.9 \mu\text{m}$ .



## Irradiance and Exitance

The amount of radiant flux incident upon a surface per unit area of that surface is called *Irradiance* ( $E_\lambda$ ), where:

$$E_\lambda = \frac{\Phi_\lambda}{A}$$

- The amount of radiant flux leaving per unit area of the plane surface is called *Exitance* ( $M_\lambda$ ).

$$M_\lambda = \frac{\Phi_\lambda}{A}$$

- Both quantities are measured in watts per meter squared ( $\text{W m}^{-2}$ ).

## Radiant Flux Density

Radiant flux,  $\Phi_\lambda$

$$\text{Irradiance} \quad E_\lambda = \frac{\Phi_\lambda}{A}$$

a.

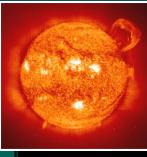
Area,  $A$

Exitance

$$M_\lambda = \frac{\Phi_\lambda}{A}$$

b.

Area,  $A$

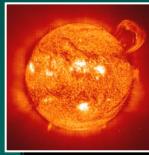


## Radiant Flux Density

The concept of *radiant flux density* for an area on the surface of the Earth.

- *Irradiance* is a measure of the amount of radiant flux incident upon a surface per unit area of the surface measured in  $\text{watts m}^{-2}$ .
- *Exitance* is a measure of the amount of radiant flux leaving a surface per unit area of the surface measured in  $\text{watts m}^{-2}$ .

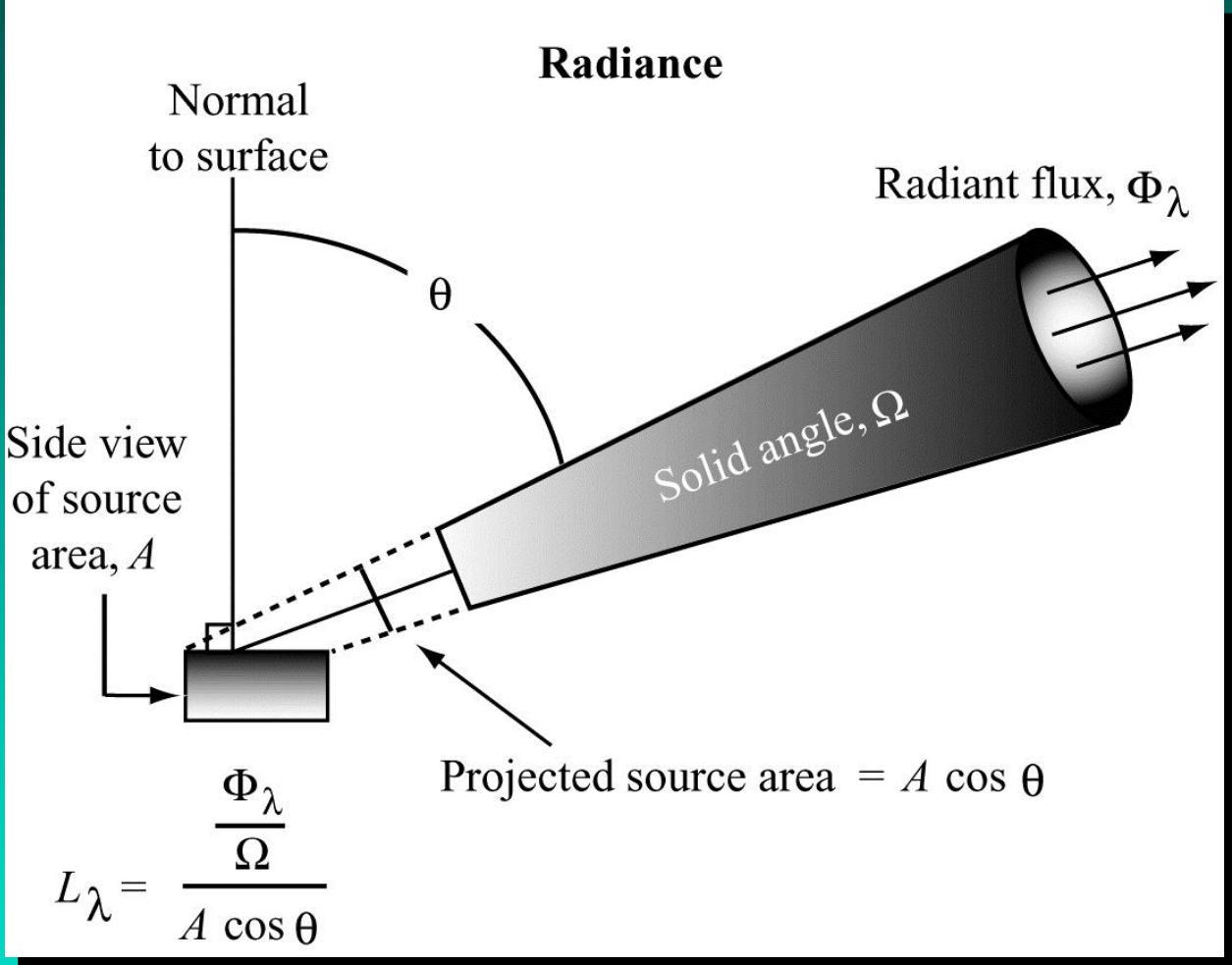
Jensen 2005



# Radiance

Radiance ( $L_\lambda$ ) is the radiant flux per unit solid angle leaving an extended source in a given direction per unit projected source area in that direction and is measured in watts per meter squared per steradian ( $\text{W m}^{-2} \text{ sr}^{-1}$ ). We are only interested in the radiant flux in certain wavelengths ( $L_\lambda$ ) leaving the projected source area ( $A$ ) within a certain direction ( $\theta$ ) and solid angle ( $\Omega$ ):

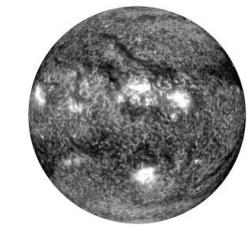
$$L_\lambda = \frac{\Phi}{A \cos \theta}$$



The concept of *radiance* leaving a specific projected source area on the ground, in a specific direction, and within a specific solid angle.

Jensen 2005

### Various Paths of Radiance Received by a Remote Sensing System



Solar irradiance

$E_o$

Diffuse sky irradiance

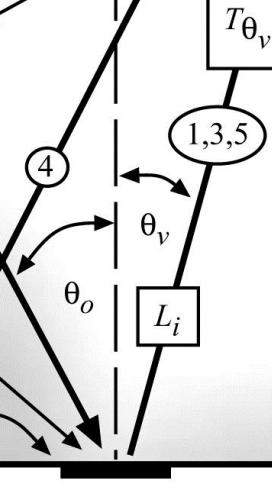
$E_d$

Total radiance at the sensor

$L_S$

Remote sensing system

90°



Reflectance from neighboring area,

$\rho_{\lambda_n}$

Reflectance from study area,

$\rho_{\lambda}$

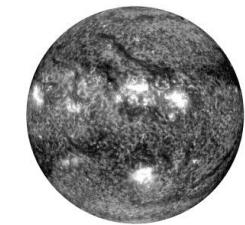
Atmosphere

Atmosphere

Radiance ( $L_T$ ) from paths 1, 3, and 5 contains intrinsic valuable spectral information about the target of interest. Conversely, the path radiance ( $L_p$ ) from paths 2 and 4 includes diffuse sky irradiance or radiance from neighboring areas on the ground. This path radiance generally introduces unwanted radiometric noise in the remotely sensed data and complicates the image interpretation process.

Jensen 2004

## Various Paths of Radiance Received by a Remote Sensing System



Solar irradiance

$E_o$

Diffuse sky irradiance

$E_d$

Reflectance from neighboring area,  
 $\rho_{\lambda_n}$

Reflectance from study area,  
 $\rho_{\lambda}$

Total radiance at the sensor



Remote sensing system

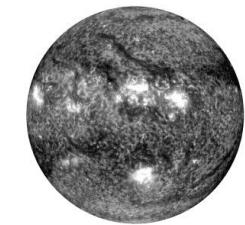
90°

(1)  
(2)  
(3)  
(4)  
(5)

$T_{\theta_o}$   
 $T_{\theta_v}$   
Atmosphere  
 $L_i$

Path 1 contains spectral solar irradiance ( $E_{o_\lambda}$ ) that was attenuated very little before illuminating the terrain within the IFOV. Notice in this case that we are interested in the solar irradiance from a specific solar zenith angle ( $\theta_o$ ) and that the amount of irradiance reaching the terrain is a function of the atmospheric transmittance at this angle ( $T_{\theta_o}$ ). If all of the irradiance makes it to the ground, then the atmospheric transmittance ( $T_{\theta_o}$ ) equals one. If none of the irradiance makes it to the ground, then the atmospheric transmittance is zero

## Various Paths of Radiance Received by a Remote Sensing System



Solar irradiance

$$E_o$$

Diffuse sky irradiance

$$E_d$$

Reflectance from neighboring area,

$$\rho_{\lambda_n}$$

Reflectance from study area,

$$\rho_{\lambda}$$

Total radiance at the sensor



Remote sensing system

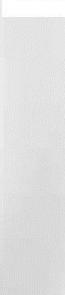
90°

Atmosphere



Upward

Atmosphere



Downward

Path 1

Path 2

Path 3

Path 4

Path 5

Path 1, 3, 5

Path 2

Path 3

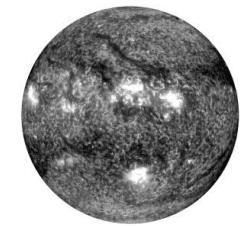
Path 4

Path 5

*Path 2* contains spectral diffuse sky irradiance ( $E_{d\lambda}$ ) that never even reaches the Earth's surface (the target study area) because of scattering in the atmosphere. Unfortunately, such energy is often scattered directly into the IFOV of the sensor system. As previously discussed, Rayleigh scattering of blue light contributes much to this diffuse sky irradiance. That is why the blue band image produced by a remote sensor system is often much brighter than any of the other bands. It contains much unwanted diffuse sky irradiance that was inadvertently scattered into the IFOV of the sensor system. Therefore, if possible, we want to minimize its effects. Green (2003) refers to the quantity as the upward reflectance of the atmosphere ( $E_{du\lambda}$ ).

$$E_{du\lambda}$$

**Various Paths of Radiance Received by a Remote Sensing System**



Solar irradiance

$$E_o$$

Diffuse sky irradiance

$$E_d$$

Reflectance from neighboring area,

$$\rho_{\lambda_n}$$

Reflectance from study area,

$$\rho_{\lambda}$$

Total radiance at the sensor

Remote sensing system

90°

- (1)
- (2)
- (3)
- (4)
- (5)

$$L_P$$

Atmosphere

$$L_i$$

$$L_T$$

1,3,5

$$\theta_v$$

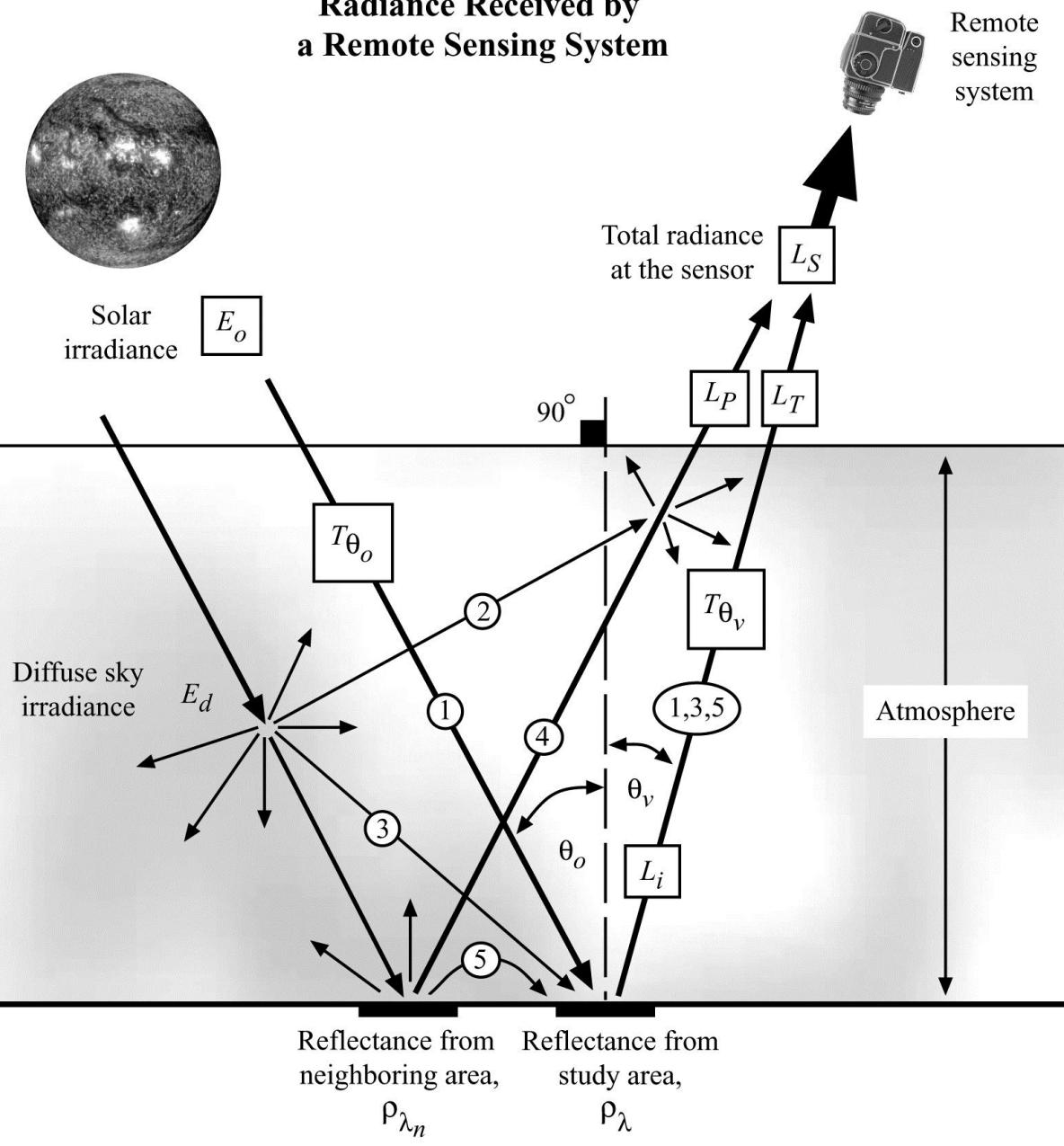
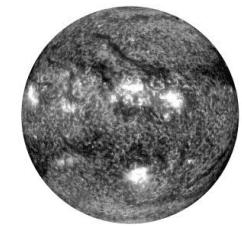
$$\theta_o$$

$$T_{\theta_o}$$

$$T_{\theta_v}$$

**Path 3** contains energy from the Sun that has undergone some Rayleigh, Mie, and/or nonselective scattering and perhaps some absorption and reemission before illuminating the study area. Thus, its spectral composition and polarization may be somewhat different from the energy that reaches the ground from path 1. Green (2003) refers to this quantity as the downward reflectance of the atmosphere ( $E_{dd\lambda}$ ).

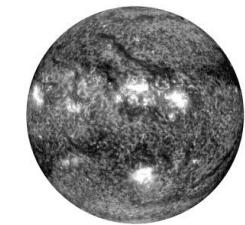
### Various Paths of Radiance Received by a Remote Sensing System



Path 4 contains radiation that was reflected or scattered by nearby terrain ( $\rho_{\lambda_n}$ ) covered by snow, concrete, soil, water, and/or vegetation into the IFOV of the sensor system. The energy does not actually illuminate the study area of interest. Therefore, if possible, we would like to minimize its effects.

Path 2 and Path 4 combine to produce what is commonly referred to as *Path Radiance*,  $L_p$ .

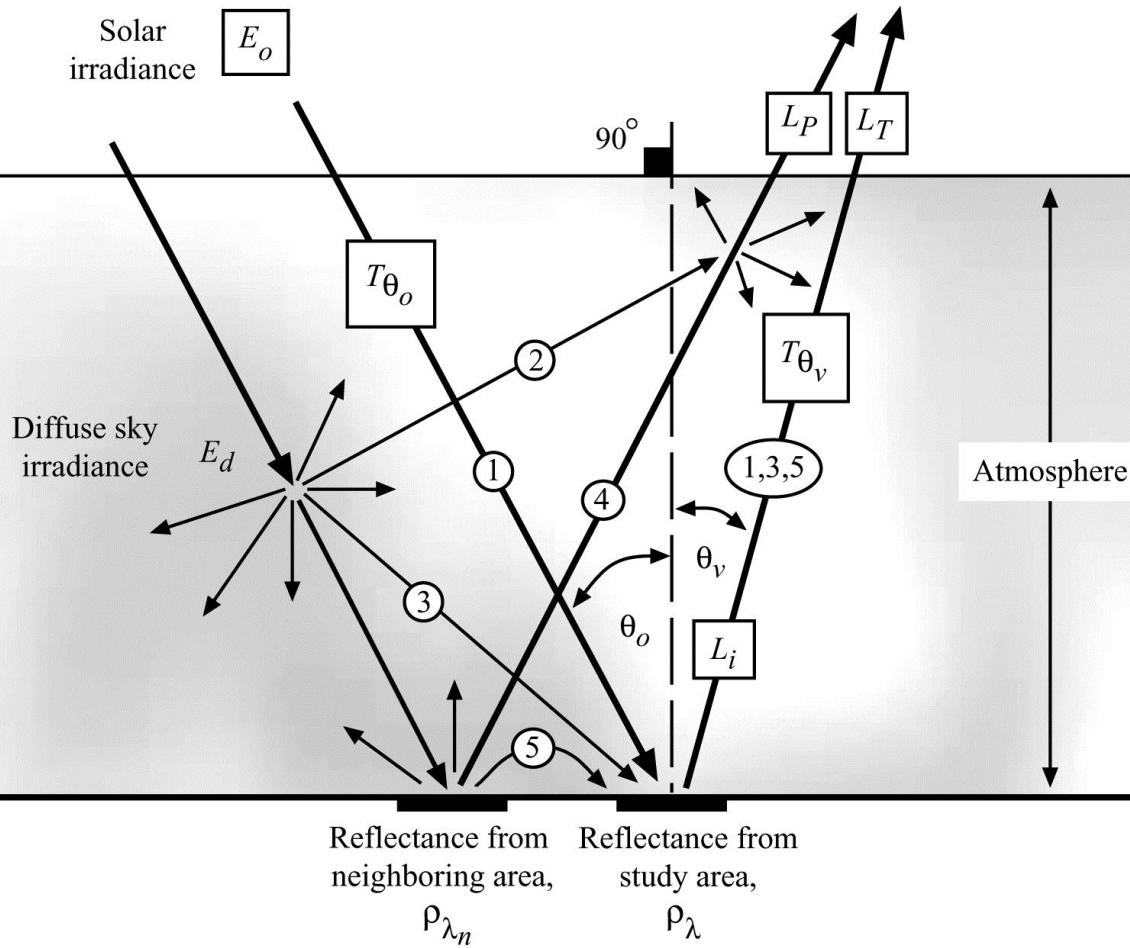
## Various Paths of Radiance Received by a Remote Sensing System



Solar irradiance  $E_o$

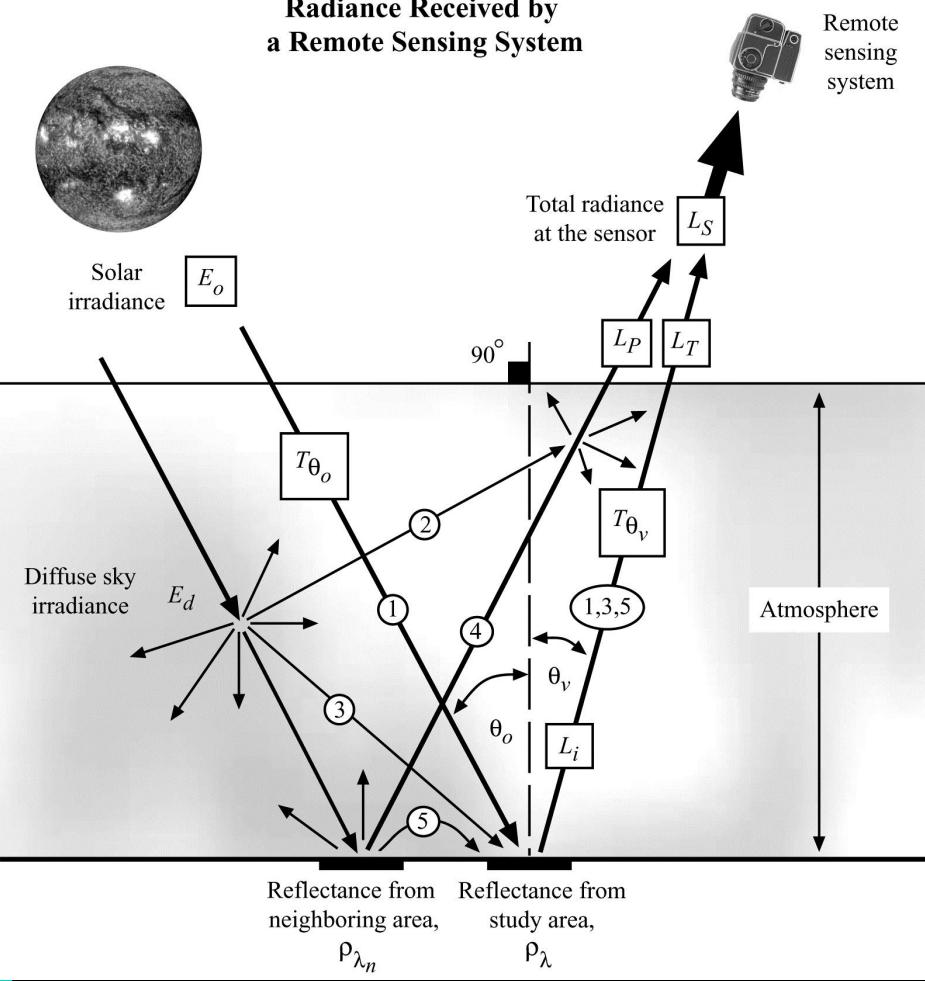
Total radiance at the sensor

Remote sensing system



Path 5 is energy that was also reflected from nearby terrain into the atmosphere, but then scattered or reflected onto the study area.

**Various Paths of  
Radiance Received by  
a Remote Sensing System**

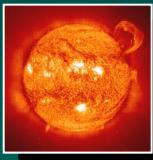


**The total radiance reaching the sensor is:**

$$L_S = \frac{1}{\pi} \rho T_{\theta_v} (E_{o\Delta\lambda} T_{\theta_o} \cos \theta_o \Delta\lambda + E_d) + L_p$$

**This may be summarized as:**

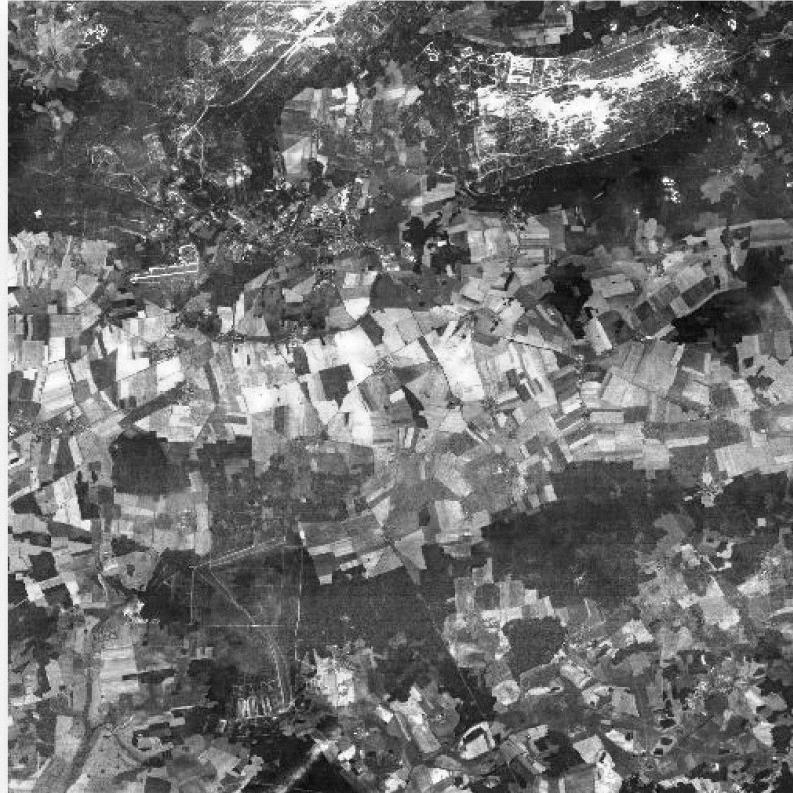
$$L_S = L_T + L_p$$



## Atmospheric Correction Using ATCOR

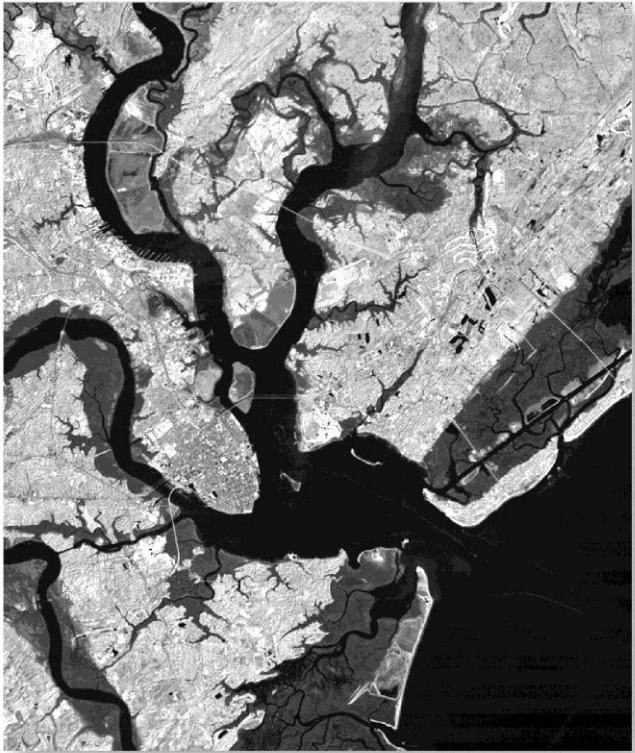


a. Before atmospheric correction.



b. After atmospheric correction.

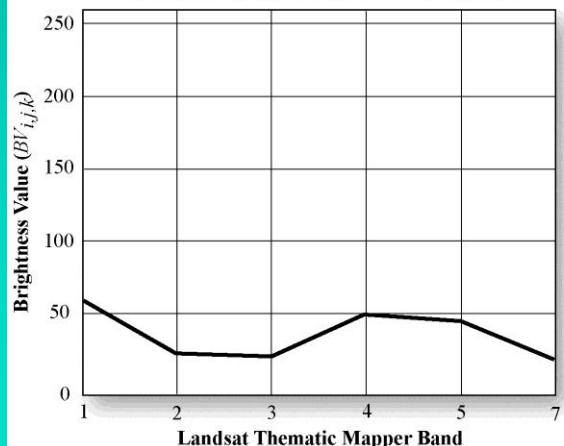
a) Image containing substantial haze prior to atmospheric correction. b) Image after atmospheric correction using ATCOR (Courtesy Leica Geosystems and DLR, the German Aerospace Centre).



a. Empirical line calibrated Landsat Thematic Mapper band 4 image of Charleston, SC.

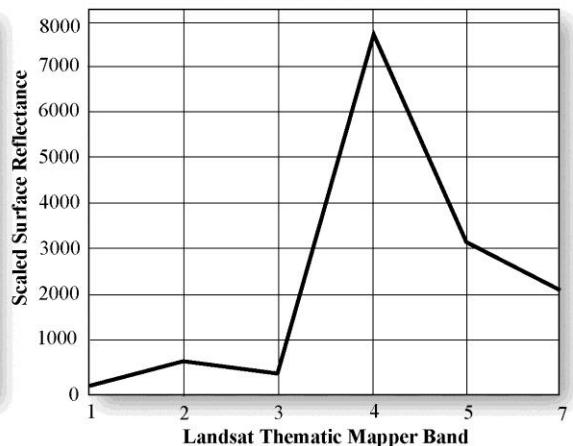
b.

Original Landsat TM Brightness Values  
Loblolly Pine (*Pinus taeda*) near Charleston, SC



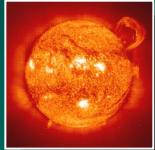
c.

Empirical Line Calibration of Landsat TM Data to Scaled Surface Reflectance



## Empirical Line Calibration

- a) Landsat Thematic Mapper image acquired on February 3, 1994 was radiometrically corrected using empirical line calibration and paired NASA JPL and Johns Hopkins University spectral library beach and water *in situ* spectroradiometer measurements and Landsat TM image brightness values ( $BV_{i,j,k}$ ).
- b) A pixel of loblolly pine with its original brightness values in six bands (TM band 6 thermal data were not used).
- c) The same pixel after empirical line calibration to scaled surface reflectance. Note the correct chlorophyll absorption in the blue (band 1) and red (band 3) portions of the spectrum and the increase in near-infrared reflectance.



## Index of Refraction

The *index of refraction* ( $n$ ) is a measure of the optical density of a substance. This index is the ratio of the speed of light in a vacuum,  $c$ , to the speed of light in a substance such as the atmosphere or water,  $c_n$  (Mulligan, 1980):

$$n = \frac{c}{c_n}$$

The speed of light in a substance can never reach the speed of light in a vacuum. Therefore, its index of refraction must always be greater than 1. For example, the index of refraction for the atmosphere is 1.0002926 and 1.33 for water. Light travels more slowly through water because of water's higher density.



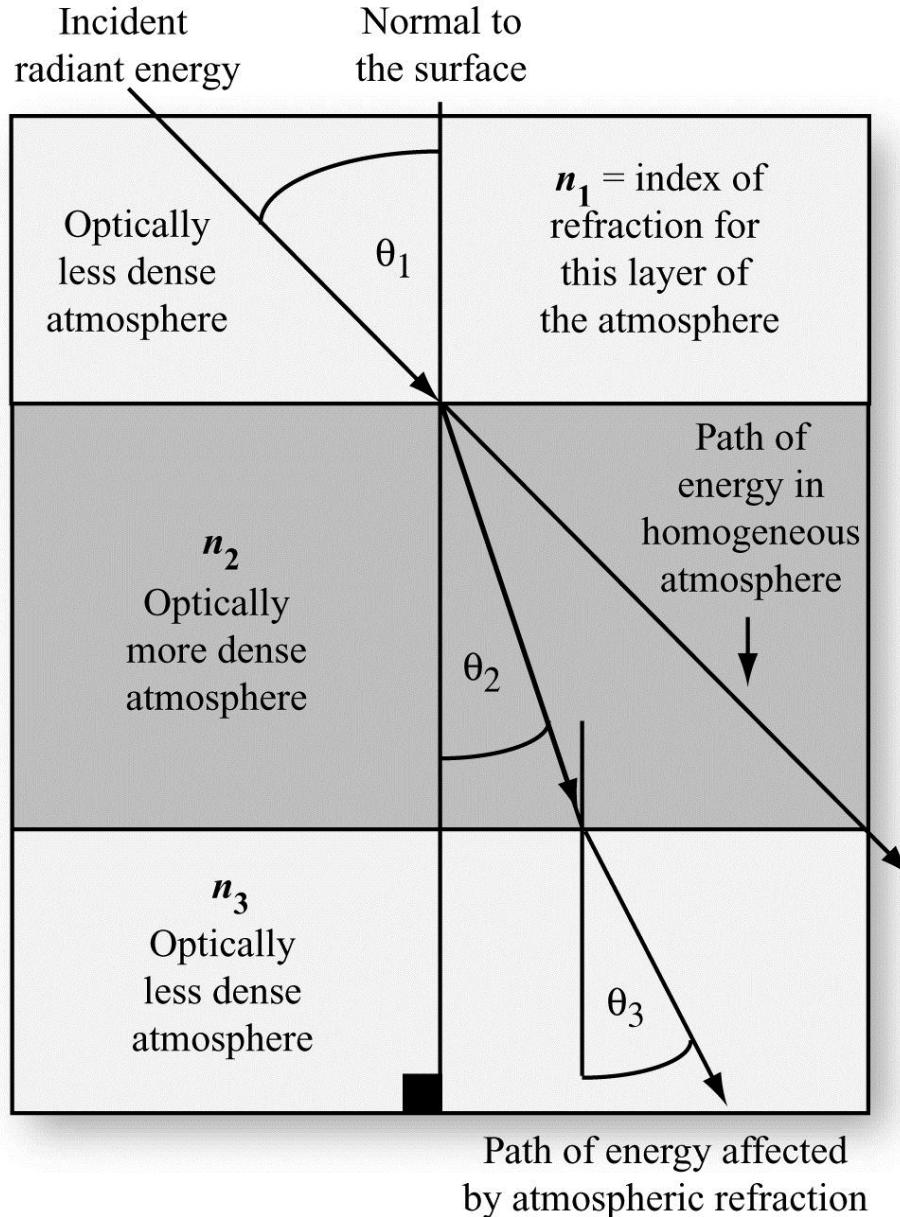
## Snell's Law

Refraction can be described by Snell's law, which states that for a given frequency of light (we must use frequency since, unlike wavelength, it does not change when the speed of light changes), the product of the index of refraction and the sine of the angle between the ray and a line normal to the interface is constant:

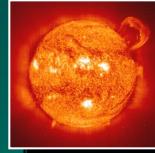
$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

From the accompanying figure, we can see that a nonturbulent atmosphere can be thought of as a series of layers of gases, each with a slightly different density. Anytime energy is propagated through the atmosphere for any appreciable distance at any angle other than vertical, refraction occurs.

## Atmospheric Refraction



## Atmospheric Refraction



Refraction in three nonturbulent atmospheric layers. The incident energy is bent from its normal trajectory as it travels from one atmospheric layer to another. Snell's law can be used to predict how much bending will take place, based on a knowledge of the angle of incidence ( $\theta$ ) and the index of refraction of each atmospheric level,  $n_1$ ,  $n_2$ ,  $n_3$ .



## Snell's Law

The amount of refraction is a function of the angle made with the vertical ( $\theta$ ), the distance involved (in the atmosphere the greater the distance, the more changes in density), and the density of the air involved (air is usually more dense near sea level). Serious errors in location due to refraction can occur in images formed from energy detected at high altitudes or at acute angles. However, these location errors are predictable by Snell's law and thus can be removed. Notice that

$$\sin \theta_2 = \frac{n_1 \sin \theta_1}{n_2}$$

Therefore, if one knows the index of refraction of medium  $n_1$  and  $n_2$  and the angle of incidence of the energy to medium  $n_1$ , it is possible to predict the amount of refraction that will take place ( $\sin \theta_2$ ) in medium  $n_2$  using trigonometric relationships. It is useful to note, however, that most image analysts never concern themselves with computing the index of refraction.