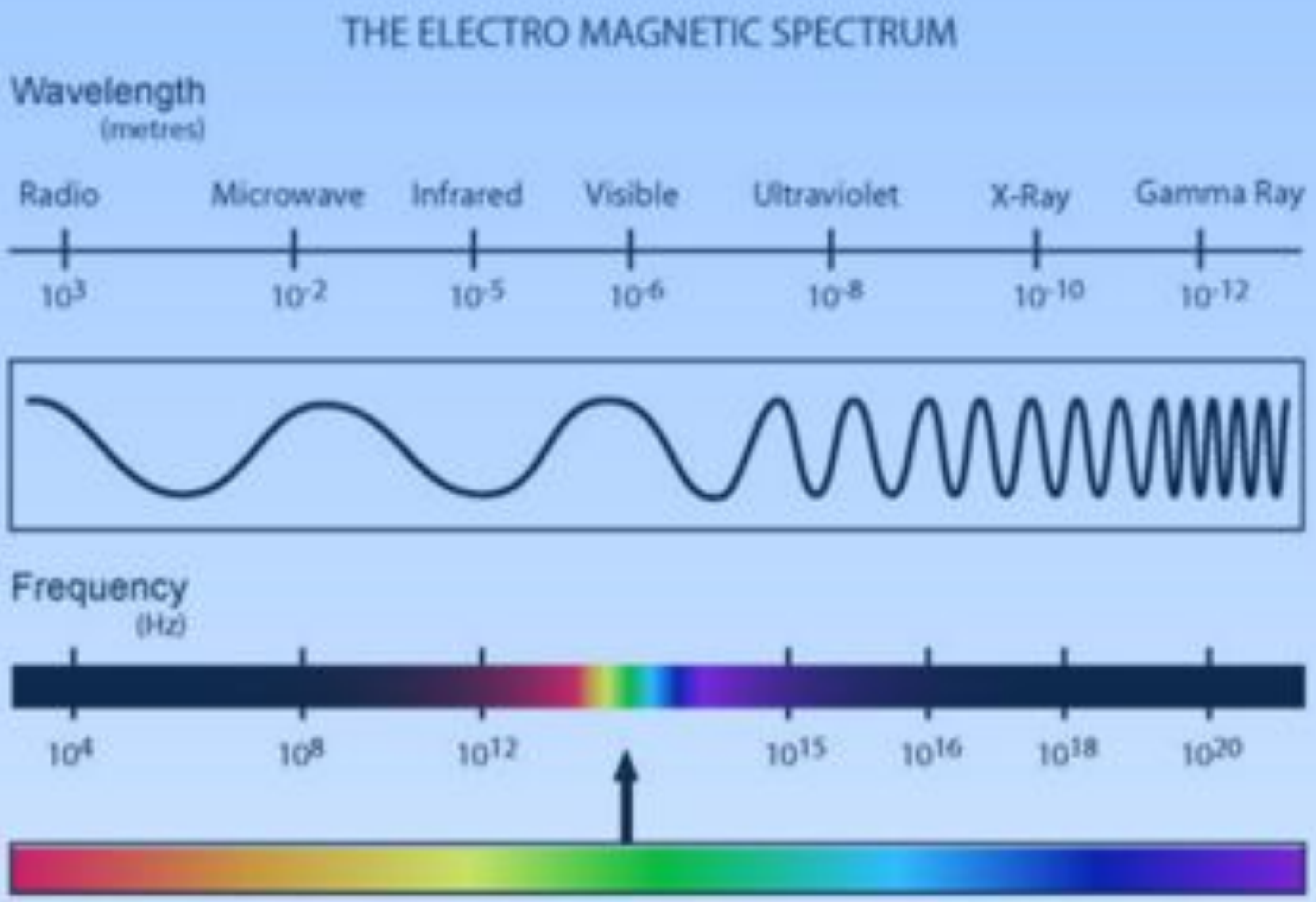
Solar Radiation: The basics

- Sunlight is the source of all of Earth's energy.
- Heat & Food.
- Fossil fuels are stored solar energy from millions of years ago.
- Biomass converts solar energy to fuel.
- Wind energy is the result of solar heated air & earth's rotation.
- Even hydro-power is generated by the sun since evaporated water returns to earth as rain & fills the dams.

Basic properties of light



Basic properties of light

Light exists as a wave -> wavelength & frequency.
Light also is a particle -> momentum & energy.

$$E = h\nu = hc/\lambda$$

Characteristics of light that are relevant to energy

- Spectral content of incident light
- Radiant power density of sunlight
- Angle at which the incident sunlight strikes absorber
- Radiant energy from sun throughout year

Basic properties of light

Energy of a photon

$$E = h\nu = hc/\lambda$$

h = Planck's constant = 6.626×10^{-34} Js

We also express energy in electron-volts (eV). 1eV is the energy required to raise an electron through 1Volt potential.

1 eV = 1.602×10^{-19} J

Photon Flux

Photon flux is defined as the number of photons per second per unit area. This determines the number of electrons generated in a solar cell, for instance.

Φ = # of photons / (time X area) $[s^{-1}m^{-2}]$

Basic properties of light

But photon flux doesnt give any information on photon energy. So power density is calculated by multiplying photon flux by the energy of a single photon.

H (W/m^2) = Φ X hc/λ Note that this is wavelength dependent.

If a red beam has the same power density as a blue beam, which beam has higher photon flux ?

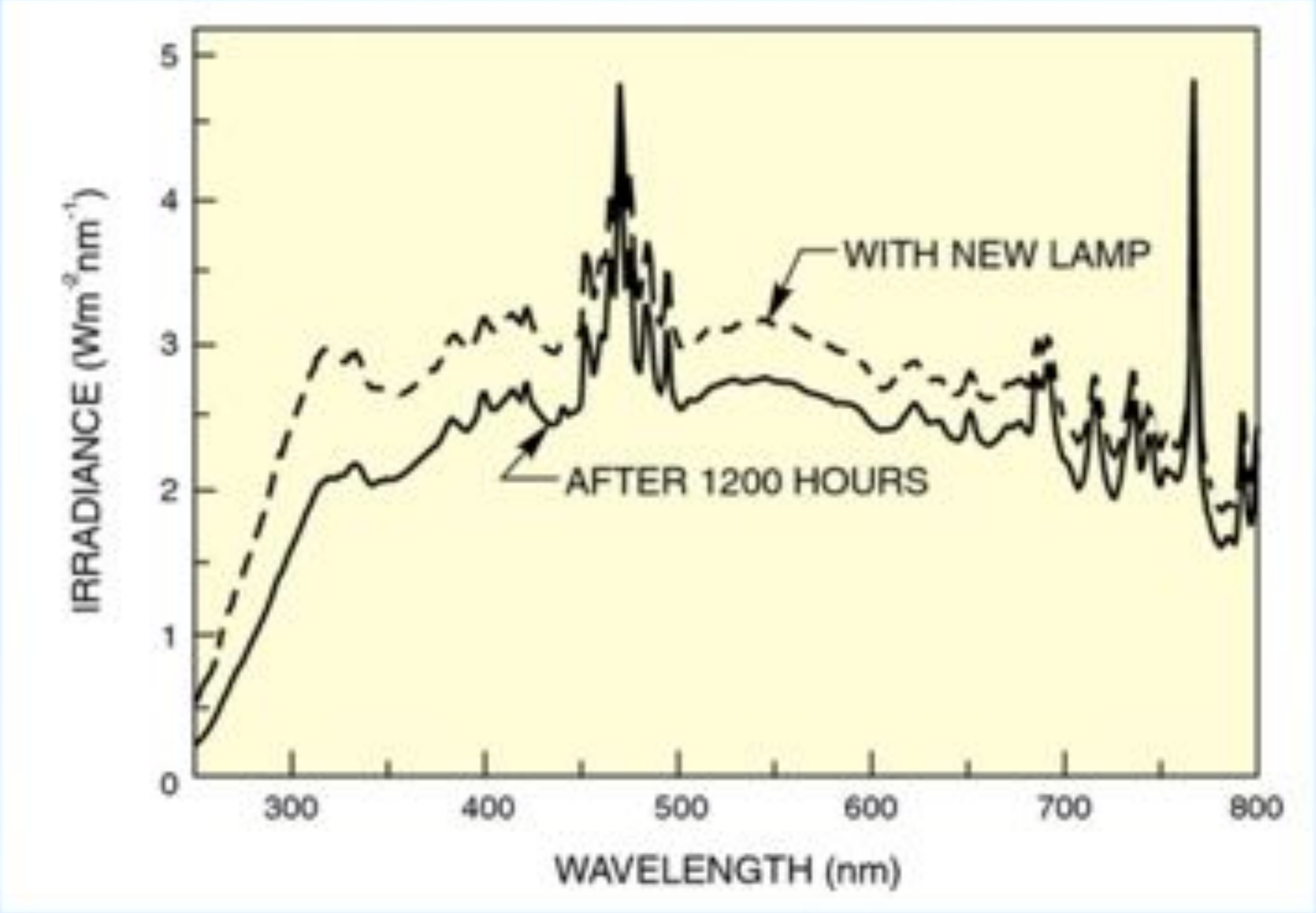
Basic properties of light

Spectral Irradiance

= power density as a function of wavelength

This is the most common way to characterize a light source.

$$F = \frac{H}{\lambda} = \phi \frac{hc}{\lambda^2}$$



Radiant Power Density

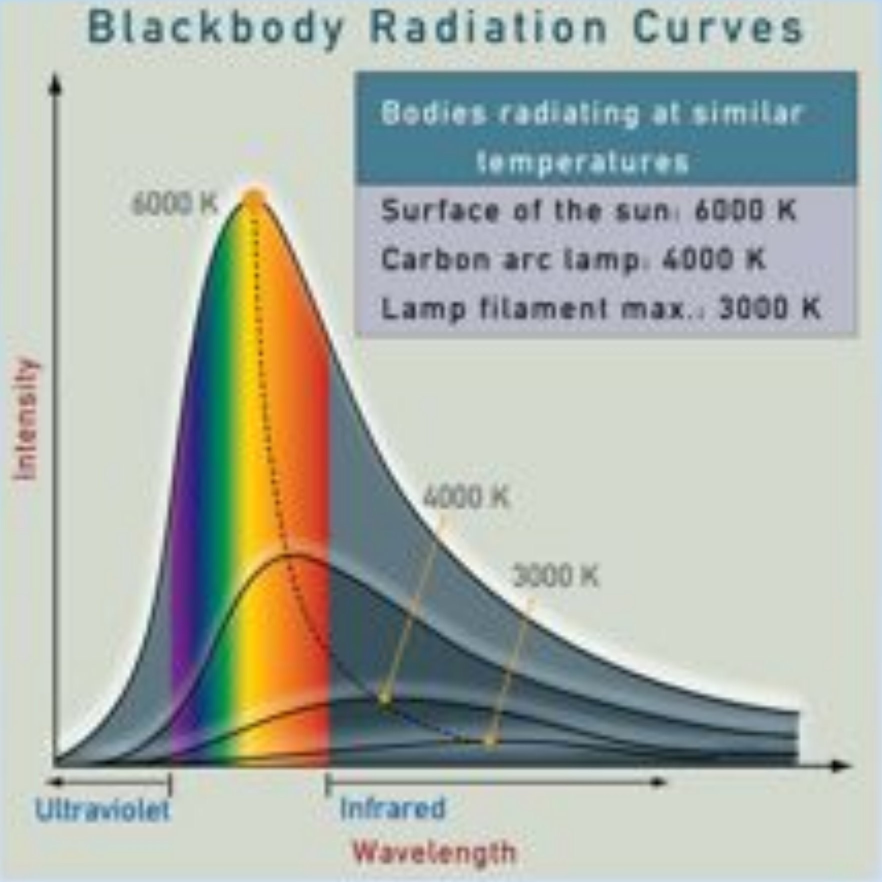
The total power density emitted from a light source can be calculated by integrating the spectral irradiance over all wavelengths of interest.

$$H = \int_0^{\infty} F(\lambda)d\lambda$$

What are the units of H ?

Blackbody Radiation

Light sources such as the sun, incadenscent lamps, etc. are modeled as blackbody emitters. An ideal blackbody absorbs all radiation incident on its surface & emits based upon its temperature.



The spectral irradiance is governed by Planck's radiation law:

$$F(\lambda) = \frac{2\pi hc^2}{\lambda^5}\left\{\frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1}\right\}$$

T = temperature of blackbody (K)

The total power density is then given by:

$$H = \int_0^\infty F(\lambda)d\lambda$$

$H = \sigma T^4$ **Stefan-Boltzmann Law**

$\sigma = 5.67 \, X \, 10^{-8} \, Js^{-1}m^{-2}K^{-4}$ **Stefan-Boltzmann Constant**

Blackbody Radiation

Another important parameter is the wavelength where spectral irradiance is maximum.

$$F(\lambda) = \frac{2\pi hc^2}{\lambda^5}\left\{\frac{1}{\exp\left(\frac{hc}{\lambda kT}\right)-1}\right\}$$

$$\frac{\partial F}{\partial \lambda} = 0$$

$$\lambda_{peak}(\mu m) = \frac{2900}{T\,(K)}$$

Wein's law.

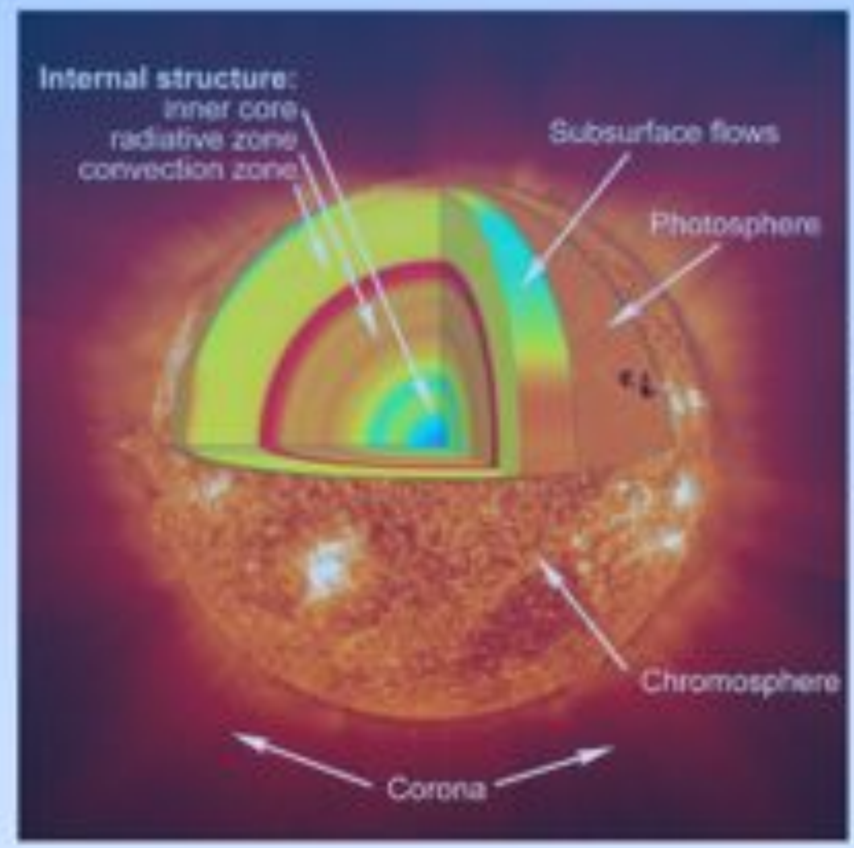
Orion Constellation

So the temperature of the blackbody affects both the spectral distribution as well as the total power density emitted.

Which star is hotter ?

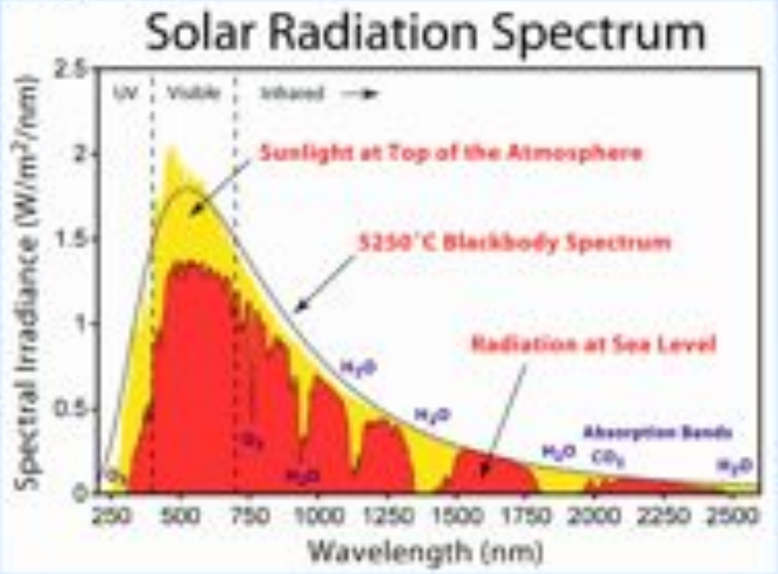
The Sun

The sun is a hot sphere, whose internal temperatures reach over 20 Million K due to nuclear reactions in its core, which convert H2 to He.

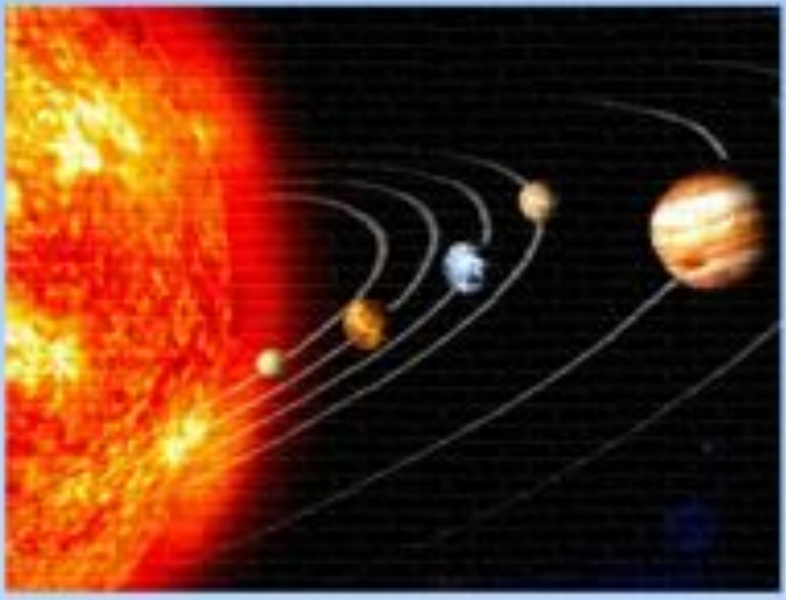


Inner core: H2 -> He (20MK)
Radiation from inner core absorbed by H ions closer to surface.
Sun's surface (photosphere) temperature is about 6000K.

Solar spectral irradiance resembles blackbody at ~6000K.
Total power emitted by the sun = power-density X surface area of sun ~ 9.5 X 10^{25} W.


Solar Radiation Spectrum

Solar Radiation in Space



Solar irradiance on an object some distance D from the sun is found by dividing the total power emitted from the sun by the surface area over which the light falls.

$$H_0 = (\sigma T^4)\,X\,\frac{4\pi R_{sun}^2}{4\pi D^2} = (\sigma T^4)\frac{R_{sun}^2}{D^2}$$

	distance	Irradiance
Venus	108×10^9 m	2611 W/m^2
Earth	150×10^9 m	1366.1 W/m^2
Pluto	5806×10^9 m	0.878 W/m^2

The actual power density changes as earth moves in its elliptical orbit & the sun's emitted power is not constant. Earth is closest to sun in January & farthest away in July.

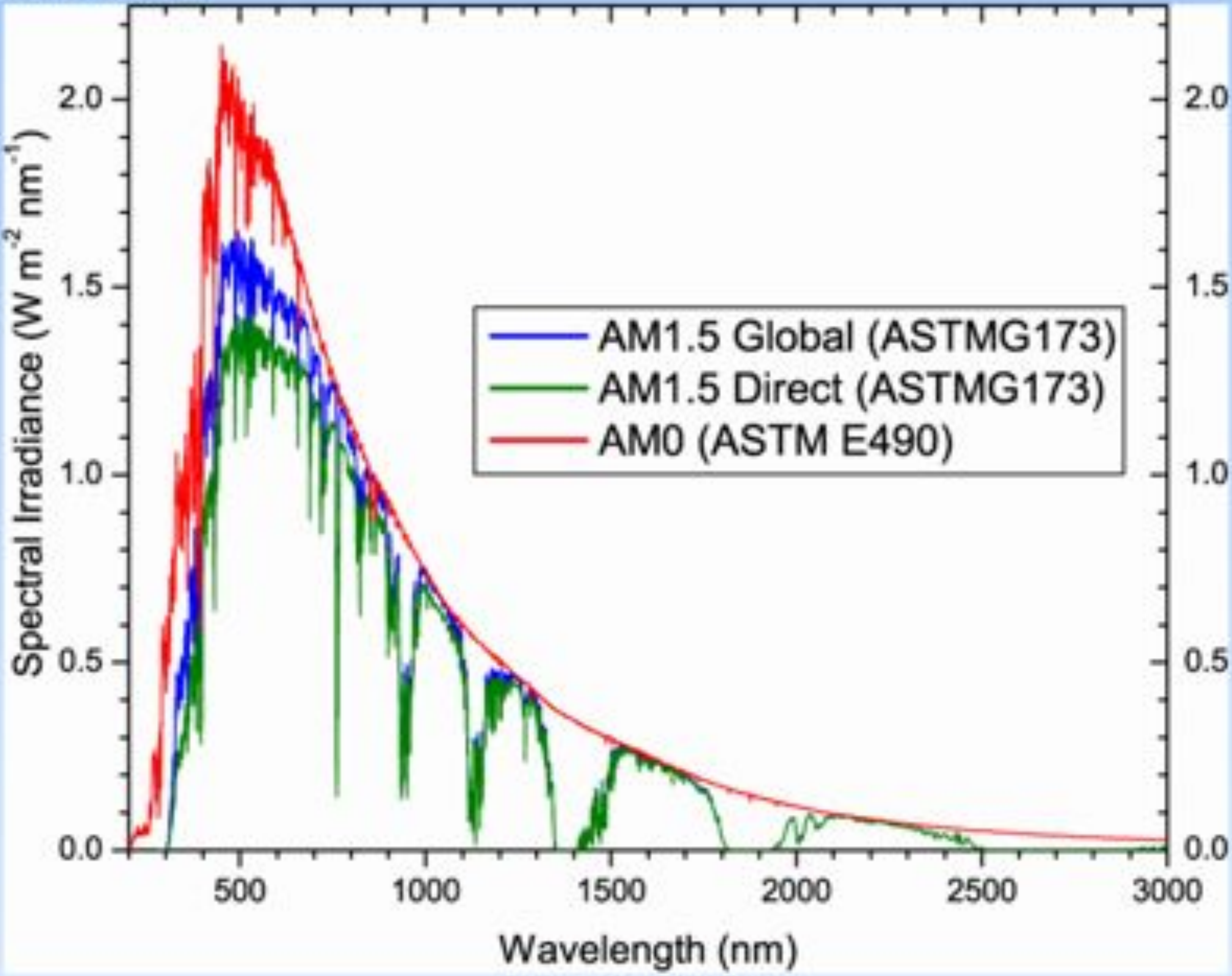
$$\frac{H}{H_{constant}} = 1 + 0.033\cos\left(\frac{360(n-2)}{365}\right.$$

$H_{constant}$ = solar constant ~ 1353 W/m^2

n = day of year

Standard Solar Spectra

These variations are small for most energy applications. Hence, standard spectra are used.



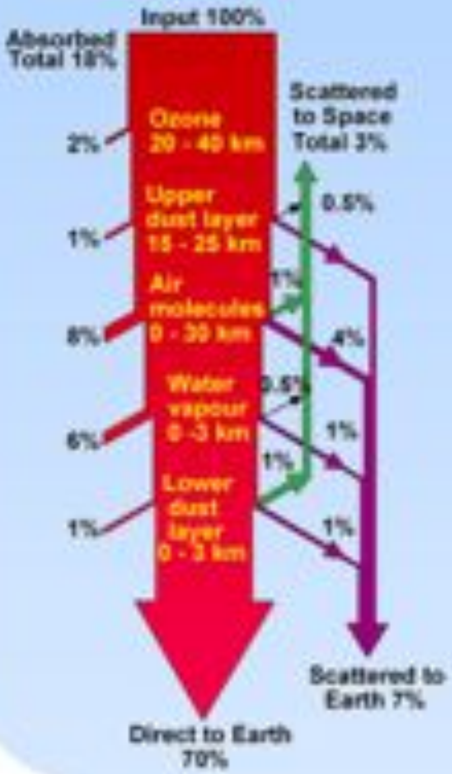
Solar radiation at earth's surface

While the solar radiation incident on earth's atmosphere is fairly constant, the radiation at the earth's surface varies widely due to:

- atmospheric effects including absorption & scattering.
- local variations in the atmosphere such as water vapor, clouds & pollution
- Latitude of location
- Season of year & time of day.

Parameters that change are: spectral irradiance, power density, angle of incidence.

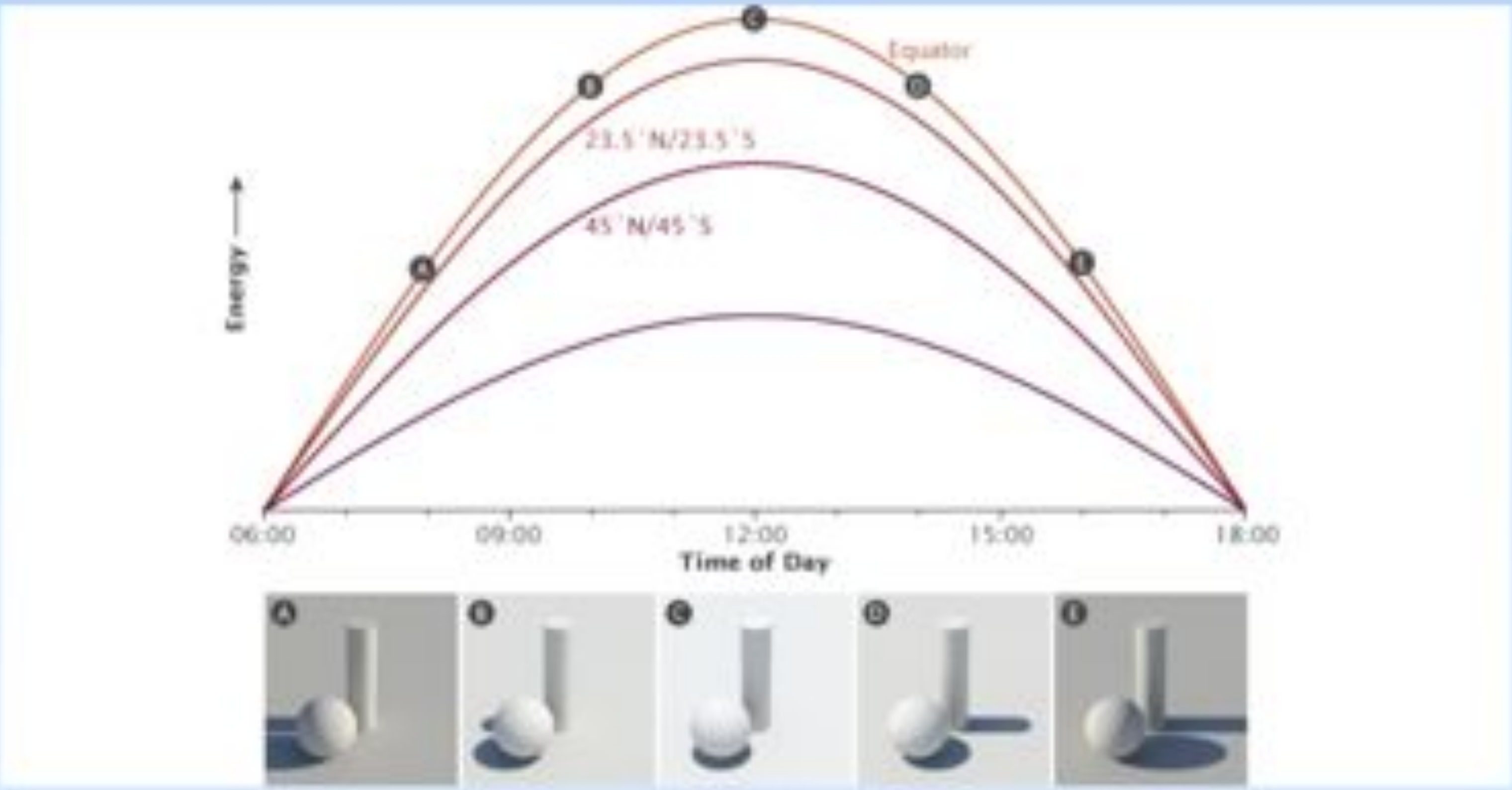
Atmospheric Effects



- Reduction in power due to scattering, absorption & reflection.
- Change in spectral content due to greater absorption &scattering at certain wavelengths.
- Introduction of diffuse or indirect component to solar radiation.
- Local variations in atmosphere, which affect total power & spectral content.

Atmospheric Effects

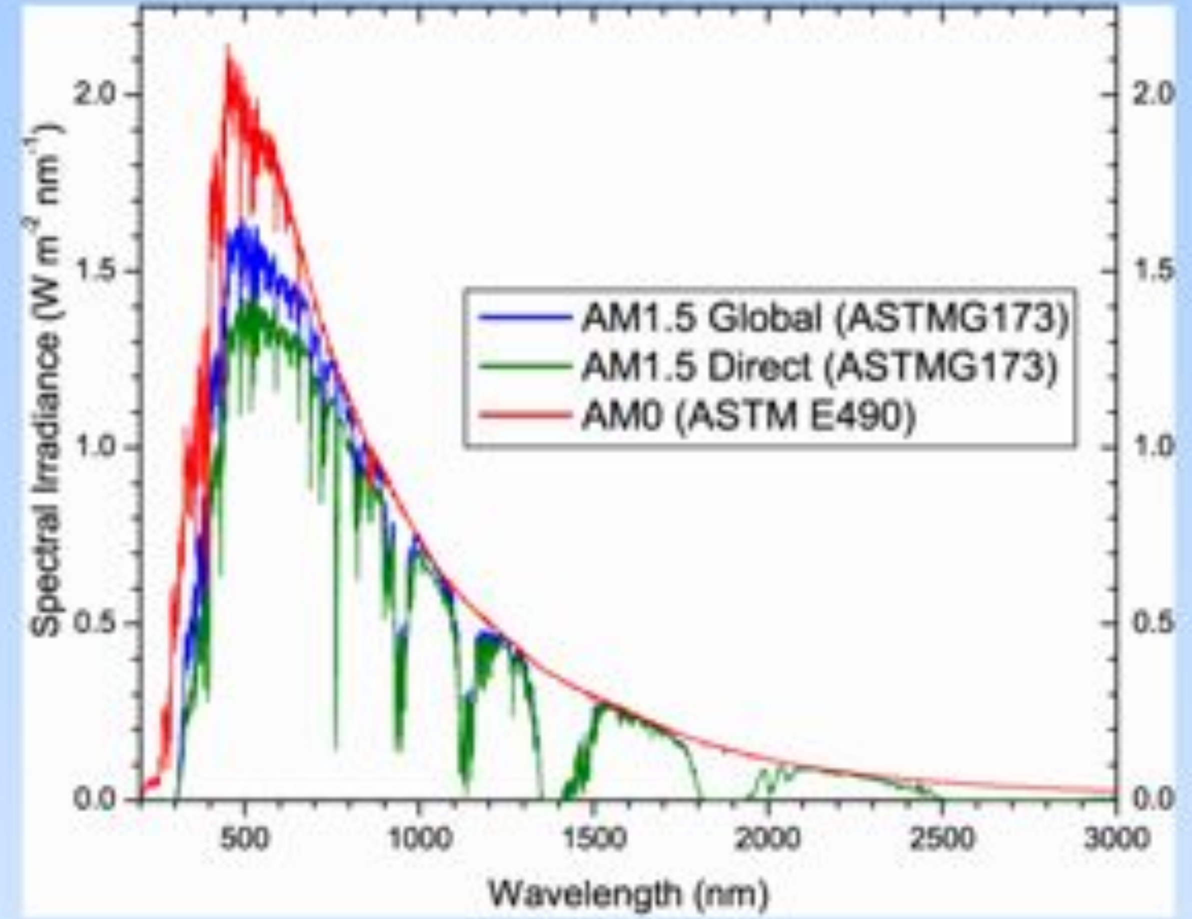
- High absorption at wavelengths where photon energies are close to te bond energies of specific gases - Ozone, CO2, water vapor.
- Most of far-IR (>2micron) is absorbed by H2O & CO2.
- Most of UV (< 300nm) is absorbed by Ozone [But not enough to prevent sunburn!]
- These cause deep troughs in spectrum.
- Dust & air molecules absorb across spectrum & reduce overall power. When sun is overhead, all wavelengths are uniformly absorbed & sun looks white. During morning & evening, the optical paths are longer & shorter wavelengths are more effectively absorbed & scattered. This gives rise to a reddish color & lower power density.



Atmospheric Effects

Direct vs Diffuse sunlight

Rayleigh Scattering -> shorter wavelengths are scattered much more than longer ones. Hence, sky looks blue. About 7-10% is diffuse on a clear day.

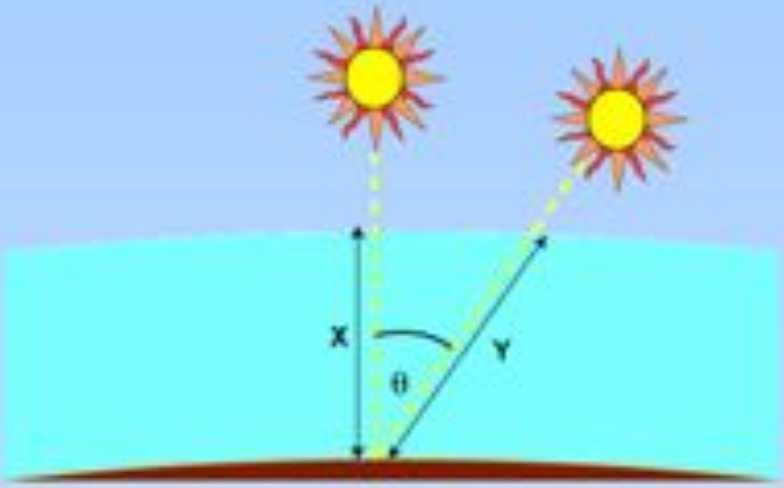


Power density in AM1.5 is about 28% less than in AM0.
Am0 is used to characterize solar cells in space.

Atmospheric Effects

Air-mass

Air mass is the path length which light takes through the atmosphere normalized to the shortest path possible (i.e., when the sun is overhead). It quantifies the reduction in power as light passes through air.



$$AM = \frac{1}{cos\theta}$$

If we take the curvature of the earth into account, a more accurate formula can be derived.

$$AM = \frac{1}{cos\theta + 0.50572(96.07995 - \theta)^{-1.6364}}$$

Direct component on a plane perpendicular to sun's rays:

$$I_d = 1.353\ X\ 0.7^{AM^{0.678}}$$

Intensity increases with height above sea level. So Utah & the desert southwest has higher solar power densities.

$$I_d = 1.353\ X\ (\ (1 - 3.14h)0.7^{AM^{0.678}} + 3.14h\ )$$ h = height above sea level (km)

Even on clear (cloudless) days, the diffuse component in 10% of the direct portion.

Project Teams

Solar Refrigeration/Air conditioning
Xiaoyu Wei, Ryan Snowball, Tyler Hafen.

Solar Desalination (and pasteurization if interested)
Na Wu, Rob Shapper, Dan Jacobs.

Solar-thermal applications (heating, hot-water, greenhouses, etc.)
Jacob Soto, Farhana Masid, Apratim Majumder, Faisal K.C.

Photovoltaics (could be concentrated PV, other approaches)
Jinqi Wang, Xiaowei Wan, Erik Johnson.

Hybrid systems (combining different technologies, system level).
Trevor Dick, Ben Bunes, Zongzhi Hu, Nelson Berhold.

Course Schedule

Tentative Schedule for ECE 5962/6961 Optics for Energy. Fall 2012

8/21	Week #1 Tuesday	Overview of course; Intro to project topics
8/23	Week #1 Thursday	Introduction to project topics
8/28	Week #2 Tuesday	Solar Radiation: The basics
8/30	Week #2 Thursday	Thermodynamics of solar heating & cooking
9/4	Week #3 Tuesday	Introduction to Geometrical Optics
9/6	Week #3 Thursday	Optical design for recycling
9/11	Week #4 Tuesday	Lagrangian & Hamiltonian Optics
9/13	Week #4 Thursday	Rays & Wavefronts [Literature reviews due]
9/18	Week #5 Tuesday	Light tools optical design software tutorial (Guest lecture: Dr. Mohit Diwekar)
9/20	Week #5 Thursday	Technology Commercialization (Guest lecture: Frank Norris, TCO UofU)
9/25	Week #6 Tuesday	[No Class]
9/27	Week #6 Thursday	Reflection & Refraction
10/2	Week #7 Tuesday	Symmetry
10/4	Week #7 Thursday	Etendue in phase space [Your idea section due]
10/9, 10/11	Week#8	Fall Break