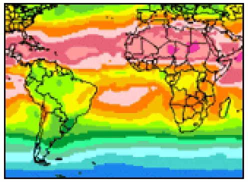

SECOND YEAR: 2604
PLANETARY REMOTE SENSING 2

ELECTROMAGNETIC *RADIATION*

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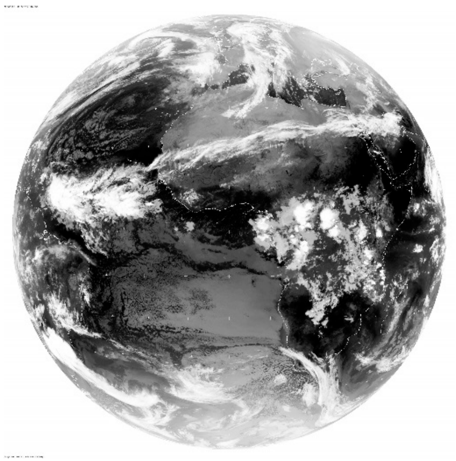
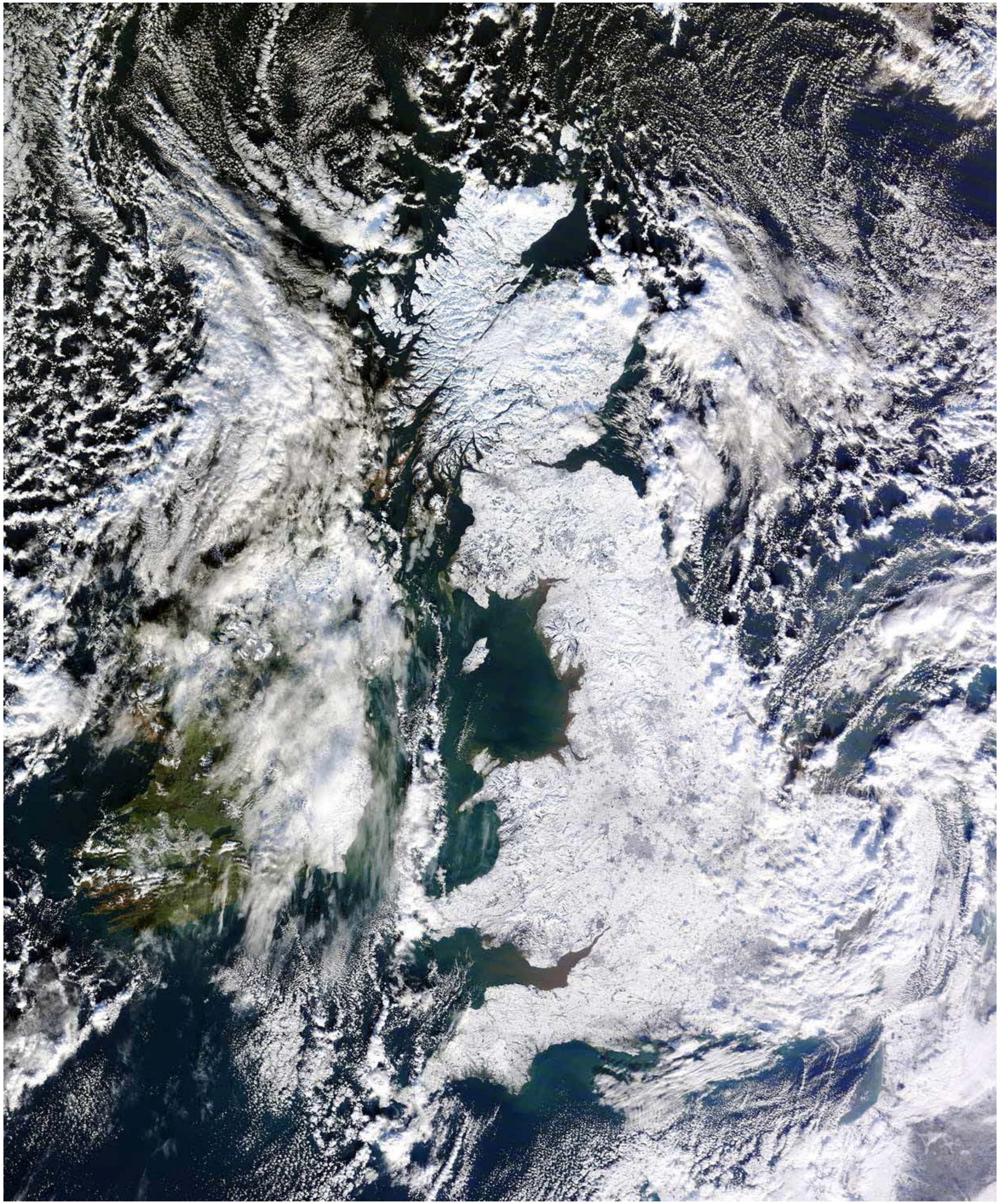
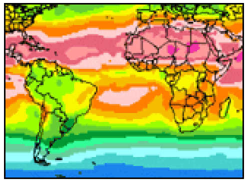
http://www2.le.ac.uk/departments/physics/research/earth-observation-science







Applications of remote sensing in planetary science

Land (snow cover, soil moisture, crop yield, floods/earthquake)

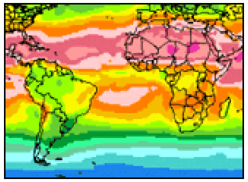
Sea (level, temperature, sea-ice, Phytoplankton, winds)

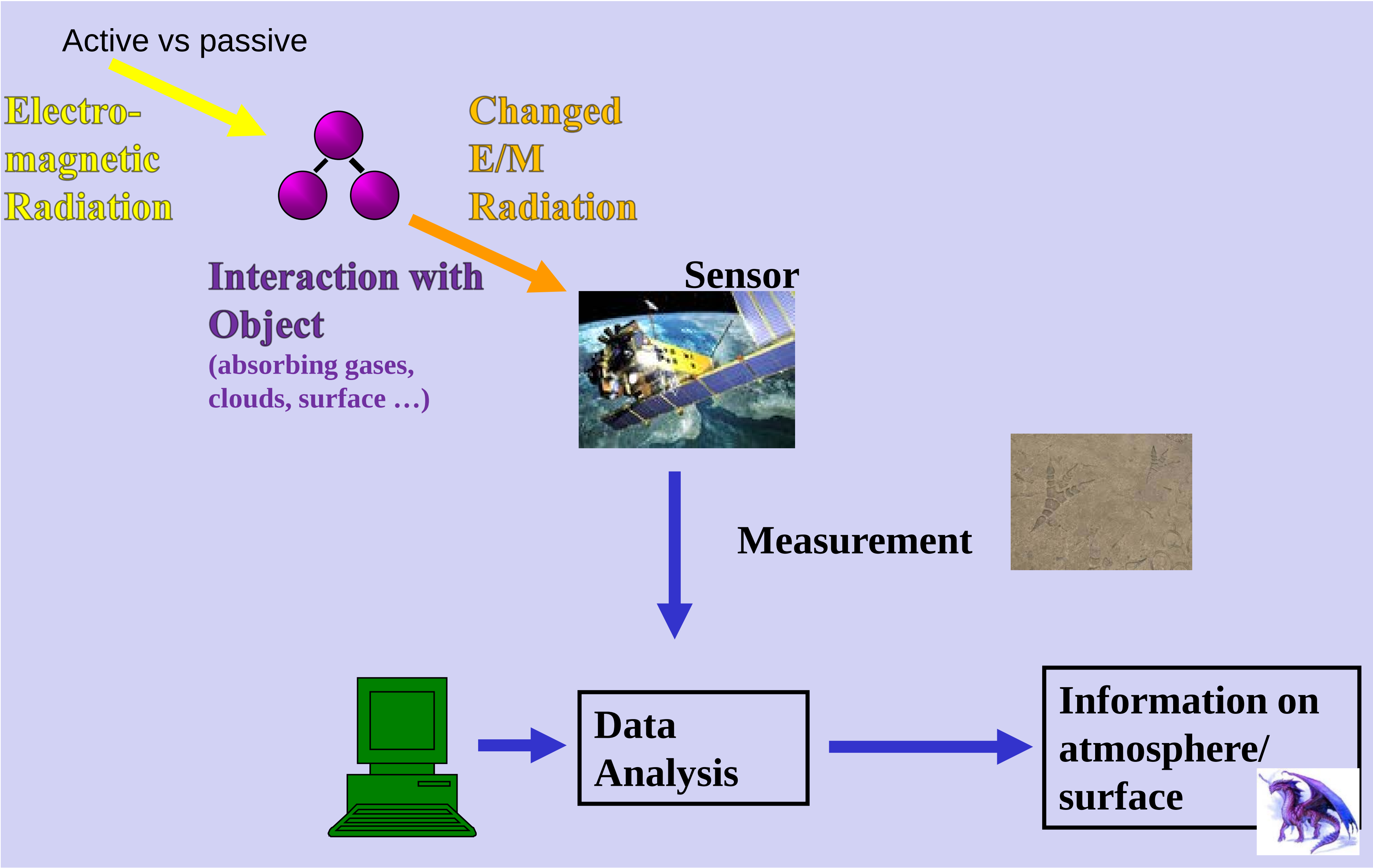
Atmosphere (composition, cloud cover, rainfall, winds)

Good textbooks (available in the university library) :

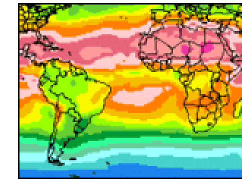
G.W. Petty – A first introduction in atmospheric radiation

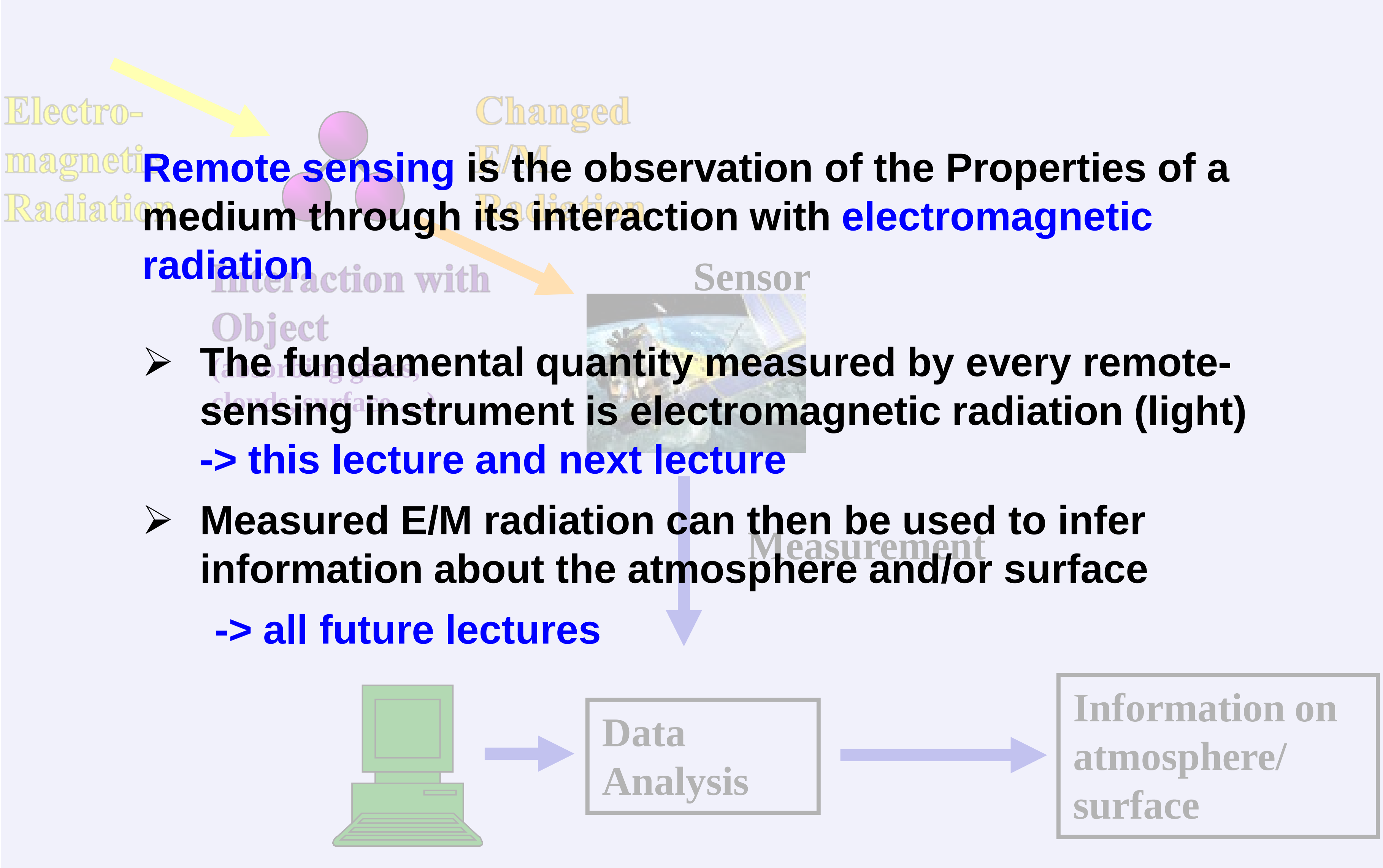
Principle of Remote Sensing Observations





Principle of Remote Sensing Observations



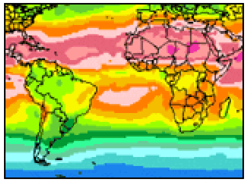


Remote sensing is the observation of the Properties of a medium through its interaction with electromagnetic radiation

- The fundamental quantity measured by every remote-sensing instrument is electromagnetic radiation (light) -> this lecture and next lecture
- Measured E/M radiation can then be used to infer information about the atmosphere and/or surface

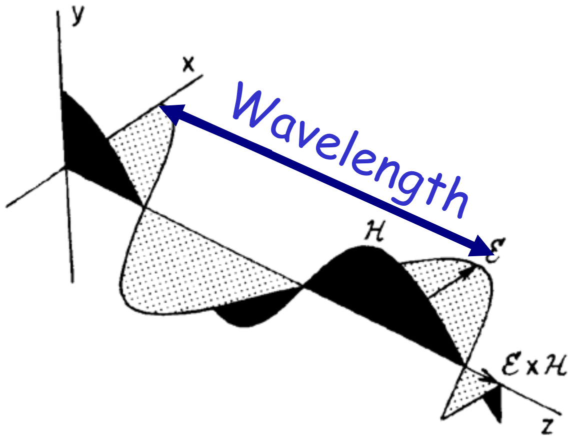
  -> all future lectures

Electro-Magnetic Radiation: Basic Properties



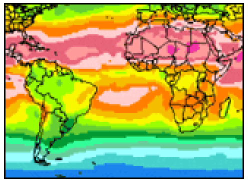
- EM radiation is created via mutual oscillations of electric E and magnetic fields *H*
- Direction of propagation of an EM wave is orthogonal to direction of oscillations
- EM waves travel at the speed of light: $c = c_0/n$, where n is refractive index of medium. Refractive index is a complex number in absorbing material

- Oscillations can be described in terms of:
  - wavelength (λ): distance between individual peaks in the oscillation
  - frequency (ν): number of oscillations per second $\lambda\nu=c/n$
  - wavenumber ($\tilde{\nu}= 1/ \lambda$): number of wave crests (or troughs) per length
  - Wavelength, (frequency) and wavenumber are often used interchangeably



See PA2240 (Electromagnetic fields)

Electro-Magnetic Radiation: Basic Properties

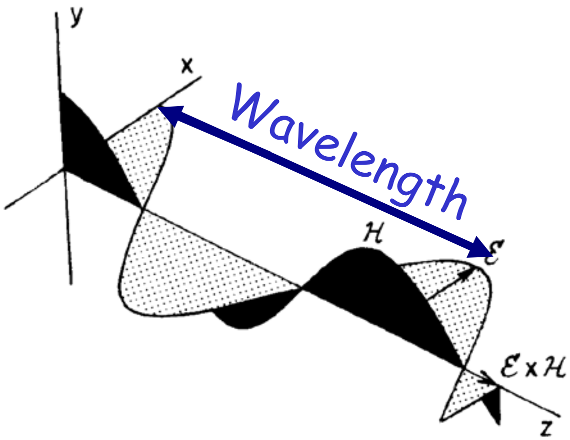


Three basic properties describe EM radiation:

1) ***Frequency*** **determines how radiation interacts with matter.**

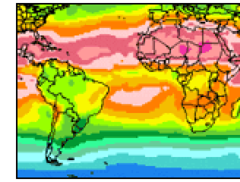
2) ***Amplitude*** **E_o directly defines the amount of energy carried by an EM wave**

3) ***Polarization*** **defines orientation of oscillation – which can affect way radiation interacts with matter (e.g. Fresnel laws)**

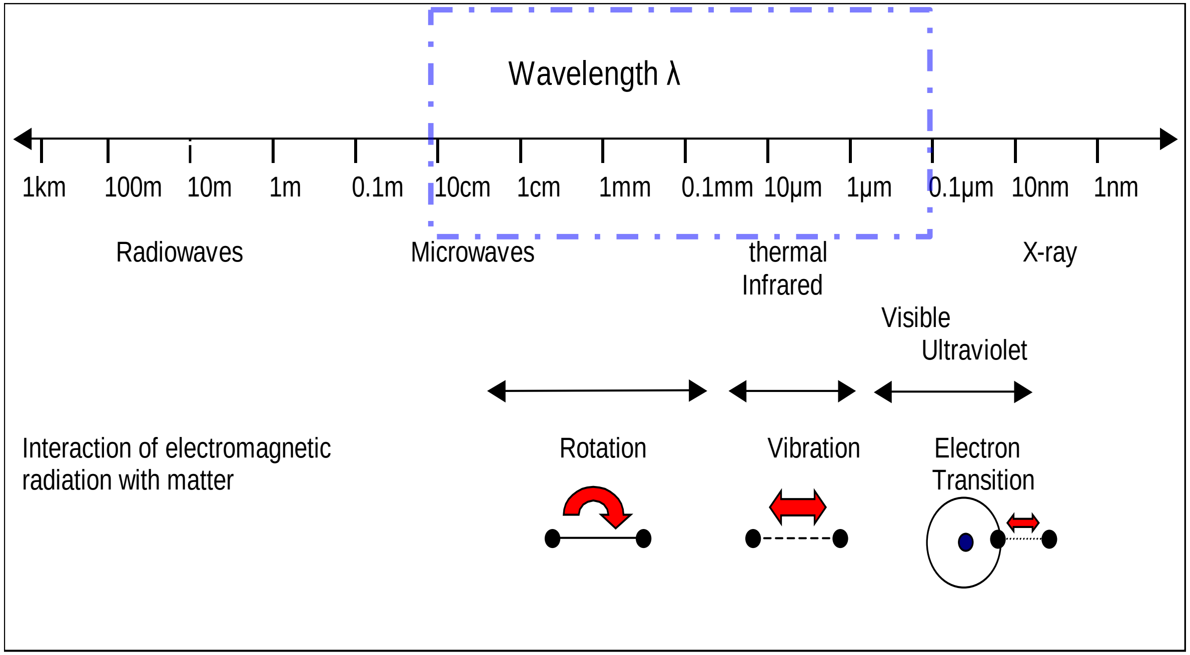


For the purposes of this course, we are interested primarily in energy carried by EM radiation, how it is affected by interactions with matter, and how those interactions vary spectrally (as a function of wavelength).

Electromagnetic spectrum



Highest Energy



Lowest Energy

The energy of a photon is determined by frequency ν:

$$E = h\nu = h\frac{c}{\lambda}$$

c: speed of light

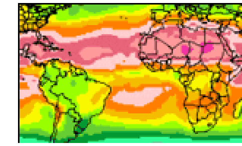
h: Planck constant

- **UV/Vis and near-IR:** **Electronic and vibrational transitions**
- **Thermal IR:** **Vibrational transitions**
- **Microwaves:** **Rotational transitions**

Usually a combination of the different transition types occur

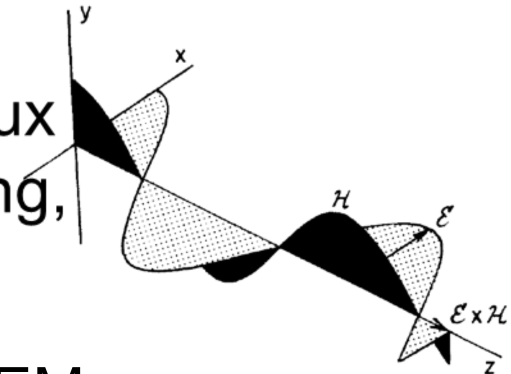
Rule of thumb: fast oscillations (e.g., UV wavelengths) affect smallest matter (e.g. electrons), while slow oscillations (IR and microwave affect larger more massive parts of matter (molecules,…).

Radiation Quantities: flux (irradiance)



The Poynting Vector

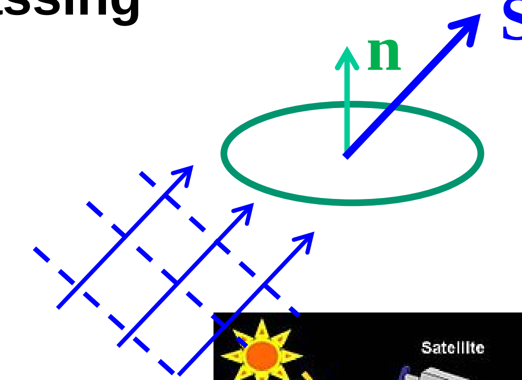
$\vec{S} = \vec{E} \times \vec{H}$ is the instantaneous energy flux density (Wm^{-2}) of an EM wave (John Pointing, 1852-1914).



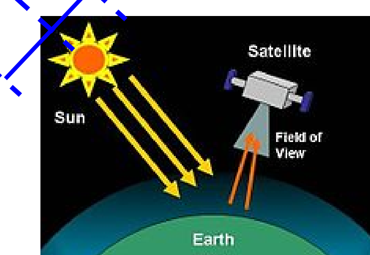
If we build the average over one cycle of an EM wave, we find

$$\langle \vec{S} \rangle = \langle \vec{E} \times \vec{H} \rangle = \frac{1}{2} c \varepsilon_o E^2 \propto |E|^2$$

Irradiance (flux): Energy flow (Radiant Flux) passing through an area identified by a normal $\hat{n}$

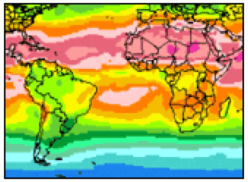


$$F(\vec{r}, \hat{n}) = \left\langle \vec{S} \right\rangle \bullet \hat{n}$$



N.B. It is only meaningful to talk of flux relative to a surface with an orientation➔ in Earth science most of our interest is in horizontal surfaces (n is either the zenith or nadir)

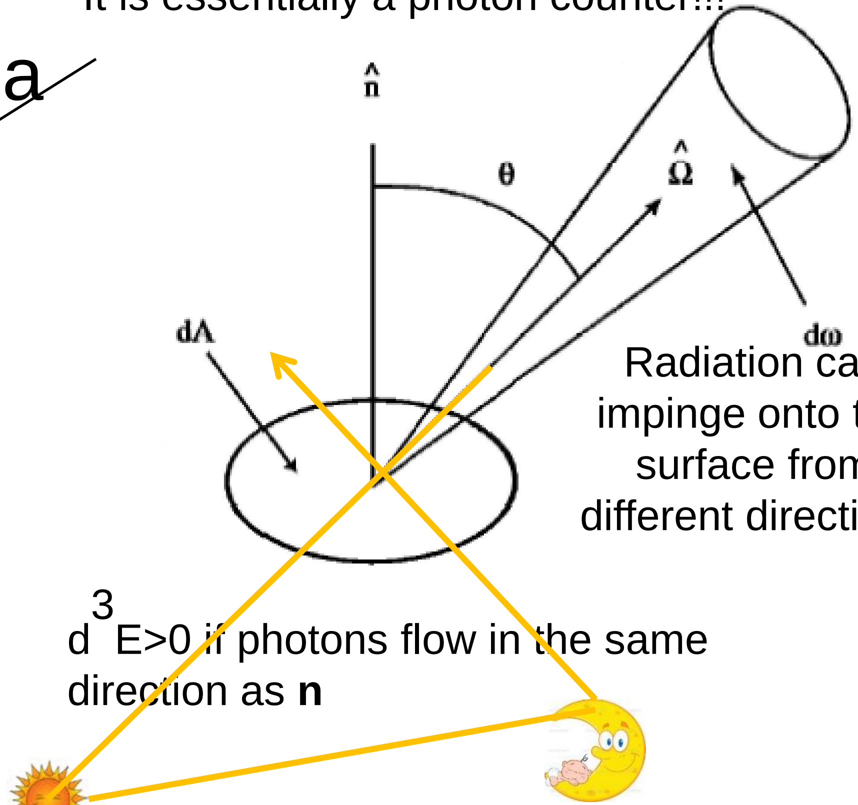
Spectral radiative Flux / Irradiance



- Net rate of radiative flow of energy (power) per unit area within a small spectral interval $d\lambda$ is called the ***spectral net flux***

$$F_\lambda(\vec{r},\hat{n}) = \frac{d^3E}{dA\,dt\,d\lambda}\left(W\,m^{-2}\,\mu m^{-1}\right)$$

It is essentially a photon counter!!!



Radiation can impinge onto the surface from different directions

$d^3E>0$ if photons flow in the same direction as **n**

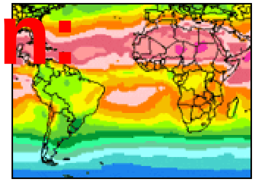
Flux is positive if energy is mainly flowing upward
Flux is negative if energy is mainly flowing downpward

Summing over all frequencies we obtain **the net flux or net irradiance**

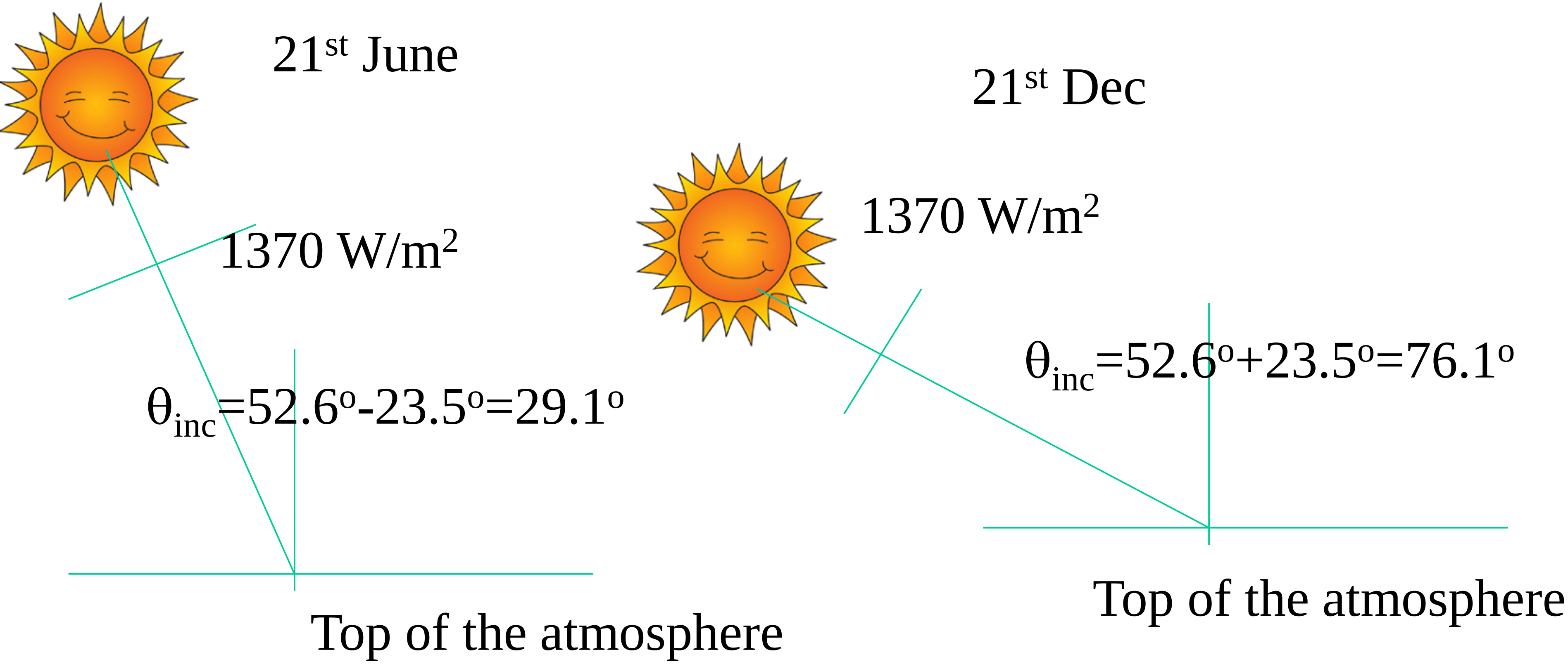
$$F = \int_0^\infty d\lambda\, F_\lambda \quad \left[\frac{W}{m^2}\right]$$

How much radiation is impinging at Top Of Atmosphere? ➔Sun ‘constant’
How is it spectrally distributed? Sun spectrum

Sun flux over Leicester at local noon: (21st Dec vs 21 June)



Leicester latitude: 52.6 N

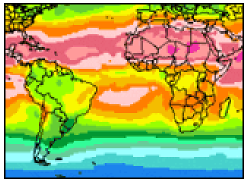


$$F = 1370 \times \cos\left(\theta_{inc}\right) = 1205\ W/m^2$$

$$F = 1370 \times \cos\left(\theta_{inc}\right) = 331\ W/m^2$$

Fluxes do not describe thoroughly the radiation field ➔ need to account for direction in space

Polar coordinate system



Direction plays an important role for radiation

Spherical coordinates are usually used to describe direction

- **The distance of the point from the origin, r**
- **The angle between $\vec{r}$ and z (zenith angle)**
- **The angle between $\hat{x}$ and the projection of $\vec{r}$ in the xy plane (azimuth angle)**

Direction vector ξ is a unit vector given by

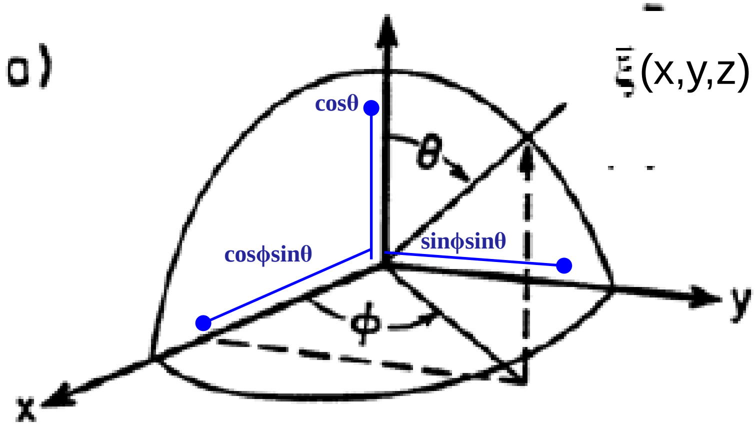
$$\vec{\xi} = \frac{\vec{r}}{|\vec{r}|} = \frac{(x, y, z)}{(x^2 + y^2 + z^2)^{1/2}}$$

$$x = \vec{\xi} \bullet \hat{\vec{x}} = \cos\phi \sin\theta$$

$$y = \vec{\xi} \bullet \hat{\vec{y}} = \sin\phi \sin\theta$$

$$z = \vec{\xi} \bullet \hat{\vec{z}} = \cos\theta = \mu$$

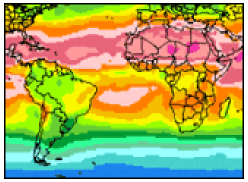
or $\vec{\xi} = (\cos\phi \sin\theta, \sin\phi \sin\theta, \cos\theta)$



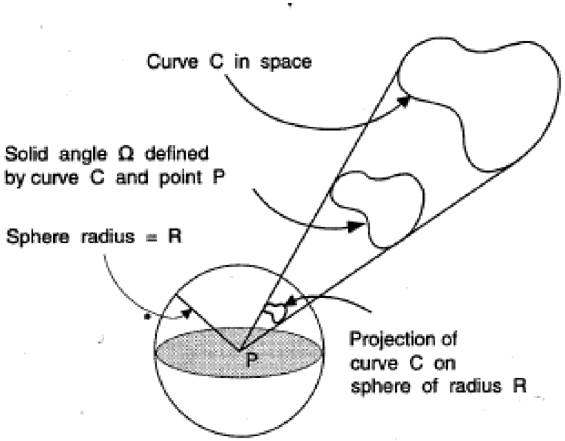
Azimuth angle φ: 0 < φ < 2π

Zenith angle θ: 0< θ < π

Solid Angle



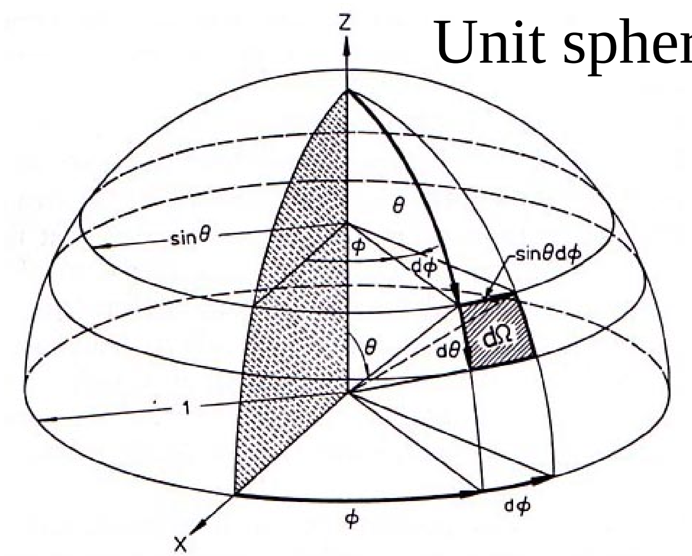
We often want to characterize the radiation from a direction of from a small cone of directions



Now consider a unit sphere (radius r = 1). Solid angle is the area subtended by an object on this sphere as viewed from its origin

Definition of infinitesimal solid angle element:

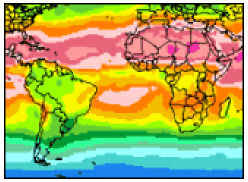
$$d\Omega = d\phi \sin\theta \, d\theta = \frac{r\,d\theta\, r\sin\theta\, d\phi}{r^2} = \frac{A}{r^2}$$



Units of Solid Angle: steradian (sr)

Solid angle is to angle what area is to length

Hemispheric Integrals

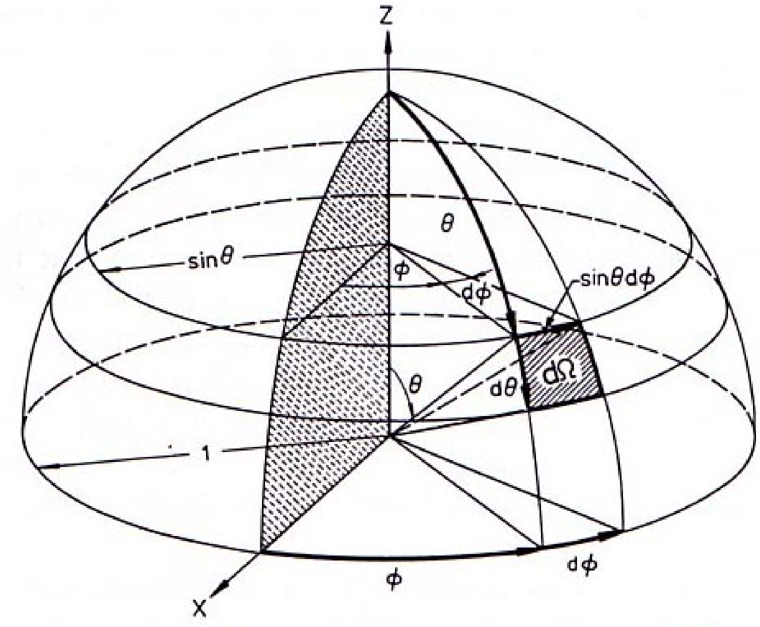


We can use the definition of the differential solid angle ($d\Omega = \sin\theta\, d\theta\, d\phi$) to compute the value of solid angle of a hemisphere, or of an entire sphere.

For a hemisphere:

$$\Omega(hemisphere) = \int_{\Omega(hemisphere)} d\Omega$$

$$\Omega(hemisphere) = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} \sin\theta d\theta d\phi$$

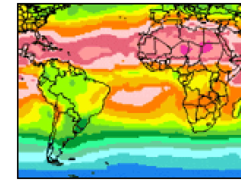


Hemisphere:

Azimuth angle ϕ: $0 < \phi < 2\pi$

Zenith angle θ: $0 < \theta < \pi/2$

Hemispheric Integrals



For a hemisphere:

$$\Omega(hemisphere) = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} \sin\theta d\theta d\phi = 2\pi\left[-\cos\theta\right]_0^{\pi/2} = 2\pi\left(1-0\right) = 2\pi$$

(**which is simply the surface area of a hemisphere (A = $4\pi r^2/2 = 2\pi r^2$) for a unit sphere)**

And for a sphere:

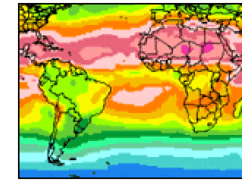
$$\Omega(sphere) = \int_{\phi=0}^{2\pi} \int_{\theta=-\pi/2}^{\pi/2} \sin\theta d\theta d\phi = 2\pi\left[-\cos\theta\right]_{-\pi/2}^{\pi/2} = 2\pi\left(1+1\right) = 4\pi$$

(which is simply the surface area of a unit sphere (A = $4\pi r^2$))

$$\boxed{0 \le \Omega \le 4\,\pi}$$

THIS IS THE RANGE OF POSSIBLE VALUES

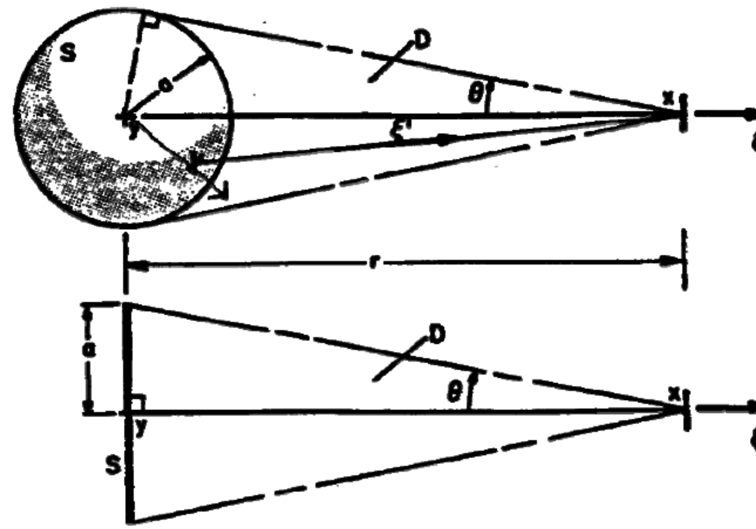
Solid Angle subtended by Sphere



Solid angle of a spherical cap

$$\Omega = \int_0^{\theta^*} \sin\theta d\theta \int_0^{2\pi} d\phi$$

$$D\sin(\theta^*) = a$$



$$\Omega = 2\pi \int_0^{\theta^*} \sin\theta d\theta$$

$$\Omega = 2\pi(1 - \cos\theta^*)$$

Small cap assumption: cosθ = 1 – θ²/2 + …

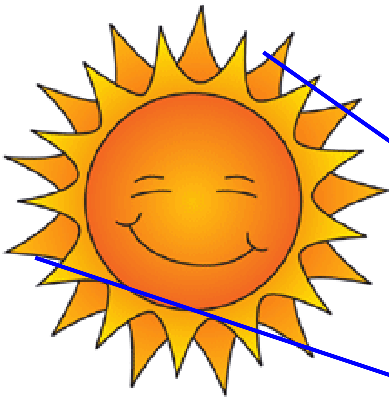
$$\Omega \approx \pi(\theta^*)^2$$

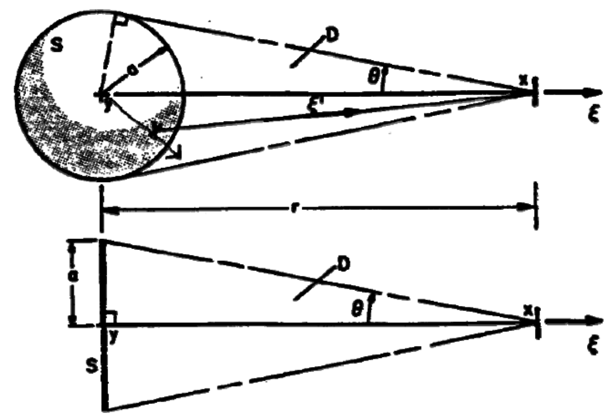
$$\theta^* \approx \frac{a}{D} \quad for \quad small \quad \theta^*$$

$$\Omega \approx \pi\left(\frac{a}{D}\right)^2 = \frac{A}{D^2}$$

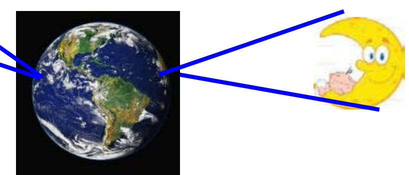
A is cross-sectional area

Solid Angle subtended by Sun and Moon





$$\Omega \approx \pi \left(\frac{a}{D} \right)^2$$



r_{sun} = 7x10^{5}km

D_{sun} = 1.5x10^{8}km

Ω_{sun} = π (r_{sun}/D_{sun})^2 = π (7x10^{5}km/1.5x10^{8}km)^2 = 6.8x10^{-5} sr

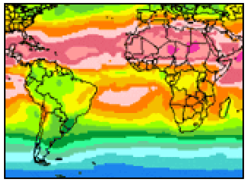
r_{moon} = 1.7x10^{3}km

D_{moon} = 3.8x10^{5}km

Ω_{moon} = π (r_{moon}/$D_{moon-earth}$)^2 = π (1.7x10^{3}km/3.8x10^{5}km)^2 = 6.5x10^{-5} sr

Solar eclipses are possible (except for crown)

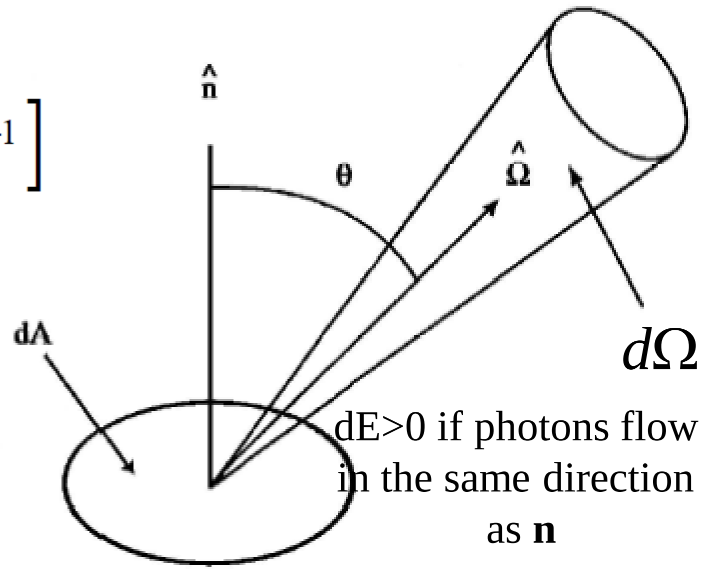
Spectral Radiance or Intensity



Spectral Radiance (spectral intensity):

d^4E=Energy passing through a surface dA from a small cone of directions defined by dΩ from direction Ω over a small increment of wavelengths λ

$$I_\lambda(\vec{r},\hat{\Omega}) = \frac{d^4E}{\underbrace{\cos\theta\, dA}_{\text{surface orthogonal to }\Omega}\, dt\, d\Omega\, d\lambda}\left[W\, m^{-2}\ sr^{-1}\, \mu m^{-1}\right]$$



In contrast to flux *F*, intensity *I* takes into account direction and is independent on n (i.e. on surface orientation)

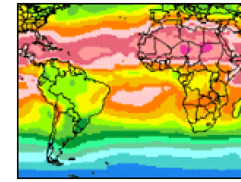
N.B.

$$\cos\theta = \hat{n}\bullet\hat{\Omega} > 0 \Rightarrow d^4E > 0$$

$$\cos\theta = \hat{n}\bullet\hat{\Omega} < 0 \Rightarrow d^4E < 0$$

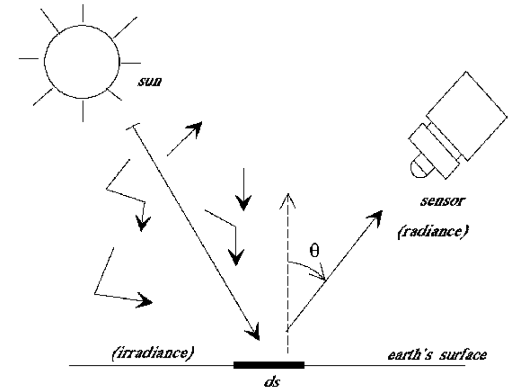
Intensity is always positive!!

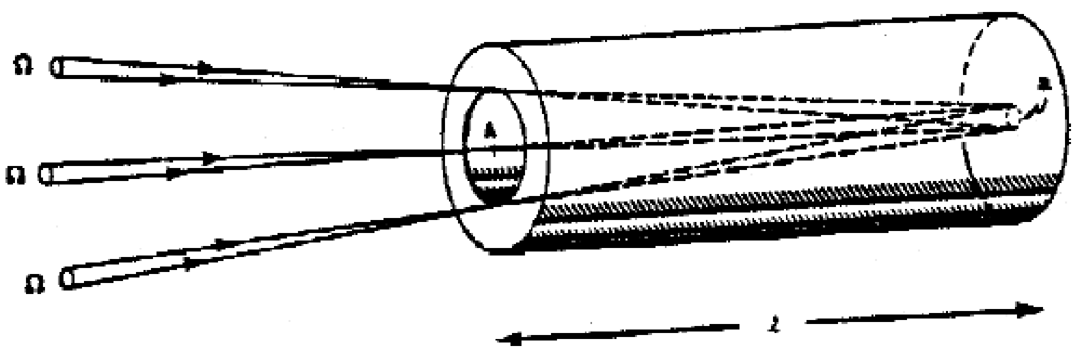
Spectral Radiance intensity



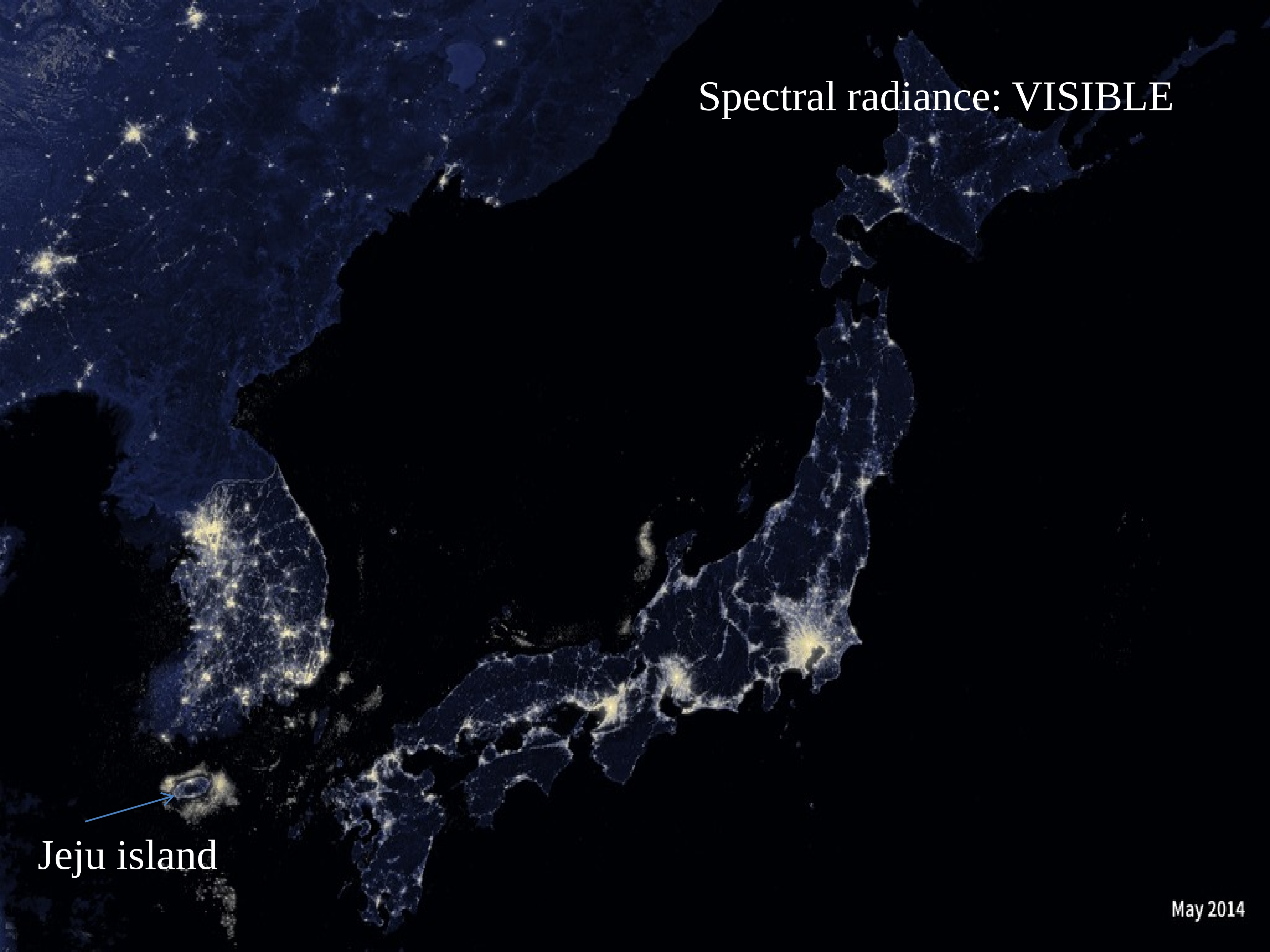
Radiance or intensity is the fundamental quantity since we can ***measure it*** **and all other relevant parameters of interest (e.g. fluxes) derive from it.**

$$I_\lambda(\vec{r},\hat{\Omega}) = \frac{d^4E}{\cos\theta\, dA\, dt\, d\Omega\, d\lambda}\left[W\, m^{-2}\ sr^{-1}\, \mu m^{-1}\right]$$





With collimators we make sure to receive radiation only from a small solid angle **dΩ=A/l²** centred around a given direction


Spectral radiance: VISIBLE
Jeju island
May 2014

Under new moon conditions

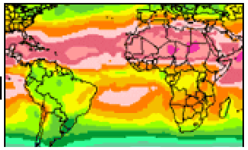
5 days of GERB data from MSG

Broad band Flux: TOTAL

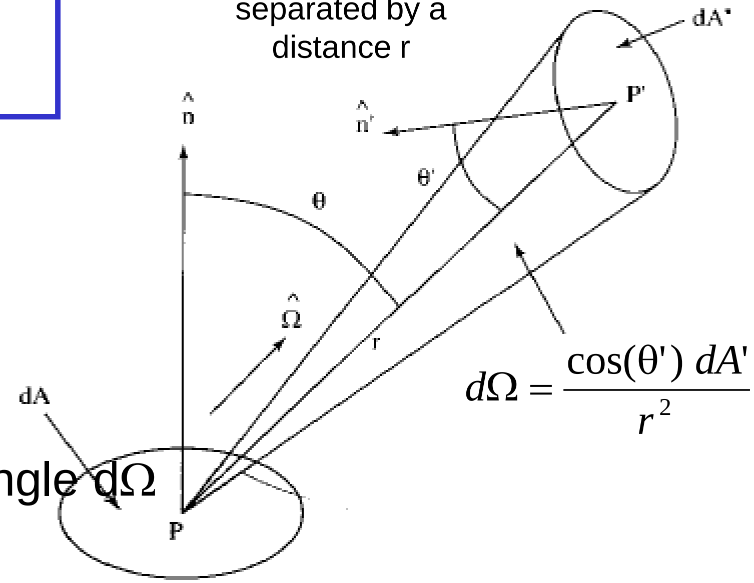
Broad band Flux: VISIBLE

Theorem:
In a **transparent medium**, the ***radiance is constant along a ray***.

$$I\,(P,\hat{\Omega}) = I\,(P',\hat{\Omega})$$



Arbitrarily oriented surface elements separated by a distance r



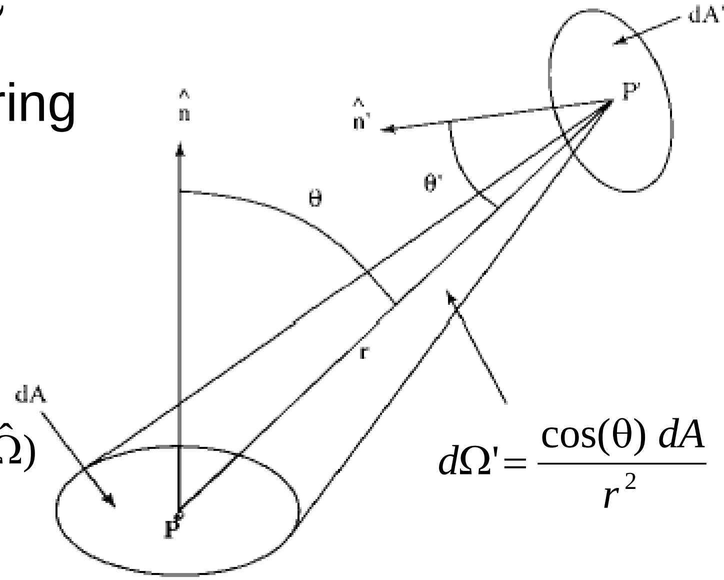
$$d\Omega = \frac{\cos(\theta')\, dA'}{r^2}$$

Energy crossing dA in time dt and entering the solid angle dΩ

$$d^4E = I_\lambda\,(P,\hat{\Omega})\,\cos(\theta)\; dA\; d\Omega\; dt\; d\lambda$$

=Energy passing through dA' in time dt and entering the solid angle dΩ' (subtended by dA)

$$d^4E = I_\lambda\,(P',\hat{\Omega})\,\cos(\theta')\; dA'\; d\Omega'\; dt\; d\lambda$$

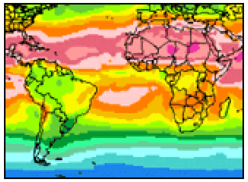


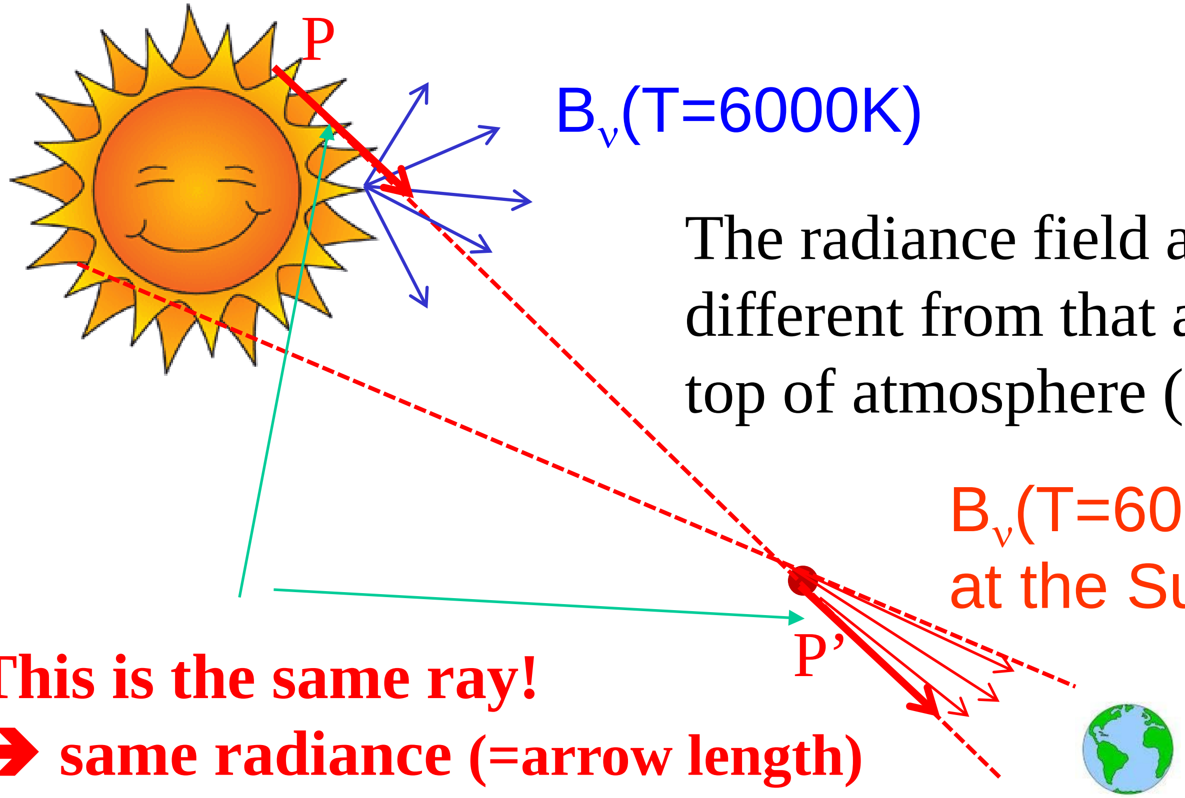
$$d\Omega' = \frac{\cos(\theta)\, dA}{r^2}$$

$$I_\lambda\,(P,\hat{\Omega}) = \frac{d^4E}{\cos(\theta)\; dA\; d\Omega\; dt\; d\nu} = \frac{I_\lambda\,(P',\hat{\Omega})\,\cos(\theta')\; dA'\; d\Omega'}{\cos(\theta)\; dA\; d\Omega} = I_\lambda\,(P',\hat{\Omega})$$

N.B. The intensity remains constant along a ray upon reflection by any mirror

Radiation coming from the sun





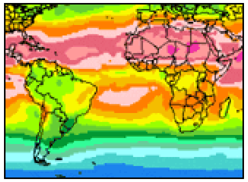
The radiance field at the Sun's surface is different from that at Earth's top of atmosphere (TOA)

B_ν(T=6000K) i.e. same value as at the Sun surface

This is the same ray!
➔ same radiance (=arrow length)

At Sun's surface➔ the field is isotropic in the upward hemisphere
At TOA➔the field is very collimated
(inside the atmosphere the radiation field is more diffuse, why?).

Relation between Flux and Intensity

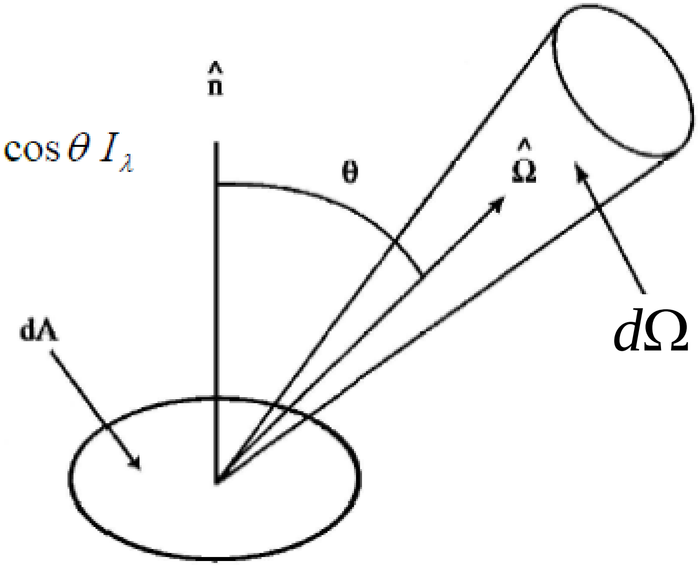


The spectral flux flowing into the NH is given by

$$F_\lambda^{\uparrow} = \frac{d^3E^{\uparrow}}{dAdtd\lambda} = \int_{Northern\ Hemisphere} \underbrace{\frac{d^4E}{\cos\theta\, dA\, dt\, d\Omega\, d\lambda}}_{I_\lambda(\hat{\Omega})} \cos\theta\, d\Omega = \int_{NH} d\Omega \cos\theta\, I_\lambda$$

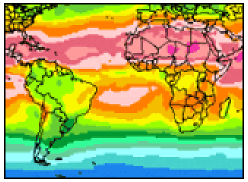
$$F_\lambda^{\downarrow} = \frac{d^3E^{\downarrow}}{dAdtd\lambda} = \int_{Southern\ Hemisphere} -\underbrace{\frac{d^4E^{\downarrow}}{\cos\theta\, dA\, dt\, d\Omega\, d\lambda}}_{I_\lambda(\hat{\Omega})} \cos\theta\, d\Omega = -\int_{SH} d\Omega \cos\theta\, I_\lambda$$

$$\boxed{F_\lambda(\vec{r},\hat{n}) = F_\lambda^{\uparrow} - F_\lambda^{\downarrow} = \int_{4\pi} d\Omega \cos\theta\, I_\lambda(\vec{r},\hat{\Omega}) \quad \left[W\, m^{-2}\, Hz^{-1}\right]}$$



Given I_λ you can compute F (but not viceversa)!

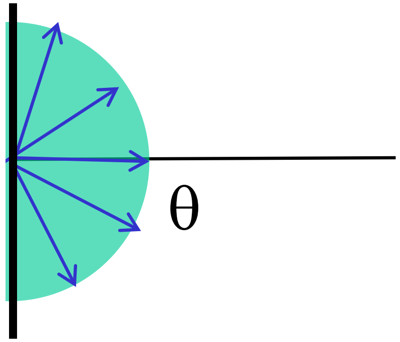
Example 1: isotropic Distribution



Assumption: Radiance independent of angle

$$I_\nu(\theta,\phi) = I'_\nu = \text{const} \quad \text{for } 0<\theta<\pi/2$$

Integral over one hemisphere



$$F_\nu^\uparrow = \int_0^{2\pi} d\phi \int_0^{\pi/2} I_\nu(\theta,\phi)\cos\theta\sin\theta d\theta$$

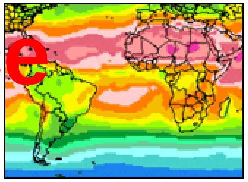
$$F_\nu^\uparrow = \int_0^{2\pi} d\phi \int_0^{1} I_\nu(\theta,\phi)\sin\theta \, d\sin\theta$$

$$F_\nu^\uparrow = I'_\nu 2\pi \left[\frac{\sin^2\theta}{2}\right]_0^{\pi/2}$$

$$F_\nu^\uparrow = \pi I'_\nu$$

Black body emission or reflection from 'Lambert=diffusive' surfaces

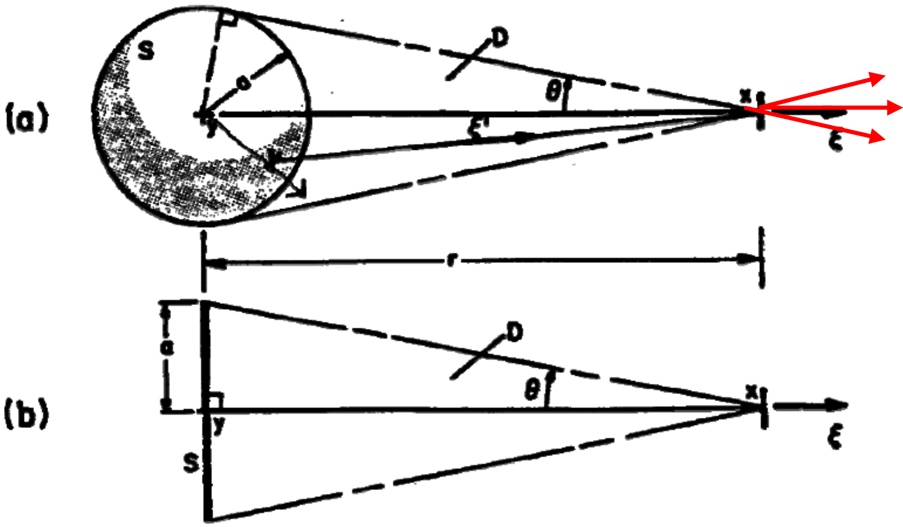
Example 2: flux from an extended source



Assume isotropic emission with intensity *I_0* from extend source. Compute the flux incident on a surface (with normal in direction of source) at distance D

$$
\begin{aligned}
F(D) &= \int I_0 \cos\theta \, d\Omega \\
&= I_0 \int_{subtended} d\,\Omega \cos\theta \\
&= I_0 \int_0^{2\pi} d\varphi \int_0^{\theta_0} \cos\theta \sin\theta \, d\theta \\
&= I_0 \pi \sin^2\theta_0
\end{aligned}
$$

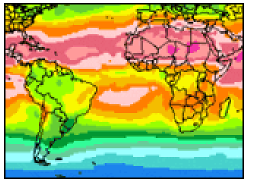
$$F(D) = \underbrace{I_0}_{F(a)} \pi\, a^2 / D^2 = I_0 \Omega_0(D)$$



Thus *F(D) ~ 1/D²*

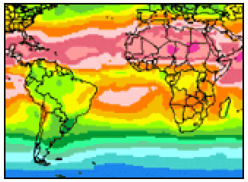
Which is the expected $1/r^2$ dependence: fluxes are preserved

Home thinking



An infrared thermometer allows the temperature of objects to be measured at a distance, assuming that they emit radiation more or less like blackbodies. Based on this description, would you infer that the instrument is designed to measure infrared flux or intensity (radiance)? Why?

What do you need to know?



- ❑ Basics of EM waves
- ❑ Radiation Quantities
- ❑ Units, solid angles
- ❑ Converting from Radiance to Irradiance
- ❑ Calculation of radiance and irradiances

Good textbooks (available in the university library) :

G.W. Petty – A first introduction in atmospheric radiation

G.L. Stephens – Remote sensing of the lower atmosphere – an introduction

Homework: problem

A black satellite is orbiting at an altitude H=2000km above the ground.

1) Compute the solid angle subtended by the Earth.

2) If the Earth irradiates as a black body at T=255 K, compute the Earth radiation flux impinging onto the satellite (assumed as a sphere of radius R_{sat}=1m).

3) Compute the radiative equilibrium temperature of the satellite when it is in the shadow of the Earth.

4) How does your answer change when the satellite is also illuminated by the Sun?

Homework: lizard vs man

1. Plot the spectral radiance emitted by the lizard as a function of wavelength in the range 1-20 micron. Treat the lizard as a black body emitter.

2. Plot the radiance emitted by the human as a function of wavelength in the range 1-20 micron

3. Find the spectral ratio of the two radiances.

4. What is the ratio of the total fluxes for the two bodies?