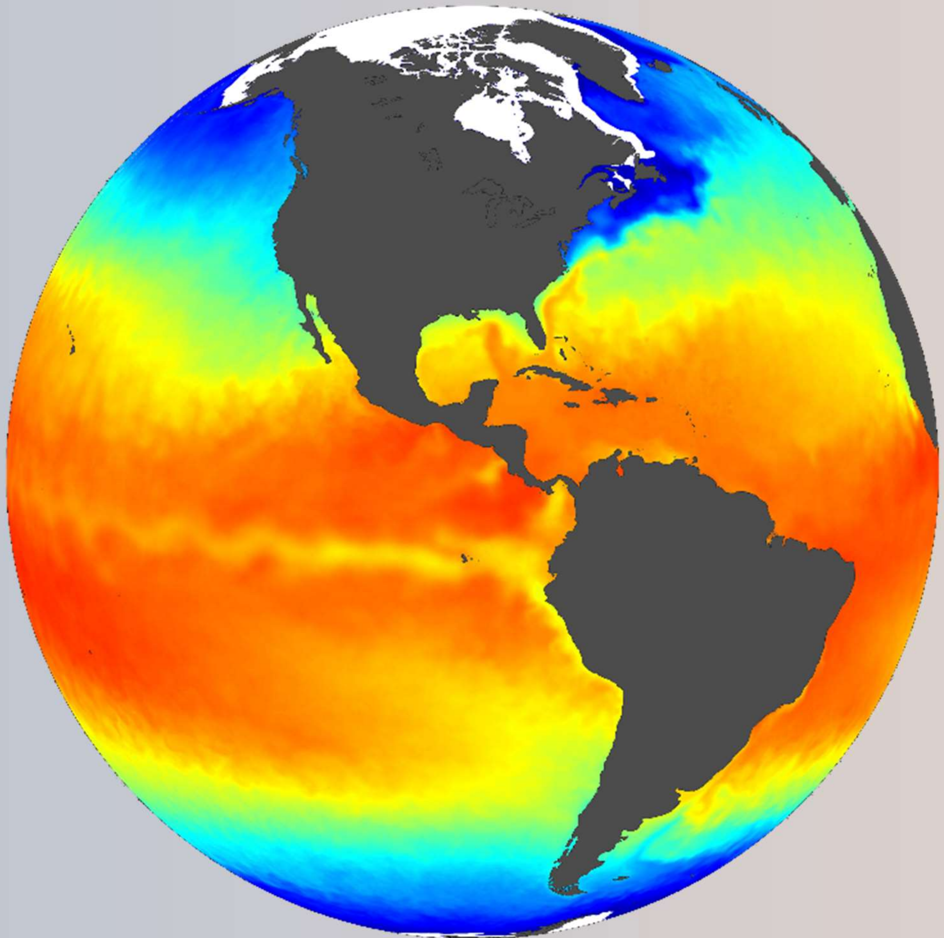


***To provide operational users and the science community with the SST measured by the satellite constellation***

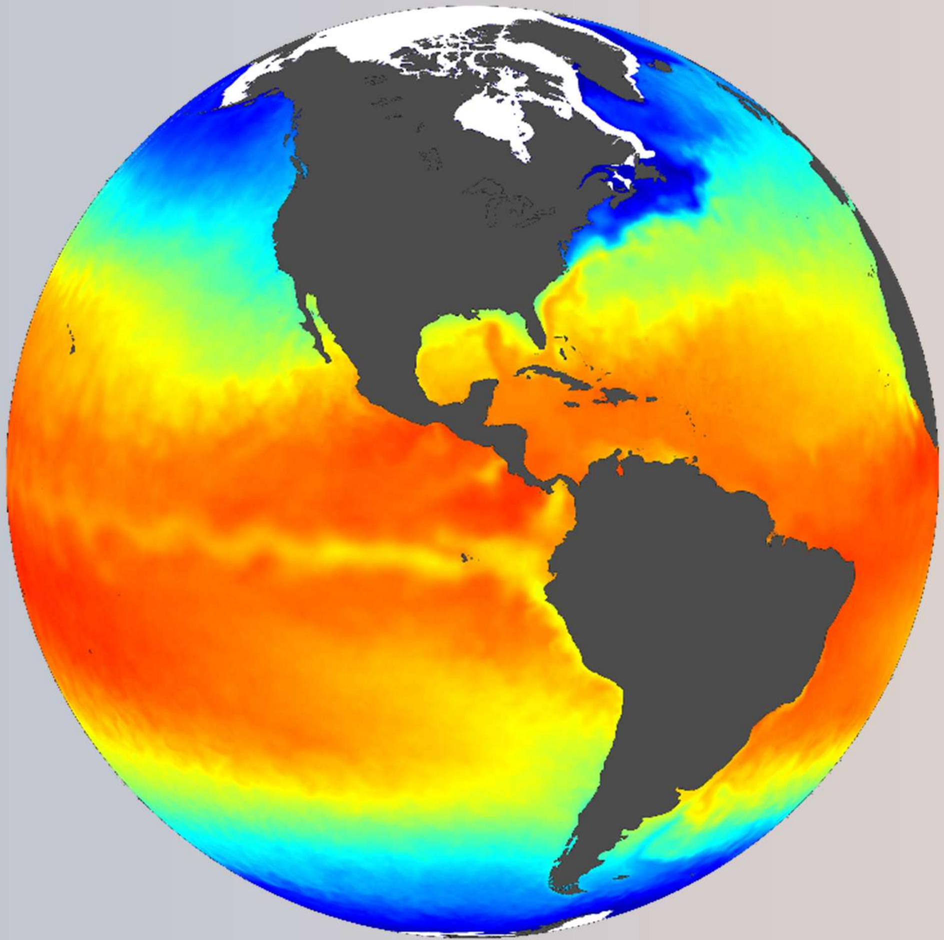
# Principles of electromagnetic radiation and radiative transfer

*Peter Minnett and*

*Chris Merchant*

GHRSST
Group for High Resolution Sea Surface Temperature

CEOS
Committee on Earth Observation Satellites
Sea Surface Temperature Virtual Constellation



*To provide operational users and the science community with the SST measured by the satellite constellation*

# Planck's Function

*Peter Minnett*

GHRSST
Group for High Resolution Sea Surface Temperature

CEOS Committee on Earth Observation Satellites
Sea Surface Temperature Virtual Constellation

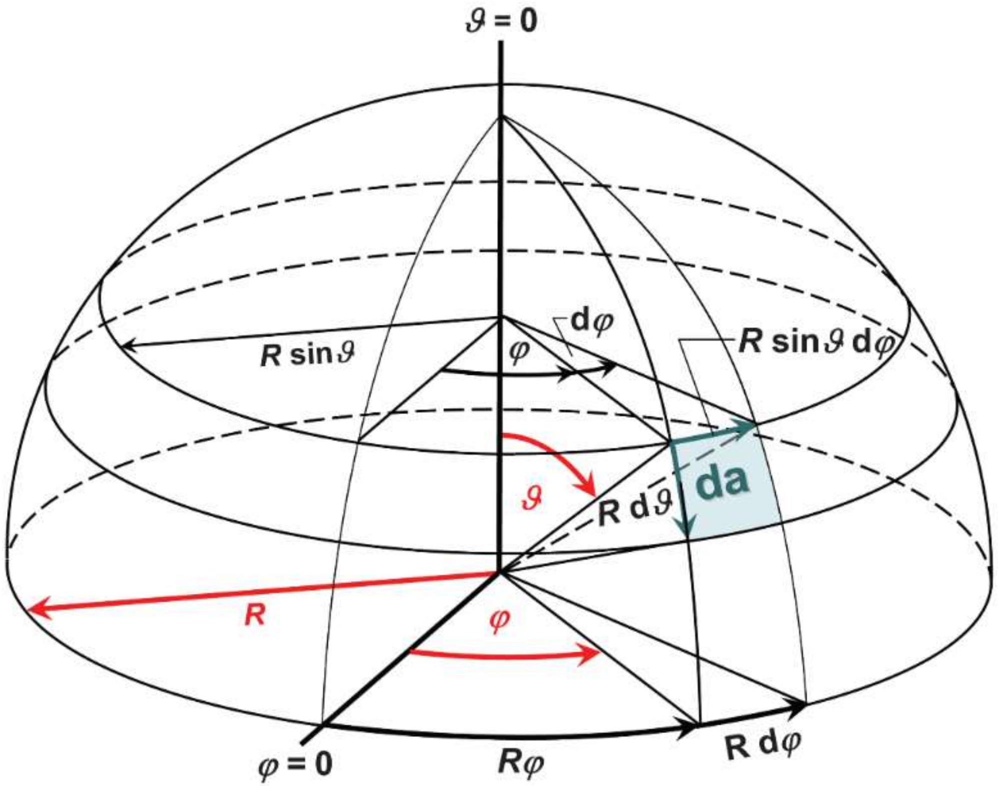
# Some definitions

- Power: The time rate of flow of radiant energy [$W = Js^{-1}$]
- Flux: Time rate of flow of energy; the radiant power in a beam [W]
- Flux Density: Flux crossing a unit area normal to the beam [$Wm^{-2}$]
- Irradiance: Flux incident per unit area of a surface. Also called radiant flux density [$Wm^{-2}$]
- Spectral irradiance: Irradiance per unit spectral interval at a given wavelength, wavenumber or frequency unit range [$Wm^{-2}\,\mu m^{-1}$; $Wm^{-2}\,(cm^{-1})^{-1}$; $Wm^{-2}\,(s^{-1})^{-1}$]

  (Wavenumber – the number of wavelengths in a cm)
- Radiance: Radiant power per unit source area per unit solid angle [$Wm^{-2}\,st^{-1}$]
- Spectral radiance: Radiance per unit spectral interval at a given wavelength, wavenumber or frequency, expressed in watts per steradian per unit area per spectral interval. [$Wm^{-2}\,st^{-1}\mu m^{-1}$; $Wm^{-2}\,st^{-1}(cm^{-1})^{-1}$; $Wm^{-2}\,st^{-1}(s^{-1})^{-1}$]

For more definitions, see http://www.photonics.com/edu/Dictionary.aspx

# Solid Angle

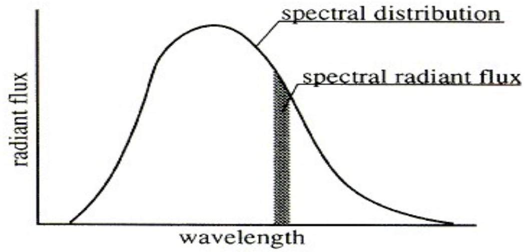



$$da = R\sin\vartheta d\varphi \, R d\vartheta$$

# Definitions with diagrams

**Radiant energy** *Qe*

The energy carried by electromagnetic radiation

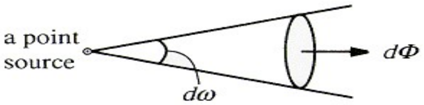



**Radiant flux** *Φ*

Radiant energy transmitted per unit time

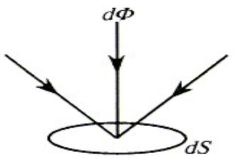
**Radiant intensity** *Ie*

Radiant energy radiated from a point source per solid angle in a radial direction per unit time



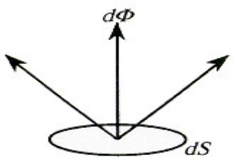

**Irradiance** *Ee*

Radiant energy incident upon a unit area per unit time



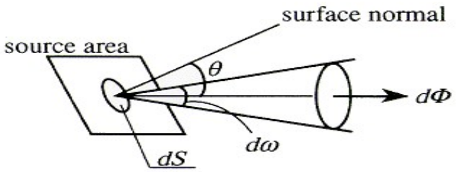

**Radiant emittance** *Me*

Radiant energy radiated from a unit area per unit time



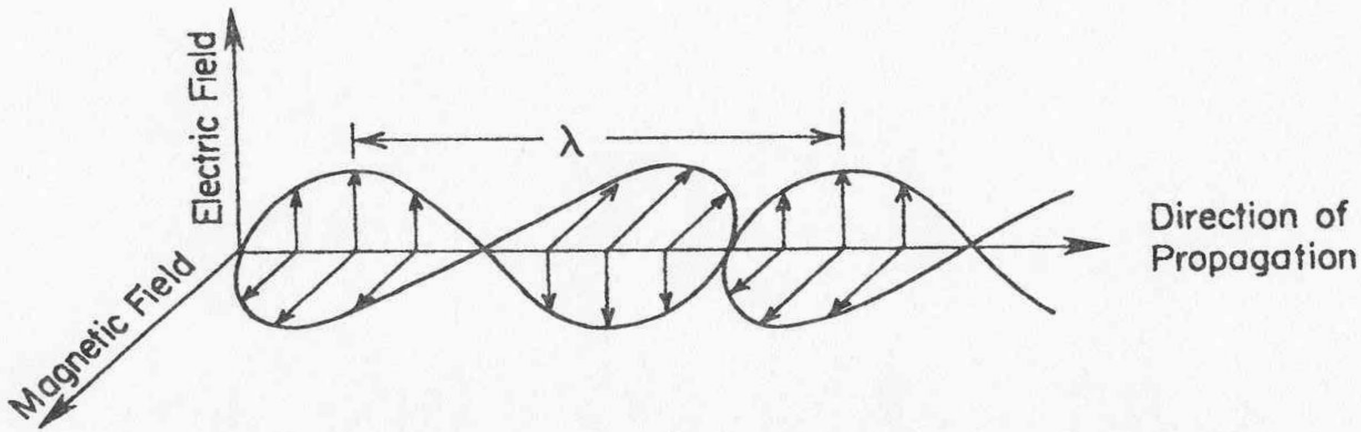

**Radiance** *Le*

Radiant energy radiated from a unit projected area per unit solid angle in a radial direction per unit time




NB – there is not a consistent use of symbols (with a few exceptions).

# Electromagnetic waves




Schematic representation of electromagnetic waves.

# Theory of Electromagnetic Waves

The physical theory is ‘classical’ i.e. pre-Quantum Theory. While it can successfully explain many phenomena, it cannot, for example, explain the spectrum of radiant emitted energy – for this we need Planck’s equation, based on quantum theory.

# Planck Function

### The Planck Function

In searching for a theoretical derivation of blackbody radiation, Planck made the revolutionary assumption that an oscillating atom in the wall of a cavity can exchange energy with the radiation field inside a cavity only in discrete bundles called *quanta* given by $\Delta E = h\nu$, where $h$ is known as *Planck's constant*.

With this assumption, he showed that the radiance being emitted by a blackbody is given by

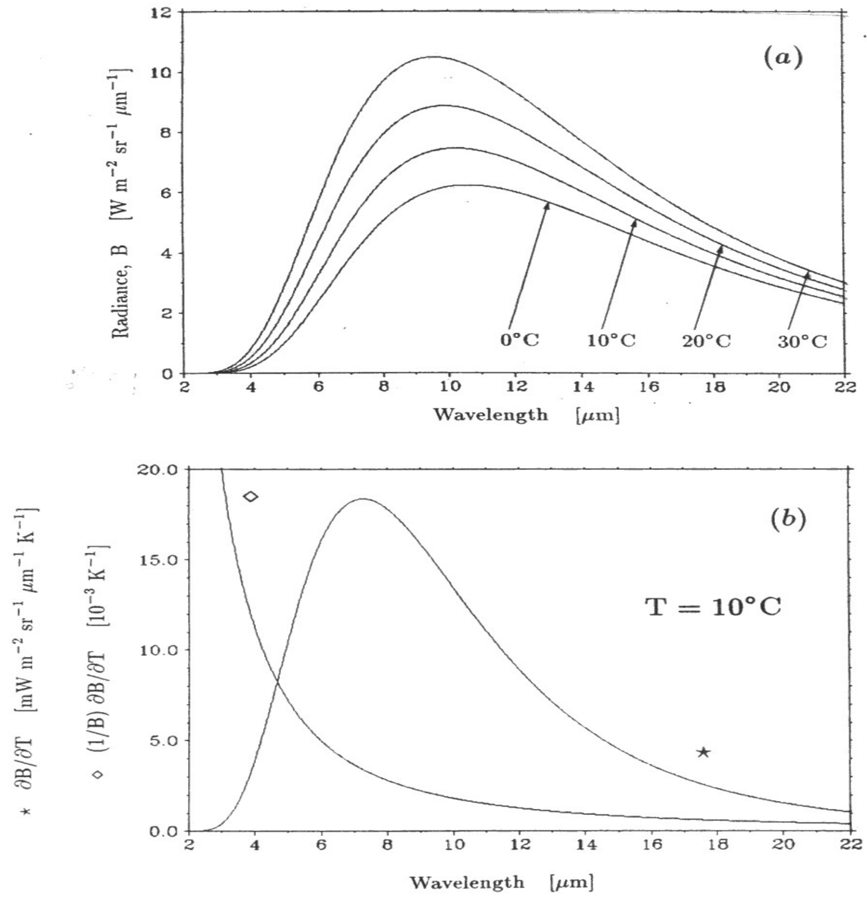
$$B_\lambda(T) = \frac{2hc^2\lambda^{-5}}{\exp\left(\dfrac{hc}{\lambda k T}\right) - 1},$$

where $k$ is Boltzmann's constant, and $T$ is the absolute temperature.

This is the *Planck function*; it earned him the Nobel Prize in 1918. The Planck function is more conveniently written as

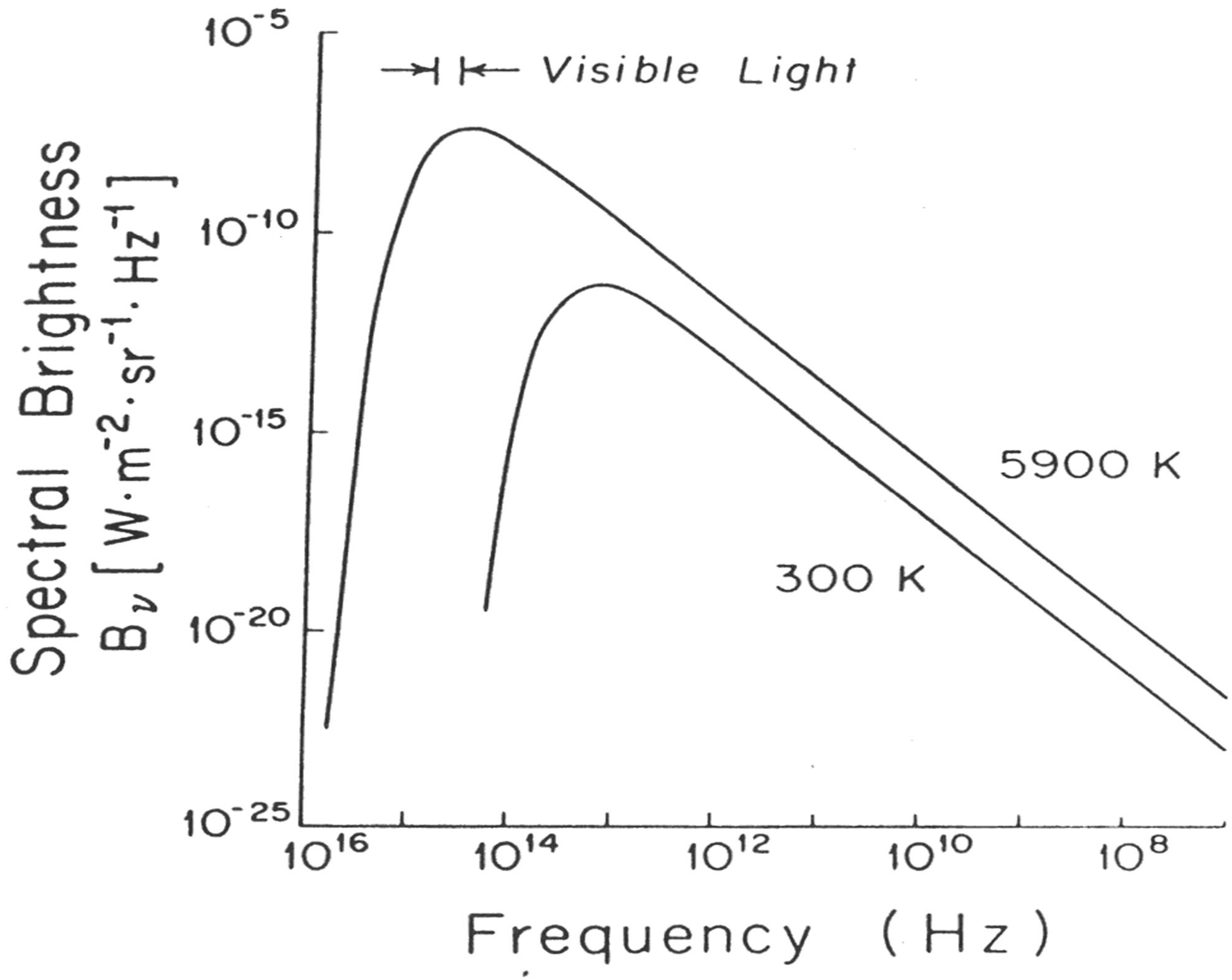
$$B_\lambda(T) = \frac{c_1\lambda^{-5}}{\exp\left(\dfrac{c_2}{\lambda T}\right) - 1},$$

where $c_1$ and $c_2$ are the first and second radiation constants.



# Planck Function – different variables

The independent variable in plots of the Planck Function is often wavelength, wavenumber, frequency, or period.



# Rayleigh-Jeans Approximation

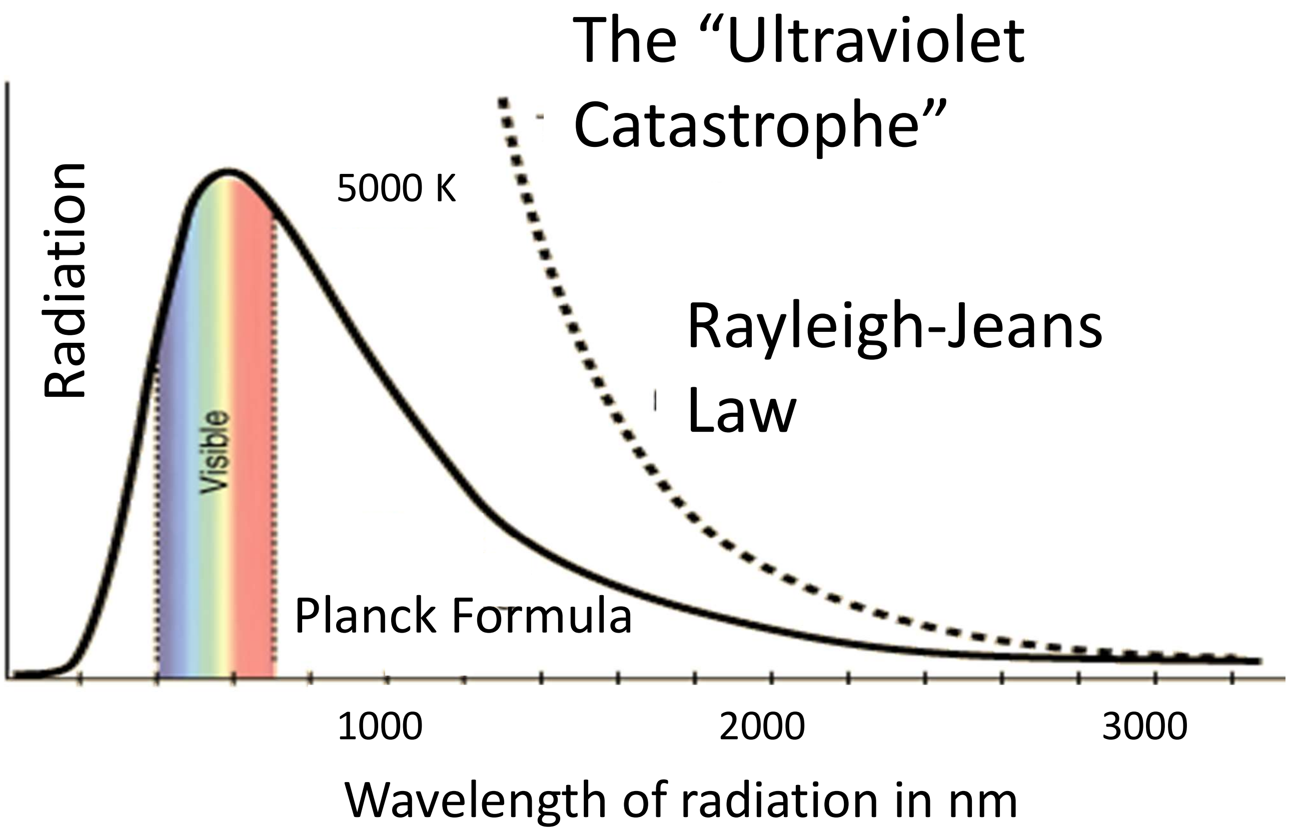
Rayleigh-Jeans Law corresponds to the Planck Law in the case of small frequencies, in which case hν/(kT)<< 1 allows the approximation

$e^{h\nu/(kT)} \approx 1 + h\nu/(kT) + \ldots.$

Putting this into the Planck law gives

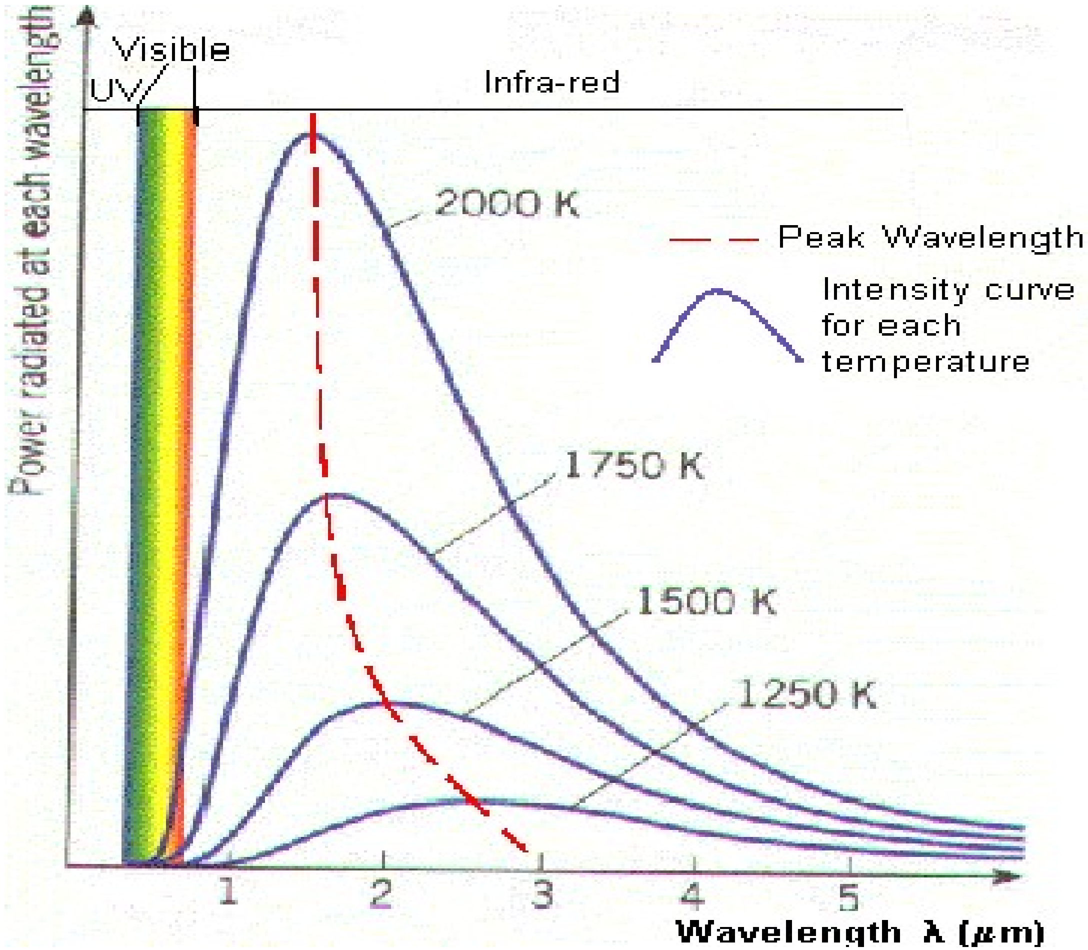
$$R_\nu(T) \approx \frac{2\nu^3 h}{c^2} \frac{1}{(1+h\nu/(kT)+\ldots.) - 1}$$

$$= 2\nu^2 kT/c^2$$




See http://hyperphysics.phy-astr.gsu.edu/hbase/mod6.html

# Temperature dependence of the Planck Function




Wien's Displacement Law: $\lambda_{max} = b/T$

$\lambda_{max}$, is the wavelength of peak spectral emission.

*T* is the temperature of the blackbody in kelvin (K)

*b* is Wien's displacement constant

$= 2.897 \times 10^{-3}$ m K

# Non-Black Bodies

## Nonblackbodies

Since real material is not perfectly black, a way must be devised to quantify how closely it approximates a blackbody. The *emittance* of a body is defined as

$$\varepsilon_\lambda \equiv \frac{\text{emitted radiation at } \lambda}{B_\lambda(T)}.$$

Emittance can be a function of temperature and viewing geometry as well as wavelength. For a blackbody, $\varepsilon_\lambda$ is identically one.

# Stefan-Boltzmann's Law

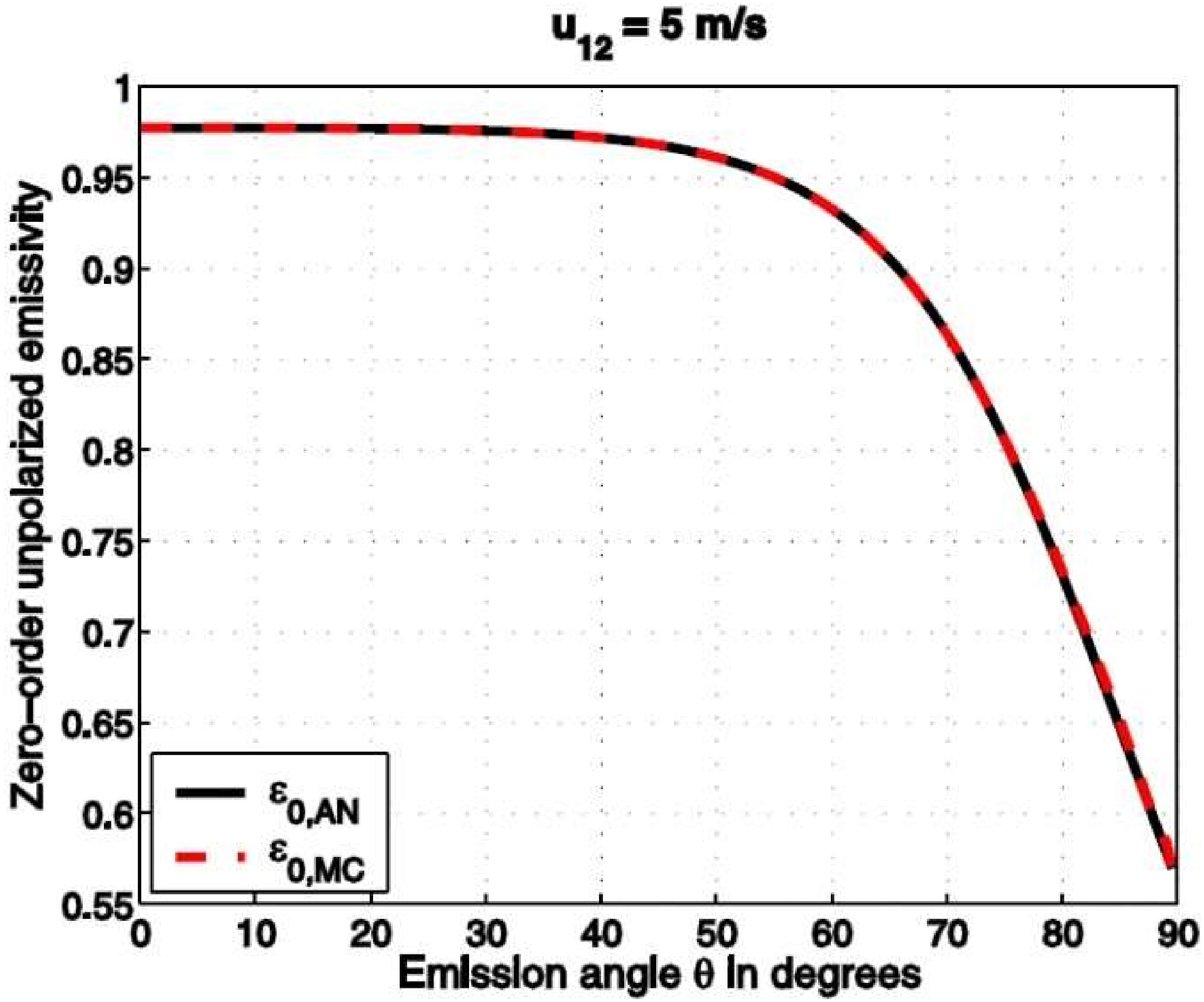
By integrating Planck's Function over all wavelengths (or frequencies or wavenumbers), the total energy radiated per unit surface area of a black body in unit time (known variously as the black-body emittance, energy flux density, radiant flux, or the emissive power), *Q*, is directly proportional to the fourth power of the black body's thermodynamic temperature T (also called absolute temperature):

$$Q = \varepsilon\sigma T^4$$

$$\sigma = (2\pi^5 k^4) / (15c^2 h^3) = 5.6704\ 10^{-8}\ \mathrm{Js^{-1}m^{-2}K^{-4}}$$

A measurement of the radiant energy flux at all wavelengths, and a knowledge of the emissivity, can lead to a remote measurement of temperature.

# Emission angle dependence




Sea surface emissivities computed from an analytical approach (AN) and a Monte Carlo ray-tracing method (MC) versus the emission angle.

Wind $u_{12}$ = 5 $ms^{-1}$; λ = 4 μm.

Bourlier, C. (2006), Unpolarized emissivity with shadow and multiple reflections from random rough surfaces with the geometric optics approximation: application to Gaussian sea surfaces in the infrared band, *Appl. Opt.*, *45*(24), 6241-6254.

# Wind speed effects on emissivity

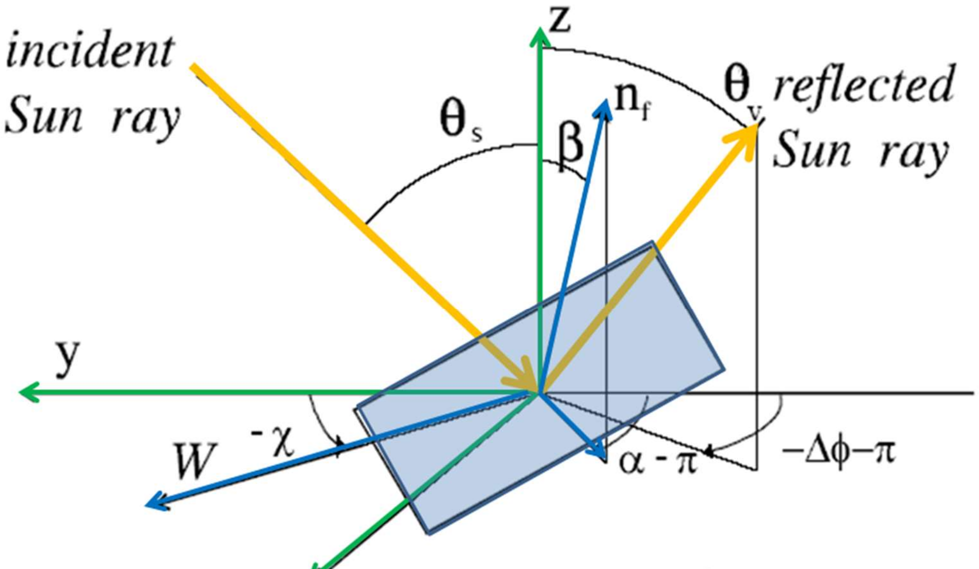
The intensity of sun-glitter can be calculated by the theory of Cox and Munk (1954), who showed, empirically, that for a uniform ocean surface roughness, there is a near-Gaussian distribution of surface wave slope with a probability function:

$$P(\beta, \sigma) \approx (2\pi\sigma^2)^{-1} (\exp - (\tan^2(\beta))/\sigma^2)$$

Where $\sigma$ is the standard deviation of P, and is related, again empirically, to U10, the near-surface wind speed (in ms-1), by:

$$\sigma^2 = 0.00512\ U_{10} + 0.003$$

$\beta$ is the zenith angle of the normal at the point on a surface wave at which reflection occurs.



Sun glint geometry

# Cox & Munk surface slopes

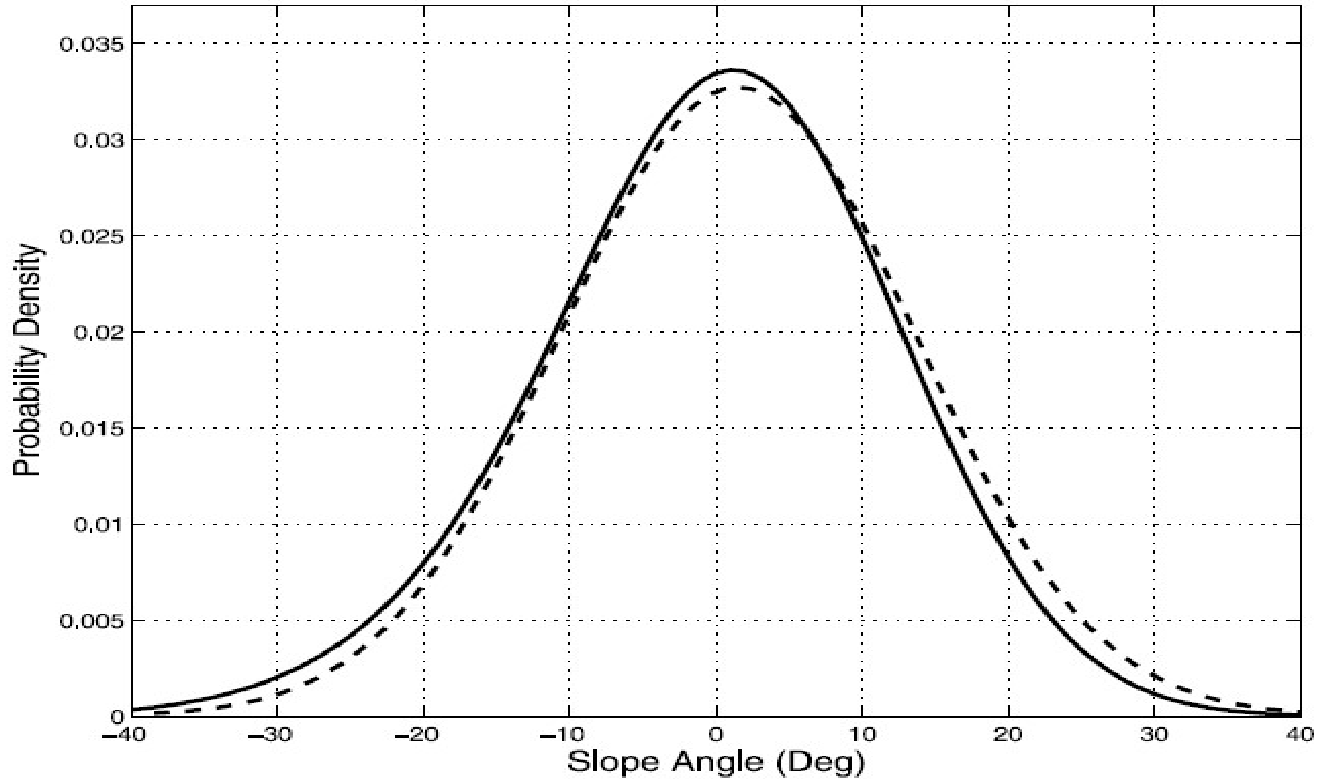
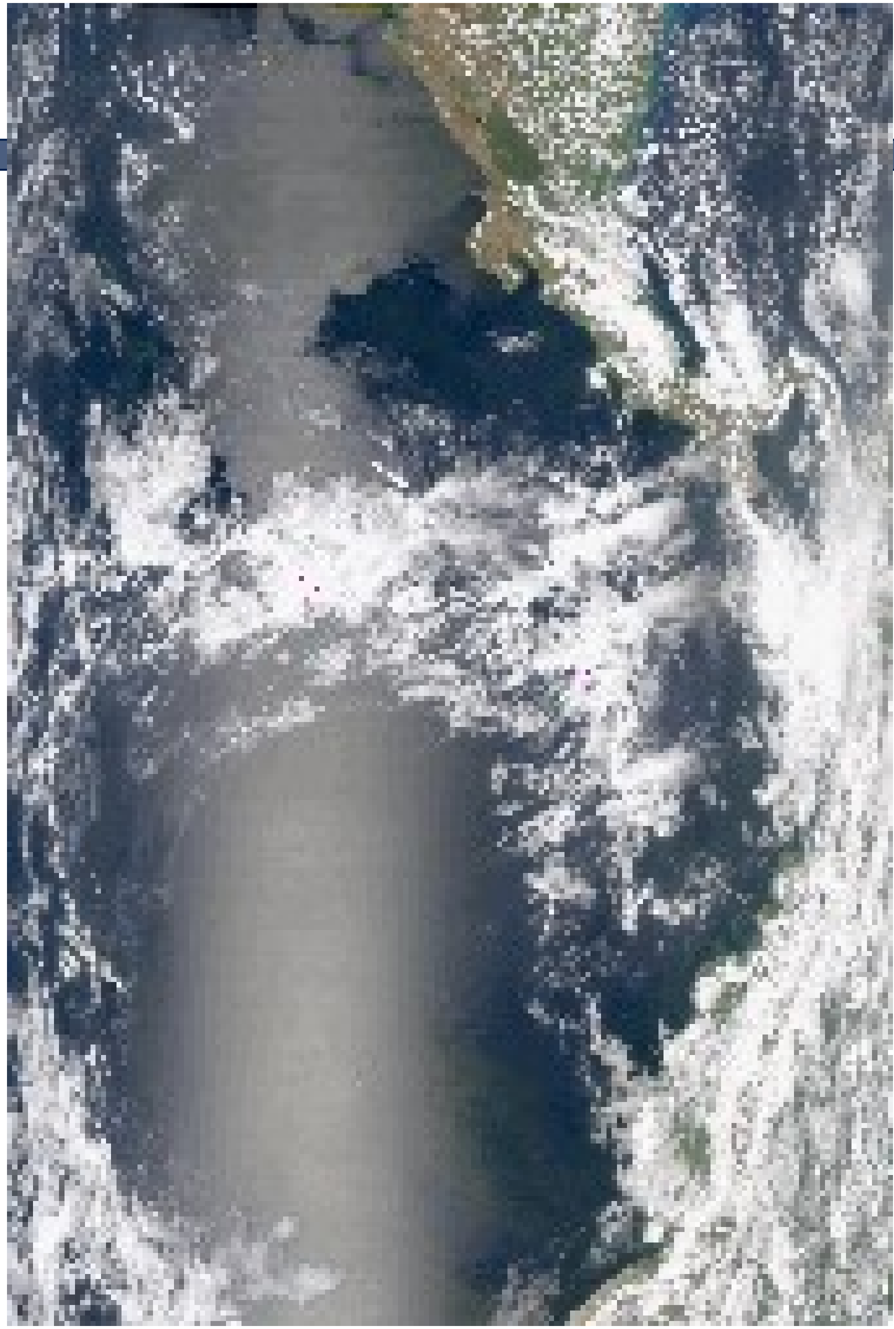



**Figure 1.** Comparison of an upwind/downwind sea-surface slope PDF fit by *Cox and Munk* [1954] to their optical data (solid curve) with a Gaussian PDF having the same variance (dashed curve). Downwind slopes are positive. The wind speed at 12.5 m height was 10.2 m/s.

From Plant, W, A new interpretation of sea-surface slope probability density functions. JGR, 2003.

# Sun glint



Bright sea is sun glint.

# Wind speed dependence

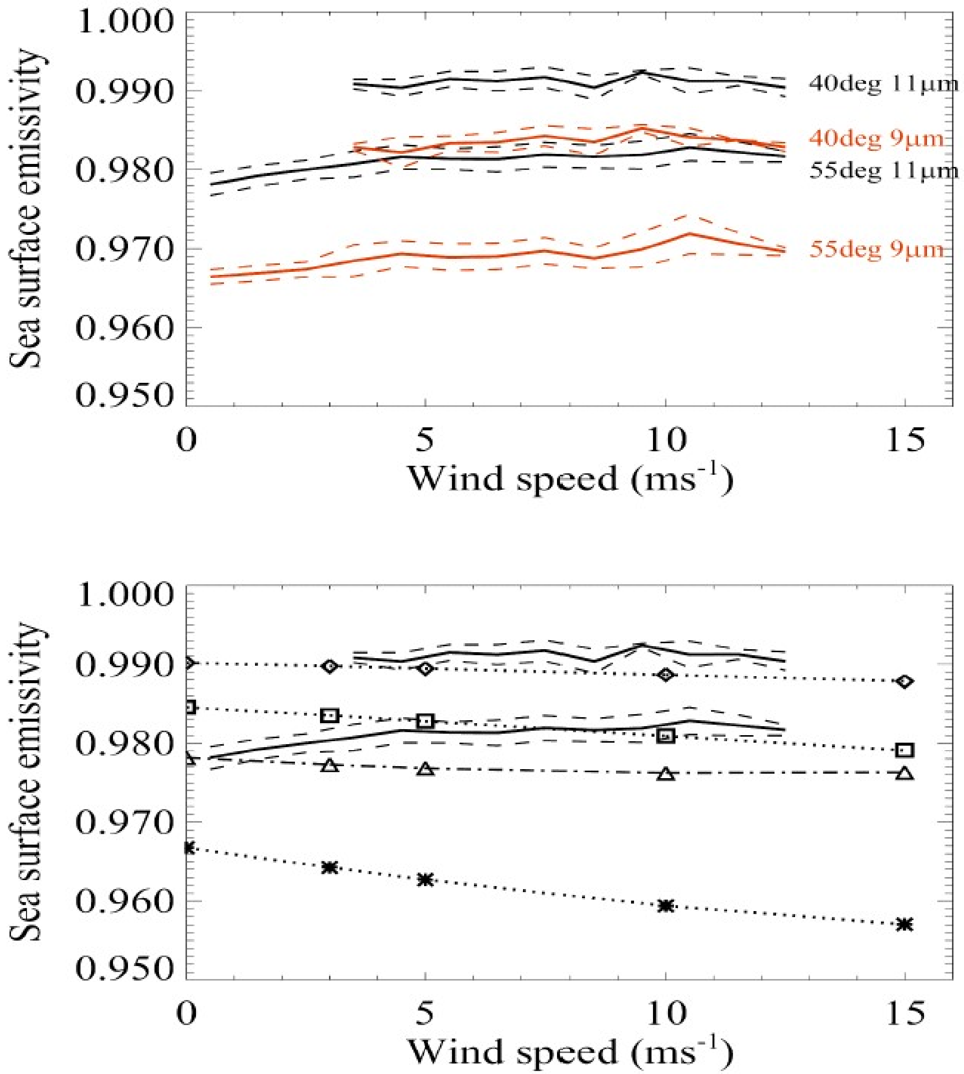
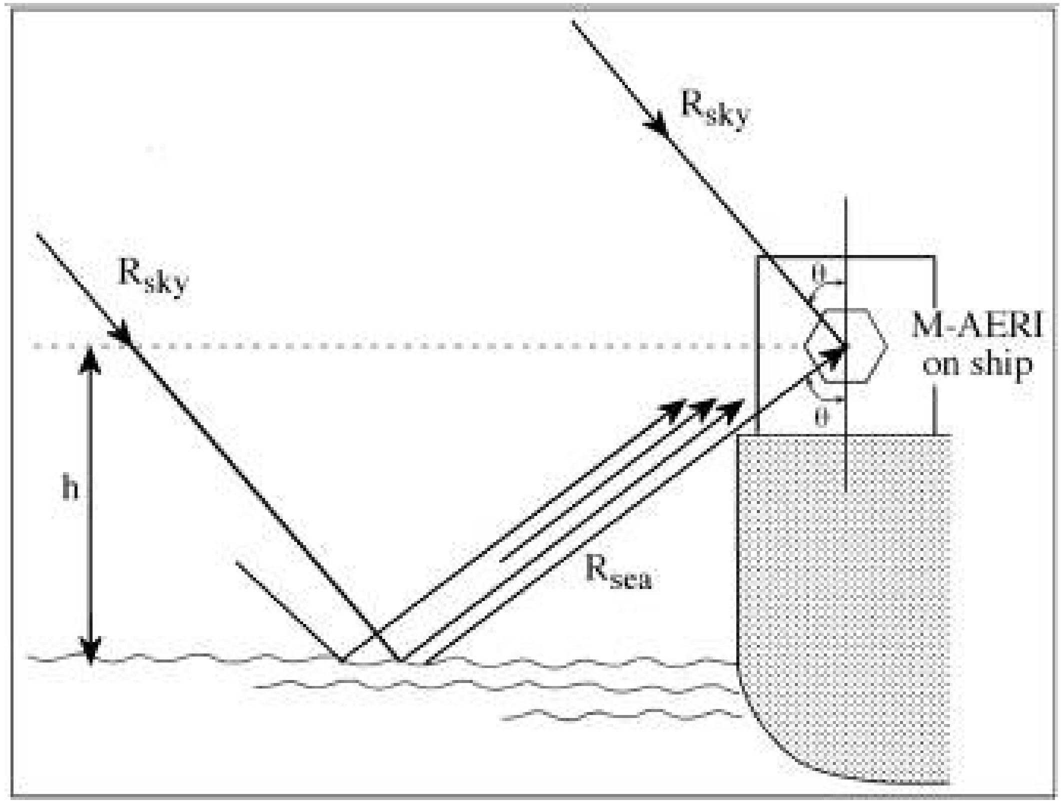



Figure 6. Observed mean (solid lines) and standard deviation (dashed lines) of sea surface emissivity in $1ms^{-1}$ wind speed bins for 9μm and 11μm at 40° and 55° incidence angles (top). Below, the solid lines are the measured 11μm emissivity for the 40° and 55° views, the dashed line with triangular markers represents values predicted by *[Watts et al., 1996]* for 55° at 11μm (the coefficients given in that paper are valid for 52°-55° viewing angle). The dotted lines are those predicted by *[Masuda et al., 1988]* for 40° (diamonds), 50° (squares) and 60° (asterisks). From: J.A. Hanafin, Ph.D. Thesis, University of Miami, 2002.

# Measurements of skin SST by ship-board radiometers

$$T_{skin} = B^{-1}\langle\{R_{water}(\lambda, \theta) - [1 - \varepsilon(\lambda, \theta)]R_{sky}(\lambda, \theta) - R_h(\lambda, \theta)\}/\varepsilon(\lambda, \theta)\rangle$$

$$R_{water}(\lambda, \theta) = \varepsilon(\lambda, \theta)B(\lambda, T_{skin}) + (1 - \varepsilon(\lambda, \theta))R_{sky}(\lambda, \theta) + R_h(\lambda, \theta)$$




- Scan-mirror mechanism for directing the field of view at complementary angles.
- Very good calibration for ocean radiances
- Moderately good calibration at low radiances

# Ship radiometers

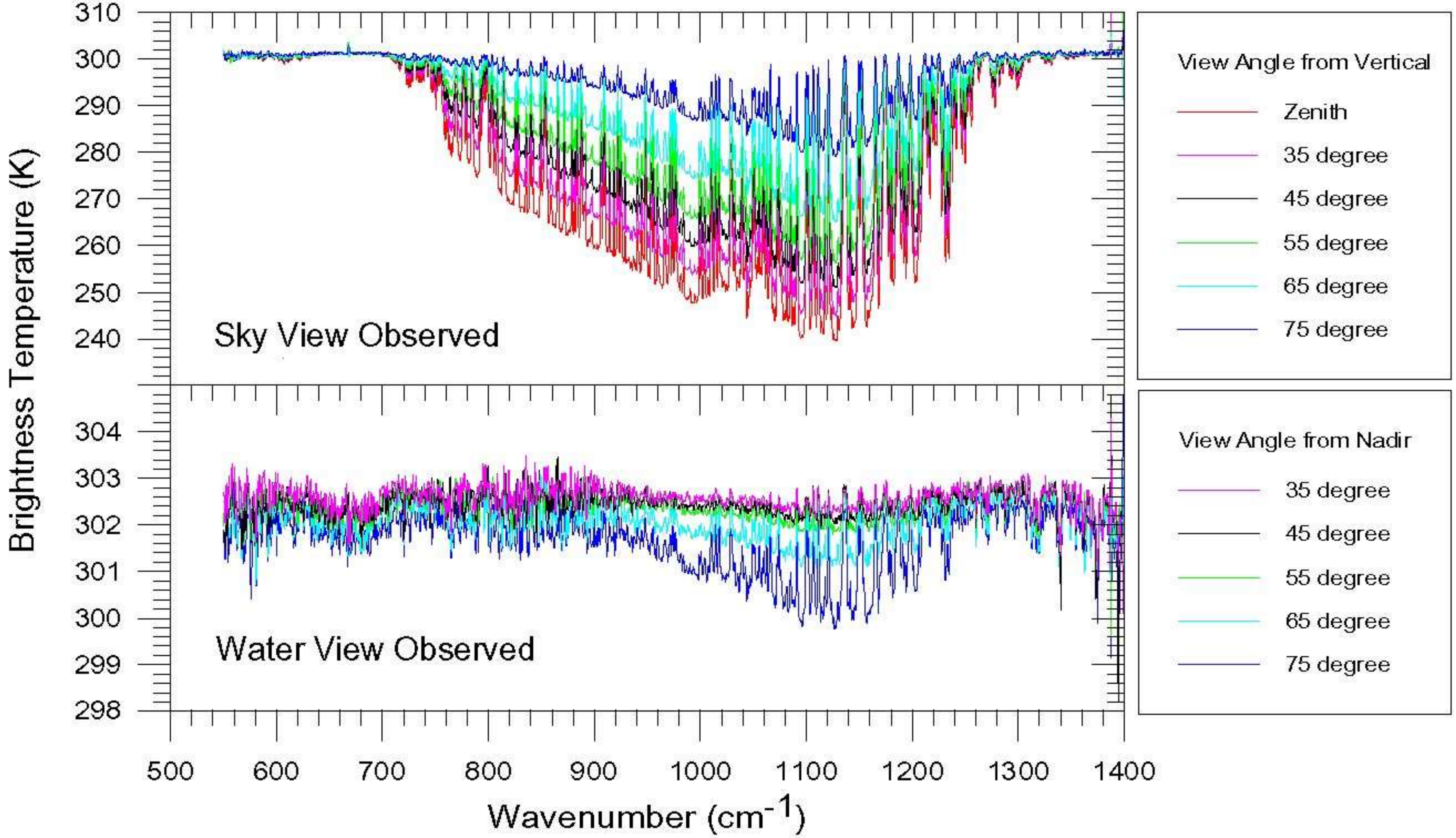
## M-AERI

- M-AERI is a very well-calibrated and stable sea-going Fourier Transform Infrared Interferometer.
- At sea calibration by two internal blackbody cavities with thermometers with NIST-traceable calibration.
- Calibration sequence before and after each cycle of measurements.
- Calibration before and after deployments using NIST-designed water-bath blackbody calibration target at RSMAS. Uses SI-traceable thermometers at mK accuracy.
- Periodic radiometric characterization of RSMAS water-bath blackbody calibration target by NIST TXR.

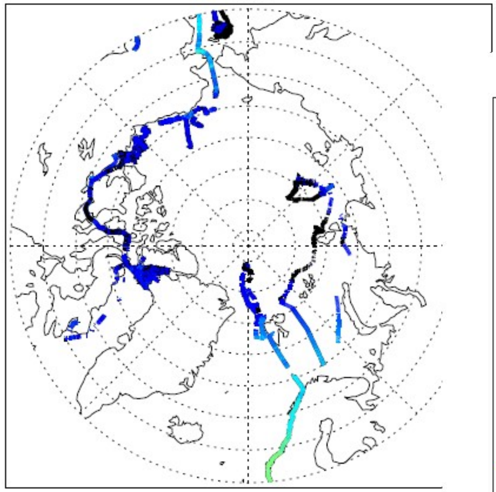
## ISAR

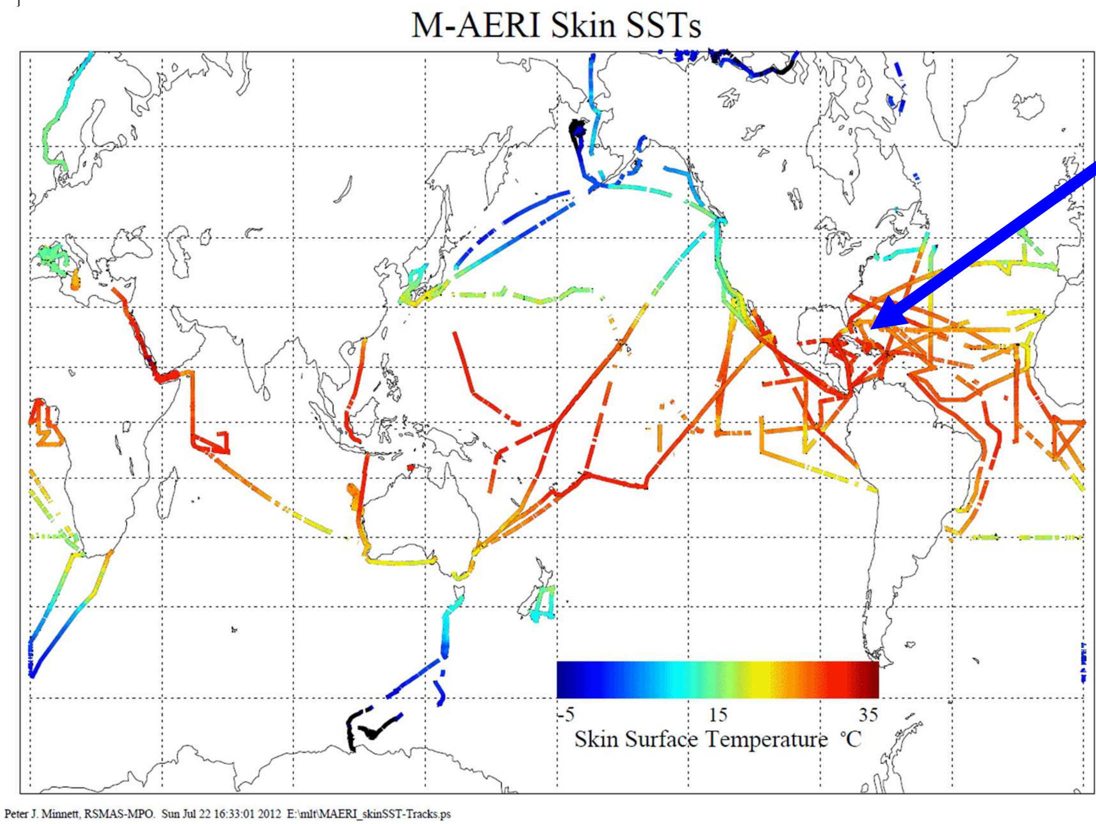
- ISAR is a very well-calibrated and stable sea-going filter radiometer.
- At sea calibration by two internal blackbody cavities with thermometers with SI-traceable calibration.
- Calibration sequence before and after each cycle of measurements.
- Calibration before and after deployments using NIST-designed water-bath blackbody calibration target at RSMAS or UW-APL. Use SI-traceable thermometers at mK accuracy.
- Periodic radiometric characterization of RSMAS water-bath blackbody calibration target by NIST TXR.

# Measured spectra of atmospheric and sea-surface emission



# M-AERI cruises



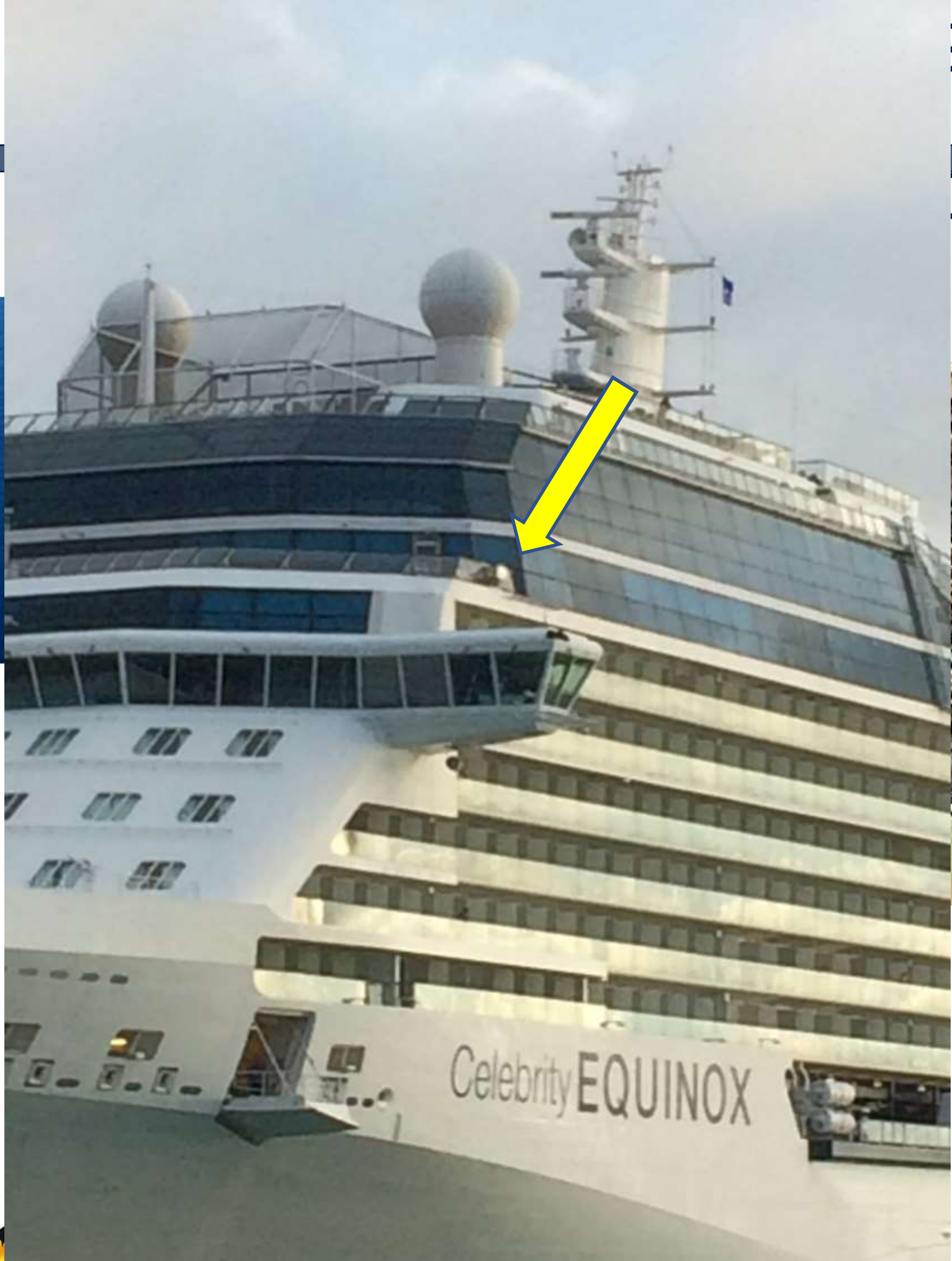



*Explorer of the Seas*



*Explorer of the Seas: near continuous operation December 2000 – December 2007.*

## Caribbean Cruise Lines

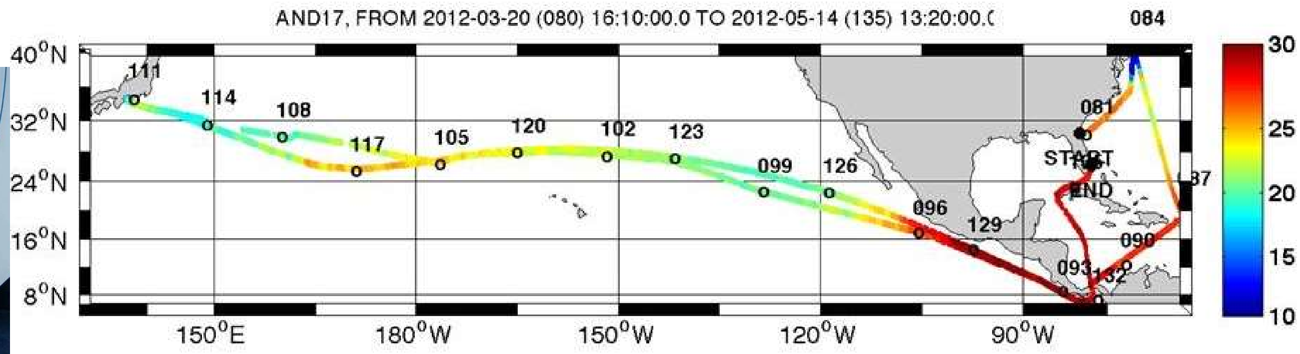




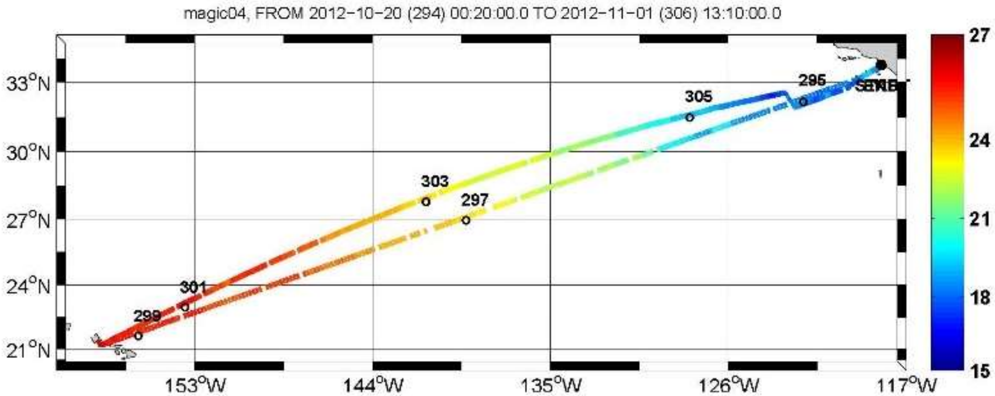
3rd ship being negotiated

# Ship radiometers: ISARs

M/V *Andromeda Leader*



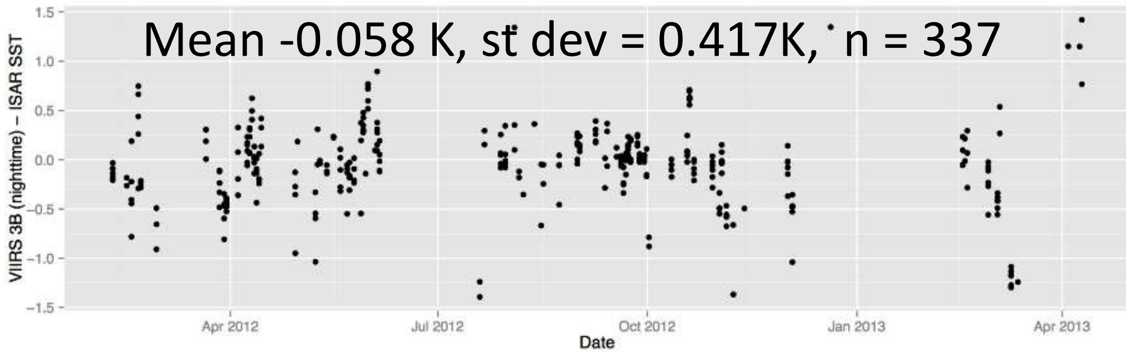

M/V *Horizon Spirit*

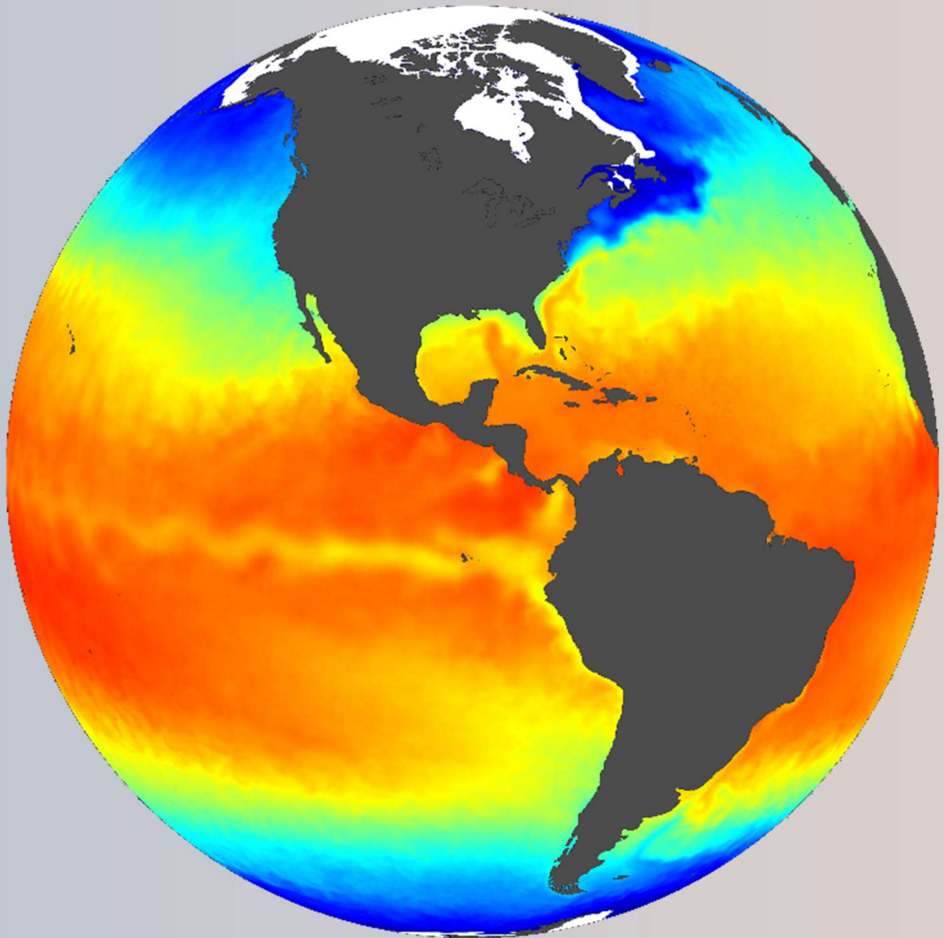



ISARs are autonomous filter radiometers with two internal blackbody calibration targets.

Pre- & post-deployment lab calibration against NIST-traceable calibrators.

Data relayed in real-time by Iridium.





To provide operational users and the science community with the SST measured by the satellite constellation

# Radiative transfer in the atmosphere

*Chris Merchant*

GHRSST
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# Radiation interactions with matter

- Absorption and scattering by gases
- Absorption and scattering by clouds and aerosol
- Absorption / reflection / scattering at solid / liquid surfaces
- All matter emits thermal radiation too!

- Absorbed radiation heats the absorbing matter

- Start by considering scattering, and then look at emission and absorption

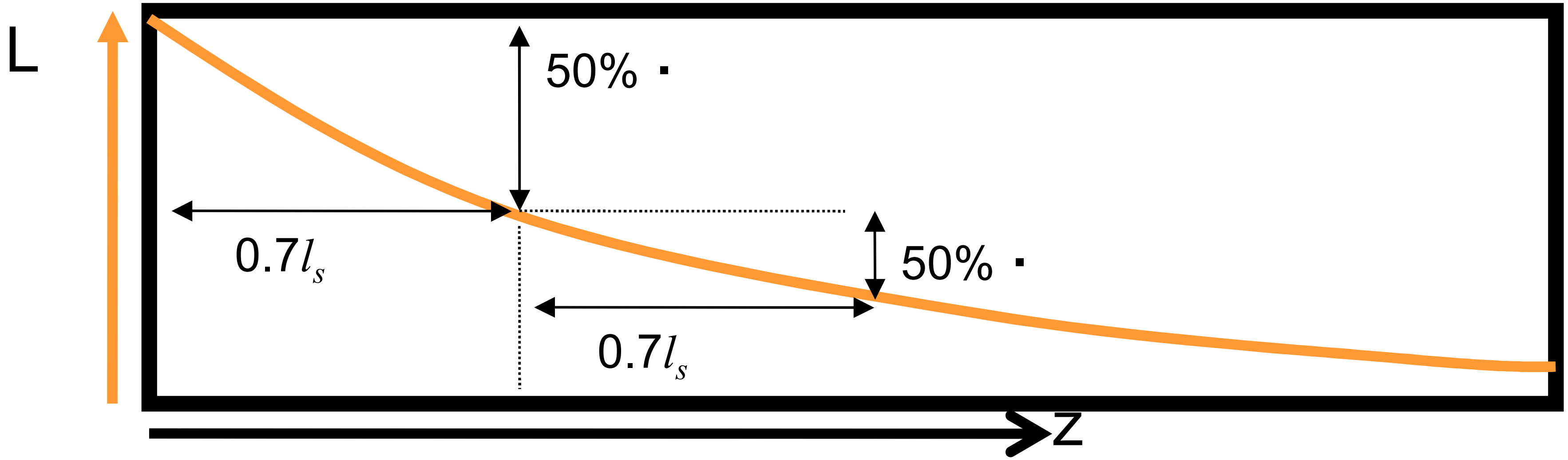
# Scattering

- Scattering changes the direction of radiation, without absorbing its energy

- The measures of scattering are therefore
  - the amount of scattering
  - the angular distribution of the scattered radiance

# Attenuation of a beam by scattering

- Assume
  - Negligible emission and no absorption
  - No scattering into the beam direction

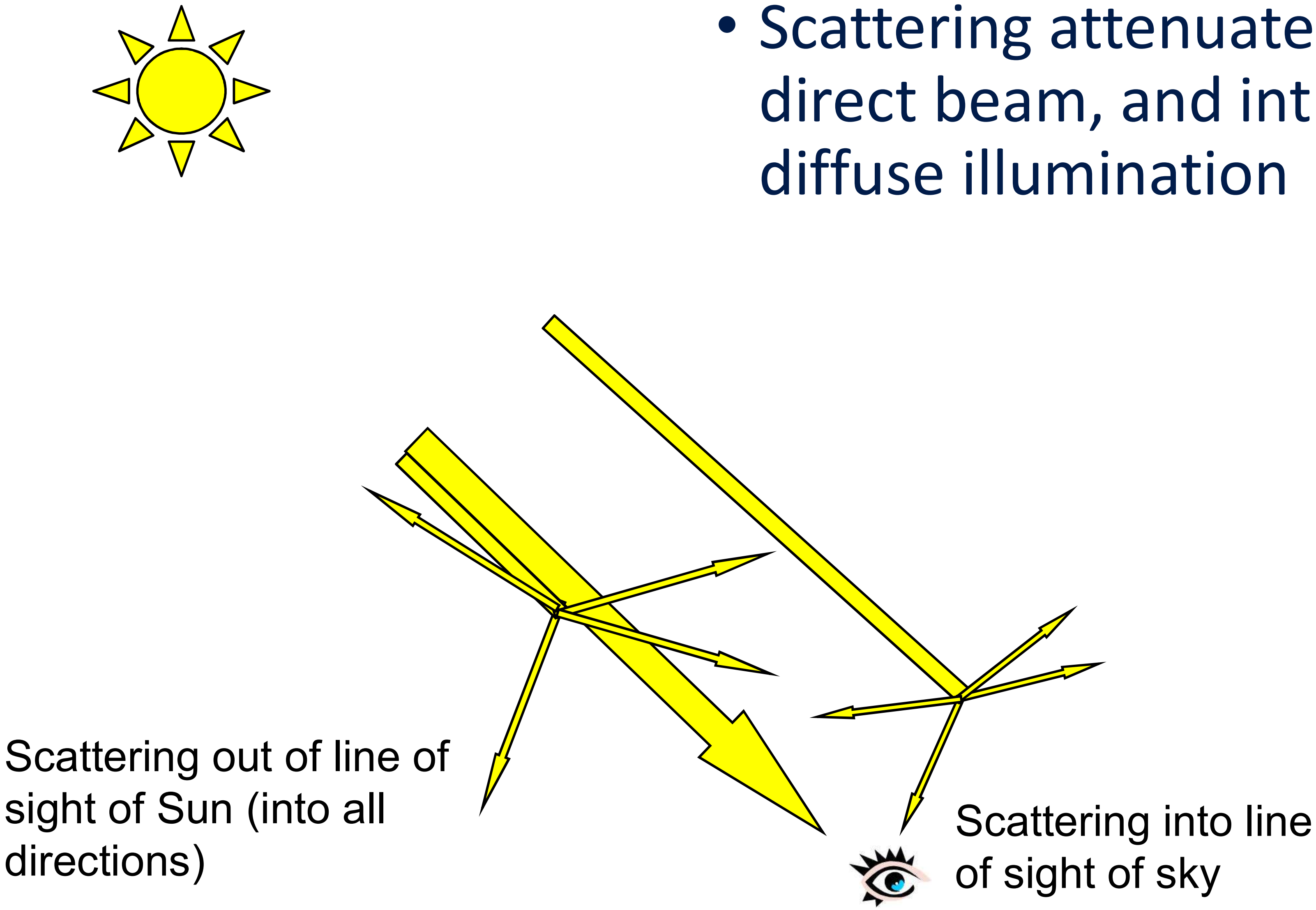



$$L = L_{z=0} \exp(-z/l_s) \quad ; \quad t(0,z) = \exp(-z/l_s)$$

The shorter the characteristic scattering length, the greater the amount of scattering.

# Effect of scattering on solar radiance

- Scattering attenuates the direct beam, and introduces diffuse illumination



# Thinking

- What is the spectral distribution of the diffuse irradiance?
- What does this tell us about the spectral variation of the amount of scattering?

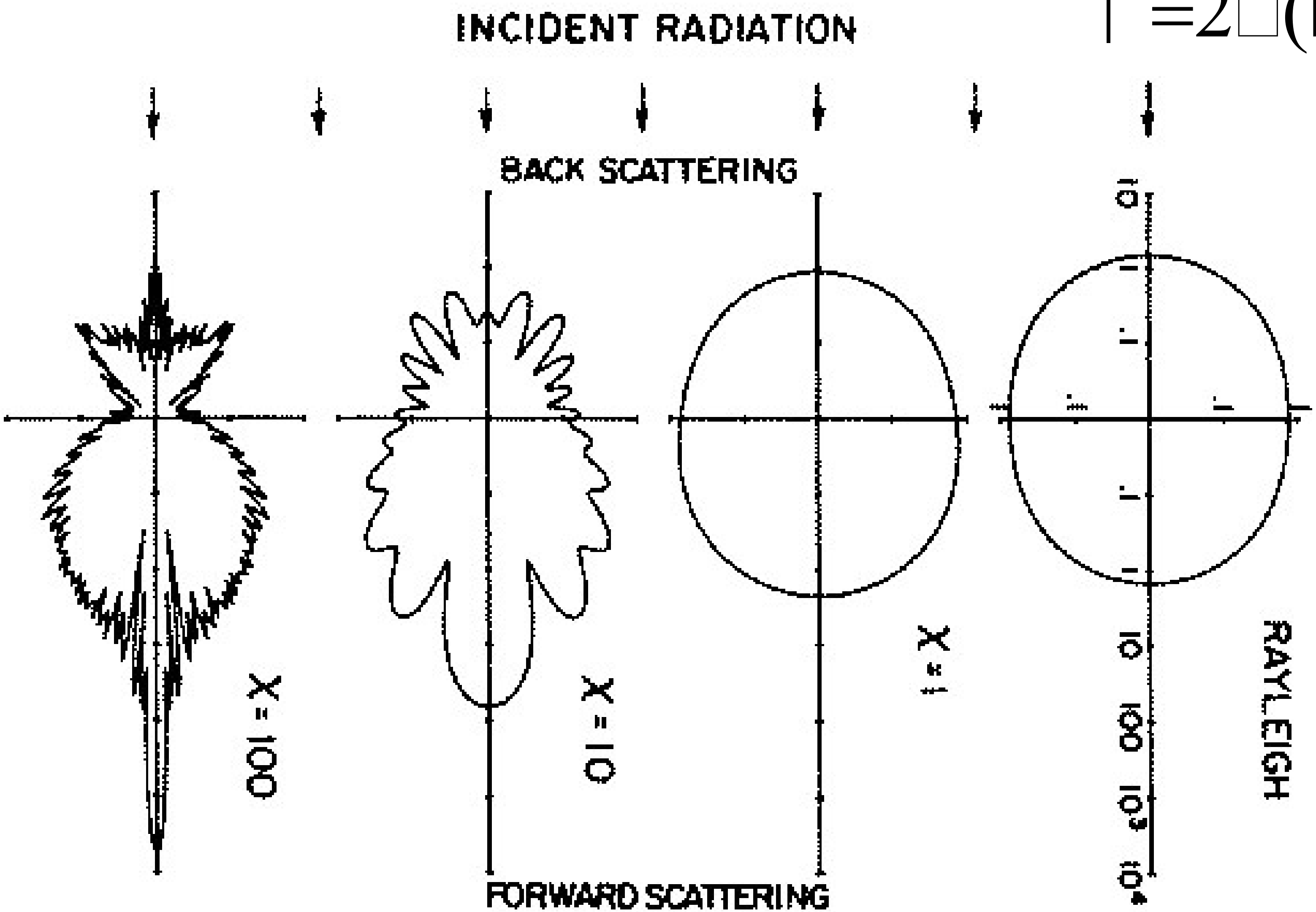
# What scatters in the atmosphere?

- In the atmosphere (for VIS):
  - molecules – Rayleigh scattering □ 1/⎣$^{4}$
  - aerosols (haze) -- □ 1/⎣$^{n}$, where $0.2 < n < 2$
  - water droplets – independent of wavelength (n=0)

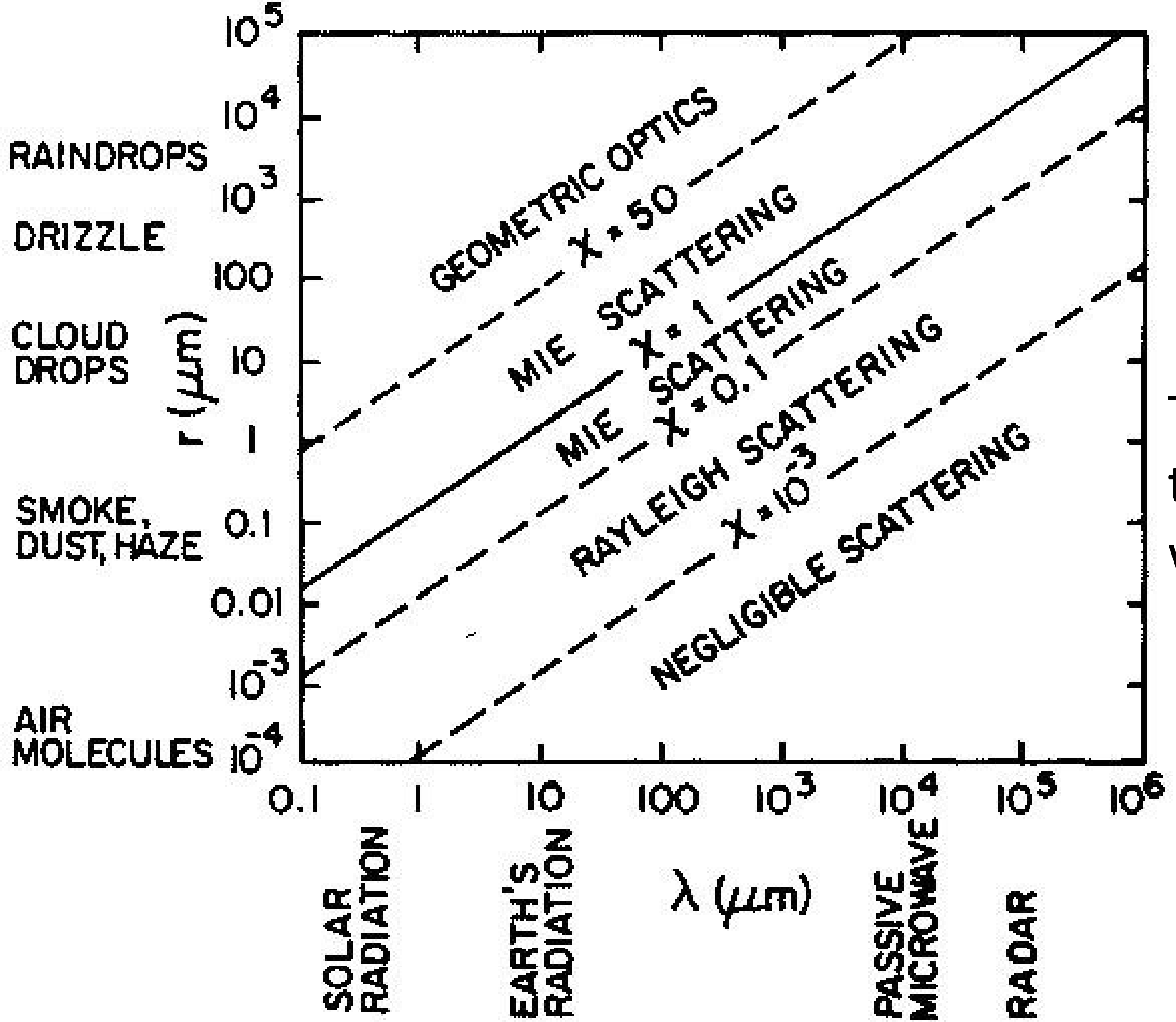
- These different spectral signatures correspond to different regimes of scattering
  - Rayleigh
  - Mie
  - Geometric
- The angular distributions also differ for the regimes

# Angular distribution

$\chi = 2\pi(r/\lambda)$



# Scattering regimes




$\chi = 2\pi(r/\lambda)$

Think about thermal wavelengths

# Kirchhoff's Law: emission and absorption

- Efficient absorbers are efficient emitters
- … and *vice versa*

- If a surface has ∑⌊ =1, it also absorbs all incident spectral radiance at that wavelength

- If a surface absorbs only 80% of the spectral radiance incident on it, then ∑⌊ =0.8

- If a layer of gas, aerosol or cloud of temperature T absorbs a fraction ɑ of IR irradiance incident on it, then it *also* emits/radiates a contribution to exitance of ɑ ⌠$T^4$

# Thinking question

- Radiators are often painted white, which means they absorb little of the light incident on them.

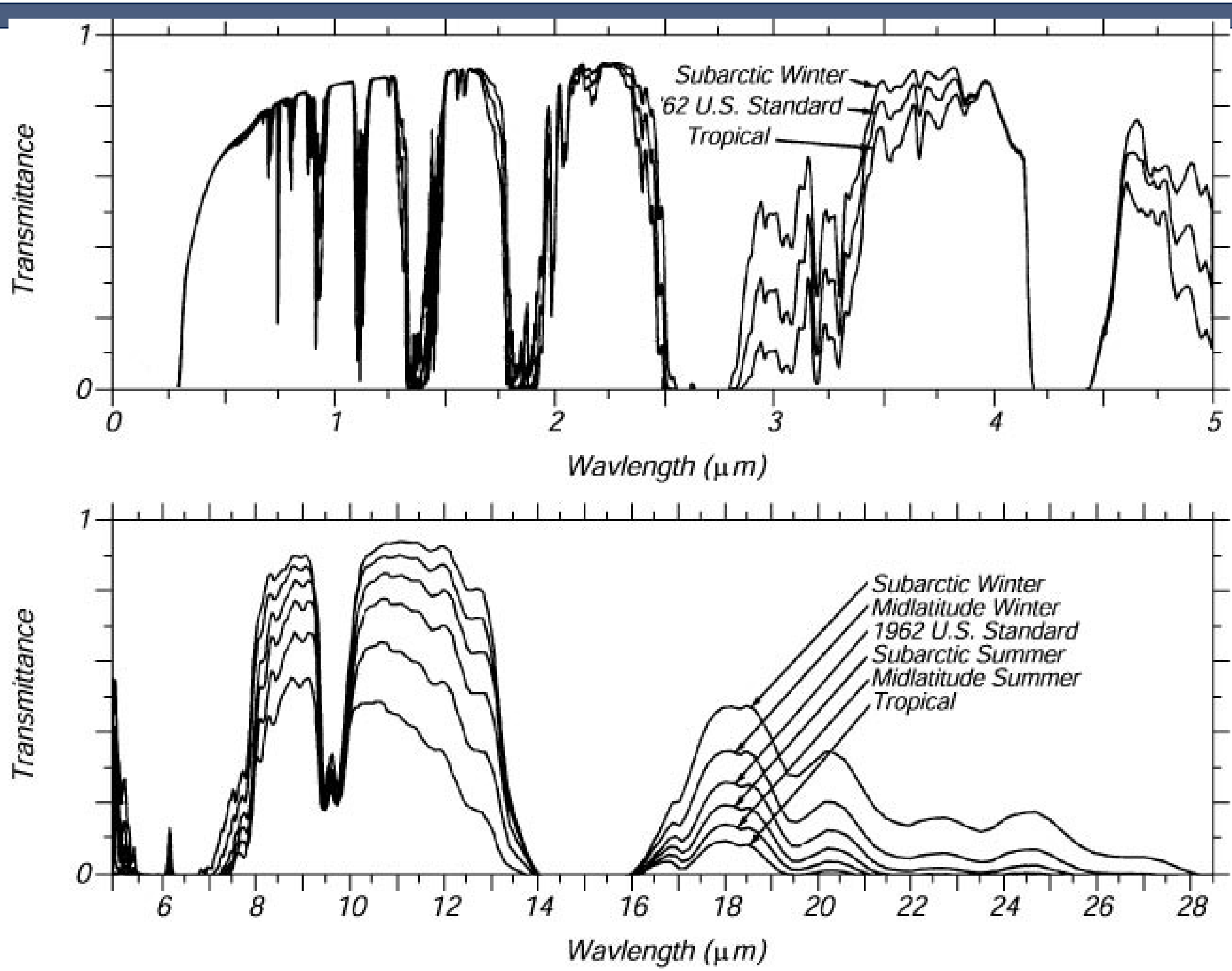
- If they were black, does Kirchhoff's law tells us they would also be better emitters of radiation?
- Would radiators therefore be more efficient at heating rooms if painted black?

# Absorption in transmitting media

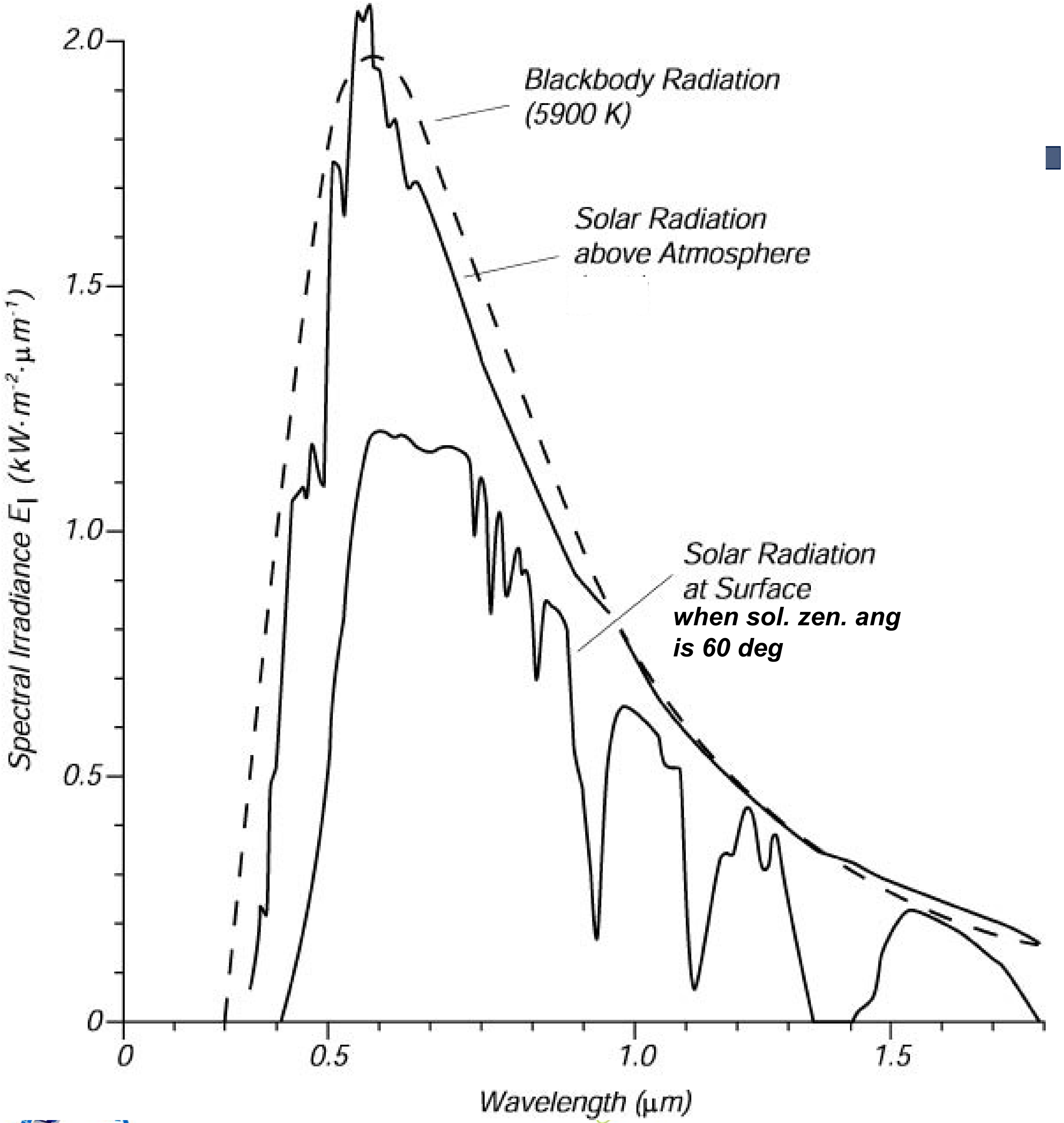
- Transmission = allowing to pass through*
- The atmosphere generally partially transmits
- **Transmittance** is the fraction transmitted
  - $t(z_1, z_2)$ means transmittance from $z_1$ to $z_2$
  - that which is not transmitted is absorbed …
  - … so: $t + \alpha = 1$ (neglecting scattering)

- *Note, in everyday English, people talk of “radio transmitters” meaning the masts that broadcast radio etc. Strictly, such a mast is actually an **e**mitter: the air is the radio **trans**mitter! Sometimes in remote sensing, “transmission” is used for “emission” as well.

# Clear-sky transmittance



# Effect of $t_l$ on solar irradiance

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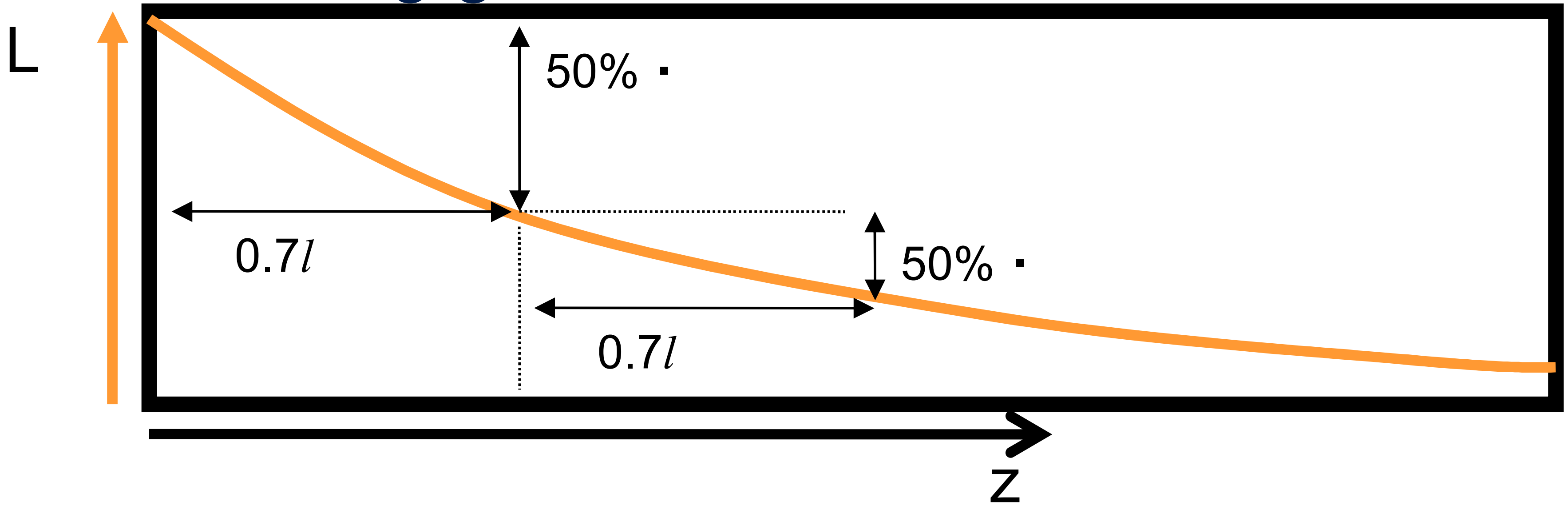
# Attenuation of a beam by absorption

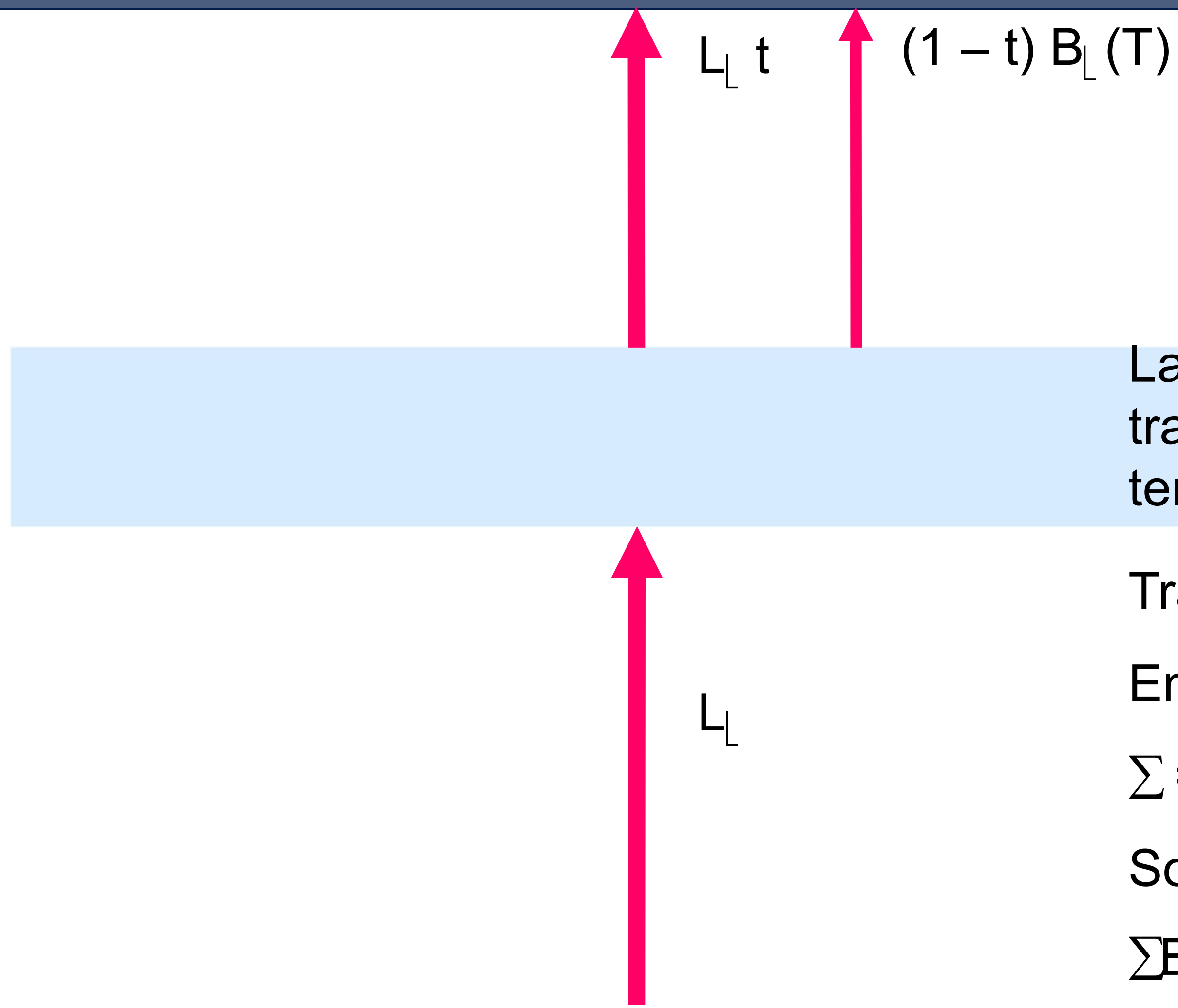
- Uniform medium => const. fraction absorbed in any given length
- Assume negligible emission




$$L = L_{z=0} \exp(-z/l) \quad ; \quad t(0,z) = \exp(-z/l)$$

$z/l$ is called the optical path,

# Absorption and emission




Layer of atmosphere with transmission t and temperature T

Transmission is $t = \exp(-\tau)$ .

Emissivity of this layer is

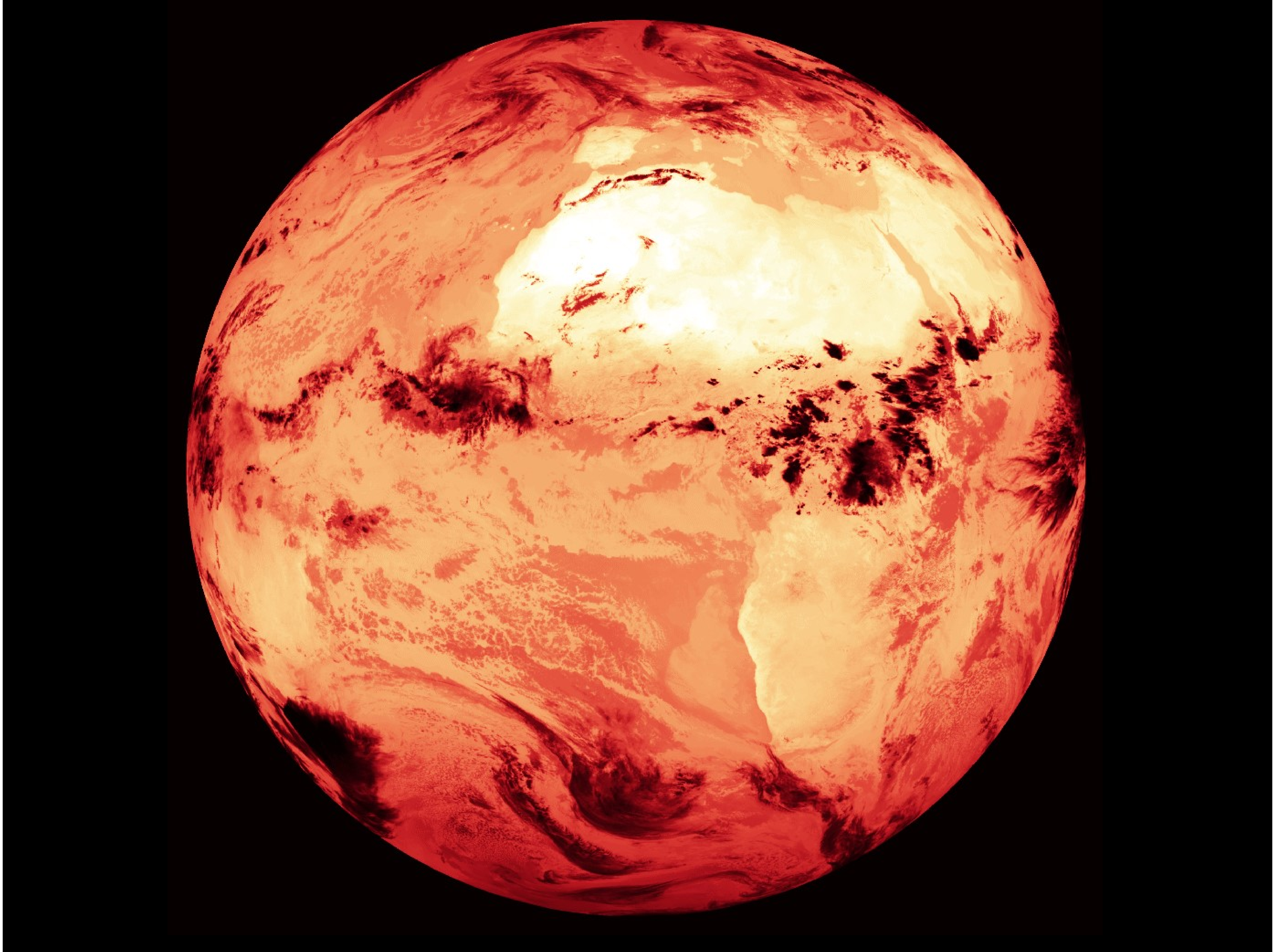
$\varepsilon = \alpha = 1 – t$ .

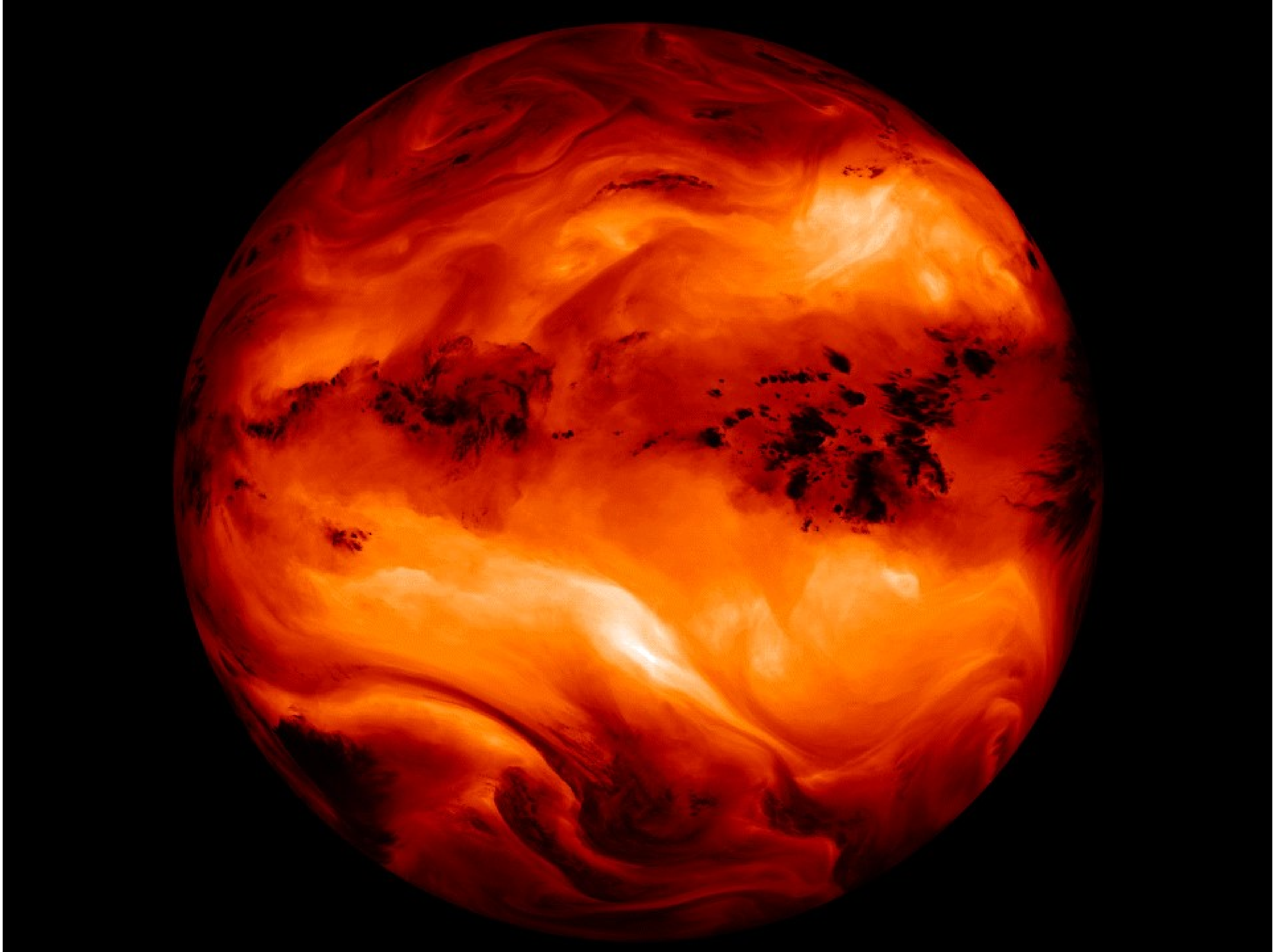
So the emission is

$\varepsilon B_\lambda (T) = (1 – t) B_\lambda (T)$ .

# Thinking

- Total upward spectral radiance (from last slide) is
- $$L_{\lambda} t + (1 - t) B_{\lambda}(T)$$
- When t → 0 …
- When $t > 0$ and $L_{\lambda} > B_{\lambda}(T)$ …
- When $t > 0$ and $L_{\lambda} < B_{\lambda}(T)$ …





# Thermal imagery at 11 and 6.7 ⌠m

- Which image is which wavelength?
- Explain the main features of each image.
- Hint: refer to “clear-sky transmittance” curve from earlier slide

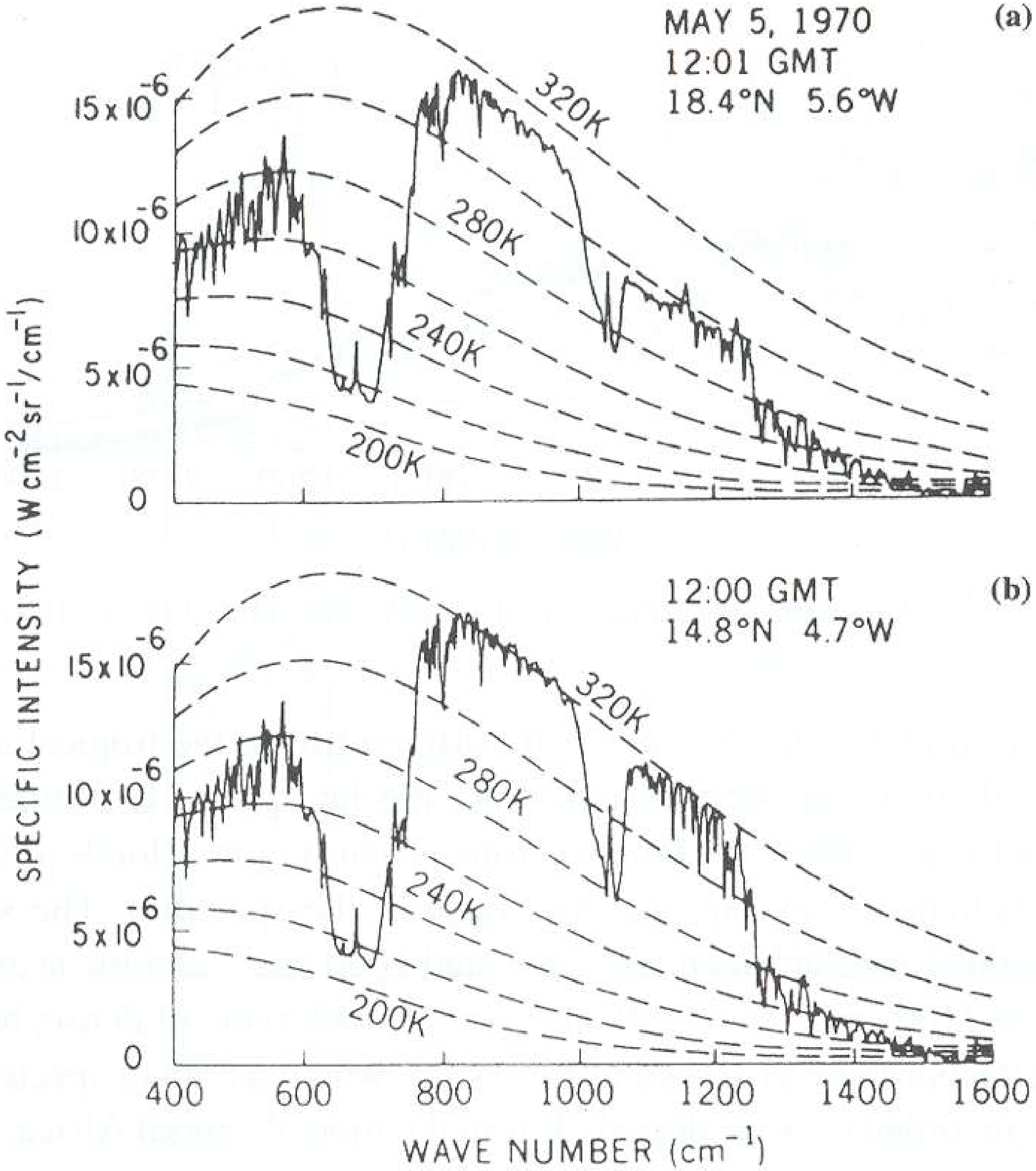
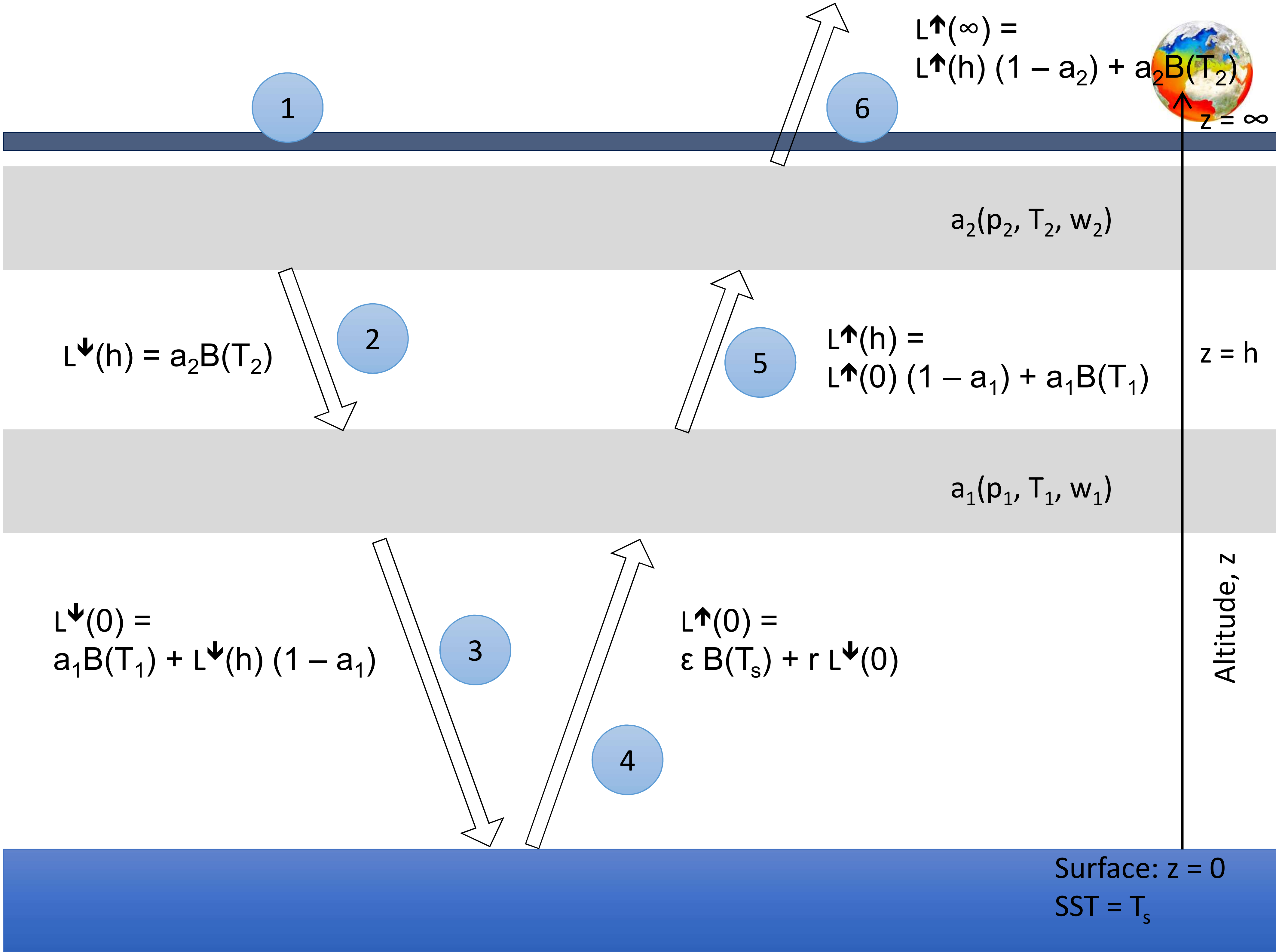



Fig. 6.2.6 (a) Emission spectra from a desert area showing the effect of low emissivity between 1100 and 1250 $cm^{-1}$ caused by residual rays in quartz sand. (b) The comparison spectrum from an area covered by vegetation shows nearly the same brightness temperature on both sides of the ozone band at 1042 $cm^{-1}$ (Hanel *et al.*, 1972*c*).



1
6
$L^{\uparrow}(\infty) =$
$L^{\uparrow}(h)\,(1 - a_2) + a_2B(T_2)$
$z = \infty$
$a_2(p_2, T_2, w_2)$
2
$L^{\downarrow}(h) = a_2B(T_2)$
5
$L^{\uparrow}(h) =$
$L^{\uparrow}(0)\,(1 - a_1) + a_1B(T_1)$
$z = h$
$a_1(p_1, T_1, w_1)$
$L^{\downarrow}(0) =$
$a_1B(T_1) + L^{\downarrow}(h)\,(1 - a_1)$
3
$L^{\uparrow}(0) =$
$\varepsilon\, B(T_s) + r\, L^{\downarrow}(0)$
4
Altitude, z
Surface: z = 0
SST = $T_s$

# How to link BT to surface temperature?



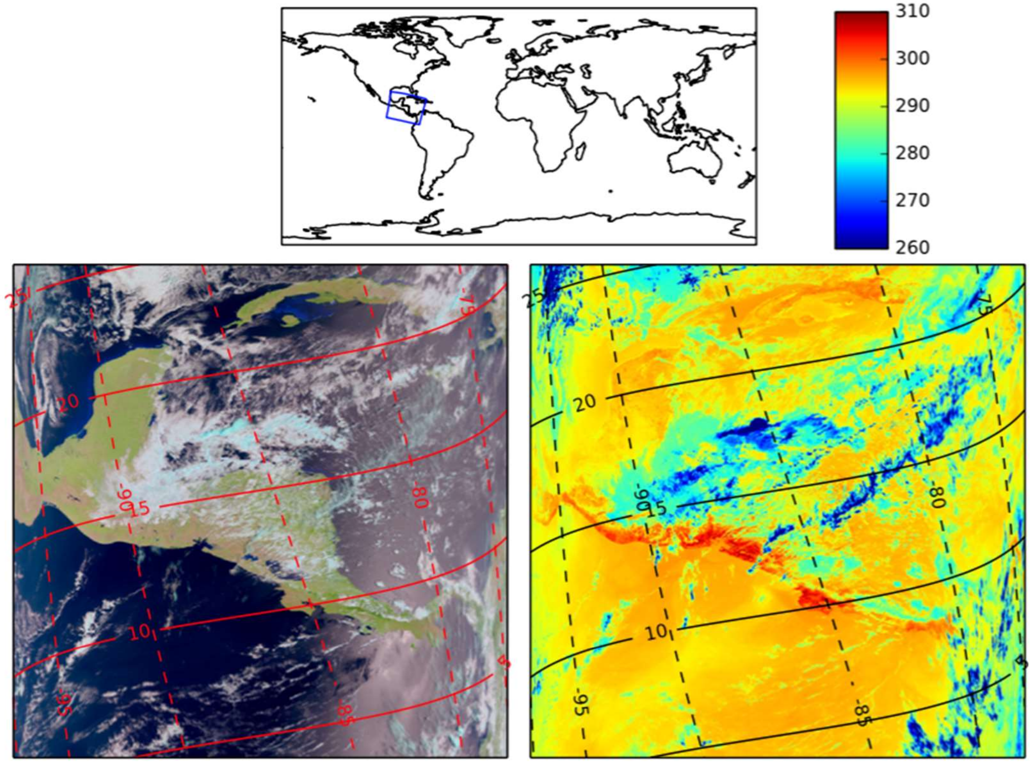



**FIGURE 8** Scene observed by the Metop AVHRR instrument: lines of longitude (dashed) and latitude (solid) show how the image is distorted toward the edge of swath. Left panel: false-color RGB using 1.6 μm (red), 0.8 μm (green), and 0.6 μm (blue) channels. This choice of channels results in a "natural" looking image—oceans are blue, clouds are white, and vegetation is green. Right panel: thermal image observed at 11 μm. Clouds are colder than the surface with high clouds appearing in blue and lower clouds in green and yellow. The temperature of the land can be greater than the ocean and shows greater variability.