



# Satellite Remote Sensing

## SIO 135/SIO 236

## Lecture 6: Thermal Radiation

Helen Amanda Fricker



### How is EMR generated?

**Radio frequency** generated by periodic currents of electric charges in wires.

**Microwave** generated by electron tubes that use the motion of high speed electrons in specially designed structure to generate E/B fields which is then guided by a waveguide to radiation structure

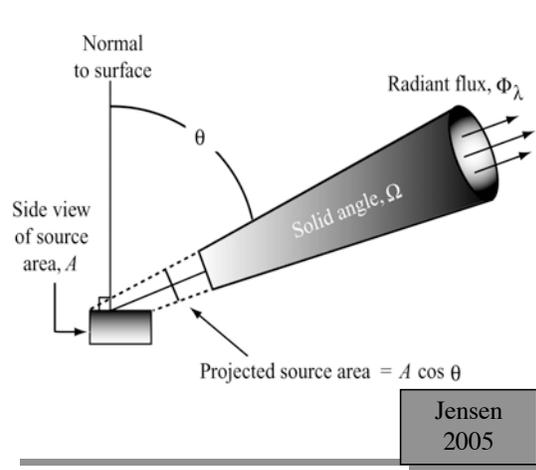
**Visible** high frequency wave in the infrared and visible are generated by molecular excitation (vibrational or orbital) followed by decay. The emitted frequency is exactly related to the energy difference between the 2 energy level of the molecules.

**Heat** kinetic energy of random motion of particles of matter. The random motion results in excitation (electronic, vibrational, rotational) due to collisions followed by random emission of EM wave during the decay. Because of its random nature this type of energy transformation leads to emission over a wide spectral band.

## 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 interested in the radiant flux in certain wavelengths ( $L_\lambda$ ) leaving the projected source area ( $A$ ) within a certain direction ( $\theta$ ) and solid angle ( $\Omega$ ):

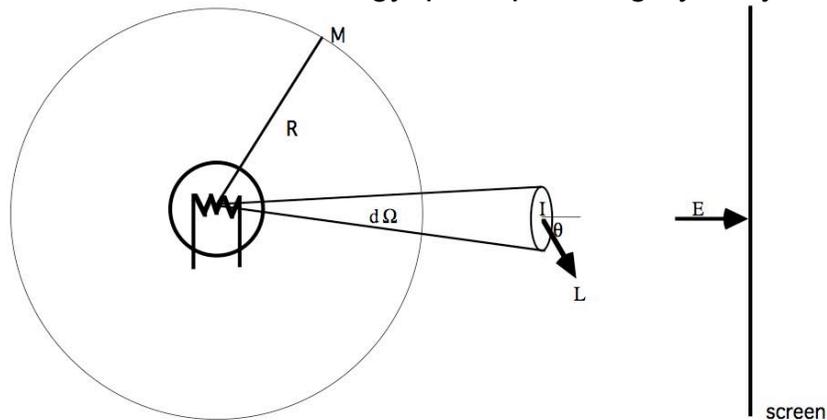


$$L_\lambda = \frac{\frac{\Phi}{\Omega}}{A \cos \theta}$$

units  $\text{W m}^{-3} \text{sr}^{-1}$

## Terminology

Consider a 60 W light bulb. An electric current passes through the tungsten filament and heats it to about  $3000^\circ\text{K}$ . Our bulb is perfect in the sense that it radiates all of this energy, perhaps as a gray body.



radiant flux (total)	$\phi$		60	W
radiant intensity	$I$	$d\phi/d\Omega$	$60/4\pi$	$\text{W sr}^{-1}$
radiant exitance	$M$	$d\phi/dA$	$60/4\pi R^2$	$\text{W m}^{-2}$
radiance (brightness temp.)	$L$	$\cos\theta d^2\phi/(d\Omega dA)$		$\text{W sr}^{-1} \text{m}^{-2}$
irradiance	$E$	$d\phi/dA$		$\text{W m}^{-2}$

# Electromagnetic Spectrum

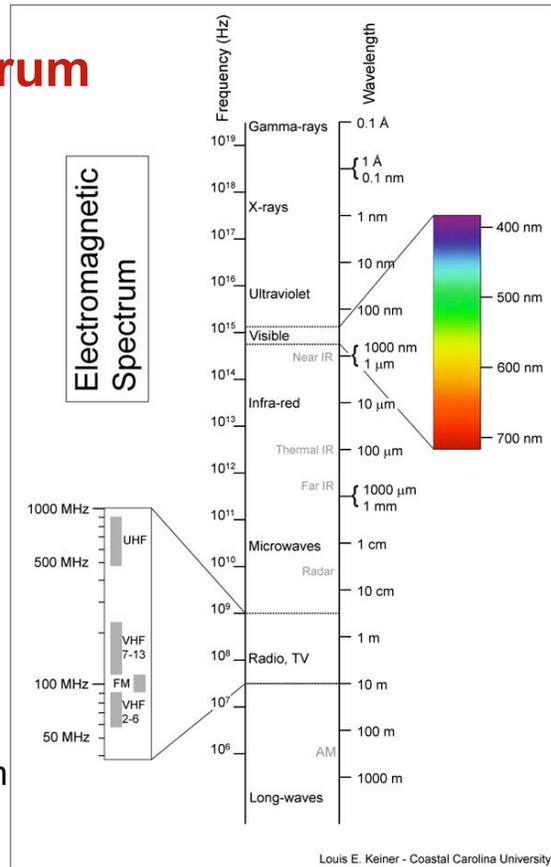
**Visible:** Small portion of the EMS that humans are sensitive to:  
 blue (0.4-0.5  $\mu\text{m}$ ); green (0.5-0.6  $\mu\text{m}$ );  
 red (0.6-0.73  $\mu\text{m}$ )

**Infrared:** Three logical zones:

1. Near IR: reflected, can be recorded on film emulsions (0.7 - 1.3 $\mu\text{m}$ ).
2. Mid infrared: reflected, can be detected using electro-optical sensors (1.3 - 3.0 $\mu\text{m}$ ).
3. Thermal infrared: emitted, can only be detected using electro-optical sensors (3.0 - 5.0 and 8 - 14  $\mu\text{m}$ ).

## Microwave

Radar sensors, wavelengths range from 1mm - 1m ( $K_a$ ,  $K_u$ , X, C, S, L & P)

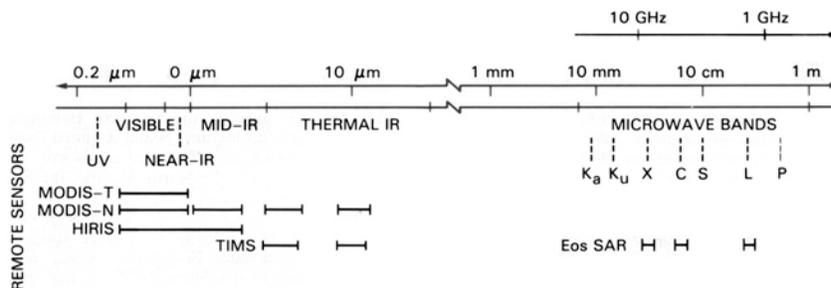


# Spectral bands

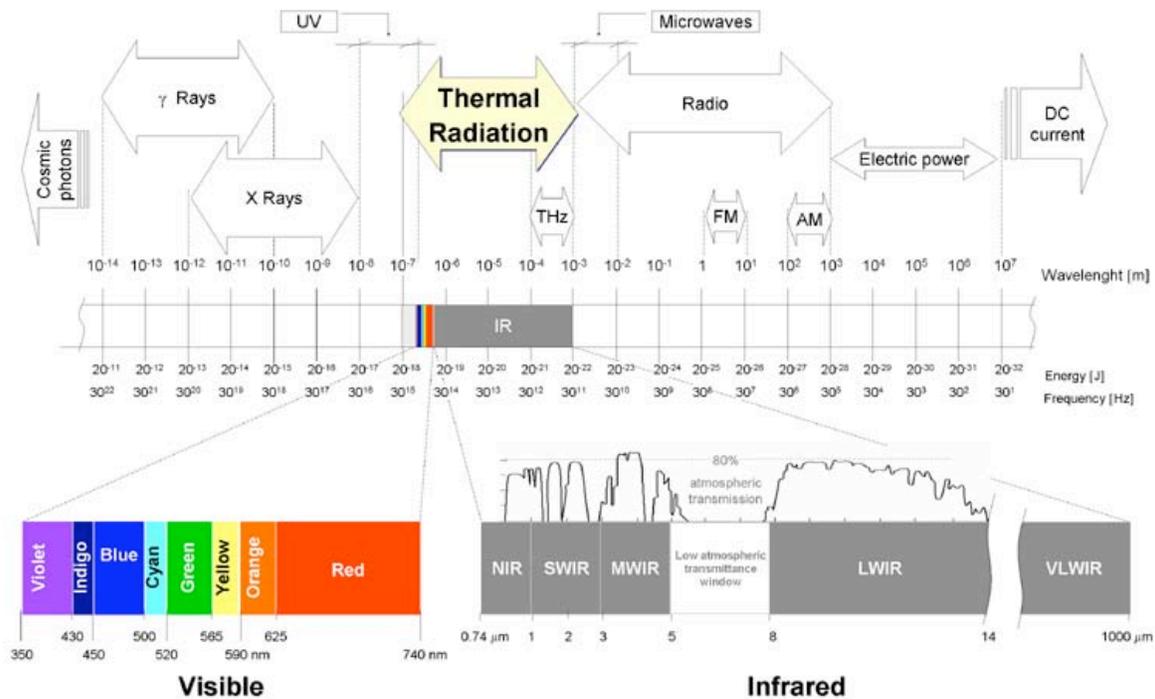
Three important spectral bands in remote sensing:

- visible light
- infrared radiation
- microwave radiation

Image from NASA 1987. SAR: Synthetic Aperture Radar. Earth Observing System, Vol. IIf.



# Thermal channels of the EM spectrum



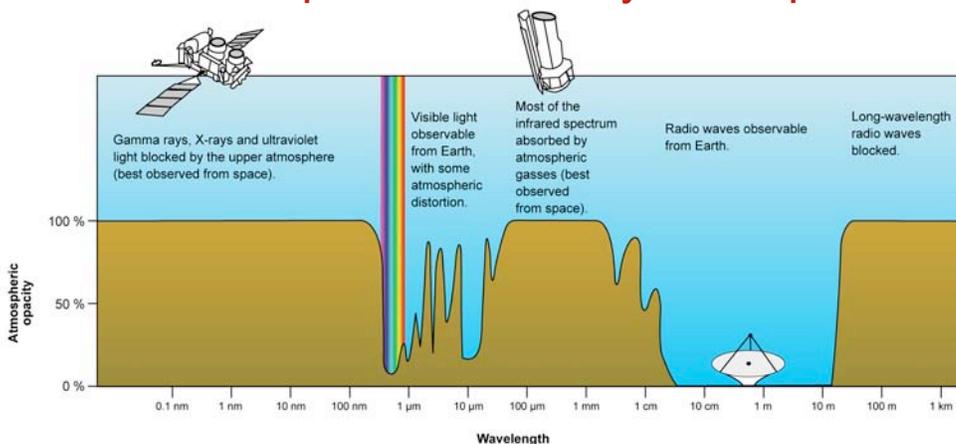
## Absorption

- **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<sub>2</sub>O), carbon dioxide (CO<sub>2</sub>), oxygen (O<sub>2</sub>), ozone (O<sub>3</sub>), and nitrous oxide (N<sub>2</sub>O).
- 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.
- **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 EMR by atmosphere

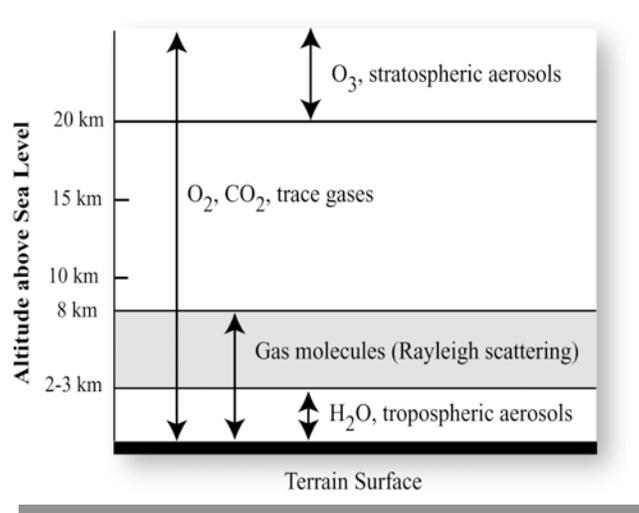


Different molecules absorb different wavelengths of radiation:

- $\text{O}_2$  and  $\text{O}_3$  absorb almost all wavelengths shorter than 300 nm.
- Water ( $\text{H}_2\text{O}$ ) absorbs many wavelengths above 700 nm, but this depends on the amount of water vapor in the atmosphere.

When a molecule absorbs a photon, it increases the energy of the molecule. We can think of this as heating the atmosphere, but the atmosphere also cools by emitting radiation.

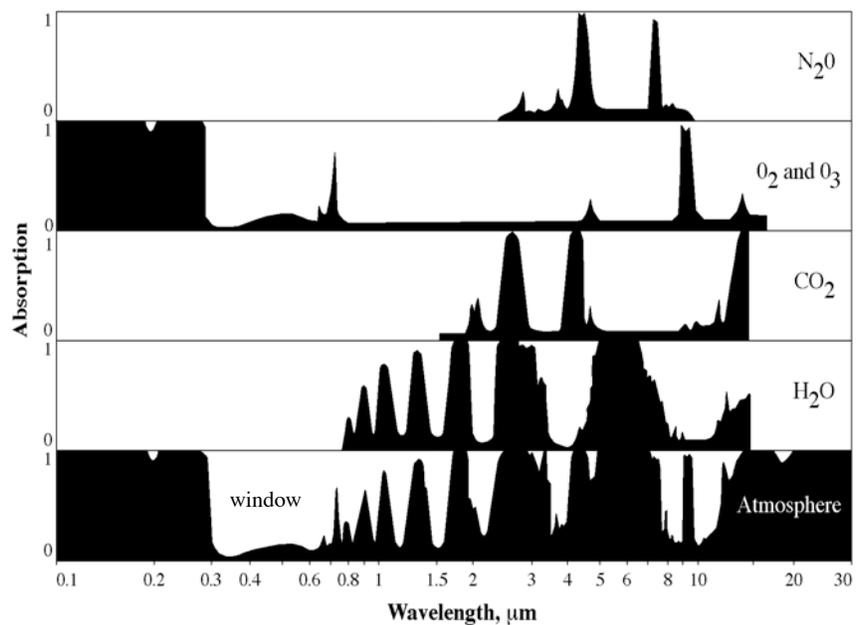
# Atmospheric Layers and Constituents



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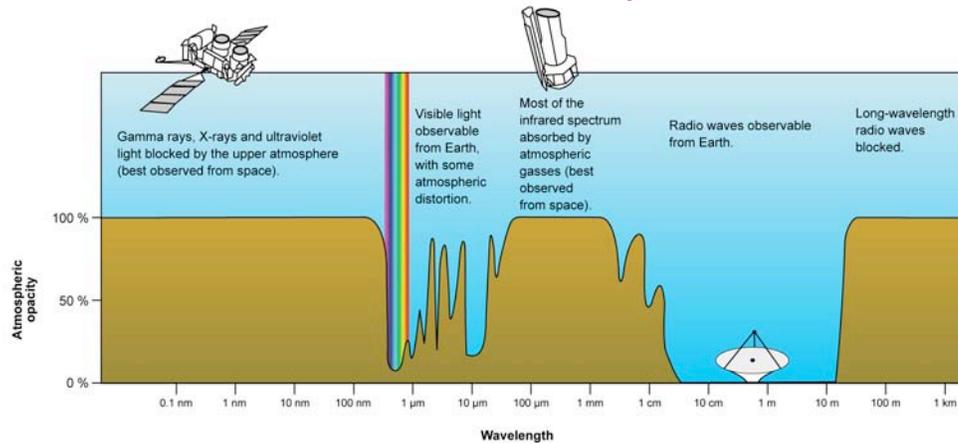
Major subdivisions of the atmosphere and the types of molecules and aerosols found in each layer.

Absorption of the Sun's incident electromagnetic energy in the Region from 0.1 to 30 mm by various atmospheric gases



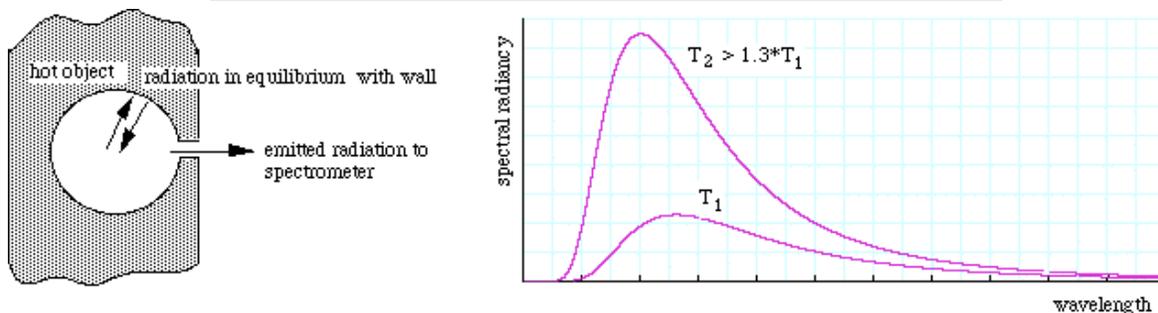
Jensen 2005

## Absorption of EMR by atmosphere



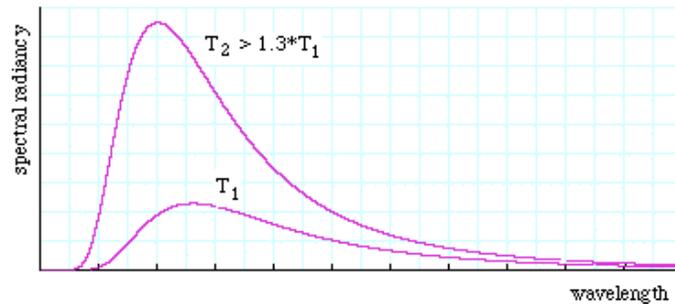
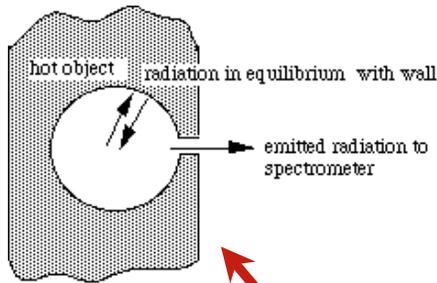
- When you combine the absorption spectra of the gasses in the atmosphere, you are left with "windows" of low opacity, allowing the transmission of only certain EMR.
- Optical window runs from around 300 nm (UV-C) up the visible spectrum (commonly called light), at roughly 400–700 nm and continues to the infrared to around 1100 nm.
- There are also infrared and radio windows.

## Black body lab experiment



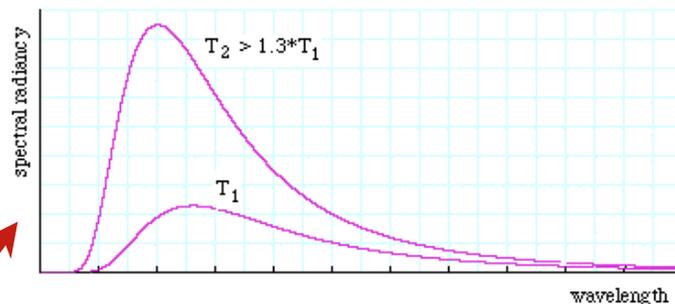
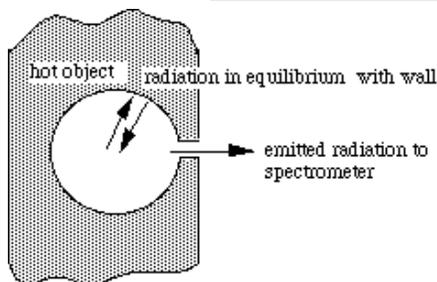
- Let us think of a box with a cavity and hot walls giving off and receiving photons at an equal rate
- If we drill a small hole through the side, the radiation coming out will have the same spectrum, and this is what we measure with our spectrometer to determine the black body radiation spectrum.
- The spectral radiancy is given by Planck's radiation law, which was initially empirical.

## Black body lab experiment



- An object of controlled temperature  $T$  contains a cavity, joined to the outside by a small hole.
- If the hole is very small, the radiation in the cavity comes to equilibrium with the walls.
- The hole allows a small fraction of the radiation to pass to a spectrometer.

## Black body lab experiment



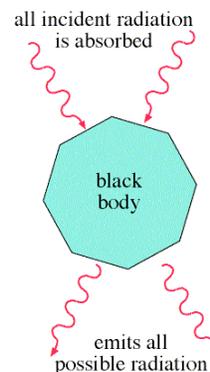
- Plot of Planck's radiation law for two temperatures. Note that the peak of the curve moves to the left as the temperature increases: hotter objects output a larger fraction of their EMR at shorter wavelengths.
- Note also the strong dependence on temperature of the total emission. The radiance is the power emitted per unit area per increment of wavelength and so has units of  $W m^{-3}$ .

## Black body lab experiment

- The spectral radiance from the hole is independent of the material used and only depends on the temperature
- This was a remarkable observation at the turn of the century and many physicists strived to explain it
- Lord Rayleigh and Sir James Jeans developed a classical theory using a principle of equipartition of energy
- Considered all possible standing waves in the cavity and counted the number of standing waves that could occur in a frequency interval  $dv$  they noted that each standing wave could have 2 degrees of freedom so they assigned an energy of  $kT$  to each, where  $k$  is the Boltzmann constant
- The result is the Rayleigh-Jeans approximation for long wavelengths (more later on that)

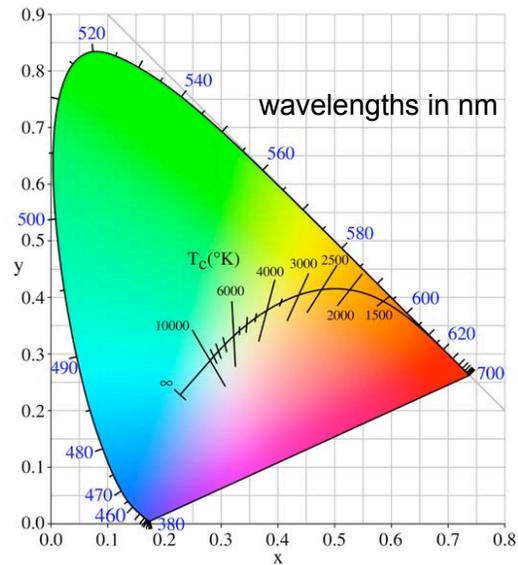
## What is a “black body”?

- A black body is an idealized object that absorbs all EMR that falls on it -- no EMR passes through it and none is reflected.
- The term "black body" was introduced by Gustav Kirchhoff in 1860.
- Because no light (visible EMR) is reflected or transmitted, the object appears black when it is cold.



## What is a “black body”?

- A black body emits a temperature-dependent spectrum of light. This thermal radiation from a black body is termed **black-body radiation**.
- At room temperature, BBs emit mostly infrared light, but as the temperature increases past a few hundred °C, BBs start to emit visible wavelengths, from red, through orange, yellow, and white before ending up at blue, beyond which the emission includes increasing amounts of UV.



Colour of BB radiation depends on the temperature of the BB.

## What is a “black body”?

**Blackbody:** is an ideal source that transforms heat energy into radiant energy with the maximum rate permitted by thermodynamic laws at a given temperature  $T$  and for a given  $\lambda$

We can also say: any object that is a perfect emitter and a perfect absorber of radiation

-- object does not have to appear "black"

-- Sun and Earth behave approximately as black bodies

**The spectral emittance  $S(\lambda)$**  of a blackbody is given by the Planck's formula as:

$$S(\lambda) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{ch/\lambda kT} - 1}$$

$c$  = speed of light

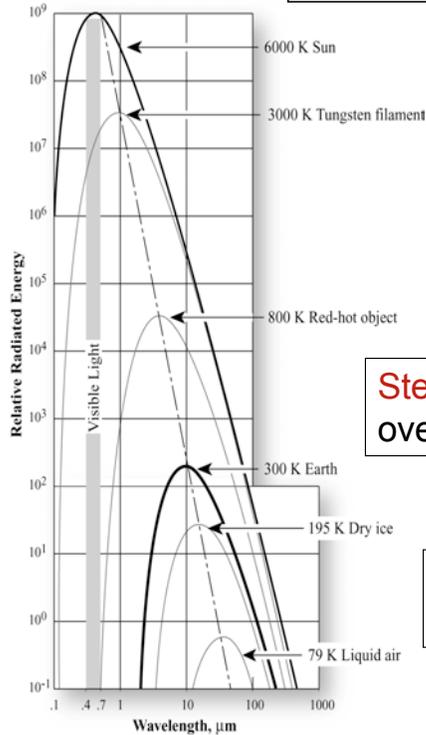
$h$  = Planck's constant

$k$  = Boltzmann constant

$\lambda$  = wavelength

$T$  = absolute temperature in deg K

# Thermal Radiation



- Thermal radiation is emitted by all objects above absolute zero
- In many cases the spectrum of this radiation (i.e. intensity vs wavelength) follows the idealized black-body radiation curve

**Stefan-Boltzmann law:** Total energy emitted over time by a black body is proportional to  $T^4$

**Wiens displacement law:** The wavelength of the spectral peak is proportional to  $T^{-1}$

## Rayleigh-Jeans approximation

Convenient and accurate description for spectral radiance for wavelengths much greater than the wavelength of the peak in the black body radiation formula i.e.  $\lambda \gg \lambda_{\max}$

$$L_{\lambda} = \frac{2kcT}{\lambda^4} \text{ or } L_{\nu} = \frac{2kT\nu^2}{c^2}.$$

Approximation is better than 1% when  $hc/\lambda kT \ll 1$   
or  $\lambda T > 0.77 \text{ m K}$ .

For example, for a body at 300°K, the approximation is valid when  $\lambda > 2.57 \text{ mm}$ ; in other words this approximation is good when viewing thermal emissions from the Earth over the microwave band.

## Stephen-Boltzmann Law

The *total emitted radiation* ( $M_\lambda$ ) from a black body is proportional to the fourth power of its absolute temperature.

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

where  $\sigma$  is the Stefan-Boltzmann constant,  $5.6697 \times 10^{-8} \text{ W m}^{-2} \text{ }^\circ\text{K}^{-4}$ .

→ the amount of energy emitted by an object such as the Sun or the Earth is a function of its temperature.

→ This can be derived by integrating the spectral radiance over the entire spectrum

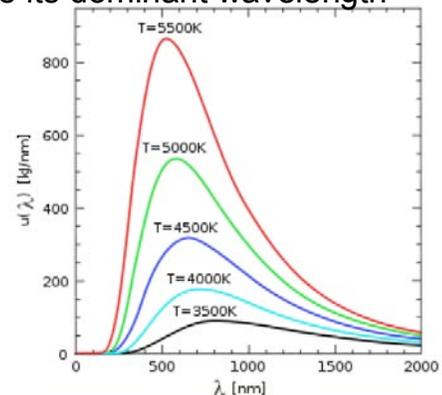
$$L = \int_0^\infty L_\lambda d\lambda = \frac{2\pi^4 k^4}{15 c^2 h^3} T^4 \quad \text{or } M = \pi L = \sigma T^4$$

## Wien'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 *Wien's displacement law*:

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

where  $k$  is Wien's displacement constant =  $2.898 \times 10^{-3} \text{ K m}$ , and  $T$  is the absolute temperature in K.



Black body thermal emission intensity as a function of wavelength for various (absolute) temperatures.

i.e. there is an inverse relationship between the wavelength of the peak of the emission of a black body and its temperature.

Therefore, as the Sun approximates a 6000 K blackbody, its dominant wavelength ( $\lambda_{\max}$ ) is 0.48  $\mu\text{m}$ .

# Real materials

Real materials are not black bodies, so we introduce a property, its emissivity  $\epsilon$ :

- describes the actual absorption and emission properties of real objects, or gray bodies.
- is wavelength dependent  $\epsilon(\lambda)$
- is the ratio of the energy radiated (emitted) by the material to the energy radiated by a black body at the same temperature
- is a measure of a material's ability to absorb and radiate energy
- has a value from 0 to 1

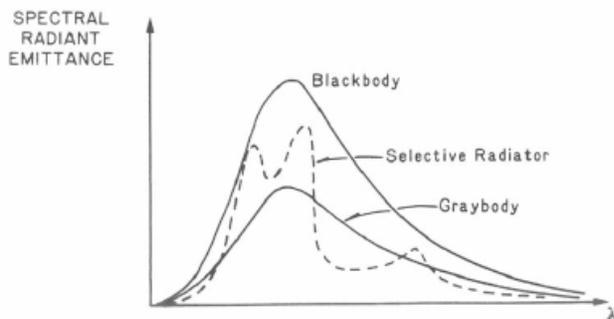
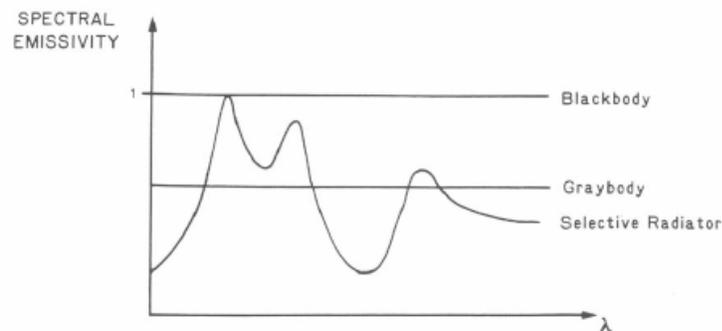
$$L_{\lambda} = \epsilon(\lambda) L_{\lambda,p}$$

Black-body radiance

**Graybody:** an object that reflects part of the incident radiation

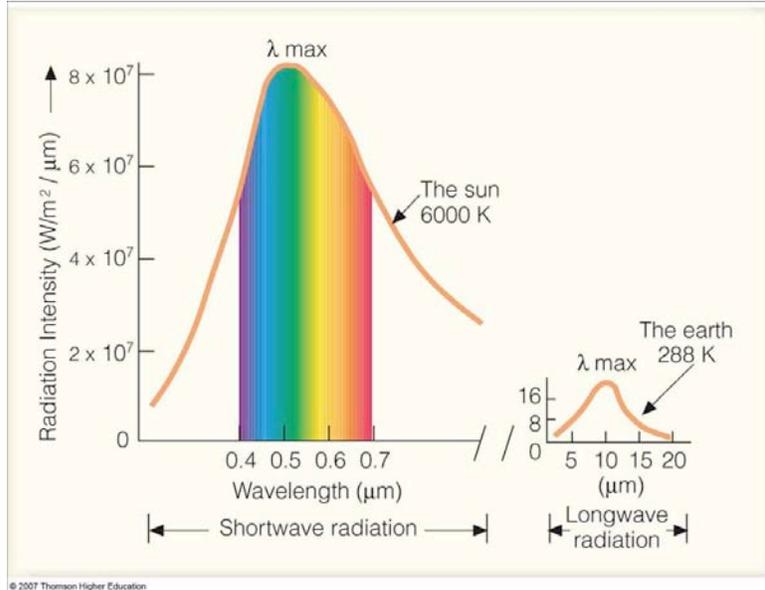
Reflectivity is  $1 - \epsilon(\lambda)$

# Real materials



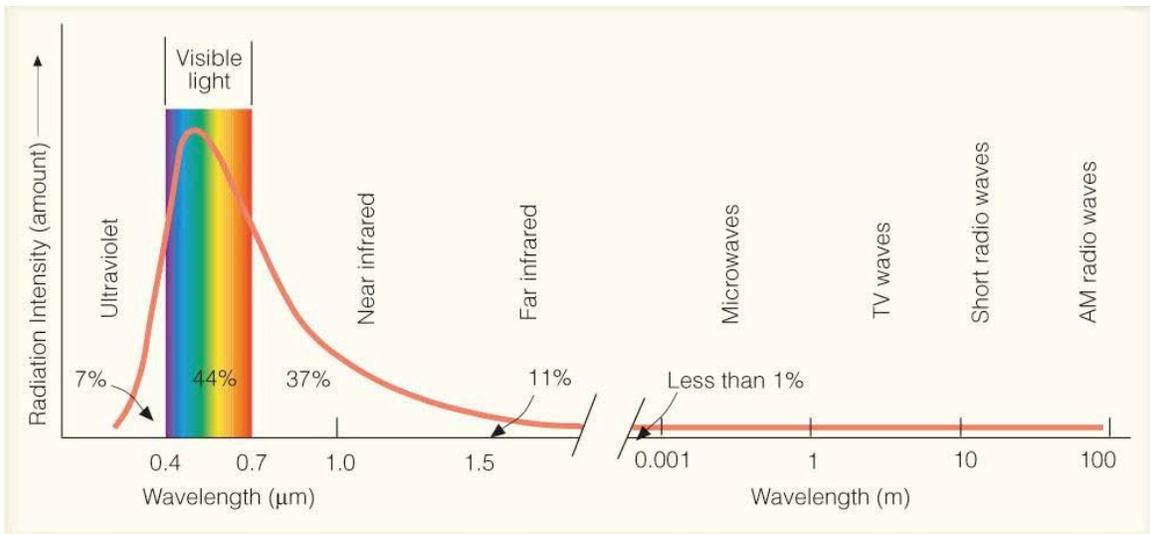
# The Sun as a black-body

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 Sun as a black-body

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## Temperature of lava flow

The temperature of a P\_hoehoe lava flow can be estimated just by observing its colour. The result agrees well with the measured temperatures of lava flows at about 1000 to 1200°C.



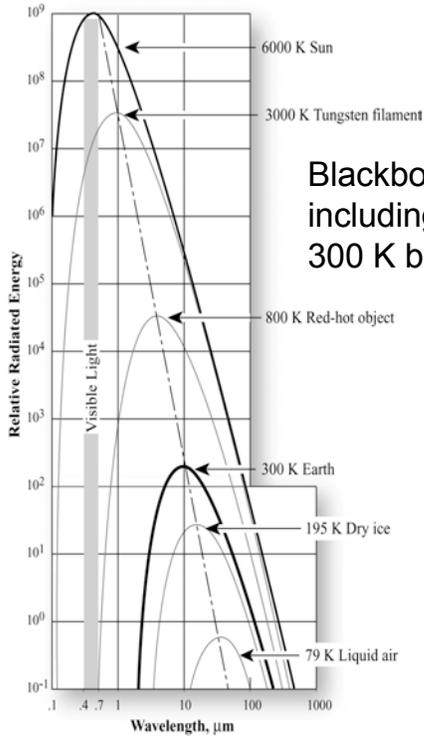
## Thermal radiation



Thermal cameras and imaging systems respond to infra-red radiation and, suitably calibrated for emissivity, can produce images of the surface temperatures of bodies.

In this picture, false colour is used in the display.

# Blackbody Radiation Curves

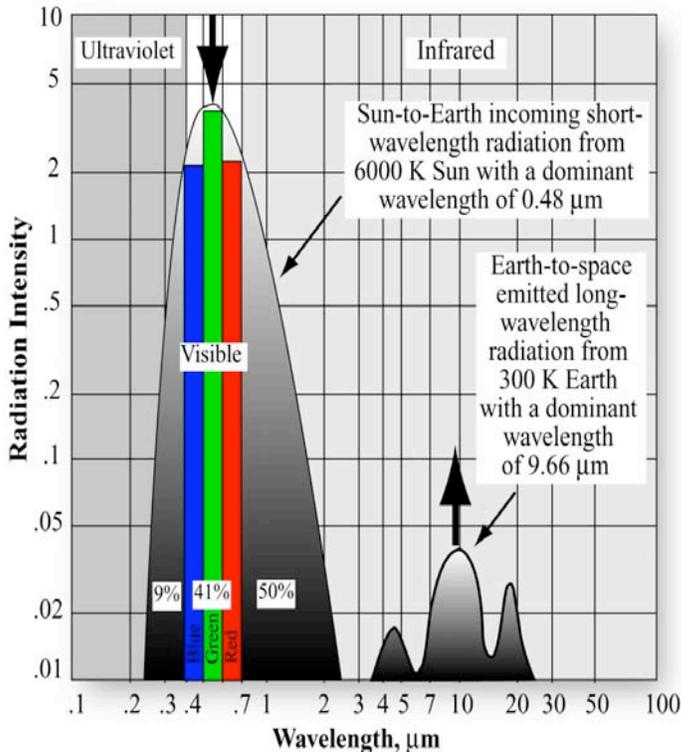


Blackbody radiation curves for several objects including Sun & Earth (they approximate 6,000 K and 300 K blackbodies).

Area under each curve may be summed to compute the total radiant energy ( $M_i$ ) exiting each object. Thus, the Sun produces more radiant exittance 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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# Radiant Intensity of the Sun

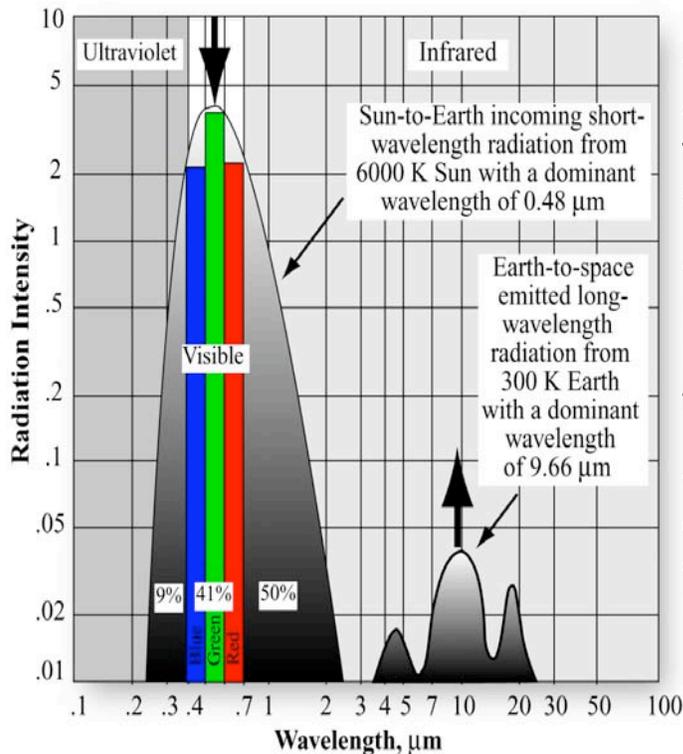


- The Sun approximates a 6000 K blackbody with a dominant wavelength of 0.48 μm (green).

- Earth approximates a 300 K blackbody with a dominant wavelength of 9.66 μm.

Jensen 2005

# Radiant Intensity of the Sun



- The Sun produces 41% of its energy in the visible region from 0.4-0.7 μm (blue, green, and red light).
- The other 59% of the energy is in wavelengths shorter than blue light (<0.4 μm) and longer than red light (>0.7 μm).
- Remote sensing detectors can be made sensitive to energy in the non-visible regions of the spectrum.

Jensen 2005

# Planck's law

Describes the amplitude of radiation emitted (i.e., spectral radiance) from a black body. It is generally provided in one of two forms;  $L_{\lambda}(\lambda)$  is the radiance per unit wavelength as a function of wavelength  $\lambda$  and  $L_{\nu}(\nu)$  is the radiance per unit frequency as a function of frequency  $\nu$ .

The first form is:

$$L_{\lambda}(\lambda) = \frac{2hc^2}{\lambda^5} \left[ \exp \frac{hc}{\lambda kT} - 1 \right]^{-1} \text{ where}$$

$T$	-	temperature	
$c$	-	speed of light	$2.99 \times 10^8 \text{ m s}^{-1}$
$h$	-	Planck's constant	$6.63 \times 10^{-34} \text{ J s}$
$k$	-	Boltzmann's constant	$1.38 \times 10^{-23} \text{ J}^{\circ}\text{K}^{-1}$
$L_{\lambda}$	-	spectral radiance	$\text{W m}^{-3} \text{ sr}^{-1}$
$L_{\nu}$	-	spectral radiance	$\text{W m}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$

## Planck's law

To relate the two forms and establish  $L_\nu(\nu)$ , we take the derivative of  $L$  with respect to  $\nu$  using the chain rule:

$$\frac{\partial L}{\partial \nu} = - \frac{\partial L}{\partial \lambda} \frac{\partial \lambda}{\partial \nu}$$

Since  $\lambda = c/\nu$ , so that  $\frac{\partial \lambda}{\partial \nu} = -\frac{c}{\nu^2}$

which gives:

$$L_\nu(\nu) = \frac{2h\nu^3}{c^2} \left[ \exp \frac{h\nu}{kT} - 1 \right]^{-1}$$

## Thermal remote sensing

### Strengths

- ✓ Good resolution and accuracy.
- ✓ Long heritage (~ 20 years)

### Weaknesses

- ❖ Obscured by clouds.
- ❖ Atmospheric corrections required.

## Some Applications of Thermal Remote Sensing



ASTER thermal IR image taken at night, showing (in light tones signifying warmer temperatures) the Red Sea and a small land area (dark; cooler) in Eritrea in eastern Africa.

## Thermal satellite sensors

### Along-Track Scanning Radiometer ATSR

ATSR on ERS-1 (1991-19)

ATSR-2 on ERS-2

AATSR on Envisat

ATSR consists of two instruments, an Infra-Red Radiometer (IRR) and a Microwave Sounder (MWS). On board ERS-1 the IRR is a four-channel infra-red radiometer used for measuring sea-surface temperatures (SST) and cloud-top temperatures, whereas on board ERS-2 the IRR is equipped with additional visible channels for vegetation monitoring. The MWS is a two channel passive radiometer.

ATSR-1/2 Spectral Bands ( $10^{-6}$  m)

0.545 - 0.565 (only ATSR-2)

0.649 - 0.669 (only ATSR-2)

0.855 - 0.875 (only ATSR-2)

1.580 - 1.640

3.550 - 3.930

10.40 - 11.30

11.50 - 12.50



ATSR nighttime false color image of Typhoon Saomai over the East China Sea.

# Thermal satellite sensors

Bands are carefully chosen!

AVHRR 3.7 $\mu$ m window sits in the small overlap region between reflected solar radiation & emitted radiation from the earth and clouds.

At night there is no solar radiation component & the radiation in this channel comes from the earth.

By day there is a mixture of radiation of solar & terrestrial origin, but the solar radiation dominates.

At night, enhancing the resolution at the warm end of the grey scale can provide better discrimination of the low cloud cover than can be obtained from other IR images.

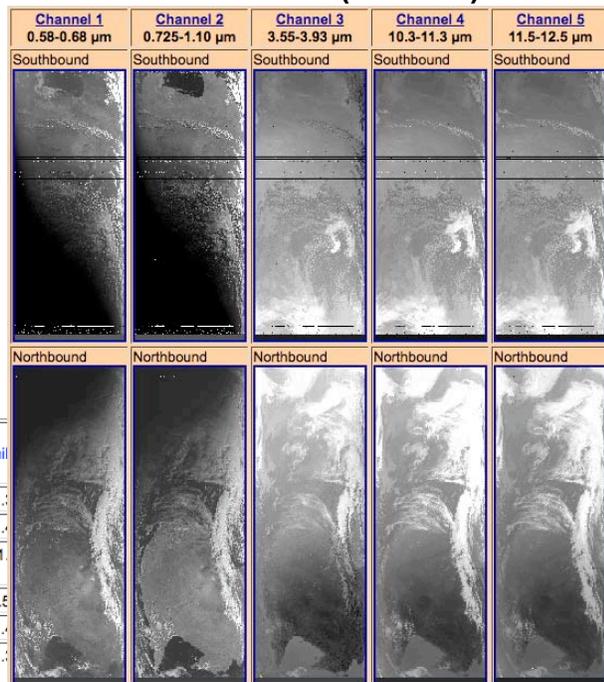
Channel Number	Wavelength (micrometers) NOAA-6,8,10,12	Wavelength (micrometers) NOAA-7,9,11	IFOV (milliradians)	Primary Uses
1	0.58 - 0.68	0.58 - 0.68	1.39	Daytime cloud/surface and vegetation mapping
2	0.725 - 1.10	0.725 - 1.10	1.41	Surface water, ice, snow melt, and vegetation mapping
3A	-	1.58-1.64 (NOAA 15-16)	1.3	Snow and ice detection
3B	3.55 - 3.93	3.55 - 3.93	1.51*	Sea surface temperature, night-time cloud mapping
4	10.50 - 11.50	10.3 - 11.3	1.41	Sea surface temperature, day and night cloud mapping
5	Channel 4 repeated	11.5 - 12.5	1.30	Sea surface temperature, day and night cloud mapping

# Thermal satellite sensors

## Advanced Very High Resolution Radiometer (AVHRR)

AVHRR is a broad-band, 4 or 5 channel (depending on model) scanner, sensing in the visible, near-infrared, and thermal infrared portions of EMS.

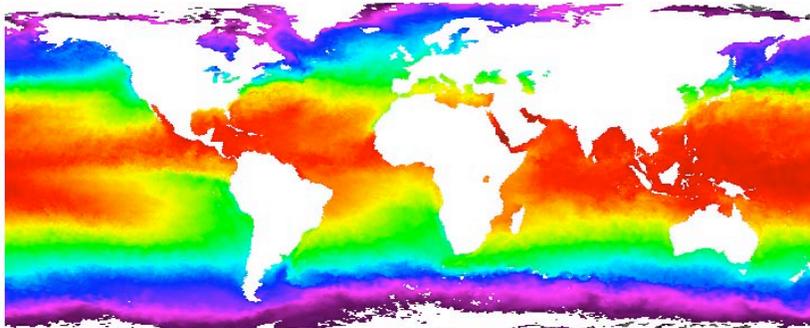
Carried on the NOAA's Polar Orbiting Environmental Satellites (POES), beginning with TIROS-N in 1978.



Channel Number	Wavelength (micrometers) NOAA-6,8,10,12	Wavelength (micrometers) NOAA-7,9,11	IFOV (mil)
1	0.58 - 0.68	0.58 - 0.68	1.39
2	0.725 - 1.10	0.725 - 1.10	1.41
3A	-	1.58-1.64 (NOAA 15-16)	1.3
3B	3.55 - 3.93	3.55 - 3.93	1.51*
4	10.50 - 11.50	10.3 - 11.3	1.41
5	Channel 4 repeated	11.5 - 12.5	1.30

## Sea surface temperature

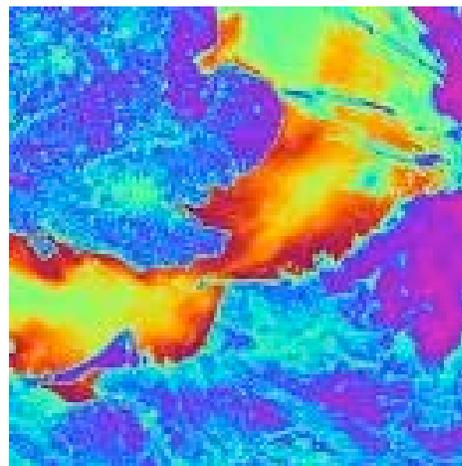
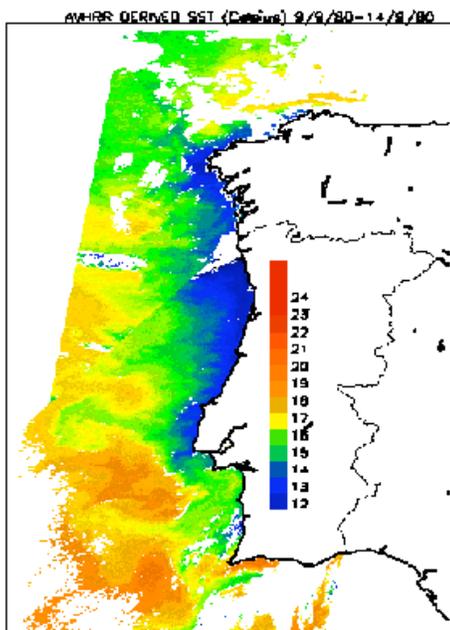
- Sea surface temperature (SST) is an important geophysical parameter, providing the boundary condition used in the estimation of heat flux at the air-sea interface.
- On the global scale this is important for climate modeling, study of the earth's heat balance, and insight into atmospheric and oceanic circulation patterns and anomalies (such as El Niño).
- On a local scale, SST can be used operationally to assess eddies, fronts and upwellings for marine navigation and to track biological productivity.



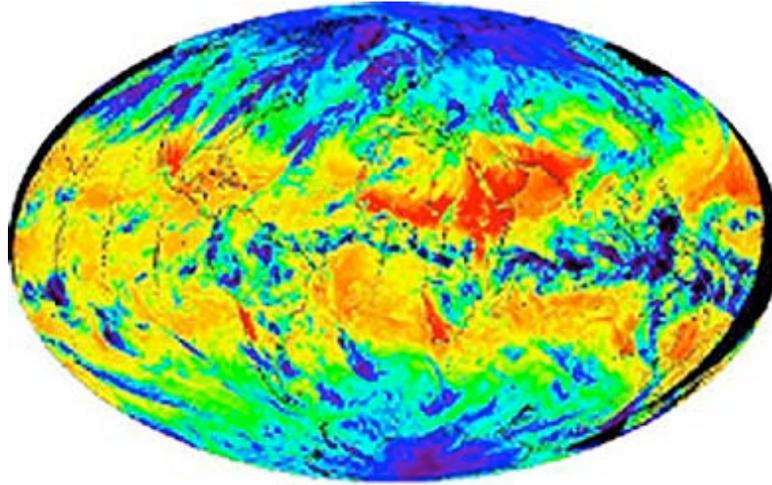
Calibration is very important for trends in SST!

AVHRR Sea Surface Temperature, October 2001 (NASA/JPL PO.DAAC)

## Sea surface temperature



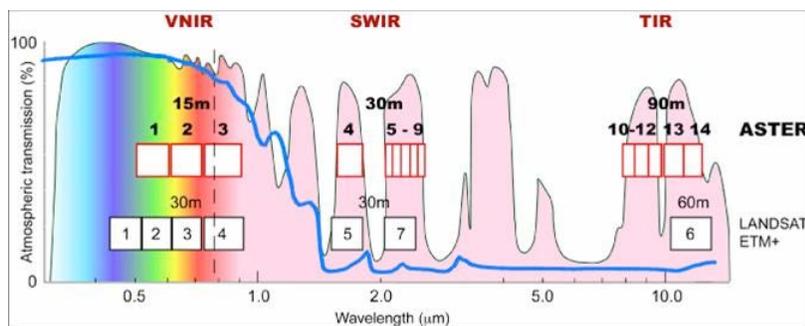
# Thermal radiation from Earth



Emitted thermal radiation from both the atmosphere and land surfaces (with color assignments of red/yellow to warm and green/blue to cooler). From MODIS on Terra.

## Thermal satellite sensors

ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) on Terra (launched 1999)



The broad spectral coverage and high spectral resolution of ASTER provides critical information for surface mapping, and monitoring of dynamic conditions and temporal change.

E.g.: monitoring glaciers; monitoring volcanoes; identifying crop stress; determining cloud morphology and physical properties; wetlands evaluation; thermal pollution monitoring; coral reef degradation; surface temperature mapping of soils and geology; measuring surface heat balance.

## Thermal satellite sensors

ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) on Terra (launched 1999)



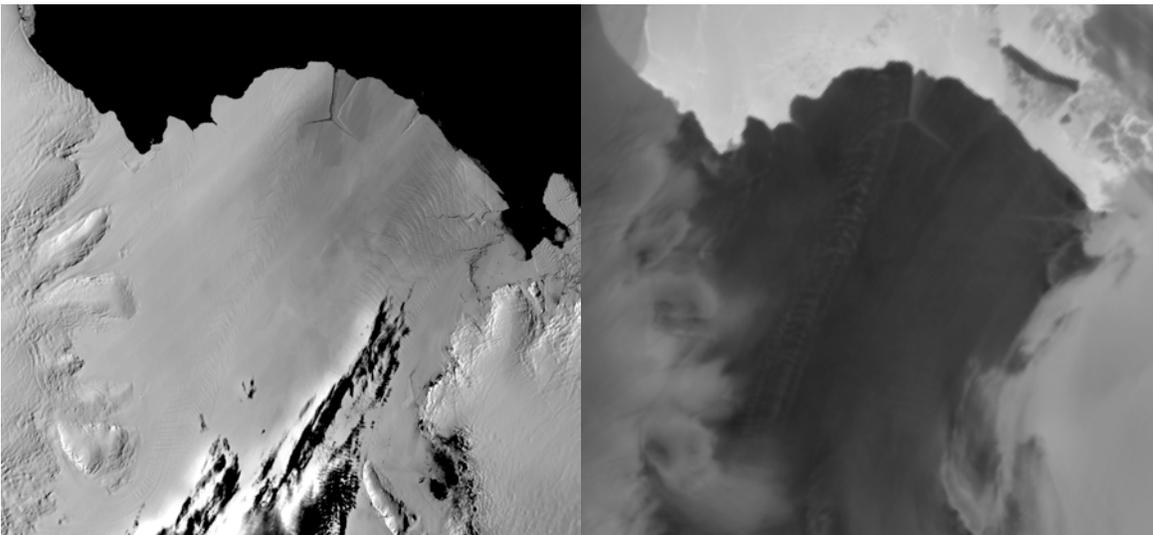
The broad spectral coverage and high spectral resolution of ASTER provides critical information for surface mapping, and monitoring of dynamic conditions and temporal change.

E.g.: monitoring glaciers; monitoring volcanoes; identifying crop stress; determining cloud morphology and physical properties; wetlands evaluation; thermal pollution monitoring; coral reef degradation; surface temperature mapping of soils and geology; measuring surface heat balance.

Augustine Volcano, Cook Inlet, Alaska (22:50 AST January 31, 2006).  
This ASTER thermal image was acquired at night during an eruptive phase.

## Monitor the ice sheets during polar winter

- During polar darkness, cannot get visible images from Antarctica
- Thermal helps to lengthen time series (although lower resolution)  $\lambda/d!$

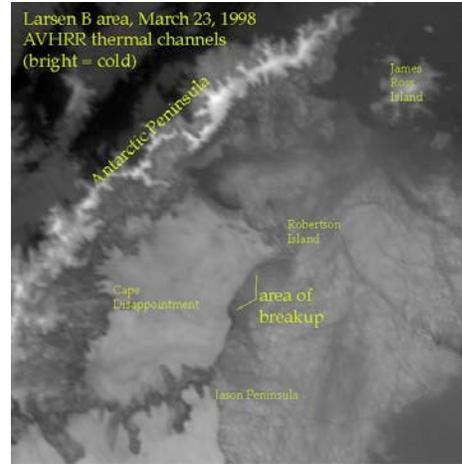
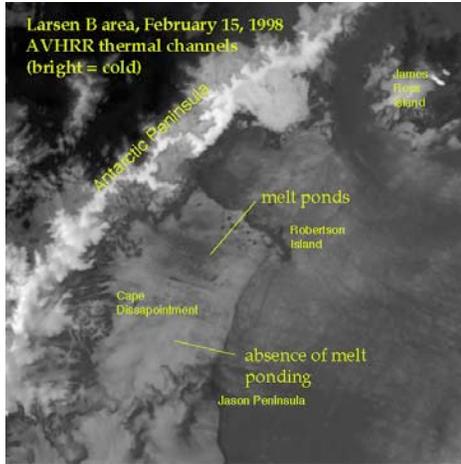


MODIS Terra visible 13 March 2009

MODIS Aqua thermal 6 April 2009

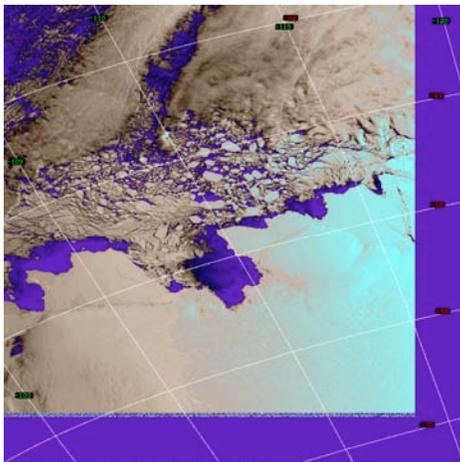
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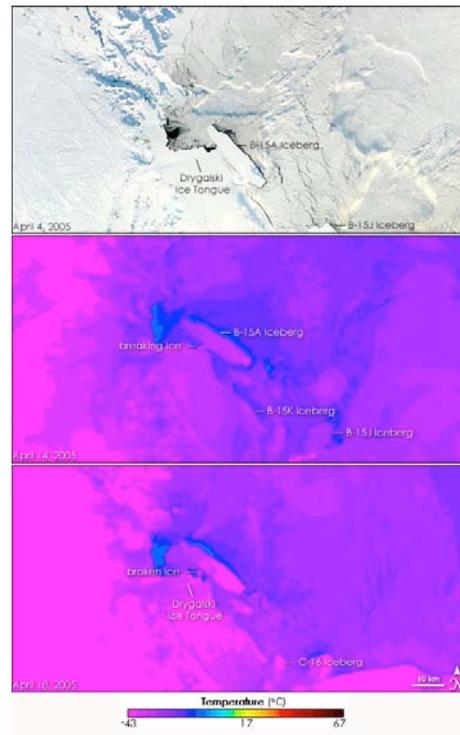
## Sea-ice mapping

- Monitor extent of sea-ice in the Arctic and Antarctic
- Thermal remote sensing can distinguish between the sea-ice and “leads” (open water between the sea-ice) -- useful for navigation and for science

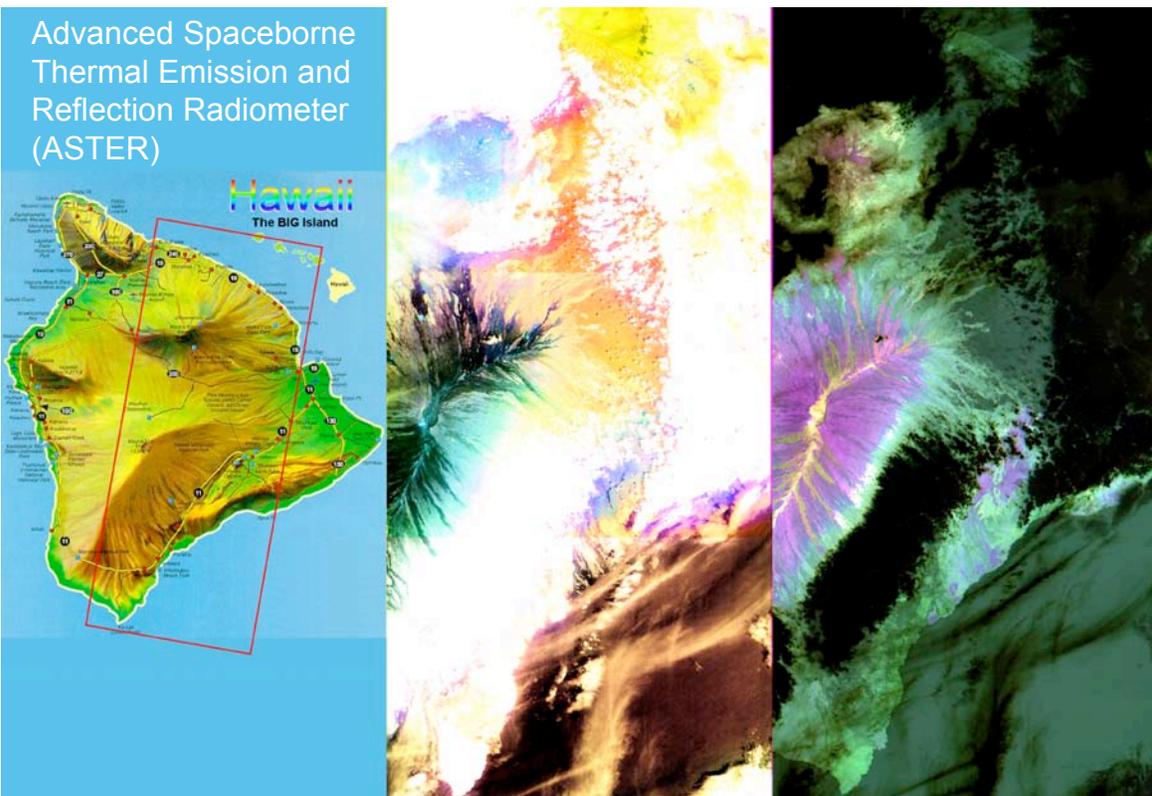


# Thermal satellite sensors

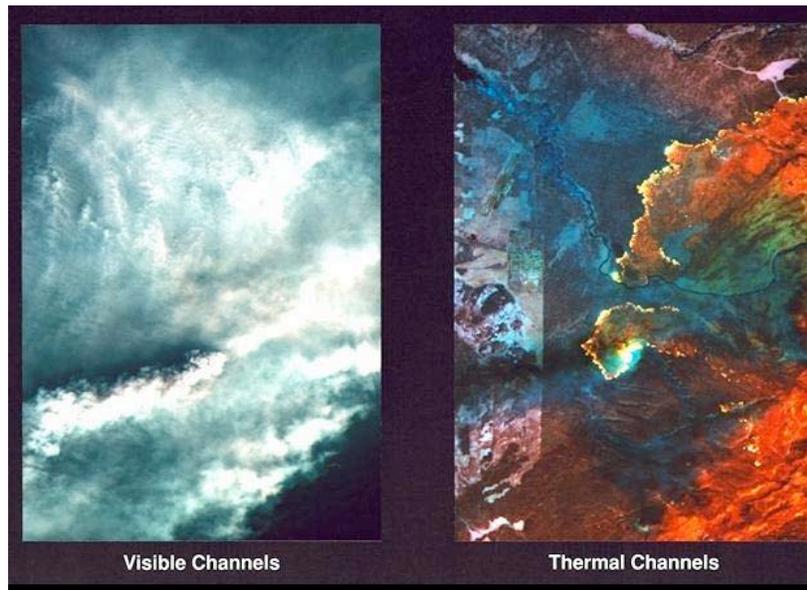
NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) has several bands in the thermal IR



## Hawaii March 19, 2000



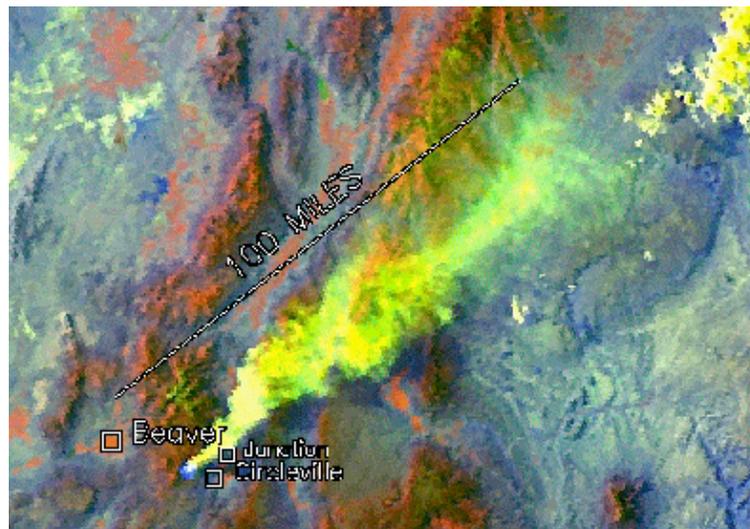
## Fire monitoring



Images of 1988 Yellowstone fires. Visible image is what you'd see flying over a forest fire - smoke! Right image combines several infrared bands (reflective and thermal infrared) to cut through the smoke. Bright yellow areas are actively burning fire lines.

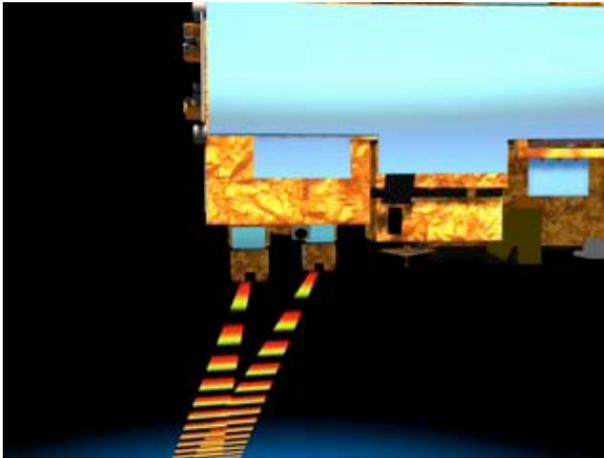
## Fire monitoring

Major fires are commonly imaged by satellites, and the extent of the burn damage is easily assessed afterwards by the dark patterns in the visible bands.



“False color” AVHRR composite (made by assigning channel 1 image to red, channel 2 to green, and channel 3 to blue). In this version, the smoke shows as yellow and the fire, at the head of the smoke column, appears as bright blue.

## Clouds and the Earth's Radiant Energy System (CERES)



CERES is a scanning broadband radiometer radiometer instrument

Measures the reflected sunlight and emitted thermal energy from the surface of the Earth and the atmosphere.

The radiometer is made up of three sensors, each with its own telescope mounted on a gimbaled platform that scans across the Earth in a 6.6-second cycle.

## Thermal satellite sensors

### Landsat Multi-spectral scanner (Landsat-1 to 5)

MSS were the first global monitoring systems capable of producing multispectral data in digital format.

Landsat MSS collects reflected and/or radiated energy from the Earth in four bands or channels of the electromagnetic spectrum: two in the visible spectrum and two in the near-infrared spectrum

Channel (Band)		Channel (Band)		Wavelength Range (mm)
Landsat 1,2,3	Resolution	Landsat 4,5	Resolution	
MSS 4	79 m	MSS 1	82 m	0.5 - 0.6 (green)
MSS 5	79 m	MSS 2	82 m	0.6 - 0.7 (red)
MSS 6	79 m	MSS 3	82 m	0.7 - 0.8 (near infrared)
MSS 7	79 m	MSS 4	82 m	0.8 - 1.1 (near infrared)

# Thermal satellite sensors

## Landsat Thematic Mapper (Landsat-4 onwards)

Advanced, multispectral scanning, with improvements over MSS:

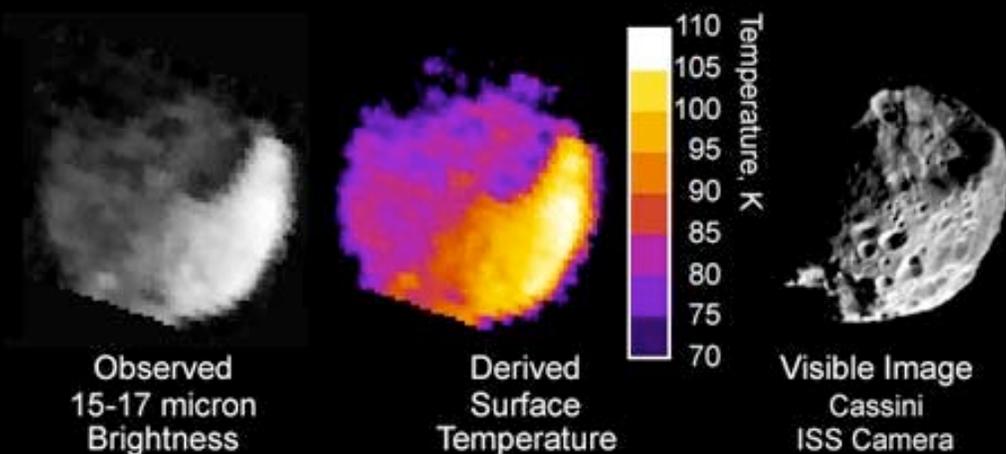
- higher spatial and radiometric resolution
- finer spectral bands
- seven vs four spectral bands acquired simultaneously.

Band 6 senses thermal (heat) infrared radiation. Landsat can only acquire night scenes in Band 6.

Channel	Wavelength Range (mm)	Resolution	Spectrum
TM 1	0.45 - 0.52	30 m	Blue
TM 2	0.52 - 0.60	30 m	Green
TM 3	0.63 - 0.69	30 m	Red
TM 4	0.76 - 0.90	30 m	Near IR
TM 5	1.55 - 1.75	30 m	Short Wave IR
TM 6	10.4 - 12.5	120 m	Thermal IR
TM 7	2.08 - 2.35	30 m	Mid IR

TM replaced MSS completely after Landsat-5

## Temperature of Saturn's moon Phoebe



taken by the composite infrared spectrometer onboard Cassini