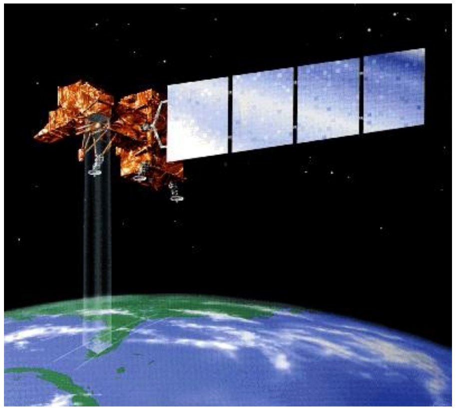
Satellite Remote Sensing
SIO 135/SIO 236

Thermal Radiation



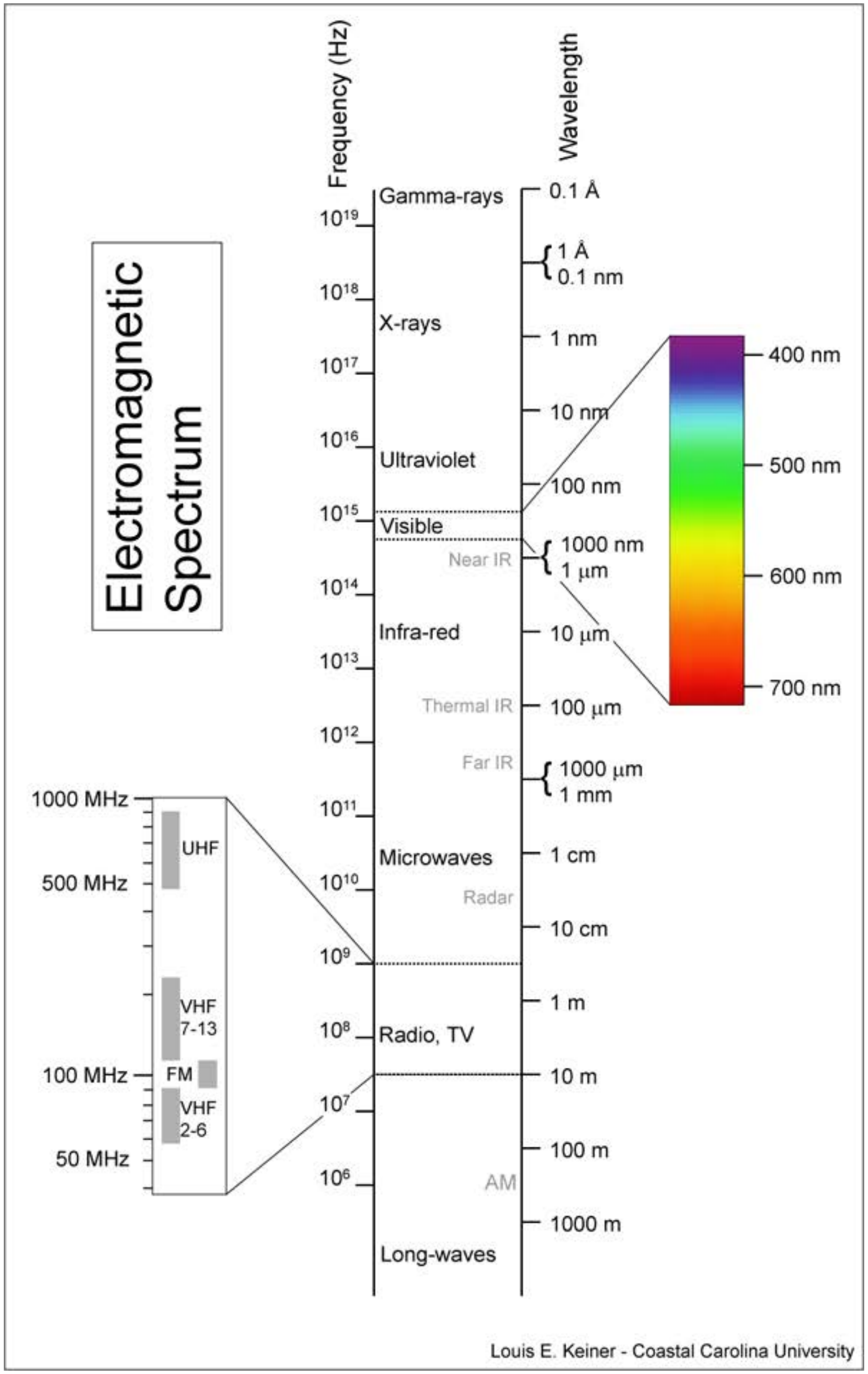
How is EMR generated?

Radio 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

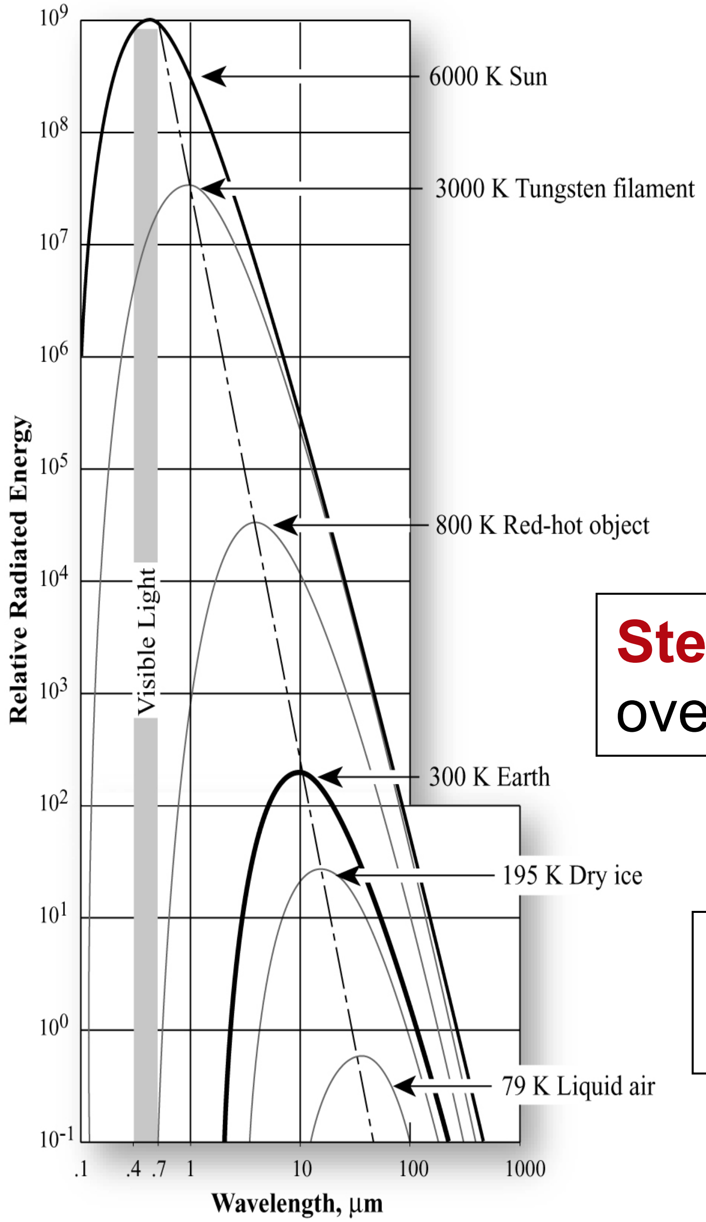
Visible high frequency wave in the infrared and visible are generated by molecular excitation (vibrational or orbital) followed by decay. The emitted frequency is exactly related to the energy difference between the two energy level of the molecules.

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.



Louis E. Keiner - Coastal Carolina University

Thermal Radiation



- ★ Thermal radiation is emitted by all objects above absolute zero (-273.15 °C)
- ★ Spectrum of this radiation (i.e. intensity vs wavelength) usually follows the idealized **black-body radiation curve**

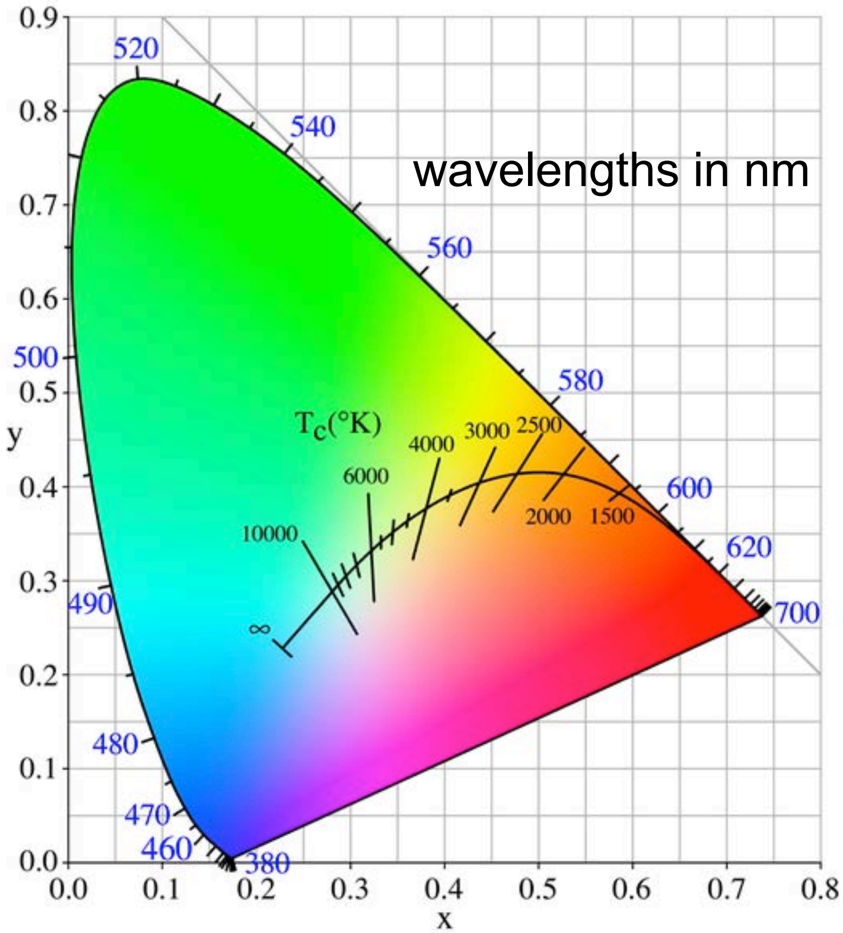
Stefan-Boltzmann law: Total energy emitted over time by a black body is proportional to T^4

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

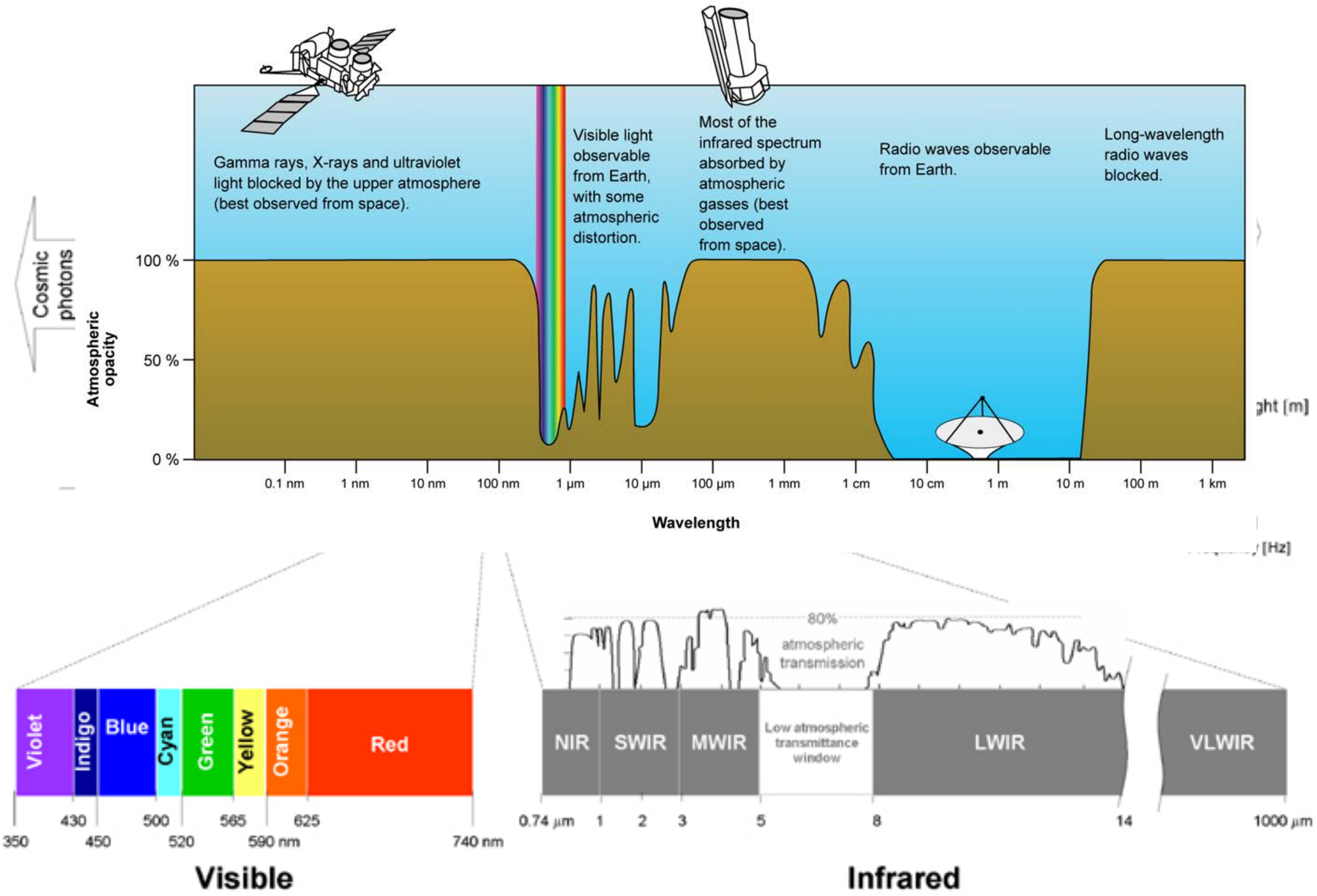
What is a “black body”?

- A black body (BB) emits a temperature-dependent spectrum of light
- 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 ºC, BBs start to emit visible wavelengths (shorter and shorter)
red ➔ orange➔ yellow➔ white ➔blue
beyond this the emission includes increasing amounts of UV.



Wavelength (color) of BB radiation depends on the temperature of the BB.

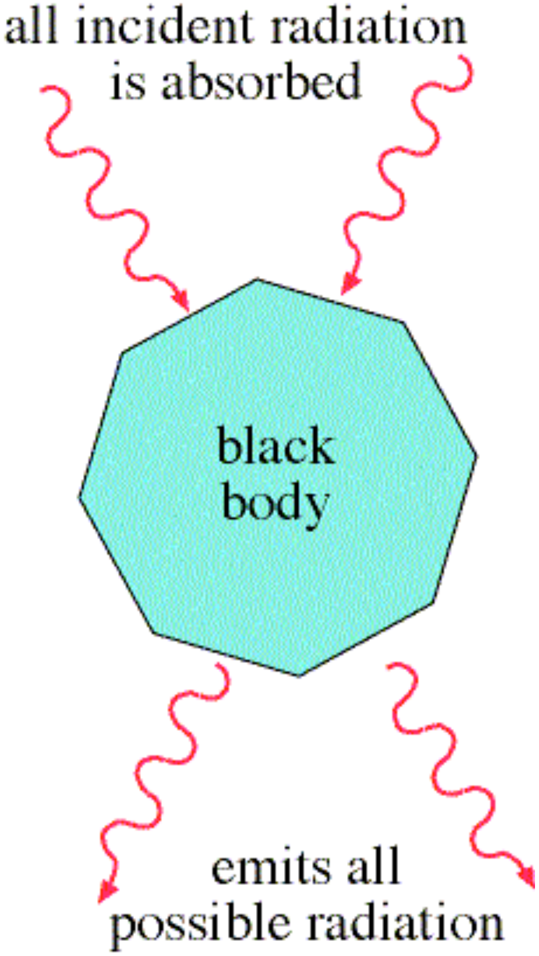


In general a hot object will distribute its emission over a range of wavelengths in a continuous spectrum.

What is a “black body”?

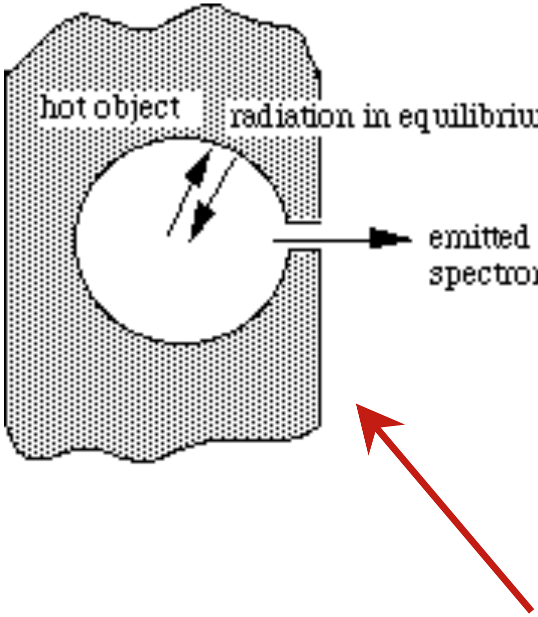
- A black body is an idealized object that absorbs all EMR that falls on it -- no EMR passes through it and none is reflected (perfect emitter and perfect absorber)

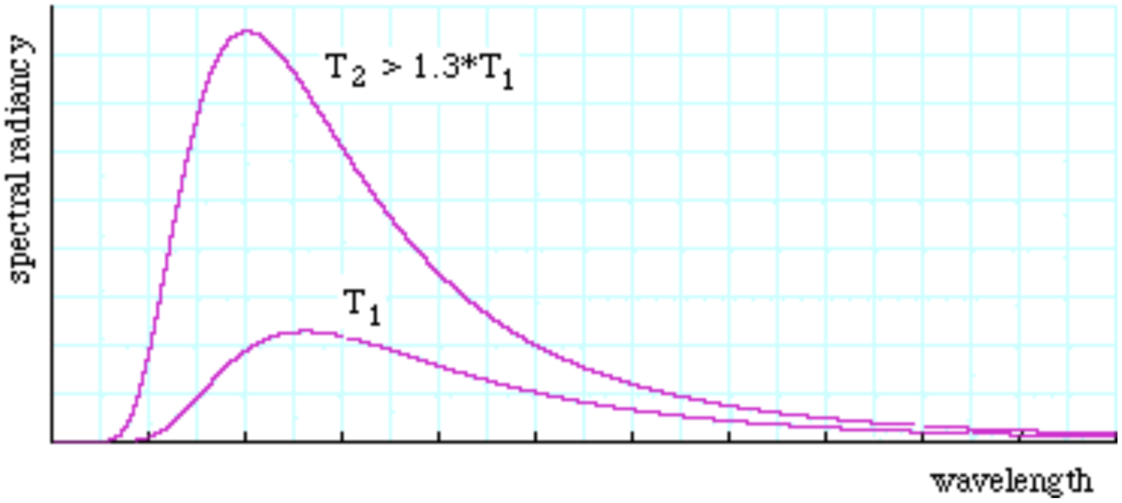
- Because no light (visible EMR) is reflected or transmitted, the object appears black when it is cold.



Term “introduced by Gustav Kirchhoff in 1860.

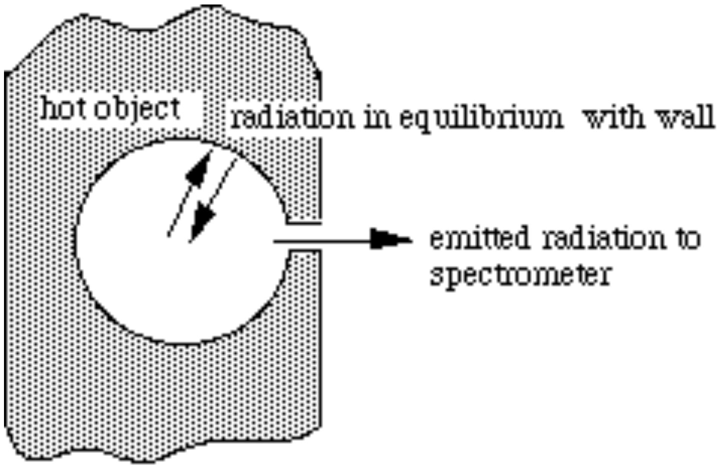
Black body lab experiment

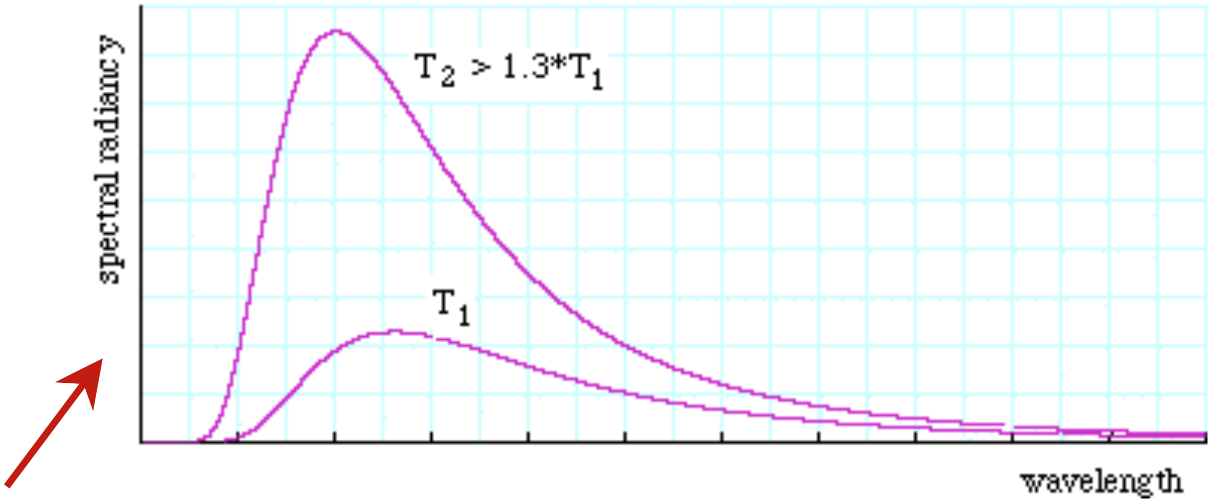




- An object of controlled temperature T contains a cavity, joined to the outside by a small hole.
- If the hole is small, the radiation in the cavity comes to equilibrium with the walls.
- The hole allows a small fraction of the radiation to pass to a spectrometer -- the radiation coming out has the same spectrum as what is inside

Black body lab experiment

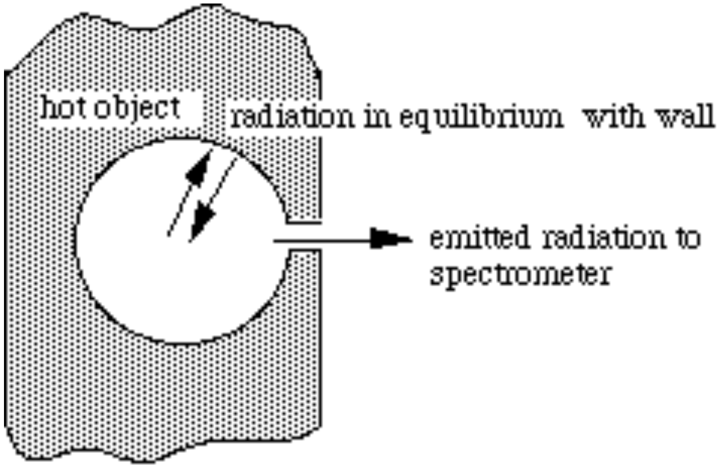


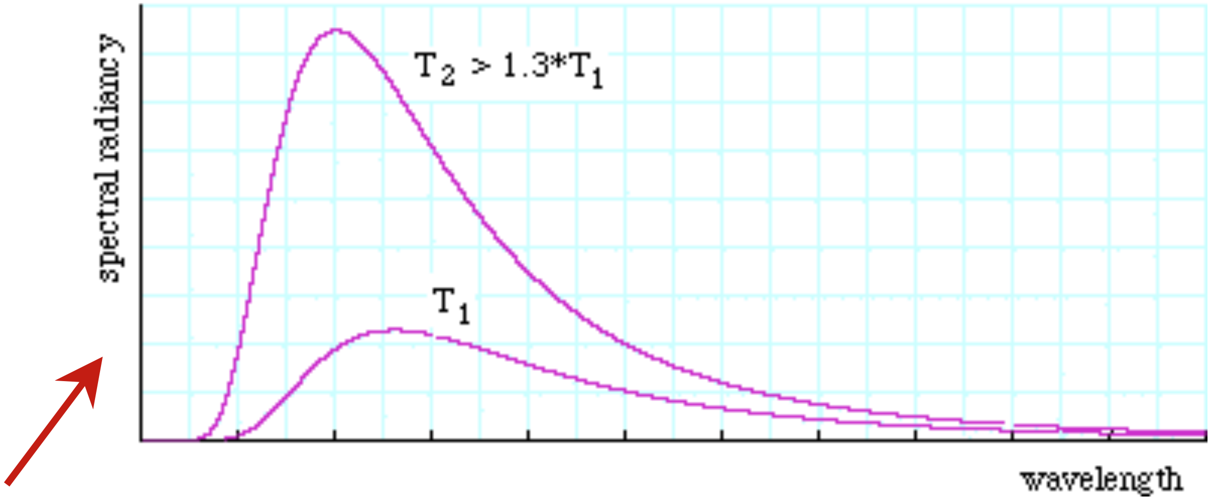


- Plot of Planck's radiation law for two temperatures. Note that the peak of the curve moves to the left as the temperature increases: hotter objects output a larger fraction of their EMR at shorter wavelengths.

- Note also the strong dependence on temperature of the total emission. The radiancy is the power emitted per unit area per increment of wavelength and so has units of W m^{-3}.

Black body lab experiment



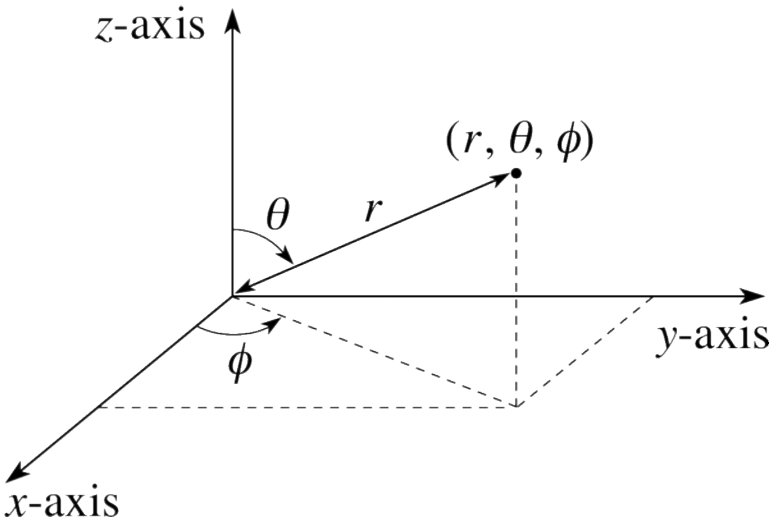


- The spectral radiance from the hole is independent of the material used and only depends on the temperature

Describing angular distributions of radiation

Consider a plane surface illuminated by EMR from a variety of directions

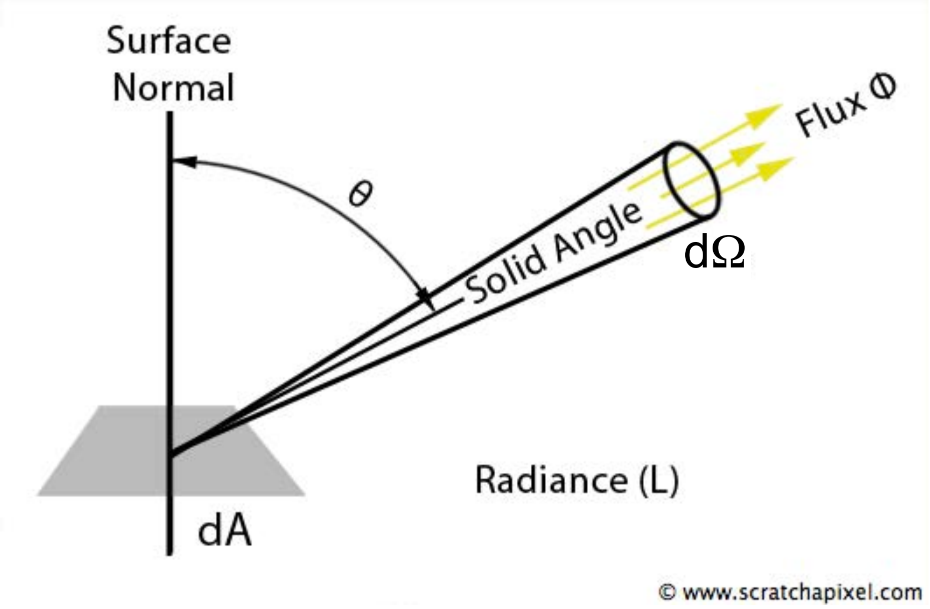
Two angles are needed to specify a particular direction of incident radiation:



θ - angle between incident ray and normal to surface

ϕ - azimuthal angle, measured around normal in place of surface

Describing angular distributions of radiation



Consider element dA of the surface, and radiation incident over range of angles θ to $\theta+d\theta$ and ϕ to $\phi + d\phi$

Solid angle $d\Omega = \sin\theta \, d\theta \, d\phi$

Power incident on the element dA from this range of directions is proportional to dA & $d\Omega$, and a term L which gives the strength of radiation

$$dP = L \cos\theta \, dA \, d\Omega$$

L is **radiance** - SI unit is W m^{-2} sr^{-1}

Spectral radiance

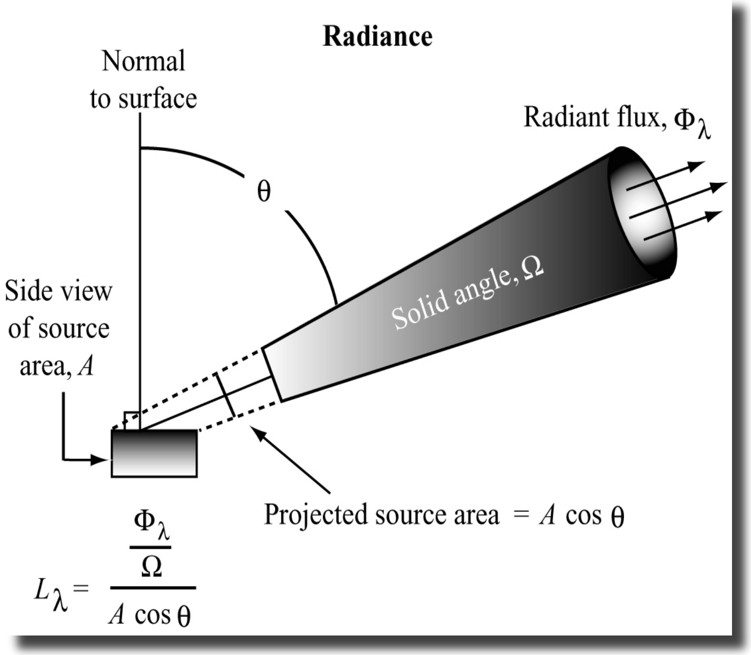
Spectral radiance L_λ is defined as the radiance ΔL contained in a small range of wavelengths $\Delta\lambda$ and given by:

$$\Delta L = L_\lambda \, \Delta\lambda$$

L_λ is the differential of L wrt λ

$$L_\lambda = | \delta L / \delta\lambda |$$

Spectral radiance - SI unit is $W\ m^{-2}\ sr^{-1}\ m^{-1}$
$= W\ m^{-3}\ sr^{-1}$

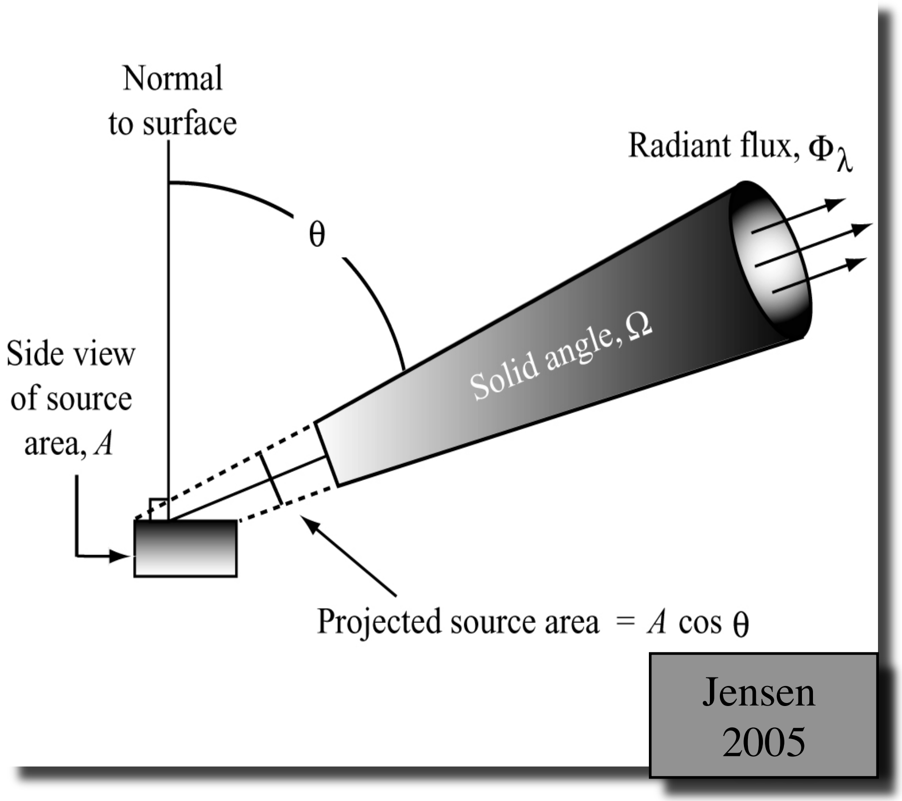


Radiance

Spectral radiance (L_λ) is the radiant flux per unit solid angle leaving an extended source in a given direction per unit projected source area in that direction

Radiant flux in certain wavelengths (L_λ) leaving the projected source area (A) within a certain direction (θ) and solid angle (Ω):

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



Jensen
2005

units W m^{-3} sr^{-1}

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:

1) $L_\lambda(\lambda)$ is the radiance per unit wavelength as a function of wavelength λ
2) $L_\nu(\nu)$ is the radiance per unit frequency as a function of frequency ν.

1)

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

T	-	temperature	
c	-	speed of light	2.99 x 10^{-8} m s^{-1}
h	-	Planck's constant	6.63 x 10^{-34} J s
k	-	Boltzmann's constant	1.38x10^{-23} J °K^{-1}
$L\lambda$	-	spectral radiance	W m^{-3} sr^{-1}
$L\nu$	-	spectral radiance	W m^{-2} Hz^{-1} sr^{-1}

Planck’s law

To relate the two forms and establish L $\nu(\nu)$, we take the derivative of *L* with respect to ν 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:

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

Stefan-Boltzmann Law

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

$$\boxed{M_\lambda = \sigma T^4}$$

where σ is the Stefan-Boltzmann constant, 5.6697 x 10^{-8} W m^{-2} $^oK^{-4}$.

→ 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

$$L = \int_o^\infty L_\lambda \, d\lambda \quad = \frac{2\pi^4 k^4}{15\, c^2 h^3} T^4$$

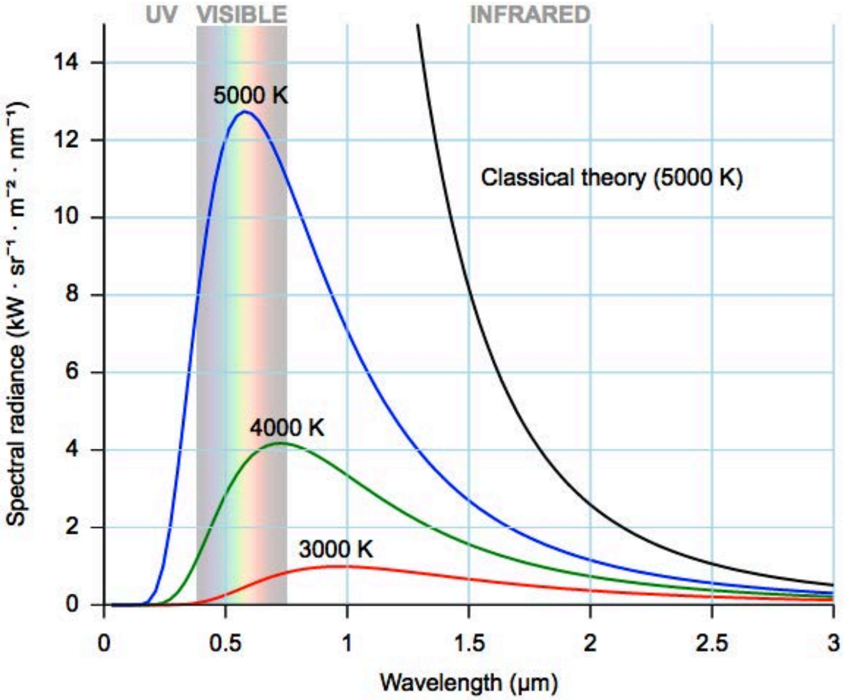
or $M = \pi L = \sigma T^4$

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 (λ_{max}) based on *Wien's displacement law*:

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

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



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 (λ_{max}) is 0.48 μm.

Rayleigh-Jeans approximation

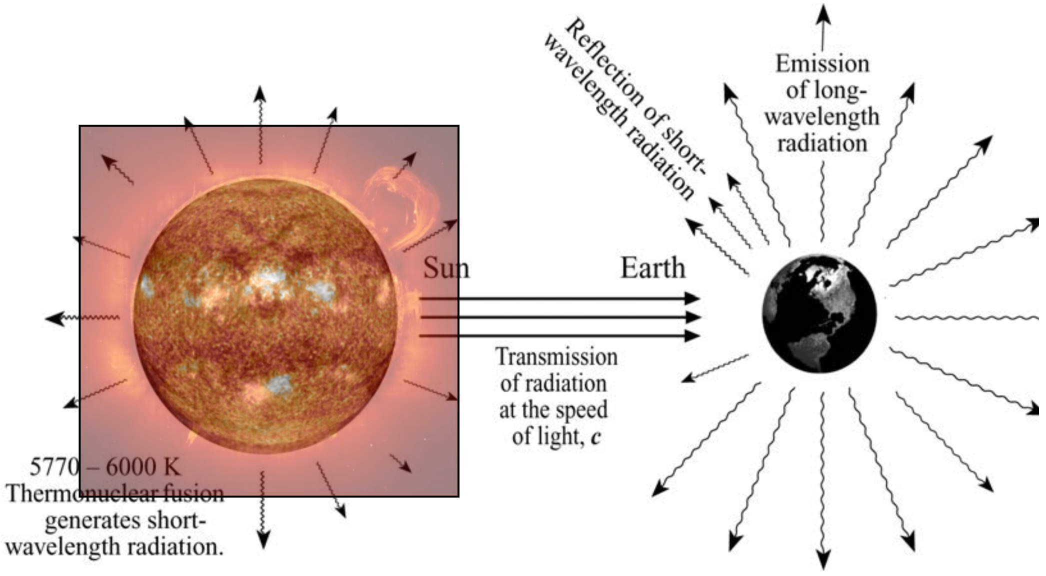
Convenient and accurate description for spectral radiance for wavelengths much greater than the wavelength of the peak in the black body radiation formula i.e. $\lambda >> \lambda_{max}$

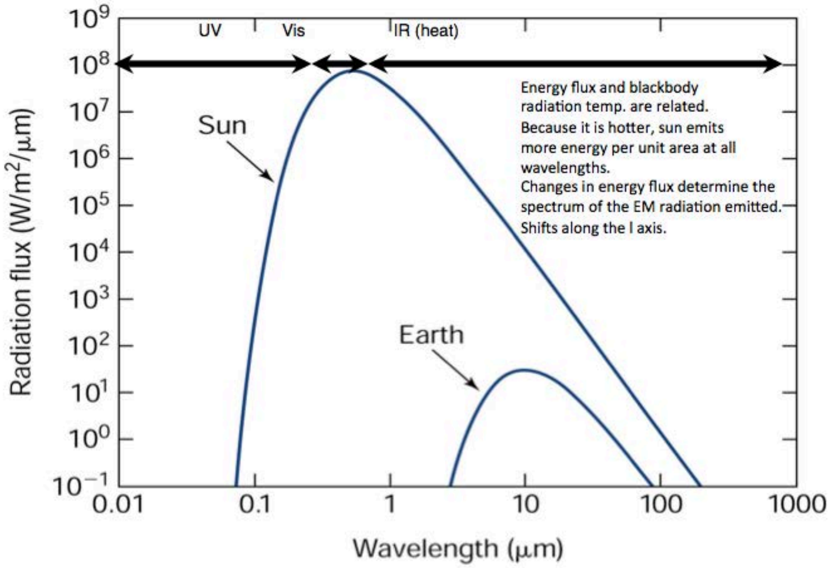
$$L_\lambda = \frac{2kcT}{\lambda^4} \quad or \quad L_\nu = \frac{2kT\nu^2}{c^2}.$$

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

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

EM Energy from the Sun

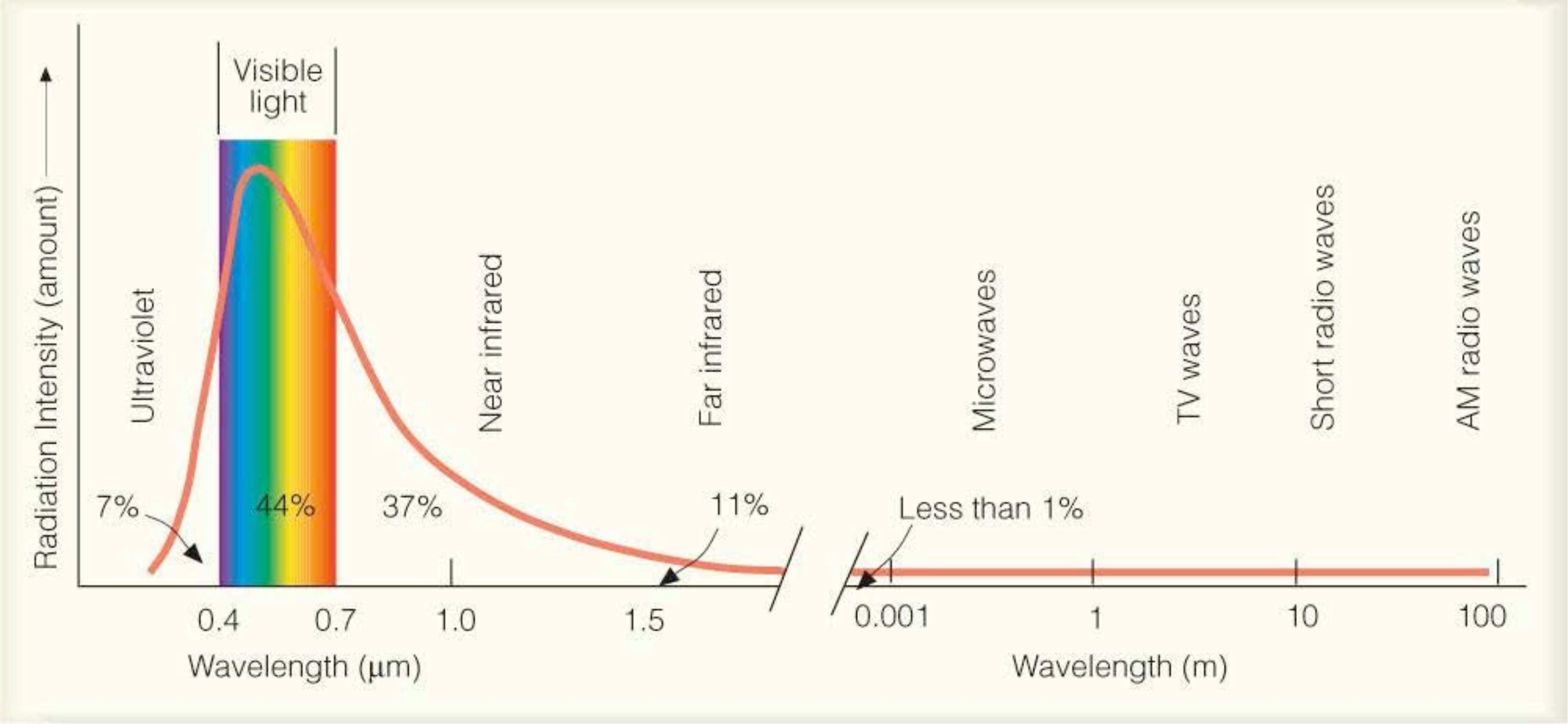




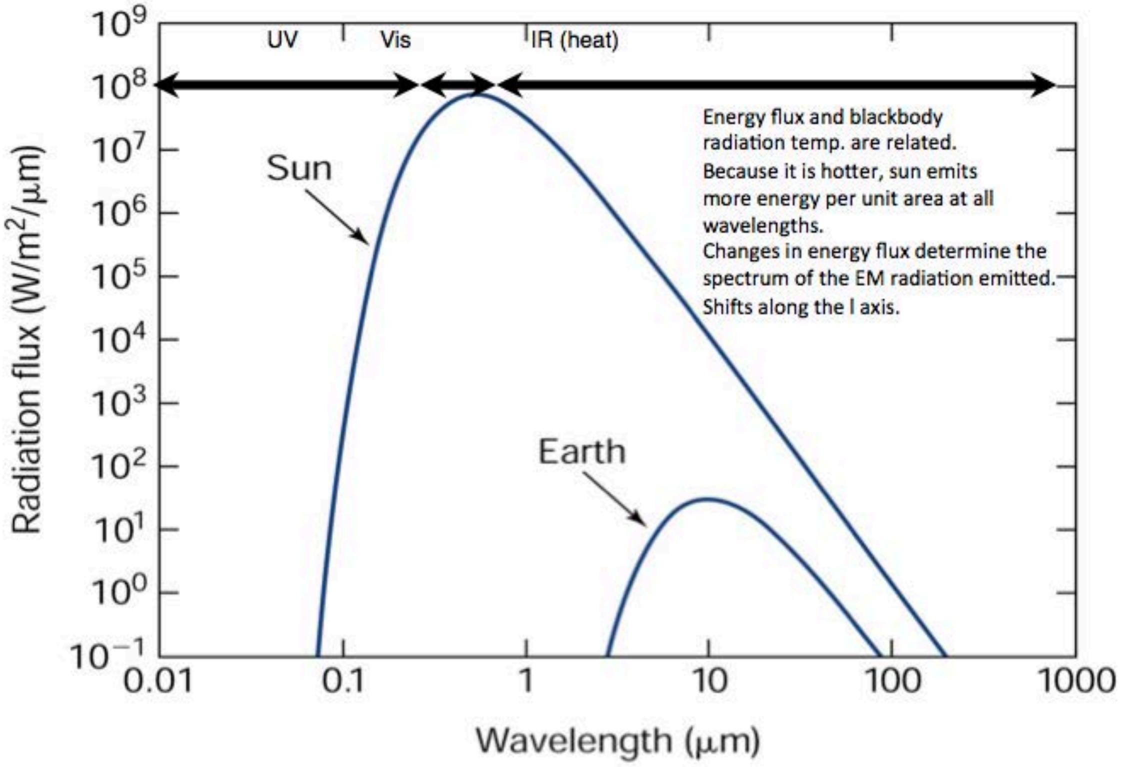
Energy flux and blackbody radiation temp. are related.
Because it is hotter, sun emits more energy per unit area at all wavelengths.
Changes in energy flux determine the spectrum of the EM radiation emitted.
Shifts along the l axis.

- ★ Thermonuclear fusion on the surface of the Sun (temp 5770 – 6000 K) yields a continuous spectrum of EM energy ranging from short, high frequency gamma & cosmic waves to long, low frequency radio waves; majority of the energy is relatively short wavelength
- ★ Travels through space at the speed of light & takes 8 minutes reach Earth (150 million km)
- ★ Some energy is intercepted by the Earth, where it interacts with the atmosphere and surface materials; some is reflected directly back out to space; and some is absorbed and then re-emitted it at a longer wavelength
- ★ Earth approximates a 300 K (27˚C) blackbody, dominant wavelength is ~ 9.7 mm

EM Energy from the Sun



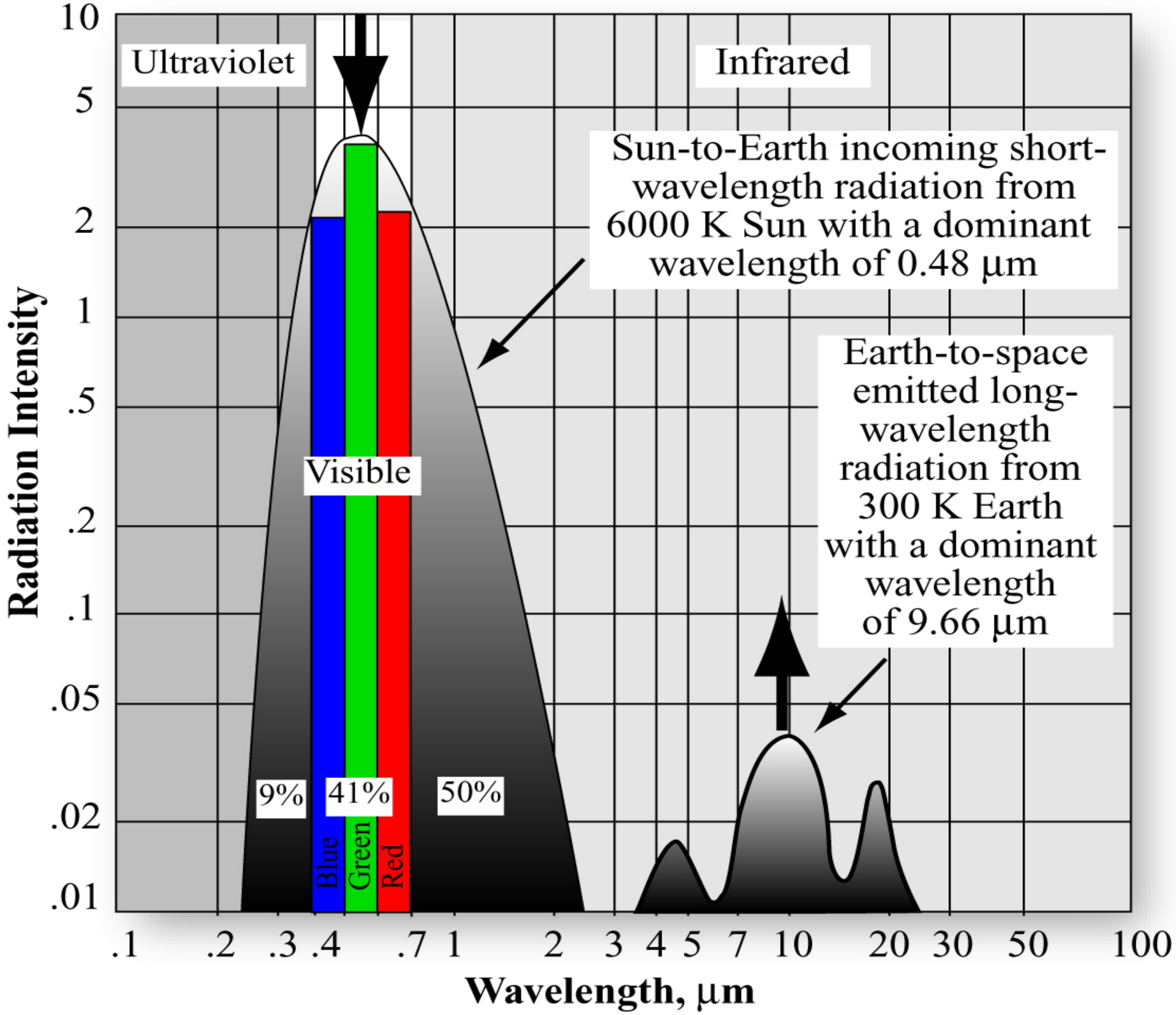
EM Energy from the Sun



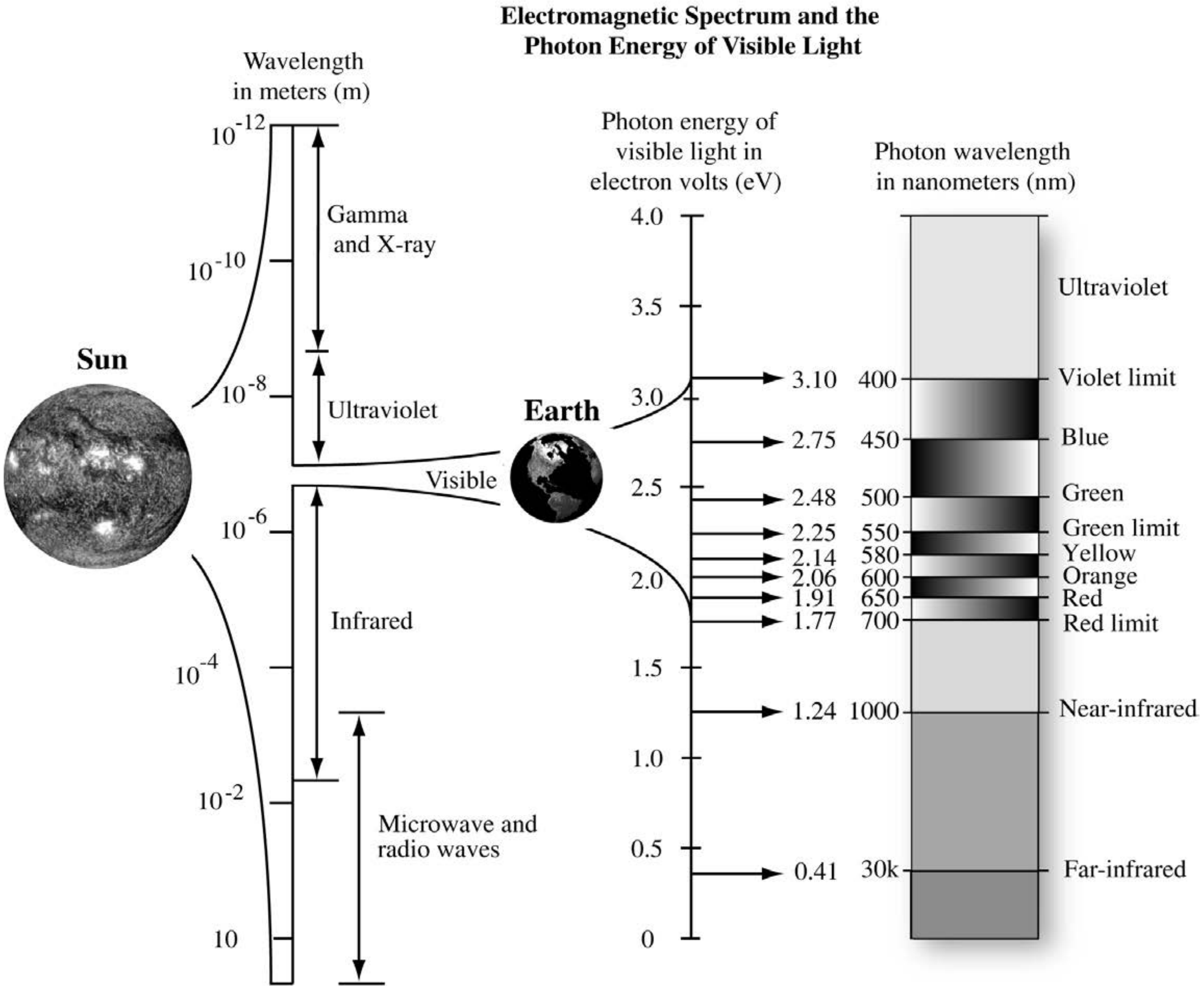
Energy flux and blackbody radiation temp. are related. Because it is hotter, sun emits more energy per unit area at all wavelengths. Changes in energy flux determine the spectrum of the EM radiation emitted. Shifts along the l axis.

- Max radiation emission (41%) is in the visible (0.4 – 0.7 μm)
- 59% of the energy is in wavelengths shorter than blue light (<0.4 μm) and longer than red light (>0.7 μm).
- Large component of high energy UV
- Remote sensing detectors can be made sensitive to energy in the non-visible regions of the spectrum.

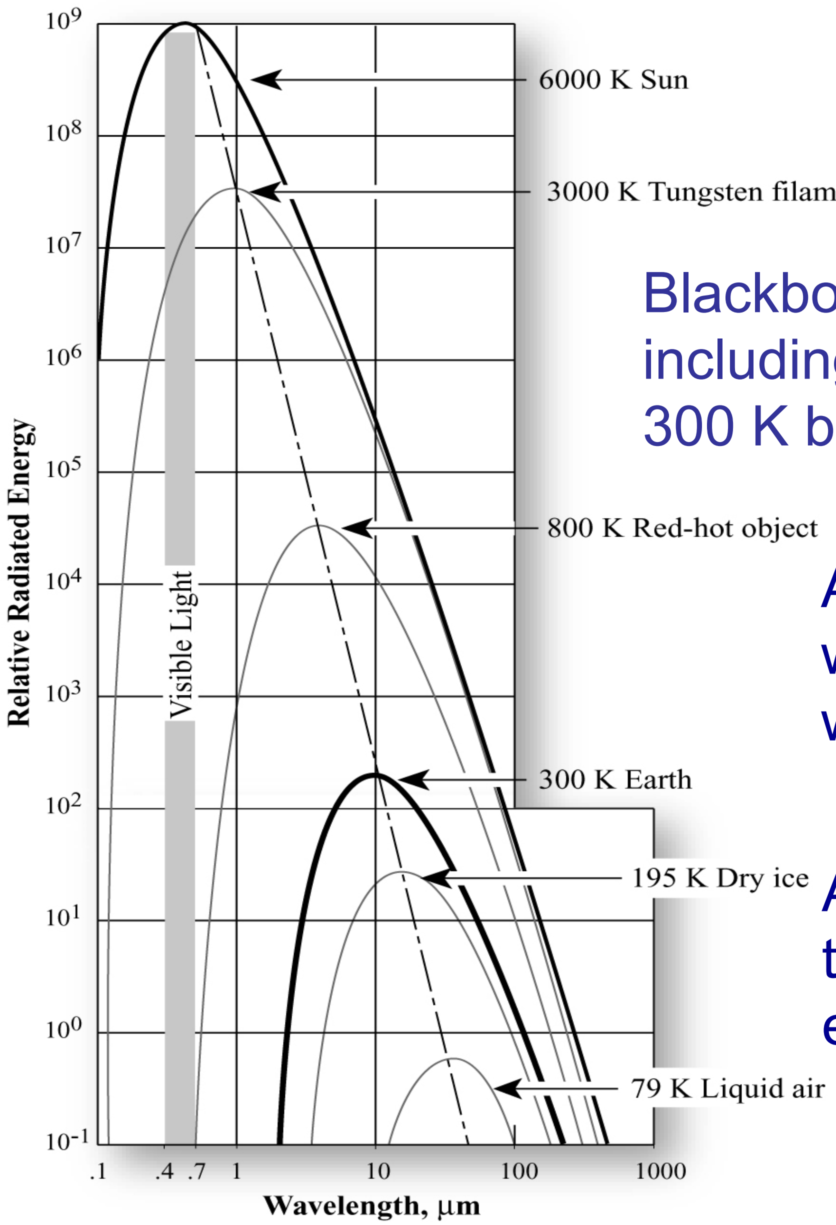
EM Energy from the Sun



EM Energy from the Sun



Blackbody Radiation Curves



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

As the temperature increases, dominant wavelength (λ_{max}) shifts toward shorter wavelengths.

Area under each curve may be summed to compute the total radiant energy (M_l) exiting each object.

Real materials

Real materials are not black bodies, so we introduce a property, *emissivity* ε:

- describes the actual absorption and emission properties of real objects, or gray bodies.
- is wavelength dependent $\varepsilon(\lambda)$
- 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

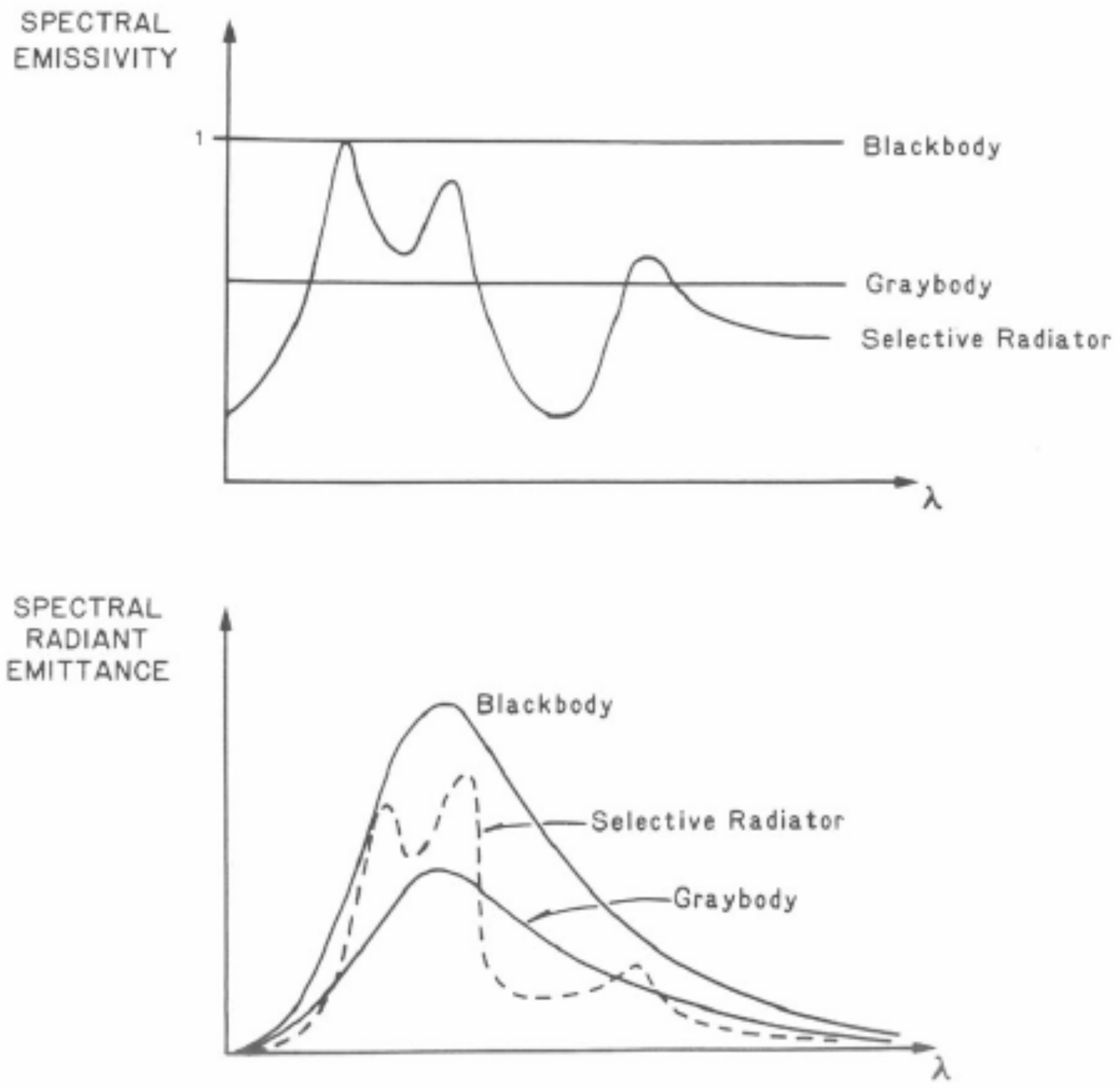
$$L_\lambda = \varepsilon(\lambda)\, L_{\lambda,p}$$

Black-body radiance

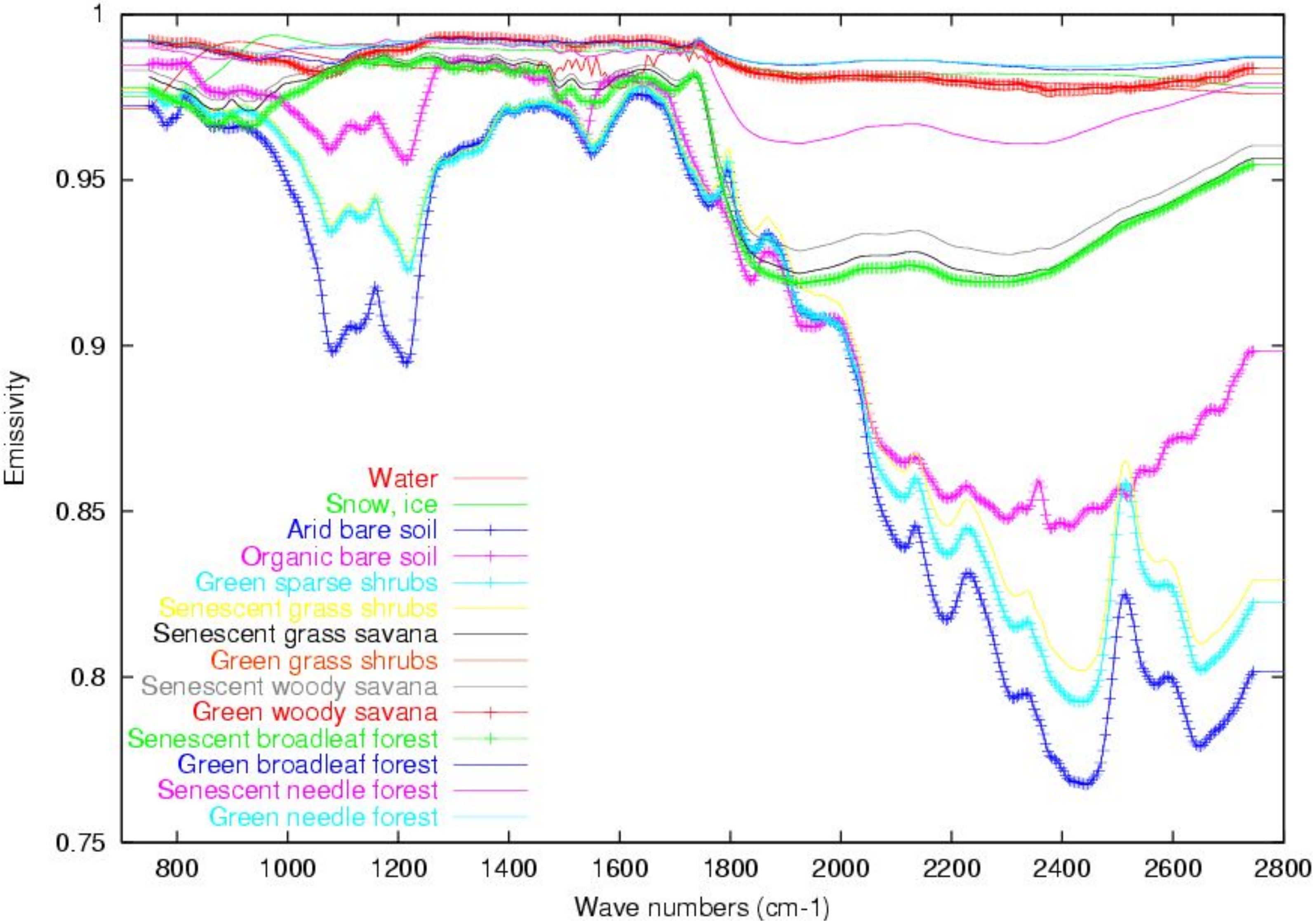
Graybody: an object that reflects a fraction of the incident radiation

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

Real materials



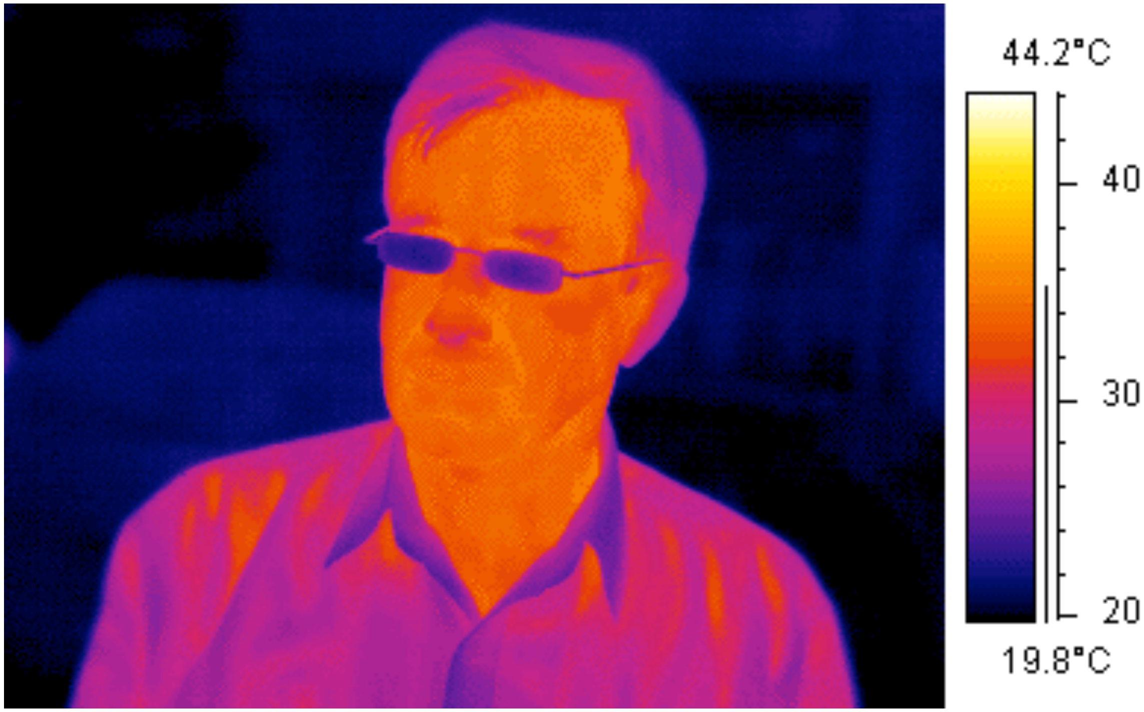
Real materials



Temperature of lava flow

The temperature of a Pāhoehoe 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.

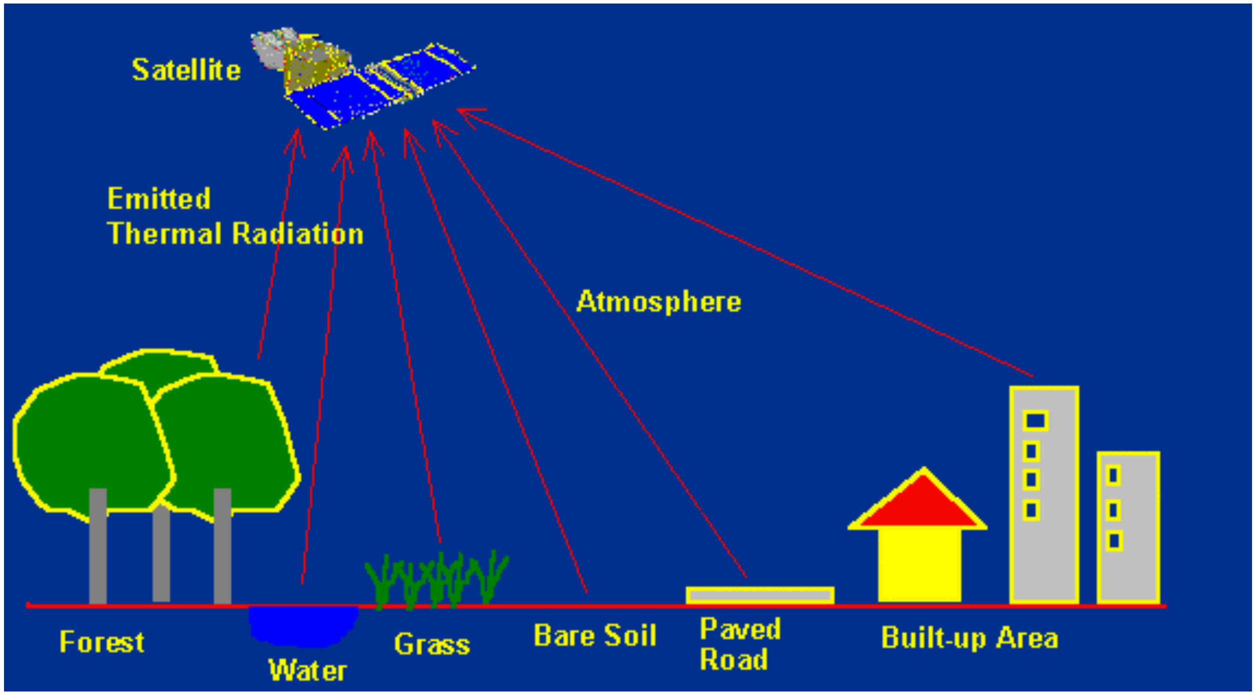
Thermal remote sensing

Strengths

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

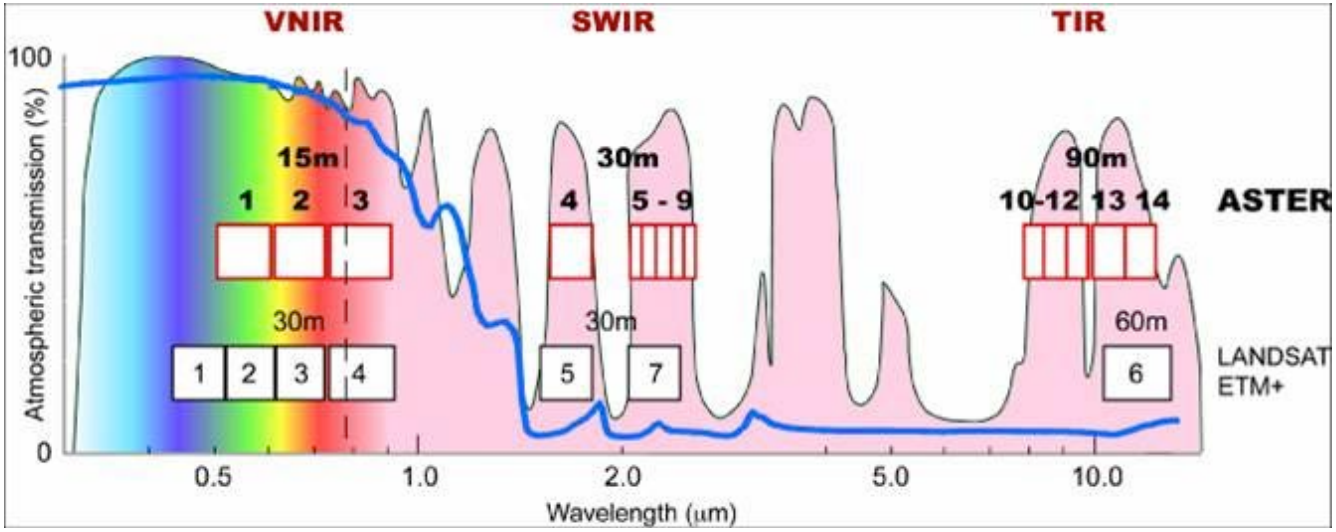
Weaknesses

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



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.

Used for: monitoring glaciers and ice sheets; 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.

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.

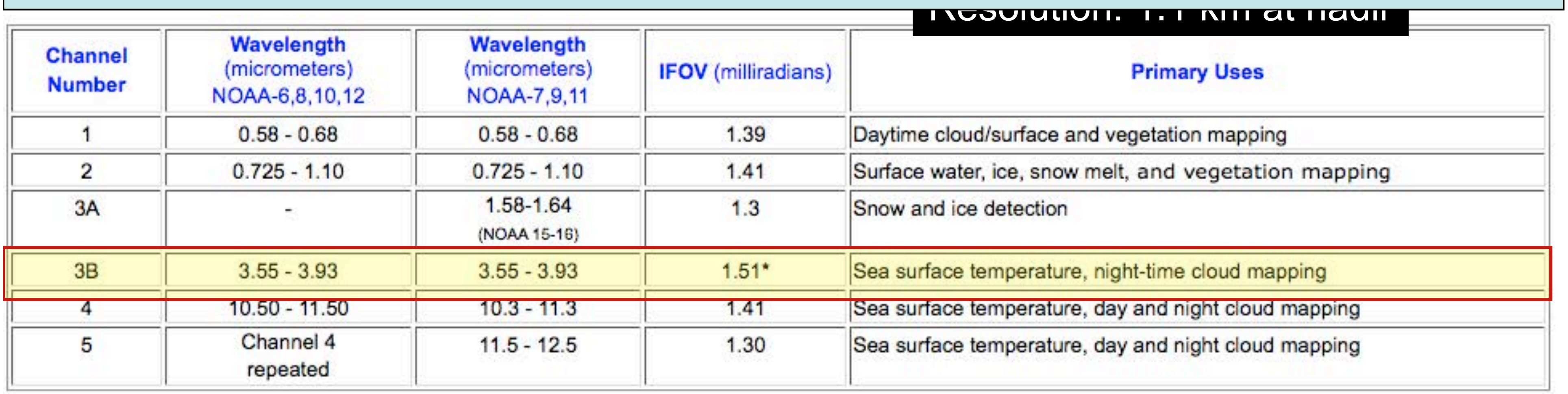
ATSR-1/2 Spectral Bands (10^{-6} m)
0.545 - 0.565 (only ATSR-2)
0.649 - 0.669 (only ATSR-2)
0.855 - 0.875 (only ATSR-2)
1.580 - 1.640
3.550 - 3.930
10.40 - 11.30
11.50 - 12.50

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

Thermal satellite sensors

Bands are carefully chosen!

AVHRR 3.7μm 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.



Resolution: 1.1 km at nadir

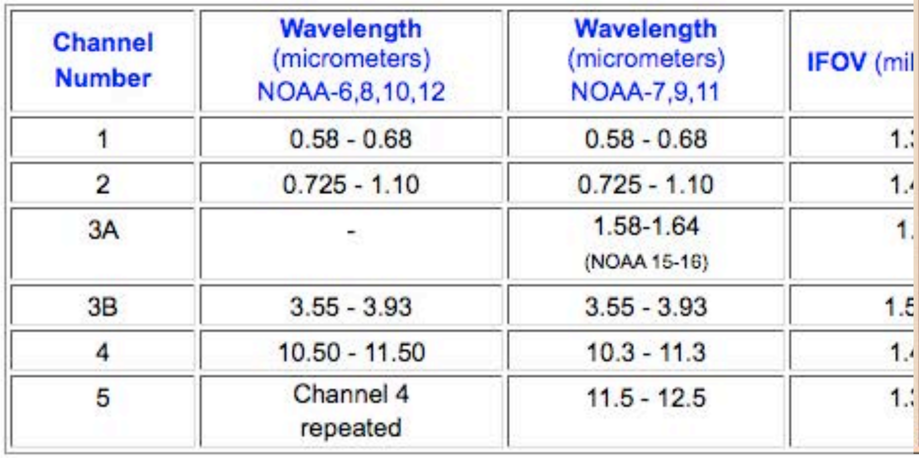
Channel Number	**Wavelength** (micrometers) NOAA-6,8,10,12	**Wavelength** (micrometers) NOAA-7,9,11	**IFOV** (milliradians)	**Primary Uses**
1	0.58 - 0.68	0.58 - 0.68	1.39	Daytime cloud/surface and vegetation mapping
2	0.725 - 1.10	0.725 - 1.10	1.41	Surface water, ice, snow melt, and vegetation mapping
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.



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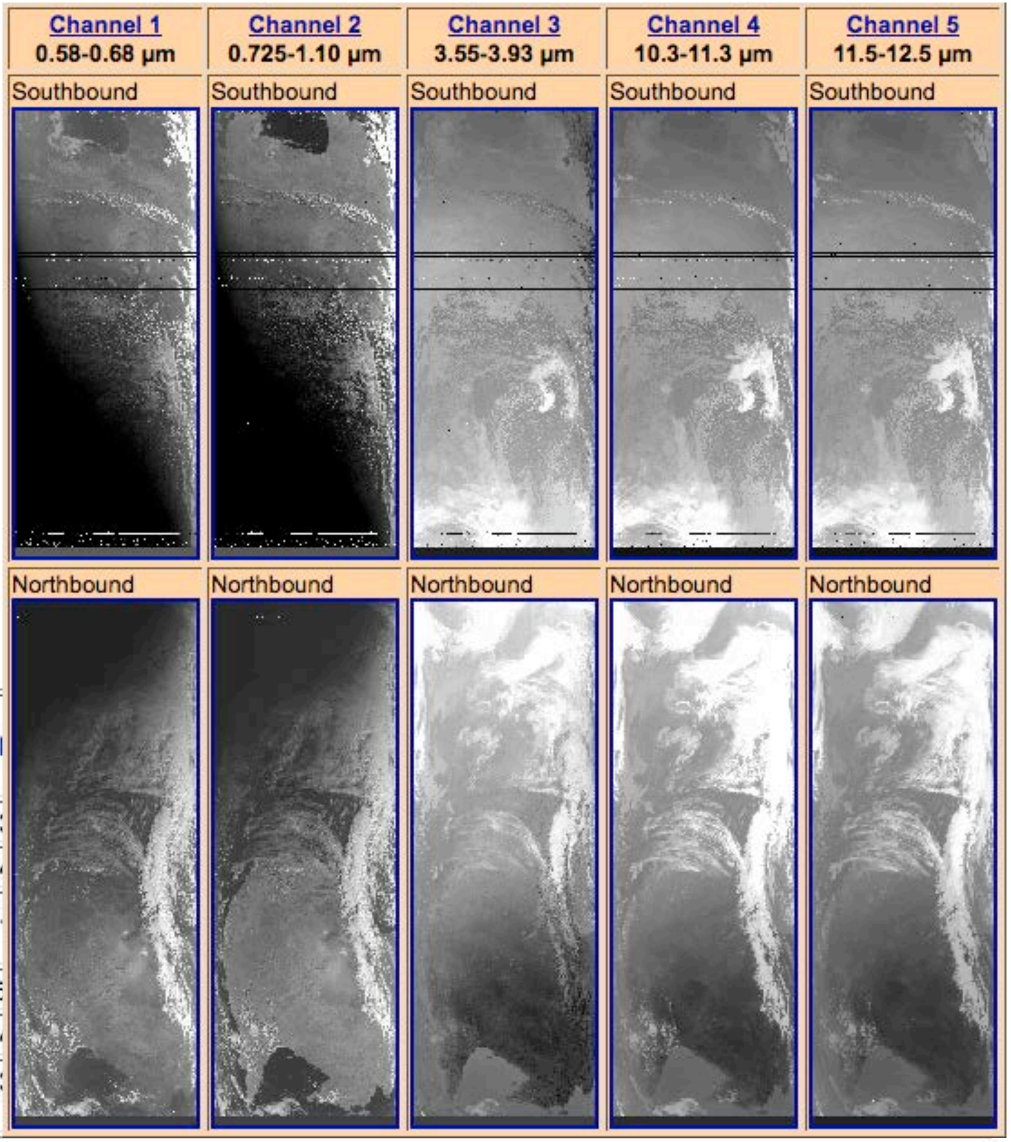
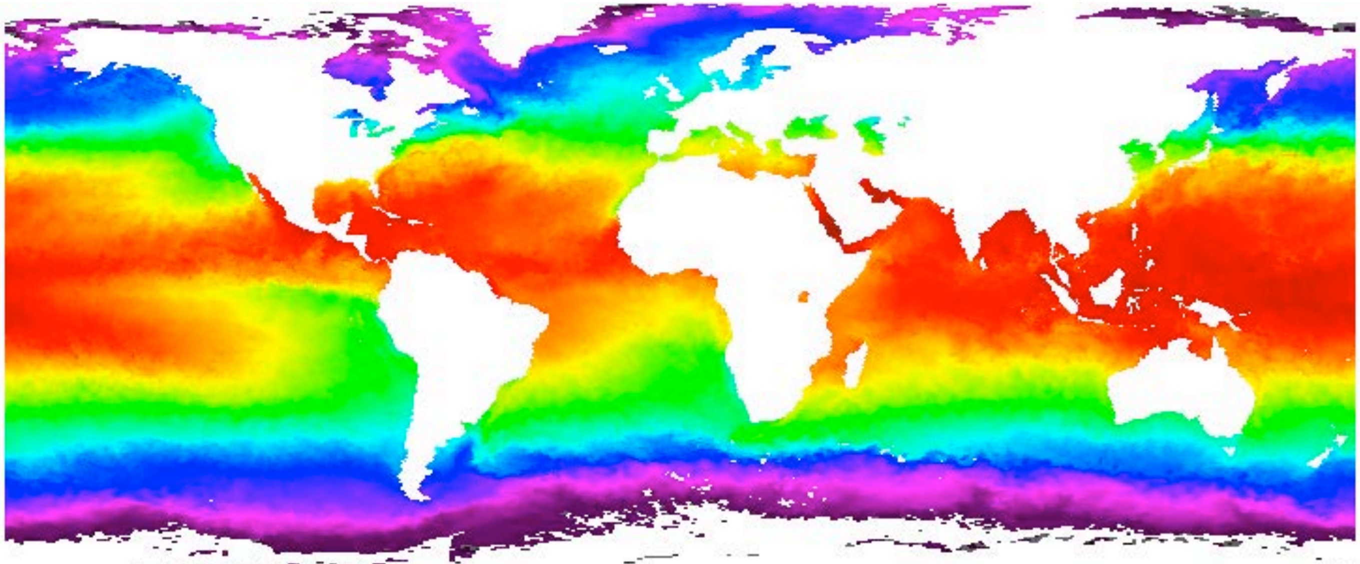
3A	-	1.58-1.64 (NOAA 15-16)	1.
3B	3.55 - 3.93	3.55 - 3.93	1.5
4	10.50 - 11.50	10.3 - 11.3	1.
5	Channel 4 repeated	11.5 - 12.5	1.



Sea surface temperature

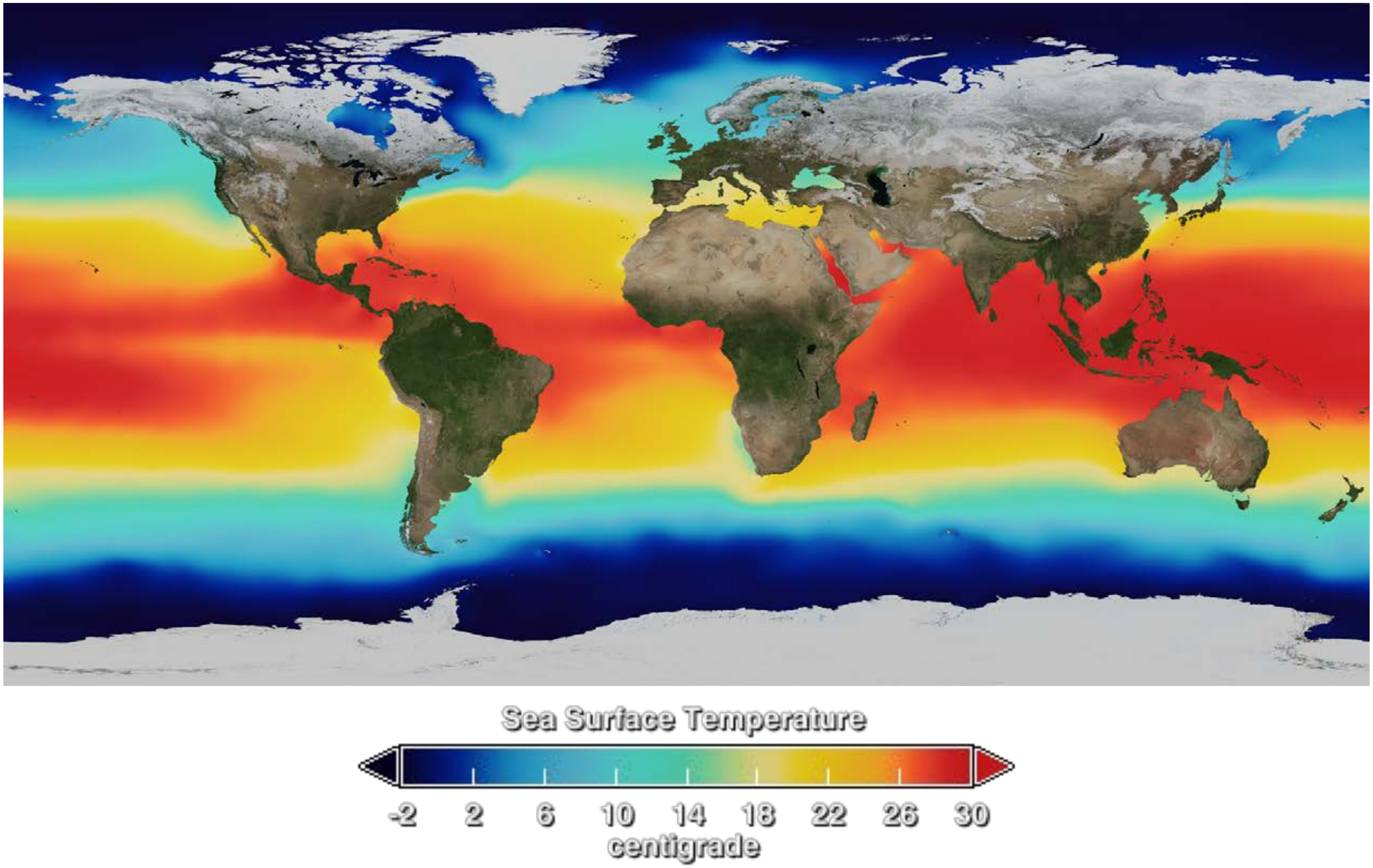
- Sea surface temperature (SST) is an important geophysical parameter, providing the boundary condition used in the estimation of heat flux at the air-sea interface.
- On the global scale this is important for climate modeling, study of the earth's heat balance, and insight into atmospheric and oceanic 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!

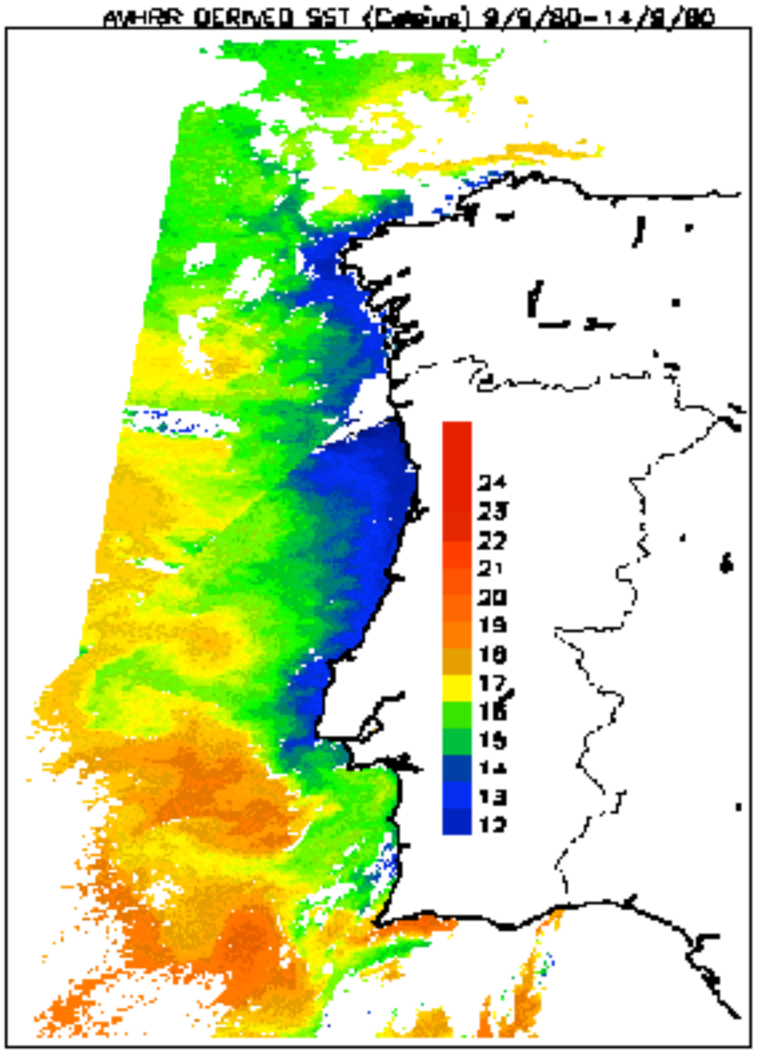
AVHRR Sea Surface Temperature, October 2001 (NASA/JPL PO.DAAC)

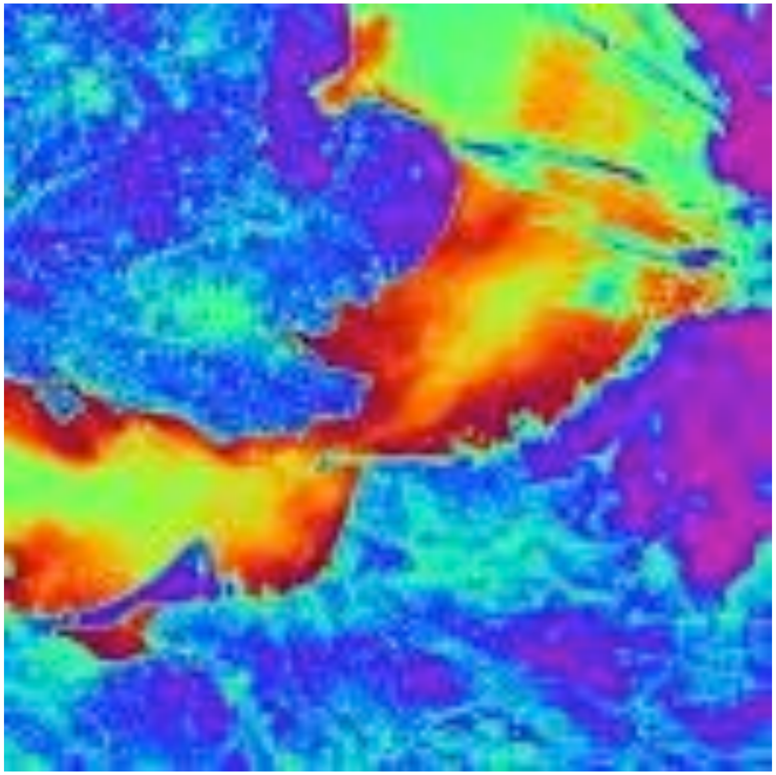
Sea surface temperature



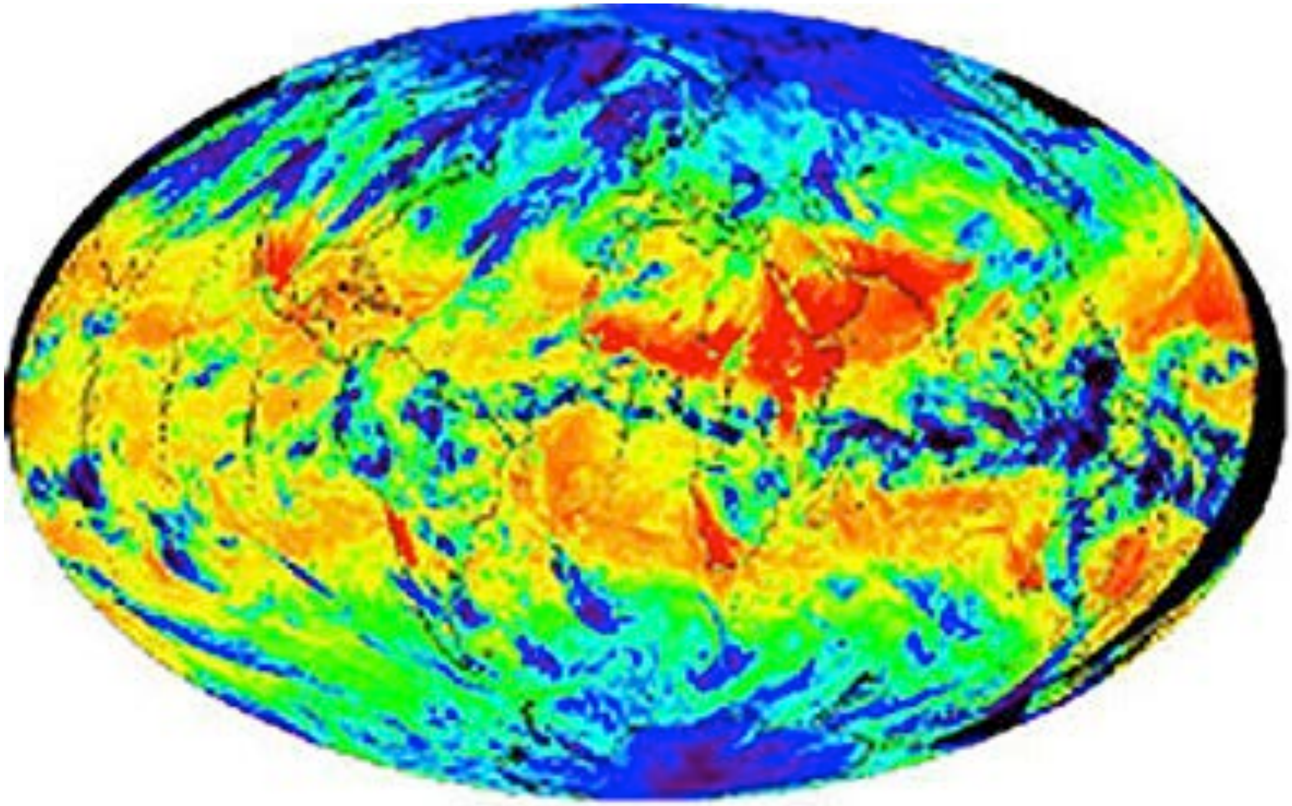
https://svs.gsfc.nasa.gov/3652

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)

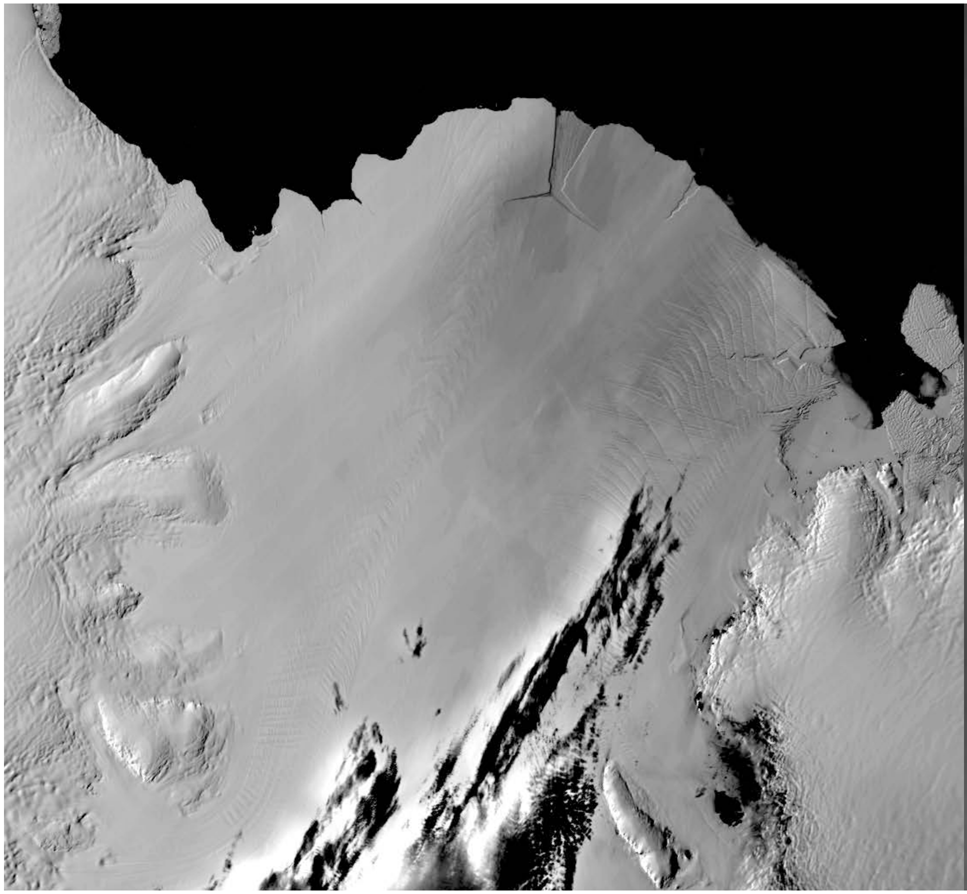
The broad spectral coverage and high spectral resolution of ASTER provides critical information for surface mapping, and monitoring of dynamic conditions and temporal change.

Applications: 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.

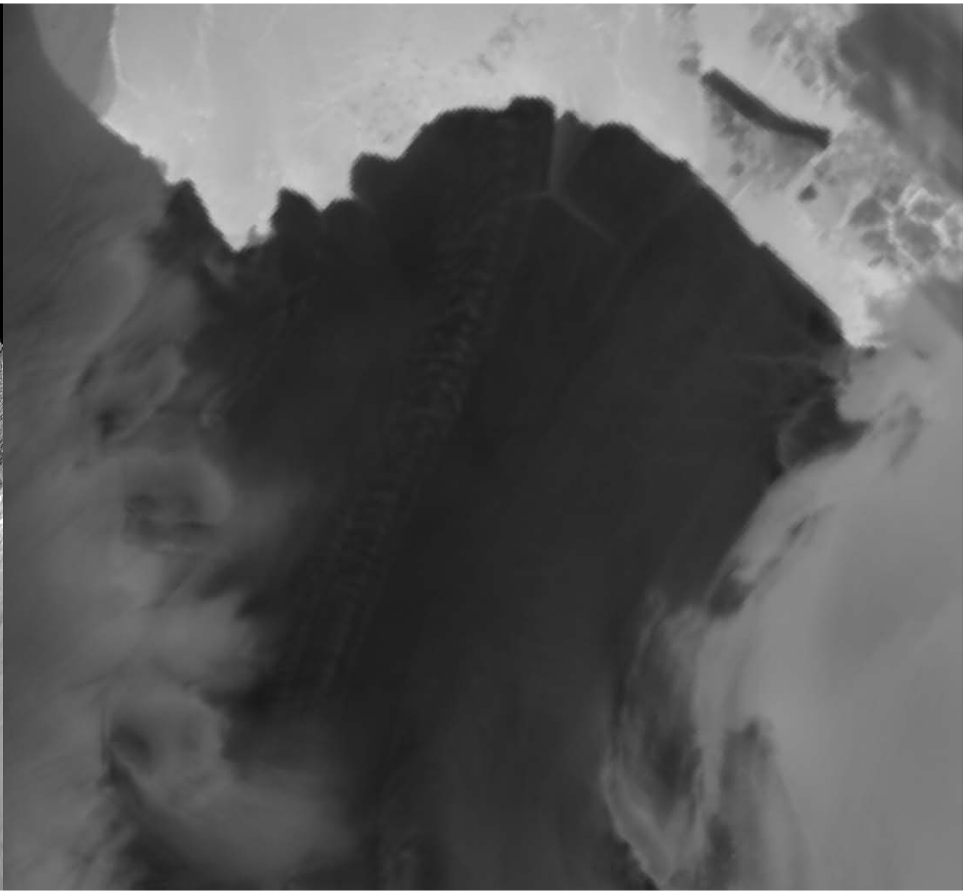
Augustine Volcano, Cook Inlet, Alaska (22:50 AST January 31, 2006).
This ASTER thermal image was acquired at night during an eruptive phase.

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) λ/d!



MODIS Terra visible 13 March 2009



MODIS Aqua thermal 6 April 2009

Monitor the ice sheets during polar winter

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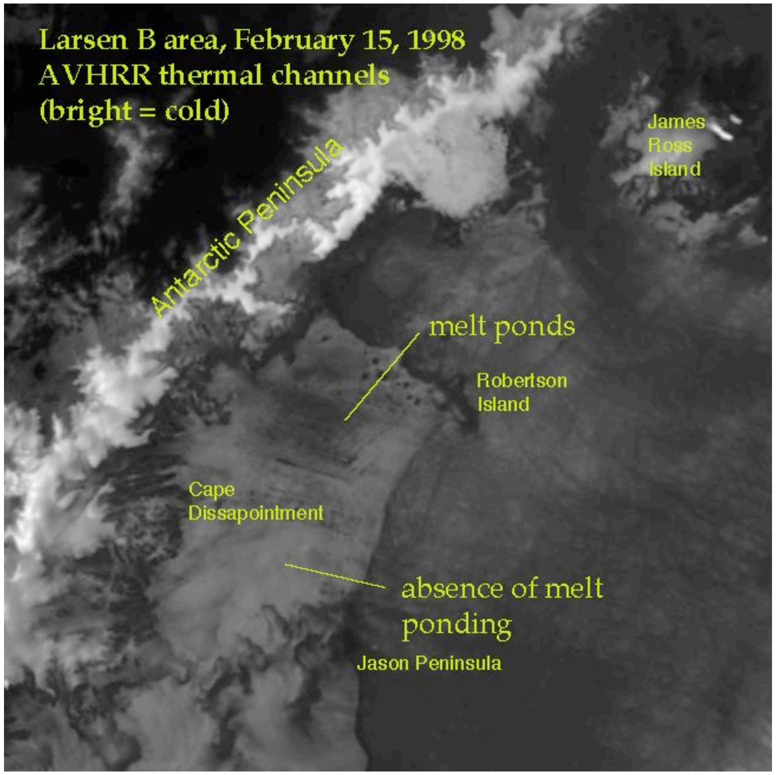
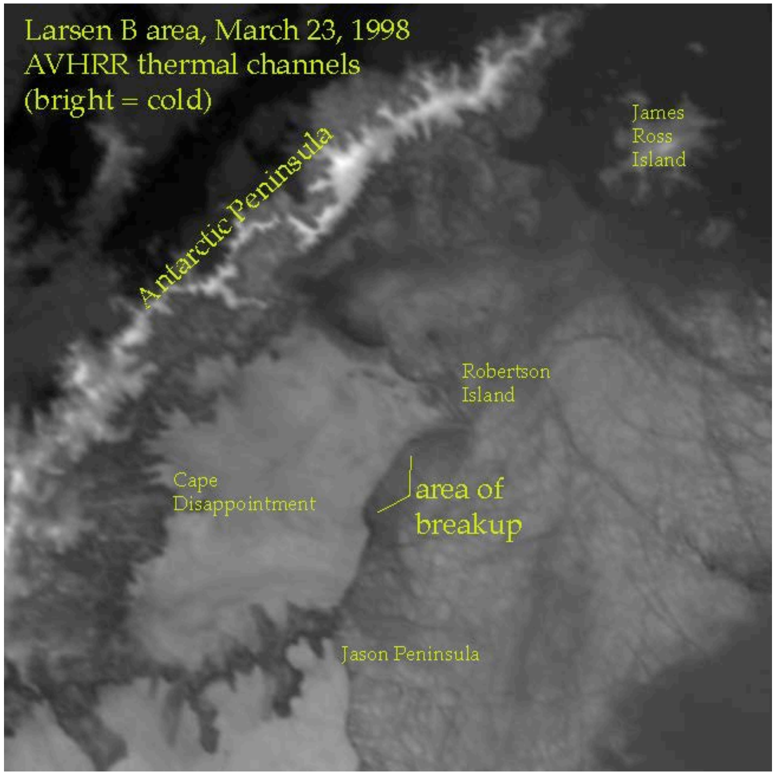
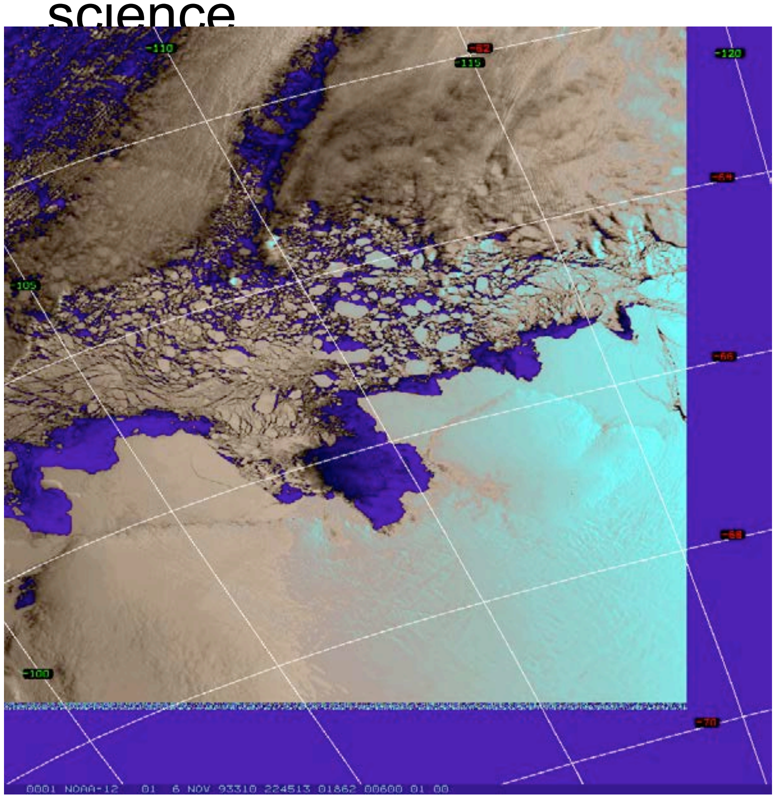




Sea-ice mapping

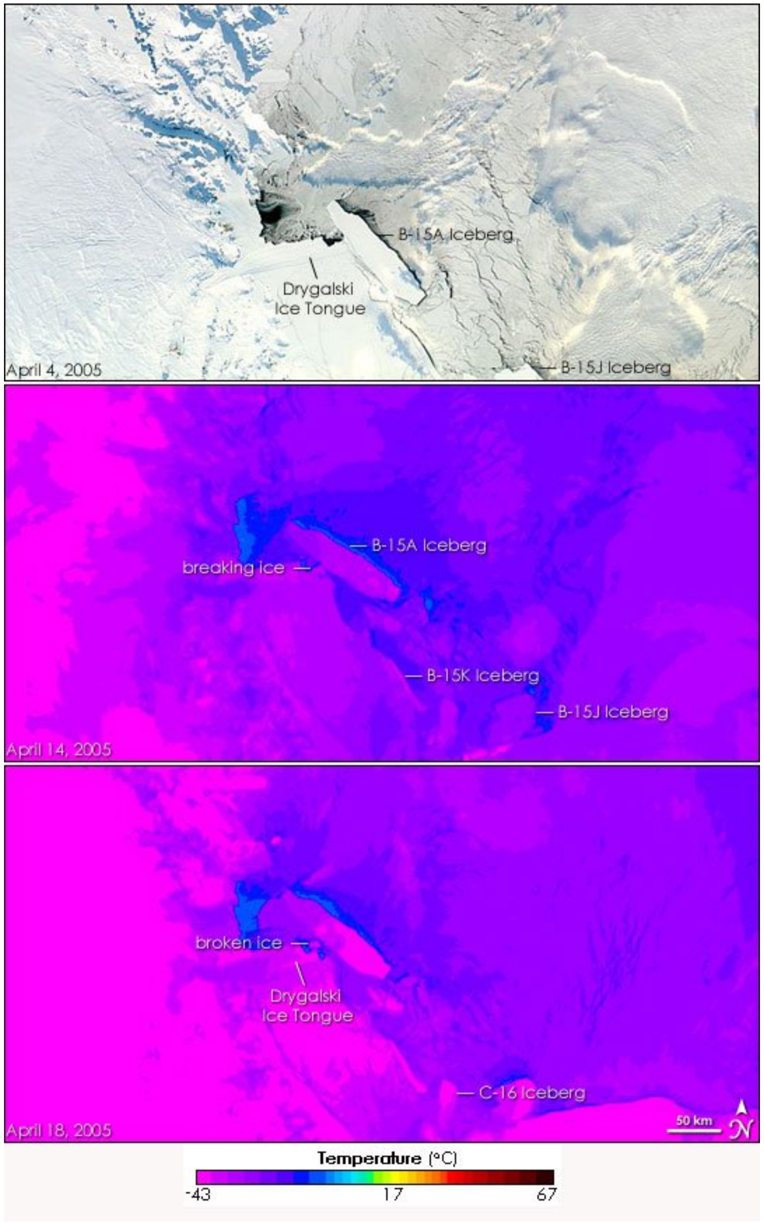
- Monitor extent of sea-ice in the Arctic and Antarctic

- Thermal remote sensing can distinguish between the sea-ice and "leads" (open water between the sea-ice) -- useful for navigation and for science



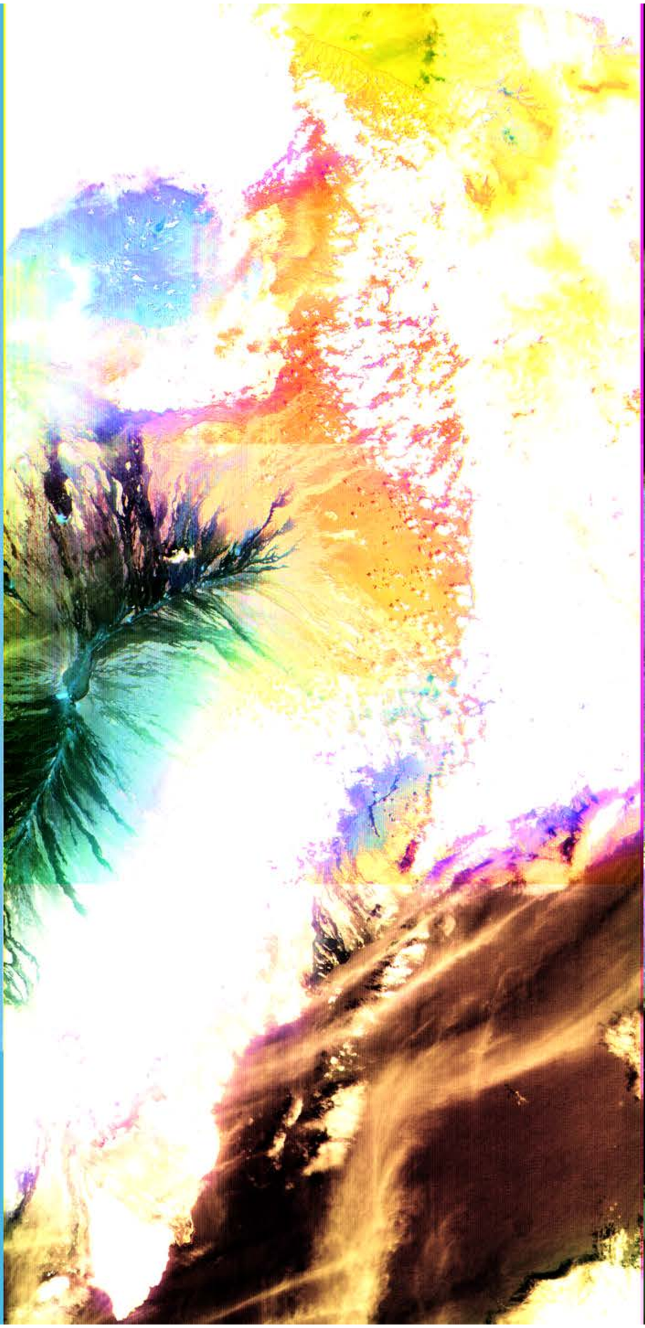
Thermal satellite sensors

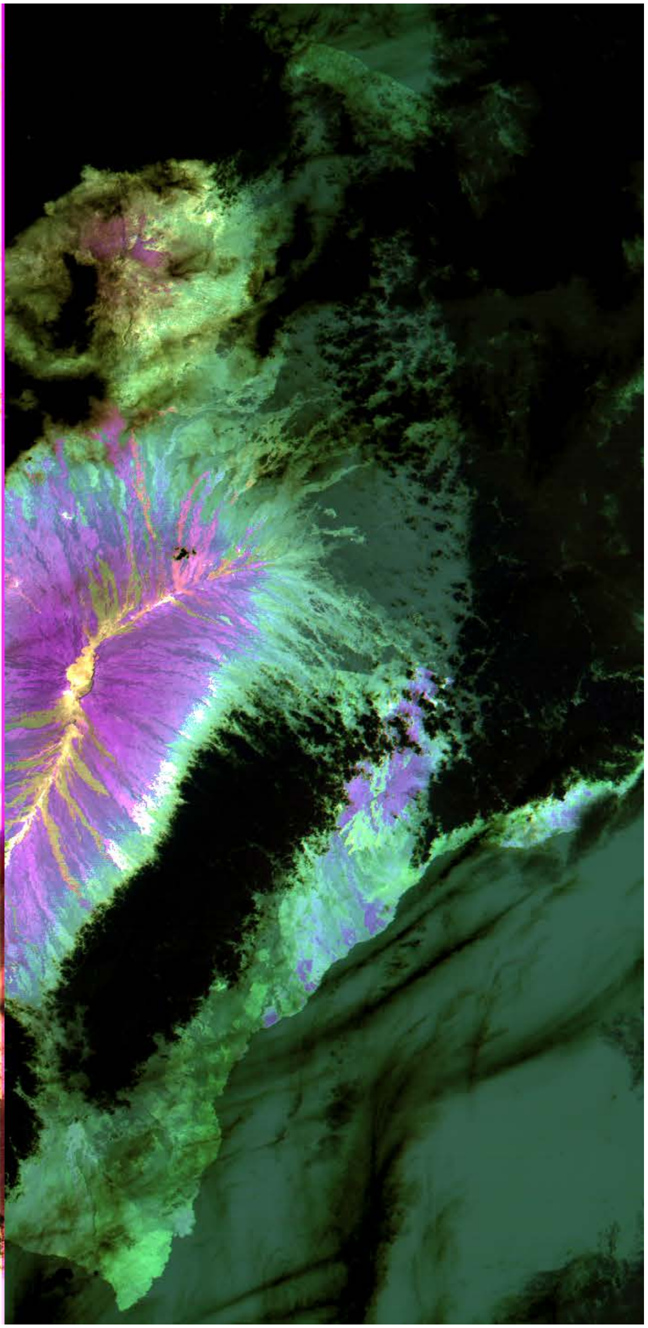
NASA’s Moderate Resolution Imaging Spectroradiometer (MODIS) has several bands in the thermal IR



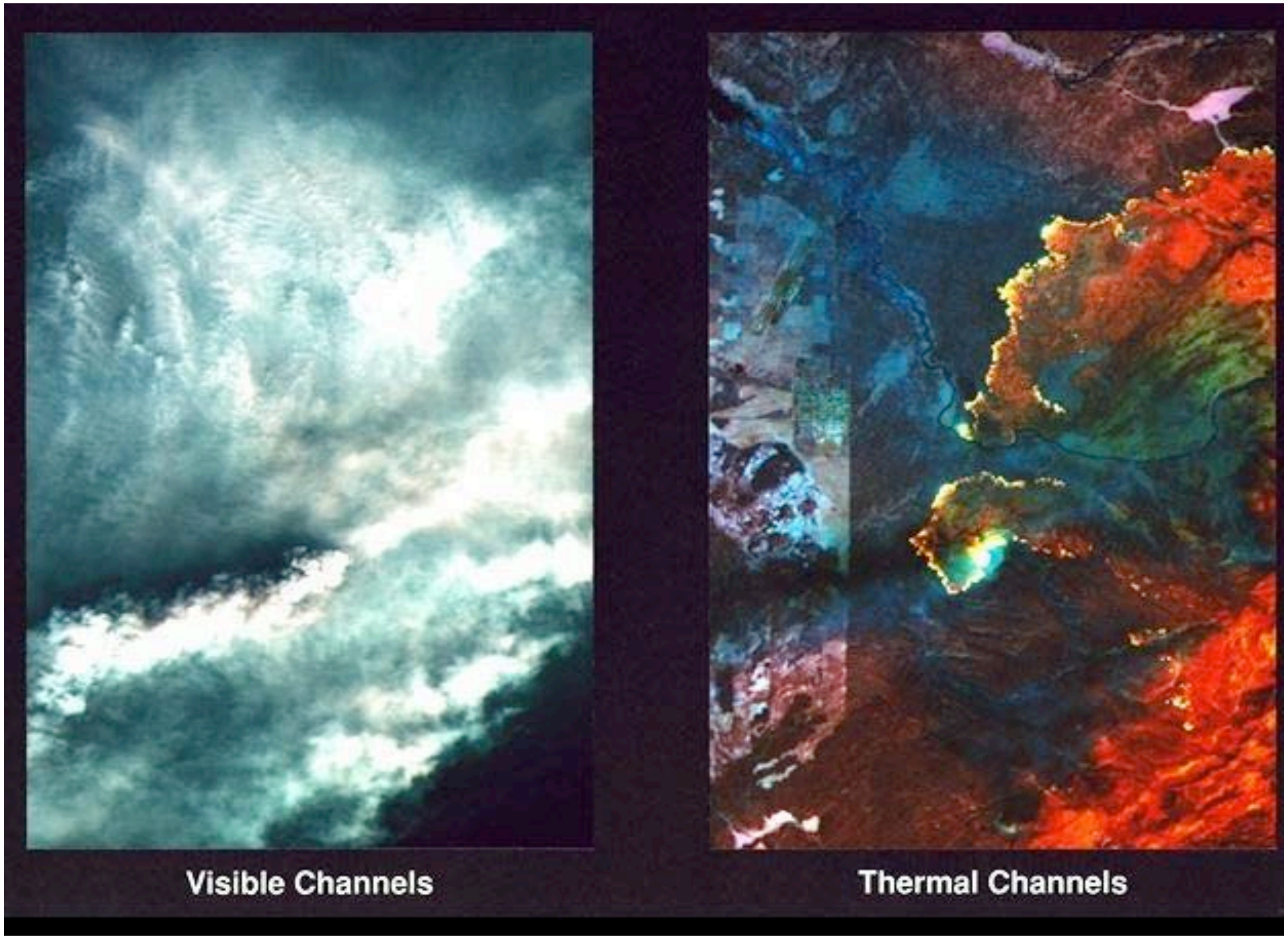
Hawaii March 19, 2000

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)





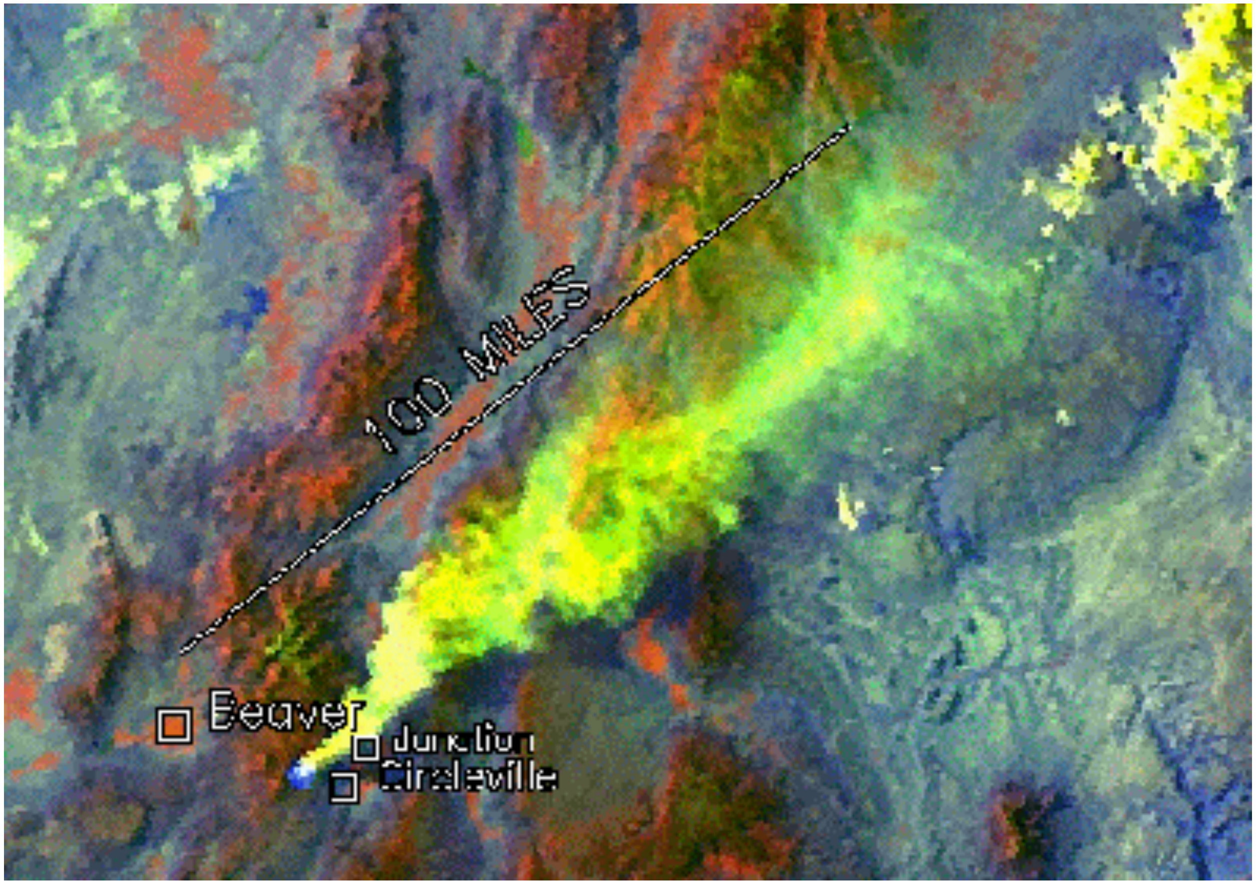
Fire monitoring



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.

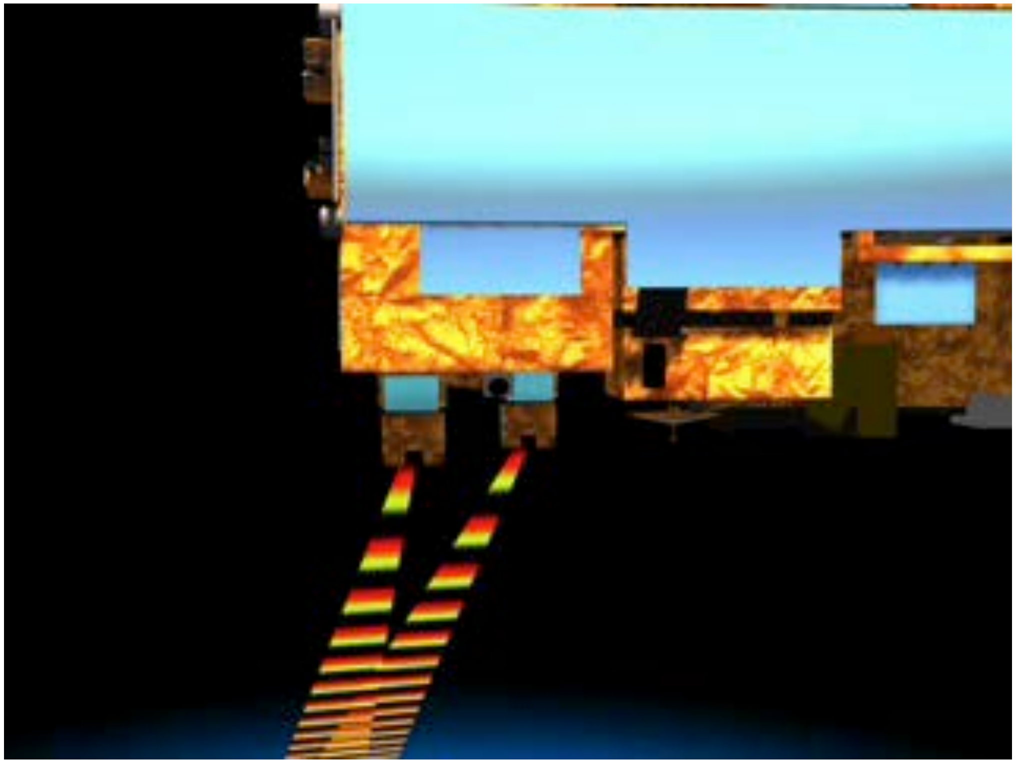
Fire monitoring

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

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

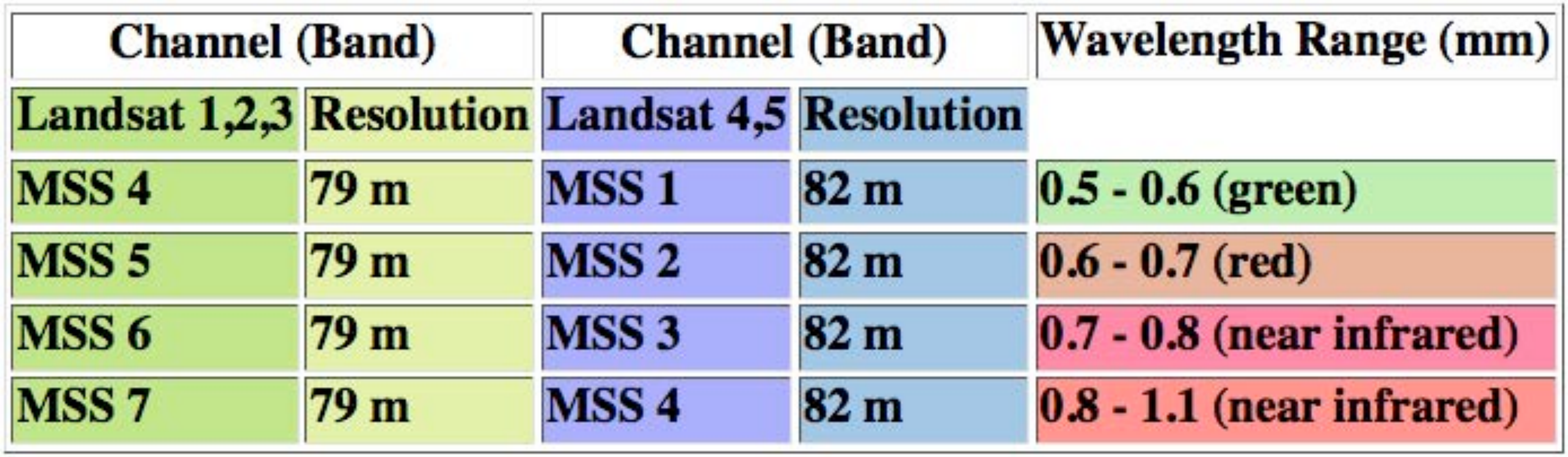
The radiometer is made up of three sensors, each with its own telescope mounted on a gimbaled platform that scans across the Earth in a 6.6-second cycle.

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)

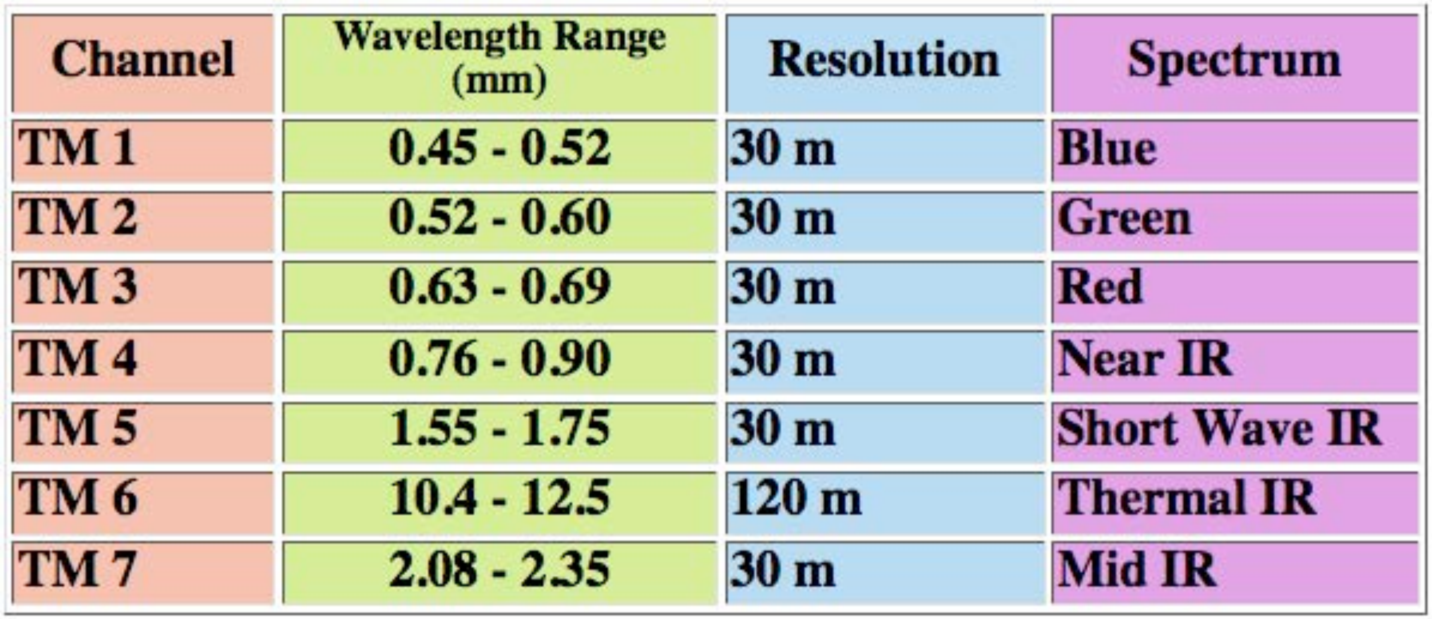
Thermal satellite sensors

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.

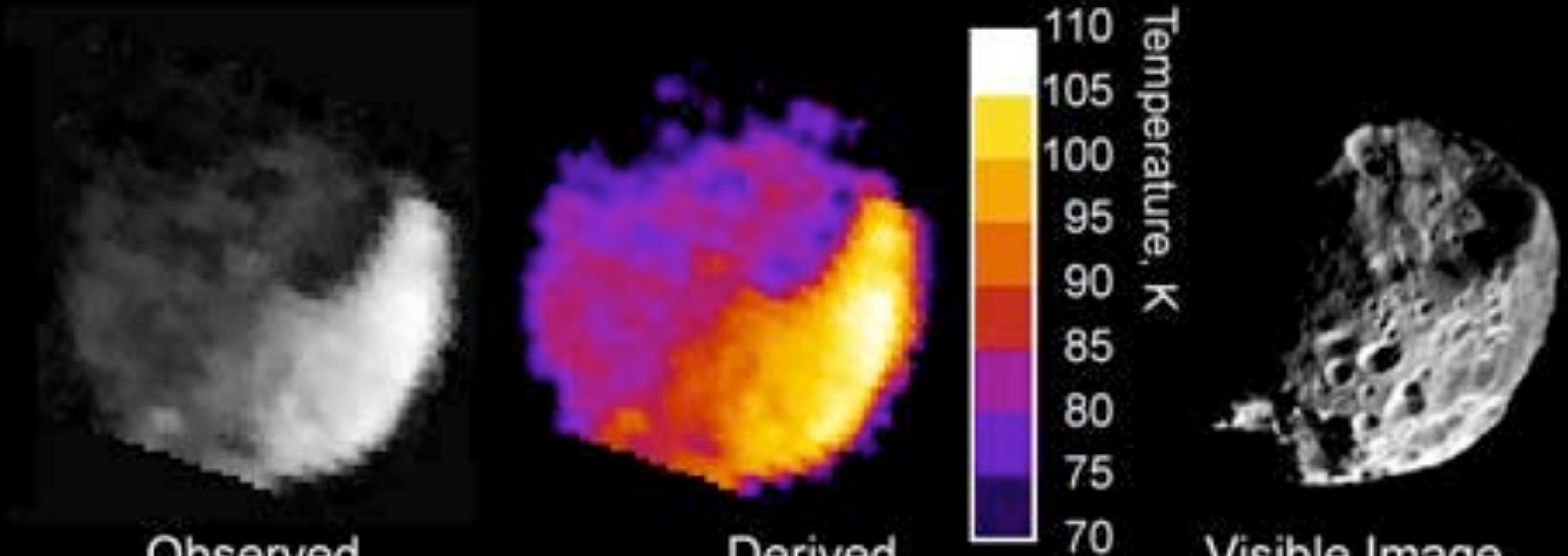
Band 6 senses thermal (heat) infrared radiation. Landsat can only acquire night scenes in Band 6.



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



Observed
15-17 micron
Brightness

Derived
Surface
Temperature

Visible Image
Cassini
ISS Camera

taken by the composite infrared spectrometer onboard Cassini


IR NFOV
Auto Mod
Blk
Day
GeoRate
R
- NEU Fault
LRF: Lat: N 42° 21.981' Lon: W 71° 10.447' Slant Range: 590 m
LRF Armed
1935 ft
LP Armed
+30
0
-30
-60
-90
-120
-180
-90
0
+90
+180
MASSACHUSETTS
STATE
POLICE
TLat N 42° 21.987' TLon W 71° 10.444' Alt 39f S Rng: 307m Ins Nav HdgUncert=0.06
Lat: N 42° 21.858' Lon: W 71° 10.486' Az: -107.2° El: -27.5° 19-Apr-2013 20:01:24L