Climate Change Science
Prof. J. Srinivasan
Department of Environmental Science
Indian Institute of Science, Bangalore

Lecture 03
Blackbody Radiation

In the last lecture, we emphasized the importance of the Earth's global mean temperature, which influences the climate everywhere. We discussed how the global mean temperature is primarily controlled by carbon dioxide, which might seem surprising given that carbon dioxide is much less abundant in the atmosphere compared to water vapor. While both water vapor and carbon dioxide affect Earth's climate, carbon dioxide is the primary controller because it remains a gas in the atmosphere and does not condense.

Water vapor, on the other hand, exists in all three phases: vapor, liquid, and ice. This ability to exist in different phases means that the amount of water vapor, ice, and liquid water present on Earth is dependent on temperature. And importantly, the temperature of the Earth is controlled by carbon dioxide. So, even though carbon dioxide is a minor gas in terms of quantity, it has a disproportionate impact on the climate because it regulates the Earth's temperature, which in turn influences the amount of water vapor in the atmosphere.

This relationship is not immediately intuitive, which is why a solid understanding of thermal radiation and heat transfer is crucial. By understanding how radiation works, you'll be able to appreciate why carbon dioxide, despite being a minor component, plays a major role in regulating the Earth's climate.

This lecture focuses on providing a basic background in radiative heat transfer. To support this, two key books will be used. The first is *Thermal Radiation Heat Transfer* by Howell, Menguc, and Siegel, which has been in circulation for over 50 years. The sixth edition is currently available, but any edition can be used, as the course is based on an earlier, simpler version. The newer editions are more complex. The second relevant book is *An Introduction to Atmospheric Radiation* by K. N. Liou. The major simple energy balance model used in this course is based on a chapter from this book.

Radiation is characterized by the emission and absorption of photons by surfaces. These photons are defined by their wavelength and frequency. From fundamental physics, the product of wavelength and frequency equals the speed at which radiation propagates through a medium, with the relationship expressed as

$$c = \lambda \nu$$

where, λ – wavelength (microns, 10^{-6} m)

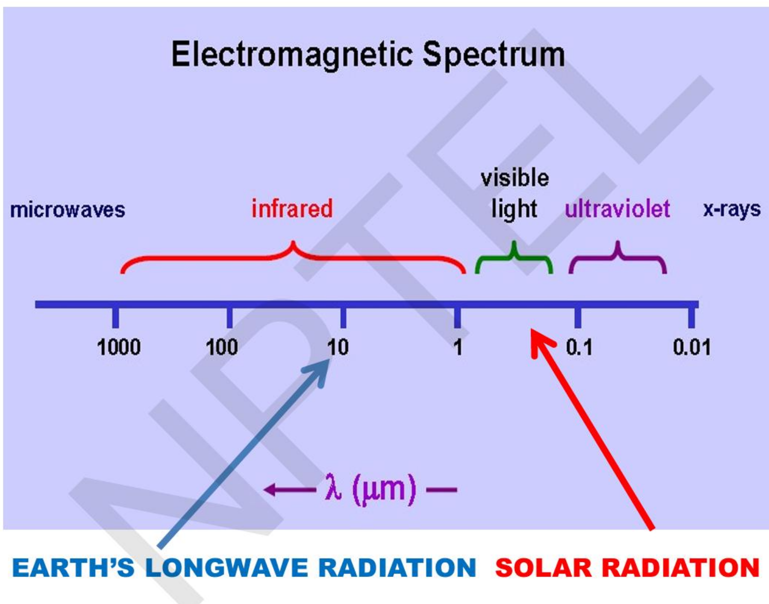
ν – frequency (Hertz, 1/s)

c – speed of electromagnetic wave

Wave-number (ω) is defined as the reciprocal of the wavelength and is expressed in units of inverse meters (or sometimes inverse centimetres).

$$\omega = \frac{1}{\lambda}$$

The speed of electromagnetic waves in a vacuum, $'c'$ is a constant and does not vary in a vacuum. This value of $'c'$ is universally accepted.



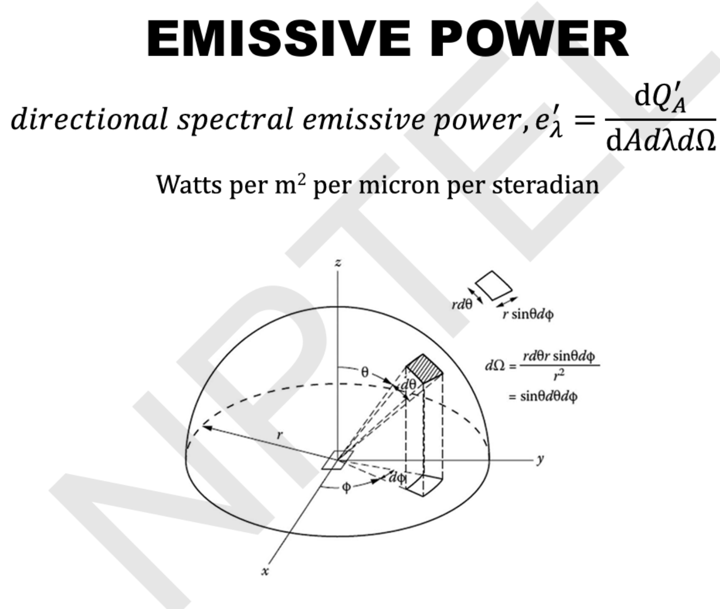
The range of radiation present on Earth is broad, spanning from X-rays at the low-wavelength end (around 0.02 microns) to microwaves with wavelengths exceeding 1000 microns. For the purposes of this course, the focus will primarily be on radiation in the visible and infrared spectra. The radiation from the Sun primarily falls within the visible spectrum, with some in the infrared range, while the radiation emitted by the Earth's surface and atmosphere lies in the range of approximately 4 microns to 100 microns.

It is important to understand how radiation from the Sun is absorbed by the atmosphere and the Earth, as well as how radiation emitted from the Earth's surface is absorbed by the atmosphere and subsequently radiated into space. In this course, we will focus on solar radiation and the Earth's longwave radiation.

A fundamental quantity in radiation is the emissive power. The directional spectral emissive power is defined as follows,

$$e'_\lambda = \frac{dQ'_\lambda}{dA\, d\lambda\, d\Omega}$$

It represents the amount of radiation emitted per unit surface area of the body, per unit wavelength, per unit solid angle.



The solid angle is a key concept in radiation because photons are emitted in all directions, covering 4π steradians. For example, photons can be emitted perpendicular to the surface or at other zenith angles (θ) and azimuthal angles (φ). It is essential to define the radiation emitted for each angle, both zenith and azimuth.

The concept of a solid angle is an extension of the familiar angle concept from high school physics. In that case, the angle $d(\theta)$ is the arc length $d(s)$ divided by the distance from the origin r. This concept is extended into three dimensions, where the area element on the surface of a sphere with radius r is expressed as $(r\, d(\theta)\, r \sin(\theta)\ d\varphi)$. This area is then divided by the square of the radius, to define the solid angle.

$$d\Omega = \frac{r\, d(\theta)\, r \sin(\theta)\ d\varphi}{r^2}$$

In contrast to a regular angle, which spans 360^0 in a circle, a solid angle spans 4π steradians. The total solid angle for a sphere is 4π, and for a hemisphere, it is 2π. This solid angle is fundamental in describing how radiation is emitted in three dimensions.

This is a fundamental aspect of radiation that must be clearly understood, as the emission and propagation of radiation inherently occur in three dimensions. To simplify analysis in many practical problems, angle-averaging techniques are often employed. Although emissive power is the primary definition describing radiation emitted per unit surface area, per unit solid angle, and per unit wavelength, another closely related and equally important quantity is intensity.

The main difference between emissive power and intensity lies in the incorporation of the projection factor $cos(\theta)$. Instead of dividing by the actual surface area, intensity considers the area projected normal to the direction of radiation propagation. When radiation is emitted at an angle θ from the surface normal, the relevant projected area becomes $dA \cdot cos(\theta)$. This leads to the introduction of the directional spectral intensity, denoted as i'_λ, which is defined per unit projected area, per unit solid angle, and per unit wavelength.

$$i'_\lambda = \frac{dQ'_\lambda}{dA\, cos(\theta)\, d\lambda\, d\Omega}$$

One might question the need for introducing this alternate definition. The justification lies in a useful simplification: for many idealized surfaces, the directional spectral intensity is assumed to be independent of the angles θ and φ. When this angular independence holds, integration over these angles becomes significantly easier, as the intensity can be treated as a constant in such cases.

In reality, this assumption does not hold for all surfaces. Some surfaces exhibit angular dependence in the intensity of emitted radiation. However, for the purposes of this introductory course, the angular variation of intensity with respect to θ and φ will be neglected. Thus, i'_λ will be treated as angle-independent.

By definition, there is a direct mathematical relationship between directional spectral emissive power and intensity. Specifically, if one multiplies the directional spectral intensity i'_λ by $cos(\theta)$, the result is the directional spectral emissive power e'_λ.

$$e'_\lambda = i'_\lambda cos(\theta)$$

This relation arises directly from the geometric projection of the surface area along the direction of emission. Consequently, even when i'_λ is assumed to be constant with respect to angle, the emissive power e'_λ remains a function of the zenith angle θ, due to the $cos(\theta)$ term.

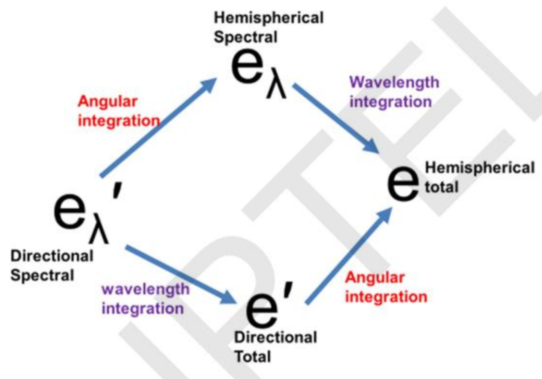
This relationship between intensity and emissive power arises directly from their definitions and is essential to remember. The key distinction lies in how the surface area is treated:

- Intensity is defined per unit area normal to the direction of radiation (i.e., along the direction of the rays).
- Emissive power is defined per unit actual surface area of the emitting body.

When performing energy balance calculations—an essential method in radiative heat transfer and climate analysis—the relevant quantity is emissive power, because energy exchanges are typically expressed per unit surface area.

In this course we will assume the intensity of radiation emitted by a surface is independent of angle θ and φ. Such a surface is called diffuse emitter. This is not strictly true but does not lead to large error in most applications. Note that if a surface is diffuse emitter, then the directional spectral emissive power will be proportional to $\cos(\theta)$.

In radiative heat transfer, the foundational approach begins with the directional spectral quantity, which provides the most detailed description of radiation—defined per unit wavelength and per unit solid angle. This serves as the starting point for all other derived quantities.



To arrive at more practical forms used in applications like Earth's energy balance, two types of integration are carried out:

1. Angular integration (over zenith angle θ and azimuthal angle φ) yields the hemispherical quantity, representing radiation integrated over all directions above a surface.
2. Spectral (wavelength) integration gives the total quantity over all wavelengths.

These two types of integration can be performed in either order:

- First integrating over angles (to get hemispherical spectral values), followed by wavelength integration (to get the hemispherical total), or
- First integrating over wavelength (to get directional total values), followed by angular integration.

Both paths lead to the same final result—the hemispherical total—which is the most relevant quantity for understanding radiation exchanges and conducting energy balance analysis on Earth. The same procedure applies to intensity, starting from directional spectral intensity and integrating over both angle and wavelength to obtain the hemispherical total intensity.

The directional spectral radiative quantities can be expressed either as functions of wavelength (λ) or frequency (ν), depending on the chosen coordinate system. While the wavelength-based formulation is more common in heat transfer, frequency-based expressions are also widely used in fields such as atmospheric science and astrophysics.

To define emissive power in frequency terms, the energy emitted per unit surface area, per unit solid angle, and per unit frequency is considered. The corresponding units are:

$$\left[\frac{W}{m^2\ s^{-1}\ sr}\right]$$

This parallels the wavelength-based formulation, where the units are:

$$\left[\frac{W}{m^2\ \mu m\ sr}\right]\ or\ \left[\frac{W}{m^2\ m\ sr}\right]$$

The relationship between directional spectral emissive power in the two coordinate systems is derived from the fact that wavelength (λ) and frequency (ν) are inversely related through the speed of light. Therefore, an increase in one corresponds to a decrease in the other, and the differential elements are related by:

$$d\nu = -\frac{c}{\lambda^2}d\lambda$$

From energy equivalence,

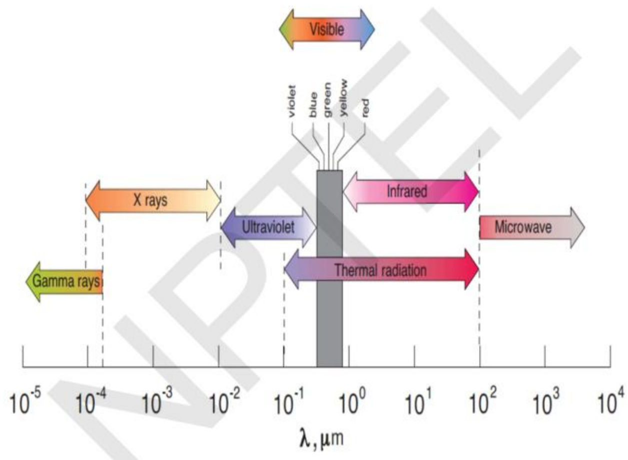
$$e'_\lambda d\lambda = -e'_\nu d\nu$$

The negative sign appears because as wavelength increases, frequency decreases, which is a consequence of the inverse relationship between λ and ν.

A blackbody is an idealized object that absorbs all radiation incident upon it, regardless of the wavelength or angle. It is a theoretical concept used as a reference in radiation studies, but it does not exist in reality. The term blackbody refers to this ideal, not to any object that happens to appear black in color.

It is important to distinguish between an object that looks black in the visible spectrum and a blackbody. The color of an object, as perceived by the human eye, only tells us about how it interacts with light in the visible range. An object that appears black may absorb visible light but may not necessarily absorb radiation across all wavelengths, such as ultraviolet or infrared. To be classified as a blackbody, the object must absorb radiation across the full electromagnetic spectrum, from X-rays to microwaves, not just in the visible range.

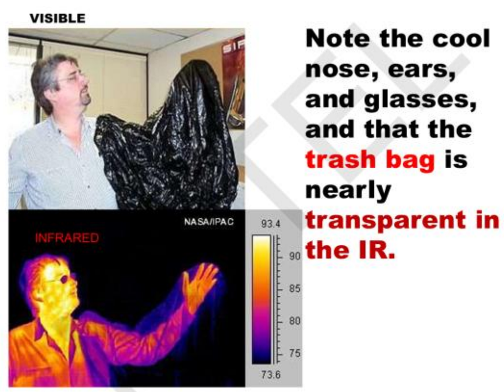
In summary, while the term "blackbody" may sound similar to describing something that is black in color, it refers specifically to an idealized object that absorbs all incident radiation, making it a key reference for understanding radiation and energy transfer.



In this course, the focus will be on the ultraviolet (UV), visible, and infrared (IR) regions of the electromagnetic spectrum, as these are the key wavelengths associated with radiation from both the Sun and the Earth. The electromagnetic spectrum encompasses a wide range of wavelengths, including gamma rays, X-rays, ultraviolet light, visible light, infrared radiation, and microwaves.

While gamma rays are not covered in this course, they represent a part of the spectrum, and X-rays and ultraviolet light are part of the higher energy radiation. Visible light is the portion of the spectrum that the human eye can detect. Infrared radiation is emitted by the Earth as thermal radiation, and microwaves, which are familiar to us through technologies like mobile phones, are part of the longer wavelength radiation.

In the context of climate science and Earth's energy balance, the primary focus is on the radiation from the Sun, which primarily emits in the UV, visible, and IR ranges, and the radiation emitted by the Earth's surface, which also lies within these regions. These wavelengths are crucial for understanding the dynamics of Earth's climate and energy interactions.



The distinction between a body that appears black in color and a true blackbody is important. A body that is black in color in the visible spectrum does not necessarily absorb all radiation across all wavelengths. For example, a plastic sheet that appears black in visible light might be transparent in the infrared (IR) spectrum. This means it does not absorb IR radiation, and therefore, it is not a blackbody.

A blackbody is defined as an idealized object that absorbs all incident radiation, across all wavelengths and angles, from the ultraviolet to the microwave range. So, to confirm if a body is a blackbody, one must evaluate its absorption properties across the entire electromagnetic spectrum. A surface may appear black in one region, but it cannot be considered a blackbody unless it absorbs all radiation across all wavelengths, not just the visible spectrum.

A blackbody is an idealized object that not only absorbs all radiation across all wavelengths (from X-rays to microwaves) but also emits radiation uniformly in all directions. This means that the directional spectral intensity of a blackbody is independent of the angles θ (zenith angle) and φ (azimuthal angle). This property simplifies calculations because it allows for the assumption that the intensity of radiation is the same in every direction, making it easier to integrate over angles.

In this course, we will adopt the approximation that real surfaces also behave like blackbodies in terms of their angular dependence, even though in reality, real surfaces do show angular dependence. The simplification assumes that the directional spectral intensity of a real surface is independent of angle, though this approximation may introduce errors. However, for this introductory course, the consequences of these errors are minimal.

For a blackbody, the hemispherical spectral emissive power can be calculated by integrating the directional spectral intensity over angles. This involves two simple integrations: first, integrating over the angle φ gives 2π, and then integrating over θ gives $\frac{1}{2}$. This results in the following equation for the hemispherical spectral emissive power.

$$e_{\nu b} = \int e'_{\nu b}\, d\Omega = i'_{\nu b} \int \cos\theta\, d\Omega = i'_{\nu b} \int_0^{2\pi} \int_0^{\frac{\pi}{2}} \cos\theta \sin\theta\, d\theta\, d\varphi$$

$$e_{\nu b} = \pi i'_{\nu b}$$

While this approach applies to blackbodies, we will also use it for real surfaces in this course, keeping in mind that it is an approximation. Advanced courses, however, may require considering more detailed angular dependencies for real surfaces.

The Planck radiation law, formulated by Max Planck in 1901, is a foundational result in the study of thermal radiation and marked a significant milestone in the development of quantum mechanics. Planck derived an expression for the hemispherical spectral emissive power of a blackbody shown below, revealing how the intensity of radiation emitted by a blackbody varies with wavelength and temperature.

Planck's Blackbody Radiation law

$$e_{\nu b} = \frac{2\pi h\nu^3}{c^2\left[e^{\frac{h\nu}{\kappa T}} - 1\right]} \quad \text{Watts}/\{\text{m}^2 \text{ sec}^{-1}\}$$

h = Planck's constant
κ = Boltzmann constant
c = speed of light in the medium

We can obtain $e_{\lambda b}$ from the above equation using the identity , $e_{\lambda b}\, d\lambda = -\, e_{\nu b} d\nu$

$$e_{\lambda b} = \frac{2\pi c_1}{\lambda^5\left[e^{\frac{c_2}{\lambda T}} - 1\right]} \qquad \text{Where,} \quad c_1 = hc^2, \quad c_2 = \frac{hc}{\kappa}$$

Although Planck's derivation was based on certain assumptions that were not fully consistent with classical physics, the result itself was remarkably elegant and accurate. His work introduced the concept of energy quantization, laying the groundwork for quantum theory.

Later, Albert Einstein proposed an alternative derivation of Planck's law that combined ideas from both classical physics and quantum mechanics, offering deeper insight into the nature of light and radiation. Despite its elegance, even Einstein's approach retained elements from both paradigms.

Subsequently, the Indian physicist Satyendra Nath Bose, in his mid-twenties, presented a more rigorous and purely statistical derivation of Planck's law using statistical thermodynamics. His work, sent to Einstein in a letter, impressed Einstein so much that he translated it into German and helped publish it. This work led to the development of Bose-Einstein statistics, which became fundamental in quantum theory and paved the way for concepts like Bose-Einstein condensates.

Thus, Planck's law is not only central to the understanding of blackbody radiation but also pivotal in the history of modern physics.

Although there was initial skepticism surrounding the validity of Planck's law, its accuracy has been confirmed through extensive observations—not just in laboratory settings, but also on a cosmic scale. A particularly compelling validation comes from the cosmic microwave background (CMB) radiation, which represents the remnant radiation from the Big Bang, approximately 13.8 billion years ago.

When one observes the night sky—specifically the dark regions between the stars—the CMB can be detected as a faint, uniform radiation arriving from all directions. This radiation behaves almost exactly like that emitted by a perfect blackbody. Precise measurements of the CMB, especially those conducted by satellite missions such as COBE, WMAP, and Planck, have confirmed that its spectrum matches the blackbody radiation curve described by Planck's law with remarkable accuracy.

These measurements show that Planck's equation holds true not only in controlled experimental conditions but also in the vast and complex environment of the universe. The law remains accurate to many decimal places, making it one of the most precisely validated results in physics. Consequently, any lingering doubts about its applicability have been resolved, and Planck's law is now regarded as a fundamental and universally valid law of physics, free from approximation.

Planck originally derived the law of blackbody radiation in frequency space, expressing the hemispherical spectral emissive power of a blackbody as a function of frequency (ν). While this formulation is mathematically convenient for certain analyses, in many practical applications—especially in atmospheric sciences and engineering—it's often more useful to express the law in terms of wavelength (λ).

To convert the frequency-based formulation to a wavelength-based one, a fundamental identity is used that relates energy distributions per unit wavelength and per unit frequency:

$$e'_{\lambda} d\lambda = -e'_{\nu} d\nu$$

We know that

$$\frac{d\nu}{d\lambda} = -\frac{c}{\lambda^2}$$

On substituting this in the Planck's equation in frequency space and rearranging appropriately, we arrive at the wavelength form of Planck's law for hemispherical spectral blackbody emissive power.

$$e_{\lambda b} = \frac{2\pi hc^2}{\lambda^5 \left(e^{\frac{hc}{\lambda k_b T}} - 1 \right)}$$

When the Planck function $e_{\lambda b}(T)$ is plotted as a function of wavelength for different blackbody temperatures, the resulting curves display a distinct shape: they rise steeply, peak at a certain wavelength, and then fall more gradually—making the curve asymmetric about its maximum. This asymmetry means there is more radiation at longer wavelengths (to the right of the peak) than at shorter wavelengths (to the left).

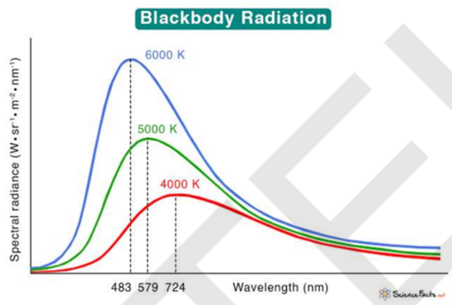
To find the wavelength at which the emissive power is maximum for a given temperature, one differentiates the Planck function with respect to wavelength and sets the derivative to zero. This yields Wien's Displacement Law, which states:

$$\lambda_{max} T = 2898 \; \mu m \; K$$

Here:

- λ_{max} is the wavelength at which the blackbody emission peaks,
- T is the absolute temperature of the blackbody in Kelvin.

This relationship was discovered by Wilhelm Wien, prior to the derivation of Planck's law, and it is now known as Wien's Law. It is one of the key tools for understanding blackbody radiation and is especially useful in estimating the dominant wavelength of emission based on temperature—for example, identifying whether an object radiates primarily in the visible, infrared, or ultraviolet region.



Spectral emissive power of a blackbody is not symmetric around the maximum. Note that 25% of the radiation lies to the left of the maximum while 75% lies to the right

$$\frac{de_{\lambda b}}{d\lambda} = 0, \text{gives} \quad \lambda T = 2898 \mu K$$

The maximum value of the blackbody emissive power is at λ(in microns) is equal to 2898/T

A key insight from the blackbody radiation curve is the asymmetry around the peak. Specifically, only about 25% of the total emitted radiation lies to the left (shorter wavelengths) of the peak, while the remaining 75% lies to the right (longer wavelengths). This long tail toward the infrared is a critical feature of the radiation distribution and must be accounted for in any radiative transfer analysis. It highlights that the maximum of the curve does not represent the average energy or dominant energy output—it simply marks the wavelength of maximum emissive power.

This peak wavelength is described by Wien's Displacement Law:

$$\lambda_{max} = \frac{2898}{T} \; \mu m$$

Using this, for Earth's surface at T = 289.8 K, the peak emission occurs at $\lambda_{max} = 10\ \mu m$, and for the Sun at T = 5796 K, the peak emission occurs at $\lambda_{max} = 0.5\ \mu m$.

This contrast has major implications for climate studies:

- The Sun emits primarily in the visible spectrum (centered around 0.5 µm),
- The Earth emits primarily in the thermal infrared (centered around 10 µm).

This difference determines how different surfaces on Earth interact with solar versus terrestrial radiation. For instance:

- Snow appears white in the visible spectrum because it reflects most visible light,
- However, at 10 µm, snow behaves like a blackbody, absorbing nearly all thermal infrared radiation—thus appearing black in thermal imaging.

This underscores an essential concept: reflectivity and absorptivity are strongly wavelength-dependent. Surfaces may appear highly reflective (or black) in one part of the spectrum and behave completely differently in another. Consequently, one must never rely on visible appearance to infer radiative properties across all wavelengths. Understanding this wavelength dependence is crucial for accurately modelling Earth's energy balance, surface temperature, and climate feedbacks like those involving ice and snow.

So far, we have examined blackbody radiation as a spectral quantity, meaning it's defined per unit wavelength (or per unit frequency). But in many practical applications—like estimating how much energy the Sun emits in the visible range (0.4–0.7 µm)—we need to determine how much radiation lies within a specific range of wavelengths, not just at a single point.

To do this, we integrate the spectral emissive power $e_{\lambda b}$ over the desired wavelength interval, say from λ_1 to λ_2

$$E_{b(\lambda_1 \rightarrow \lambda_2)} = \int_{\lambda_1}^{\lambda_2} e_{\lambda b}\, d\lambda$$

To find the fraction of the total blackbody emission that falls within this range, we divide the result by the total blackbody emissive power, which is the integral over all wavelengths:

$$F_{(\lambda_1 \rightarrow \lambda_2)} = \frac{\int_{\lambda_1}^{\lambda_2} e_{\lambda b}\, d\lambda}{\int_{0}^{\infty} e_{\lambda b}\, d\lambda}$$

where,

$$e_{\lambda b} = \frac{2\pi h c^2}{\lambda^5 \left(e^{\frac{hc}{\lambda k_b T}} - 1 \right)}$$

To simplify the integration of the spectral blackbody emissive power, we make use of a transformation that reveals a very important and elegant property. The spectral function $e_{\lambda b}(T)$, when normalized by T^5, becomes a function of just λT- a product of wavelength and temperature.

$$\frac{e_{\lambda b}}{T^5} = \frac{2\pi c_1}{(\lambda T)^5\left(e^{\frac{c_2}{\lambda T}} - 1\right)} = f(\lambda T)$$

Then

$$F_{(\lambda_1 T \to \lambda_2 T)} = \int_{\lambda_1}^{\lambda_2} f(\lambda T) d(\lambda \mathrm{T})$$

In order to estimate the total emissive power of a blackbody we need to integrate the Planck's equation over all wavelengths. It can be done either in the frequency space or the wavelength space, both of which will yield the same answer.

Consider the integration in the frequency domain.

$$e_b = \int_0^{\infty} \frac{2\pi h\nu^3}{c^2\left(e^{\frac{h\nu}{k_b T}} - 1\right)} d\nu$$

On substituting $\eta = \frac{h\nu}{k_b T}$ and rearranging the terms in the above equation yields

$$e_b = \frac{k_b T}{h} \frac{2\pi h}{c^2} \left(\frac{k_b T}{h}\right)^3 \int_0^{\infty} \frac{\eta^3}{(e^{\eta} - 1)} d\eta$$

So, the Planck function gets expressed in terms of η, and the entire integral depends only on constants and the function $\int_0^{\infty} \frac{\eta^3}{(e^{\eta}-1)} d\eta$. This integral is famous and has a known analytical result from complex analysis.

$$\int_0^{\infty} \frac{\eta^3}{(e^{\eta} - 1)} d\eta = \frac{\pi^4}{15}$$

So, the total emissive power of a blackbody integrated over all wavelengths is equal to

$$e_b = \frac{2\pi^5 {k_b}^4}{15 c^2 h^3} (T)^4$$

This leads to an important and elegant expression for the total emissive power of a blackbody referred to as the Stefan-Boltzmann's Law:

$$e_b = \sigma T^4$$

Here, σ is the Stefan–Boltzmann constant, derived from fundamental constants—Planck's constant h, Boltzmann's constant k_B, and the speed of light c. This constant was initially obtained from laboratory measurements, but now it can be computed directly from these universal constants, confirming that its value is the same everywhere in the universe. Its accepted value is:

$$\sigma = 5.67 \times 10^{-8}\ Wm^{-2}K^{-4}$$

This quantity is fundamental to thermal radiation and will be repeatedly used in this course.

How much radiation lies between two different wavelengths at a given temperature?

λT $\mu m \cdot K$	$F_{0\rightarrow\lambda T}$
1,448	0.01
$2{,}898 = \lambda_{max} T$	0.25
4,107	0.50
6,148	0.75
22,890	0.99

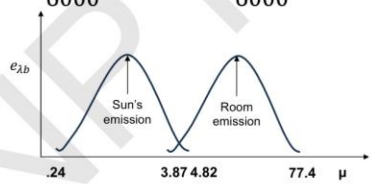
98%

$$At\ Room\ temperature, T = 300K$$

$$\frac{1448}{300} = 4.82\mu\ to\ \frac{23220}{300} = 77.4\mu$$

$$At\ Sun's\ temperature, T = 6000K$$

$$\frac{1448}{6000} = 0.24\mu\ to\ \frac{23220}{6000} = 3.87\mu$$



Having developed a fundamental understanding of blackbody radiation, we can now determine how much of this radiation lies within specific wavelength ranges. Referring back to Wien's displacement law, it becomes possible to estimate these ranges for different temperatures. For example, at 300 K, the product $\lambda T = 1448\ \mu mK$ corresponds to 1% of the radiation lying below 4.82 µm. Similarly, the value $\lambda T = 23{,}220\ \mu mK$ gives 77.4 µm, above which only 1% of the radiation lies. Therefore, for a blackbody at 300 K, 98% of the radiation lies between 4.82 µm and 77.4 µm. In contrast, if we consider the Sun, approximated as a blackbody at 6000 K, a similar calculation shows that 98% of its radiation lies between 0.24 µm and 3.87 µm.

The critical insight from this analysis is that the radiation emitted by the Earth and by the Sun occupy almost entirely separate parts of the electromagnetic spectrum. The Earth's radiation lies mostly in the infrared, while the Sun's radiation is concentrated in the visible and near-ultraviolet. This mutual exclusivity is a fundamental concept in radiative transfer and climate science, as it helps distinguish between solar radiation (shortwave) and terrestrial radiation (longwave), both of which interact differently with the Earth's atmosphere and surface. This distinction forms the basis for understanding Earth's energy balance and climate processes.