Lecture 8

Third stage

AL-MUSTAQBAL UNIVERSITY COLLEGE

Rayleigh scattering

By

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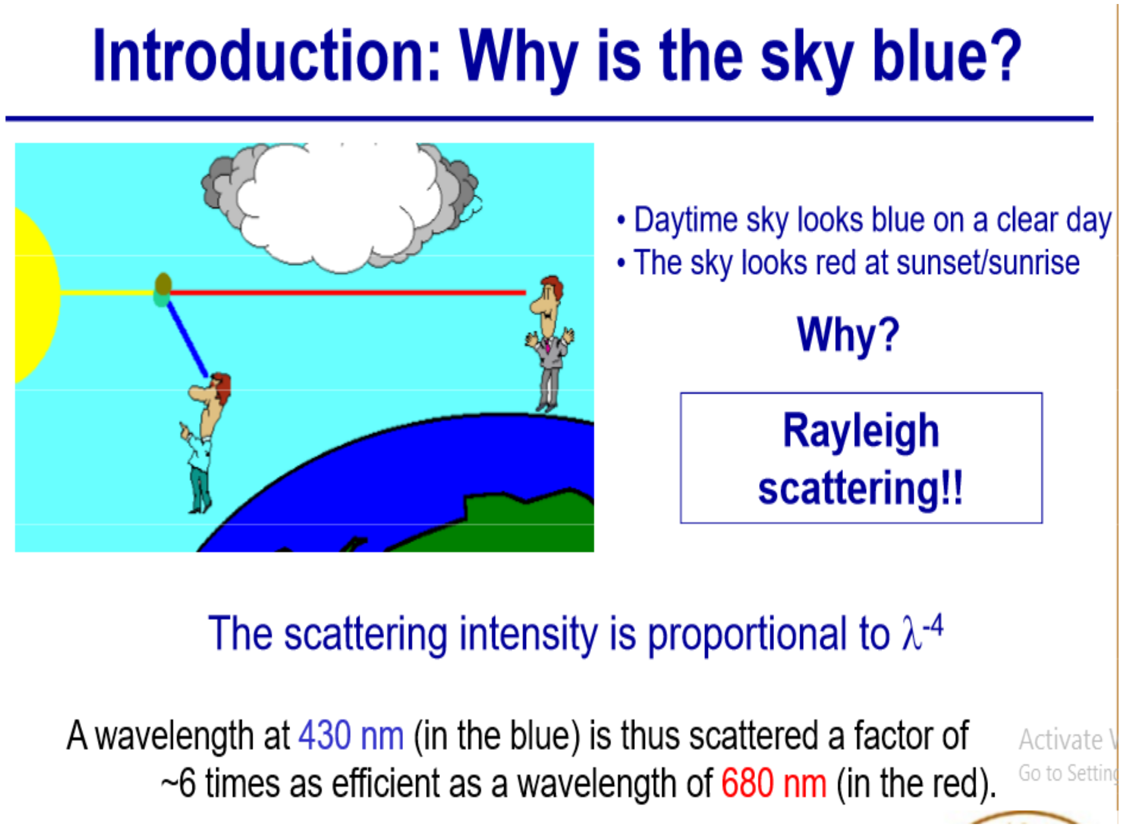
Rayleigh scattering results from the electric polarizability of the particles. The oscillating electric field of a light wave acts on the charges within a particle, causing them to move at the same frequency. The particle, therefore, becomes a small radiating dipole whose radiation we see as scattered light. The particles may be individual atoms or molecules; it can occur when light travels through transparent solids and liquids, but is most prominently seen in gases.

Scattering by particles with a size comparable to or larger than the wavelength of the light is typically treated by the Mie theory, the discrete dipole approximation and other computational techniques. Rayleigh scattering applies to particles that are small with respect to wavelengths of light, and that are optically "soft" (i.e., with a refractive index close to 1). Anomalous diffraction theory applies to optically soft but larger particles.

In 1869, while attempting to determine whether any contaminants remained in the purified air he used for infrared experiments, John Tyndall discovered that bright light scattering off nanoscopic particulates was faintly blue-tinted. He conjectured that a similar scattering of sunlight gave the sky its blue hue, but he could not explain the preference for blue light, nor could atmospheric dust explain the intensity of the sky's color
.

In 1871, Lord Rayleigh published two papers on the color and polarization of skylight to quantify Tyndall's effect in water droplets in terms of the tiny particulates' volumes and refractive indices. In 1881 with the benefit of James Clerk Maxwell's 1865 proof of the electromagnetic nature of light, he showed that his equations followed from electromagnetism. In 1899, he showed that they applied to individual molecules, with terms containing particulate volumes and refractive indices replaced with terms for molecular polarizability.



Introduction: Why is the sky blue?

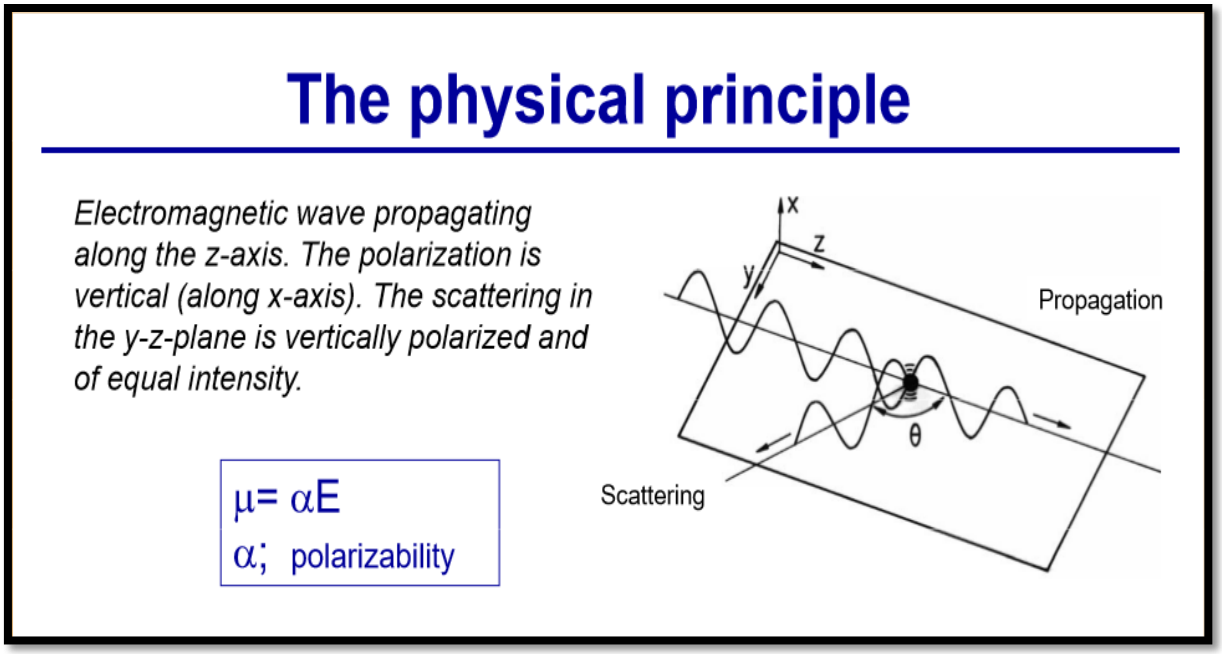
- Daytime sky looks blue on a clear day
- The sky looks red at sunset/sunrise

Why?

Rayleigh scattering!!

The scattering intensity is proportional to λ^{-4}

A wavelength at 430 nm (in the blue) is thus scattered a factor of ~6 times as efficient as a wavelength of 680 nm (in the red).

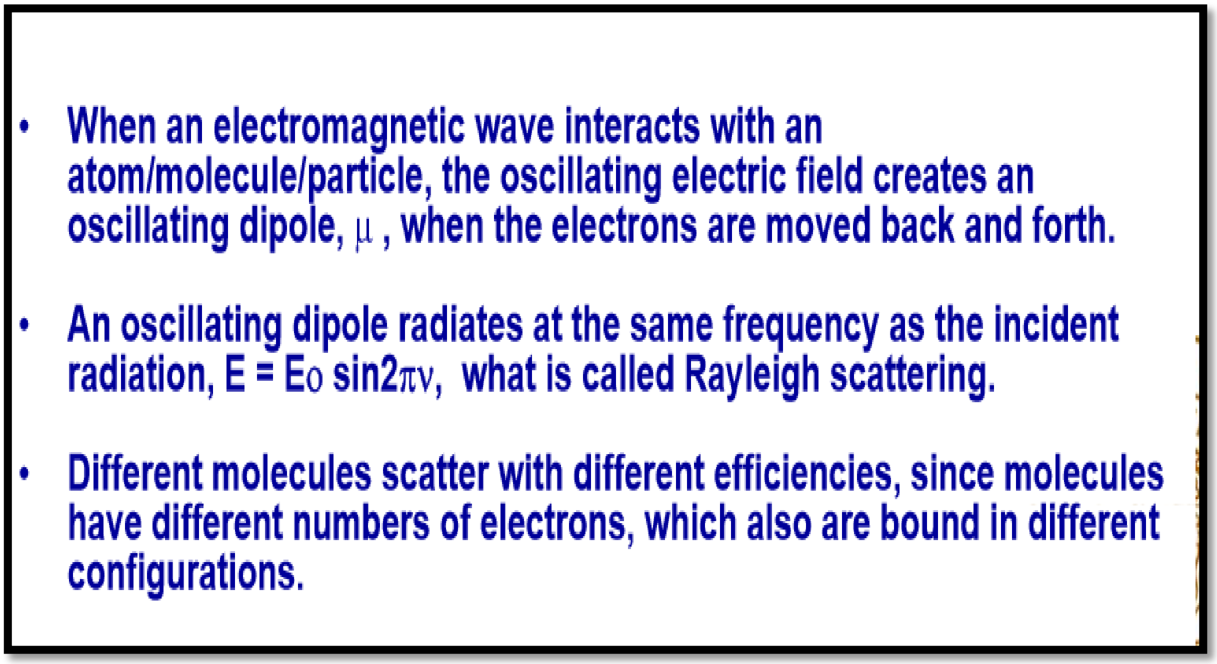


The physical principle

Electromagnetic wave propagating along the z-axis. The polarization is vertical (along x-axis). The scattering in the y-z-plane is vertically polarized and of equal intensity.

$\mu = \alpha E$

α; polarizability

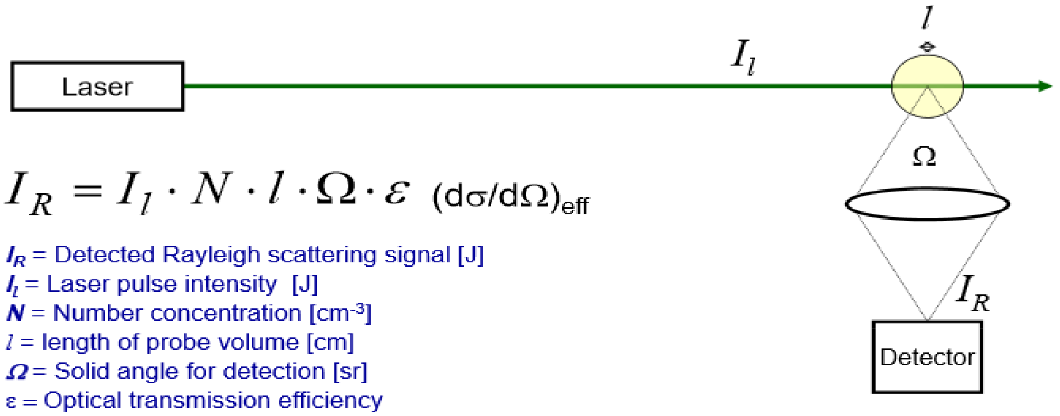


- **When an electromagnetic wave interacts with an atom/molecule/particle, the oscillating electric field creates an oscillating dipole, μ, when the electrons are moved back and forth.**
- **An oscillating dipole radiates at the same frequency as the incident radiation, $E = E_0 \sin 2\pi\nu$, what is called Rayleigh scattering.**
- **Different molecules scatter with different efficiencies, since molecules have different numbers of electrons, which also are bound in different configurations.**

Diagnostic potential

- **Rayleigh scattering is mostly used for temperature measurements. 2-D measurements can be performed. Examples will be shown.**
- **The possibility to make concentration measurements is in general limited. The reason is that all molecules scatter at the same wavelength. However, when a species with very large cross-section (fuel) is probed, species visualization is possible**

A Rayleigh scattering setup



$$I_R = I_l \cdot N \cdot l \cdot \Omega \cdot \varepsilon \ (d\sigma/d\Omega)_{eff}$$

I_R = Detected Rayleigh scattering signal [J]
I_l = Laser pulse intensity [J]
N = Number concentration [cm^{-3}]
l = length of probe volume [cm]
Ω = Solid angle for detection [sr]
ε = Optical transmission efficiency

$(d\sigma/d\Omega)_{eff}$ = Rayleigh cross section for gas mixture [cm^2/sr]

$$(d\sigma/d\Omega)_{eff} = \sum_i X_i \, (d\sigma_i/d\Omega)$$

X_i = Mole fraction of species i
σ_i = Rayleigh cross section of species i [cm^2/sr]

Rayleigh scattering thermometry (1)

$$I_R = I_l \cdot N \cdot l \cdot \Omega \cdot \varepsilon \cdot (d\sigma/d\Omega)_{eff}$$

The Rayleigh scattering signal is proportional to the number concentration of species and the cross section of the gas mixture.

If the cross section $(d\sigma/d\Omega)_{eff}$ is assumed to be constant: $\boxed{I \sim N}$

According to the perfect gas law: $N = \frac{p\,A_o}{R\,T}$

Since A_0 and R are constants, and pressure can be considered to be constant in a combustion situation, it means that:

Rayleigh scattering signal is inversely proportional to the temperature, i.e. $I_R \propto 1/T$

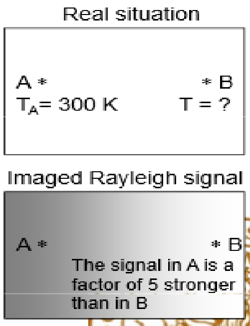
Rayleigh scattering thermometry (2)

$$I_R \propto 1/T$$

This expression can now be applied to a two-dimensional image of Rayleigh scattering.

Example

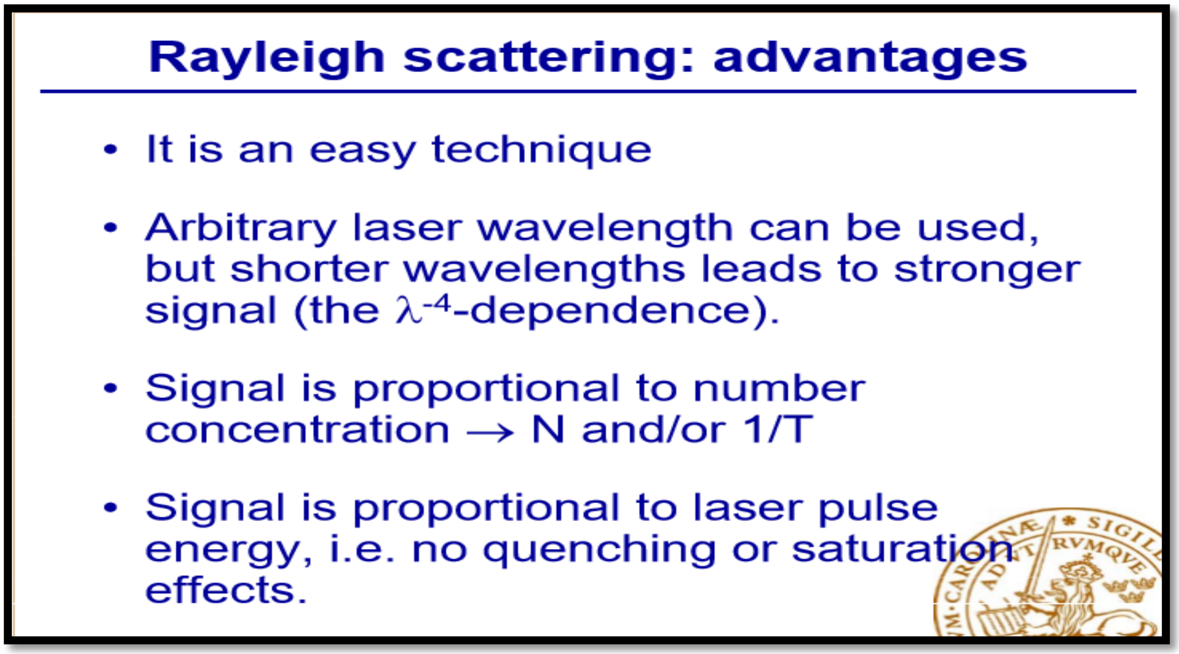
Assume an imaging Rayleigh measurement where
1) the temperature is 300 K in measurement point A.
2) the signal is a factor of five stronger in A than in B.



Then we can calculate the temperature in point B:

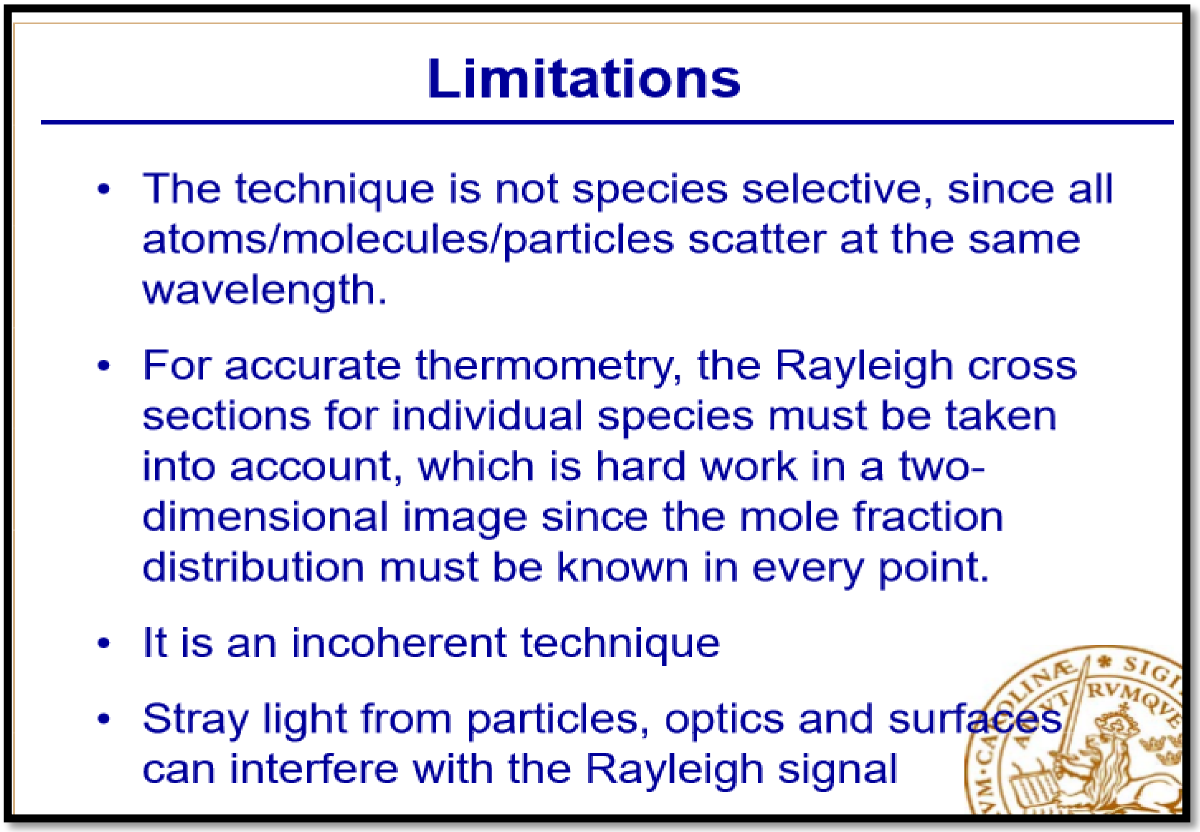
$$T_B = T_A \frac{I_{R,A}}{I_{R,B}} = 300\ K\,\frac{5}{1} = 1500\ K$$

Warning: Differences in Rayleigh cross sections for different species may give large errors!



Rayleigh scattering: advantages

- It is an easy technique
- Arbitrary laser wavelength can be used, but shorter wavelengths leads to stronger signal (the λ^{-4}-dependence).
- Signal is proportional to number concentration → N and/or 1/T
- Signal is proportional to laser pulse energy, i.e. no quenching or saturation effects.



Limitations

- The technique is not species selective, since all atoms/molecules/particles scatter at the same wavelength.
- For accurate thermometry, the Rayleigh cross sections for individual species must be taken into account, which is hard work in a two-dimensional image since the mole fraction distribution must be known in every point.
- It is an incoherent technique
- Stray light from particles, optics and surfaces can interfere with the Rayleigh signal