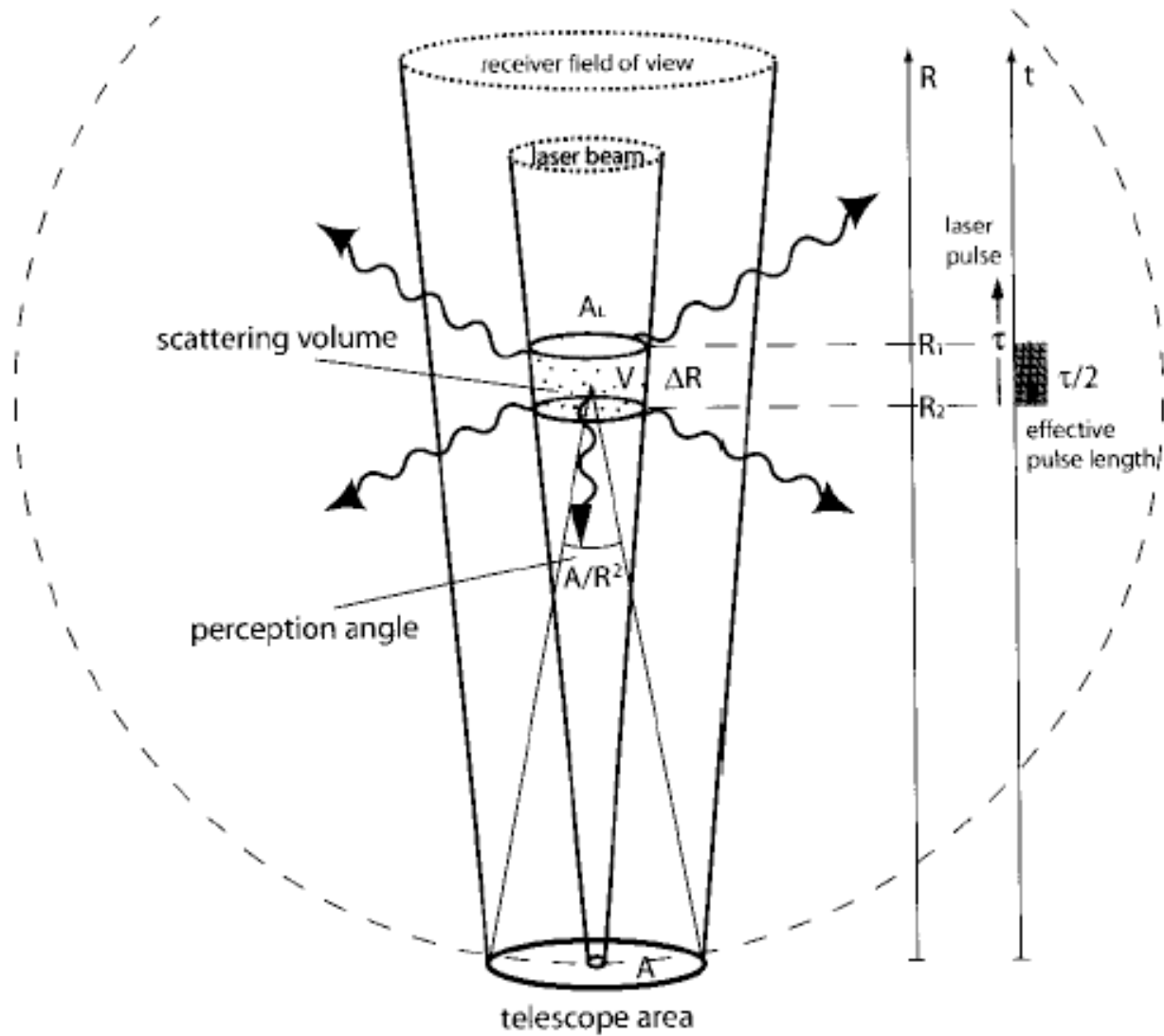


Lecture 06. Physical Processes Involved in Lidars

- ❑ General Illustration of lidar equation
- ❑ Overview of physical processes in lidar
- ❑ Elastic and in-elastic scattering vs polarization
- ❑ Absorption and differential absorption
- ❑ Fluorescence and resonance fluorescence
- ❑ Comparison of backscatter cross section
- ❑ Summary

Illustration of LIDAR Equation



General Form of LIDAR Equation

$$N_S(\lambda, R) = N_L(\lambda_L) \cdot [\beta(\lambda, \lambda_L, \theta, R) \Delta R] \cdot \frac{A}{R^2} \cdot [T(\lambda_L, R) T(\lambda, R)] \cdot [\eta(\lambda, \lambda_L) G(R)] + N_B$$

$$N_S(\lambda, R) = N_L(\lambda_L) \cdot [\beta_T(\lambda, \lambda_L, R) \Delta R] \cdot \frac{A}{4\pi R^2} \cdot [T(\lambda_L, R) T(\lambda, R)] \cdot [\eta(\lambda, \lambda_L) G(R)] + N_B$$

Angular
scattering coefficient

$$\beta(\lambda, \lambda_L, \theta, R) = \sum_i \left[\frac{d\sigma_i(\lambda_L)}{d\Omega} n_i(R) p_i(\lambda) \right]$$

Total
scattering coefficient

$$\begin{aligned} \beta_T(\lambda, \lambda_L, R) &= \int_0^{4\pi} \beta(\lambda, \lambda_L, \theta, R) d\Omega \\ &= \int_0^{4\pi} \sum_i \left[\frac{d\sigma_i(\lambda_L)}{d\Omega} n_i(R) p_i(\lambda) \right] d\Omega \\ &= \sum_i [\sigma_i(\lambda_L) n_i(R) p_i(\lambda)] \end{aligned}$$

General Lidar Equation in β and α

$$N_S(\lambda, R) = \left[\frac{P_L(\lambda_L)\Delta t}{hc/\lambda_L} \right] \left[\beta(\lambda, \lambda_L, \theta, R)\Delta R \right] \left(\frac{A}{R^2} \right) \\ \cdot \exp\left[-\int_0^R \alpha(\lambda_L, r') dr'\right] \exp\left[-\int_0^R \alpha(\lambda, r') dr'\right] \left[\eta(\lambda, \lambda_L)G(R) \right] + N_B$$

Transmission

$$T(\lambda_L, R)T(\lambda, R) = \exp\left[-\left(\int_0^R \alpha(\lambda_L, r) dr + \int_0^R \alpha(\lambda, r) dr\right)\right]$$

Overview of Lidar Physical Processes

❑ Interaction between light and objects

(1) Scattering (instantaneous elastic & inelastic): Mie, Rayleigh, Raman

(2) Absorption and differential absorption

(3) Laser induced fluorescence

(4) Resonance fluorescence

(5) Doppler shift and Doppler broadening

(6) Boltzmann distribution

(7) Reflection from target or surface

❑ Light propagation in atmosphere or medium: transmission vs extinction

Extinction = Scattering + Absorption

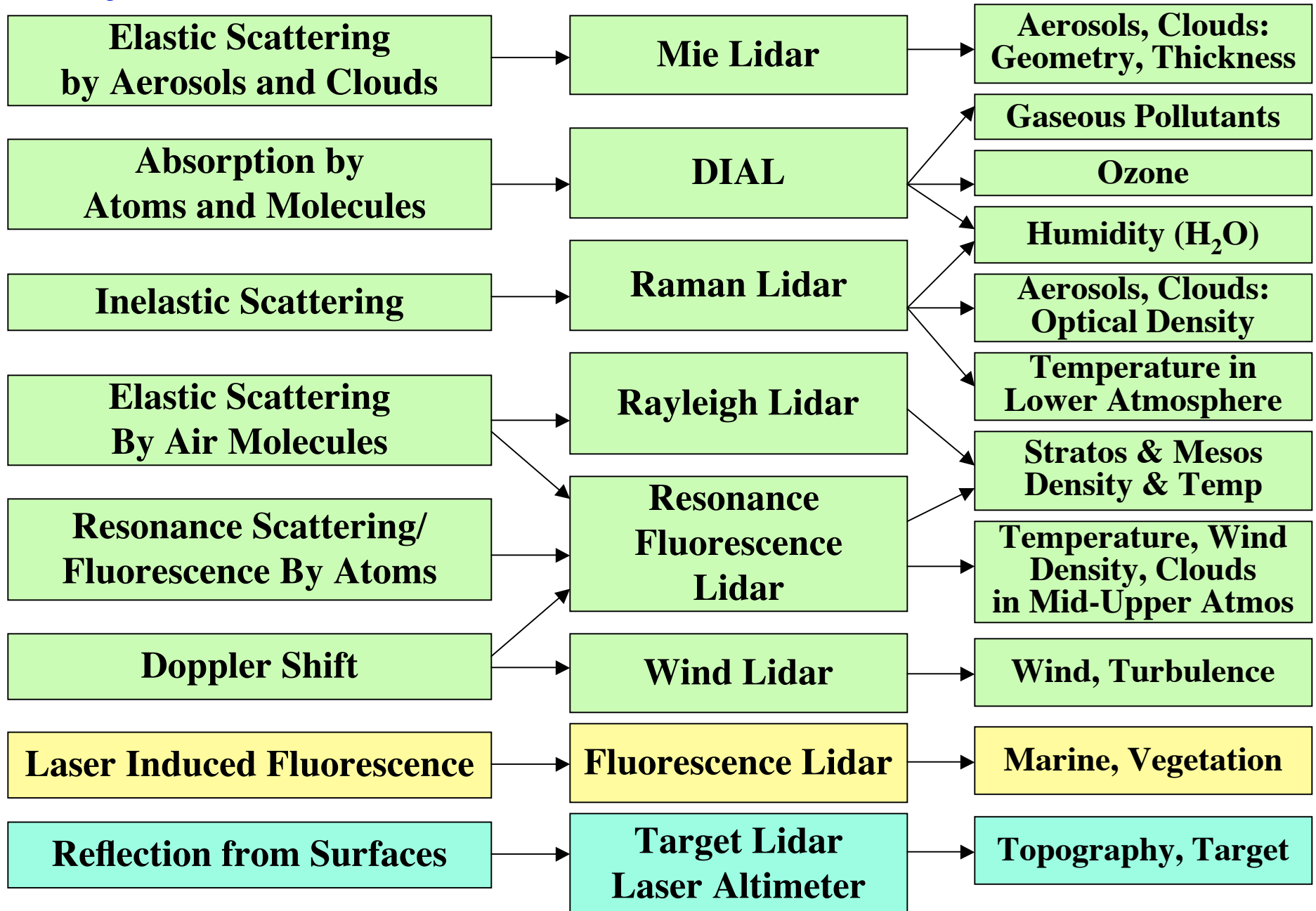
$$T(\lambda, R) = \exp\left[-\int_0^R \alpha(\lambda, r) dr\right]$$

$$\alpha(\lambda, R) = \sum_i [\sigma_{i,ext}(\lambda) n_i(R)]$$

Physical Process

Device

Objective



Elastic and Inelastic Scattering

□ Elastic scattering:

scattering with no apparent change of wavelength

Sum of elastic scattering from atmospheric molecules and elastic scattering from aerosol particles and cloud droplets

Rayleigh scattering and Mie scattering

(There are confusions in definitions of these scatterings.)

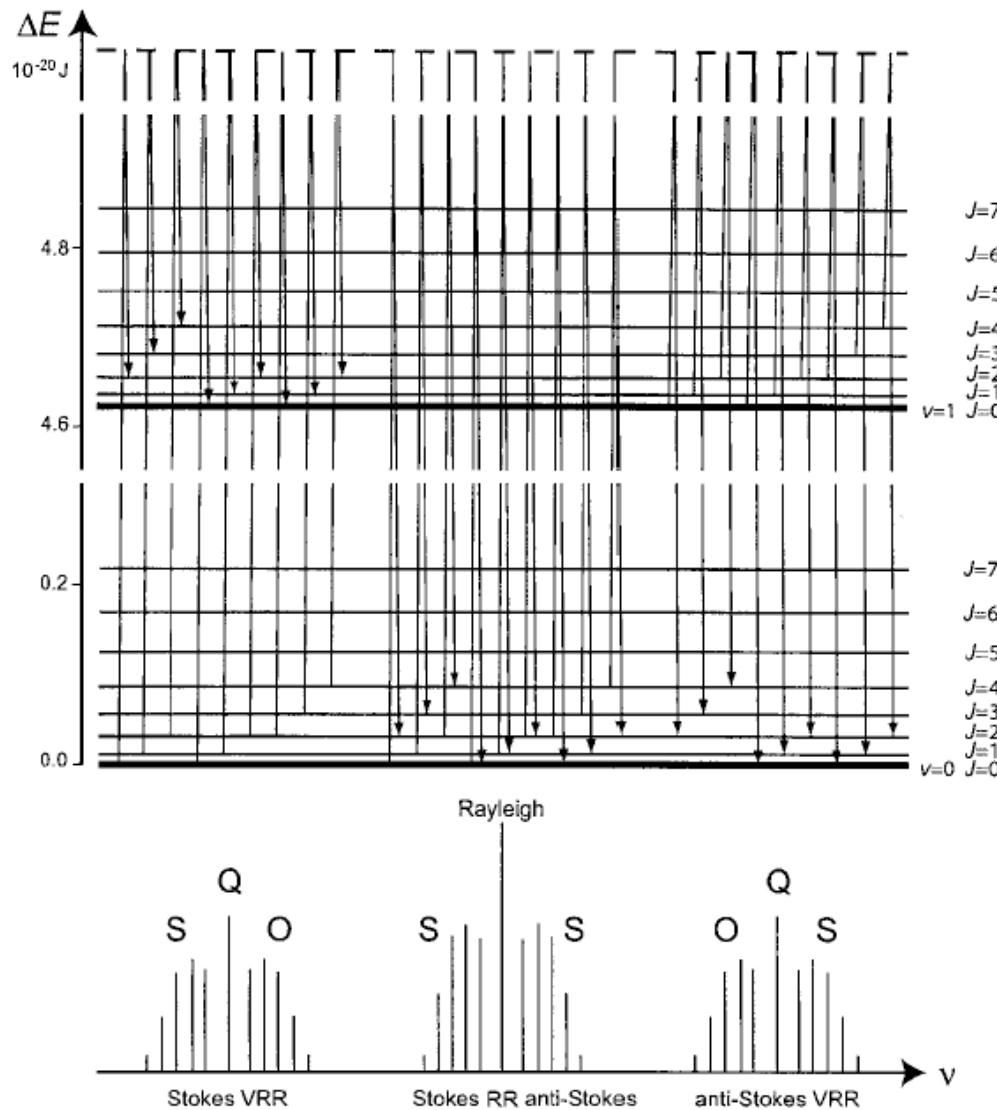
□ Inelastic scattering:

scattering with apparent change of wavelength

Raman scattering

Pure rotational Raman and vibration-rotational Raman

Definitions for Different Scatterings



Virtual
Energy Levels

Real
Energy Levels

Real
Energy Levels

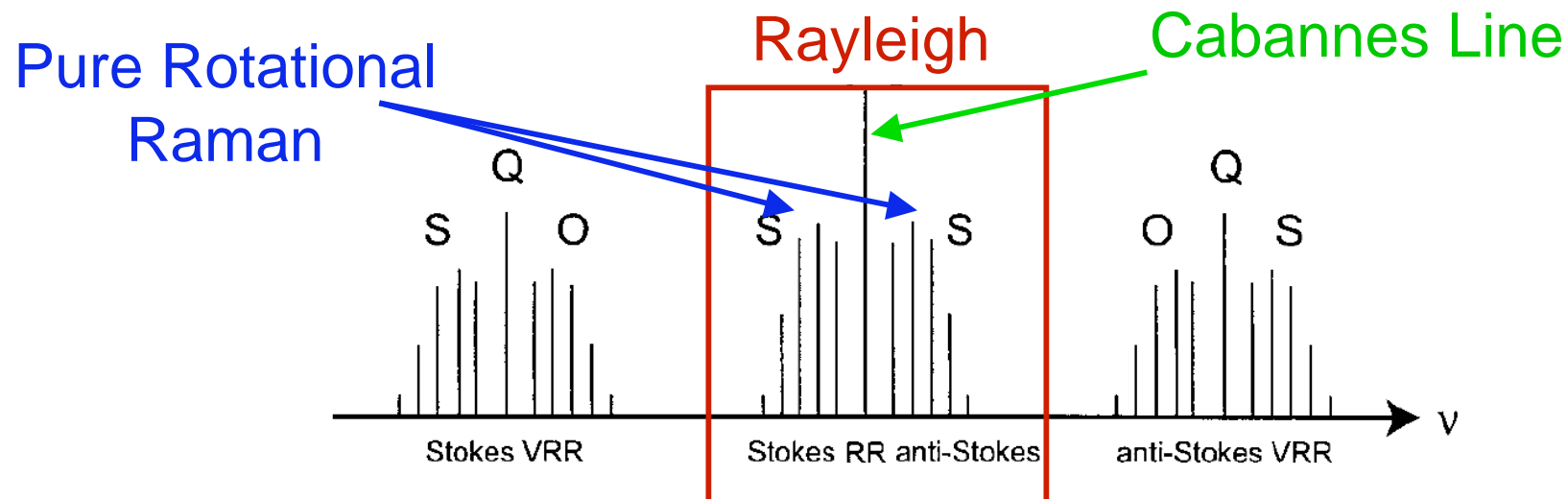
$$\Delta v = 0, \quad \Delta J = 2$$

$$\Delta v = \pm 1, \quad \Delta J = 0, \pm 2$$

Fig. 9.1. Vibration-rotation energy levels of the N₂ molecule, Raman transitions, and resulting spectrum.

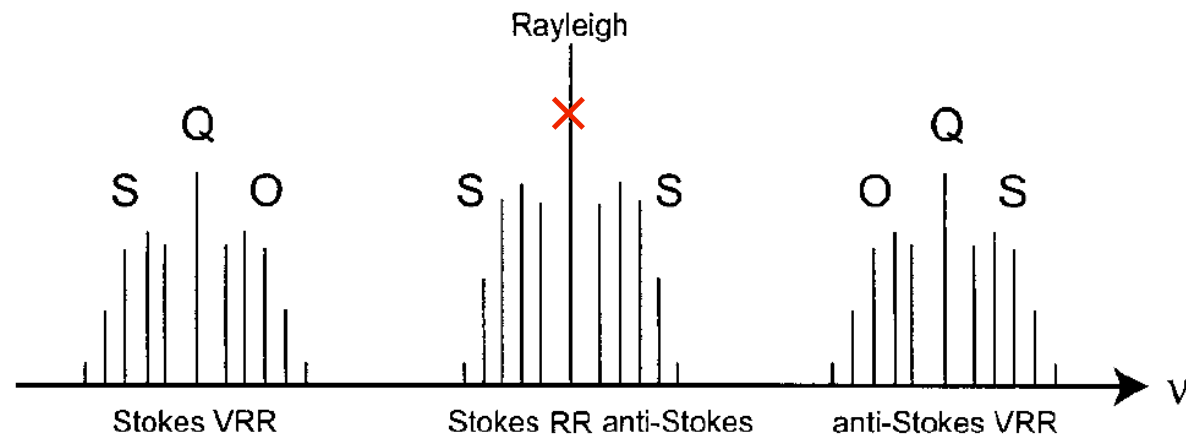
Definition for Rayleigh Scattering

- Rayleigh scattering is referred to the elastic scattering from atmospheric molecules (particle size is much smaller than the wavelength), i.e., scattering with no apparent change of wavelength, although still undergoing Doppler broadening and Doppler shift.
- However, depending on the resolution of detection, Rayleigh scattering can consist of the Cabannes scattering (really elastic scattering from molecules) and pure rotational Raman scattering.



Raman Scattering

□ Raman scattering is the inelastic scattering with rotational quantum state or vibration-rotational quantum state change as the result of scattering



- Separation between Cabannes line and the nearest pure rotational Raman (O_2 and N_2) is about $10 \text{ cm}^{-1} = 300 \text{ GHz}$.
- For vibration-rotational Raman, Q branch is not a single line, but consists of many lines with very small separations, $< 0.1 \text{ cm}^{-1} = 3 \text{ GHz}$, due to the different splitting of the rotational levels in the lower and upper vibrational levels.

Definition for Mie Scattering

- ❑ Strictly speaking, Mie scattering is the elastic scattering from spherical particles [Mie, 1908], which includes the solution of Rayleigh scattering.
- ❑ However, in lidar field, first, Mie scattering is referred to the elastic scattering from spherical particles whose size is comparable to or larger than the wavelength.
- ❑ Furthermore, Mie scattering is generalized to elastic scattering from overall aerosol particles and cloud droplets, i.e., including non-spherical particles.
- ❑ To precisely calculate the scattering from non-spherical particles, Mie scattering theory has to be replaced by non-spherical particle scattering theories. This is a complicated issue in the elastic lidar field.

Polarization in Scattering

- ❑ According to Mie theory, backscattering from spherical particles does not change the polarization state of the radiation. The backscattered light has polarization parallel to that of the transmitted beam (usually linearly polarized).
- ❑ As long as the particles are small compared to the wavelength, the actual particle shape does not play a major role for the scattering properties as theories for non-spherical scatters show.
- ❑ Large non-spherical particles lead to a depolarization of backscattered radiation, i.e., partial backscattered light has polarization perpendicular to that of the transmitted beam.
- ❑ The range-resolved linear depolarization ratio is

$$\delta(R) = [\beta_{\perp}(R) / \beta_{\parallel}(R)] \exp(T_{\parallel} - T_{\perp})$$

Rayleigh Backscatter Coefficient

- ❑ Precise equations should be obtained from Rayleigh theory and experimental measurements of parameters.
- ❑ In lidar field, a common practice is to use the equation

$$\beta_{Rayleigh}(\lambda, z, \theta = \pi) = 2.938 \times 10^{-32} \frac{P(z)}{T(z)} \cdot \frac{1}{\lambda^{4.0117}} \left(m^{-1} sr^{-1} \right)$$

where P is the atmosphere pressure in mbar and T is the temperature in Kelvin at altitude z , λ is the wavelength in meter, and $\beta_{Rayleigh}$ is the backscatter coefficient (angular).

- ❑ Total scatter coefficient β_T has relationship:

$$\beta(\theta) = \frac{\beta_T}{4\pi} P(\theta) = \frac{\beta_T}{4\pi} \times 0.7629 \times (1 + 0.9324 \cos^2 \theta)$$

Rayleigh Backscatter Cross Section

□ It is also common in lidar field to calculate the Rayleigh backscatter cross section using the following equation

$$\frac{d\sigma_m(\lambda)}{d\Omega} = 5.45 \cdot \left(\frac{550}{\lambda}\right)^4 \times 10^{-32} \left(m^2 sr^{-1}\right)$$

where λ is the wavelength in nm.

- For K lidar, $\lambda = 770$ nm, $\Rightarrow 1.42 \times 10^{-32} m^2 sr^{-1}$
- For Na lidar, $\lambda = 589$ nm, $\Rightarrow 4.14 \times 10^{-32} m^2 sr^{-1}$
- For Fe lidar, $\lambda = 372$ nm, $\Rightarrow 2.60 \times 10^{-31} m^2 sr^{-1}$
- For Rayleigh lidar, $\lambda = 532$ nm, $\Rightarrow 6.22 \times 10^{-32} m^2 sr^{-1}$

Scattering Form of Lidar Equation

$$N_S(\lambda, R) = \left(\frac{P_L(\lambda) \Delta t}{hc/\lambda} \right) (\beta(\lambda, R) \Delta R) \left(\frac{A}{R^2} \right) T^2(\lambda, R) (\eta(\lambda) G(R)) + N_B$$

- Rayleigh, Mie, and Raman scattering processes are instantaneous scattering processes, so there are no finite relaxation effects involved, but infinitely short duration. For **Rayleigh and Mie scattering**, there is no frequency shift when the atmospheric particles are at rest, so

$$N_S(\lambda, R) = \left(\frac{P_L(\lambda_L) \Delta t}{hc/\lambda_L} \right) (\beta(\lambda, \lambda_L, R) \Delta R) \left(\frac{A}{R^2} \right) (T(\lambda_L, R) T(\lambda, R)) (\eta(\lambda, \lambda_L) G(R)) + N_B$$

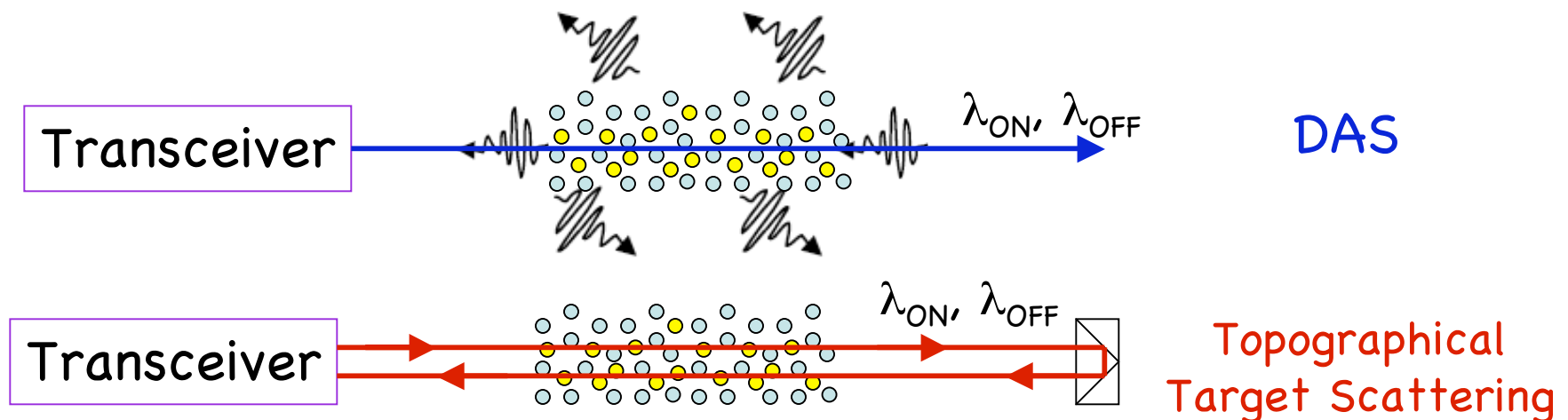
- For Raman scattering, there is large frequency shift and

$$\lambda \neq \lambda_L, \quad p_i(\lambda) \neq 1, \quad p_i(\lambda) < 1$$

$$T(\lambda, R) = \exp \left[- \int_0^R \alpha(\lambda, r) dr \right]$$

Differential Absorption

- ❑ For the molecular species to be detected by DIAL, usually they have strong absorption, however, nearly none resonance fluorescence due to strong relaxation processes other than fluorescence (e.g., frequent collisions with surrounding atmosphere molecules can make molecules decay from excited states to ground state without giving fluorescence).
- ❑ Thus, in the lidar equation for DIAL, the influence of molecular species is in the extinction (atmosphere transmission) part, not in the backscatter part. In other words, the molecular absorption contributes to the extinction of light when incident light and scattered light propagate through atmosphere, while the return signals are from the scattering of laser light by air molecules and aerosols.



Differential Absorption/Scattering Form

- For the laser with wavelength λ_{on} on the molecular absorption line

$$N_S(\lambda_{on}, R) = N_L(\lambda_{on}) \left[\beta_{sca}(\lambda_{on}, R) \Delta R \right] \left(\frac{A}{R^2} \right) \exp \left[-2 \int_0^z \bar{\alpha}(\lambda_{on}, r') dr' \right] \\ \times \exp \left[-2 \int_0^z \sigma_{abs}(\lambda_{on}, r') n_c(r') dr' \right] \left[\eta(\lambda_{on}) G(R) \right] + N_B$$

- For the laser with wavelength λ_{off} off the molecular absorption line

$$N_S(\lambda_{off}, R) = N_L(\lambda_{off}) \left[\beta_{sca}(\lambda_{off}, R) \Delta R \right] \left(\frac{A}{R^2} \right) \exp \left[-2 \int_0^z \bar{\alpha}(\lambda_{off}, r') dr' \right] \\ \times \exp \left[-2 \int_0^z \sigma_{abs}(\lambda_{off}, r') n_c(r') dr' \right] \left[\eta(\lambda_{off}) G(R) \right] + N_B$$

- Differential absorption cross-section

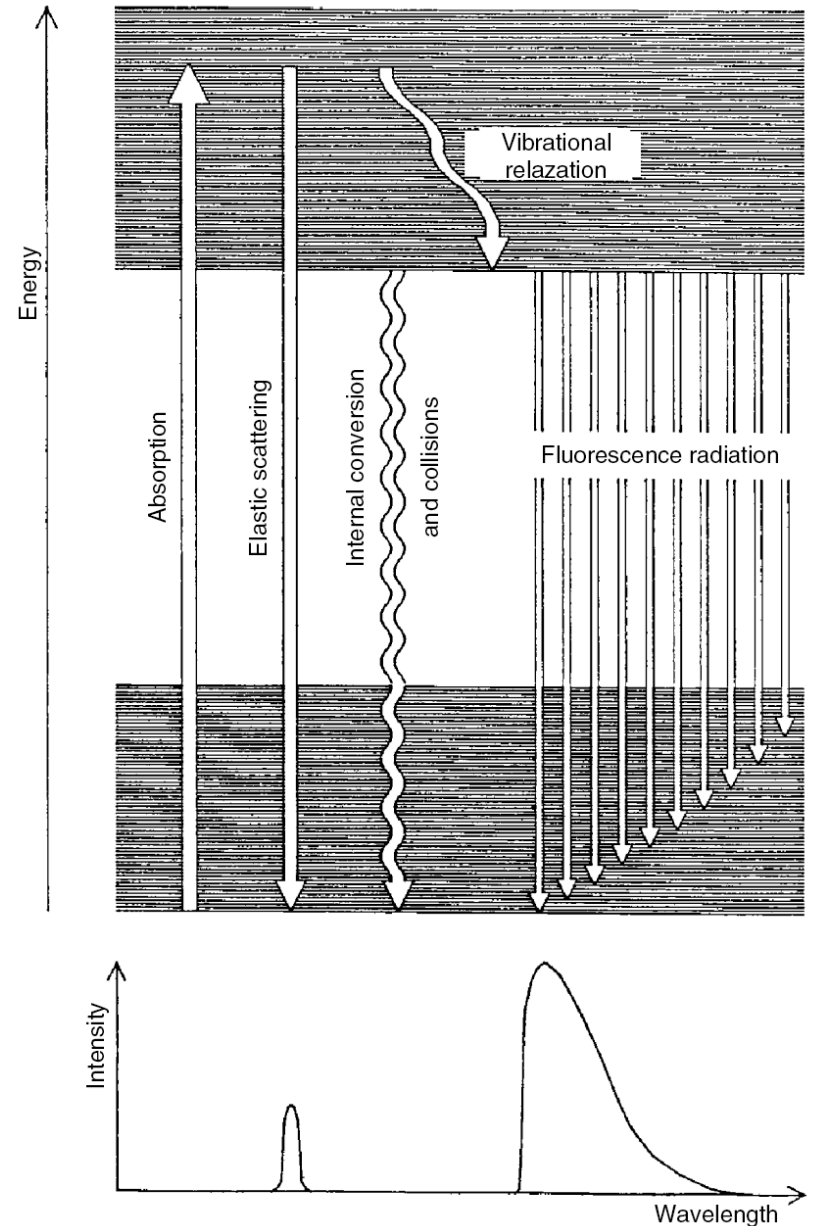
$$\Delta \sigma_{abs}(R) = \sigma_{abs}(\lambda_{ON}, R) - \sigma_{abs}(\lambda_{OFF}, R)$$

Resonance Fluorescence

- ❑ In the middle and upper atmosphere, there exist some metal atoms and atomic ions. They have large absorption cross section, and quenching is not a problem in that region. Therefore, laser tuned to the resonance frequency of the absorption lines can excite resonance fluorescence from these atoms and ions.
- ❑ Resonance fluorescence is a two-step process: absorption first, and then spontaneous emission. Therefore, there is finite time delay between these two steps (radiative lifetime).
- ❑ This subject has been studied extensively in our spectroscopy class.

Laser Induced Fluorescence

- ❑ In contrast to free atoms and molecules, solids and liquids exhibit broad absorption and emission spectra because of the strong intermolecular interactions.
- ❑ A fixed frequency laser can be used for the excitation due to the broad absorption.
- ❑ Following the excitation, there is a very fast (ps) radiationless relaxation down to the lowest sub-level of the excited state, where the molecules remain for a typical excited-state fluorescence lifetime.
- ❑ The decay then occurs to different sub-levels of the ground state giving rise to a distribution of fluorescence light, which reflect the lower-state level distribution.
- ❑ Fixing the excitation wavelength, we can obtain fluorescence spectra. While fixing the detection channel and varying the excitation wavelength, an excitation spectrum can be recorded.



Fluorescence Form of Lidar Equation

$$N_S(\lambda, R) = \left(\frac{P_L(\lambda) \Delta t}{hc/\lambda} \right) (\sigma_{eff}(\lambda, R) n_c(z) R_B(\lambda) \Delta R) \left(\frac{A}{4\pi R^2} \right) (T_a^2(\lambda, R) T_c^2(\lambda, R)) (\eta(\lambda) G(R)) + N_B$$

□ Here, $T_c(R)$ is the extinction coefficient caused by the absorption.

$$T_c(R) \equiv E(R) = \exp\left(-\int_{R_{bottom}}^R \sigma_{eff}(\lambda, r') n_c(r') dr'\right) = \exp\left(-\int_{R_{bottom}}^R \alpha_c(\lambda, r') dr'\right)$$

□ Here, $\alpha(\lambda, R)$ is the extinction coefficient caused by the absorption.

$$\alpha_c(\lambda, R) = \sigma_{eff}(\lambda, R) n_c(R)$$

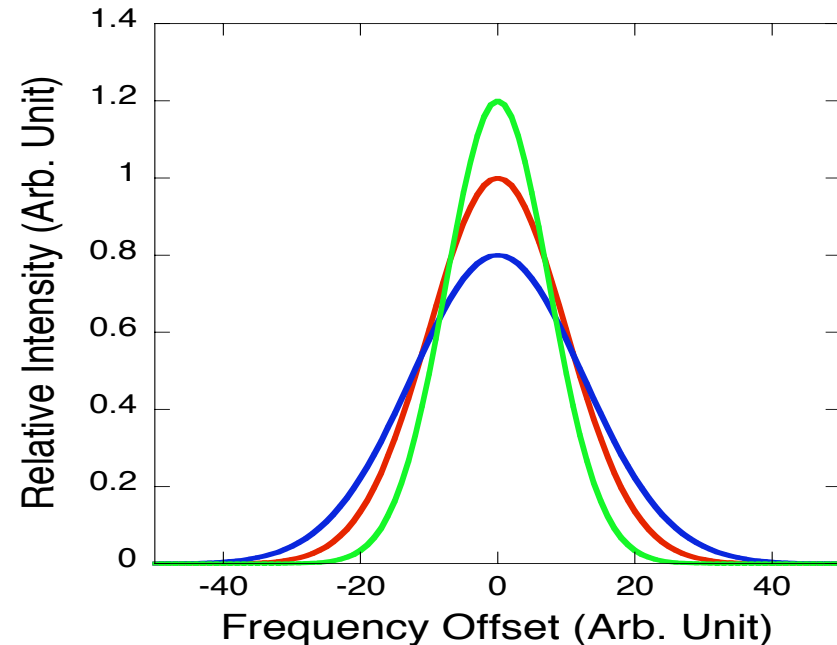
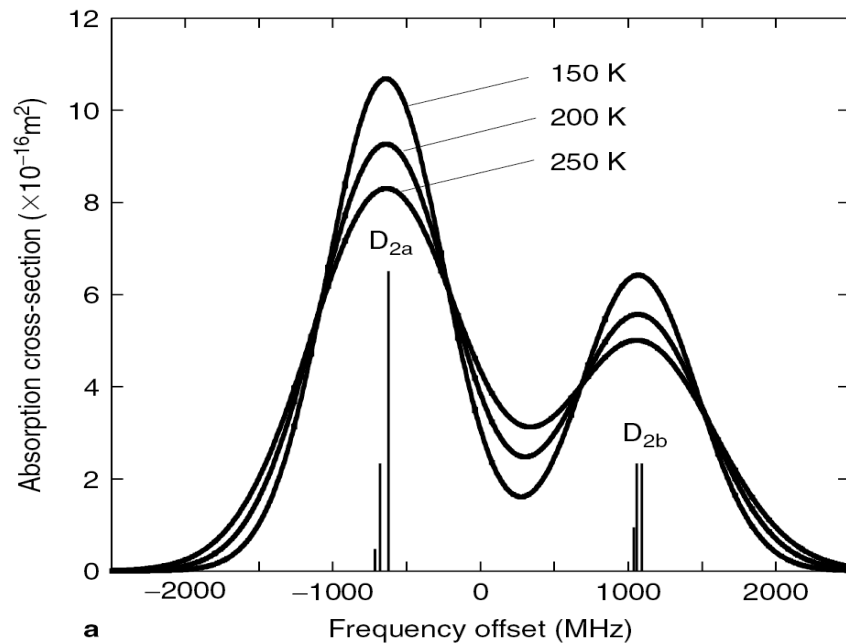
□ Resonance fluorescence and laser-induced-fluorescence are NOT instantaneous processes, but have delays due to the radiative lifetime of the excited states.

Backscatter Cross-Section Comparison

| Physical Process | Backscatter Cross-Section | Mechanism |
|---|---|---|
| Mie (Aerosol) Scattering | $10^{-8} - 10^{-10} \text{ cm}^2\text{sr}^{-1}$ | Two-photon process Elastic scattering, instantaneous |
| Resonance Fluorescence | $10^{-13} \text{ cm}^2\text{sr}^{-1}$ | Two single-photon process (absorption and spontaneous emission) Delayed (radiative lifetime) |
| Molecular Absorption | $10^{-19} \text{ cm}^2\text{sr}^{-1}$ | Single-photon process |
| Fluorescence from molecule, liquid, solid | $10^{-19} \text{ cm}^2\text{sr}^{-1}$ | Two single-photon process Inelastic scattering, delayed (lifetime) |
| Rayleigh Scattering | $10^{-27} \text{ cm}^2\text{sr}^{-1}$ | Two-photon process Elastic scattering, instantaneous |
| Raman Scattering | $10^{-30} \text{ cm}^2\text{sr}^{-1}$ | Two-photon process Inelastic scattering, instantaneous |

Doppler Shift and Broadening

□ **Doppler Technique** - Doppler linewidth broadening and Doppler frequency shift are temperature-dependent and wind-dependent, respectively (applying to both Na, K, Fe resonance fluorescence and molecular scattering)

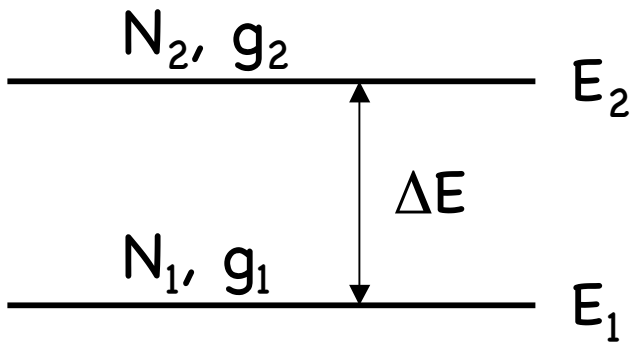


$$\sigma_{rms} = \frac{\omega_0}{c} \sqrt{\frac{k_B T}{M}} = \frac{1}{\lambda_0} \sqrt{\frac{k_B T}{M}}$$

$$\Delta\omega = \omega - \omega_0 = -\vec{k} \cdot \vec{v} = -\omega_0 \frac{v \cos\theta}{c}$$

Boltzmann Distribution

□ Boltzmann distribution is the law of particle population distribution according to energy levels



$$\frac{N_k}{N} = \frac{g_k \exp(-E_k / k_B T)}{\sum_i g_i \exp(-E_i / k_B T)}$$

$$\frac{N_2}{N_1} = \frac{g_2}{g_1} \exp\left\{-\frac{(E_2 - E_1)}{k_B T}\right\}$$



$$T = \frac{\Delta E / k_B}{\ln\left(\frac{g_2 \cdot N_1}{g_1 \cdot N_2}\right)}$$

N_1 and N_2 - particle populations on energy levels E_1 and E_2
 g_1 and g_2 - degeneracy for energy levels E_1 and E_2 , $\Delta E = E_2 - E_1$
 k_B - Boltzmann constant, T - Temperature, N - total population

Population Ratio \Rightarrow Temperature

Transmission vs Extinction

$$T(\lambda, R) = \exp\left[-\int_0^R \alpha(\lambda, r) dr\right]$$

$$\alpha(\lambda, R) = \sum_i [\sigma_{i,ext}(\lambda) n_i(R)]$$

Extinction = Absorption + Scattering (Integrated)

$$\sigma_{i,ext}(\lambda) = \sigma_{i,abs}(\lambda) + \sigma_{i,sca}(\lambda)$$

Total Extinction = Aerosol Extinction + Molecule Extinction

$$\alpha(\lambda, R) = \alpha_{aer,abs}(\lambda, R) + \alpha_{aer,sca}(\lambda, R) + \alpha_{mol,abs}(\lambda, R) + \alpha_{mol,sca}(\lambda, R)$$

Summary

- ❑ Numerous physical processes are involved in lidars.
- ❑ Main physical processes include elastic and inelastic scattering, absorption and differential absorption, resonance fluorescence, laser induced fluorescence, Doppler effect, Boltzmann distribution, and reflection from target or surface.
- ❑ To understand these processes precisely is the key to successful lidar estimate and applications.
- ❑ Lidar equation may change form to best fit for each particular physical process and lidar application.