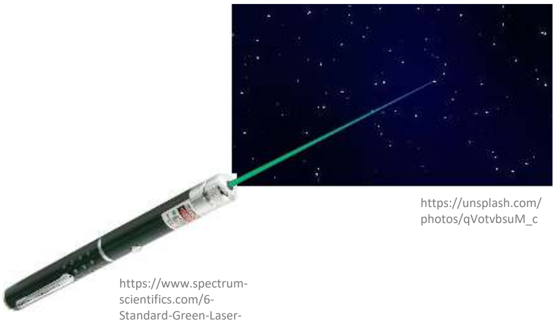
Atmospheric Lidar

2. Atmospheric Optics

Lidar Tutorials

21st Coherent Laser Radar Conference

Motivation

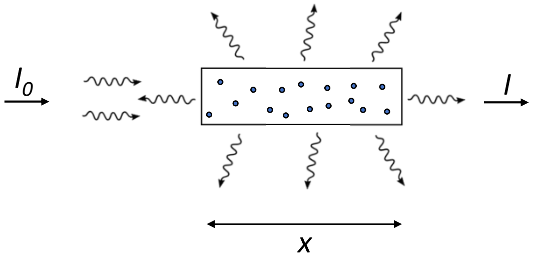


https://unsplash.com/photos/qVotvbsuM_c

https://www.spectrum-scientifics.com/6-Standard-Green-Laser-Pointer-p/3397.htm

- If you send a laser beam into the night sky, what will you see?
- Light travels in straight lines - how does it get back to your eyes?
- What color is the beam of light? The same as transmitted, or other colors?
- What is the polarization of the light?
- What can we learn about the atmosphere from the backscattered light?

Light interacts with matter



Transmittance = $I/I_0 = \exp(-\sigma x)$

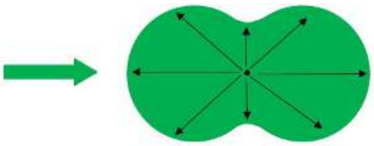
- σ is the extinction coefficient (1/m)
- β is the backscatter coefficient (1/m-sr)

- The primary atmospheric interaction is scattering
  - By molecules
  - By particles
- The lidar signal is due to backscattered light
- Light may also be absorbed
  - Turned to heat
  - Re-radiated
- Scattering + absorption = extinction
- Lidars exchange *radiant energy* with the atmosphere

The three scattering regimes

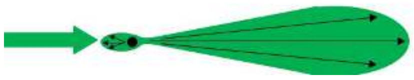
- The scattering parameter is defined as $\alpha = 2\pi r/\lambda$, where r is a characteristic dimension
- For a sphere, it is the circumference divided by the light wavelength

Scattering Parameter Range	Type of Scattering	Wavelength Dependence
$\alpha < 0.5$	Rayleigh	$1/\lambda^4$
$0.5 < \alpha < 50$	Mie	Typically $1/\lambda$ to $1/\lambda^2$
$50 < \alpha$	Geometrical Optics	λ^0



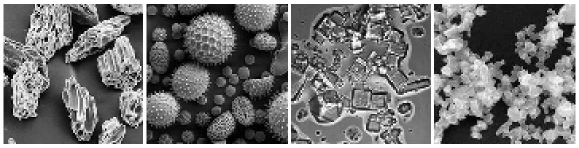
With small α, particles scatter equal amounts forward & backward

GTRI graphic



With large α, particles scatter primarily forward

Aerosol optical properties



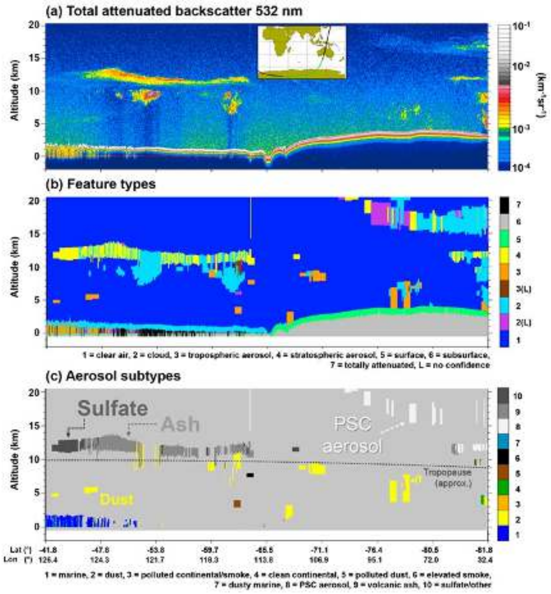
From left to right: volcanic ash, pollen, sea salt, and soot.

https://earthobservatory.nasa.gov/features/Aerosols

- Aerosol optical properties depend on the composition, shape, and size distribution – they are highly variable, as is the aerosol concentration.
- They are very difficult to model!
- Two advanced lidar techniques produce quantitative profiles of aerosol σ and β.
- The roughness of aerosols causes depolarization of backscattered light.

Classifiers

- By measuring the backscattered signal at 532 and 1064 nm plus depolarization at 532 nm, the CALIOP lidar (and others) can be used to generate automated maps of features and aerosol subtypes.
- CALIOP identifies 10 types of aerosol.
- Other inputs are the surface type (land/ocean), the latitude, and the month of the year.

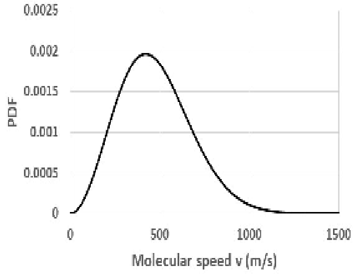


The CALIPSO version 4 automated aerosol classification and lidar ratio selection algorithm Atmospheric Measurement Techniques 11(11):6107-6135 · November 2018 DOI: 10.5194/amt-11-6107-2018

Energetics of the molecular atmosphere

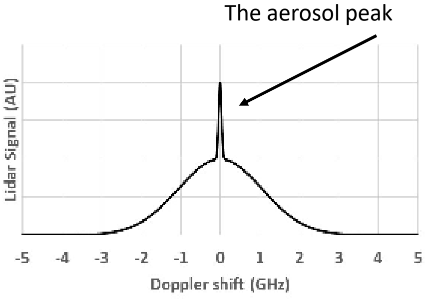
- Molecules can store energy in four modes:
  - Translation
  - Rotation
  - Vibration
  - Electronic levels
- These modes all have implications for lidar.
- The first three can change the wavelength!
- The last three are *quantized.*

The Doppler-broadened spectrum



The molecular speed probability distribution function for nitrogen gas at 300 K. The mean speed is ~500 m/s!

G.G. Gimmestad graphic



The Doppler-broadened lidar signal

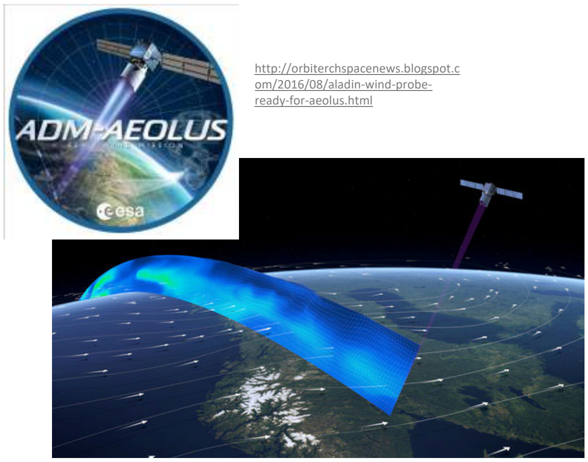
G.G. Gimmestad graphic

- The spectrum is very close to Gaussian, with a span of about ± 2 GHz, or about ± 1.7 pm at 532 nm.
- The aerosols are massive* and slow. They contribute a peak at the center.
- The aerosol signal can be separated from the molecular signal with High Spectral Resolution Lidar (HSRL).
- The molecular spectrum is used in high-altitude wind sounding.

*The mass of a 1-micron water drop is 4.2×10^{-15} kg

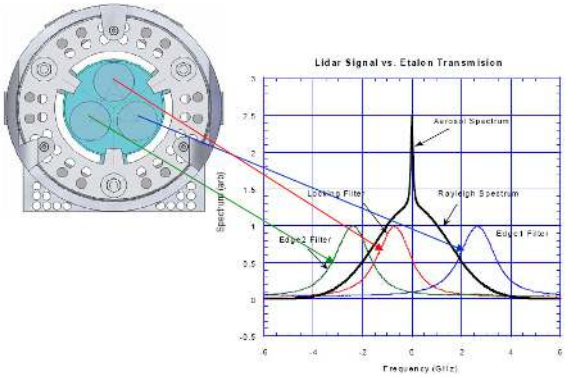
Molecular masses for N_2, O_2, and Ar are in the range $5 – 7 \times 10^{-26}$ kg.

Spaceborne wind lidar



http://orbiterchspacenews.blogspot.com/2016/08/aladin-wind-probe-ready-for-aeolus.html

https://wpo-altertechnology.com/satellite-aeolus/

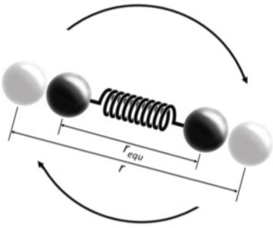


https://www.researchgate.net/publication/237468429_THE_TROPOSPHERIC_WIND_LIDAR_TECHNOLOGY_EXPERIMENT_TWiLiTE_AN_AIRBORNE_DIRECT_DETECTION_DOPPLER_LIDAR_INSTRUMENT_DEVELOPMENT_PROGRAM

- Aeolus used the incoherent double edge technique
- Launch date: 22 August 2018

Molecular rotation and vibration

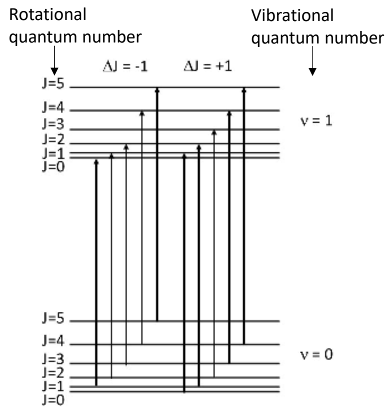
- The classical picture of a diatomic molecule is two masses connected by a spring. The system stores energy by rotating and vibrating.



G.G. Gimmestad graphic

- The energies of rotation and vibration are *quantized*.
- If the system changes energy by absorbing or emitting a photon, then the photon energy is $h\nu = E_2 - E_1$, where h is the Planck constant.
- The frequency ν (equivalently λ) is characteristic of the molecule.

The CO absorption spectrum



G.G. Gimmestad graphic

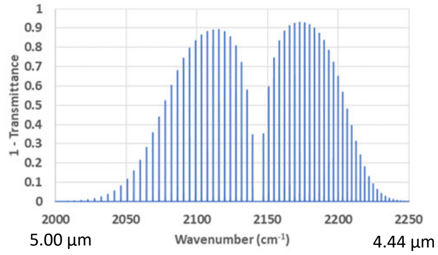
Radiative transitions are only allowed for ΔJ = ± 1, and the molecule must have an electric dipole moment.

- Relative populations of states are given by the *Boltzmann distribution*

$$\frac{N_2}{N_1} = \exp[-(E_2 - E_1)/kT]$$

- For CO, the energy difference between ν = 0 and ν = 1 is 2143 cm^{-1}. At 300 K, kT = 207 cm^{-1}.
- Spatial frequency $\bar{\nu}$ (called *wavenumbers*) is proportional to energy.
- Wavelength (µm) = 10,000/wavenumbers (cm^{-1}).
- Energy (J) = $hc\bar{\nu}$, where c = 3 x 10^{10} cm/s.

The final result: the absorption spectrum of CO at 300 K

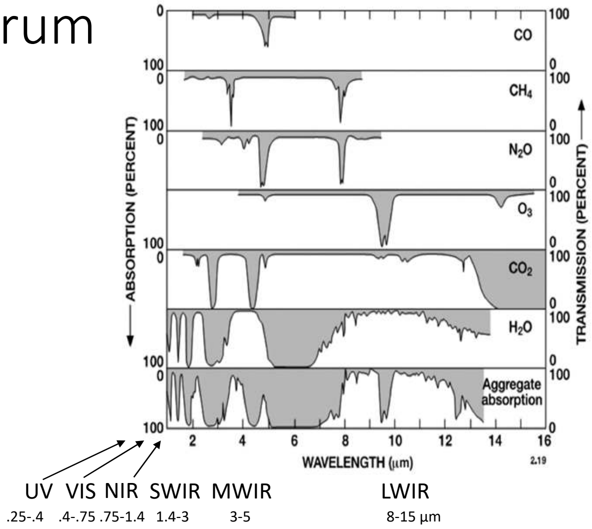


G.G. Gimmestad graphics. Spectrum data from SpectralCalc.com

- Triatomics and larger molecules have more complicated spectra, but they follow the principles sketched here.
- Their spectra are in the IR.

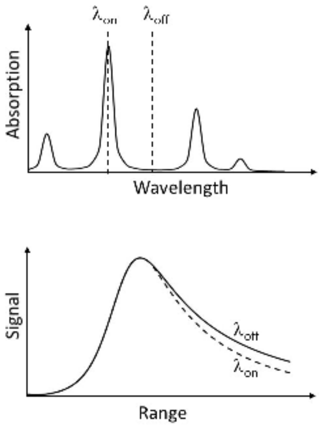
The atmospheric spectrum

- Most of the atmosphere's IR absorption is caused by H_20, CO_2, and O_3.
- What about N_2 and O_2? They have no dipole moments and hence no IR absorption spectra.
- The gas spectra determine the *window regions* where lidar systems operate.
- Some trace gas spectra (such as O_3 & CH_4) are in window regions.
- Trace gas concentration profiles can be measured with Differential Absorption Lidar (DIAL).



From Gimmestad and Roberts, *Lidar Engineering: Introduction to basic principles.*

Spectra enable DIfferential Absorption Lidar (DIAL)



G.G. Gimmestad graphic

- Pairs of wavelengths can be used to profile trace gases including greenhouse gases (GHG).
- The gas concentration profile $N(R)$ is calculated by

$$N(R) = \frac{1}{2\Delta\sigma\Delta R}\ln\left(\frac{P_{off}(R+\Delta R)}{P_{off}(R)}\frac{P_{on}(R)}{P_{on}(R+\Delta R)}\right)$$

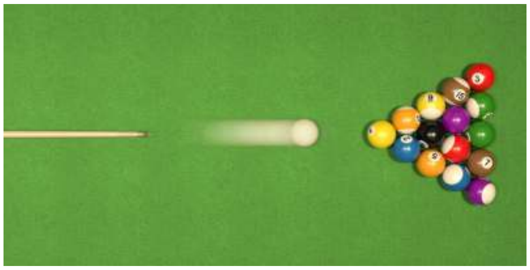
where $\Delta\sigma$ = cross section difference, and

ΔR = range interval.

- DIAL is self-calibrating.

How do photons scatter?

Like billiard balls?

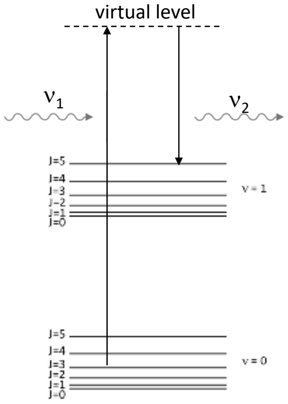


https://letstalkscience.ca/educational-resources/stem-in-context/billiards-and-collisions

- Do photons “bounce off” of the scatterers?
- Backscatter would require a photon to stop and reverse its direction.
- But photons travel at the speed of light, so a stopped photon is gone.
- The billiard ball analogy cannot be correct.

How do photons scatter?

Or Raman?



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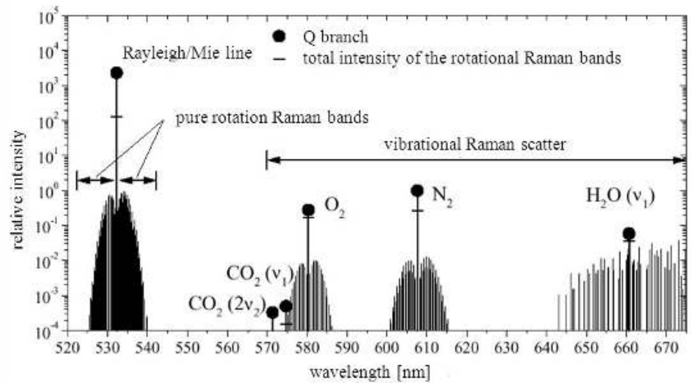
- Raman scattering is inelastic.
- The absorbed photon raises the molecule from a rotation-vibration level to a virtual level.
- It decays to a different ro-vibe level, emitting a photon of a different wavelength.
- The selection rules are $\Delta J = 0, \pm 2$ and $\Delta\nu = 0, \pm 1$.
- The wavelength shift is characteristic of the molecule (N_2, O_2, or H_2O).
- Raman cross sections are orders of magnitude weaker than Rayleigh.
- Raman cross sections are proportional to $1/\lambda^4$.

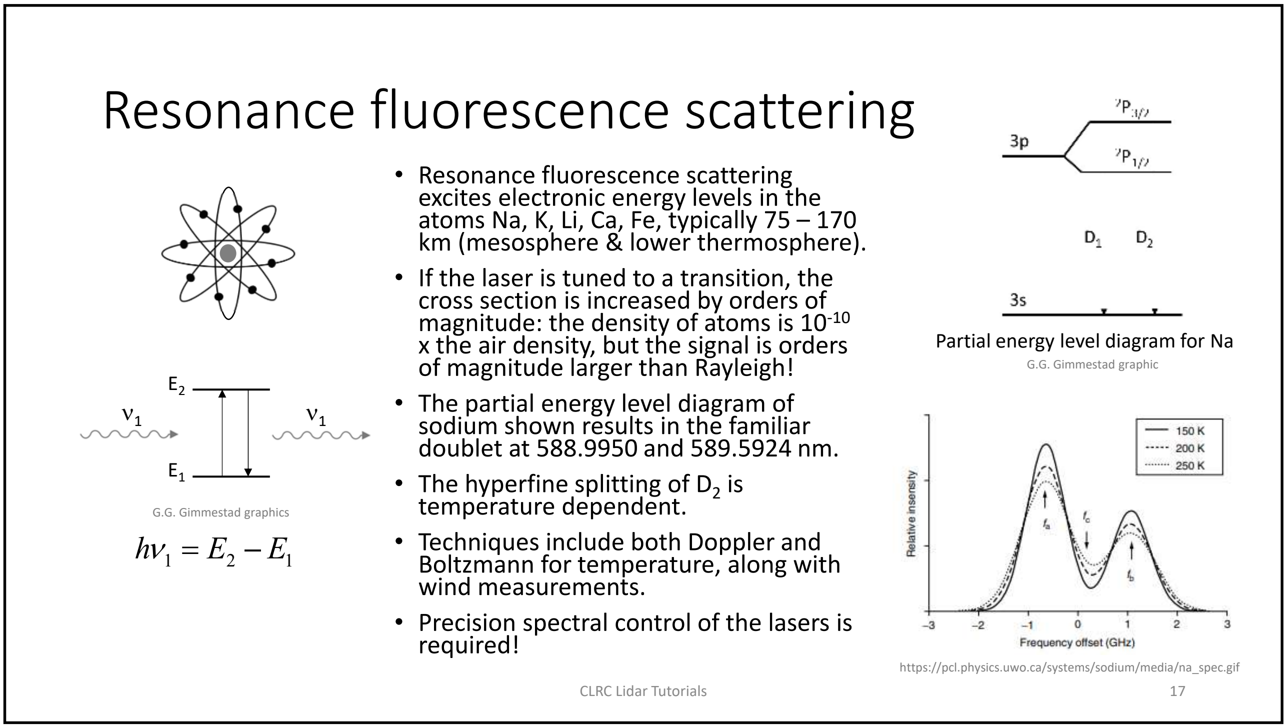
Rayleigh scattering (elastic) is the special case when $\Delta J = 0$ and $\Delta\nu = 0$.

Atmospheric Raman spectra



Combined Raman lidar for the measurement of atmospheric temperature, water vapor, particle extinction coefficient, and particle backscatter coefficient, Andreas Behrendt, Takuji Nakamura, Michitaka Onishi, Rudolf Baumgart, and Toshitaka Tsuda, Applied Optics Vol. 41, 7657 (2002)

- Atmospheric Raman spectra enable water vapor profilers, which find the mixing ratio $[H_2O]/[N_2]$ by recording the Raman signal from both gases.
- The rotational lines are temperature dependent. This fact is exploited in Raman temperature profiling lidars.
- The elastic (Rayleigh) line and the N_2 line are used in Raman aerosol lidars to find extinction coefficient profiles.



Resonance fluorescence scattering

- Resonance fluorescence scattering excites electronic energy levels in the atoms Na, K, Li, Ca, Fe, typically 75 – 170 km (mesosphere & lower thermosphere).
- If the laser is tuned to a transition, the cross section is increased by orders of magnitude: the density of atoms is 10^{-10} x the air density, but the signal is orders of magnitude larger than Rayleigh!
- The partial energy level diagram of sodium shown results in the familiar doublet at 588.9950 and 589.5924 nm.
- The hyperfine splitting of D_2 is temperature dependent.
- Techniques include both Doppler and Boltzmann for temperature, along with wind measurements.
- Precision spectral control of the lasers is required!

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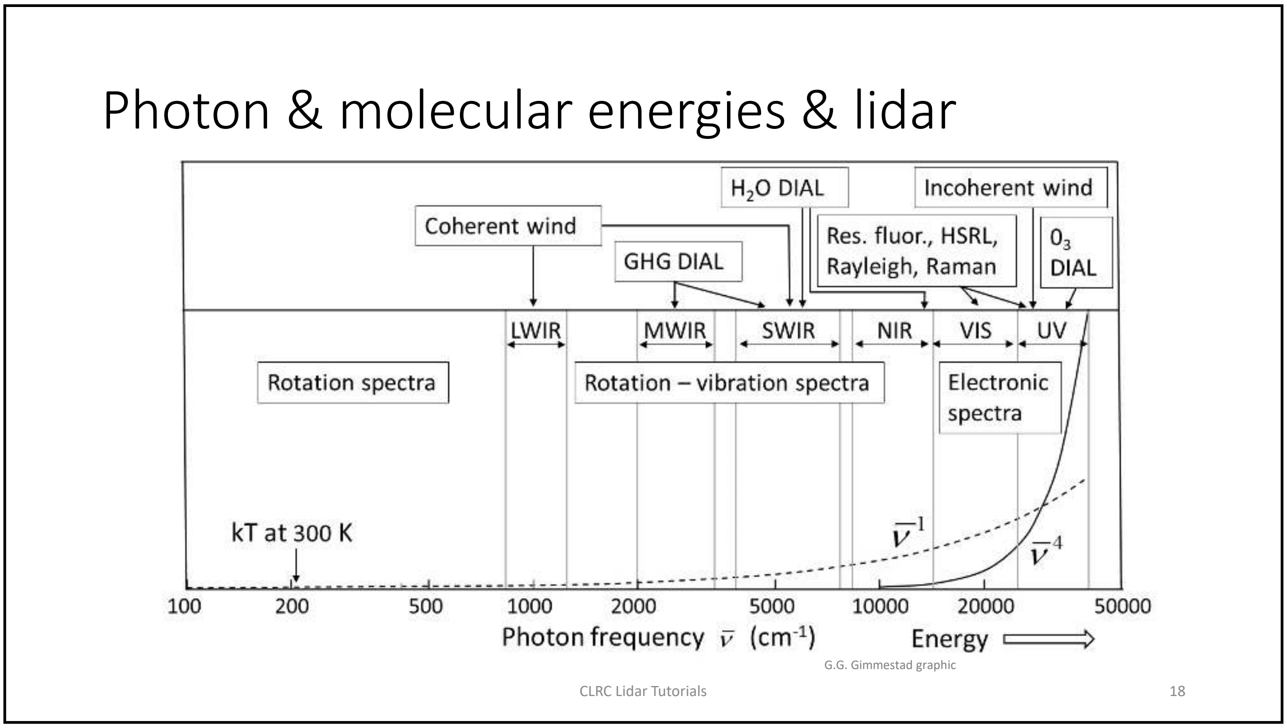
$$h\nu_1 = E_2 - E_1$$

Partial energy level diagram for Na

G.G. Gimmestad graphic

https://pcl.physics.uwo.ca/systems/sodium/media/na_spec.gif



Photon & molecular energies & lidar

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