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How does light interact with matter?

V. F. Weisskopf, Sci Am 1968

Among other interesting questions:

Why is water transparent?

WATER

Jackson Section 7.5.E.

Water has three phases:

- Gas, or vapor

Isolated molecules can absorb photons in three ways

  - electronic transitions at ultraviolet energies;
  - vibrational transitions at infrared energies;
  - rotational transitions mix with the vibrational spectrum

Water vapor in the atmosphere is a good greenhouse gas.

■ Liquid

We' ll focus on this phase. Again, there are ultraviolet and infrared resonances. The lowest energy exciations are rotational energy levels, which absorb *microwaves*.
(microwave ovens)

■ Solid

Or, rather, solids.
There are > 15 crystalline structures of ice, plus amorphous ice.

Optical properties

As far as visible light is concerned, water is nearly transparent.

Outside the range of visible light, the physics is more interesting.

Review : Electromagnetic waves in an absorbing medium

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Review $\vec{E}(\vec{x},t) = \vec{E}_0 \, e^{i(\vec{k}\cdot\vec{x}-\omega t)}$

$$\vec{D}(\vec{x},\omega) = \epsilon(\omega)\vec{E}_0 \, e^{i\vec{k}\cdot\vec{x}}$$

$$\nabla\times\vec{H} = \frac{\partial\vec{D}}{\partial t} = -i\omega\vec{D}$$

The Lorentz–Drude model for dispersion

$$m\left[\ddot{\vec{x}} + \gamma\dot{\vec{x}} + m\omega_0^2\vec{x}\right] = -e\vec{E}$$

$$\Rightarrow \quad \frac{\epsilon(\omega)}{\epsilon_0} = 1 + \frac{Ne^2}{\epsilon_0 m}\sum_{\text{states}}\frac{f_i}{\omega_i^2-\omega^2-i\omega\gamma_i}$$

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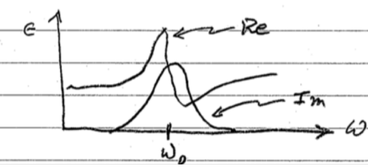
For a conductor, add contribution with $\omega_0 = 0$

$$-\frac{Ne^2}{\epsilon_0 m}\frac{f_0}{\omega^2+i\omega\gamma_0} = \frac{i Ne^2 f_0}{\epsilon_0 m\omega\,(\gamma_0-i\omega)}$$

Apply to dielectrics, metals, plasmas

<u>Propagation</u> $\quad k = \frac{\omega}{v_{\text{phase}}} = \omega\sqrt{\mu_0\epsilon(\omega)} = \beta + \frac{i\alpha}{2}$

$$\alpha = \frac{\omega^2}{\beta^2 c^2}\,\mathrm{Im}\!\left(\frac{\epsilon}{\epsilon_0}\right) \quad \text{and} \quad \beta \approx \frac{\omega}{c}\sqrt{\mathrm{Re}\!\left(\frac{\epsilon}{\epsilon_0}\right)}$$



Jackson' s Figure 7.9

The index of refraction (n) and absorption coefficient (α) of liquid water, as functions of frequency;

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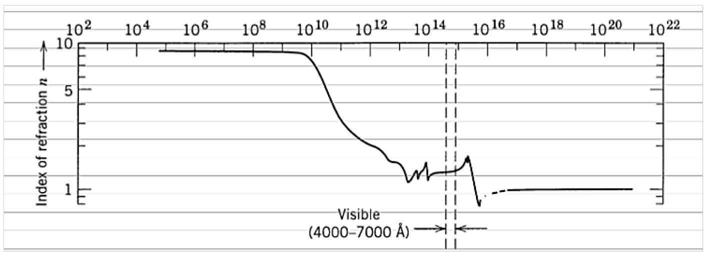

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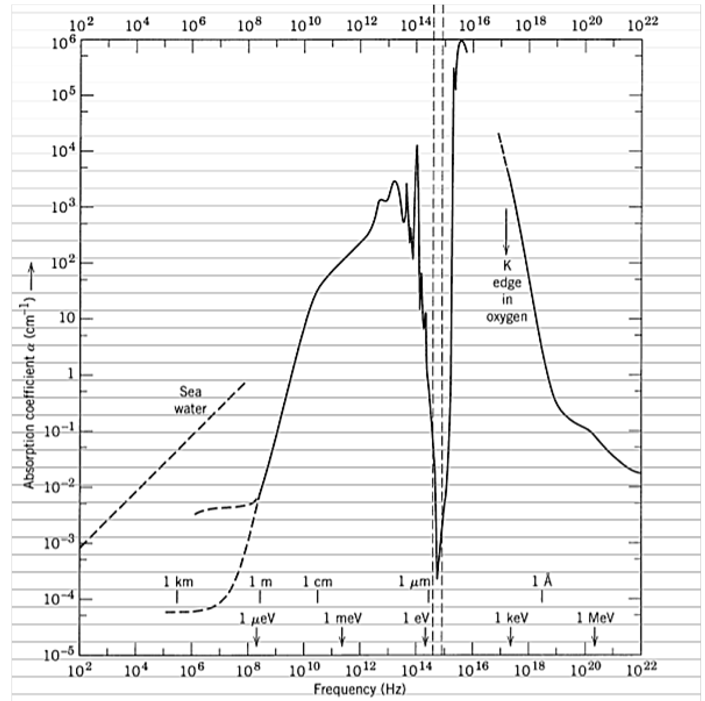

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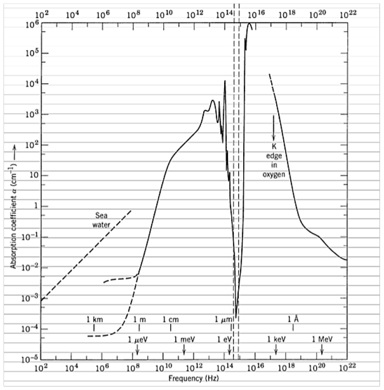

n and α versus $f = \omega / (2\pi)$

log log plots

ranging from radio waves to X rays

- IR resonances
  (vibrations and rotations)
- large UV absorption
  (electron transitions)
- very small absorption in the optical

Index of refraction of liquid water at NTP

Normal **T**emperature and **P**ressure means 20^o C

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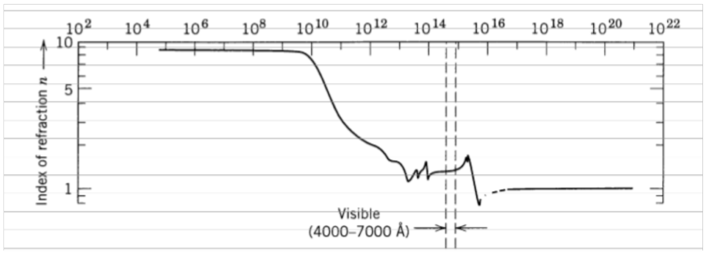

Index of refraction = n(ω) = Re $\sqrt{\frac{\epsilon(\omega)}{\epsilon_0}}$

▫ For electrostatics, i.e., $\omega \to 0$, n = 9 implies $\epsilon/\epsilon_0 = 81$. The H2O molecule has a permanent electric dipole moment, which aligns with the electric field at low frequencies.

▫ IR resonances come from 3 modes of vibration

▫ For visible light, n ≈ 1.33 with a slight normal dispersion ($dn/d\omega > 0$)
⇒ the colors of the rainbow

Water is transparent but it can separate the colors of white light by refraction.

▫ For ultraviolet light, there is a broad electronic resonance at 10^{16} Hz .

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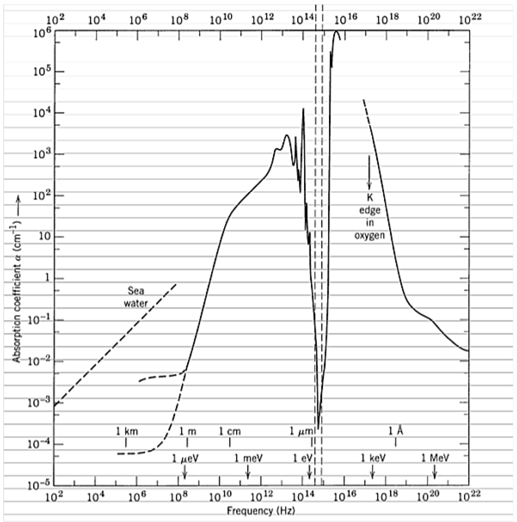

Absorption of light by liquid water

Absorption coefficient = $\alpha(\omega)$

$$= 2 \text{ Im } \sqrt{\mu_0\, \epsilon(\omega)}\ \omega$$

▫ α is small at low frequencies (but see seawater)

▫ microwave absorption for λ ~ 1 cm ;
f ~ 2×10^{10} Hz ; E_γ ~ 10^{-4} eV;
α ~ 100 cm^{-1};
attenuation length ~ 0.1 mm;
the microwave oven

▫ infrared absorption bands

▫ the absorption window in the visible range;
water is transparent.

"The reader may meditate on the fundamental question of biological evolution on this water-soaked planet, of why animat eyes see the spectrum from red to violet and of why the grass is green Mother Nature has certainly exploited her window!"

▫ X-rays, and high energy processes

Optical properties of water for visible light

Here is a better graph of the absorption coefficient [unit : cm^{-1}]
for UV → visible → IR light.

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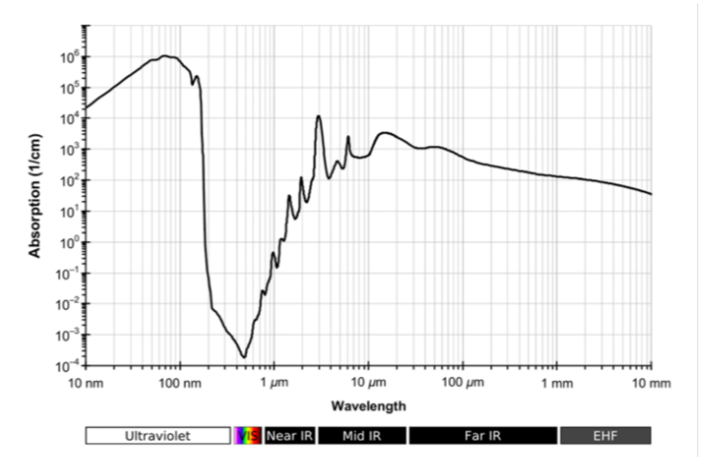

Absorption Spectrum of Water

In the visible range, α is small;
$\Longrightarrow$ the extreme transparency of liquid water.

But α is not 0. Over sufficiently long distances there is observable absorption. Dispersion of the absorption may give water an intrinsic color (as perceived by the human eye and brain).

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