ATMOSPHERIC OPTICS

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P460
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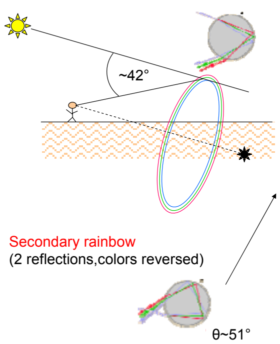
WATER DROPS

- sun or moon light interacts with spherical drops in the atmosphere (refraction, diffraction, scattering).

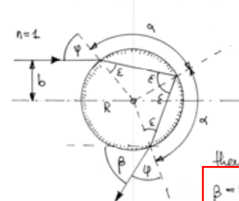
rainbow basics

Primary rainbow (1 reflection)



Secondary rainbow
(2 reflections,colors reversed)

calculate the rainbow angles



$\sin\varepsilon = \frac{1}{n}\sin\varphi$

$\sin\varphi = b/R$

$\alpha = \pi - 2\varepsilon$

$\beta = 2\pi - 2\varphi - 2\alpha$

$R = 1$

then:

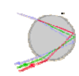
$$\beta = 2\left(2\arcsin\frac{b}{n} - \arcsin b\right)$$

$$\frac{d\beta}{db} = 2\left(\frac{2}{\sqrt{n^2-b^2}} - \frac{1}{\sqrt{1-b^2}}\right)$$

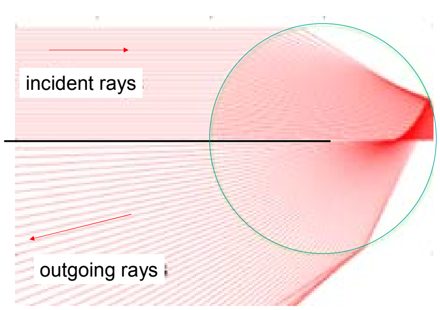
$$\frac{d\beta_{max}}{db} = 0 \rightarrow b_{max} = \sqrt{\frac{4-n^2}{3}} \qquad \beta_{max} = \beta(b_{max})$$

2 reflections: analogous ... $\beta = 2\left(3\arcsin\frac{b}{n} - \arcsin b\right) - \pi$

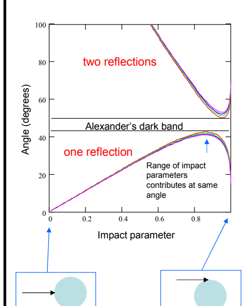
$$b^{(2)}_{max} = \sqrt{\frac{9-n^2}{8}}$$



rays through a water drop

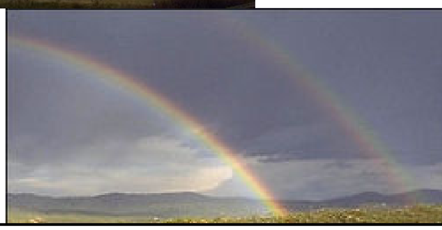


results from ray optics

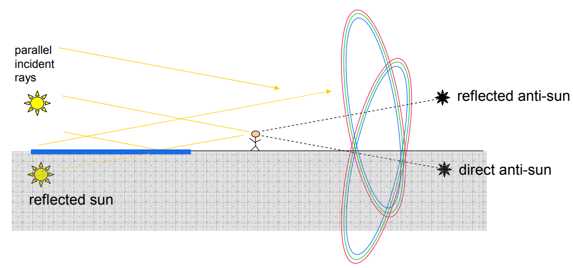


Alexander of Aphrodisias (Anatolia); Greek philosopher, 200 AD

more rainbows



reflection of incident sun light

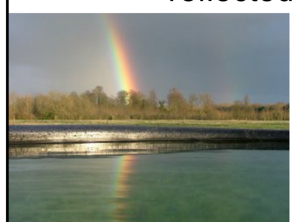


reflection of incident sun (examples)

reflected secondary is visible

direct and reflected bows meet at the horizon

reflected rainbows



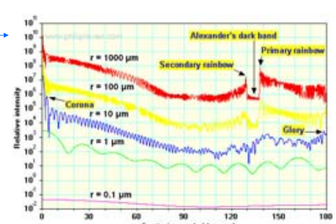
Reflected rainbows are not a simple reflection of the one in the sky, but rather the reflection of the bow that would have been seen by someone whose eye was the same distance below the water level as the camera was above.

The reflection of the primary bow is shifted to the left and does not correspond to the bow in the sky.

Mie theory

Gustav Mie (1908): theoretical analysis of light scattering from spherical particles of any size

Intensity for a fixed wavelength versus scattering angle and particle size

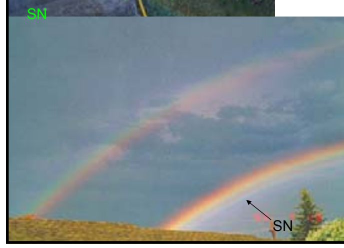


Wavelength dependence is weak for spheres larger than λ

The Mie algorithm models all of the "traditional" scattering processes caused by a spherical drop of water, such as external reflection, multiple internal reflections, transmission and surface waves and diffraction.

Supernumeraries

necessary condition:
droplets must have very similar diameters.
Due to interference between different paths through drop.



Quantitative explanation needs Mie theory

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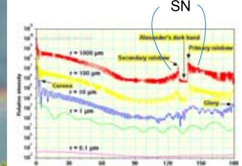
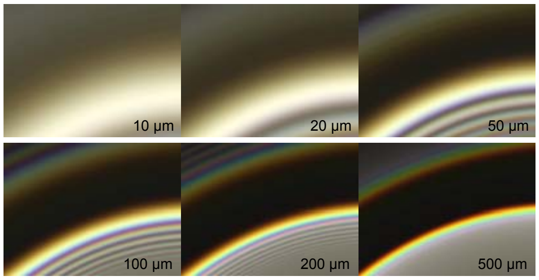
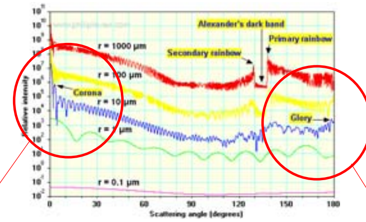


Supernumeraries (2)

Supernumeraries require uniform droplet size. Spacing depends on droplet size. Explained by Mie theory. Below is a simulation (Phillip Laven).

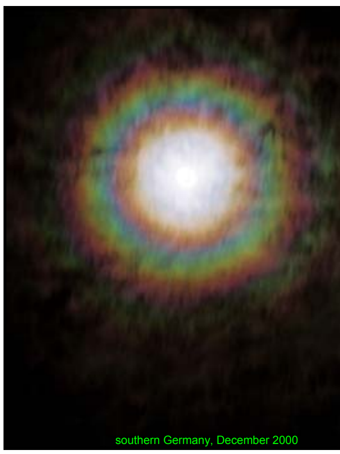


Forward and backward scattering



Forward scattering for θ < 10°. A diffraction phenomenon. May be caused by water droplets, *or* ice/dust particles. Location of bumps depends on particle size and wavelength (color)

Back-scattering of light by small water drops. The radius of the glory depends on the size of the drops - the smaller the drops, the larger the glory.



Corona or Aureole

An extraordinary colorful Corona, also called Aureole, around the full moon (southern Germany, December 2000).

If the atmospheric droplets, or particles, have similar sizes the diameter of the diffraction maxima depends on wavelength. Thus the colors.

Notice the (white) Airy disk in the center.

Corona, Crepuscular Rays

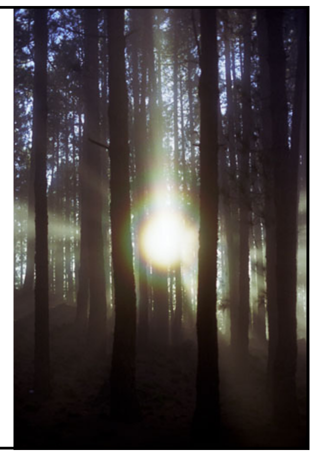
Corona

A Corona with colorful interference rings, appears because there are small water drops, that all have similar sizes. The drops are quite close to the observer as the appearance is even visible in front of the trees.

Crepuscular Rays

The radial spokes are called Crepuscular Rays. They are produced by the partial obscuration of the solar light by the trees.

“crepuscular”: pertaining to twilight



More crepuscular rays

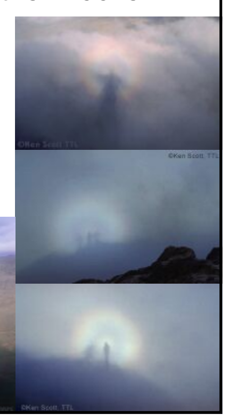
If the air is hazy and the sun is shining in between of the clouds, bundles of light are seen. These seem to point radially away from the sun.

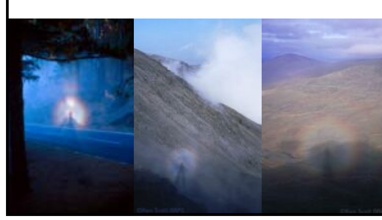
Scattering by the haze (dust, water vapor) makes the "path" of the sunlight visible.

“crepuscular”: pertaining to twilight

Glory and the specter of the Brocken

The glory is formed due to the favored back-scattering of light by the small water drops. The radius of the glory depends on the size of the drops - the smaller the drops, the larger the glory.





Iridescent clouds

Sometimes one sees colorful clouds in the vicinity of the sun.

Such 'iridescent clouds' appear due to diffraction effects if the water droplets in the cloud are of similar sizes.

Since the particle size varies inside a cloud, the colors often follow the shape of the cloud.

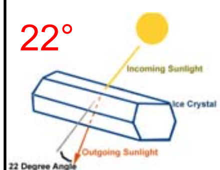
Close to the sun the angular distance to it becomes more important and iridescence evolves to a so-called Aureole or Corona with concentric rings.

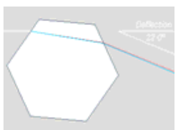
ICE CRYSTALS

- Refraction from hexagonal water crystals, suspended in the atmosphere

Hexagonal ice crystals

22°





$n_{ice} = 1.31$

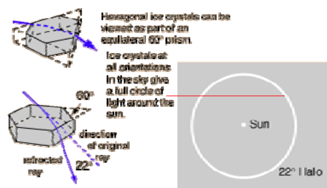
The 22° halo results from "in one side, out another side";
the 46° halo from "in one side, out the bottom".

46°

No light is refracted through >22° and so the area inside the halo is dark .

The (most common) 22° halo

The basic 22° halo around the Sun or Moon occurs because of refraction in tiny hexagonal ice crystals in the air. With the 60° apex angle of the prism formed by extending the sides of the crystal and the index of refraction of ice (n=1.31) one can calculate the angle of minium deviation to be 21.84°.



Further refinement using n=1.306 for red and n=1.317 for blue gives angles of 21.54° and 22.37° for red and blue respectively. The inner edge of the halo is sharp and appears reddened - the angle of minimum deviation for red is less, so red is seen from crystals closer to the Sun or Moon direction (inside of ring)..

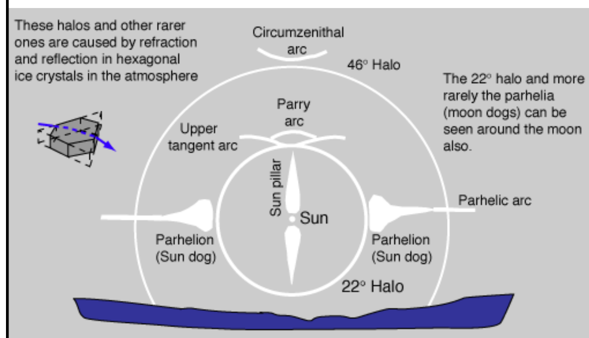
example of a 22° halo

the most common halo phenomenon: the **22°-circle**.
It is mainly white with a red rim at the inner edge (minimum deflection angle)

Another 22° halo

46° halo

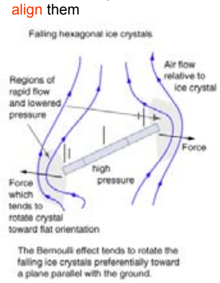
Halos (overview)



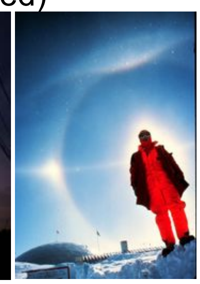
Orientation by drag forces

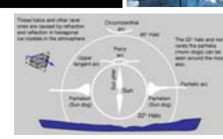
The actual crystal shapes responsible for the halo are uncertain.

As crystals drift downwards in clouds the drag forces tend to align them



Halos (observed)





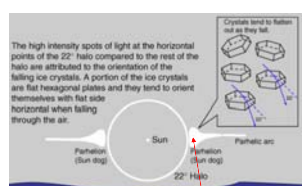
Parry Arc

The Parry arc is moonlight or sunlight deflected by elongated airborne ice crystals.

As the crystals fall, they tend to align themselves with their long axes horizontal.

W. E. Parry, explorer, reported seeing the phenomenon while searching for a northwest passage in 1819-1820

Sun dogs (Parhelion, mock sun)



Sundog example

isolated sun dog

SMALL SCATTERERS

- Rayleigh scattering: light scattering from particles that are small compared to a wavelength
- Particles may be density fluctuations (on a molecular scale): Einstein-Smoluchowski effect.
- Scattering by larger particles is explained by Mie scattering

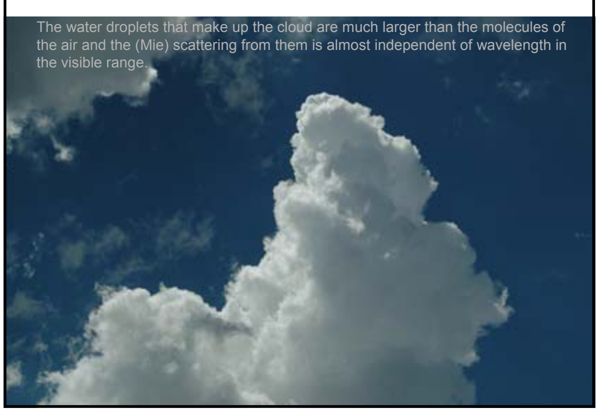
Blue sky

The blue color of the sky is caused by Rayleigh scattering of sunlight off the molecules of the atmosphere. Therefore the light scattered down to the earth at a large angle with respect to the direction of the sun's light is predominantly in the blue end of the spectrum.

Note that the blue of the sky is more saturated when you look further from the sun.

White clouds

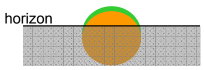
The water droplets that make up the cloud are much larger than the molecules of the air and the (Mie) scattering from them is almost independent of wavelength in the visible range.

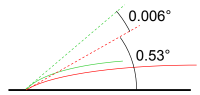


Red sunset

Short wavelengths are more efficiently scattered out of the sunlight by Rayleigh scattering. Aerosols and particulate matter contribute to the scattering so brilliant reds are seen when there are many airborne particles, as after volcanic eruptions.

Green Flash





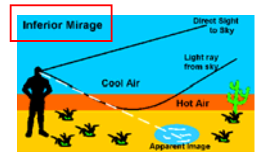
refraction in the atmosphere:
Index of refraction
red n=1.000292
blue n=1.000295

Red and green rims separate, but only by 0.006°, or about 20 arc seconds, compared to a 120 arc sec resolution for the eye.

One needs special conditions (mirage).

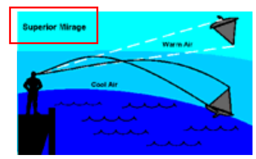
(Green flash is easily seen with a telescope when bright planets are setting)

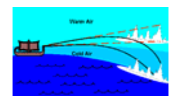
mirages

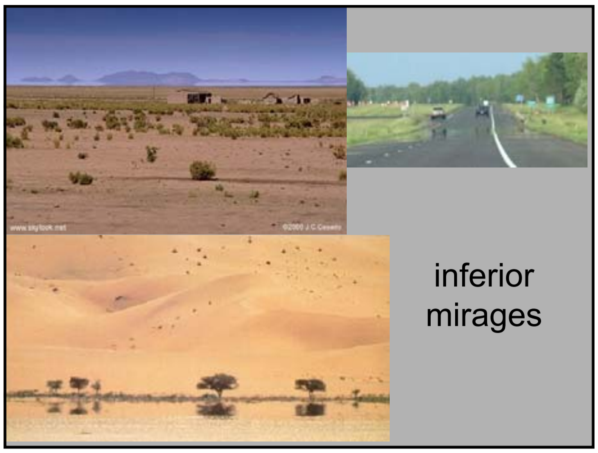


"a phenomenon due to atmospheric conditions by which refracted images of distant objects are seen"

Needed: strong vertical thermal gradients in the air

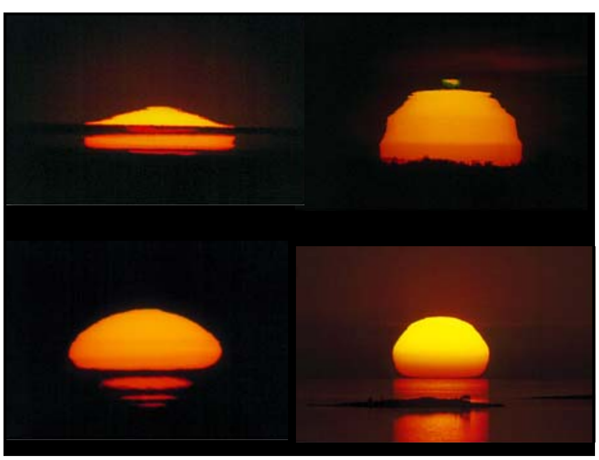


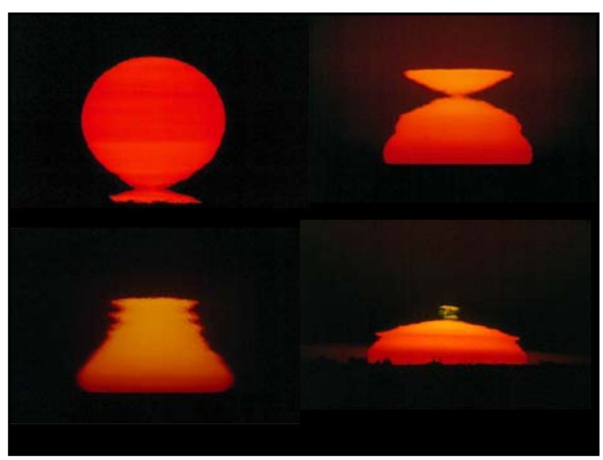


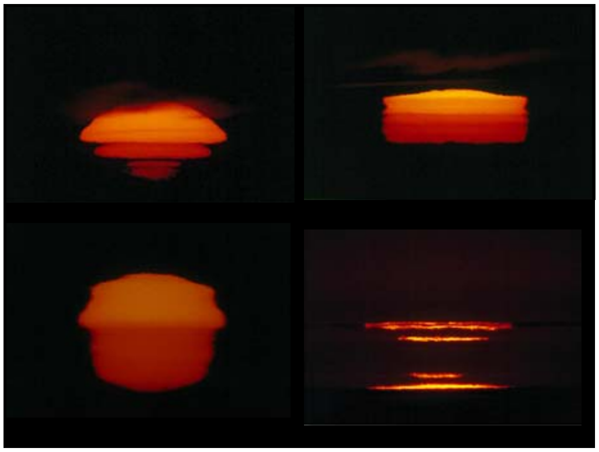


inferior mirages

Superior mirages







ATOMS AND MOLECULES

- Excitation by bombardment with energetic protons from the sun
- Light emission by excited atoms and molecules

Aurora

Energetic charged particles from the solar are channeled toward the poles by the magnetic field of the earth. They are energetic enough to excite air molecules.

Red and green light is emitted from excited oxygen atoms. Atmospheric nitrogen also plays a role.

near north pole: “aurora borealis”,

near south pole: “aurora australis”.