PHSC 3033: Meteorology
Atmospheric Optics
Hot Radiating Objects

Imagine a piece of metal placed in a hot furnace.

At first, the metal becomes warm, although its visual appearance doesn't change.

As it heats up, it begins to glow dull red, then orange, brilliant yellow, and finally white hot.

Objects that emit light energy are called blackbody radiators.

How do we explain this change in color?
Spectrum

Light Intensity as a function of Wavelength.
Blackbody Radiation

Stefan-Boltzmann Law (Amount of Energy)

Energy Flux $E = \sigma T^4$

As the temperature increases, the energy output increases more dramatically.

Stefan-Boltzmann Constant $\sigma = 5.6705 \times 10^{-5}$ erg cm$^2$/K$^4$ s
Wien’s Law

Wien's law relates the temperature $T$ of an object to the maximum wavelength at which it emits the most radiation.

Mathematically, if we measure Temperature ($T$) in kelvins and the wavelength maximum ($\lambda$) in nanometers, we find that

$$\lambda_{\text{max}} = \frac{3,000,000}{T}$$

*3,000,000 is an approximation of the value 2,900,000 like 300,000,000 m/s approximates the speed of light 299,792,458.*
Solar Radiation Output

The sun looks “yellowish,” -- WHY
With a spectrum peak at $\sim 517$ nm, the surface temperature of the sun can be estimated

$$T = \frac{3,000,000}{517}$$

$$T = 5800 \text{ K}$$
Scattering and Size

Scattering is very dependent upon the size of the object compared to the wavelength ($\lambda$) of light.

Very little effect occurs if the wavelength ($\lambda$) is very much smaller or very much bigger than the object.
Scattering is most efficient when the wavelength of light is roughly comparable to the size of the object.
Scattering

For larger sized particles > \( \lambda \)
Mie Scattering

Water droplets and ice crystals scatter all wavelengths more uniformly. Clouds are white.
Scattering

For smaller sized particles $< 1/10 \lambda$

Rayleigh Scattering is highly wavelength dependent $\sim 1/\lambda^4$
Blue Sky

Scattering by air molecules preferentially selects light of shorter wavelengths because of their size. (Rayleigh \( \sim 1/\lambda^4 \))
Zenith Distance

• There is much less atmosphere to travel through directly overhead than near the horizon.

• By the time the sun light gets through on the horizon, most of the blue light has been preferentially scattered.
The Principle of Reflection

The Angle of Incidence = The Angle of Reflection
Sun Pillar

Horizontal plate crystals form them. Light rays are externally and internally reflected by their upper and lower faces.
Venus Pillars
Reflection and Transmission

Light incident on water from air.

Reflectance and Transmittance (flux)
Reflection and Transmission

Water/air interface.

Reflectance and Transmittance (flux)

![Graph showing reflectance and transmittance](image)
Bending of Light

Principle of Refraction:

A light wave will **slow down** upon entering a **denser** medium. The refracted light will be bent toward the normal to the surface in this case.

A light wave will **speed up** upon entering a **less dense** medium. The refracted light will be bent away from the normal to the surface in this case.
Beach Party

Pavement

Sand
Beach Party

Pavement

Sand
Beach Party

Pavement

Sand
Beach Party

Pavement

Sand
Beach Party

Pavement

Sand
Refraction

Light waves, like people wave fronts can slow down also.
Refraction

Velocity slows down and is bent toward the normal to the surface, then speeds up upon exiting the glass and is bent away.
Index of Refraction

To characterize the change in velocity of a light wave in a transparent medium, we use the index of refraction (n). It is the ratio of the speed of light in a vacuum (c) compared to the slower speed of light in a non-vacuum (v).

\[ n = \frac{c}{v} \]

Note:
since \( c = 3 \times 10^8 \text{ m/s} \) is the speed limit for light, \( v \) for any other medium is less than \( c \).

Therefore, the index of refraction is always \( > 1.0 \).
<table>
<thead>
<tr>
<th>Transparent Medium</th>
<th>Index of Refraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>1.0000000</td>
</tr>
<tr>
<td>Air</td>
<td>1.00029</td>
</tr>
<tr>
<td>Water</td>
<td>1.33</td>
</tr>
<tr>
<td>Ice</td>
<td>1.31</td>
</tr>
</tbody>
</table>
Snell’s Law

The amount of bending is dependent upon indices of refraction

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]
Total Internal Reflection

If $n_1 > n_2$, then there is a critical angle at which $\theta_2$ goes to $90^\circ$

$$n_1 \sin \theta_1 = n_2 \sin 90$$

$$\sin \theta_c = \frac{n_2}{n_1}$$
Atmospheric Refraction

Star appears to be here

Actual position of star

Star
Refracted Sun Light

• When the sun sets, it is actually 1/2 of a degree below the physical horizon because of atmospheric refraction.
Green Flash
Mirage action of a temperature inversion layer. The layer need only be a few feet above the surface (the vertical scale here is exaggerated). Parallel rays from the setting sun follow two paths to the observer above the layer and up to three solar images are seen (the uppermost is erect and for clarity is not shown here). The mirage can greatly magnify small angular differences in ray directions. The separation between red and green images is enhanced and can give a green flash.
Atmospheric Refraction

Warm air immediately above the ocean causes the sun's rays to be mirrored back upwards. The rays produce an inverted sun beneath the 'real' one. When the sun has almost set the mirroring becomes very sensitive to the angle of the rays. Small differences between the angles of red and green rays are vertically magnified. A patch of almost pure green is seen - a green flash. The diagram greatly exaggerates the ray curvatures and vertical scale.
Bending of Light in a Mirage

- With Increase in Temperature Near the Ground, there is a decrease in the air density.

- Refraction is dependent upon the air temperature (density).
Index of Refraction

Height (meters)

(Refractive Index - 1) x 1000
Light Paths

![Graph showing light paths with points A, B, and C.]
Hot Pavement Mirage
Bending of Light in a Mirage

- Density is dependent upon temperature. Warm air is less dense than cold air and refraction depends upon density.
Mirage
Superior Mirage
Refraction is Dispersive

Light of different frequencies is refracted by different amounts.
Rainbow
The Beauty of Refraction and Dispersion

White Light Through a Glass Prism
Rain Drops As Prisms

Sun Light Through A Raindrop
Rainbow Geometry
Rainbow Raindrop Light Paths

Primary: Single Reflection
Secondary: Double Internal Reflection
Rainbows

- Inner Rainbow: Violet inside, Red outside
- Outer Rainbow: Red inside, Violet outside
Rainbows
Not all cirrus clouds or ice crystals produce halo displays. Sometimes the crystals are smaller than \(~0.01\) mm and light is significantly diffracted rather than undergoing the refraction and reflection that produce halos. Sometimes the crystals are not of sufficient optical quality, but sometimes the crystals are just right!
Halos

A 22° radius circular halo centered on the sun (or moon) is the most frequently seen of all the halos. Often milky white, it is sometimes colored with a reddish inner edge.
22° Halo

The 22° halo is formed by rays which enter the side faces of hexagonal prism shaped crystals, and are refracted across the crystal, then leave through another side face inclined at 60°.

A large enough fraction of quality crystals need to be oriented correctly.
Upper Tangent Arc

An Upper Tangent Arc is sometimes only apparent as a brightening of a 22° halo above the sun.

They form by refraction through side faces of hexagonal column crystals falling in clouds with their long axes nearly horizontal.
22 Degree Halo Tilt

Random Orientations
Spread Over Several Degrees Create More Uniform Halos
Parhelia (Sun Dog)
Bright Sun Dog

Sun dogs, the second most frequent of the halos, show that the clouds are hosting horizontal plate crystals. The plates drift down like leaves with their large faces nearly horizontal and sun dogs are formed by light passing through crystal side faces inclined at 60° to each other.
Sun Dog Geometry

- Flat ice crystals
Double Sun Dogs
Circumzenithal Arc

The refraction of rays all in nearly the same direction through faces inclined at 90° produces very pure and well separated prismatic colors.
Circumzenithal Arc, 2000
Ice Crystal Phenomena

Atmospheric Optics

http://ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/opt/ice/halo/22.rxml
Aurora
Magnetic Field
What If the **Current** is this…

Then the **Magnetic Field** is this...
Oersted’s Experiment

A current carrying wire produces a magnetic field dependant upon the current direction.
Magnetic Force

Force on a positive charge.

Magnetic Force = Charge • Velocity • Magnetic Field Strength

\[ F = q \times v \times B \]
Moving Charges

Moving Charges in a Magnetic Field Experience a Force

Moving Charges can also create a Magnetic Field.
Particles Spiraling

• Charged particles and a Magnetic Field (simulations)

http://www.phy.ntnu.edu.tw/java/emField/emField.html
Magnetosphere

- Solar Wind (charged particles) and Earth’s Magnetic Field
Auroral Ionization Ring

http://www.pfrr.alaska.edu/~pfrr/AURORA/
Arkansas Aurora 2011-10-24
Summary

• Scattering Causes…
  – White Clouds
  – Blue Skies, Red Sunsets

• Reflection Causes…
  – Sun Pillars

• Refraction Yields...
  – Changes in position of celestial objects (Earth’s atmosphere)
  – Mirages (air density fluctuations affecting index of refraction)

• Reflection and Refraction (+ dispersion) Yields...
  – Rainbows (water droplets)
  – Sun Dogs and other Halo phenomena (ice crystals)

• Solar Wind and Earth’s Magnetic Field Yields...
  – Aurora
Online Resources

http://www.atoptics.co.uk/

http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/atmoscon.html

http://optics.kulgun.net/