The Nature of Light and Matter
My Teaching website in located at:  
http://chartasg.people.cofc.edu/chartas/Teaching.html

Lecture: Tuesday and Thursday  
Location: Harbor Walk, HWWE room 112  
Time: TR 11:20 am-12:35 pm

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Syllabus  
Required materials:  
The textbook for the course is Universe 10th Edition (8th and 9th Editions are OK as well) by Roger A. Freedman, Robert M. Geller, and William J. Kaufmann. You will also need a scientific calculator capable of computing exponential functions.
Midterm Exams Homework and Quizzes:
There will be 3 midterm exams over the semester. The worst score of the three may be dropped. Homework will be assigned after each chapter and I expect it to be turned in by the assigned due date listed on the schedule web site. Several quizzes will be given during lectures. The quizzes will be based on material already presented in lectures. There will be a final exam that will cover most of the material presented in the lectures.

**Grades**

Your final grade will be calculated as follows:

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Homework</td>
<td>5%</td>
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<tr>
<td>Quizzes</td>
<td>15%</td>
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<tr>
<td>Midterms</td>
<td>40%</td>
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<tr>
<td>Final + signature assignment</td>
<td>30% + 10%</td>
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Your number grade will be converted into a letter grade as follows.
The Sun – Eight Minutes ago

Distance from Sun = $1.5 \times 10^8$ km, $c = 3 \times 10^5$ km/s
Time = ?
The Sun – Eight Minutes ago

Distance from Sun = \(1.5 \times 10^{11}\) m
\(c = 3 \times 10^5\) km/s

\[ c = \frac{s}{t} \]
\[ \rightarrow t = \frac{s}{c} = \frac{1.5 \times 10^8}{3 \times 10^5} \text{ km/sec} \]
\[ \rightarrow t = 500 \text{ sec} \]

Light Year = ly : distance light travels in one year

\[ 1 \text{ ly} = c \times 1 \text{ yr} = 3 \times 10^5 \text{ km/s} \times 1 \text{ yr} = 3 \times 10^5 \text{ km/s} \times 3.1557 \times 10^7 \text{s} \]
\[ 1 \text{ ly} = 9.46 \times 10^{12} \text{ m} \]
The Nearest Stars – Few Years Ago

1 pc = 3.26 ly
Andromeda Galaxy – 2.5 Million Years Ago

disk radius \sim 110,000 \text{ ly}
Distant Galaxies – Billions of Years Ago
The Nature of Light

The Ring Nebular (M57): A shell of glowing gases surrounded by a white dwarf.

- red light from nitrogen
- green light from oxygen
- blue light from helium
Measuring the Speed of Light

1. Galileo
   → concluded that the speed of light was too fast for him to measure.

2. Olaus Romer
   → By recording the time of eclipses of Io Romer noticed that they occurred several minutes later when the earth was far from Jupiter (in conjunction) and earlier when closer the Jupiter.
2. Olaus Romer

Question: Estimate the speed of light if the range in variation in the times at which eclipses are observed is about 16.6 min.

hint: light has to travel an extra 2*AU to reach Earth in opposition. 1 AU = 1.5 \times 10^8 \text{ km}
Measuring the Speed of Light

3. The Fizeau-Foucault Method

4. By 1975 the speed of light was known to be 299,792,458 m/s with a relative measurement uncertainty of 4 parts per billion. In 1983 the meter was redefined in the International System of Units (SI) as the distance travelled by light in vacuum in 1/299,792,458 of a second.
The Nature of Light

**What is light?** How is it produced? What is it made of? How does it propagate?

1. Newton’s experiments showed that white light is a combination of all the colors that appear in its spectrum.
The Nature of Light

A second prism bends the light but does not change the color thus indicating that it actually separates the white light into the colors it's made up of. Newton suggested that light is composed of particles too small to detect individually.
The Nature of Light

2. Huygens and Young: **Wavelike nature of light**.
3. **Maxwell**: light is electromagnetic radiation

- Light is electromagnetic radiation that consists of oscillating electric and magnetic fields.
- Maxwell showed that electromagnetic waves travel through space at the speed of light.
- The distance between successive wave crests is called the wavelength of the light.
The Nature of Light

\[ \lambda = \text{wavelength} \]

Visible light
\[ \lambda: \text{400 nm (violet) – 700 nm (red)} \quad (1 \text{ nm} = 1 \times 10^{-9} \text{m}) \]

**William Herschel** discovered **infrared radiation**
\[ \lambda: \text{700 nm – 1000 } \mu \text{m} \quad (1 \mu \text{m} = 1 \times 10^{-6} \text{m}) \]

In experiments using electric sparks **Heinrich Hertz** discovered **radio waves**
\[ \lambda: \text{10 cm – 100 km} \quad (1 \text{ km} = 1 \times 10^{3} \text{m}, \ 1 \text{ cm} = 1 \times 10^{-2} \text{m}) \]

**Wilhelm Rontgen** discovered **X-rays** by bombarding targets with high energy particles
\[ \lambda: 10^{-2} \text{ nm – 10 nm} \]
Frequency and Wavelength of light

The **frequency** of a wave is just the number of crests that pass a given point per sec or the number of complete cycles that pass per sec.

\[ c = \frac{\lambda}{T_{\text{crest}}} = \lambda \nu \]

**\( \nu \)** = frequency of an electromagnetic wave
**\( c \)** = speed of light = \( 3 \times 10^8 \) m/s
**\( \lambda \)** = wavelength of the wave in meters

Unit of frequency 1 Hz = s\(^{-1}\)

**AM radio**: 535 kHz - 1605 kHz  
**FM radio**: 88 MHz - 108 MHz
Frequency and Wavelength of light

21-centimeter line An electron orbiting a proton with parallel spins (pictured) has higher energy than if the spins were anti-parallel.

Question: Neutral Hydrogen emits radio waves with a wavelength of 21.1 cm. What’s the frequency, Kenneth?

Use $c = 3 \times 10^8$ m/s
**Frequency and Wavelength of light**

**21-centimeter line** An electron orbiting a proton with parallel spins (pictured) has higher energy than if the spins were anti-parallel.

**Question:**
Neutral Hydrogen emits radio waves with a wavelength of 21.1cm. What is the frequency?

**Answer:**
\[ \nu = \frac{c}{\lambda} = \frac{3 \times 10^{10} \text{ cm s}^{-1}}{21.1 \text{ cm}} = \sim 1420 \text{ MHz} \]
Thermal Radiation

Thermal radiation is electromagnetic radiation emitted from an object’s surface and is related to its temperature.

Thermal radiation is generated when kinetic energy from the movement of charged particles within atoms is converted into electromagnetic radiation.

Examples of objects that emit thermal radiation:
The solid filament of a light bulb emits white light that is a mixture of light of many wavelengths.

The sun and stars, even though are gaseous, emit light that is very similar to that emitted by a very hot solid.
Thermal Radiation

Example: Imagine a bar of iron being heated up. As the bar starts to glow it will first appear to glow with a deep red color. As the temperature of the bar increases the color of the bar goes from red to orange to yellow.
Thermal Radiation

The **amount of energy** and the **dominant wavelength** of the light emitted **depends on the temperature** of the object. *Higher temperatures result in shorter wavelengths and more energy emitted per unit time.*

The reason we don't see bodies in the dark is that the dominant wavelength emitted by bodies is in the infrared.

Our eyes are not sensitive to infrared.
Kinetic Energy

The kinetic energy of an object of mass $m$ and velocity $v$ is:

$$E_k = \frac{1}{2}mv^2$$

If $m$ is expressed in kg and $v$ in m/s, the kinetic energy is expressed in Joules (J).
Temperature of a Gas

The temperature of a gas is a direct measure of the average amount of kinetic energy per atom or molecule. The average kinetic energy of a gas atom or molecule is:

$$E_k = \frac{3}{2} kT$$

$E_k =$ average kinetic energy of a gas atom or molecule in joules (J)

$k = 1.38 \times 10^{-23}$ J/K (Boltzmann constant)

$T =$ temperature of gas, in kelvins
Absolute Temperature Scale

The SI unit for temperature ($T$) is the kelvin. The Kelvin scale is a thermodynamic (absolute) temperature scale where absolute zero, the theoretical absence of all thermal energy, is zero kelvin ($0\,\text{K}$).

$$T(\text{K}) = T(\degree\text{C}) + 273.15\degree$$

For example the average surface temperatures of Mercury and Mars are about $700\,\text{K}$ and $300\,\text{K}$, respectively.

The temperatures in the upper atmospheres of Jupiter and Neptune are about $125\,\text{K}$ and $55\,\text{K}$, respectively.
\[ T_C = \frac{5}{9}(T_F - 32) \]

\[ T_K = T_C + 273.15 \]

- \( T_C \) temperature in degrees Celsius
- \( T_F \) temperature in degrees Fahrenheit
- \( T_K \) temperature in kelvin
Average speed of a gas molecule or atom

The average speed \( v \) (m/s) of a gas molecule or atom is:

\[
\frac{1}{2}mv^2 = \frac{3}{2}kT \Rightarrow v = \sqrt{\frac{3kT}{m}}
\]

\( k = 1.38 \times 10^{-23} \text{ J/K} \) (Boltzmann constant)

\( T = \text{temperature of gas, in kelvins} \)

\( m = \text{mass of atom or molecule in kg} \)

The average speed of the oxygen molecules that you breathe at a room temperature of 20°C is about 0.478 km/s.
Intensity vs. Wavelength: Spectra

This figure shows the intensity of light emitted by a solid as a function of wavelength for three different temperatures of the emitting solid.

Notice that the dominant wavelength decreases with increasing temperature.
Temperatures of Stars

An ideal **blackbody absorbs** all the radiation that falls on it.

The spectra of stars are often approximated with blackbody spectra.

Property of blackbody spectra: 
*The higher an object's temperature the more intensely the object emits EM radiation and the shorter the wavelength it emits more strongly.*
Temperatures of Stars

Example: The star Bellatrix in Orion that looks blue has a higher temperature than the red star Betelgeuse.
The Sun’s Spectrum
Blackbody Radiation: Wien’s Law

Wien’s Law

\[ \lambda_{\text{max}} (m) = \frac{0.0029Km}{T(K)} \]

\( \lambda_{\text{max}} \) = wavelength of maximum emission in meters

\( T \) = temperature of object in kelvins
Wien’s Law: Sun

The maximum intensity of sunlight is at a wavelength of roughly 500 nm = 5.0 \times 10^{-7} \text{ m}. Use this information to determine the surface temperature of the Sun.
Wien’s Law: Sun

The maximum intensity of sunlight is at a wavelength of roughly 500 nm = 5.0 \times 10^{-7} \text{ m}. Use this information to determine the surface temperature of the Sun.

Sun: \lambda = 0.0029 \text{ Km} / T(\text{K})

\[ \text{Tsun} = \frac{0.0029 \text{ K m}}{5 \times 10^{-7} \text{ m}} = 5800 \text{ K} \]
Wien’s Law: Sirius

Sirius, the brightest star in the night sky, has a surface temperature of about 10,000 K. Find the wavelength at which Sirius emits most intensely.
Wien’s Law: Sirius

Sirius, the brightest star in the night sky, has a surface temperature of about 10,000 K. Find the wavelength at which Sirius emits most intensely.

Sirius: \( \lambda = \frac{0.0029}{T} \) \( \rightarrow \)

\[ \lambda = \frac{0.0029 \text{ K m}}{10,000 \text{ K}} \rightarrow \]

\[ \lambda = 2.9 \times 10^{-7} \text{ m} = 290 \text{ nm (UV band)} \]
Wien’s Law: Black Hole Accretion Disk

\[ T_{\text{disk}} \approx 10^6 \text{K}, \lambda = ? \]
Wien’s Law: Black Hole Accretion Disk

\[ T_{\text{disk}} \sim 10^6 \text{K}, \lambda = ? \]

Black Hole: \( \lambda = \frac{0.0029}{T} = \frac{0.0029 \text{ K m}}{1 \times 10^6 \text{ K}} \rightarrow \lambda = 2.9 \times 10^{-9} \text{ m} = 2.9 \text{ nm} \) (X-ray band)
Flux Energy Density and Luminosity

Flux Energy Density \( F = \frac{E}{At} \) (J m\(^{-2}\) s\(^{-1}\))

Luminosity \( L = \frac{E}{t} \) (J s\(^{-1}\))

\( E = \) energy crossing an area \( A \) within a time \( t \)

Since the area of a sphere is \( 4\pi R^2 \), as one moves away from the source the flux will decrease by \( 1/R^2 \)
Blackbody Radiation: Stefan-Boltzmann

\[ F = \sigma T^4 \]

- \( F \) = energy flux at the surface of a star, \((W \text{ m}^{-2})\)
- \( T \) = temperature of object, (kelvin)

\[ \sigma = 5.67 \times 10^{-8} W \text{ m}^{-2} K^{-4} \]
Stefan-Boltzmann’s Law: Sirius vs. Sun

How does the energy flux from Sirius compare to the Sun’s energy flux?

\[ T_{\text{sirius}} = 10,000 \text{ K}, \ T_{\text{sun}} = 5,800 \text{ K} \]
Stefan-Boltzmann’s Law: Sirius vs. Sun

How does the energy flux from Sirius compare to the Sun’s energy flux?

\[
\frac{F_{\text{sirius}}}{F_{\text{sun}}} = \frac{\sigma T^4_{\text{sirius}}}{\sigma T^4_{\text{sun}}} = \left(\frac{10,000 \text{ K}}{5800 \text{ K}}\right)^4 = 8.84
\]
Stefan-Boltzmann’s Law: Sun’s Surface Temperature

Using detectors above Earth’s atmosphere, astronomers have measured the average flux of solar energy arriving at Earth. This value, called the solar constant, is equal to 1370 W m\(^{-2}\). Use this information to calculate the Sun’s surface temperature. (This calculation provides a check on our result from the preceding example.)

\[
R_\odot = 695,500 \text{ km}, \ 1 \text{ AU} = 1.5 \times 10^{11} \text{ m},
\]
\[
\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}
\]
Photon Hypothesis

In 1900 **Planck** formulated a theory to explain blackbody radiation curves.

In 1905 **Einstein** postulated that light is composed of discrete, particlelike packets that he called quanta, now known as photons.
Planck’s Law: Energy vs Frequency

The dual nature of light is evident in the formula that relates the energy of a photon to its wavelength:

\[ E = h\nu = h\frac{c}{\lambda} \]

- \( E \) = energy of photon (eV)
- \( \nu \) = frequency of photon (s\(^{-1}\))
- \( h = 4.135 \times 10^{-15} \text{ eV s} \) (Planck's Constant)
- \( c = \text{speed of light} = 3 \times 10^8 \text{ m s}^{-1} \)
- \( \lambda = \text{wavelength of the wave} \text{ (m)} \)
Planck’s Law: Energy vs Frequency

The dual nature of light is evident in the formula that relates the energy of a photon to its wavelength:

\[ E = h \nu = h \frac{c}{\lambda} \]

- \( E \) = energy of photon (J)
- \( \nu \) = frequency of photon (s\(^{-1}\))
- \( h = 6.625 \times 10^{-34} \) J s (Planck's Constant)
Planck’s Law: Energy vs Frequency

Electron-positron annihilation

$E_{\text{photon}} = 511\text{keV}, \lambda = ?$
Numerous dark spectral lines are seen in this image of the Sun’s spectrum. The spectrum is spread out so much that it had to be cut into segments to fit on this page.
Emission Lines

1. Add a chemical substance to a flame

2. Send light from the flame through a narrow slit, then through a prism

3. Bright lines in the spectrum show that the substance emits light at specific wavelengths only
Each Chemical Produces a Unique Pattern of Spectral Lines

Helium (He)

Hydrogen (H₂)

Krypton (Kr)

Mercury (Hg)

Neon (Ne)

Water vapor (H₂O)

Xenon (Xe)
(a) Continuous spectrum (blackbody emits light at all wavelengths)

(b) Absorption line spectrum (atoms in gas cloud absorb light of certain specific wavelengths, producing dark lines in spectrum)

(c) Emission line spectrum (atoms in gas cloud reemit absorbed light energy at the same wavelengths at which they absorbed it)
Kirchoff's Laws

(a) A **hot opaque body** (such as a blackbody) or a hot dense gas produces a **continuous spectrum**.

(b) A **cooler transparent low density gas** placed in front of a source of a continuous spectrum produces **absorption lines**.

(c) **Emission lines** are produced from a **low density transparent gas**.

The field of spectroscopy was thus born. **Spectroscopy** is the systematic study of spectra and spectral lines.

By studying the spectral lines from an object we can learn about its chemical composition, the density and temperature of the gas, the velocity of the gas and more…
Iron in the Sun’s Atmosphere: The upper part of this figure is a portion of the Sun’s spectrum at violet wavelengths, showing numerous dark absorption lines. The lower part of the figure is a corresponding portion of the emission line spectrum of vaporized iron. The iron lines coincide with some of the solar lines, which proves that there is some iron (albeit a relatively small amount) in the Sun’s atmosphere.
Hot stars within the nebular NGC 346 (a star forming region in SMC) emit high energy ultraviolet photons that are absorbed by the surrounding gas to heat it up to high temperatures.

What is remarkable is that the emission spectrum produced by heated hydrogen gas on Earth contains the same 656 nm red line as the one found in the spectrum of NGC 346 located 210,000 light years away.
Rutherford’s Experiment

Radioactive substance emits alpha particles.

Most alpha particles pass through the foil with very little deflection.

Occasionally an alpha particle rebounds (like A or B), indicating that it has collided with the massive nucleus of a gold atom.
The number of protons in the nucleus of an atom determines the element that the atom represents.
Balmer Lines of Hydrogen

\[ \frac{1}{\lambda} = R \left( \frac{1}{4} - \frac{1}{n^2} \right), \text{ for } n \geq 3 \]

\( R \) is the Rydberg constant

\( R = 1.097 \times 10^7 \text{ m}^{-1} \)
Niels Bohr’s Model for the Atom

\[ \frac{1}{\lambda} = R \left( \frac{1}{n_{\text{in}}^2} - \frac{1}{n_{\text{out}}^2} \right) \]
Niels Bohr’s Model for the Atom

(a) Atom absorbs a 656.3-nm photon; absorbed energy causes electron to jump from the $n = 2$ orbit up the $n = 3$ orbit

(b) Electron falls from the $n = 3$ orbit to the $n = 2$ orbit; energy lost by atom goes into emitting a 656.3-nm photon
Niels Bohr’s Model for the Atom

The diagram illustrates the energy levels of an atom according to Niels Bohr's model. The energy levels are represented by horizontal lines, with the ground state at the bottom at 0 eV. Transitions between these levels can result in absorption, emission, and ionization of the atom. The transitions are marked with arrows and labeled with series names such as Lyman, Balmer, and Paschen series. The energy differences are indicated in electron volts (eV), with key transitions at 10.2 eV, 12.1 eV, 12.8 eV, and 13.6 eV.
1. $H_\delta$ Wavelength?
(hint $R = 1.097 \times 10^7 \text{m}^{-1}$)

2. What lines in the Balmer series fall in the UV?

3. What are the energy ranges for the Lyman, Balmer and Paschen Series?

$$\frac{1}{\lambda} = R \left( \frac{1}{n_{in}^2} - \frac{1}{n_{out}^2} \right)$$
1. A Hydrogen atom in the ground state absorbs a $L_\beta$ photon. What photon might that atom emit when de-excited.
Atomic Excitation

(a) UV Photon
- Ground state
- First excited state
- Ground state

(b) UV Photon
- Ground state
- Second excited state
- Ground state
- Visible Photon
- First excited state
- Ground state
- UV Photon
Hydrogen Spectra
Modern Model for the Atom

(a) Ground state

(b) Excited state
Modern Model for the Atom

\[ E_{nj} = -\frac{13.6eV}{n^2} \left(1 + \frac{\alpha^2}{n^2} \left( \frac{n}{j + \frac{1}{2}} - \frac{3}{4} \right) \right) \]

where,
\( \alpha \approx 1/137 \) is the fine-structure constant
j is a number which is the total angular momentum eigenvalue, i.e. \( l \pm 1/2 \) depending on the direction of the electron spin.
Doppler Effect

Wave crest 1: emitted when light source was at \( S_1 \)

Wave crest 2: emitted when light source was at \( S_2 \)

Wave crests 3 and 4: emitted when light source was at \( S_3 \) and \( S_4 \), respectively

This observer sees \textbf{blueshift}

This observer sees \textbf{redshift}

\[
\frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta \lambda}{\lambda_0} = \frac{v}{c}
\]
Doppler Effect

Megrez:

$H_\beta$ observed = 486.112nm
$H_\beta$ laboratory = 486.133nm

Is the star coming towards us or moving away?

At what speed?

$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta \lambda}{\lambda_0} = \frac{v}{c}$$
Doppler Shift

$H_{\alpha} \, (\text{Rest Wavelength}) = 656.3\text{nm}$
Doppler Shift

\[ H_\alpha \text{ (Rest Wavelength)} = 656.3 \text{nm} \]
**Redshift**

Gravitational Redshift:

\[
\frac{\nu_{\text{obs}}}{\nu_{\text{em}}} = \left(1 - \frac{2M}{\em} \right)^{1/2} \quad \frac{\nu_{\text{em}}}{\nu_{\text{obs}}} = \left(1 - \frac{2M}{\text{robs}} \right)^{1/2}
\]

Doppler Effect (non-relativistic):

\[
\lambda_{\text{obs}} = \lambda_{\text{em}} \left(1 - \frac{u}{c} \cos \theta \right) \quad \frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{em}}} = \frac{v_r}{c}
\]

Doppler Effect (Relativistic):

\[
\lambda_{\text{obs}} = \lambda_{\text{em}} \gamma \left(1 - \frac{u}{c} \cos \theta \right) \quad \frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{em}}} = \frac{\lambda_{\text{em}} \gamma \left(1 - \frac{u}{c} \cos \theta \right) - \lambda_{\text{em}}}{\lambda_{\text{em}}} = \gamma \left(1 - \frac{v_r}{c} \right) - 1
\]

Cosmological redshift due to expansion of the Universe:

\[
\frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{em}}} = z
\]
Lyman series (ultraviolet) of spectral lines: produced by electron transitions between the $n = 1$ orbit and higher orbits ($n = 2, 3, 4, \ldots$)

Balmer series (visible and ultraviolet) of spectral lines: produced by electron transitions between the $n = 2$ orbit and higher orbits ($n = 3, 4, 5, \ldots$)

Paschen series (infrared) of spectral lines: produced by electron transitions between the $n = 3$ orbit and higher orbits ($n = 4, 5, 6, \ldots$)
Particles Faster Than the Speed of Light? Not So Fast, Some Say
Experiments
A group of physicists from Italy claimed they had observed the subatomic particles called neutrinos traveling faster than the speed of light.
Neutrinos produced at CERN and beamed to a facility in Italy about 450 miles away, arrived about 58 billionths of a second sooner than would a light beam.
Consequences:
A neutrino or anything else that went faster than the speed of light could go backward in time.

Problems with Experiment Discovered:
It turns out connectors in the timing system were faulty resulting in the erroneous measurement. Einstein’s theory of special relativity is still valid.

neutrino song
References:

New York Times Science Section
http://www.nytimes.com

Scientists Report Second Sighting of Faster-Than-Light Neutrinos
By DENNIS OVERBYE