Introductory Astronomy

Week 2: Newton’s Universe

Clip 6: Matter and Radiation

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Matter

- By early 1900s: a unified understanding through atomic theory
- All matter made of a hundred or so elements – types of atoms labeled by Z
- These bind to form molecular compounds
- Three states: solid, liquid, gas
- Bulk properties determined by microscopic dynamics

- Temperature is a measure of average random motion of atoms and molecules
- In ideal gas

$$\begin{aligned} \langle \frac{mv^2}{2} \rangle &= \frac{3}{2} k_B T \\ PV &= N k_B T \end{aligned}$$

- T measured in K

$$k_B = 1.381 \times 10^{-23} \, \frac{\mathrm{J}}{\mathrm{K}}$$

- P pressure in $\mathrm{N/m^2}$

- At low temperature and sufficient pressure form (almost) incompressible liquid.
- Density decreases with temperature: hot fluid rises
- In equilibrium with gravity pressure increase with depth proportional to density

- In solid state positions of atoms fixed – maintain shape under external force
- Perturbations travel through matter as sound waves with a speed characteristic of the material
- We hear sound in air.

Waves

- Periodic disturbances characterized by frequency f in $\mathrm{Hz} = \mathrm{s}^{-1}$
- Traveling at speed c produce periodic wave with wavelength λ

$$\lambda f = c$$

- Amplitude A is value of the perturbation at maximum
- Energy flux in $\frac{\mathrm{J/s}}{\mathrm{m}^2} = \frac{\mathrm{W}}{\mathrm{m}^2}$ carried by wave is $\propto A^2$
- When two waves meet disturbances add
- If opposite sign - subtract!

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Doppler Effect

- Sound from a moving source heard at higher/ lower when source approaching/receding
- Doppler (1842)

$$\lambda = \lambda_0(1 - v/c)$$

Heat Transfer

- An object hotter than environment will lose energy until temperatures equilibrate
- Conduction: Heat can be transferred through continuous contact. Rare in astronomy
- Convection: Physical motion of fluid carries energy. Works well when heating from below - Heated fluid less dense so rises
- Radiation: Hot objects glow losing energy to light

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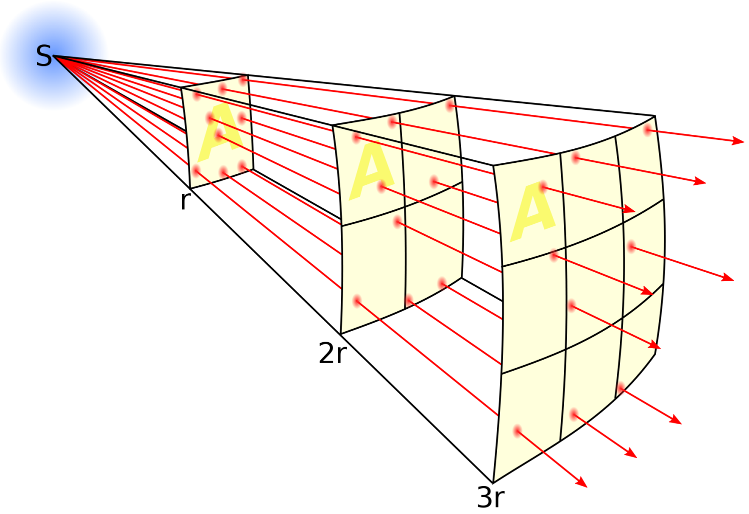
Luminosity and Brightness

- Sun is hot so radiates energy at a rate L
- Luminosity in $\mathrm{J/s} = \mathrm{W}$
- Brightness b is flux in $\mathrm{W/m^2}$
- At a distance R radiation distributed uniformly on surface of sphere $b = \dfrac{L}{4\pi R^2}$



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Another Wave?

- Light carries energy at a speed of $c = 2.998 \times 10^8 \ \frac{\mathrm{m}}{\mathrm{s}}$
- Newton 1670: white light contains all colors. A stream of particles
- Young 1799: observes interference. Light is a wave
- Young 1802: we observe relative intensity of RGB
- Color is the frequency of light. For visible light of order $10^{12}\ \mathrm{Hz}$. Wavelength $\lambda = c/f$ is 400-700nm

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Another Force

- Dominant force in most of physics: electromagnetism
- Coulomb force $F = \frac{kq_1q_2}{R^2}$

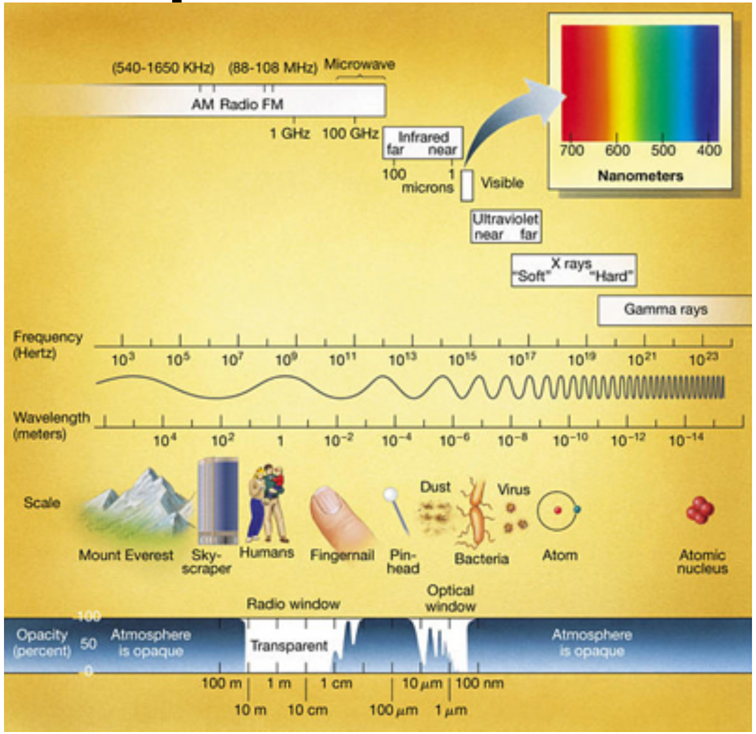
  can be attractive or repulsive
- Opposite charges attract so most objects neutral
- Charge is conserved
- A charge creates and is affected by electric field

Magnets – and Light

- Moving charges create and are affected by magnetic fields (Ørsted 1820)
- Changing magnetic field creates electric field (Faraday 1831)
- Changing electric field creates magnetic field (Maxwell 1861)
- Leads to propagating waves with velocity $c = 2.998 \times 10^8 \, \frac{\mathrm{m}}{\mathrm{s}}$
- Coincides with speed of light (Fizeau-Foucault 1850)
- Light is an electromagnetic wave!

Electromagnetic Spectrum

- Electromagnetic waves can have any wavelength
- What we see is limited by our eyes which are adapted to transparency of atmosphere
- What the Universe produces is not. Observing the Universe in many bands produces additional data



Heat Radiation

- A hot object radiates
- For dense dark objects radiation completely characterized by temperature – blackbody radiation
- Hotter objects are blue

Wien 1893 $\lambda_{\max} T = b$

$$b = 2.9 \times 10^{-3}\,\mathrm{m} \cdot \mathrm{K}$$

- Hotter objects radiate more. Stefan-Boltzmann 1879

$$F = \sigma T^4$$

F flux at object

$$\sigma = 5.670 \times 10^{-8} \frac{\mathrm{W}}{\mathrm{m}^2 \mathrm{K}^4}$$

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Example: Our Sun

- Measure Solar constant $b_\odot = 1361\,\mathrm{W/m^2}$
- Compute luminosity $L_\odot = 4\pi D_\odot^2 b_\odot = 3.83 \times 10^{26}\,\mathrm{W}$
- Sun radius $R_\odot = 6.96 \times 10^8\,\mathrm{m}$
- Luminosity is $4\pi R_\odot^2 F$ so $F = b_\odot \left(\frac{D_\odot}{R_\odot}\right)^2 = 6.29 \times 10^7\,\mathrm{W/m^2}$
- Set $F = \sigma T^4$ to find $T = (F/\sigma)^{1/4} = 5770\,\mathrm{K}$
- Use Wien $\lambda_{\max} = \frac{0.0029\,\mathrm{m}}{5770} = 503\,\mathrm{nm}$
- This is green

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Credits

- Physics Simulations: PhET Interactive Simulations, University of Colorado http://phet.colorado.edu
- Astronomy Animations: University of Nebraska-Lincoln Astronomy Education Group http://astro.unl.edu/
- EM Spectrum: Salt Lake City Atmospheric Carbon Dioxide Measurements http://co2.utah.edu/co2tutorial.php?site=7&id=4
- Demonstration videos: Duke Media Services

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