

# Lecture 2: Electromagnetic Radiation from Infrared to Gamma Rays

## The Electromagnetic Spectrum

Light is **electromagnetic radiation**, composed of oscillating **electric** and **magnetic** fields that propagate as a wave, but can behave as a **photon**, a massless, quantized packet of energy

- **Speed of light in a vacuum:**  $c = \underline{300 \text{ million}}$  meters/second = 670 million mph
- **Wavelength** ( $\lambda$ ) - distance between **crests** of the EM wave (meters)
- **Frequency** ( $\nu = c/\lambda$ ) - number of crests that passes a given point each second (Hz)
- **Energy:**  $E = h\nu$  (ergs)
  - Planck's constant:  $h = 6.62607015 \times 10^{-34} \text{ m}^2 \text{ kg / s}$

**Blackbody radiation** - radiation emitted by matter in thermal equilibrium (same **temperature** throughout)

- **Planck blackbody spectrum:**

$$I_{\nu} = B_{\nu}(T) = \frac{2h\nu^3/c^2}{e^{h\nu/kT} - 1}$$

- **Wien displacement law:**

$$\lambda_{\text{peak}} T = 0.290 \text{ cm K}$$

- **Stefan Boltzmann law - total flux:**

$$F = \sigma T^4, \sigma = 5.670374419 \times 10^{-8}$$

$$\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$$

## Geometric Optics and Telescopes

- **Geometrical/Ray Optics** - describes light using 'rays' pointing in the direction of travel
  - **Law of reflection** - the angle of incidence of a ray is equal to angle of reflection

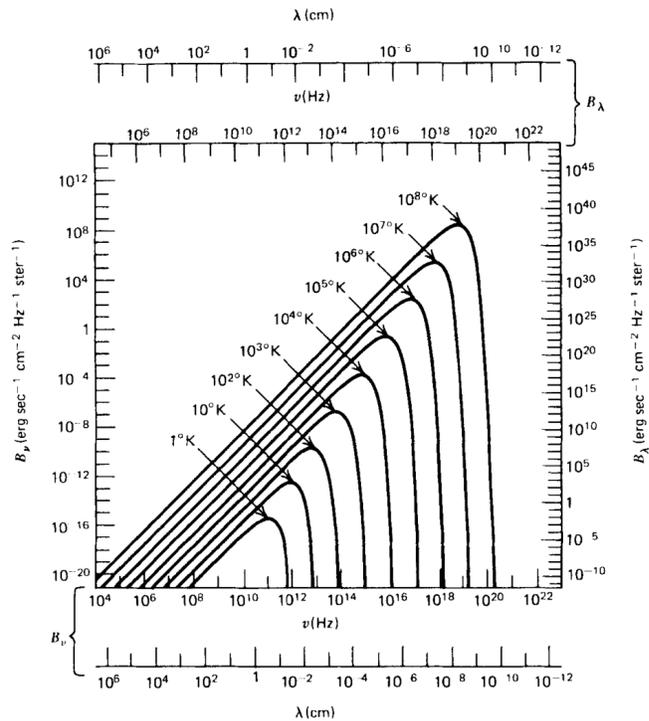
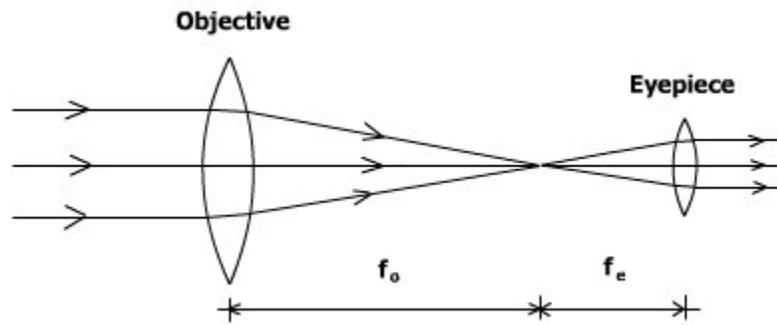


Figure 1.11 Spectrum of blackbody radiation at various temperatures (taken from Kraus, J. D. 1966, Radio Astronomy, McGraw-Hill Book Company)

- **Refraction** - light rays travel at different **speeds** in different materials, causing light to **bend** when passing from one **medium** (e.g. air, water, vacuum) to another
  - **Index of refraction**:  $n = c/v$  = speed of light in vacuum divided by the speed of light in the **medium** (glass, water, air, etc.)
  - **Snell's Law of refraction** - light rays bend **towards** the normal when going from a material with smaller **index of refraction** to larger index of refraction :  $\frac{\sin\theta_a}{\sin\theta_b} = \frac{n_b}{n_a}$

- **Refractive telescopes**

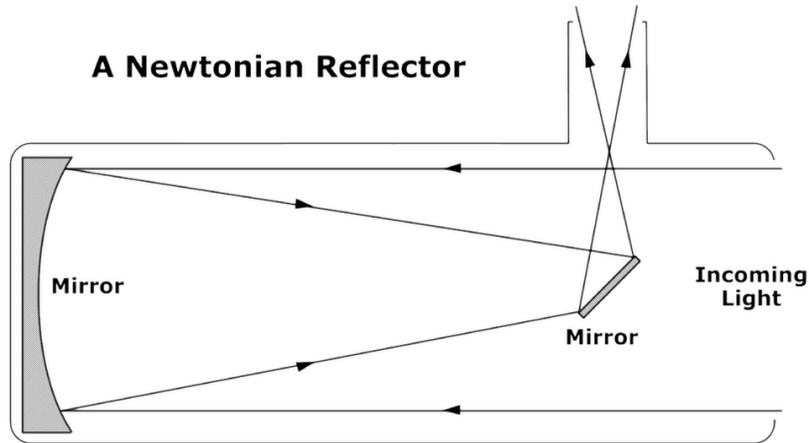
- **Convex lens** - converging, bends rays toward a single **focal point**
- **Concave lens** - diverging, bends rays away from a focal point; image appears to come from behind the lens
- **Focal length** - distance from the lens to the focal point
- A telescope places two lenses with different **focal lengths** such that they have the same **focal point**



- **Magnification** - ratio of objective focal length to the eyepiece focal length
- But refractive telescopes are limited due to **chromatic aberration**, **manufacturing difficulties**, and **warping**

- **Reflective telescopes**

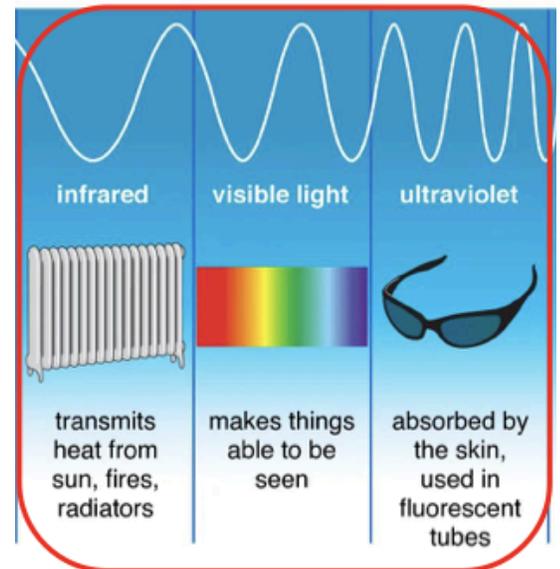
- **Convex mirror** - reflects light towards focal point in front of mirror
- **Plane mirror** - reflects light at the angle of incidence
- **Concave mirror** - reflects light away from focal point behind mirror



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- **Adaptive optics** - mirror is composed of segments with actuators to adjust to atmospheric conditions
- **Charge-Coupled Devices (CCDs) and Complementary Metal-Oxide Semiconductor (CMOS) Detectors** - use the photoelectric effect to raise electron energies when photons hit
- **Point-spread function** - spatial response of the detector due to the aperture size ; single lens makes an Airy function PSF (“spherical aberration”)

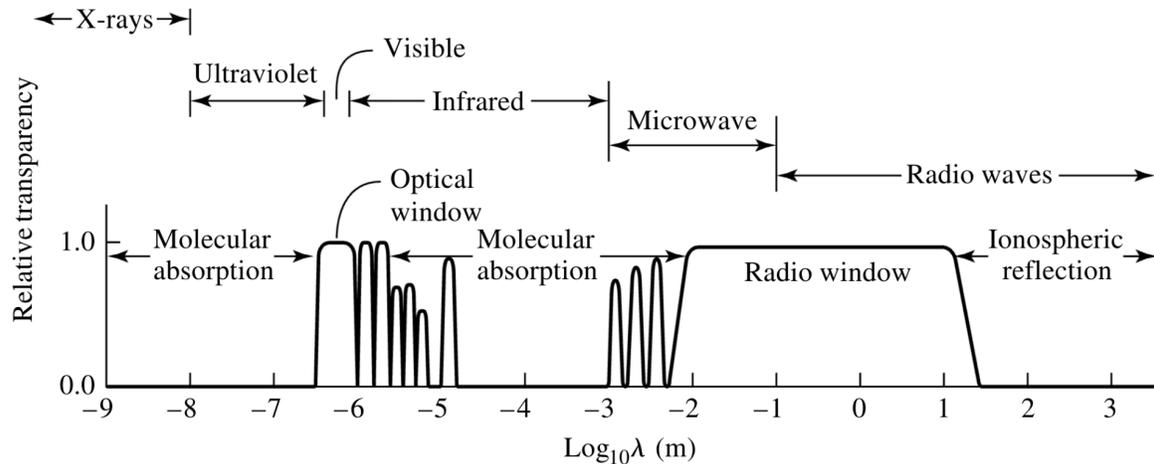
## Optical, Infrared (IR), and UltraViolet (UV) Astronomy

- **Photometry** - process of measuring brightness
  - **Magnitude (flux)** - brightness measured over specific wavelength range
  - **Color index** - difference in magnitude between two filters, which can tell us about the temperature and chemical composition of a star



Johnson (UBVRI)	Kron-Cousins (UBVRI)	Thuan-Gunn (uvgrI)	UKIDSS (ZYJHK)
Ultraviolet (U): 331-399 nm Blue (B): 391-389 nm Visual (V): 505.6 - 595.6 nm	Ultraviolet (U): 325-395 nm Blue (B): 390-490 nm Visual (V): 505 - 595 nm Red (R): 600 nm - 700 nm Infrared (I): 725 - 875 nm	Ultraviolet (U): 333-373 nm Blue (B): 378-418 nm Visual (V): 458-528 nm Red (R): 610 nm - 700 nm Infrared (I): 755 - 885 nm	Z: 836-929 nm Y: 979-1081 nm J: 1169- 1328 nm H: 1492-784 nm K: 2029-2380 nm

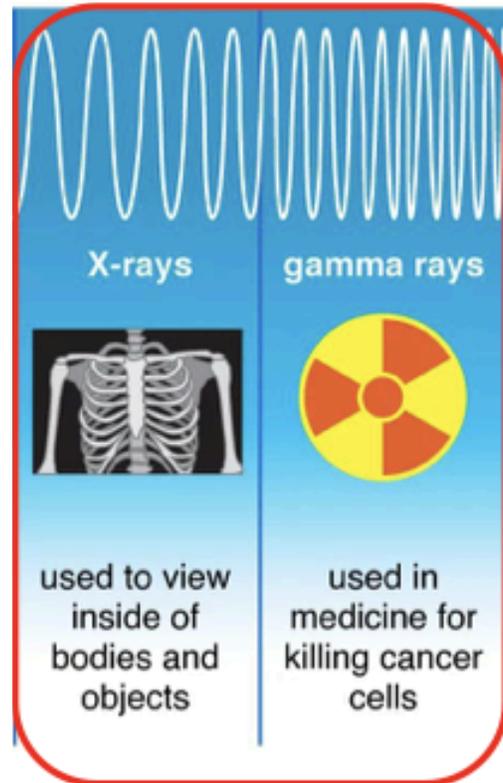
- Telescopes typically have their own set of **filters** with sensitivity that varies across the band (**bandpass/throughput**)
- **Kirchoff's laws:**
  - (1) a perfect **blackbody** has continuous spectrum with no spectral lines
  - (2) **hot diffuse** gas produces bright **emission lines** at individual wavelengths
  - (3) **cool dense** gas in front of continuous spectrum source produces dark **absorption lines** at individual wavelengths
- **Color-magnitude diagrams** are analogous to **Hertzsprung-Russel diagrams**, show stellar main sequence and evolution
  - **Temperature sequence** initially classified stars based on their spectra before associating them with temperatures (O, B, A, F, G, K, M)
  - Temperatures create different absorption and emission spectra because electrons occupy different orbitals in their atoms
- **Spectroscopy** - measuring chemical composition from emission and absorption lines
  - **Dispersion** - splitting light into its component wavelengths/frequencies
  - **Prism** - disperses light using the frequency-dependence of a material's index of refraction
  - **Diffraction** - constructive and destructive **interference** of light through **superposition** from multiple sources or light travelling through multiple pathways/slits
    - **Since constructive and destructive interference depend on the wavelength, light of different colors will interfere for different path length differences**
  - **Diffraction grating** - mirror or lens with closely spaced lines or slits which causes incident light to diffract
  - Different wavelengths have maxima at different angles, so they separate out and can be reflected onto a CCD/CMOS detector, creating a **spectrograph**
  - **Resolving power/resolution** - minimum wavelength difference that can be distinguished by diffraction grating:  $R = \frac{\lambda}{\Delta\lambda} = Nm$  where N is the number of slits and m is the maximum used
- **Atmospheric windows** - wavelength ranges that pass through the atmosphere without scattering or absorption



**FIGURE 6.25** The transparency of Earth's atmosphere as a function of wavelength.

## X-ray and Gamma-Ray Astronomy

- Astrophysical sources produce such small numbers of photons that X-ray and gamma ray telescopes detect **single-photons** with CCD or CMOS detectors
  - **X-rays:** 100 eV - 100 keV
    - **Soft x-rays :** < 500 eV
    - **Hard x-rays:** >500 eV
  - **Gamma Rays:** 100 keV - 1000 TeV
  - **Grazing incidence** - X-rays and Gamma rays would pass through mirrors if they impact them directly, so instead we focus light using mirrors at incidence angles close to **90 degrees**
  - **Bragg spectrometry** - uses Bragg scattering of X-rays on **crystal** lattice to disperse X-ray light into a spectrum; similar to single-slit, but slit width is the distance between atoms (~0.1 nm)
  - **Scintillometry** - gamma rays incident on scintillating material (e.g. crystallines like sodium iodide (NaI) or bismuth germanate (BGO)) excites molecules, which emit visible light when they de-excite, which is detected by **photomultiplier**



**tubes (PMTs;** amplify visible light signal by releasing electrons at initial cathode which are accelerated towards positively charged dynodes and release more electrons as they collide with each, which are finally read out as an electric current)

- **Supernovae** - explosions release energy as radio, optical, IR, and gamma rays
  - **Superluminous Supernovae** - result from NS-NS or BH-NS merger
  - **Gamma-ray bursts** - extremely bright bursts of gamma-rays lasting seconds at a time, thought to result from SLSNe in other galaxies
- **Pulsars** - neutron stars with strong magnetic fields that produce radio, gamma ray, x-ray emission from their magnetic poles
  - Exact emission mechanism is still unknown, but likely results from charges accelerating and radiating coherently in the neutron star's **magnetosphere**
- **X-ray binaries** - as a black hole or neutron star in a binary star accretes from its stellar companion, gravitational energy is released as x-rays
  - *Strongly magnetized neutron star primary* => accreted material diverted to poles and x-ray jets are released from the poles
  - *Weakly magnetized neutron star primary* => accretion disk collides with NS surface and releases energy as x-rays
  - *Black hole* => x-rays from viscous heating of the inner disk