# Welcome to Phys 321
# Astronomy & Astrophysics II

Course Instructor:

Prof. Bin Chen

Tiernan Hall 101

bin.chen@njit.edu

# NJIT Astronomy Courses

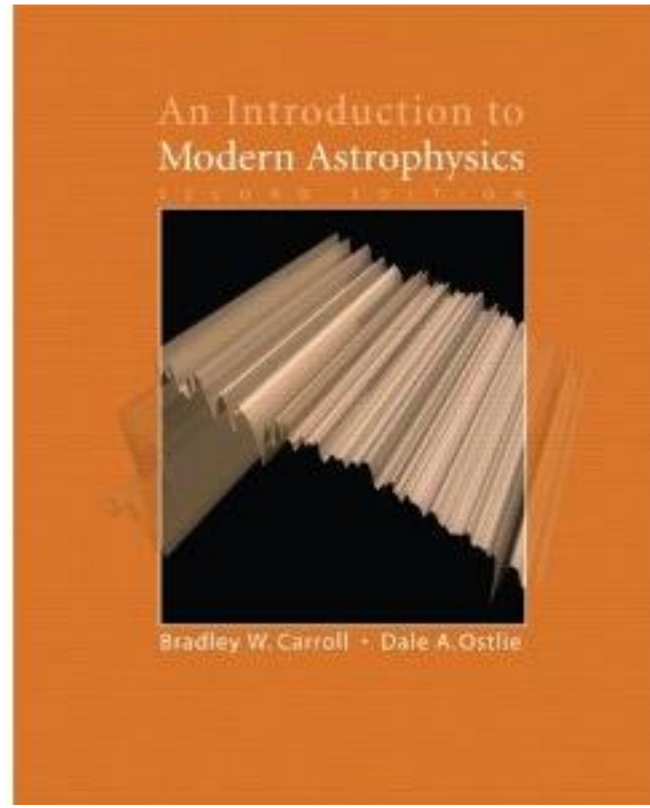
- The Physics Department has an **undergraduate minor and a concentration in Astronomy**, which includes the following courses:
  - Phys 202, 202A – Intro to Astronomy and Cosmology
  - Phys 203, 203A – The Earth in Space
  - Phys 320 – Astronomy & Astrophysics I (last semester)
  - **<u>Phys 321 – Astronomy & Astrophysics II (this course)</u>**
  - Phys 322 – Observational Astronomy
  - Phys 420 – Special Relativity
  - Phys 421 – General Relativity
  - Phys 444 – Fluid and Plasma Dynamics

# Course Theme

- Use the physical laws and forces that govern our everyday lives
  - Gravity, electricity & magnetism…
- To understand the cosmos
- Use physics and math to quantitatively determine the physical properties of astrophysical objects
  - Planets, stars, galaxies, clusters of galaxies, and the Universe

# Course Information: Material

- MW 11:30 am–12:55 pm. KUPF 208
- Textbook: "**An Introduction to Modern Astrophysics**", 2nd Edition, by Carroll and Ostlie (the same book as Phys320)
- Topics include stars, galaxies, and the Universe
- Discussed in chapters 3, 5, 8, 9, 10, 12, 13, 15, 16, 17, 18, 24, 25, 26, 27, 28, and 29 of the textbook.



# Science and Math Disclaimer

- This is astrophysics course using quantitative methods, NOT just general descriptive astronomy
- We use mostly freshman/sophomore physics (physics I, II, III) and calculus
- We will also introduce some very basic quantum physics and relativity
- Be prepared for quite some computation in HWs, quizzes, and exams

# Course Information: Homework

- About one set a week, given after the lecture
- Okay to work in **small** groups (<=2). But must be open and acknowledge who you have worked with. In all cases, you have to write answers clearly in your own words.
- Due in a week (the following Monday/Wednesday) at the **start** of the class
- **Late** submissions will have grades **reduced by 50%**. All assignments **must** be turned in by **the last class** to receive any credit.

# Class Information: Grading

- Homework (20%)
- Class participation and final presentation (20%)
- Two in-class exams (15% each, 30% total)
- Final Exam (30%)
- Conversion chart to letter grade

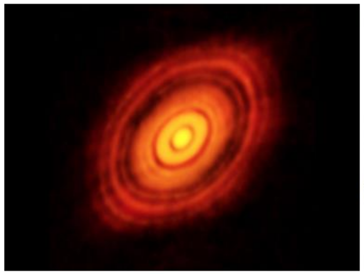
| | |
|---|---|
| **A** | **>85** |
| **B+** | **>75-85** |
| **B** | **>65-75** |
| **C+** | **>55-65** |
| **C** | **50-55** |
| **D, F < 50** | |

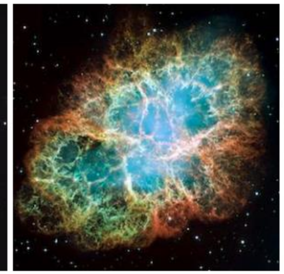
# Final presentation

- Team of 2; Each presentation 20-40 min (depending on 1 or 2 classes we can use toward the end)
- Select any topic in astronomy
  - Objects: Red giants, neutron stars, black holes, accretion disks, exoplanets…
  - Processes: stellar evolution, star/planet formation, merging galaxies…
  - Phenomena: supernovae, gamma-ray bursts, fast radio bursts, gravitational waves…
- Presentation content
  - Basic background introduction of the topic
    - What is it?
    - Fun facts?
    - History
  - What has been understood on this topic?
    - Observational facts
    - Theoretical model
  - Problems/questions that have not been solved
  - Perspectives in the future

Course Website: https://web.njit.edu/~binchen/phys321

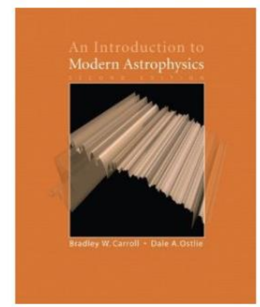
# PHYS 321 - Astronomy & Astrophysics II Spring 2019





## Course Information

- **Instructor:** Prof. Bin Chen
- **Email:** bin.chen at njit dot edu
- **Class Time:** Tuesdays and Thursdays 02:30 pm—03:50 pm
- **Classroom:** Kupfrian Hall, Room 203
- **Office Hours:** Tuesdays 01:00-02:00 pm, in Tiernan Hall Room 101
- **Textbook:** Introduction to Modern Astrophysics, 2nd Edition, Carroll & Ostlie (same textbook as Phys 320).
- **Homework:** Assigned approximately every week. Collected at the *beginning* of the lecture in the following week.
- **Exams:** Two in-class exams and one final exam.
- **Grades:** Your grade will be based on your homework (20%), class participation and presentations (20%), two in-class exams (15% each, 30% total), and final exam (30%).
- **Syllabus**: Download PDF




## Course Schedule and Lecture Notes

(subject to change during the semester; please check regularly)

| WEEKS | | TOPICS | TEXT STUDIES | HOMEWORK ASSIGNMENT |
|---|---|---|---|---|
| Week 1: | 1/21 | Light, Blackbody Radiation, and Color Index | Chapt 3, Section 3, 4, 5, 6 | TBD |
| Week 2: | 1/28 | The Interaction of Light and Matter | Chapt 5 | TBD |
| Week 3: | 2/4 | Stellar Spectra and H-R Diagram | Chapt 8 | TBD |

# Phys 321: Lecture 1

## Light, Blackbody Radiation, Color Index

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# Outline

- The Wave nature of light (3.3)
- Blackbody radiation (3.4)
- The quantization of energy (3.5)
- The color index (3.6)

# The Wave Nature of Light

- In 1600s, Isaac Newton believed that light consists of a rectilinear stream of particles
- Christian Huygens proposed that the light must consist of waves
- If light = waves:
  - It has a wavelength of $\lambda$ and frequency of $\nu$
  - Light travels at $c = 2.99792458 \times 10^{8}$ m $s^{-1}$

$$\boxed{c = \lambda \nu.}$$

# Young's double-slit experiment

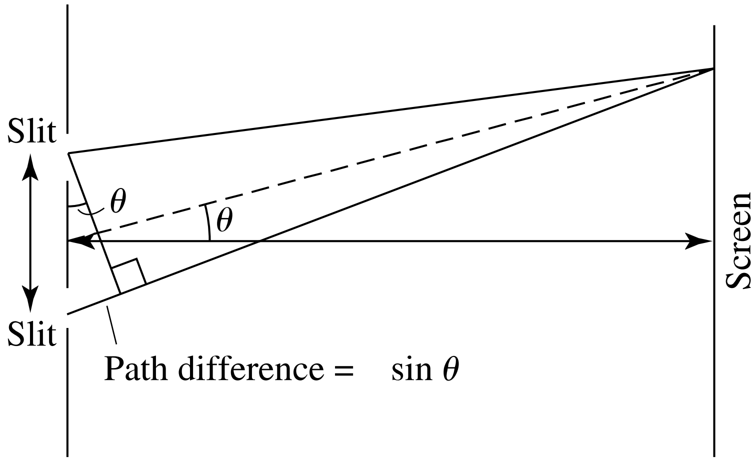
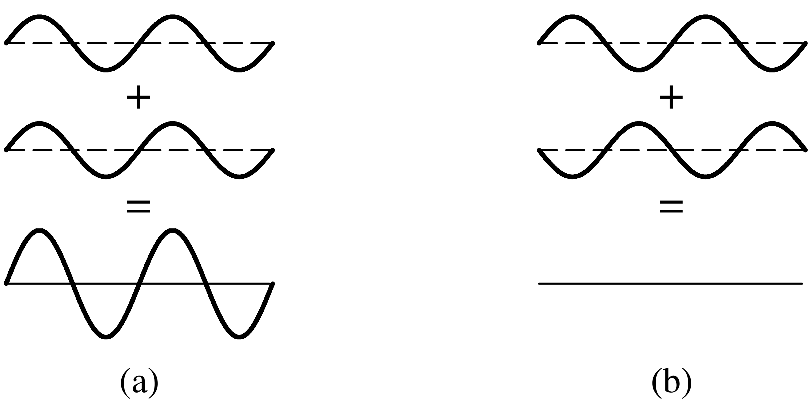



**FIGURE 3** Double-slit experiment.

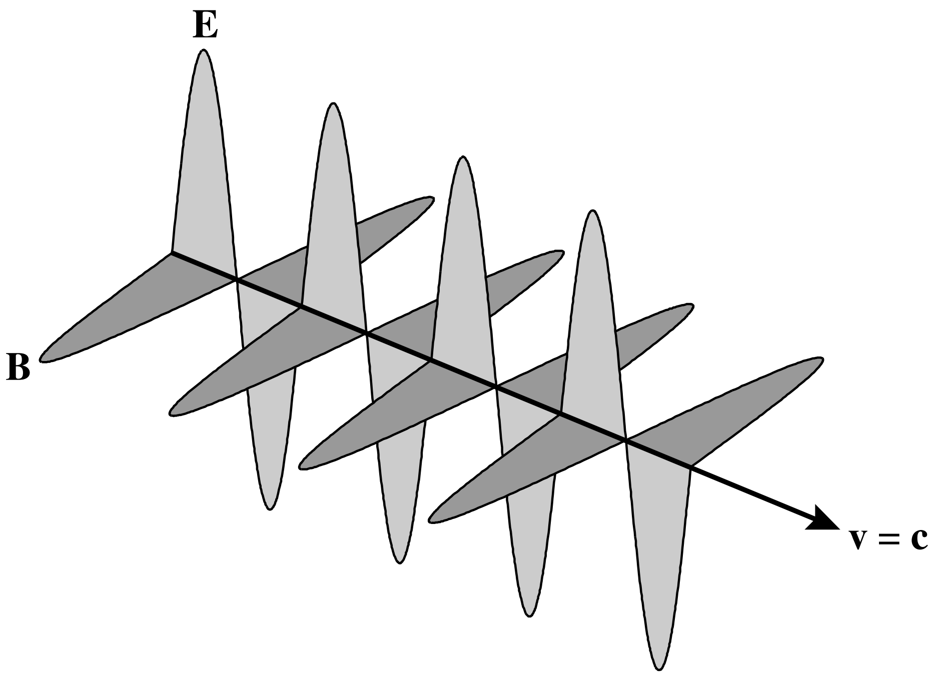



Bright Fringes

$$d \sin \theta = \begin{cases} n\lambda \\ \left(n - \frac{1}{2}\right)\lambda \end{cases}$$

Dark Fringes

# Maxwell: Light = Electromagnetic Waves




**E ⊥ B**

**Poynting Flux**: $\mathbf{S} = \frac{1}{\mu_0}\mathbf{E} \times \mathbf{B},$

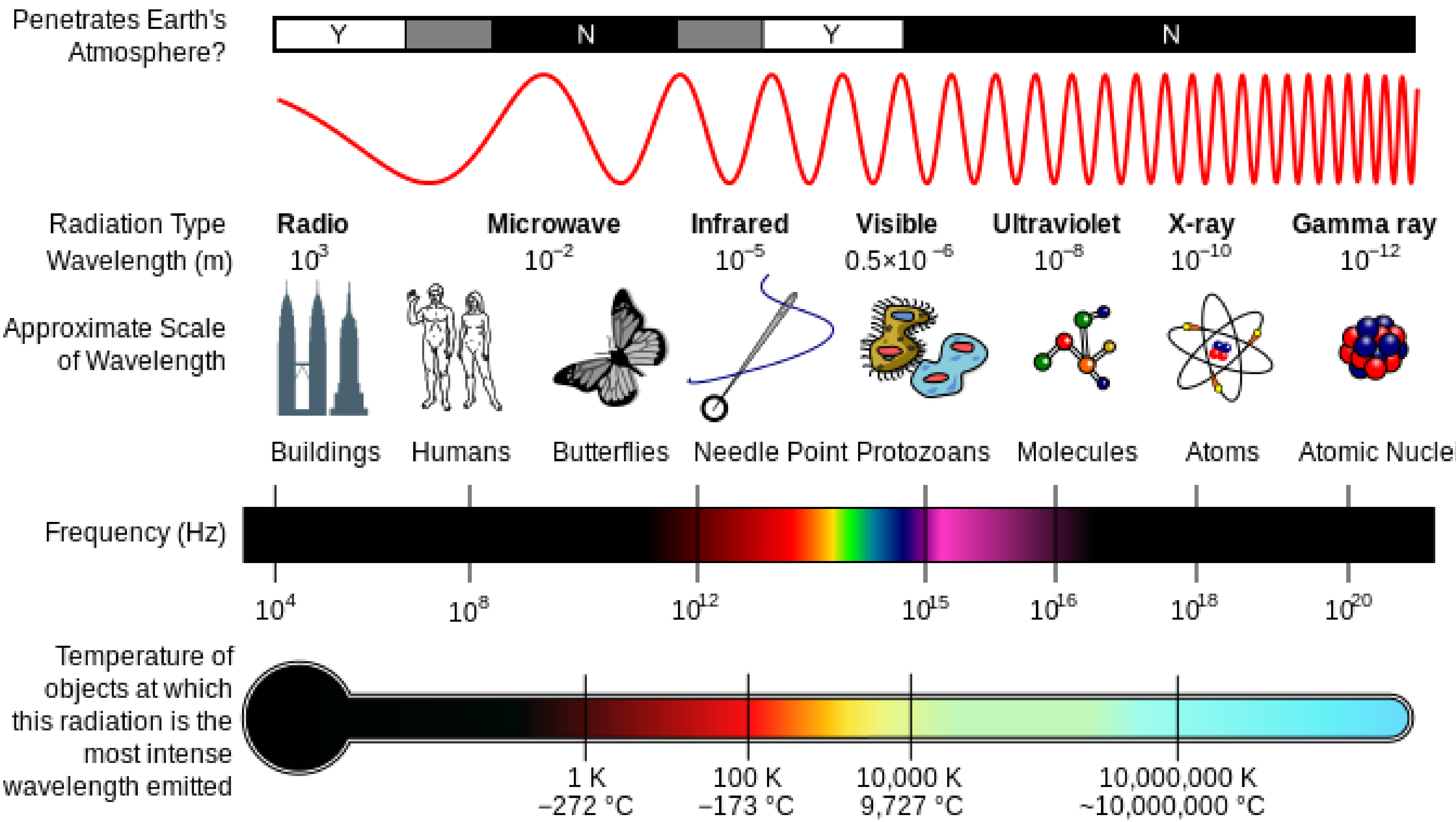
Time-averaged **Poynting Flux**:

$$\langle S \rangle = \frac{1}{2\mu_0} E_0 B_0$$

This is the **flux** (unit: W $m^{-2}$) carried by a light wave at a *single wavelength* (monochromatic wave)

The flux **F** we discussed before is the result of ***integration over all wavelengths***

# The Electromagnetic Spectrum




From Wikipedia

# Color and Temperature

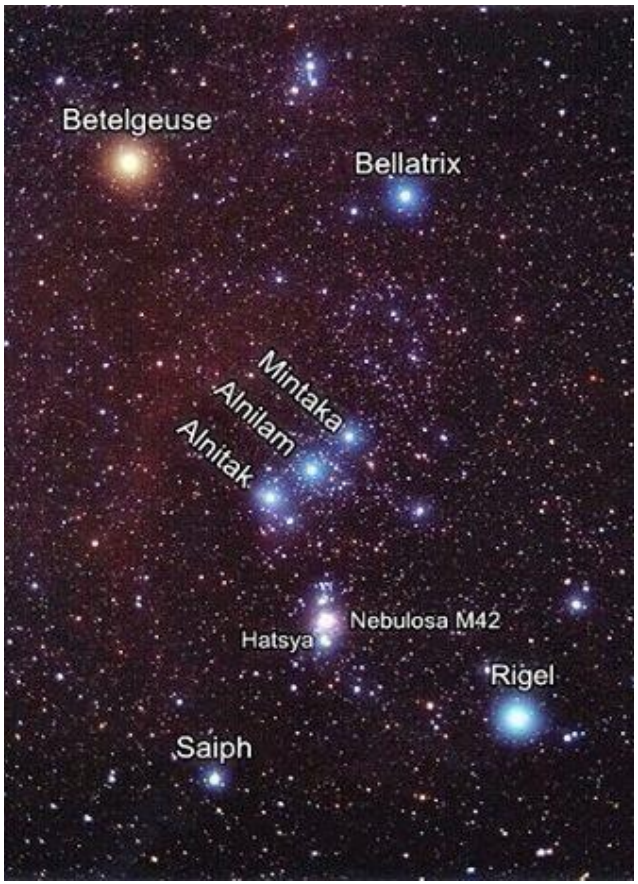
A “red-hot” nail

| Temperature (°C) |
|---|
| 550 |
| 630 |
| 680 |
| 740 |
| 770 |
| 800 |
| 850 |
| 900 |
| 950 |
| 1000 |
| 1100 |
| 1200 |
| 1300 |

Which part of the nail is hotter?

# Color and Temperature: Stars

**Constellation Orion**

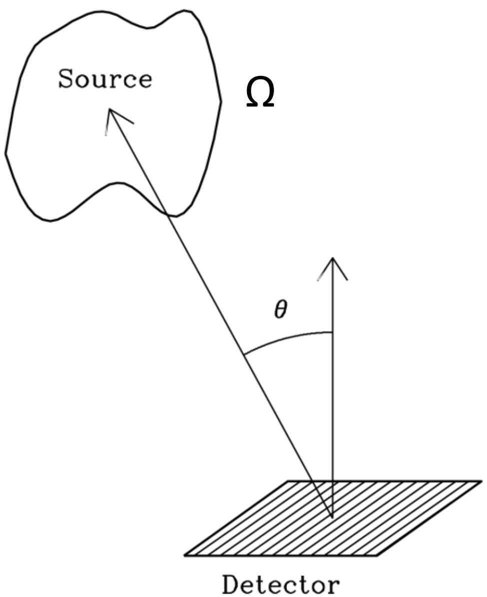



Which star is the coolest?

| Color | Example | Surface Temperature (ºC) |
|---|---|---|
| | Rigel (Orion) | 28,000–11,000 |
| | Sirius (Canis Major) | 11,000–7,500 |
| | Sun & Capella (Auriga) | 6,000–5000 |
| | Aldebaran (Taurus) | 5,000–3,600 |
| | Betelgeuse (Orion) | 3,600–2,000 |

Red to blue **-> increasing** temperature

# Intensity vs. Flux




- Flux ***F***: energy received in a unit time through a unit surface area from all directions
  - unit W m$^{-2}$

- Intensity ***I*** accounts for both the direction and size of the source, so it is the energy received per unit time per unit surface area (along the direction of the light ray) per unit solid angle, in language of calculus

$$dE = I\cos\theta\, dA\, dt\, d\Omega$$

  - It is **independent of distance** (why?)
  - It is **the same at the source and detector**

- The flux ***F*** is an integration of intensity ***I*** over solid angle

$$F = \int_{source} I(\theta,\phi)\cos\theta\, d\Omega = \int_{source} I(\theta,\phi)\cos\theta\sin\theta\, d\theta\, d\phi$$

# Specific intensity and flux density

- ***I*** and ***F*** are quantities **integrated over all wavelengths**
- Light emitted from stars distribute over the entire electromagnetic spectrum
- **Specific intensity** $I_\lambda$ or $I_\nu$ and **flux density** $F_\lambda$ or $F_\nu$ are intensity and flux within given a wavelength range or frequency range ($\lambda$ to $\lambda + d\lambda$, or $\nu$ to $\nu + d\nu$)

Specific intensity (per wavelength)
Unit: J s$^{-1}$ m$^{-2}$ sr$^{-1}$ m$^{-1}$

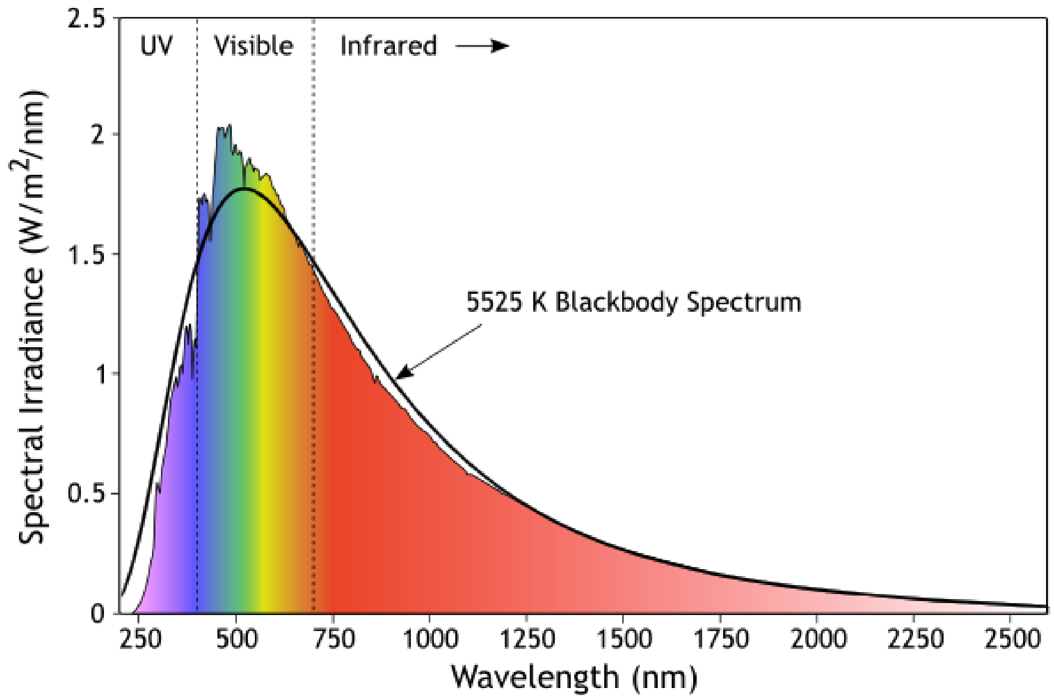
$$dE = I_\lambda \cos\theta \, dA \, dt \, d\Omega \, d\lambda$$

Flux density (per wavelength)
Unit: J s$^{-1}$ m$^{-2}$ m$^{-1}$

$$F_\lambda = \int_{source} I_\lambda(\theta, \phi) \cos\theta \, d\Omega$$

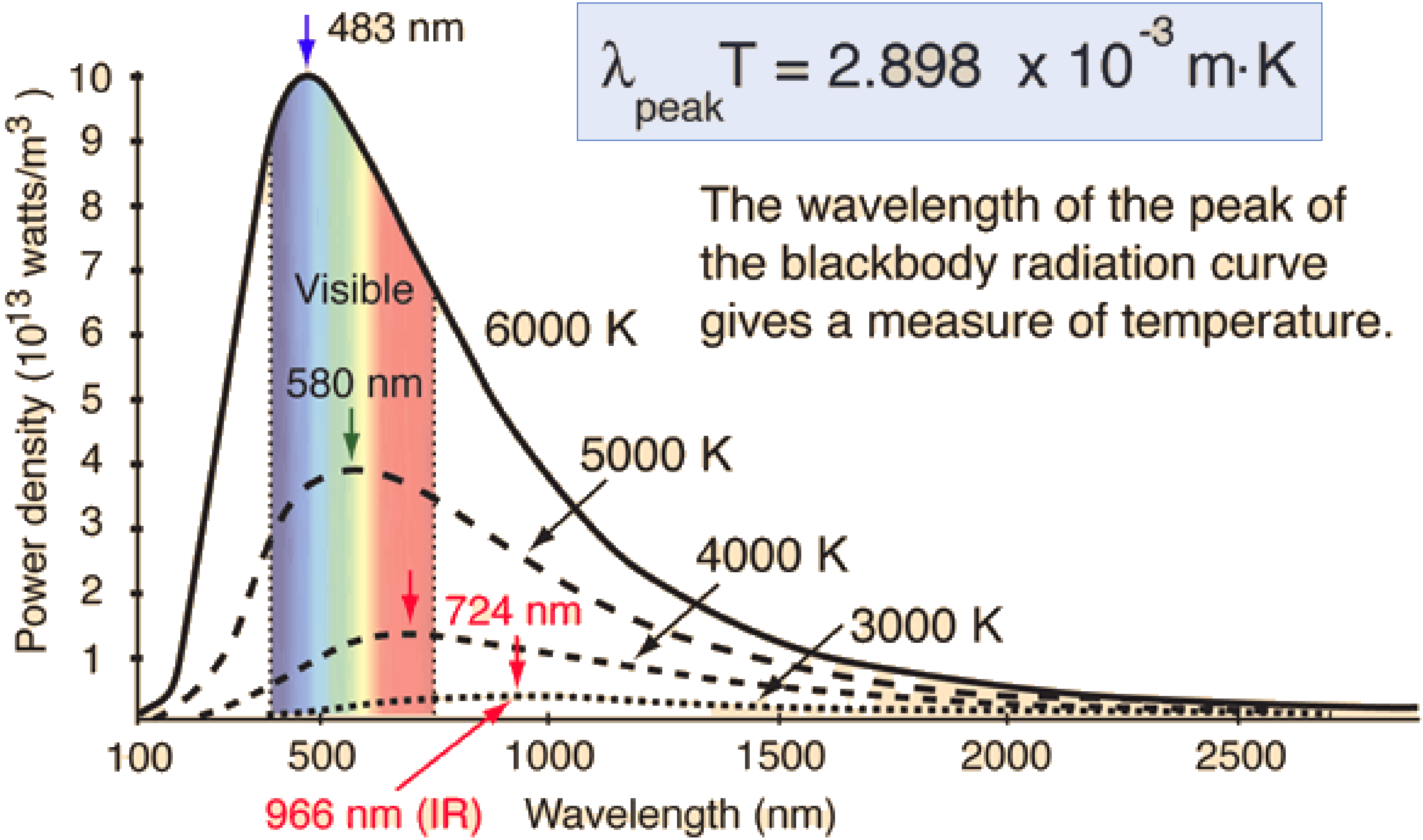
# Blackbody

- Is an idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency and angle of incidence, and reradiates all the energy with a characteristic spectrum.
- Is black hole a blackbody?
    - Yes, if Stephen Hawking is correct on his “Hawking Radiation”




Solar irradiance at Earth (no atmosphere)

# Wien's Displacement Law




$$\lambda_{peak} T = 2.898 \times 10^{-3}\ \mathrm{m \cdot K}$$

The wavelength of the peak of the blackbody radiation curve gives a measure of temperature.

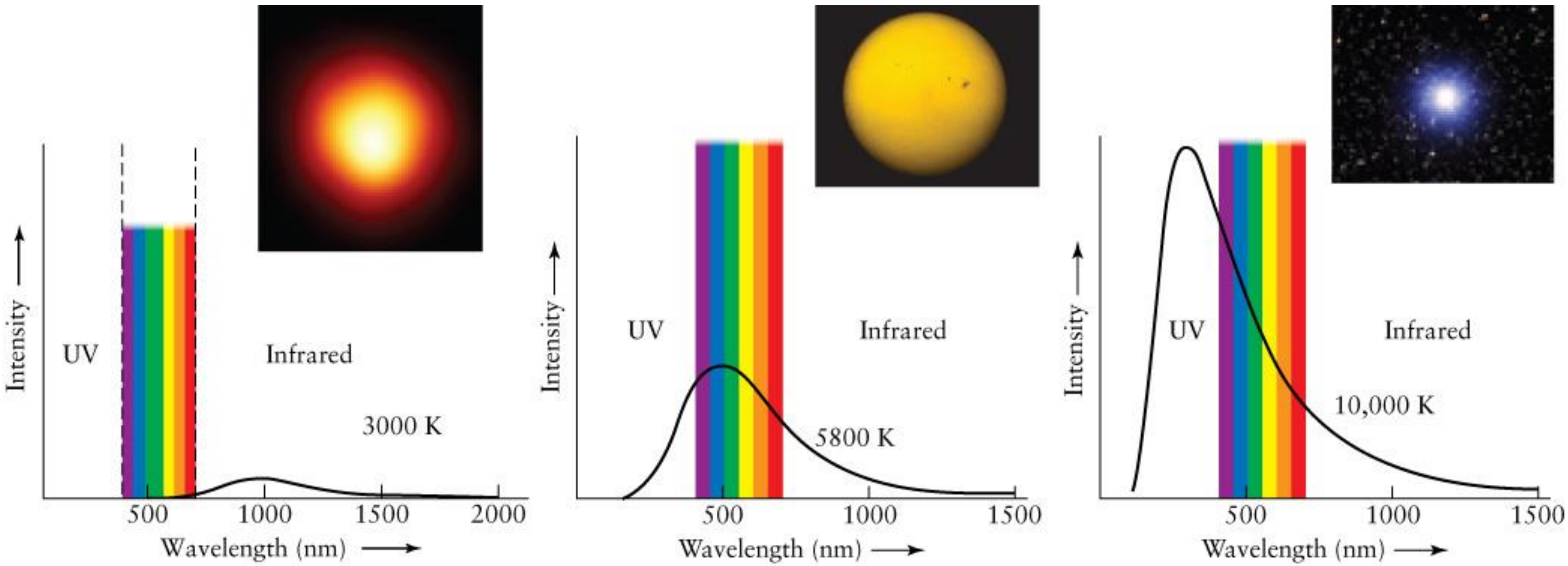
# Example: Peak wavelength of Betelgeuse and Rigel

- Betelgeuse and Rigel have surface temperature of 3,600 K and 13,000 K. What are their peak wavelengths? In which region of the electromagnetic spectrum?

Betelgeuse: $$\lambda_{\mathrm{max}} \simeq \frac{0.0029\ \mathrm{m\ K}}{3600\ \mathrm{K}} = 8.05 \times 10^{-7}\ \mathrm{m} = 805\ \mathrm{nm}$$ Infrared

Rigel: $$\lambda_{\mathrm{max}} \simeq \frac{0.0029\ \mathrm{m\ K}}{13{,}000\ \mathrm{K}} = 2.23 \times 10^{-7}\ \mathrm{m} = 223\ \mathrm{nm}$$ Ultraviolet

# Color of stars




(a) A **cool star** with surface temperature 3000 K emits much more red light than blue light, and so appears red.

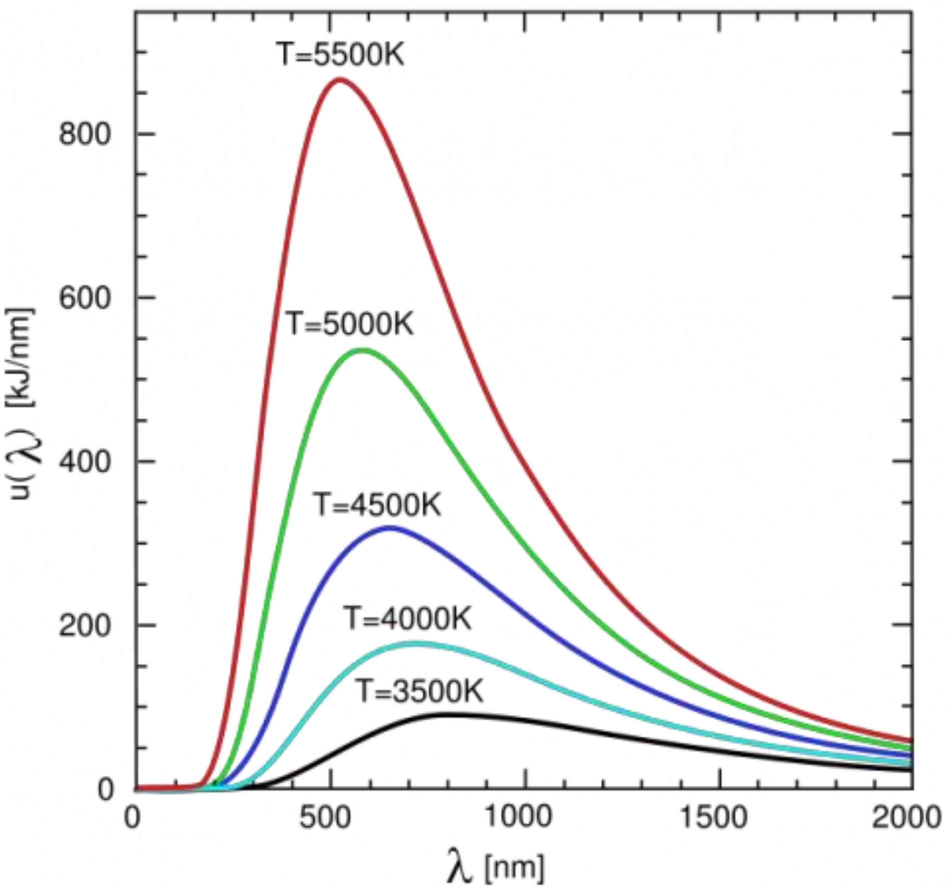
(b) A **warmer star** with surface temperature 5800 K (like the Sun) emits similar amounts of all visible wavelengths, and so appears yellow-white.

(c) A **hot star** with surface temperature 10,000 K emits much more blue light than red light, and so appears blue.

According to **Wien's law** …

- A ***low*** temperature star emits most of its energy at ***long*** wavelengths
- A ***high*** temperature star emits most of its energy at ***short*** wavelengths
- Thus, a ***cool*** star appears ***red***, while a ***hot*** one appears ***blue***

# Stefan-Boltzmann Equation




- T increases -> intensity increases at all wavelengths
- Experiment show that luminosity depends on temperature T and area A

**Stefan-Boltzamann Equation**

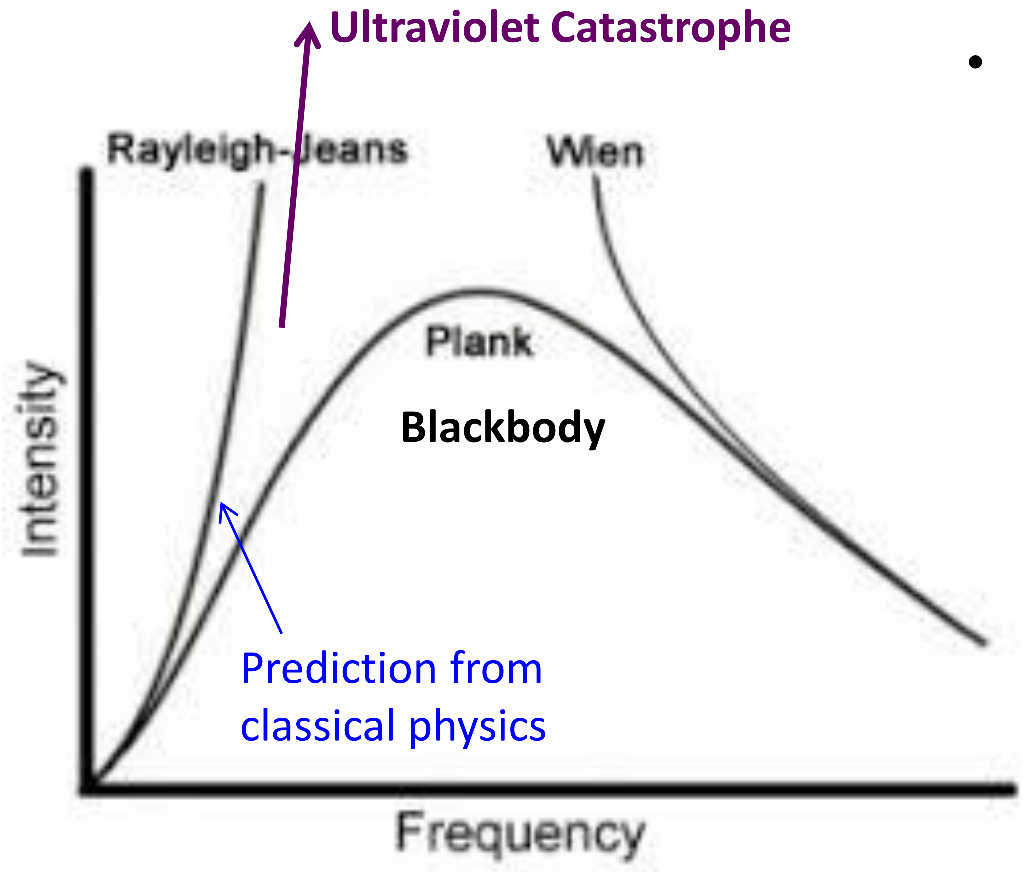
$$L = A\sigma T^4$$

Where

$$\sigma = 5.670400 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}.$$

Is the Stefan-Boltzmann constant

# The Nature of Light: Dawn of a New View




- Classical physics (thermal mechanics and Maxwell's equation) -> **Rayleigh-Jeans Law**

$$B_\lambda(T) \approx \frac{2ckT}{\lambda^4} \qquad B_\nu(T) \approx \frac{2\nu^2 kT}{c^2}$$

$B_\lambda$ : specific intensity from blackbody

$k = 1.38 \times 10^{-23}$ J K$^{-1}$: Boltzmann's constant

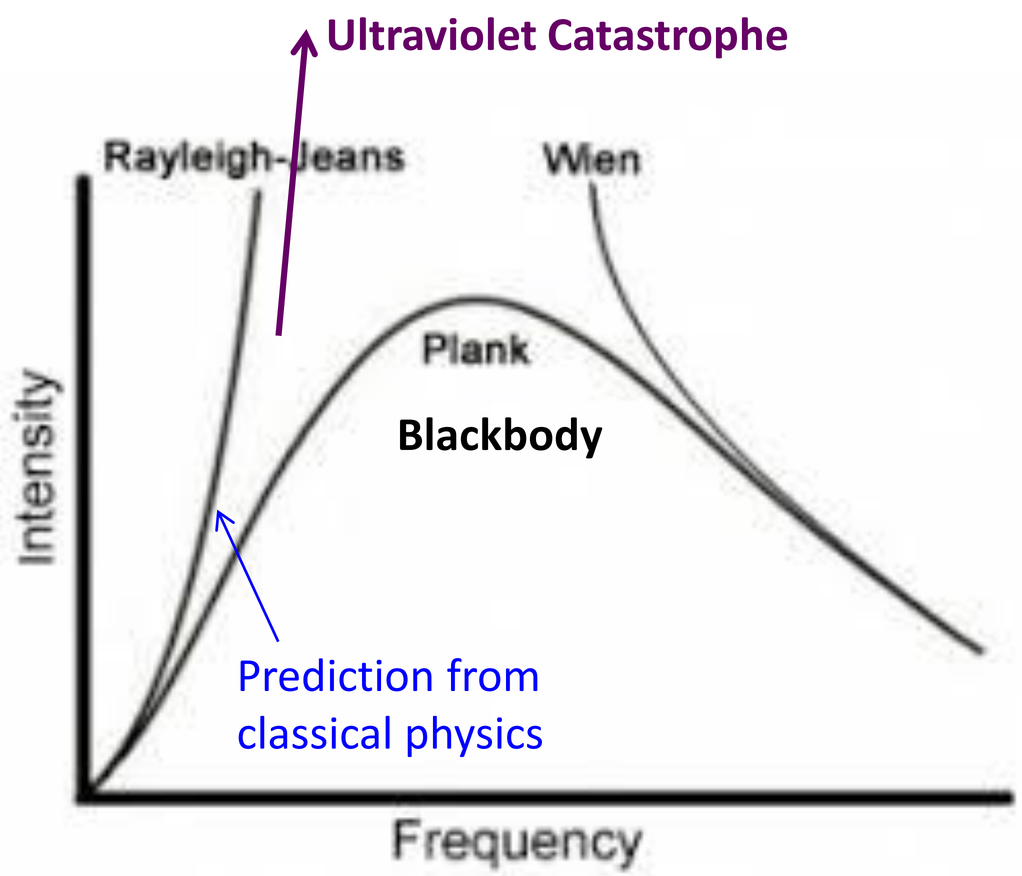
Only agrees well with the very low end of the blackbody spectrum (from experiments). At shorter wavelengths, $B_\lambda$ increases without limit

**Ultraviolet Catastrophe**

At high frequencies, an *empirical* relation is found from experiments named **Wien's Approximation**:

$$B_\lambda(T) \approx a\lambda^{-5} e^{-b/\lambda T}$$

# Classical physics goes terribly wrong at higher frequencies/shorter wavelengths!



# Photons: quantization of energy

- By late 1900, Max Planck tried to make sense of the blackbody spectra
- He assumes the allowed energy carried by any wave cannot be infinitely small, but should be an integer number of *hν,* or *hc/λ*, where *h* is a constant, i.e., the energy is **quantized**.
- This smallest, quantized energy *E* is carried by a type of elementary particles, known as **photons**. A single photon carries

$$E = hn$$

We will come back to this next week

# The Planck Function

- With quantized energy of light waves, Max Planck got the famous **Planck Function**:

Diff. in wavelength

$$\boxed{B_\lambda(T) = \frac{2hc^2/\lambda^5}{e^{hc/\lambda kT} - 1}.}$$

Diff. in frequency

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

**Long wavelength limit:**

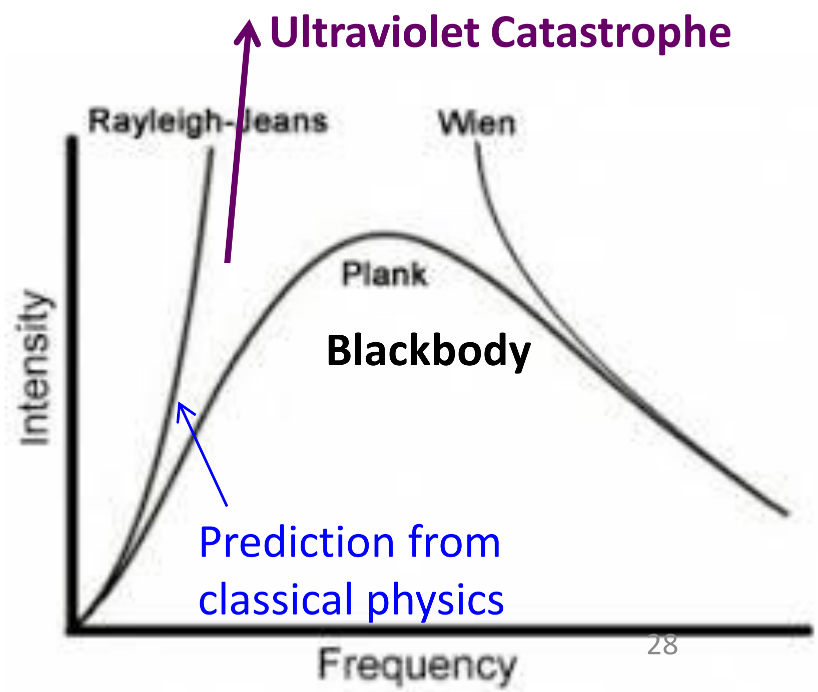
Rayleigh-Jeans Law

$$B_\lambda(T) \approx \frac{2ckT}{\lambda^4}$$

**Short wavelength limit:**

Wien's Approximation

$$B_\lambda(T) \approx a\lambda^{-5} e^{-b/\lambda T}$$



# The Planck Function and Astrophysics

- Most stellar spectra can be approximated by blackbody in general
- They emit nearly *isotropically*, i.e., independent of angle
- So the star's luminosity in a given frequency range $\nu \rightarrow \nu + d\nu$

Radius of the star

$$L_\nu d\nu = \int_{star} B_\nu \, d\nu \, dA \cos\theta \sin\theta \, d\theta \, d\phi = 4\pi^2 R^2 B_\nu d\nu$$

- Integrating $L_\nu d\nu$ over all frequencies, we recover the **Stefan-Boltzmann Equation**:

$$L = A\sigma T^4 = 4\pi R^2 \sigma T^4$$

A star's **luminosity** depends only on **radius *R*** and **temperature *T*** (if it is well approximated by a blackbody)

What is the luminosity of a star with a surface temperature of 12,000 K and a radius of $R_{sun}/2$? The Sun's surface temperature is approximately 6,000 K and its luminosity is $L_{sun}$

A. $L_{sun}/4$
B. $L_{sun}/2$
C. $L_{sun}$
D. $2\ L_{sun}$
E. $4\ L_{sun}$

# Recall from A&A I: Inverse Square Law

- The integrated flux (over all wavelengths), or “brightness”, decreases at greater distance following the *inverse square law:*

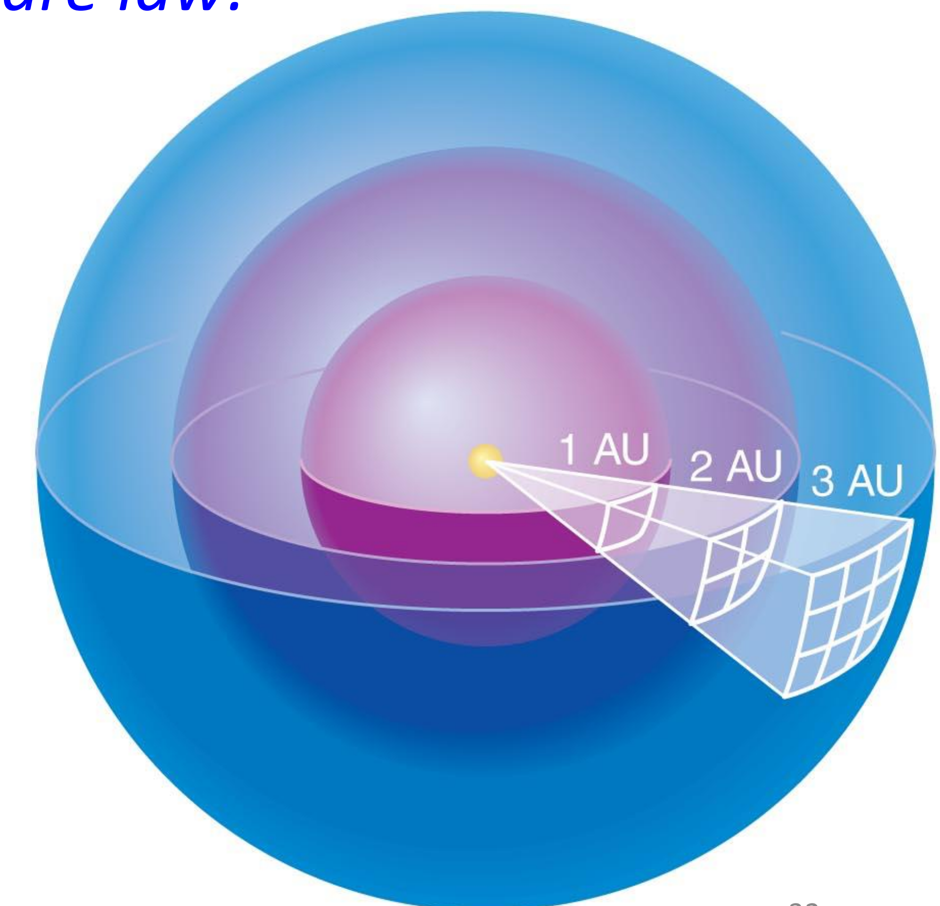
$$F\ \mu\ \frac{1}{d^2}$$

Why?

Energy is conserved!

The total amount of power passing through each sphere is the same

Area of sphere: $4\pi(\text{distance})^2$



# Luminosity and Flux

- The intrinsic "power" of the star is defined as the ***luminosity L,*** which is the total energy given off by the star per unit time (unit: J/s, or W)

For our Sun: $L_\odot = 3.839 \times 10^{26}\ \mathrm{W}$

- So, the flux is $\text{Flux} = \dfrac{\text{Luminosity}}{4\pi(\text{distance})^2}$

$$F = \frac{L}{4pd^2}$$

# The Planck Function and Astrophysics

- Flux received at a distance *d*

$$F = \frac{L}{4pd^2}$$ Where d is the distance to the light source

Substitute Stefan-Boltzmann’s Equation for stellar luminosity

$$L = 4pR^2 s T^4$$

We have

$$F = s T^4 \left( \frac{R}{d} \right)^2$$

# Revisiting Brightness and Magnitude

- Recall: A difference of 5 magnitudes, or $m_1$-$m_2$ = 5, corresponds to the smaller-magnitude star (with $m_2$) 100 times brighter in its apparent brightness than the larger-magnitude star (with $m_1$), or $F_2/F_1$=100
- It means:

$$\boxed{\frac{F_2}{F_1} = 100^{(m_1 - m_2)/5}.}$$

- Taking the logarithm of both sides

$$m_1 - m_2 = -2.5 \log_{10}\left(\frac{F_1}{F_2}\right)$$

# Absolute Magnitude M

- Apparent magnitude m depends strongly on distance – inconvenient to compare the intrinsic brightness among stars

$$F = \frac{L}{4pd^2}$$

$$\boxed{\frac{F_2}{F_1} = 100^{(m_1 - m_2)/5}.}$$

- We define ***Absolute Magnitude*** (M) of a star as the apparent magnitude the star would have if it were placed at a distance of 10 pc.

$$100^{(m-M)/5} = \frac{F_{10}}{F} = \left(\frac{d}{10\ \mathrm{pc}}\right)^2$$

# Distance Modulus

- From the expression of Absolute Magnitude

$$100^{(m-M)/5} = \frac{F_{10}}{F} = \left(\frac{d}{10\ \mathrm{pc}}\right)^2$$

- Take logarithm on both sides

$$m - M = 5\log_{10}\left(\frac{d}{10\,pc}\right)$$

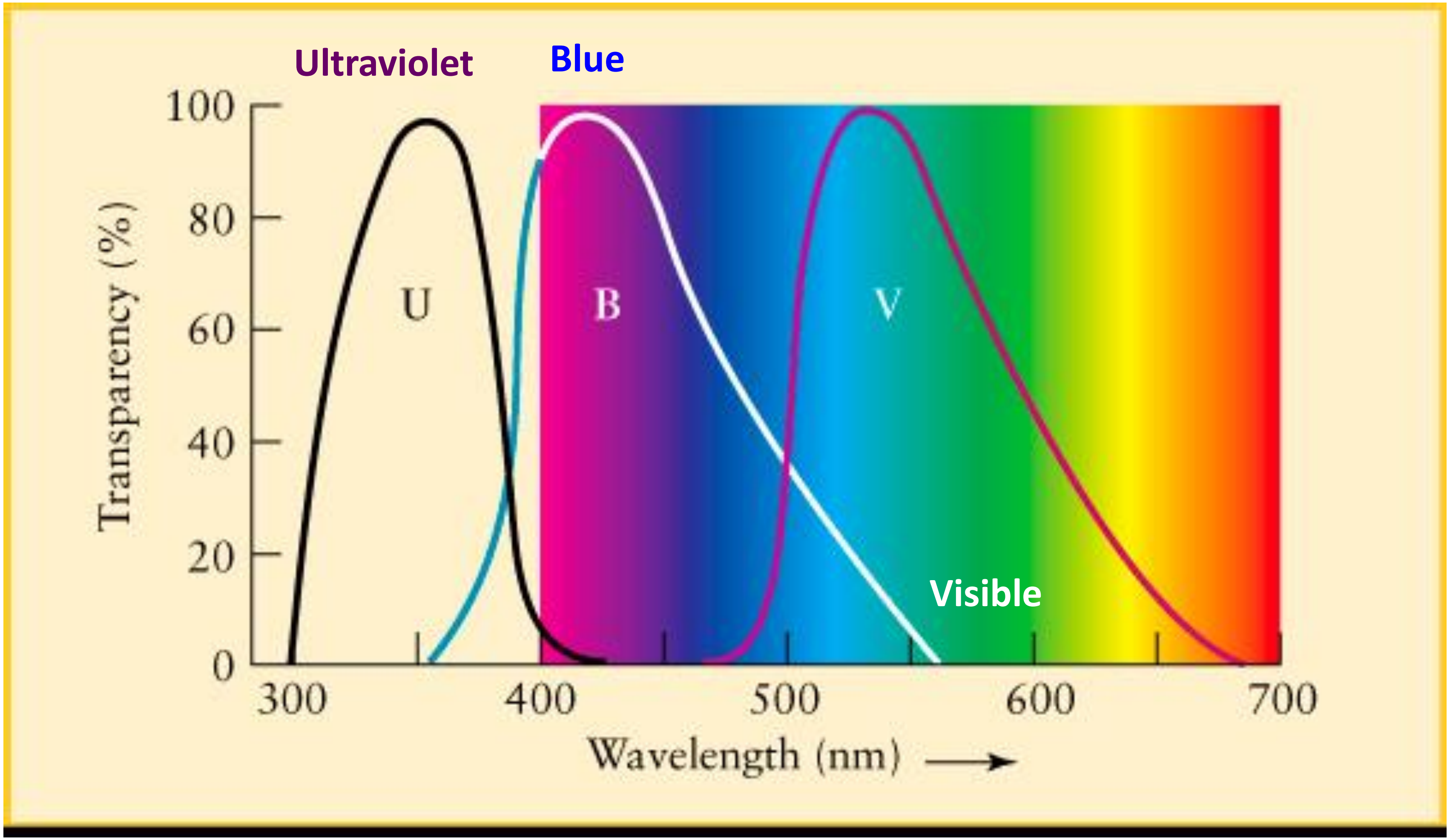
- The difference $m - M$ is a measure of the distance, called the ***distance modulus***
- Very useful in measuring distance if m is measured and M can be inferred (standard candles) –> this principle is the key in the discovery of ***the accelerating expansion of the Universe – 2011 Nobel Prize***

# Bolometric magnitudes

$$m_1 - m_2 = -2.5 \log_{10}\left(\frac{F_1}{F_2}\right) \qquad 100^{(m-M)/5} = \frac{F_{10}}{F} = \left(\frac{d}{10\ \mathrm{pc}}\right)^2$$

- The apparent and absolute magnitudes are values integrated over *the entire spectrum*, known as **bolometric magnitudes**, denoted by $m_{bol}$ and $M_{bol}$
- However, in practice, we usually only measure the flux of a star within certain wavelength ranges

# Color filters and UBV magnitude System



# UBV magnitudes

- **Apparent** bolometric magnitude

$$m_{\text{bol}} = -2.5 \log_{10}\left(\int_0^\infty F_\lambda \, d\lambda\right) + C_{\text{bol}}$$

- **Apparent** UBV magnitudes

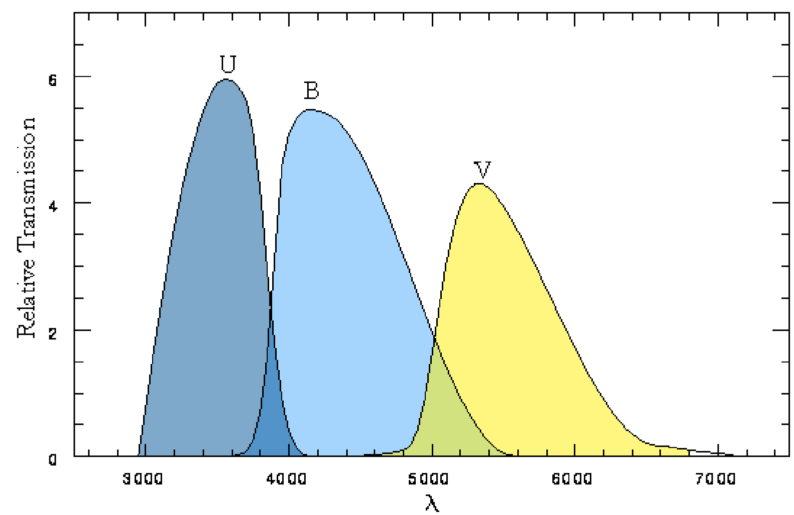
$$m_U = U = -2.5\log_{10}\left(\int_0^\infty F_\lambda S_U \, d\lambda\right) + C_U$$

$$m_B = B = -2.5\log_{10}\left(\int_0^\infty F_\lambda S_B \, d\lambda\right) + C_B$$

$$m_V = V = -2.5\log_{10}\left(\int_0^\infty F_\lambda S_V \, d\lambda\right) + C_V$$

Constants $C_u$, $C_B$, $C_V$ are chosen so that U, B, V of star Vega are all zero

$S_U$ $S_B$ $S_V$




Sensitivity Functions

# Color Indices

- A star's color index is the difference between the apparent magnitudes of two different color filters

$$U - B = m_U - m_B \quad = M_U - M_B$$

$$B - V = m_B - m_V \quad = M_B - M_V$$

These are ***independent of distance***!

$$m - M = 5\log_{10}\left(\frac{d}{10pc}\right)^2$$

# Bolometric correction

- Difference between a star's bolometric magnitude and its visual magnitude

$$\boxed{BC = \underset{\text{All wavelengths}}{\underset{\uparrow}{m_{\text{bol}}}} - \underset{\text{Visual}}{\underset{\uparrow}{V}} = M_{\text{bol}} - M_V\,.}$$

# Color Index and Surface Temperature

***Color indices*** tell us the ***colors*** of the star, which are related to their ***surface temperatures***

e.g., the ***smaller*** B-V index, the ***bluer*** the star, the ***hotter*** the star