The Continuous Spectrum of Light - Part II

Reading assignment for:

THURSDAY 9/24: Chapters 5.1, 5.2 (not in detail), 5.3, 5.4 (not in detail)

Homework assignment #1 due NOW

If the star is at a distance d from the instrument:

$$f_\nu = \frac{L_\nu}{4\pi d^2} = \frac{R^2}{d^2} F_\nu \qquad \left(\Longleftrightarrow f_\lambda = \frac{R^2}{d^2} F_\lambda \right)$$

$$L_\nu = 4\pi R^2 F_\nu$$

Incident energy flux on the detector
(a.k.a., apparent brightness)

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Incident energy flux on the detector
(a.k.a., apparent brightness)

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NOTE 1: this law is true only without interstellar absorption

NOTE 2: by measuring $\underbrace{d^2 f_\nu}_{\text{ONLY OBSERVED QUANTITIES}} \longrightarrow \underbrace{R^2 F_\nu}_{\text{ONLY PHYSICAL (INTRINSIC) QUANTITIES}}$

Assuming no interstellar absorption:

$$m_\nu = -2.5 \log f_\nu + C$$ monochromatic apparent magnitude

$$f_\nu = \frac{L_\nu}{4\pi d^2} \longrightarrow m_\nu = -2.5 \log \frac{L_\nu}{4\pi d^2} + C$$

i.e., the apparent magnitude depends on both the intrinsic luminosity and the distance of the star

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ABSOLUTE MAGNITUDE M: For an absolute comparison of intrinsic brightness, it is common to discuss the magnitudes of stars would have IF they were all at the same distance of d=10 pc, i.e., **M = m(@d=10pc):**

$$M_\nu := -2.5 \log \frac{L_\nu}{4\pi (10\,pc)^2} + c$$

$$M_\nu - m_\nu = -2.5 \log \frac{L_\nu}{4\pi(10\,pc)^2} + C + 2.5 \log \frac{L_\nu}{4\pi d^2} - C =$$

$$= \dots = 5 \log (10\,pc) - 5 \log d$$

$$\Rightarrow \boxed{M_\nu - m_\nu = 5 - 5 \log d[pc]}$$

$$m_\nu - M_\nu := \text{DISTANCE MODULUS} = 5 \log d[pc] - 5$$

$$m_{bol} = -2.5 \log \underbrace{\int_0^\infty f_\nu \, d\nu}_{\frac{L}{4\pi d^2} = \frac{4\pi R^2 \int_0^\infty F_\nu \, d\nu}{4\pi d^2} = \frac{R^2}{d^2} F} + C$$

$$M_{bol} := -2.5 \log L + C$$

$$M_{bol} - m_{bol} = 5 - 5 \log d[pc]$$

$$M_{bol} - M_{bol,\odot} = -2.5 \log \frac{L}{L_\odot}$$

$$M_{bol,\odot} = 4.74$$

$$m_\odot = -26.83$$

$$\boxed{M_{bol} = -2.5 \log \frac{L}{L_\odot} + 4.74 \qquad L_\odot = 3.839 \times 10^{33} \ \frac{erg}{s}}$$

$$m_{bol} = -2.5 \log \underbrace{\int_0^\infty f_\nu \, d\nu}_{} + c$$

$$\frac{L}{4\pi d^2} = \frac{4\pi R^2 \int_0^\infty F_\nu \, d\nu}{4\pi d^2} = \frac{R^2}{d^2} F$$

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$$\boxed{\begin{aligned} M_{bol} &= -2.5 \log \frac{L}{L_\odot} + 4.74 \\ L_\odot &= 3.839 \times 10^{33} \ \frac{erg}{s} \end{aligned}}$$

NOTE: M_{bol} is not directly measurable. To obtain the total energy radiated from a star requires making a **bolometric correction**

$$F = \frac{L}{4\pi d^2}$$

$$[F] = \frac{\text{erg}}{\text{s cm}^2}$$

$$[L] = \frac{\text{erg}}{\text{s}}$$

$$F_\odot = \frac{L_\odot}{4\pi d^2} = \frac{3.839 \times 10^{26}\ \text{W}}{(1.496 \times 10^{11}\ \text{m})^2} = 1365\ \frac{\text{W}}{\text{m}^2}$$

In bolometric units:

a.k.a. the inverse square law of light

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Solar irradiance

$$M = M_\odot - 2.5 \log \frac{L}{L_\odot}$$

w/ $M_\odot = 4.74$

$L_\odot = 3.839 \times 10^{26}$ W

$$m = M_\odot - 2.5 \log \left(\frac{F}{F_{10,\odot}} \right)$$

w/ $F_{10,\odot}$ = RADIANT FLUX OF THE SUN @ $d = 10$ pc

Given the Sun and another star:

$$M = M_\odot - 2.5 \log \frac{L}{L_\odot}$$

w/ $M_\odot = 4.74$

$L_\odot = 3.839 \times 10^{26}$ W

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Photometric systems of magnitudes:

1. Photographic system: $m_{pg}=m_{visual}$ for A0 stars (Vega)

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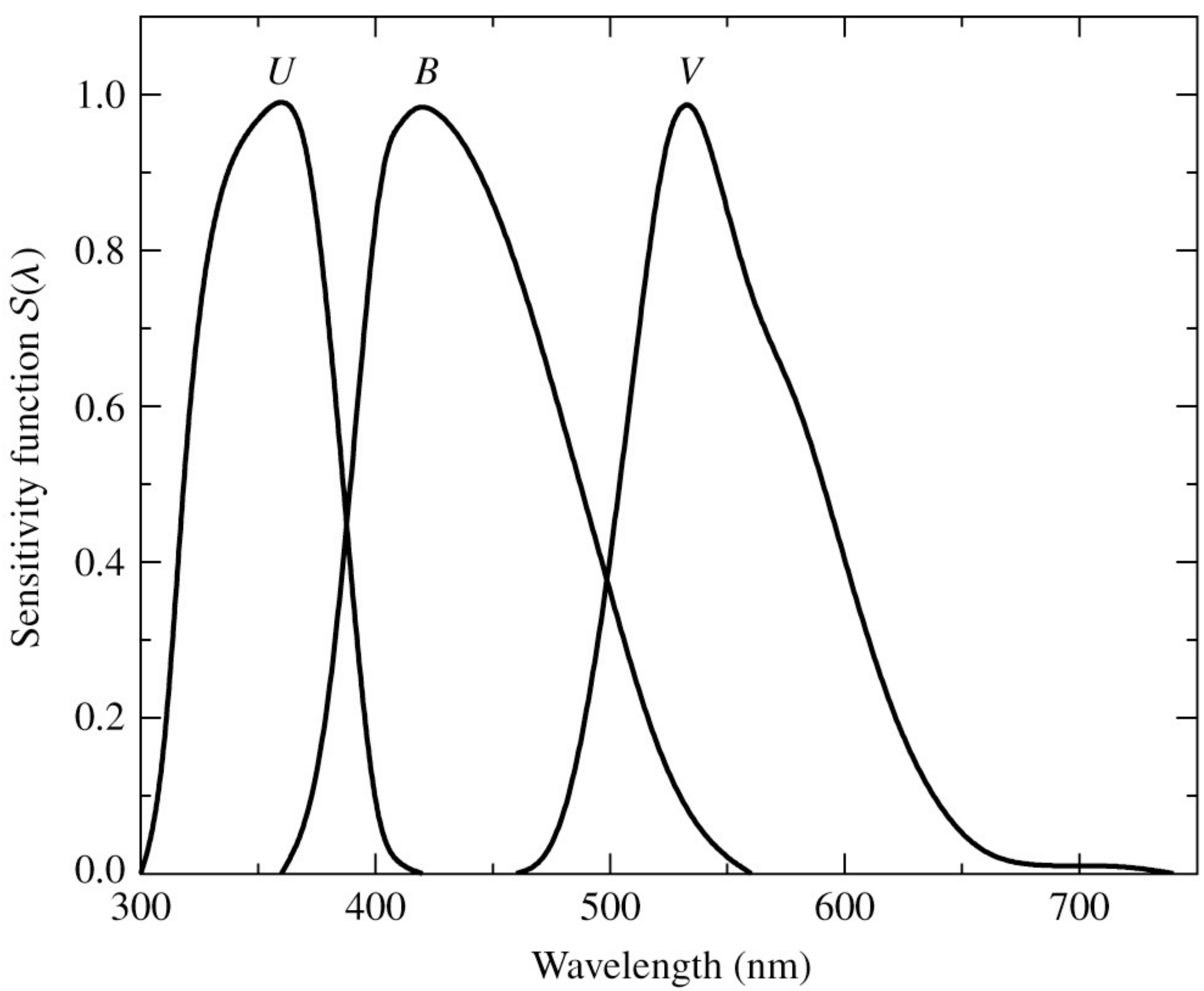
   $U = m_U$, $B = m_B$ (similar to photographic plate magnitude), $V = m_V$
   zero-point determined using the sequence of standard stars (A0 spectral type stars)
   For Vega (A0 star, $T_{surface}$=10,000K), U-B=B-V=0



$\lambda_U \simeq 3650$ Å $\quad \Delta\lambda_U \sim 680$ Å

$\lambda_B \simeq 4400$ Å $\quad \Delta\lambda_B \sim 980$ Å

$\lambda_V \simeq 5500$ Å $\quad \Delta\lambda_V \sim 890$ Å

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3. Spectro-Photometric system

$$\lambda_{eff} := \frac{\int_0^\infty \lambda P_\lambda \, d\lambda}{\int_0^\infty P_\lambda \, d\lambda}$$

w/ P_λ TRANSMISSION CURVE OF THE FILTER

EFFECTIVE WAVELENGTH

$$\nu_{eff} = c/\lambda_{eff}$$ Effective frequency

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3. Spectro-Photometric system

4. AB system (this has become the standard magnitude system):

$$m_\nu(AB) := -2.5 \log f_\nu - 48.6$$

$$\text{IF } [f_\nu] = \frac{\text{erg}}{\text{s cm}^2\text{ Hz}}$$

Apparent brightness

COLOR INDEX

$$U-B := M_U - M_B$$
$$B-V := M_B - M_V$$

The smaller (or more negative) the color index, the bluer a star is. The color index is independent on distance of the star.

$\boxed{\text{BOLOMETRIC CORRECTION}}$

$$BC := m_{BOL} - m_V$$

Astronomers measure the apparent magnitude (m) and the distance (d) of a star. The absolute magnitude (M) is computed by mentally moving the star at a distance d=10pc. The absolute magnitude is then converted to an absolute bolometric magnitude (M_{bol}) using the bolometric correction (BC).

$$M_{BOL} = M_V + BC =$$

$$= -2.5 \log L + C = -2.5 \log L\left[\frac{erg}{s}\right] + 88.70$$

$$= -2.5 \log \frac{L}{L_\odot} + 4.72$$

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$$BC := -2.5 \log \frac{\text{incident energy flux from all frequencies}}{\text{recorded energy flux}} =$$

$$= -2.5 \log \frac{\int_0^\infty f_\nu \, d\nu}{\int_0^\infty f_\nu P_\nu \, d\nu}$$

filter response curve

The BC depends on the spectral type of the star; known the spectral type, I can derive its absolute bolometric magnitude M_{bol} given BC (tabulated as a function of different spectral types) and M_V.

$$M_{V,\odot} = 4.83$$

Blackbody radiation:

Any object with a temperature above absolute zero emits light at all wavelengths with varying degrees of efficiency. An ideal blackbody is an object that absorbs all of the light energy incident upon it, and reradiates this energy with the characteristic spectrum. The radiation emitted by a blackbody is called blackbody radiation. Stars, planets, and humans are blackbodies, to a rough first approximation.

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Considering the power (energy per unit of time) radiate per unit of area per unit of wavelength by a surface in thermodynamic equilibrium (i.e., having already integrated the specific intensity over the solid angle):

Planck's function

$$F_\lambda = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} \qquad F_\nu = \frac{2\pi h \nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$$

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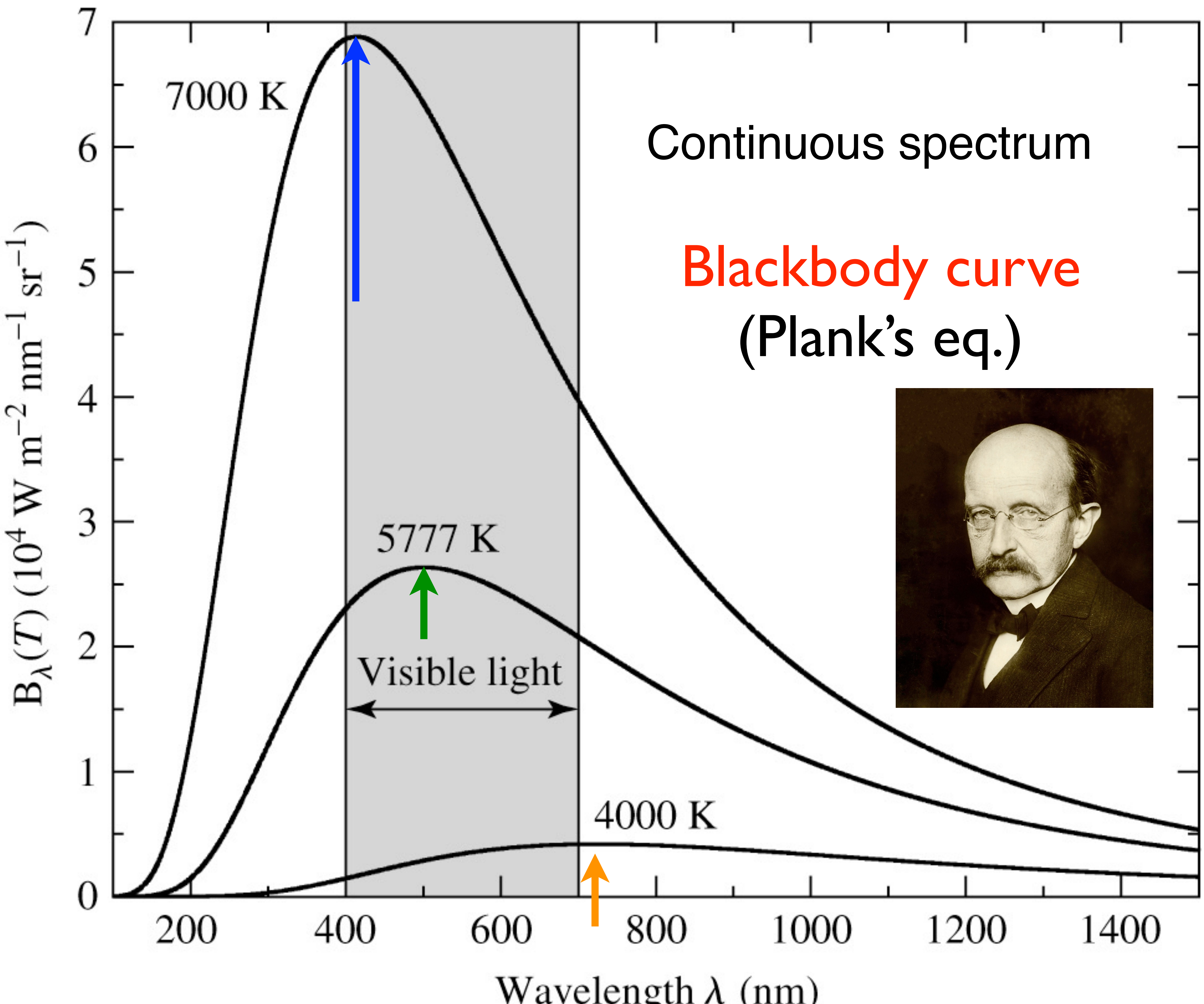
$$[F_\lambda] = \frac{\mathrm{erg}}{\mathrm{s\ cm^2\ \AA}}$$

$$[F_\nu] = \frac{\mathrm{erg}}{\mathrm{s\ cm^2\ Hz}}$$



Continuous spectrum
Blackbody curve
(Plank's eq.)
7000 K
5777 K
4000 K
Visible light
$B_\lambda(T)$ (10^4 W m^{-2} nm^{-1} sr^{-1})
Wavelength λ (nm)
0
1
2
3
4
5
6
7
200
400
600
800
1000
1200
1400

Total power (energy per unit of time) radiated per unit of area, i.e., the surface flux:

$$F = \int_0^\infty F_\lambda \, d\lambda = \frac{2\pi^5}{15} \frac{1}{c^2} \frac{k^4}{h^3} T^4 = \sigma T^4$$

$$x = hc/\lambda kT$$

$$\int_0^\infty \frac{x^3}{e^x - 1} = \frac{\pi^4}{15}$$

w/ $\sigma = 5.6704 \times 10^{-8} \frac{W}{m^2 s\, {}^\circ K^4}$

$= 5.67 \times 10^{-5} \frac{erg}{cm^2 s\, {}^\circ K^4}$

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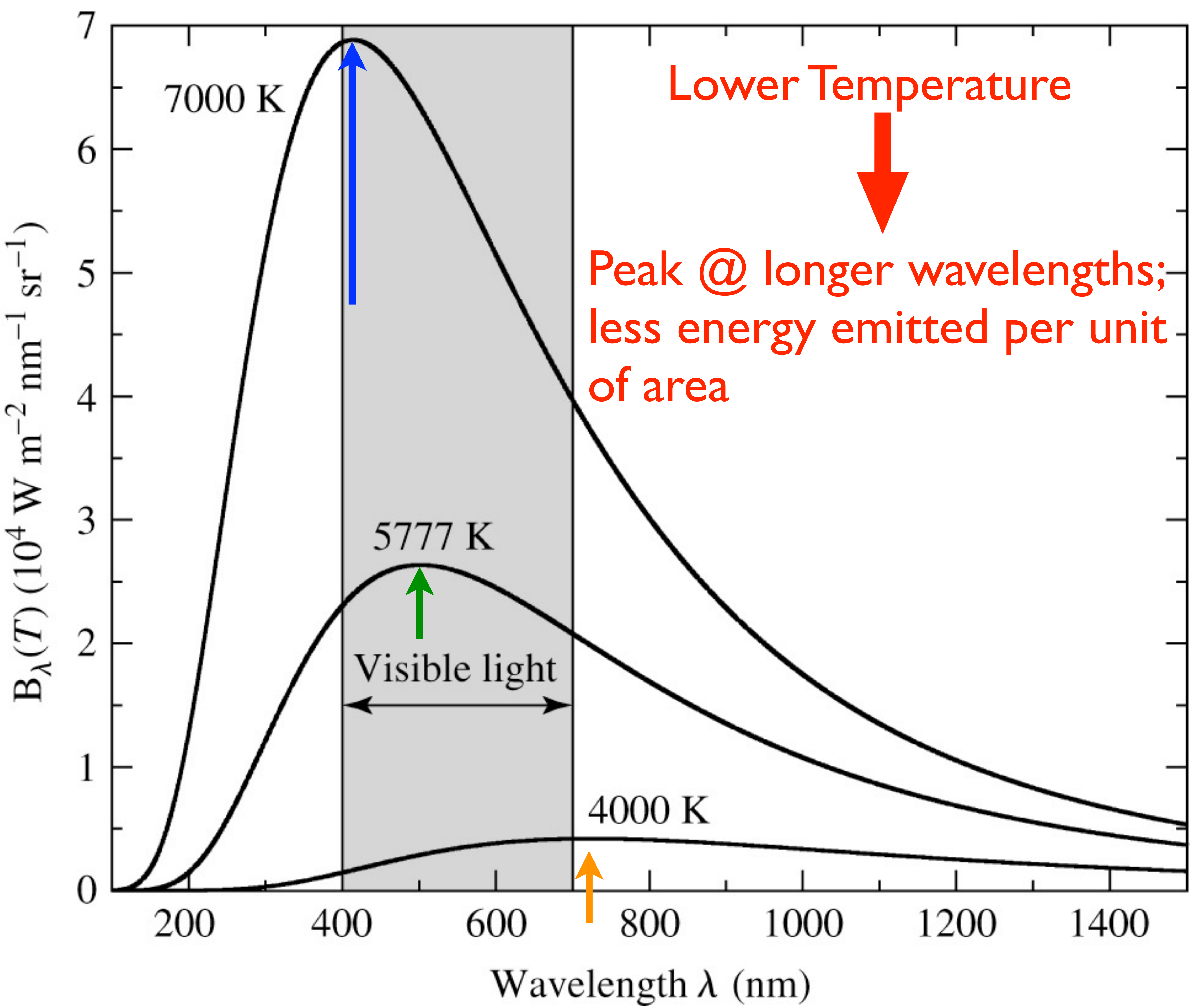
Stefan-Boltzmann law and constant



Lower Temperature
Peak @ longer wavelengths; less energy emitted per unit of area
7000 K
5777 K
4000 K
Visible light
$B_\lambda(T)$ (10^4 W m^{-2} nm^{-1} sr^{-1})
Wavelength λ (nm)
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Monochromatic luminosity:

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Luminosity:

$$L = 4\pi R^2 F = 4\pi R^2 \sigma T_{eff}^4$$

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Monochromatic flux for an observer at a distance d:

$$f_\lambda d\lambda = \frac{L_\lambda d\lambda}{4\pi d^2} = \left(\frac{R}{d}\right)^2 \frac{2\pi c^2 h}{\lambda^5} \frac{d\lambda}{e^{hc/\lambda kT} - 1}$$

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

Energy of starlight with wavelength between λ and $\lambda + d\lambda$ arriving per second on the unit of surface of detected aimed at the star.

$$[f_\lambda d\lambda] = \frac{\text{erg}}{\text{s cm}^2}$$

Position in wavelength of the maximum (peak) of the blackbody radiation:

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$$\frac{dF_\lambda}{d\lambda} = 0$$

Wien's displacement law

$$\lambda_{max} T = 0.2014 \frac{hc}{k} = \underbrace{0.2898 \text{ cm}^\circ\text{K}}_{\text{WIEN'S CONSTANT}}$$

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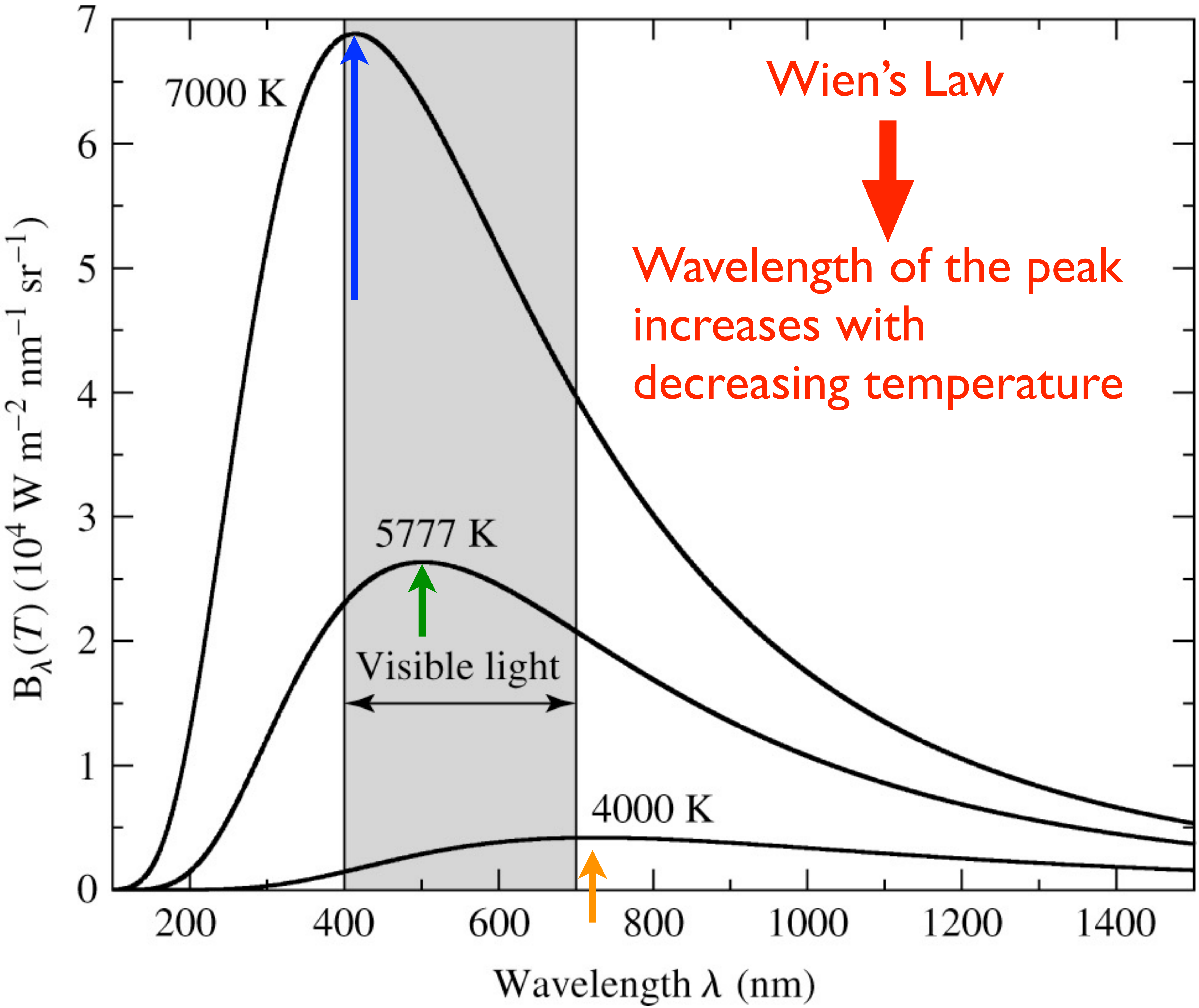
NOTE:

For λ LARGE $\quad \dfrac{1}{e^{hc/\lambda kT} - 1} \longrightarrow \dfrac{1}{hc/\lambda kT}$

$$\Rightarrow \quad F_\lambda \rightarrow \frac{2\pi ckT}{\lambda^4}$$

Rayleigh-Jeans law (the long wavelength tail of the blackbody radiation curve



7000 K
5777 K
4000 K
Visible light
Wien's Law
Wavelength of the peak increases with decreasing temperature
$B_\lambda(T)$ (10^4 W m^{-2} nm^{-1} sr^{-1})
Wavelength λ (nm)
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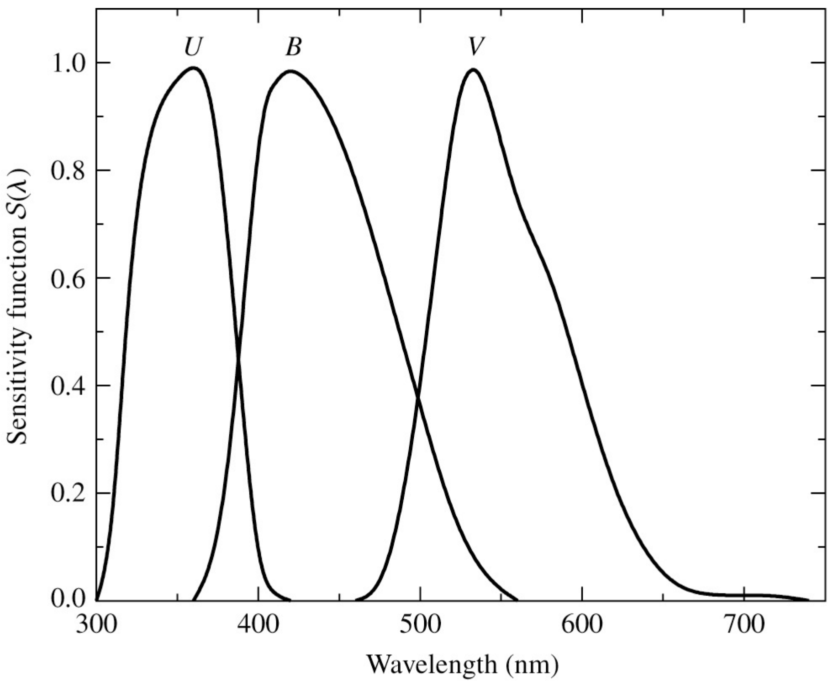
COLOR INDICES

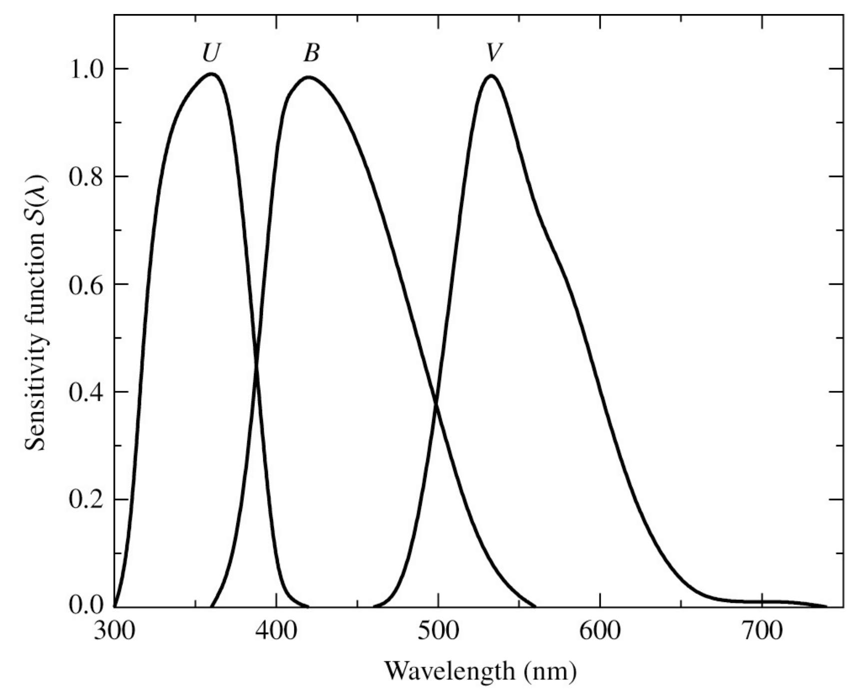


COLOR INDICES

$$m_U = U = -2.5 \log \int_0^\infty S_U f_\lambda \, d\lambda + C_U$$

transmission function

$$S(\lambda) \equiv P_\lambda$$



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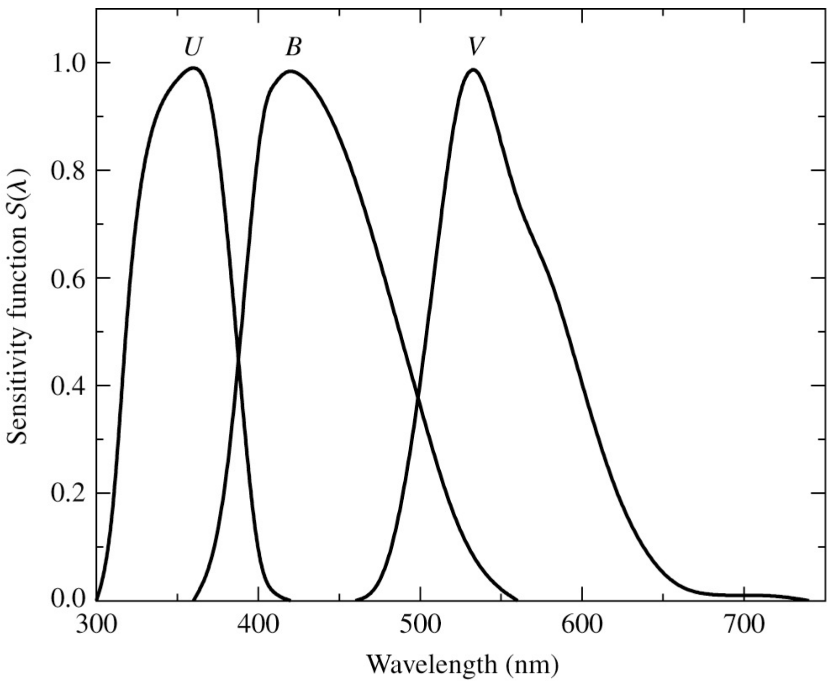
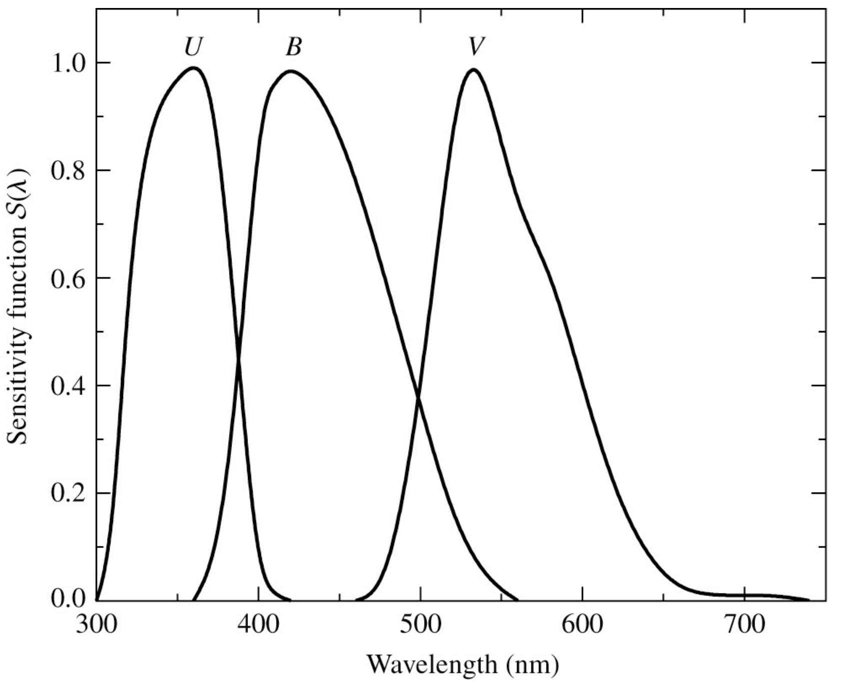
$m_B = B$
$m_V = V$



COLOR INDICES



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$m_B = B$

$m_V = V$

$m_U - m_B = U - B$

$$U - B = -2.5 \log \frac{\int_0^\infty S_U f_\lambda \, d\lambda}{\int_0^\infty S_B f_\lambda \, d\lambda} + \underbrace{C_{U-B}}_{\equiv C_U - C_B}$$

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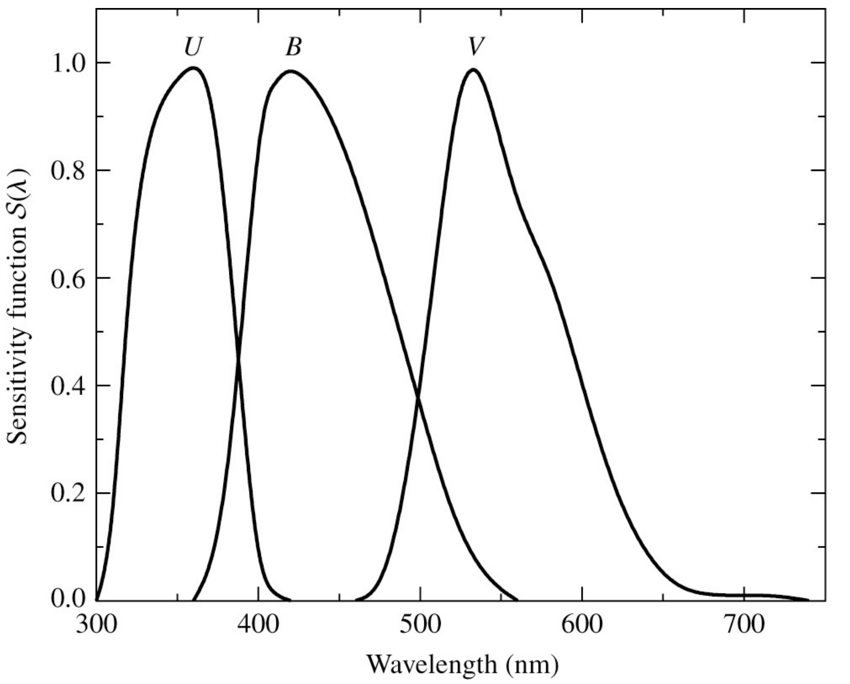

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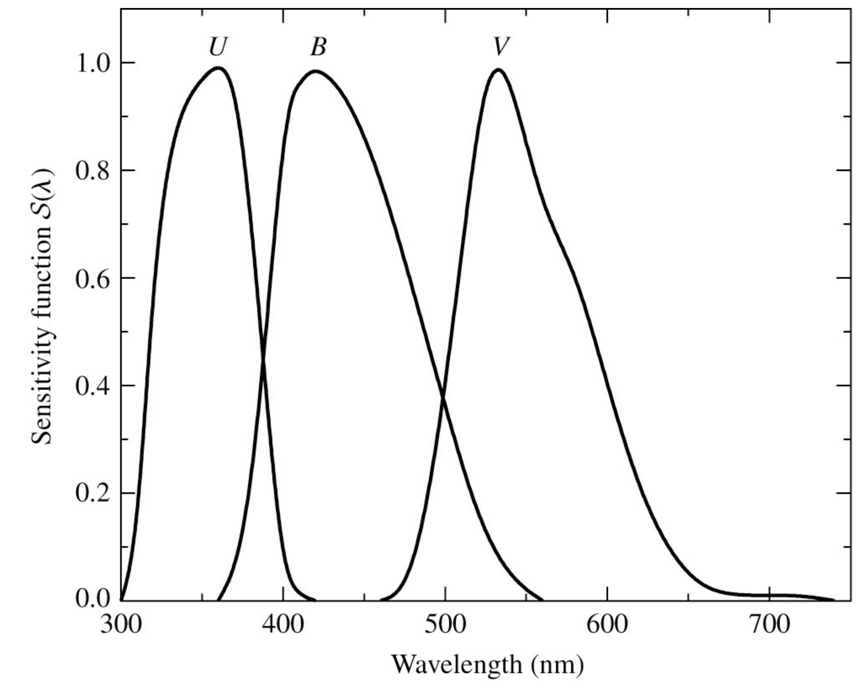

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$m_B - m_V = B-V$

NOTE: the color does not depend on $(R/d)^2$ because this term cancels out in the above equation

The color is solely dependent on the temperature of a model blackbody star

$$m_1 - m_2 = -2.5 \log\left(\frac{f_{\lambda_1}}{f_{\lambda_2}}\right) = -2.5 \log\left(\frac{F_{\lambda_1}}{F_{\lambda_2}}\right) + C$$

$$= A + \frac{1.56}{T_{color}}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) + f(T_{cd})$$

$$\text{w/} \quad f(T_c) = 2.5 \log\left(\frac{1 - e^{-hc/\lambda_2 k T_{col}}}{1 - e^{-hc/\lambda_1 k T_{col}}}\right)$$

$$\Rightarrow \quad B - V \simeq -0.586 + \frac{6850}{T_{col}\,[K]} + f(T_{col})$$

$$B - V\big|_{\odot} = 0.64$$

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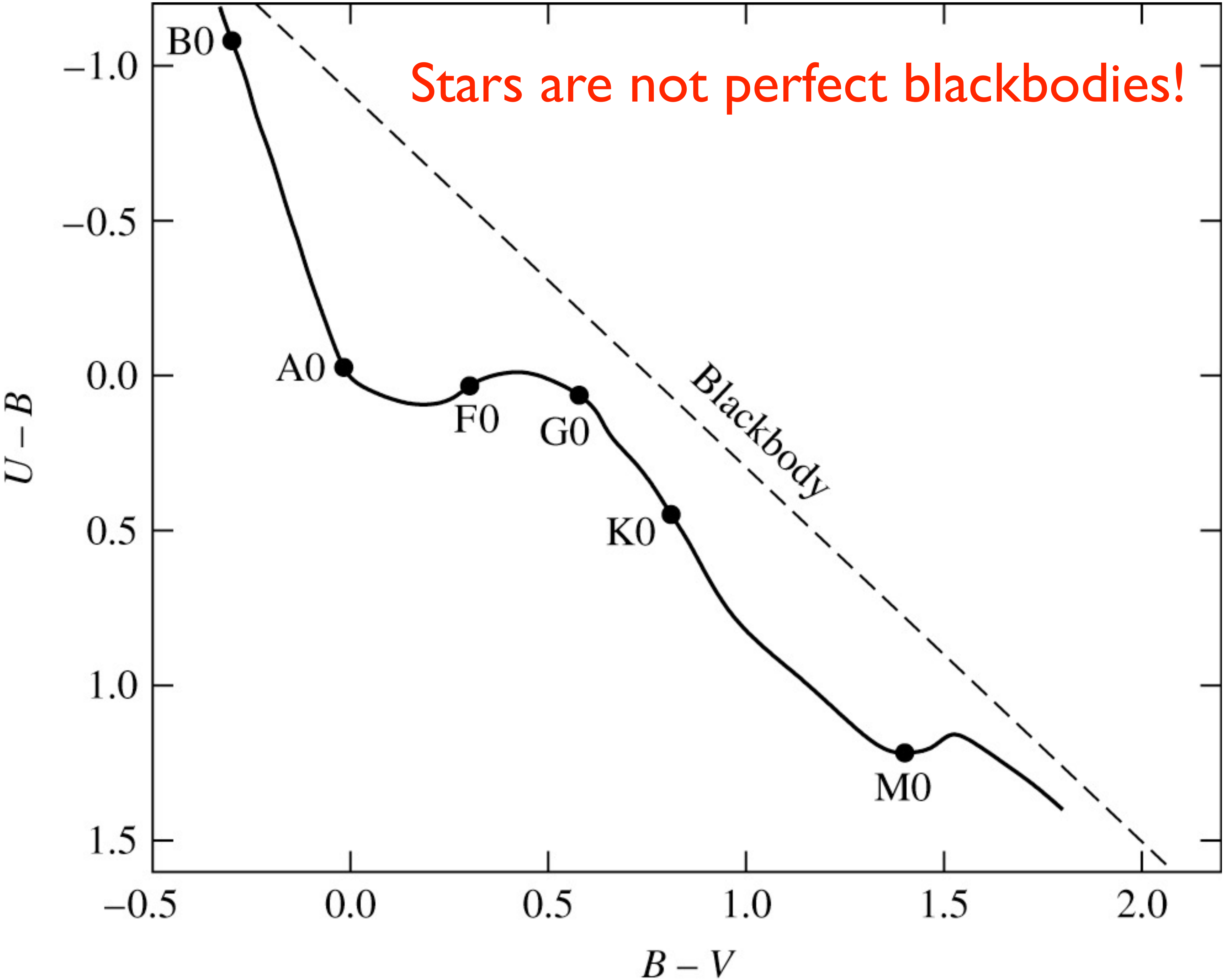
$$B-V\big|_{\odot} = 0.64$$

The hotter are star, the smaller (or more negative) the B-V color, hence the bluer the star


Stars are not perfect blackbodies!
B0
A0
F0
G0
K0
M0
Blackbody
−1.0
−0.5
0.0
0.5
1.0
1.5
U − B
−0.5
0.0
0.5
1.0
1.5
2.0
B − V

The Interaction of Light & Matter

Reading assignment for:

THURSDAY 9/24: Chapters 5.1, 5.2 (not in detail), 5.3, 5.4 (not in detail)