Astro 404
Lecture 5
Sept. 1, 2021

Announcements:

- **Problem Set 1** posted on Canvas
  due on Canvas in pdf this Friday Sept 3 at 5:00pm
  hint: can solve with info given, never need zero point flux F_{zp}
- **Office Hours:** Instructor–right after class today
  or by appointment, or post on Canvass HW discussion
  TA: Thursday 2:30-3:30 pm

Last time:

- star **luminosity**: *Q: what's that? units?*
- link between flux and luminosity
  Q: what's that?
- stellar distances *Q: what's a parsec?*

Luminosity:

• light energy emission rate: $L = d\mathcal{E}_\gamma/dt$ = power output = Wattage

• units: $[L]$ = [energy/time], ex: Watt, erg/s

Luminosity-Flux Connection: Inverse Square Law

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

Stellar Distances

if parallax angle p known, then distance is

$$D = \frac{1 \text{ pc}}{p_{\text{arcsec}}}$$

with p_{arcsec} measured in arc seconds

1 parsec = distance to star with $p = 1$ arcsec

typical separation between neighboring stars in galaxies

How Do Stars Shine? Take I

Matter, Temperature,and Light

hot matter glows (think stove burner)
temperature – radiation connection
very useful for astronomers!

but atoms made of charged particles
random thermal motion $\rightarrow$ changing EM forces $\rightarrow$ light
Maxwell eqs: accelerating charges emit EM radiation!

thus: thermal body = object at a temperature T
emits EM radiation: **thermal radiation**
spectrum of this "heat radiation" depends on T

Note: we always use **absolute temperature** $T > 0$
units: $[T] =$ K (Kelvin). Celsius: $T_{\mathrm{K}} = T_{\mathrm{C}} + 273.15$

Blackbodies

useful* to define an ideal substance:
a perfect absorber of light: **"blackbody"**
absorbs all λ, reflects none

*a useful idealization in the same way an "ideal gas" is useful:
brings out essential physics, and a good approximation to
behavior of many real substances

Q: what would such a thing look like?
Q: what are real substances almost like this?
Q: what everyday object is nearly the opposite of this?

perfect absorber of light: "blackbody"

imagine: lump of idealize coal, reflects no light

when in contact with external world at nonzero T:

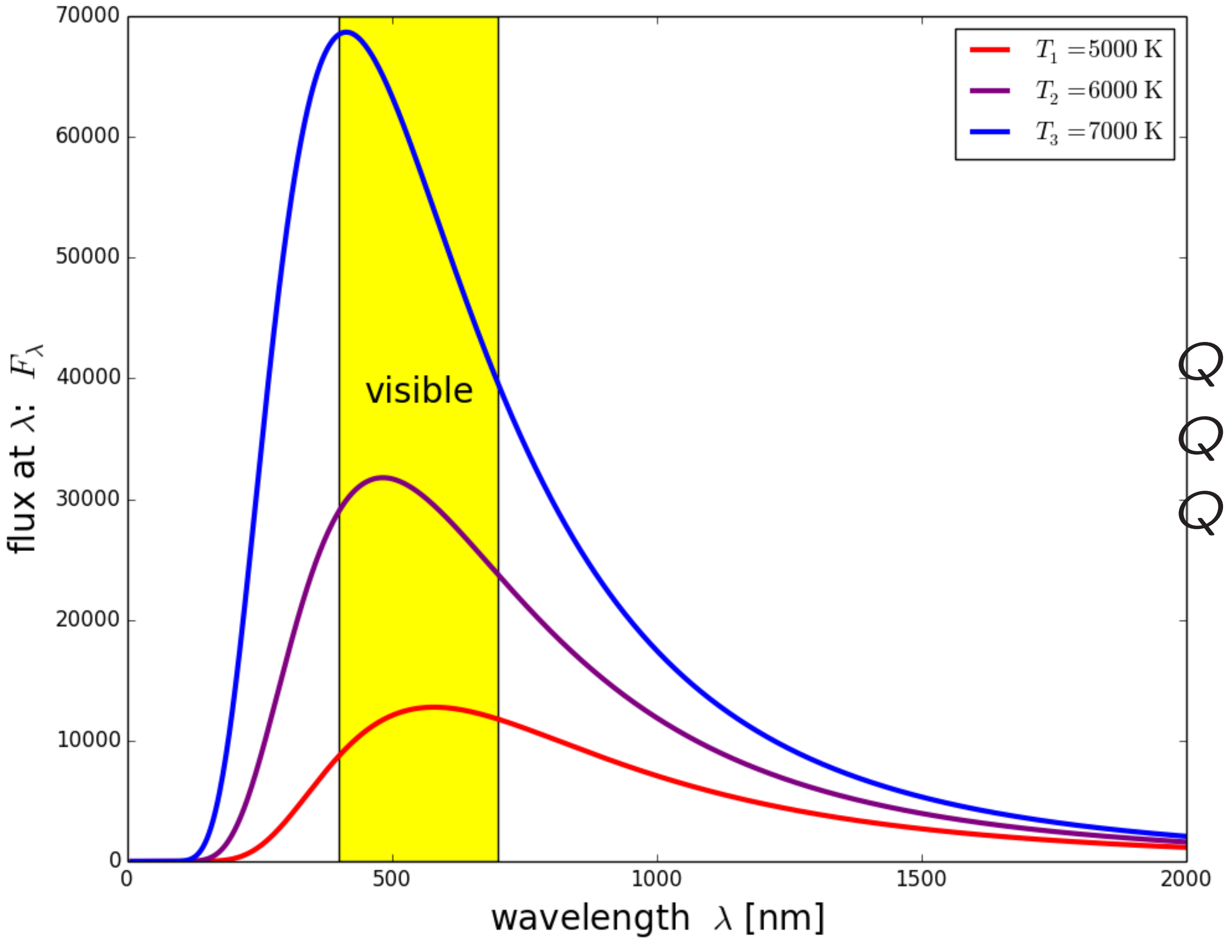
1. blackbody absorbs energy $\rightarrow$ heats up
2. re-emits according to temperature T

"blackbody radiation" $=$ thermal radiation $=$ glow due to T

spectrum depends only on T:

universal property of objects in thermal equilibrium

Blackbody Spectrum



Q: trends vs λ?

Q: trends vs T?

Q: hotter = ???

Blackbody Flux

hotter objects are glow *brighter* than cooler ones
i.e., blackbody surface flux increases with T

blackbody flux B: summed (integrated) over all λ

$$F_{\text{surface}}(T) \overset{\text{blackbody}}{\equiv} B(T) = \sigma T^4 \quad \boxed{\textbf{Stefan-Boltzmann law}} \qquad (1)$$

- applies to *surface* of blackbody (solid, liquid, dense gas)
- Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ Watt m^{-2} K^{-4}
- note very strong dependence on (absolute) T!
- note that blackbody flux depends *only* on emitter T independent of composition

Q: for blackbody sphere of radius R, sum of flux over surface?

Thermal Spectrum: Light as Thermometer!

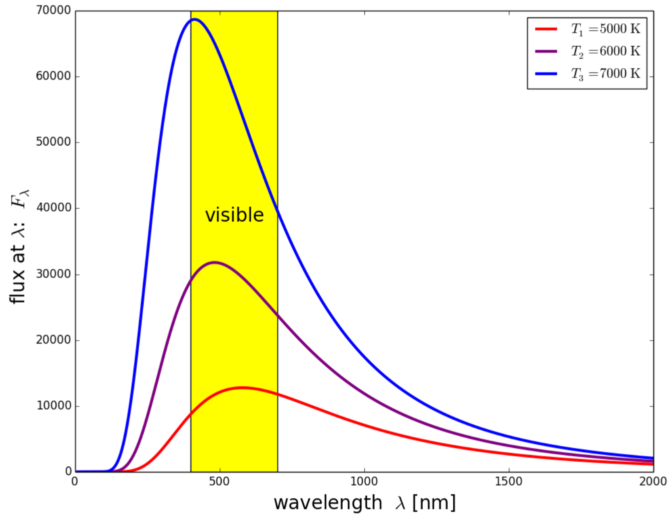
for blackbody at temperature T:

peak λ = color seen:

$\lambda_{\text{peak}} \propto 1/T$

where T is *absolute* temperature

in Kelvin units



Wien's law:

$$\lambda_{\text{peak}} = \frac{0.29 \text{ cm K}}{T} \propto \frac{1}{T} \tag{2}$$

hotter $\rightarrow$ more blue $\rightarrow$ shorter λ

∞

$\Rightarrow$ spectrum as **thermometer**

color measures temperature

iClicker Poll: Human Radiation

Humans have temperature $T > 0$

$\boxed{\text{Do humans emit blackbody radiation?}}$

$\boxed{\text{A}}$ no: T_{human} is too low to emit significant radiation

$\boxed{\text{B}}$ no: T_{human} is too high to emit significant radiation

$\boxed{\text{C}}$ yes: human radiation exists, but is invisible

$\boxed{\text{D}}$ yes: human radiation is visible seen all the time! perceived as hair color, eye color, etc.

any object with $T > 0$ emits thermal radiation!
but not always visible to naked eye

Human radiation:
$\lambda_{\rm peak} = 0.29$ cm K/300 K $\approx 10^{-3}$ cm – 10^{-5} m
`www: EM spectrum`
infrared! `www: IR gallery--people, animals`

not only good for household objects, but also for stars
`www: multiwavelength stars`

X-ray emission seen from Cassiopeia A!
`www: Cas A spectrum`
some of this is thermal emission: how hot is it?
$T \sim 0.29$ cm K/10^{-7} cm $= 3 \times 10^6$ K !
Q: what might have made it so hot?

Q: quick-and-dirty way to estimate star temperature?
Q: what part of the star has this temperature?

Stellar Thermometry: Color Temperature

recall – broadband fluxes give "poor person's spectrum"

pro: broad passband filters don't need as much light
so can measure quickly

con: don't get detailed spectra (lines, etc)

also recall: *color* $\Leftrightarrow$ *flux ratios*

usually expressed as *color index*

for bands 1 and 2: $m_2 - m_1 = 2.5 \log_{10}(F_1/F_2)$

so if spectrum is well approximated by blackbody

Wien's law: color index estimates **color temperature**

more specifically: the average surface temperature

Q: compare Betelgeuse vs Rigel?

Q: estimate Sun's T_{color}?

Color Temperature: Examples

qualitatively:

in Orion, reddish Betelgeuse is cooler than bluish Rigel
in Gemini: red Castor cooler than blue Pollux

quantitatively:

the *Sun*'s color temperature $T_{\text{color},\odot} \approx 5900$ K
check: white sunlight $\rightarrow$ peaks min-optical $\lambda_{\text{max}} \sim 500$ nm
gives $T_{\text{color}} = 0.3 \text{ mm K}/\lambda_{\text{max}} \sim 6000$ K yay!

Stellar Thermometry II: Effective Temperature

for a *blackbody sphere* of radius R
sum (really, integration) of flux over surface gives **luminosity**!

$$4\pi R^2\, B = 4\pi R^2\ \sigma T^4 = \text{flux} \times \text{area} = \text{power} = L \tag{3}$$

for a real star, if R known, can compute **effective temperature**

$$T_{\text{eff}} = \left(\frac{L}{4\pi\sigma R^2}\right)^{1/4} \tag{4}$$

Q: What is T_{eff} for a perfect blackbody?
Q: What if $T_{\text{eff}} \neq$ color temperature? How could that be?

Temperatures of Real Stars

if star were perfect blackbody:
color temperature $= T_{\rm eff} =$ true thermodynamic temperature T

but real star spectra are not perfect blackbodies
so in general, none of these "temperatures" agree!

in practice: color temp vs $T_{\rm eff}$ tests blackbody approximation
$T_{\rm eff,\odot} = 5780$ K, close to but not same as $T_{\rm color,\odot}$
blackbody approximation not too bad!

better: make detailed model of stellar atmosphere
compute spectrum in presence of lines
and changing temperature with depth
use this to infer temperature structure

A Census of Stars

We now have the technology to take a census of stars!

For large sample of stars, measure L and T for each
plot each star's (T, L) point on diagram of L vs T

Some possible trends:
- random scatter
- all stars fall onto same point
- tight clump of points
- a line or curve

Q: what would each of these imply?

iClicker Poll: Star Temperature and Luminosity

Vote your conscience!

For large sample of stars, measure L and T for each
plot points on diagram of L vs T

What will the data show?

A random scatter: stars have large range of L, and of T, and in any combination

B tight clump of points: stars are nearly identical, all with very similar L and T

C a clear trend: stars have large range of L and of T but the two vary together (correlated)

D none of the above

A Stellar Census: Hertzsprung-Russell Diagram

Hertzsprung-Russell: plot L vs$T$ for lotsa stars
really, abs mag M_V vs spectra type
but these are equivalent to L and T

`www: H-R diagram`

Q: what patterns do you notice?
Q: where are most stars?
Q: where is the Sun?
Q: how does the Sun compare to other stars?

Hertzsprung-Russell Diagram

for a “fair sample” of stars
(i.e., not a specially picked cluster)
trends emerge

most stars ($\sim 90\%$) fall on curve: “main sequence”
(including the Sun!); “dwarfs”
most of the rest: cooler but more luminous: “giants”
Q: how do we know they are giant?
a rare few: hot but luminous: “supergiants”
not rare but dim and hard to find:
very hot but very low-L objects: “white dwarfs”
Q: how do we know they are teeny?

Q: what does the HR diagram tell us about the Sun?

H-R and the Sun

The Sun on H-R diagram:
- found on the main sequence
- position is in the middle of the curve

but the main sequence is where most stars are found!

thus: *the Sun is a typical star!*
- lies in heart of main sequence L vs T trend
- neither most nor least luminous, not hottest or coolest

Other questions arise:
- *why* do stars lie on the main sequence?
- what controls their position on the diagram?
- what's up with the giants, supergiants, and white dwarfs?

...stay tuned