Astro 404

Lecture 4

Aug. 30, 2021

Announcements:

- **Problem Set 1** posted on Canvas
  due on Canvas in pdf this Friday Sept 3 at 5:00pm
- **Office Hours:** Instructor–right after class Wed
  TA: Thursday 2:30-3:30 pm

Last time: stars observed–flux and color

Q: How is flux defined?

Q: In everyday language what does flux measure?

Q: How is flux traditionally quantified for stars?

Q: How is color quantified for stars? Hint: in terms of fluxes

Flux

flux defined as:

$$F = \frac{dE/dt}{A} = \frac{\text{light power}}{\text{area}} \tag{1}$$

measures **apparent brightness**

for stars: flux measured in **magnitudes**
uses calibration "zero point" of flux from Vega $F_{\text{Vega}} = F_{\text{zp}}$

$$m = -2.5 \log_{10}\left(\frac{F}{F_{\text{zp}}}\right) \tag{2}$$

Q: m values for $F = (1, 10, 0.1)F_{\text{zp}}$?

color: use filter to measure flux in wavelength bands
example: blue B, "visual" V yellow
color measured by flux ratio: F_B/F_V
or color index $m_B - m_V = B - V = -2.5\log_{10}(F_B/F_V)$
Q: which is bluer: $B - V = 0.5$ or -0.5?

Small Group Discussion: 3min

Is it possible for two observers to see a different flux for the same lightbulb?

Fine print:
No walls or absorbing media allowed
observations use same detectors

- **if yes**, give an example when this would occur
- **if no**, explain why not

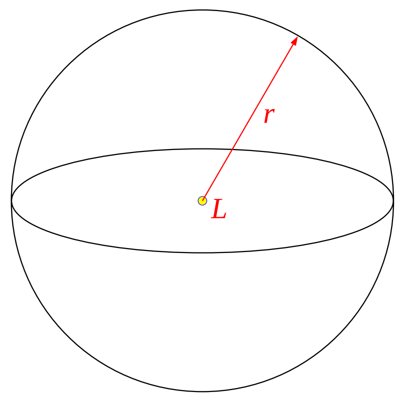
ω Link: https://docs.google.com/presentation/d/139kHcw-6138OJlp686Sf1jQvu_aJXxOw_oW

Flux from a Point Source

consider spherical source (hint: it's a star!) of size R
emitting light isotropically (same in all directions)
with constant *power* L ("**luminosity**")

at radius $r > R$ (outside of source)
area $A = 4\pi r^2$, and flux is

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



inverse square law
Q: what principle at work here?
Q what implicitly assumed?

for we observers to infer luminosity = star wattage
need *both flux F and distance r*

Inverse Square Law for Flux

Ultimately relies on *energy conservation*
$\rightarrow$ energy emitted $d\mathcal{E}_{\rm emit} = L\ dt_{\rm emit}$ from source
is same as energy observed $d\mathcal{E}_{\rm obs} = F\ A\ dt_{\rm obs}$

Thus: inverse square derivation assumes

- outside of source: no emission, absorption, or scattering
  we will revisit these
- no relativistic effects (redshifting, time dilation)
- Euclidean geometry–i.e., no spatial curvature,
  usually fine unless near strong gravity source

Luminosity

Warning! apparent brightness $\neq$ luminosity!

- **luminosity** = power emitted from star: "wattage"
  units: energy/time, e.g., Watts
- **flux** = power per unit area (at some observer location)
  units: power/area, e.g., Watts/m^2

flux (Apparent brightness) and luminosity related by

$$\text{observer-dependent } F = \frac{L}{4\pi r^2} \ \frac{\text{observer-independent}}{\text{observer-dependent}} \tag{3}$$

inverse square law!
farther $\leftrightarrow$ dimmer
hence brightness is "apparent" – depends on observer distance
but L *is* intrinsic fundamental property of a star

Q: how measure star L?

Measuring Star Power

To find the luminosity of a star

1. Measure F
2. Measure r
3. solve: $L = 4\pi r^2 F$

ergo: to compare wattage of stars, need **distances**!

Q: how to measure distances to stars?

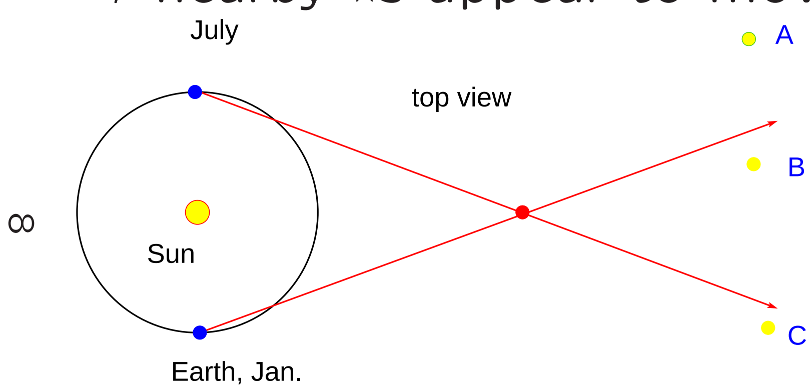
Distances to Stars: Parallax

a difficult, longstanding (ongoing!) problem
today many techniques exist
note: technology only good enough in last 2 centuries
anchor: Earth-Sun distance (gotten from radar)

$r_{\text{Earth--Sun}} \equiv 1 \text{ au} = 1.5 \times 10^{11}$ m: **astronomical unit**

Parallax – the "gold standard" of stellar distances
Demo: thumb's up–arm's length, halfway

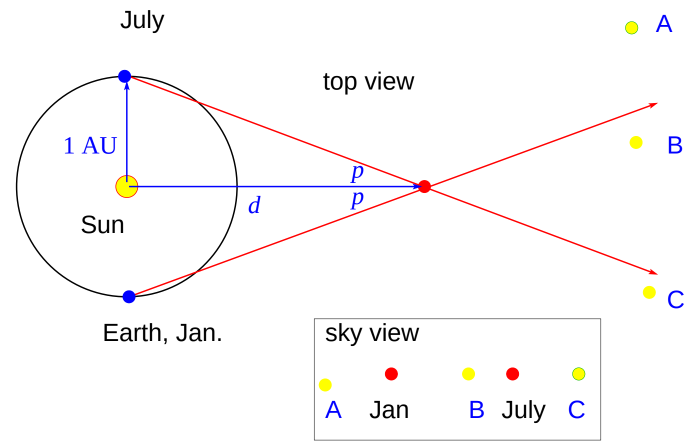
as Earth orbits, our viewpoint shifts (slightly!)
$\rightarrow$ nearby $\star$s appear to move w.r.t. background $\star$s



Q: diagram is top view–what is sky view over 1 year?
Q: what should we measure? what does it tell us?

Parallax: Geometry and Units

measure: angular shift from midpoint p



trig technology: $d \tan p = 1$ au
$\Rightarrow$ distance $d = 1$ au$/\tan p$
but p tiny! ($\lesssim 1$ arc sec $\sim 10^{-5}$ rad $\ll 1$)
$\rightarrow \tan p_{\rm rad} \approx p_{\rm rad}$, so
$d = 1$ au$/p_{\rm rad}$, or

$$d = \frac{1 \text{ pc}}{p_{\rm arcsec}} \qquad (4)$$

where $p_{\rm arcsec}$ is p in arc sec, and

$1 \text{ pc} = 1 \text{ parsec} = 1 \text{ au}/(1 \text{ arcsec})_{\rm rad} = 3.086 \times 10^{16}$ m

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

occasionally use **light year** = distance light travels in 1 yr
1 lyr $= c \times 1$ yr $= 9.5 \times 10^{15}$ m
and so: 1 pc = 3.26 lyr

Parallax: Observations

typical parallactic shift is tiny (if observable at all!)

all less than 1 arc**sec** $= \frac{1}{3600}$ deg $= 5 \times 10^{-6}$ radian!!

Sirius: $p = 0.366$ arcsec

$d = \frac{1}{0.366}$ pc $= 2.65$ pc $\simeq 5 \times 10^5$ au

nearest stars to us: α Centauri triple (!) star system

αCen A & B, Proxima: $d(\alpha\text{Cen}) = 1.3$ pc $= 4$ lyr

note: even from nearest star, light takes 4 *years* to get here!

Lessons:

- 1 pc $\sim$ typical distance between neighboring stars in our Galaxy (and others) `www: 100 nearest stars`
- parallax p tiny at best: *requires precision astrometry* until recently: parallax only available for nearest stars
- Revolution: GAIA space mission `www: GAIA`

Standard Candles

imagine we can find objects–"standard candles"
with L known somehow *Q: everyday examples?*

then when we measure F
we can immediately infer **luminosity distance**

$$d_L = \sqrt{\frac{L}{4\pi F}} \tag{5}$$

Q: why would this be incredibly useful?
Q: what are possible astrophysical standard candles?
Q: why is this not easy to do in practice?

we'll see: stars provide several possible standard candles
this will be a running theme of the course

Stellar Distances and Magnitudes

recall: *apparent magnitude* is measure of star *flux*

but if know distance, can compute: **absolute magnitude**

abs mag $M \equiv$ apparent mag if star placed at $d_0 = 10$ pc

Q: why need distance to find abs mag?

Q: what does abs mag measure, effectively?

Absolute Magnitude

absolute magnitude M = apparent mag at $d_0 = 10$ pc

places all stars at constant fixed distance

$\rightarrow$ a stellar "police lineup"

$\rightarrow$ then differences in F only due to diff in L

$\rightarrow$ absolute mag effectively measure **luminosity**

Star	absolute magnitude in visual band
Sun (symbol $\odot$)	$M_{V,\odot} = 4.76$ mag
Sirius	$M_{V,\text{Sirius}} = +1.43$ mag
Vega	$M_{V,\text{Vega}} = +0.58$ mag
Polaris	$M_{V,\text{Polaris}} = -3.58$ mag

Q: rank them in order of descending L?

Immediately see that Sun neither most nor least luminous star around

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

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

blackbody absorbs energy $\rightarrow$ heats up

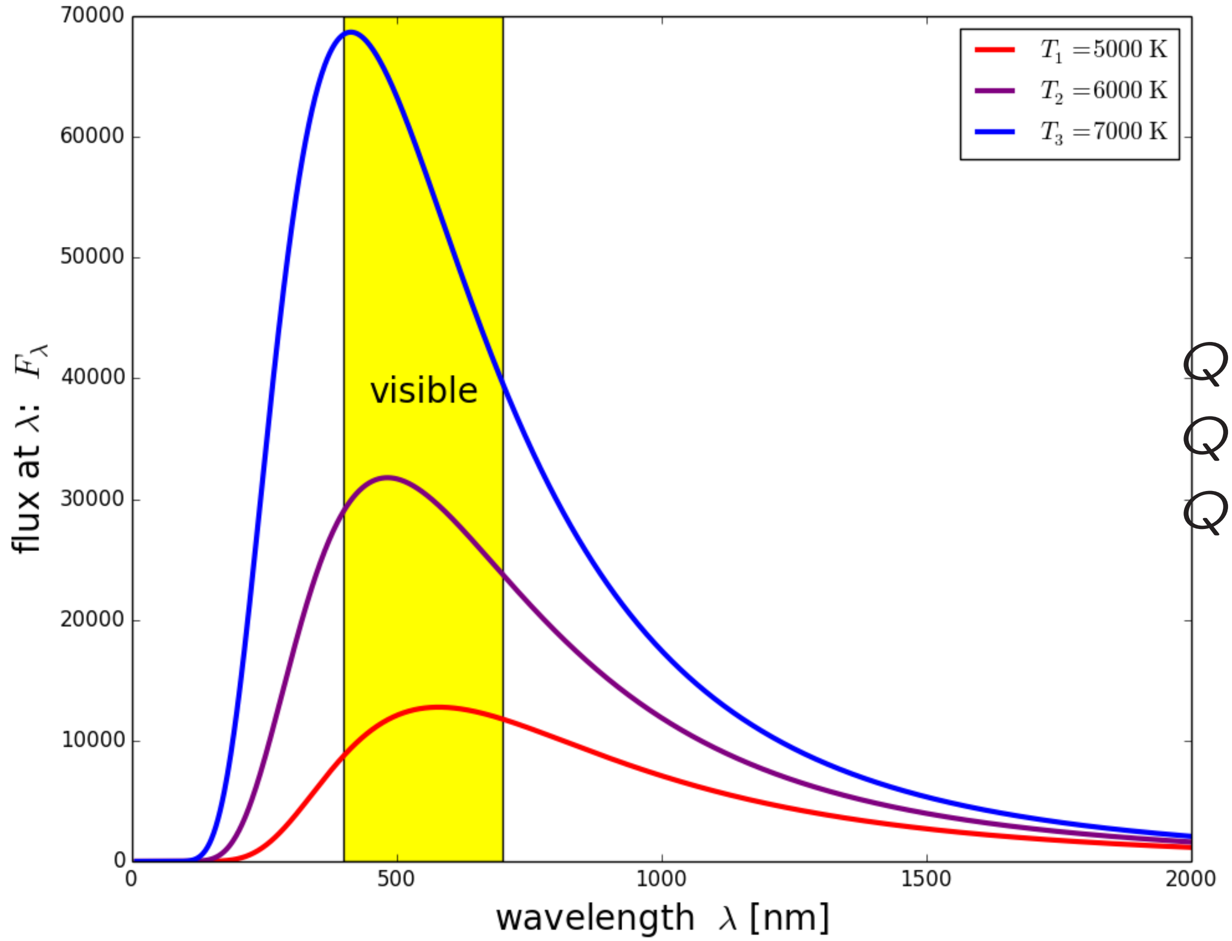
re-emits according to temperature T

“blackbody radiation” = thermal radiation

spectrum depends only on T:

universal property of objects in thermal equilibrium

Blackbody Spectrum



Q: trends vs λ?

Q: trends vs T?

Q: hotter = ???

Thermal Spectrum: Light as Thermometer!

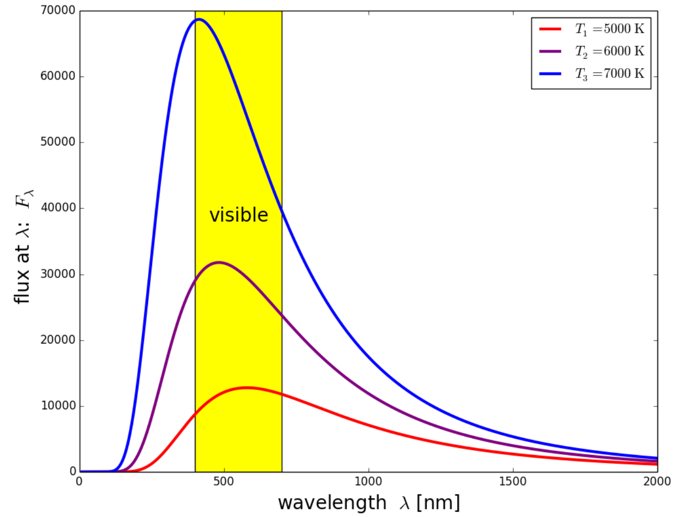
for blackbody at temperature T:

peak λ = color seen:

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

where T is *absolute* temperature

in Kelvin units



Wien's law:

$$\lambda_{\text{peak}} = \frac{0.29 \text{ cm K}}{T} \propto \frac{1}{T} \quad (6)$$

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

$\Rightarrow$ spectrum as **thermometer**

color measures temperature

iClicker Poll: Human Radiation

Humans have temperature $T > 0$

Do humans emit blackbody radiation?

A no: T_{human} is too low to emit significant radiation

B no: T_{human} is too high to emit significant radiation

C yes: human radiation exists, but is invisible

D yes: human radiation is visible seen all the time!
percieved as hair color, eye color, etc.

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

Human radiation:
$\lambda_{\text{peak}} = 0.29$ 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 flters don't need as much light
so can measure quickly
con: don't get detailed spectra (lines, etc)

also recall: *color* ⇔ *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!

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

$$F_{\text{surface}}(T) \overset{\text{blackbody}}{\equiv} B(T) = \sigma T^4 \quad \boxed{\textbf{Stefan-Boltzmann law}} \tag{7}$$

- 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?

Stellar Thermometry II: Effective Temperature

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

$$4\pi R^2 \, B = 4\pi R^2 \, \sigma T^4 = \text{flux} \times \text{area} = \text{power} = L \tag{8}$$

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

$$T_{\text{eff}} = \left(\frac{L}{4\pi\sigma R^2}\right)^{1/4} \tag{9}$$

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 pefect blackbody:
color temperature $= T_{\text{eff}} =$ 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_{eff} tests blackbody approximation
$T_{\text{eff},\odot} = 5780$ K, close to but not same as $T_{\text{color},\odot}$
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