Astro 404
Lecture 4
Sept. 4, 2019

Announcements:

- **Problem Set 1** posted on Compass
  due on Compass in pdf this Friday Sept 6 at 5:00pm
- **Office Hours:** Instructor–right after class today
  TA: Thursday noon–1:00 pm
- iClicker registration link now on Compass

Last time: stars observed–flux versus luminosity

Q: what's the difference? lightbulb analogy?

Q: how are they related?

Q: which is intrinsic to the star? what's needed to know this?

Apparent brightness and luminosity related by

$$\text{observer-dependent } F = \frac{L}{4\pi r^2} \; \frac{\text{observer-independent}}{\text{observer-dependent}} \tag{1}$$

inverse square law!

farther ↔ dimmer

hence brightness is "apparent" − depends on observer

but L *is* intrinsic fundamental property of a star

To find ⋆ luminosities

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

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

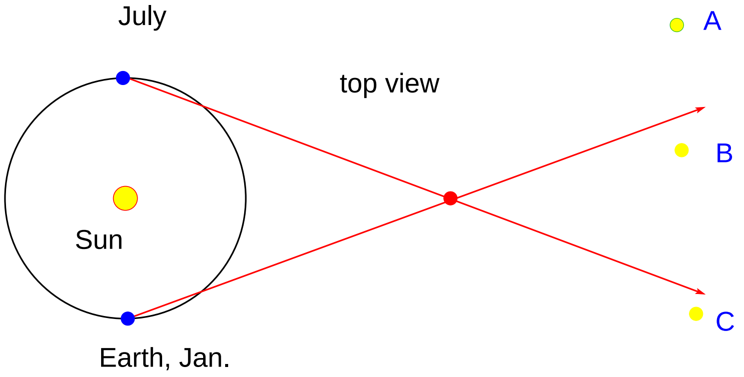
Q: how to measure?

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

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

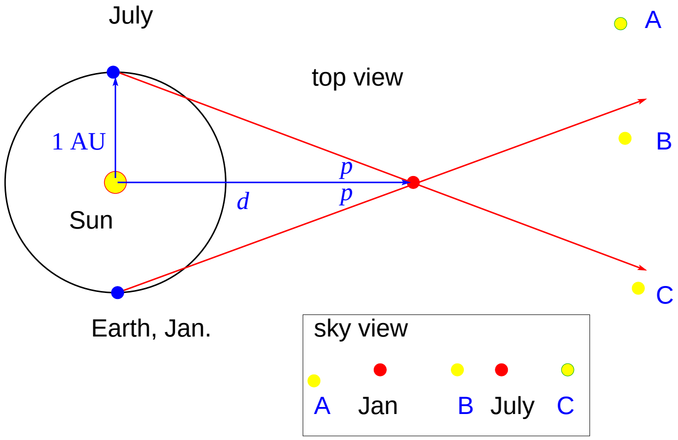
as Earth orbits, our viewpoint shifts (slightly!)
$\longrightarrow$ nearby $\star$s appear to move w.r.t. background $\star$s



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 $d = 1\ \ \text{au}/\tan p$

but p tiny! ($\lesssim 1$ arc sec $\sim 10^{-5}$ rad $\ll 1$)

$\rightarrow \tan p_{\text{rad}} \approx p_{\text{rad}}$, so

$d = 1\ \ \text{au}/p_{\text{rad}}$, or

$$d = \frac{1\ \text{pc}}{p_{\text{arcsec}}} \tag{2}$$

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

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

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

occasionally use **light year** = distance light travels in 1 yr

$1\ \text{lyr} = c \times 1\ \text{yr} = 9.5 \times 10^{15}\ \text{m}$

and so: $1\ \text{pc} = 3.26\ \text{lyr}$

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

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

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

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

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**

$$d_L = \sqrt{\frac{L}{4\pi F}} \tag{3}$$

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
→ a stellar “police lineup”
→ then differences in F only due to diff in L
→ 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

Decoding Starlight

The facts of life for stellar astrophysics:

- most stars are *unresolved*
  appear as point sources to our telescopes
- thus we cannot map their surfaces

for most stars: all we can measure are *broadband colors*
or more generally their *spectra*

`www: example spectra: the Sun, other stars`

Q: what strikes you?

Q: what physics needed to understand?

Stellar Spectra: First Impressions

observed stellar spectra: **commonalities**

- *broad wavelength* IR, optical, UV
- show *continuum* – emission at all wavelengths
  not just a collection of emission lines
- see many sharp-ish dips: *absorption lines*

spectral **variety**

- great range of weighting across wavebands → *colors*
- great variety in line patterns, depths, widths

all of this carries enormous information!

to decode: need to understand light interactions with matter

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 → changing EM forces → 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?

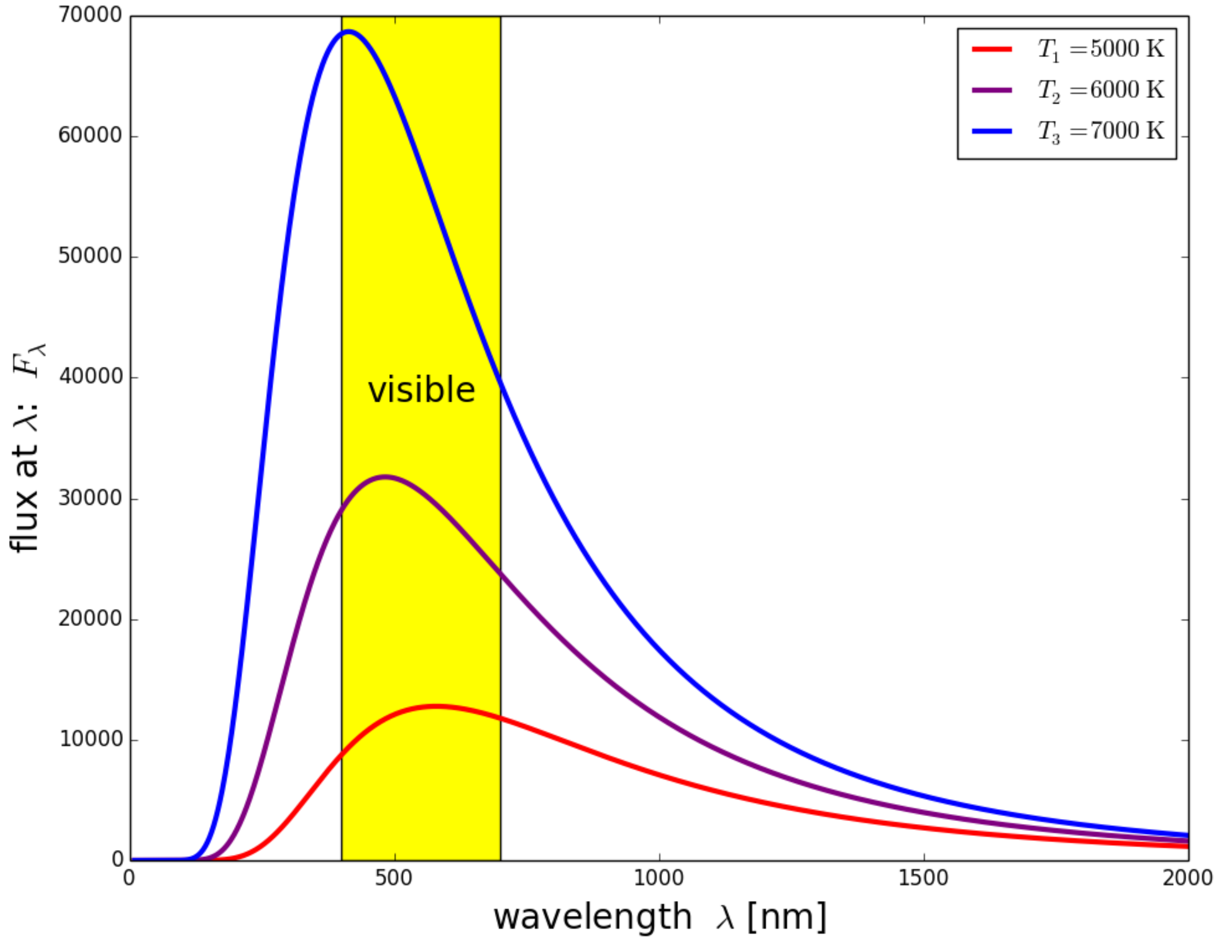
perfect absorber of light: “blackbody”

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

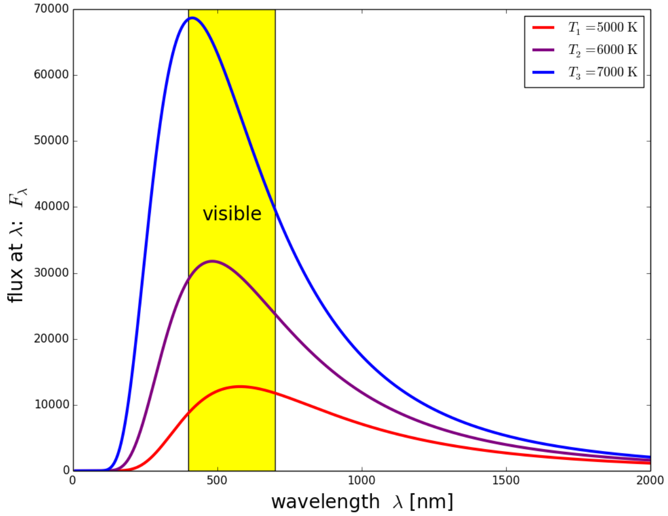


Q: trends vs λ?

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:

$$\lambda_{\text{peak}} = \frac{0.29 \text{ cm K}}{T} \propto \frac{1}{T} \tag{4}$$

hotter → more blue → shorter λ

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

not only good for household objects, but also for galaxies
`www: multiwavelength star clusters, galaxies`

X-ray emission seen from Cassiopeia A
`www: Cas A spectrum`
some of this is thermal emission: how hot is it?

$T \sim 0.29 \text{ cm K}/10^{-7} \text{ cm} = 3 \times 10^6 \text{ K !}$

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 $T_{\rm color}$*?*

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 $T_{\text{color},\odot} \approx 5900\ \text{K}$
check: white sunlight → peaks min-optical $\lambda_{\text{max}} \sim 500\ \text{nm}$
gives $T_{\text{color}} = 0.3\ \text{mm K}/\lambda_{\text{max}} \sim 6000\ \text{K}$ 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

$$F_{\text{surface}}(T) \overset{\text{blackbody}}{\equiv} B(T) = \sigma T^4 \quad \boxed{\textbf{Stefan-Boltzmann law}} \tag{5}$$

- 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**!

$$4\pi R^2\, B = 4\pi R^2\ \sigma T^4 = \text{flux} \times \text{area} = \text{power} = L \tag{6}$$

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

$$T_{\text{eff}} = \left(\frac{L}{4\pi\sigma R^2}\right)^{1/4} \tag{7}$$

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