Astro 404

Lecture 3

Aug 27, 2021

Announcements:

- **Problem Set 1** posted today on Canvas
  due **on Canvas in pdf**, next Friday Sept 3 at 5:00pm

- PS1 includes Introduction on Canvas
  remember to post your and comment on 2 others
  some work already graded, but final grades only after due date

- Reading assignments posted on course Schedule
  in Course text: Prialnik
  readings complement lectures
  assignments updated as we go along

Problem Sets

- problem sets are non-trivial
  but usually not as bad as they look
  wordy writeups are to help guide you and get the punchlines

- you may speak to me, the TA, and other students
  in person or HW Discussion on Canvas
- but you must *understand* your own answers
  and write them *yourself* and *in your own words*
- you may *not* consult old ASTR 404 problem sets/solutions

- Upload your answers as **pdf file**
  can scan handwritten *legible* solutions
  free apps make this easy
  check your file after uploading!

Last Time: Electromagnetic Radiation

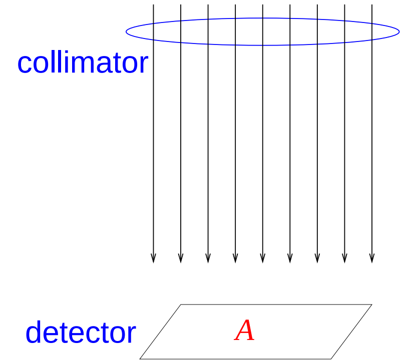
Q: why electromagnetic? why radiation?

Q: spectral regions with $\lambda < \lambda_{\text{optical}}$*?* $\lambda > \lambda_{\text{optical}}$

Q: why is EM radiation so important for stellar astrophysics?

Observables: Energy Flow

to understand light we must quantify its properties



consider idealized light detector of area A
receives incident radiation from a star
over exposure time δt

energy received in exposure: $\delta\mathcal{E}$
depends on the starlight itself, but also on detector
via A and δt

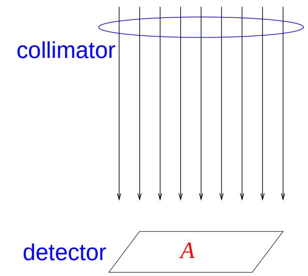
Q: how does $\delta\mathcal{E}$ depend on A? δt?
Hint: effect on $\delta\mathcal{E}$ if double detector size? exposure time?

energy received depends partly on observer:

- $\delta\mathcal{E} \propto A$

  larger collecting area = bigger "light bucket"

  $\rightarrow$ catch more starlight energy



- $\delta\mathcal{E} \propto \delta t$

  longer exposure = more energy accumulated

and thus:

$$\delta\mathcal{E} \propto A\ \delta t \tag{1}$$

so energy collected depends partly on budget and patience!

Q: how can we remove this detector dependence an thus isolate an intrinsic property of the incoming starlight?

Q: what is the common name for this property?
Q: what are its units?

Energy Flux

the quantity independent of detector, and
intrinsic to source and distance:
radiant **energy flux** (or just "flux")

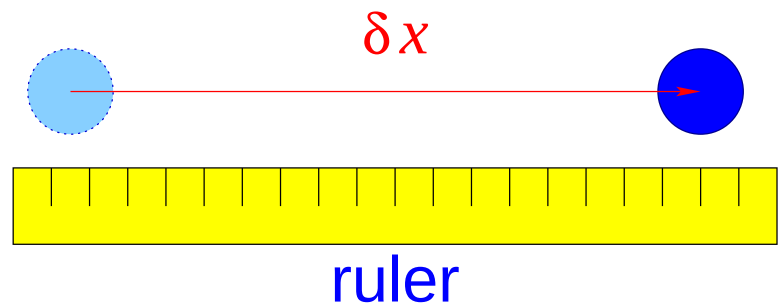
$$F = \frac{dE}{A\,dt} = \frac{dE/dt}{A} = \frac{\text{Power}}{\text{Area}} \tag{2}$$

flux also known as: (apparent) brightness

flux units: $[F] = [\text{erg cm}^{-2}\ \text{s}^{-1}]$ or $[\text{Watt m}^{-2}]$

A Possibly Useful Analogy

imagine: we want to study the motion of a particle travelling along the x-axis



we track the particle for time δt, and measure distance δx

we notice: distance travelled satisfies $\delta x \propto \delta t$
so: distance travelled depends on how long we wait

to isolate an intrinsic property of the motion: take ratio!

$$\frac{\delta x}{\delta t} \equiv v \tag{3}$$

of course: this is the velocity!
key intrinsic property of motion

by analogy: flux defined by ratio

$$F = \frac{\delta\mathcal{E}}{A\ \delta t} \to \frac{d\mathcal{E}/dt}{A} = \frac{\text{power}}{\text{area}} \tag{4}$$

and just as velocity measures rate of position change
for a localized particle
flux measures rate of EM energy change, per unit area
for a beam of light

for experts–electromagnetic flux is also

- the EM energy "current density"
- in classical EM picture: EM flux is Poynting flux $F = c|\vec{E} \times \vec{B}|/4\pi$

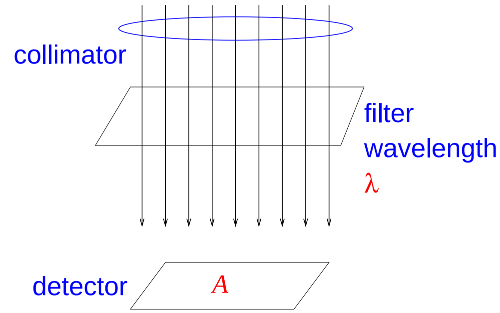
but we know light can have different wavelengths

∞

Q: how to modify experiment to isolate one λ?
Q: how to quantify the results?

tools to isolate one λ:

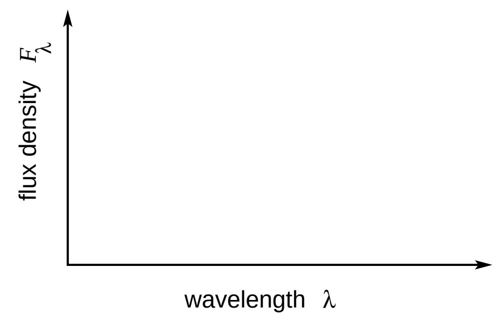
- filter
- prism
- grating



result: flux at each wavelength $F_\lambda = dF/d\lambda$

"flux density" at λ

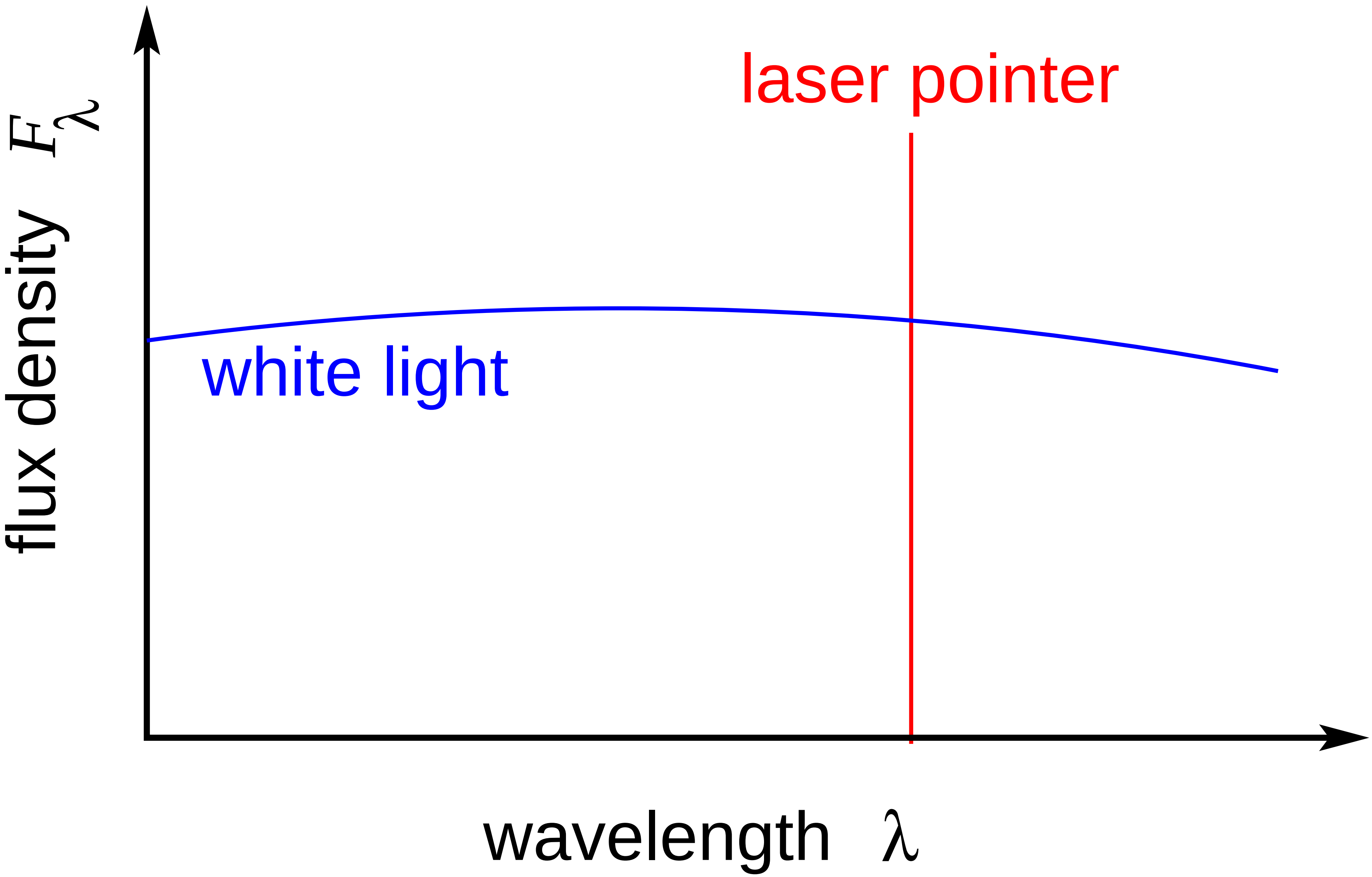
collection of all F_λ: **spectrum**



Q: spectrum of laser pointer? light bulb? Sun?

note:

- if using frequency ν, we have $F_\nu = dF/d\nu$
- total ("integrated") flux: $F = \int F_\lambda \, d\lambda = \int F_\nu \, d\nu$


laser pointer
white light
flux density F_λ
wavelength λ

Stellar Astronomy

geometry of the sky: spherical
stars appear “fixed” (on human timescales)
to a vast *celestial sphere*

star locations: angular coordinates on celestial sphere

offical celestial sphere divided into 88 regions: *constellations*
cover the sky like states on a map
so each point on sky lies in exactly one constellation

brightest star in night sky: *Sirius* in constellation Canus Major
officially: α Canis Majoris (αCMa)
unofficially: the “dog star” `www: Canus Major`

iClicker Poll: Naked-Eye Stars

Vote your conscience!

On a clear night, outside of a city,
about how many stars can you see with the naked eye?

A More than the number of people in a packed movie theater

B More than the number of people at a UI football game

C More than population of Great State of Illinois

D More than the population of Earth

Stellar Flux Observed

to naked eye, in clear sky:

about 6000 (!) stars visible over celestial sphere

$\Rightarrow$ about 3000 at any one night

...but this is just the "tip of the iceberg"

Sun: $F_\odot = 1370$ W m^{-2}

Sirius, brightest star, has

$$\frac{F_{\text{Sirius}}}{F_\odot} = 7.6 \times 10^{-11}$$

faintest stars observed with modern telescopes:

$F_{\text{faintest}}/F_\odot \lesssim 10^{-23}$ and $F_{\text{faintest}}/F_{\text{Sirius}} \lesssim 2 \times 10^{-13}$!

more than 1 trillon times fainter–a huge range in stellar fluxes!

Q: what does this suggest for how we quantify flux?

Stellar Flux Quantified

huge range in stellar fluxes suggests we focus on exponent
that is, take *logarithm* of flux
so: convenient to express measured flux as $m \propto \log F$

also: *human eye has logarithmic response to brigtness*
ancient Greeks quantified stellar brightness
each star given "**apparent magnitude**" (1st, 2nd, 3rd, etc)
due to log sensitivity of naked eye:
apparent magnitude differences correspond to *flux ratios*

$$m_2 - m_1 \propto \log F_2 - \log F_1 = \log \frac{F_2}{F_1} \tag{5}$$

very convenient! that's the good news.

Q: units of apparent magnitudes?
Q: what's the bad news?

Apparent Magnitude Scale for Flux

good news: logarithms convenient for star fluxes
this is built into magntiude scacle
mag units: dimensionless! (but usually say “mag”)
because mags are *logs* of *ratio* of two
dimensionful fluxes with physical units like W/m^2

bad news: historically, mag conceived as “rank”
brightest stars are 1st magnitude: top dog
next dimmer stars are 2nd magnitude, etc.
so $m \propto -\log F$: smaller flux $\leftrightarrow$ larger magnitude

to match historic system, modern fluxes set by:
• $m_2 - m_1 = 5$ mag corresponds to $F_1/F_2 = 100$
• magnitude “zero point” set by star Vega: $m_{\rm zp} = 0 = m(F_{\rm Vega})$
this gives magnitdue m vs flux F relation

$$m = -\frac{5}{2}\log_{10}\left(\frac{F}{F_{\rm zp}}\right) \tag{6}$$

Living with Magnitudes

stellar fluxes tabulated as magnitudes. sorry.

$$m = -\frac{5}{2} \log_{10} \left(\frac{F}{F_{\rm zp}} \right) \tag{7}$$

• ex: Sirius has $m_{\rm Sirius} = -1.45 \rightarrow$ brighter than Vega
so: $F_{\rm Sirius} = 3.8 F_{\rm Vega}$

• ex: Polaris (α Ursae Minorus = αUMi)
Q: what's this? why name?
$m_{\rm Polaris} = 2.02$
Q: rank brightness of Polaris, Sirius, Vega?

Star Color

stars have colors! and they are different!

`www: Orion, Geminiobjective prism spectra`

very useful to *quantify* color!

could try spectrum peak $\lambda_{\rm max}$ – but often,

absorption lines $\rightarrow$ spectrum not smooth

also: full spectrum from spectrometer "expensive"

$\rightarrow$ have to collect more light since spread out

Q: what's a cheaper way to get color information from an image?

Note: imaging detectors are CCDs

$\rightarrow$"democratically" count all photons they see equally

regardless of wavelength

To get color information without a spectrometer:
⇒ use **filter** which accepts light
only in a *range* of wavelengths: "passband"

`www: filter wheel`

flux F_B → $m_B = B$: blue magnitude, centered at $\lambda \approx 440$ nm
flux F_V → $m_V = V$: "visual" mag, yellowish, $\lambda \approx 550$ nm
response roughly similar to naked eye
...and many others
www: filter λ ranges

images in multiple filters ↔ crude spectrum

Q: how to quantify color based on filter data?

Color Index

measure color by comparing flux at different λ bands

"**color index**" is *magnitude difference*, e.g.,

$$B - V = 2.5 \ \log \left(\frac{F_V}{F_B} \right) + \text{const} \tag{8}$$

$\rightarrow$ measures ratio of fluxes in two bands

ex: `www: Orion`
Betelgeuse reddish, $B - V = 1.5$
Rigel bluish, $B - V = -0.1$

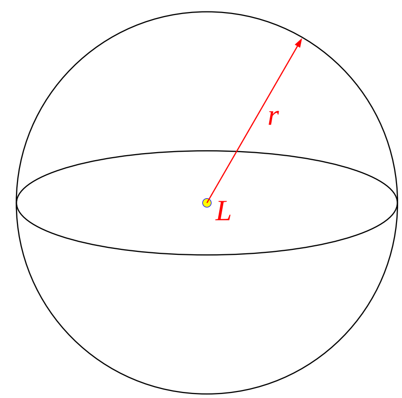
Flux from a Point Source

consider spherical source (hint: it's a star!) of size R
emitting light isotropically (same in all directions)
with constant *light power ouput* $d\mathcal{E}_{\text{emit}}/dt = L$ ("**luminosity**")

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

$$F(r) = \frac{\text{power at } r}{\text{area at } r} = \frac{L}{4\pi r^2}$$

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

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

- no emission, absorption, or scattering outside of source
  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

Apparent brightness and luminosity related by

$$\text{observer-dependent } F = \frac{L}{4\pi r^2} \; \frac{\text{observer-independent}}{\text{observer-dependent}} \tag{9}$$

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

Q: how measure star L?

To find $\star$ luminosities

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

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

Q: what about color–how does that depend on distance?