Astronomy 501: Radiative Processes

Lecture 2

Aug 24, 2022

Announcements:

- Syllabus available – look it over
- Canvas should now be visible (ahem!)
- Instructor office hours: today after class, or by appt
- plan is to *meet in person* next Mon & Wed
  will confirm before then

Last time:

⋆ Overview and Appetizer
⋆ Multimessenger observables

Today: The great work begins!

⋆ electromagnetic observables
⋆ quantifying radiation – lots of definitions!

Program Notes: ASTR 501 Bugs/Features

- ▷ notes online–but come to class!
  some people find it convenient to print 4 pages/sheet

- ▷ class $\in$ diverse backgrounds: ask questions!

- ▷ Socratic questions

- ▷ typos/sign errors
  Dirac story
  please report errors in lectures
  pretty please promptly report errors in problem sets;
  if need be, errata posted and emailed

EM Radiation Observables

Warmup: Electromagnetic Radiation

want to define terms and try to be clear about assumptions

What is light?

classically: electromagnetic waves

- move at speed c in vacuum
- monochromatic wavelength and frequency related by $\lambda\nu = c$
- visible band roughly $\lambda_{\text{vis}} \sim 400 - 700$ nm

quantum mechanically: photons

- electromagnetic quanta: massless, spin-1 particles
- Planck: energy $E_\gamma = h\nu = hc/\lambda$
- but Einstein: $E^2 - (cp)^2 = (mc^2)^2$, and here $m_\gamma = 0$, so momentum $p_\gamma = E_\gamma/c = h/\lambda$

$\rightarrow$ particle/wave duality: which description is appropriate depends on measurement

The Electromagnetic Window to the Cosmos

in this course:
we will focus mostly on *EM radiative processes*
$\rightarrow$ but much the technology we will build
also applies to other messengers

Q: very broadly, what devices/methods exist to detect EM signals?

Q: very broadly, what do the detectors measure?

Detecting EM Radiation

historically:

- until 19th century, astro-detector = human eye
- photographic film revolutionized astronomy

today: broadly, two main types of measurements

- **detecting and counting photons**
  e.g., CCDs collect photons via the photoelectric effect
  span IR, optical, UV, X ray
- **measuring energy**
  e.g., bolometers and radiometers collect energy in mm, radio

Q: what are astronomical (EM) observables?

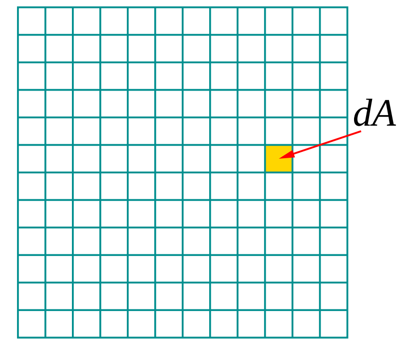
Electromagnetic Observables in Astronomy

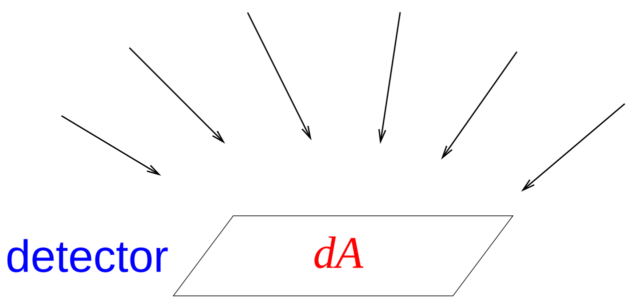
In part drawn from `http://background.uchicago.edu/~whu/Courses/ast305_10.html`

- *apparent brightness*: energy or photon flow
  really: measure *energy* accumulated over exposure time
- *spectrum:* flux distribution in
  different energy (frequency, wavelength) bands
- *direction on sky*
- *solid angle*: size on sky– *if* source is *resolved*
- *phase* information *if* measured (radio, optical)
- *polarization* (linear, circular, elliptical) *if* measured
- *light curve* = time history of observables
  if measurements span multiple epochs

Energy Flow

consider an idealized detector element (“pixel”)
with *area* dA
measures all incident radiation
all rays, all directions, all ν
over *exposure time* dt





energy received $d\mathcal{E}$ in exposure depends on detector
because $d\mathcal{E} \propto dA\, dt$ *Q: why?*

∞

thus energy received is detector-dependent via dA
Q: how to remove detector dependence?

Energy Flux

measures **apparent brightness** independent of detector, and intrinsic to source and distance: **energy flux** (or just "flux")

$$F = \frac{dE}{dA\,dt} = \frac{d\text{Power}}{d\text{Area}} \tag{1}$$

cgs units: $[F] = [\text{erg cm}^{-2}\ \text{s}^{-1}]$

Note:

- usually, detector really measures energy received during exposure, i.e., time-integrated flux
  fluence $\mathcal{F} = d\mathcal{E}/dA = \int_{\delta t} F(t)\, dt$
  derive $F_{\text{obs}} = \mathcal{F}/\delta t =$ time-avg flux during exposure

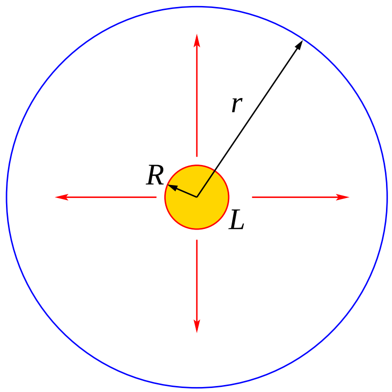
- if measure *photon counts* dN, sometimes report **photon** or **number flux** $\Phi = dN/dA\,dt$
  cgs units: $[\Phi] = [\text{photons cm}^{-2}\ \text{s}^{-1}]$

Inverse Square Law

consider spherical source of size R
emitting isotropically
with constant power L ("luminosity")

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

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



inverse square law

Q: what principle at work here?
Q what implicitly assumed?

Inverse Square Law

$F = L/4\pi r^2$ 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 soon consider these in detail
- no relativistic effects (redshifting, time dilation)
- Euclidean geometry–i.e., no spatial curvature,
  usually fine unless near strong gravity source

Note: inverse square suggests similarity with electrostatics
and invites use of Gauss' Law
for fun: think about why things aren't so simple for radiation

Standard Candles

flux is not intrinsic to source: depends on both

- emitter luminosity L which is intrinsic
- but also observer distance r

$$F = \frac{L}{4\pi r^2} \tag{3}$$

if L known somehow (*Q: how?*): "standard candle"
then measure F and infer **luminosity distance**

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

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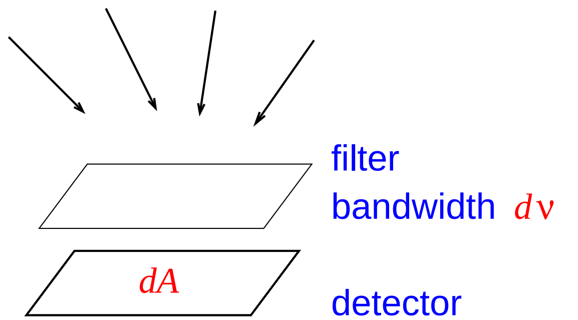
so far: (total) flux sums over all λ or ν
Q: what if we are interested in the spectrum?

Spectrum: Specific Flux

introduce a filter or grating, to disperse by λ
so detector receives small range of frequencies
in $(\nu, \nu + d\nu)$: monochromatic frequency ν
with bandwidth $d\nu$



energy received: $d\mathcal{E} \propto dA \ dt \ d\nu$

define **specific flux** or flux density

$$F_\nu = \frac{dE}{dA \ dt \ d\nu} \tag{5}$$

cgs units: $[F_\nu] = [\mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}}]$

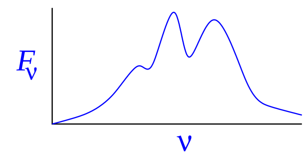
Q: what does this measure physically?
Q: how to use F_ν to find total flux F?

specific flux or flux density

$$F_\nu = \frac{dE}{dA\ dt\ d\nu} \tag{6}$$

measures **apparent brightness at each color**

- a less compact but more explicit notation is $dF/d\nu$
- flux density F_ν is a curve over ν ("spectrum") encodes *much more information* than single-valued F



- *total flux* is

$$F = \int F_\nu\ d\nu = \int \frac{dF}{d\nu}\ d\nu \tag{7}$$

- can identify monochromatic flux by λ or photon energy E and thus can also define $F_\lambda = dF/d\lambda$ and $F_E = dF/dE$

Angular Resolution and Imaging

unavoidable fact of life in imaging:
real telescopes have finite **angular resolution** $\theta_{\rm res}$

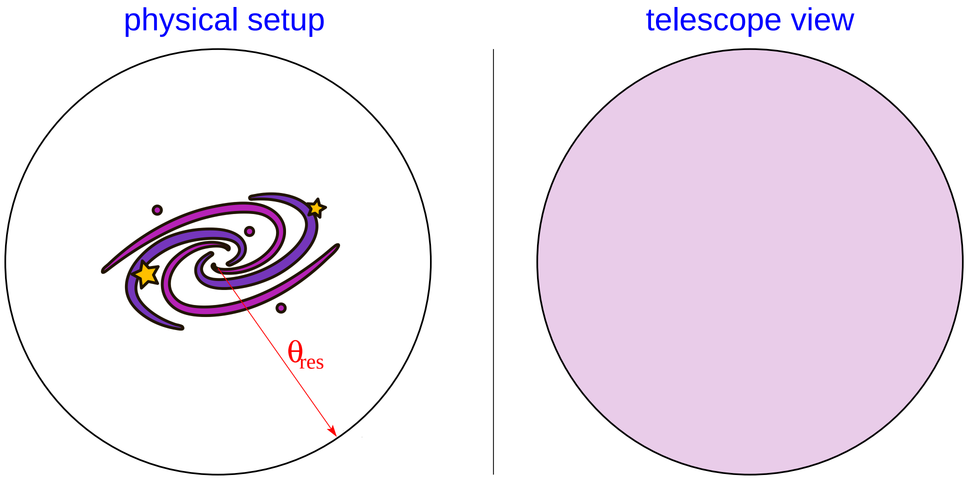
physically: smallest angular size distinguishable in an image
quantified by telescope response to idealized point source
"point spread function"

- diffraction: fundamental limit $\theta_{\rm diff} = 1.22\, \lambda/D$
- seeing: atmospheric distortion (twinkle) smears rays
  in optical $\theta_{\rm atm} \gtrsim 0.4$ arcsec
  avoid by going to space or using adaptive optics

If source angular diameter $\theta_{\rm source} < \theta_{\rm res}$
Q: What do we see? what can we measure?

Unresolved Objects

Unresolved objects: $\theta_{\text{source}} < \theta_{\text{res}}$ smaller than angular res.

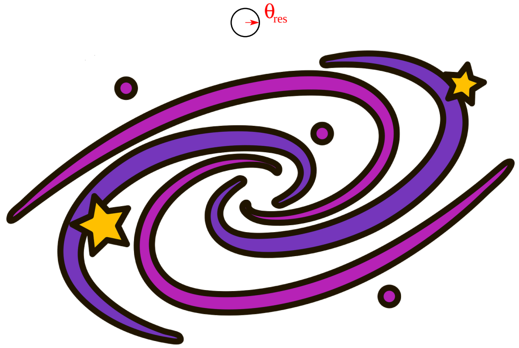


- all rays from source smeared over θ_{res}
- features not visible in image, appears pointlike ("*point source*")
- can only report combined brightness of all rays
  specific flux F_ν and total flux F_ν

In opposite limit: $\theta_{\text{source}} > \theta_{\text{res}}$

Q: What do we see? what can we measure?

Resolved Objects



Resolved objects: $\theta_{\text{source}} > \theta_{\text{res}}$

- larger than angular resolution
- image is *extended object* on the sky
  not pointlike!

Q: what would this image look like in telescope?

rays spread over finite area on sky:

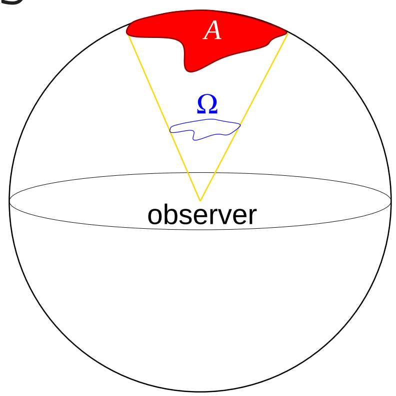
need a way to describe individual rays

"brightness at at point"

Areas on the Sky: Solid Angle

Area on sky: **solid angle** – 2D angular area
a spherical cap of area A subtends solid angle

$$\Omega = \frac{A}{r^2}$$



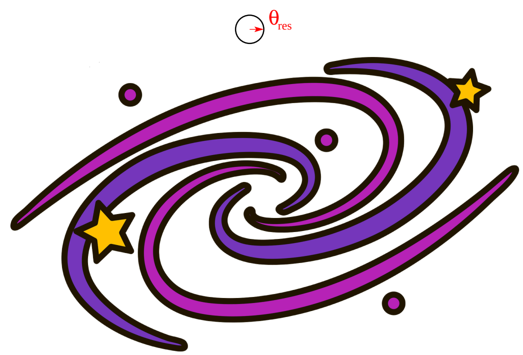
- Ω is dimensionless, but often quoted steradians [sr] = [rad^2]
- Full sky is 4π sr $= 41,252$ deg^2

In spherical coordinates: $d\Omega = \sin\theta \; d\theta \; d\phi$
spherical cap has area $dA = \sqrt{g_{\theta\theta}g_{\phi\phi}}d\theta d\phi = r^2 \sin\theta \; d\theta \, d\phi = r^2 \, d\Omega$

Compare 1D circular angular measure: for circle of radius r
arc length s subtends angle $\theta = s/r$

Imaging Extended Objects

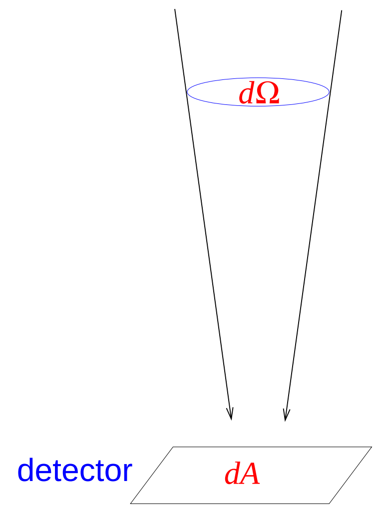
Resolved image of object on sky:
rays come from different directions
spread over finite solid angle



Q: what if we want to concentrate on one region/bundle of rays?
Q: how do we change measurement? what is new observable?

Intensity or Surface Brightness

Isolate small region (solid angle $d\Omega$) of sky by introducing a *collimator*



If source is extended over this region sky, energy flow received depends on collimator acceptance $d\Omega$: $d\mathcal{E} \propto dA\ dt\ d\Omega$

so define flux per unit "surface area" of sky: **intensity** or surface brightness (or sometimes just "brightness")

$$I = \frac{d\mathcal{E}}{dt\ dA\ d\Omega} \tag{8}$$

cgs units: $[I] = [\mathrm{erg\,cm^{-2}\,s^{-1}\ sr^{-1}}]$, with sr = steradian

Q: what has been implicitly assumed?

have assumed light travels in straight lines: "*rays*"

- for infinitesimal solid angle $d\Omega$, collimator selects a small "*bundle*" or "pencil" (Chandrasekhar) of rays
- intensity I describes *one* individual ray (one direction) while flux describes *all* rays (all directions)

thus: implicitly adopted *geometric optics* approximation:
we have ignored diffraction effects
good as long as system scales $\gg \lambda$

Note: for each direction/ray (θ, ϕ), intensity I takes single value
resulting image is "grayscale" map of all-color brightness

Q: What if we are interested in the spectrum?