Astro 404
Lecture 2
Aug 28, 2019

Announcements:

- In this course: everything due on Fridays – except this week!
- PS 1 will be posted by this Friday, due Sept 6
- Syllabus available
- Instructor Office Hours: today and every Wednesday 11:00-noon
- Physics Colloquium today at 4pm, Loomis 141
  Prof. Nicolas Yunes, U of Illinois
  "What's next in gravitational wave physics?"

Last time: overview

Now: the Great Work begins!

Program Notes: ASTR 404 Bugs/Features

- ▷ notes online–but come to class!
  if you print out, some people like 4 pages/sheet
- ▷ class $\in$ diverse backgrounds: ask questions!
- ▷ Socratic questions *Q: What's that?*
- ▷ typos/sign errors
  Dirac story
  please report errors in lectures
  pretty please promptly report errors in problem sets;
  if need be, errata posted

Online Notes

Class notes will be posted online
and available all semester

Pros:

- you are not a stenographer—can use your brain to think and not transcribe
- don't have to read my bad handwriting

Cons:

- tempting to be astro-hypnotized
  so: I'll ask questions throughout
- might give incorrect impression that there's no reason to come to class
  but: I'll give pearls of wisdom verbally
  ...and you'll miss the demos, music, and movies

ω Bargain:
- I'll avoid railroading you
- you pay attention, ask questions when confused/interested

Preliminaries

We'll see that stars interweave all 4 fundamental forces
stellar astrophysics has given rise to 9 Nobel Prizes

Upside: we'll see a symphony of physics play out
across immense scales of space and time
Downside: we will need many physics, astronomy tools
to appreciate this grandeur

Begin with the data–what we can measure

Q: what properties of stars can we directly measure?
Q: what measurements are only available for the Sun?
With partner: write list

Astrophysicist's Wishlist

Note that much of what we would *like* to know about stars (and other celestial objects), such as

- properties: distance, size, mass, temperature, speed, spin rate, composition, ...
- physics: orbits, origin, evolution, ...

are **not** directly observable
i.e., these data aren't output of a telescope

what *is* directly observable??

Observer's Toolbox

hard-nosed list of direct observables
which **do** come out of a scope: can measure

- **position on sky** – **astrometry**
- **apparent brightness** – **photometry**
- **color/spectrum** – **spectroscopy**
- **polarization** – **polarimetry**
- **time changes** in any/all of these above

lesson: can only measure light! can look but not touch!
⇒ need to understand light
and its interactions with matter
to decode maximum available cosmic information

amazingly lucky circumstance: can get there from here!

```
You can't always get what you want
No you can't always get what you want
You can't always get what you want
But if you try sometimes
You might find
You get what you need
  -- Astrophysicist Mick Jagger
```

MicroReview: Electromagnetic Radiation

Wave Properties

Maxwell's eqs: electric & magnetic fields* can support waves
and light is made of such waves
$\longrightarrow$ light is **electromagnetic radiation**

Heads-up: in physics/astrophysics "radiation" $\equiv$ EM radiation
i.e., transport of EM energy across space by particles or waves
$\neq$ radioactivity $=$ "ionizing radiation"
Q: examples of radiation in ASTR404 sense?

simplest wave: sinusoidal; more complex patterns
can be decomposed into sums of sinusoids (Fourier)
Q: basic anatomy of any propagating sinusoidal wave?
Q: corresponding properties of light waves?
i.e., how interpreted by your personal photodetectors?

* no relation to instructor

Electromagnetic Waves

- EM wave **speed**: $c = 3.0 \times 10^8$ m/s
- spatial oscillation period: **wavelength** λ
- time oscillation **period**: P [sec/cycle]
  related to **frequency**: $f = \nu = 1/P$ [cycles/sec]
- wave travels: in time $\Delta t = P = 1/f$, pattern moves
  distance $\Delta x = \lambda$, and since speed is
  $c = \Delta x / \Delta t \rightarrow$ $\boxed{c = \lambda f}$

note: EM radiation can have any wavelength
from subatomic through to macroscopic!

	radio	infrared	visible	ultraviolet	X-ray	γ-ray
ν [Hz]	$< 10^{11}$	$\sim 10^{13}$	$\sim 5 \times 10^{14}$	$\sim 10^{16}$	$\sim 10^{18}$	$\sim 10^{20}$
λ [m]	$> 10^{-3}$	$\sim 10^{-5}$	$\sim 5 \times 10^{-7}$ m	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-12}$

Radiation Particle Properties: Photons

leap forward: 20th century revolution of quantum mechanics
Max Planck (1858–1947):
light comes in "chunks" or "packets" of energy
$\rightarrow$ **quantized** $\Rightarrow$ photon (symbol γ)

A photon's energy set by color: $E_\gamma = hf = hc/\lambda$
where Planck's constant $h = 6.63 \times 10^{-34}$ J s
often also use $\hbar = h/2\pi$

Q: photons massless–how come $E_\gamma \neq 0$*??*

In general (i.e., according to Special Relativity),
a particle of mass m and momentum $\vec{p}$ has energy
$E = \sqrt{(mc^2)^2 + (cp)^2}$

but $m_\gamma = 0$
so photons have $E_\gamma = cp_\gamma$,
which means $p_\gamma = h/\lambda$:
photons carry momentum too!

so photons moving outward in a star
when scattered or absorbed: deposit momentum
photons can exert force! $\leftrightarrow$ **radiation pressure**

Q: astrophysical example? `www: example illustrated`
Q: under what conditions would effect be extreme? `www: examples`
note here the triumph of outward radiation over inward gravity

iClicker Poll

Far across the Universe, a star explodes as a supernova emitting electromagnetic radiation of many wavelengths all starting at the same time

Which of these photons will we observe *first*?

A infrared

B red

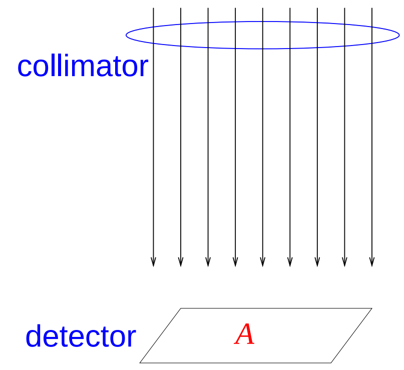
C blue

D X-ray

E it's a tie! we see them all at the same time

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?

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")

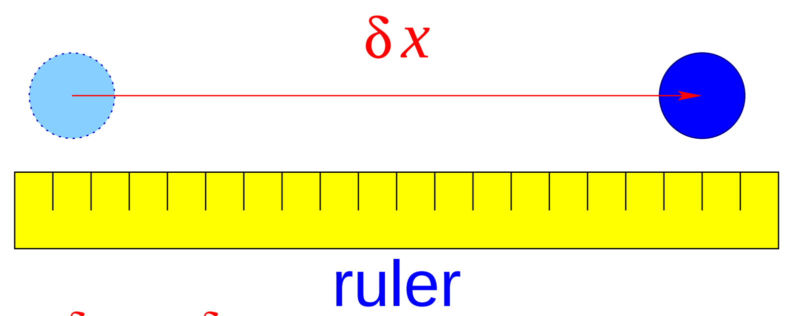
$$F = \frac{dE}{A\,dt} = \frac{dE/dt}{A} = \frac{\text{Power}}{\text{Area}} \tag{2}$$

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

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

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

for experts–flux is also

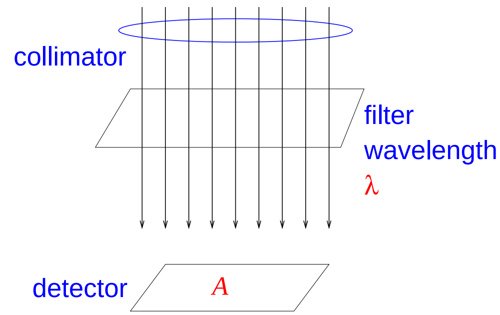
- the EM energy "current density"
- in classical EM picture: flux is Poynting flux $F = c|\vec{E} \times \vec{B}|/4\pi$

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"

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: $F = \int F_\lambda \, d\lambda = \int F_\nu \, d\nu$