Astro 210

Lecture 3

Aug 30, 2013

Announcements:

- PS 1 available online and hard copies in class
  due at start of class next Friday, Sept 6
  Note: problem sets are non-trivial
  but usually not as bad as they look
  wordy writeups are to help guide you and get the punchlines
- Syllabus available
- iClicker GO app should work for this course
- ASTR 401 due Monday:
  pick a topic & post on A401 Compass page
  and email me for appointment

Last time: electromagnetic radiation

Q: why electromagnetic? why radiation?

Q: why so important for galaxies and cosmology?

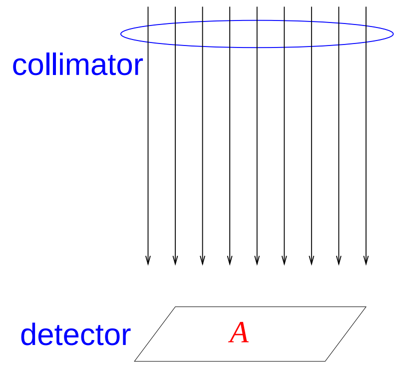
Q: directly observable radiation properties?

Q: definition of flux? units? everyday experience?

Q: what is luminosity? for how is it different from flux?

What is flux and why is it useful?

empirical approach: what do we really measure
and what does it tell us?



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

we saw:

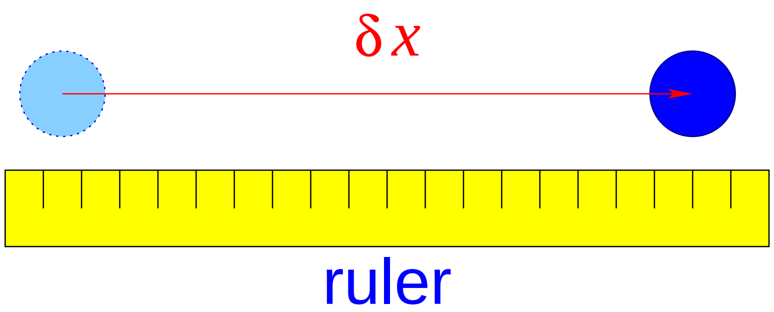
$$\delta \mathcal{E} \propto A \ \delta t \tag{1}$$

energy collected is basic observable, and *does* encode starlight info
but *also* depends on budgets and patience *how?*

goal: isolate the light signal properties *independent of detector*
i.e., *intrinsic* to the light

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!

$$\frac{\delta x}{\delta t} \equiv v \tag{2}$$

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

by analogy: flux defined by ratio

$$F = \frac{\delta \mathcal{E}}{A\ \delta t} \rightarrow d\mathcal{E}/dtA = \frac{\text{power}}{\text{area}} \tag{3}$$

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 $F = c|\vec{E} \times \vec{B}|/4\pi$

Matter, Temperature,and Light

hot matter glows (think stove burner)
temperature – radiation connection
very useful for astronomers!

but atoms made of charged particles
motion $\rightarrow$ changing EM forces $\rightarrow$ light

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
diagram: blackbody Flux F vs λ

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

diagram: BB spectrum for T_1, $T_2 > T_1$

Wien's law:

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

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`
IR!
`www: IR gallery--coffee, people, puppy`

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

X-ray emission seen from galaxies, clusters of galaxies
`www: X-ray emitting cluster`
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?

Blackbody Flux

hotter objects are glow brighter than cooler ones
i.e., blackbody surface flux increases with T

blackbody flux: summed (integrated) over all λ

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

- 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

Stars

The Facts of Life for Stars

Fact: stars constantly radiates energy
and at a huge rate!
for the Sun: $dE/dt = L_\odot = 4 \times 10^{26}$ Watts!

Fact: stars have a finite ($\neq \infty$) mass
and thus a finite fuel supply (whatever that fuel may be)

Fact: Energy is conserved
no free lunch!

Q: therefore?

Star Lives and the Consequences of Energy Conservation

the Sun and all stars:

- are constantly releasing energy to the rest of the universe, and
- require fuel, and are unable to "refuel" out of nothing, and
- thus must eventually run of out fuel

Thus:

- all stars – including the Sun – must eventually "burn out"
  = run out of fuel: *all stars are doomed to die*
  Q: important followup question?
- stars do not live forever

And thus:

- stars alive today were not alive forever
- *all stars must be born* as well as die

stars have life cycles

Stars: Stability

Consider the Sun: best-studied, most familiar star

solar size constant
$\Rightarrow$ not expanding, collapsing (on human timescales)
$\rightarrow$ surface at rest
$\rightarrow$ not accelerating
$\rightarrow$ no *net* force

yet the Sun definitely has mass & gravity
so every part of the Sun attracts every other part of the Sun
result is inward force on itself

Q: obviously the Sun does not collapse—what's going on?

Preventing Death By Black Hole

if gravity were the only force on the Sun
entire Sun in *free fall*!
$\rightarrow$ all matter pulled to center
$\rightarrow$ collapse to a black hole!

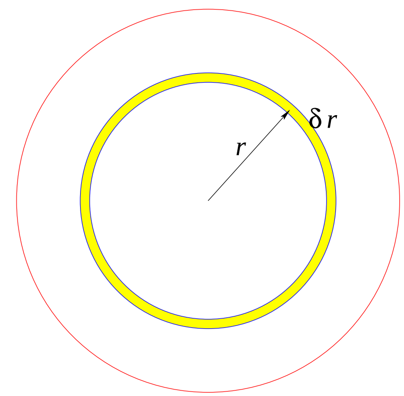
but this obviously is false! the Sun and stars do exist!
and are stable – Sun doesn't shrink daily!

must be another force acting outward: **gas pressure**

Director's Cut Extras

Stability of the Sun: Balance of Forces

Consider a shell of gas in the Sun, **at rest**
radius r, thickness $\delta r \ll r$
shell area $A = 4\pi r^2$
shell volume



$$V = \frac{4\pi}{3}[(r+\delta r)^3 - r^3] \approx 4\pi r^2\,\delta r = A\,\delta r$$

shell mass $m_{\text{shell}} = \rho V = \rho A\ \delta r$

shell weight $F_{\text{w}} = -g m_{\text{shell}} = -g\rho A\ \delta r$:
downward force, but doesn't fall!?

Q: why? gas has weight–why not all at our feet?

upward force

pressure: on bottom $P(r)$, on top $P(r + \delta r)$

net upward force

$$F_{\mathrm{p}} \;=\; \Delta P \times A = [P(r + \delta r) - P(r)]A = A\,\frac{dP}{dr}\,\delta r$$

hydrostatic equilibrium: $F_{\mathrm{weight}} = F_{\mathrm{pressure}}$

upward pressure exactly balances downward gravity

$\Rightarrow dP/dr = -g\rho = -GM(r)\rho(r)/r^2$

Note what this means:

$\rightarrow$ Sun's mechanical structure $\rho(r), M(r)$ intimately related to thermal structure $P(r) = \rho kT/\mu \propto T(r)$

analogy: balloon, basketball (inward elastic force vs outward P)

What is a Stars's "Surface"?

the Sun is made of gas
cannot have a sharp, hard boundary; has no edge

but does not look hazy; instead, do *see* sharp boundary:
Sun appears to have surface!
`www: Sun in white light`

Q: Why? what's going on?

The Solar Photosphere

observed surface $\rightarrow$ visible light emitted from
thin region/layer: "photosphere"
but why does light only come from this surface?
what defines the location of this surface?

Key idea: **photon scattering**
in Sun, photons *scatter* off electrons, ions
each photon scattered many (millions!) times
outward progress erratic: "random walk" *diagram: γ trajectories*
less scattering as move outwards and gas ρ decreases *Q: why?*
until finally γs escape $\rightarrow$ we see them

Q: so what sets photosphere location?

scattering frequency/probability increases with
higher gas $\rho \to$ more "targets" to hit
can define mean free path $\ell_{\rm mfp}$:
average γ pathlength ("stepsize") between scatterings

iClicker Poll: Mean Free Path and Density

Does photon mean free path $\ell_{\rm mfp}$ depend on the *density* ρ of the medium?

Which of these is most physically reasonable?

A $\ell_{\rm mfp} \propto \rho$

B $\ell_{\rm mfp} \propto 1/\rho$

C $\ell_{\rm mfp}$ independent of ρ

turns out: $\ell_{\rm mfp} \propto 1/\rho$

not crazy: if no medium at all, then no scattering:

so stepsize infinite $\ell_{\rm mfp} \to \infty$

and $\rho \to 0$ gives right answer

but if ultradense medium, many scatterers:

$\rho \to \infty$ means $\ell_{\rm mfp} \to 0$

Apply to photons in the Sun:

- at center: highest ρ, smallest $\ell_{\rm mfp} \sim 1$ cm (!) $\ll R_\odot$
  guaranteed scattering before leaving
- but as move outwards, $\rho \downarrow$ and so $\ell \uparrow$
- until ρ so low that $\ell_{\rm mfp} > R_\odot$
  $\to$ scattering finally "turns off"

Fun fact: the sunlight we see from the photosphere took millions of years to come from the Sun's core!