Astro 210
Lecture 26
March 26, 2018

Announcements

- good news: no new homework this week
- bad news: **Hour Exam 2** this Friday
  March 30, in class, info posted on Moodle

- **Night Observing one** *last chance after break*
  first clear night will be final opportunity
  due date extended to March 30

Shifting Gears

`www: big picture`

Thus far:

- night sky
- geocentric vs heliocentric theories
- solar system properties, bodies, origin

now–the Sun: nearest star

which leads to

- ⋆ stars
- ⋆ our Galaxy
- ⋆ other galaxies
- ⋆ the Universe

The Sun

The nearest star
and we will show: a typical star

The Sun: Vital Statistics

⋆ distance: $d = 1$ AU (by definition)!

⋆ radius: $R_\odot = 7 \times 10^8$ m $\simeq 100 R_{\rm Earth}$!

⋆ mass: $M_\odot = 2.0 \times 10^{30}$ kg
Sun has most of SS mass (99.8%)

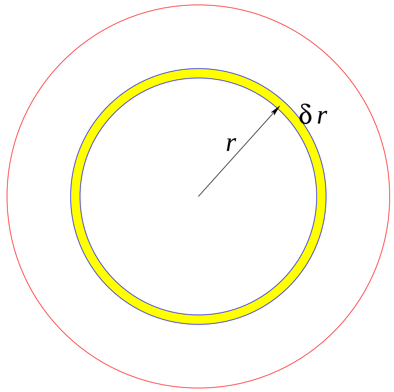
⋆ $\rho_{\rm avg} = 1400$ kg/m^3: $< \rho_{\rm rock,metals}$
composed of hot gasses (plasma)

The Sun: Stability

Sun size constant
$\Rightarrow$ not expanding, collapsing
$\Rightarrow$ $\boxed{\text{stable}}$
Why?

Note: not a trivial result, could have been otherwise
compare terrestrial, interstellar clouds–irregular shape, morph with time
$\rightarrow$ in lab, expect gasses expand to fill available space

iClicker Poll: Forces on a Shell of Solar Gas



Consider a shell of gas in the Sun, **at rest**
i.e., Sun not expanding, contracting

How many forces are acting on this shell?

A zero

B only one

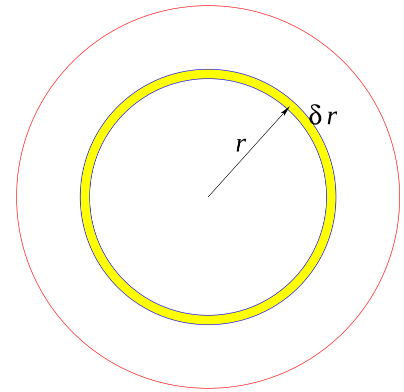
C more than one

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

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

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

net upward pressure exactly balances downward gravity

$$\frac{dP}{dr} = -g\rho = -\frac{GM(r)\rho(r)}{r^2}$$

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)

But what if equilibrium is disturbed?

⋆ consider a small perturbation (force) which
gives an extra downward push to our gas blob
Q: what might cause such a perturbation?

⋆ *Q: how does gas blob respond to this squeeze?*

extra downward force on gas blob

$\longrightarrow$ extra compression: ρ increase

but for ideal gas, $P \propto \rho T$

$\longrightarrow$ compression $\longrightarrow$ heating, pressurization

$\longrightarrow$ extra upward force

$\longrightarrow$ restores blob back to original height

(or even overshoots somewhat–oscillations: waves!)

$\Rightarrow$ no harm, no foul! equilibrium is stable!

basketball analogy: dribble

hit floor $\longrightarrow$ extra force $\longrightarrow$ compressed

internal pressure increased $\longrightarrow$ bounces back

`www: waves on Sun after flare`

What is the Sun's "Surface"?

the Sun made of gas
cannot have a sharp, hard surface, has no edge

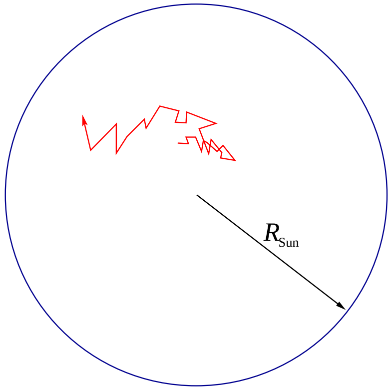
but does not look hazy; instead, do *see* sharp boundary:
Sun appears to have surface!
`www: Sun in white light`

so: 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 times ($\gg$ millions!)
outward progress erratic: "random walk"



less scattering as move outwards and gas ρ decreases
until finally γs escape $\rightarrow$ we see them

Q: what sets stepsize of random walk?

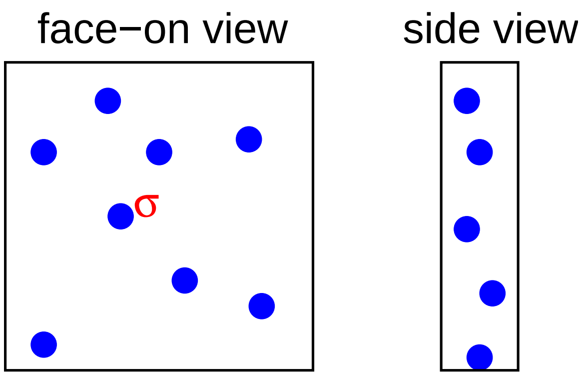
Scattering Mean Free Path

recall scattering problem in "asteroid collision" HW:
a projectile moves through obstacles ("targets") with

- *number density* $n_{\rm targets} = dN_{\rm targets}/dV = \rho_{\rm targets}/m_{\rm target}$
  where $m_{\rm target}$ is mass of a single target
- *cross section* σ
  size of a target as "seen" by projectile

mean free path for projectile is

$$\ell_{\rm mfp} = \frac{1}{n_{\rm targets}\sigma} = \frac{m_{\rm target}}{\rho\sigma}$$



Q: what is the physical significance of the mean free path?
Q: why is it sensible physically that $\ell_{\rm mfp} \propto 1/\rho$? $\propto 1/\sigma$?

Q: for photons in Sun: what are the "targets"? what sets σ?

Solar Photosphere and Sunlight Mean Free path

Apply scattering technology to photons in the Sun

- *projectiles* are *photons*
- *targets* are particles in Sun:
  electrons e^-, *ions* (mostly p^+), and *atoms*
- cross section σ set by *photon interactions with matter*
  different for bound and free charges, and different target masses
  turns out: free electrons are most important scatterers
  for experts: Thomson/Compton scattering

mean free path (MFP):
average projectile pathlength ("stepsize") between scatterings

at center of Sun: $\ell_{\rm mfp,center} \sim 0.2$ mm !!
Q: what does this imply for photons born at center?
Q: how should $\ell_{\rm mfp}$ change as we go out from center?
Q: so what sets photosphere location?

Photon Escape from the Sun

at the center of the Sun: $\ell_{\text{mfp,center}} \sim 0.2$ mm

- since $\ell \ll R_\odot$: *scatter many times before escape*
  sunlight photons so not directly probe solar core!
- but as move outwards, $\rho \downarrow$ and so $\ell \uparrow$
- until ρ so low that $\ell_{\text{mfp}} > R_\odot$
  $\rightarrow$ scattering finally "turns off"
- Fun fact: the sunlight we see from the photosphere

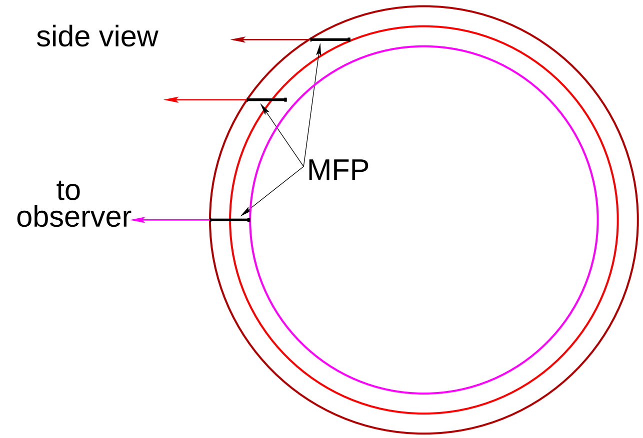
took millions of years to come from the Sun's core!

So: photons from Sun come from "last scattering" surface
this is the photosphere: region where $\ell_{\text{mfp}} \rightarrow \infty$

- $\delta r_{\text{photosphere}} \sim few$100's of km thick
- $T_{\text{photosphere}} \sim 6400$ K at base, ~ 4200 K at "top"

$\Rightarrow$ we see T "mixture" – not perfect single-T blackbody

Limb Darkening



looking across Sun's disk on sky:

- one mean free path (MFP) goes deeper (in radius) at center
- shallower at edge ("limb")

but *deeper means hotter*,
and *hotter means brighter*: $F = \sigma T^4$, so

- center of Sun's disk should be brightest,
- edges of disk dimmest–photons from higher, cooler region

observed: **"limb darkening"**
$\longrightarrow$ *shows Sun gets hotter towards center!*
you will see this in Solar Observing

Granulation: the Boiling Sun

Sun's surface shows activity!

numerous bright "cells" = *granules* surrounded by dark edges

- typical size $\sim$ 1000 km!
- each granule grows and disappears over $\sim$ 10 minutes!

What's going on?

in photosphere, gas motion:

hot rises, cool sinks: convection

Demo: lighter, show on screen

- further evidence of the Solar temperature gradient
- convective motions also a way to transport energy outwarkd

Sunspots

dark regions on photosphere

`www: today's sun in white light`

`www: sunspot seething`

spots transient, last $\sim$ 2 weeks

#, location of sunspots varies

periodic: 11-year "sunspot cycle"

`www: sunspot counts` – we're on the upswing to a maximum

sunspots move: reveal solar spin

`www: real time Sun movie`

sunspots created by magnetism

strong mag. field "locks" plasma in place

keeps hot gas from rising

cooler gas $\rightarrow$ dark spot

iClicker Poll: Study Sheet for Exam?

Consider:
being allowed to bring **1 sheet, handwritten by you** to exam
ordinary 8.5×11 paper, you may write anything on it
not graded, but turned in with exam

also note: either way, front exam page has equations

Should a study sheet be allowed in the exam?

A yes

B no