Astro 350

Lecture 12

February 14, 2022

Announcements:

- **Discussion 3** due Wednesday
- **Homework 4** due Friday
- Office Hours after class Wed or by appointment

Last time: galaxies

Q: How do other galaxies compare to ours?

Q: Why are galaxies important to cosmologists?

Ordinary matter:

Q: what do we mean by "ordinary"? example?

Q: what is ordinary matter made of?

Q: example of matter that we will not count as "ordinary"?

in this course:

"*ordinary matter*" is *anything made of atoms*
no matter how exotic their condition or temperature

center of the Sun, of the Earth, ultracold clouds in space
are all examples of "ordinary" matter

atom structure similar to Solar System:
attractive electric force $\rightarrow$ orbits

charge of nucleus $\Rightarrow$ # p
sets force on e $\rightarrow$ orbit properties
determines chemical properties
92 atom varieties = **elements**
from hydrogen = $1p$ to uranium = $92p$
`www: periodic table`

Chemical Composition

different elements combine/react differently ⇒ chemistry
ex: water = H_2O = H-O-H

So: “what made of” = “**chemical composition**”:
a census of atoms

- ▷ what *kinds of atoms*?
- ▷ which are most, least numerous?

Examples
Sun, Jupiter: about 70% hydrogen, 28% helium, 2% other = “metals”
Earth: about 50% oxygen, 30% silicon, only 0.1% hydrogen

Temperature

at microscopic level:
temperature $\rightarrow$ atom random motion ("jiggle")
hotter $\rightarrow$ *faster* random motion; *cooler* $\rightarrow$ *slower*

everyday temperature scales:
- Fahrenheit: water freezes at 32°F, boils at 212°F
- Celsius/Centigrade: water freezes at 0°C, boils at 100°C

connection:

$$T(\text{F}) = \frac{9}{5} T(\text{C}) + 32^\circ \tag{1}$$

In both scales, negative temperatures exist, not mysterious

Q: if keep cooling, what eventually happens to atom motion?

Absolute Zero and the Kelvin Scale

if cool until *no* random motion: "maximum cold"
lowest possible temperature: "**absolute zero**"

Absolute zero $= -273°\text{C} = -459°\text{F}$

define **Kelvin** (absolute) temperature scale:
choose $T(\text{K}) = 0$ at absolute zero

$$T(\text{K}) = T(\text{C}) + 273° \tag{2}$$

- room temperature $\approx 30°\text{C} \approx 300$ K
- water freezes at 273 K

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?

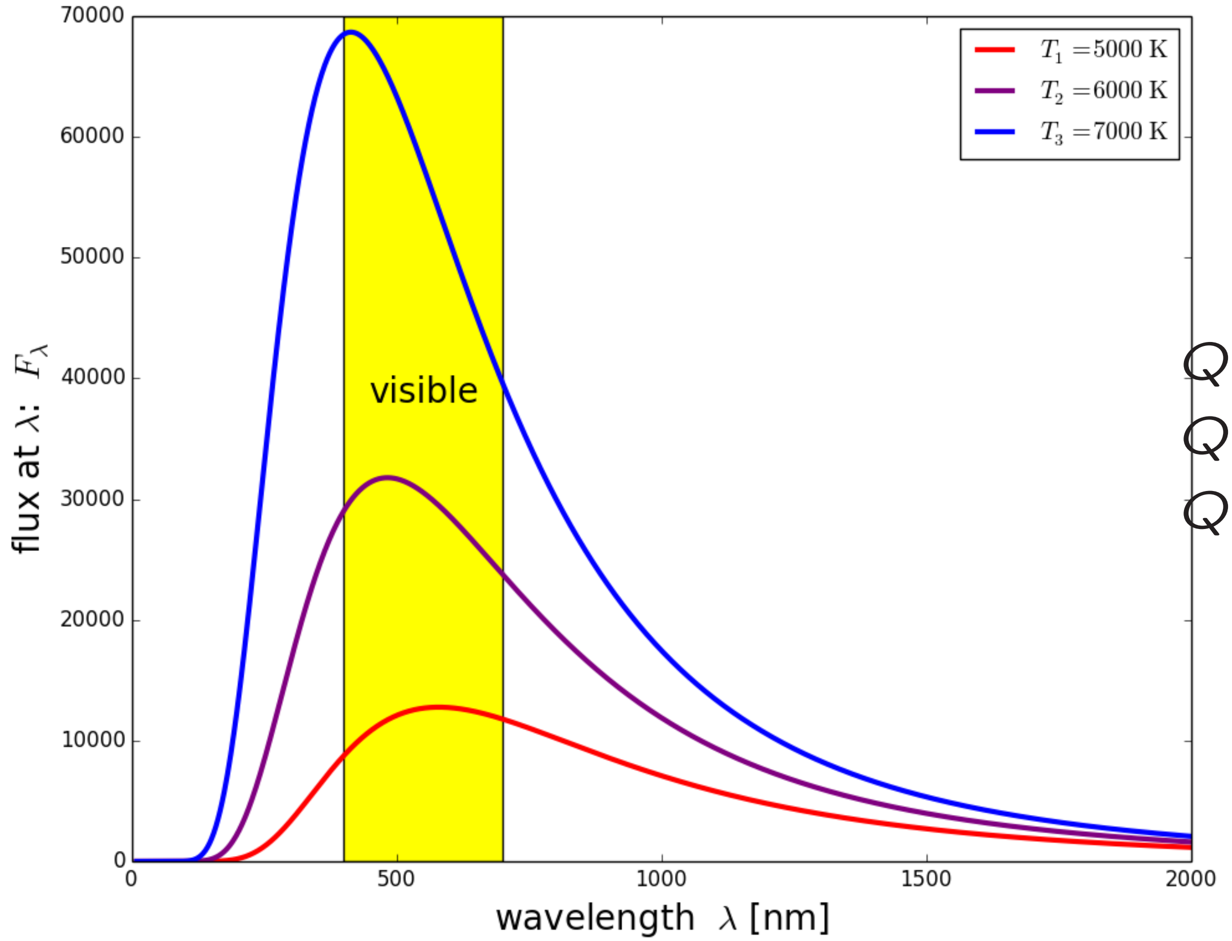
perfect absorber of light: “blackbody”

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 temperature T

Blackbody Spectrum

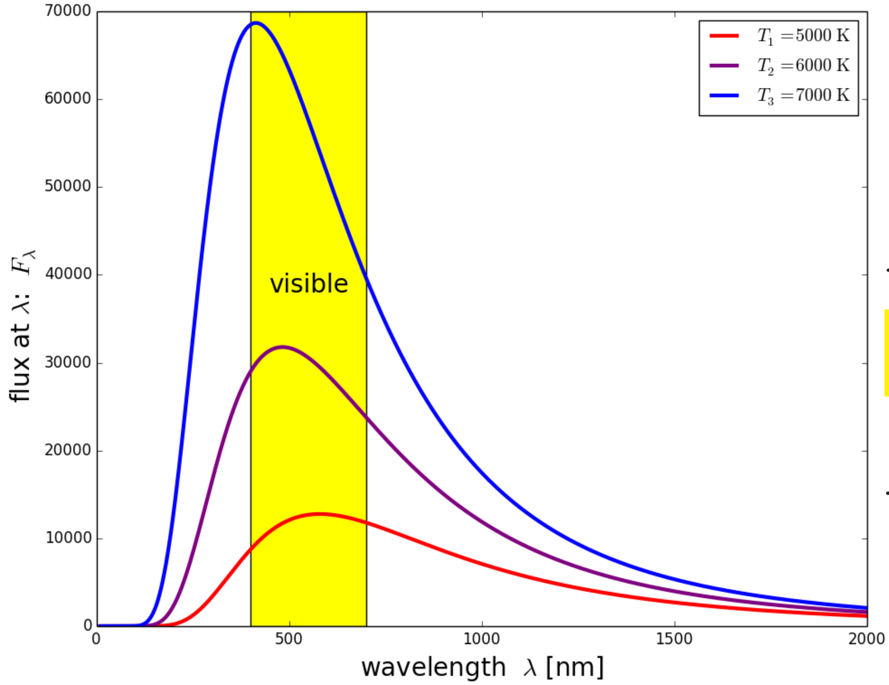


Q: trends vs λ*?*

Q: trends vs T*?*

Q: hotter = ???

Blackbody Flux



Hotter:

more *flux = brighter*

flux from surface

$F_{\text{surf}} \propto T^4$

think stovetop

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

hotter $\rightarrow$ more blue $\rightarrow$ shorter λ

"Wien's Law"

Turn the equation around: $T \propto 1/\lambda_{\text{peak}}$, namely

$$T = 3000 \text{ K} \left(\frac{10^{-6} \text{ m}}{\lambda_{\text{peak}}} \right) \tag{3}$$

so: can find T just from light!

$\Rightarrow$ spectrum as **thermometer**

color measures temperature

thermal radiation example: the Sun

`www: solar spectrum`

Sun's spectrum peaks in middle visible wavelengths:

$\lambda_{\text{peak,Sun}} \approx 500\ \text{nm}\ = 5 \times 10^{-7}\ \text{m}$

$$T_{\text{Sun}} = 3000\ \text{K} \left(\frac{10^{-6}\ \text{m}}{\lambda_{\text{peak,Sun}}}\right) = 3000\ \text{K} \left(\frac{10^{-6}\ \text{m}}{5 \times 10^{-7}\text{m}}\right) \quad (4)$$

$$= 6000\text{K} \approx 10,000^{\circ}\ \text{F} \quad (5)$$

this is *toasty!*

Q: but the Sun is not all at one temperature,
so what part of it has this T?
Q: are other parts of the Sun hotter or cooler?

Q: does Wien's Law apply to people?
Q: what about Illini fans–blue shirt vs orange shirt?

note: sunlight comes from Sun surface ("photosphere")
$\rightarrow$ we have found $T_{\text{Sun,surface}}$ $\rightarrow$ Sun's even hotter inside!

Humans and thermal radiation:
we are not at zero temperature–can and do radiate!
but infrared–invisible to naked eye, very visible to IR sensors
`www: IR humans`
But note: T-Shirt color $\neq$ thermal radiation (good thing!)
reflected light, not glow from heat!

Thermal Radiation and galaxies:
`www: M104 galaxy image--visible light vs IR`
Q: compare–what's going on?

Hunting for Dark Matter: Gas

What if dark matter is in the form of gas?

If galaxy dark halos are made of hot gas

- all galaxies–including ours–would be embedded in huge clouds of gas
- and gas would have more mass than the stars we see!

can *test* this, because thermal objects radiate!

But first, halo gas must qualify as dark matter!
Q: what temperatures would not *work?*
Q: what temperatures would *work?*

Halo Gas: Possible Temperatures

dark matter must be dark! (duh!)
$\rightarrow$ emits no/little visible light

but recall: stars glow approximately as would
blackbodies at $T_\star = 3000 - 10,000$ K
$\rightarrow$ give off visible light
$\rightarrow$ *halo gas wouldn't be dark at these temperatures!*

Conclude: if dark matter is gas, must be:

- cold: $T_{\text{gas}} \ll 3000$ K, or
- hot: $T_{\text{gas}} \gg 10,000$ K

focus today on *hot gas*:
Q: if dark matter = hot gas, which λs should it emit?
Q: where would be best place to search for these λ?

Dark Matter: A Bunch of Hot Air?

If dark matter is gas with $T_{\rm gas} \gg 10,000$ K:
Wien's law says λ very small: UV or X-ray
$\Rightarrow$ search using *X-ray* telescopes

Where best to look?
DM surrounds all galaxies, so DM most concentrated
where galaxies are most concentrated
$\rightarrow$ *galaxy clusters*: > 100 galaxies clumped in few Mpc regions

galaxy clusters are the largest objects (bound structures)
in the universe today

`www: Optical image of galaxy clusters`

Poll: Taking X-Rays of Galaxies

Vote you conscience!

Observe galaxy clusters with X-ray telescope.
What will we find?

A huge amounts of X-ray light throughout the cluster
hot gas is the dark matter!

B very little X-ray light, only from visible parts of galaxies
hot gas is not the dark matter!

C none of the above

X-Ray Observations of Galaxy Clusters

`www: clusters in X-rays`

Yes! Galaxy clusters are indeed bright X-ray sources!
also: X-ray emission is smooth throughout cluster
not just in galaxies

- *hot gas fills clusters!* – "intracluster medium"
- and intracluster gas has *more mass* than the galaxies
- but was (optically) invisible, and unknown until birth of X-ray astronomy in 1970's!

Hot gas really is (optically) dark matter!
Represents about 75% of ordinary matter in galaxy clusters!

Dark Matter Puzzle Solved?

Mystery solved?

Partially: galaxy clusters and smaller galaxy groups
known to have large amount of hot gas

But: from galaxy motions, can find *total cluster mass*
similar to method using rotation curves of spiral galaxies

Result: $M_{\text{cluster,total}} \approx 5 \times M_{\text{galaxies+hot gas}}$
$\rightarrow$ *cluster dark matter still mostly in some other form!*

Lessons:

- Dark matter search must continue!
- X-ray results encouraging: searching in new ways
  can reveal surprises!

Lineup of Dark Matter Suspects

~~hot gas~~
cold gas
} diffuse ordinary matter: gas

black holes
neutron stars
white dwarfs
brown dwarfs
planets: "Jupiters"
} clumpy ordinary matter: compact objects = dead and failed stars

neutrinos
relic particles from big bang
} diffuse matter: exotic particles

Q: what about cold gas? How to test?

Director's Cut Extras

Visible Light Revisited

Recall: visible light is only tiny part of full electromagnetic spectrum

	radio	infrared	visible	ultraviolet	X-ray	γ-ray
λ [m]	$> 10^{-3}$	$\sim 10^{-5}$	$(4-7) \times 10^{-7}$ m	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-12}$

Visible Light

- wavelengths small on human scale ($< 10^{-3}$mm) but much smaller λ light exists!
- prisms & rainbows: sort light by λ
- longest visible λ: red light
- shortest visible λ: blue light
- order, in decreasing λ
  red, orange, yellow, green, blue, indigo, violet
  think of Mr. "Roy G. Biv"

Kirchhoff's Laws

some gas absorbs light, some emits
which is which?
$\Rightarrow$ depends on gas **density**, T

Kirchhoff:

1. if solid or dense gas is hot
   emits **continuous** spectrum: blackbody

2. if thin, rarefied gas is hot
   emits **emission line** spectrum

3. if continuous spectrum passes thru cool gas
   atoms absorb light $\rightarrow$ **absorption line** spectrum