Astro 350

Lecture 10

Sept. 19, 2012

Announcements:

- *Homework 3* due at start of class
- good news: no HW next week
  bad news: **Hour Exam 1** next week; info online
- *Discussion 4* due next Wednesday
- *Bonus Participation*: class portrait on Compass
  identify yourself to help me learn your name

Pick up a diffraction grating slide

...and please return at end of class

Cosmo-Bigshot in the House!

⋆ **Monday Sept 24**: Prof. Wick Haxton, U. California Berkeley
"The Origin of the Elements"
Phi Beta Kappa Lecture, 4pm Lincoln Hall 1090

Last time: hot gas as dark matter?

Q: why is hot gas a good DM candidate? how hot?

Q: how to test for hot gas DM? results? lessons?

Recap: Hot Gas as Dark Matter?

dark matter needed to hold together galaxies,
groups and clusters of galaxies

- dark: not detected with (visible) light
- matter: gravitates = has mass

hot gas?

- has mass, but
- glows with thermal (blackbody) radiation
  but: if very hot, $T \gg 10,000$ K, peak λ is X-ray!
  not bright in optical/visible wavelengths!

Look with "X-ray vision" at clusters of galaxies

- hot gas found between galaxies!
- intracluster gas has more mass than the galaxies!

$\Rightarrow$ *hot gas* is *a form of dark matter!* (optically invisible)

- but :still find $M_{\text{galaxies}} + M_{\text{gas}} \ll M_{\text{gravitating}}$

$\Rightarrow$ the *majority of dark matter is* not *hot gas*! mystery remains!

Lineup of Dark Matter Suspects

~~hot gas~~

cold gas

black holes
neutron stars
white dwarfs
"failed stars" – "Jupiters," brown dwarfs } compact objects

neutrinos

relic particles from big bang

Q: what about cold gas? How to test?

Cold Gas as Dark Matter?

recall Wien's law–thermal radiation color: $\lambda_{\text{peak}} \propto 1/T$
hotter $\leftrightarrow$ bluer, colder $\leftrightarrow$ redder

if gas has $T \ll 3000$ K, then λ_{peak} in IR or radio
very dim at optical wavelengths

suggests obvious test: look for cold gas halos of galaxies
$\Rightarrow$ search for thermal infrared or radio

But: thermal emission depends strongly on T
for object at temperature T, of fixed size
emitted blackbody radiation (i.e., luminosity) $L_{\text{therm}} \propto T^4$
$\rightarrow$ hot objects hugely luminous, but cold objects not
$\rightarrow$ if gas very *cold*, also very *dim*–too dim to see!
$\rightarrow$ so lack of IR or radio signal does not prove lack of cold gas
Q: how else can we test for cold gas?

Energy

every closed system has a *number*, the **energy**, which:

- is related to the forces in the system
- energy measures ability of the system to affect change
  i.e., to change speeds, move with or against forces,
  or to undergo internal transformations
- Cosmologist L. Cable Guy: Energy = ability to “git-r-done”

⋆ key feature: in *closed system*, *total energy doesn’t change*
even if it changes forms

conservation of energy

ℴ more abstract (and more general) idea than forces
useful due to conservation

Energy: Important Examples

Motion: moving object with mass m, speed v carries
kinetic energy

$$KE = \frac{1}{2}mv^2 \tag{1}$$

Q: when is $KE = 0$? large?

Thermal Energy due to random motion of atoms
atoms "jiggle" solid, liquid, gas
so each atom has kinetic energy due to jiggle
$\rightarrow$ "heat" really is energy in form of all random motions
kinetic energy of average atom: $KE_{\rm avg} = 1/2\ m_{\rm atom} v_{\rm avg}^2 \propto T$
$\rightarrow$ hotter = more random KE = faster!

Forces & Energy

Forces $\neq$ energy *Q: what are some differences?*
but forces always have associated energy
for example: can "store" energy due to position
in force field (e.g., gravity) $\Rightarrow$ potential energy

examples:

force	**energy**
gravity	gravitational potential energy
electricity	electrical potential energy
gas pressure	"compression energy"
attractive forces in atoms	bonds in atoms
(chemical forces)	(chemical energy)
forces in atomic nuclei	nuclear energy

Temperature, Atoms, and States of Matter

atoms always in random motion $\rightarrow$ collide with each other!
imagine starting cold, and turning up T

- at lowest T: *cold* matter
  low speeds $\rightarrow$ gentle collisions
  if dense enough: atoms locked together
  $\rightarrow$ **solid**! random "jiggle" too weak to dislodge atoms
- if *warmer*: atoms freed to "roll" past each other
  melt $\rightarrow$ **liquid**! atoms move ("flow") but still touch
- if *warmer still*: atoms can fly free
  evaporate $\rightarrow$ **gas**! and atoms "bounce back" when collide
- if really *hot*: gas atoms collide at high speed
  atoms torn apart = ionized $\rightarrow$ free e and nuclei: **plasma**

hot gas in galaxy clusters: ionized plasma, no bound atoms
cold gas clouds: all atoms are bound, none ionized

iClicker Poll: Light and Atoms

Experiment: tube with gas under high voltage
$\rightarrow$ high-energy electrons accelerated, collide with gas atoms
atoms receive energy from collisions, emit light

Vote your conscience!
What will spectrum of tube look like?

A continuous: all visible colors = all λs

B bands of colors = λs in only some ranges

C only a few *single* colors = a few individual λ

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demo: compare spectrum for different elements
Q: why is this incredibly useful?

The Quantum Atom

at small distances (size of atoms) Newton's laws *fail*!
atoms, light obey new & different rules: **quantum mechanics**

electron orbits
nucleus + e: like solar system?
No! QM $\rightarrow$ e not like planet
in atom, acts like wave !?!
▷ *most* orbits *forbidden*!
▷ only special orbit distances allowed $\rightarrow$ "quantized" in steps

allowed orbits $\rightarrow$ **energy levels**
lowest energy $\rightarrow$ stable orbit, closest to nucleus
"ground state"

Photons

just as matter (like e) can sometimes act like waves
light can sometimes act like particles...

on small lengthscales or low intensities
light acts like *particle*: "**photon**," symbol $\boxed{\gamma}$

discrete "lump" or "packet" of energy
different colors $\leftrightarrow$ different energies
smaller $\lambda \rightarrow$ higher E:

$$E_{\text{photon}} \propto \frac{1}{\lambda} \qquad (2)$$

`www: EM spectrum as spectrum of photon energies`

Light-Atom Interactions

If light hits atom **and** photon energy = atom energy level

1. atom absorbs photon
2. e jumps to higher level
3. atom in “excited” state

but excited = unstable

after time,

1. e jumps back to ground state
2. emits photon whose energy = excited − ground *difference*

Atoms absorb/emit light

atom structure sets energies, and $\lambda \propto 1/E$

...which is different for different atoms

so energy level spacings different for different atoms

light spectrum gives atom "fingerprint" or "barcode"

spectrum $\rightarrow$ composition

Measuring the Composition of the Cosmos

Example: The Sun

Sun, stars hotter, denser in center cooler, less dense at surface

so: sunlight/starlight shows *Q: what kind of spectrum?*

`www: Sun spectrum`

amount absorbed in each line → amount of atoms

→ **composition** of Sun; works for other stars too!

Example: interstellar gas in our Galaxy

look at stars in our own Galaxy

light passes thru space between us and the star

Q: if interstellar gas, what should we see?

`www: starlight spectrum`

interstellar gas revealed! and composition found!

→ mostly hydrogen and helium, about 2% heavy elements

Dark Matter as Cold Gas Halos?

What if dark matter is in the form of cold gas?

If galaxy dark halos are made of cold gas

- all galaxies embedded in huge clouds of (neutral) atoms including our own!
- cold $\rightarrow L \propto T^4$ small – thermal glow dim, maybe missed! could "hide" from IR and radio telescopes!

But note: when we observe other galaxies
their light must pass through the halo of our own!

16 *Q: how to test for cold gas in our own halo?*

iClicker Poll

Look at **spectrum** of light from distant galaxies
if cold gas fills our dark halo
atoms will absorb photons if match energy levels $\rightarrow$ spectral lines

Vote you conscience!

What will we find in the spectra?

A strong absorption lines from our halo
cold gas is the dark matter!

B no/weak absorption lines
cold gas is not the dark matter!

C none of the above

Cold Halo Gas?

galaxy spectra show *no lines*
as light passes *into* our own dark halo
→ our Galaxy not surrounded by cold gas!

also: *no lines* from cold gas reservoirs
as light passes *out* of distant galaxies
→ other galaxies also not surrounded by cold gas!

Conclude: *cold gas is not the dark matter*
mystery persists! must look elsewhere!

Lineup of Dark Matter Suspects

~~hot gas~~

~~cold gas~~

black holes
neutron stars
white dwarfs
"failed stars" – "Jupiters," brown dwarfs

} compact objects

neutrinos

relic particles from big bang

Next candidates: compact objects

$\rightarrow$ all arise from birth and death of stars

Director's Cut Extras

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