Astro 350

Lecture 9

Sept. 17, 2012

Announcements:

- *Homework 3* due at start of class next Friday
- *Discussion 3* on Compass, due Wednesday

Last time: Milky Way dark matter

Q: what is a rotation curve? what is the MW rotation curve?

Q: how does the MW rotation curve give evidence for dark matter?

Q: what if dark matter does not exist?

What is the DM? Unknown (to date). Guesses:

black holes
neutron stars
white dwarfs
“failed stars” – “Jupiters,” brown dwarfs

} compact objects

hot gas

cold gas

neutrinos

relic particles from big bang

in the rest of the semester, we will work through list

Realm of the Nebulae

"Nebulae" – fuzzy pinwheels or blobs on sky
know for centuries (since telescope) `www: examples`
but are they in MW or beyond it?

key question: distance
Curtis-Shapley debate (1920): *What is the scale of the Universe?*

	H. Shapley	H. Curtis:
MW size	about 10 kpc	about 1 kpc
nebula distances	nearby, inside MW	far, outside MW
nebula sizes	small, like planetary nebulae	large, like our galaxy

turns out: both partially right, partially wrong
to settle the debate: need more data
$\rightarrow$ need to find *distances* to galaxies

Hubble–The Man: Scale of the Universe

Edwin Hubble: grew up in Wheaton, college in Chicago
pioneered observations of galaxies

his idea: find a **standard candle**

recall: apparent brightness (flux F) depends on luminosity
but also on distance: $F = \frac{L}{4\pi R^2}$

⋆ imagine object with **known luminosity** L_{candle}: "standard candle"
i.e., all such objects have same Wattage
e.g., 100 Watt lightbulb, or a star of known type `www: cartoon`

- can measure flux F_{obs} (how bright as seen in telescope)
- then using known L_{candle}, solve for distance: $R = \sqrt{\frac{L_{\text{candle}}}{4\pi F_{\text{obs}}}}$

in 1920's: Hubble found standard candle in "Cephieds"
$\rightarrow$ luminous variable stars,
with periodically fluctuating brightness
`www: animation`

Cephieds pulsate due to instability in atmosphere
pulsation period related to luminosity
so measure period $\rightarrow$ know L $\rightarrow$ standard candle

Hubble found Cephied in M31 `www: Hubble's discovery image`
$\rightarrow$ established that it is 100's of kpc away
$\rightarrow$ extragalactic! "island universe"

Hubble realized the "Realm of the Nebulae"
is a vast region beyond our Galaxy
$\rightarrow$ greatly expanded known scale of the Universe

Galaxies

galaxies fill universe
galaxies are the “building blocks” of the present-day Unvierse
ra stars & other matter concentrated in them
much less matter in spaces in between

typical neighbor separation $\sim 10^6$ pc $=$ 1 Mpc (megaparsec)
most distant 1000’s of Mpc

Galaxies sizes range large (like MW) to small “dwarf”
different shapes (“morphology”):

spiral: disk+bulge
gas, dust evident → star formation ongoing

elliptical: elongated sphere, no disk
no/very little gas, dust → star formation ceased

irregular: no simple geometry
gas, dust present $\rightarrow$ can form stars

Milky Way one of many galaxies $\rightarrow$ a typical spiral

Revolution Re-Revisited

Copernican Revolution I (17th Century):

Earth is one typical planet among many

not center of solar system

Copernican Revolution II (earth 20th Century):

Sun is one typical star among many

not center of Milky Way Galaxy

Copernican Revolution III (1920's):

Milky Way is one typical galaxy among many

Universe much larger than previously thought

... stay tuned for more...

iClicker Poll: Rotation Curves of Other Galaxies

Would like to compare Milky Way rotation curve
to those of other galaxies

Compared to the Milky Way,
measuring the rotation curve of a nearby galaxy is

A easier, but only if the galaxy's disk is seen edge-on

B easier, but only if the galaxy's disk is seen face-on

C always harder

D sorry, can't measure rotation curve of other galaxies

Galaxy Rotation Curves

`www: rotation curves`

Results:

- *all* galaxies show flat rotation curves similar to MW – we are not a weirdo!
- flat portion very clearly extends well beyond visible matter (stars/gas/dust)

Q: which means?

Galaxies Are Made of Dark Matter

Interpretation:
- *all* galaxies contain large amounts of dark matter!
- in fact, *most* have a *larger* proportion than in MW!

Dark matter fills the Universe!
all galaxies are made mostly of dark matter!
the gravity of dark matter is what holds them together!

Any successful cosmology theory must
- include dark matter as a key ingredient
- explain what the DM is
- explain why we have so much of it

Starting now and in the next classes:
- test dark matter candidates
- will end up excluding most of list

Matter

in hunting unknown dark matter, need to sharpen our tools
make full use of hard-won science to date:

- what has been learned about known *matter*
- *and how light can be used to probe it*

Q: As we “zoom in” to everyday matter, what do we find?

“Ordinary” Matter*

All known substances ever found *in any lab*
which we will call **“ordinary” matter**
have the following structure

matter
↓
molecules
↓
atoms
↙ ↘
nucleus electrons
↙ ↘
protons neutrons
↘ ↙
quarks

*Dark matter not included!

"If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis (or the atomic fact, or whatever you want to call it) that **all things are made of atoms**–little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied."

–Cosmologist Richard Feynman

Atom Structure one or more **electrons** orbit a single **nucleus**

electron (e): electric charge -1

nucleus: made of protons (charge +1) & neutrons (charge 0)

mass: $m_p \approx m_n \approx 2000 m_e$

$\Rightarrow$ most of atom mass is in dense nucleus

$\Rightarrow$ most of atom volume occupied by electron orbits

total charge of atom: set by # electrons

$\# \ e = \# \ p \rightarrow$ neutral

$\# \ e = \# \ p - 1 \rightarrow$ charge $= +1$: singly ionized etc.

e moves around nucleus

Q: what does this tell us about forces in atoms?

orbits: curved paths – motion must be accelerated

$\rightarrow$ needs to be a net force–and there is!

nucleus & e attracted by **electric** force

rule: opposite charges attract, like charges repel

atom structure similar to Solar System:

attractive force $\rightarrow$ orbits

big object in center, orbiting smaller objects

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":
▷ 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

Matter, Temperature,and Light

hot matter glows (think stove burner)
temperature – radiation connection

microscopic picture:
temperature $\rightarrow$ atom motion

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

thermal body (at some temp T)
emits EM radiation: which λ emitted?

spectrum of light; depends on T

perfect absorber of light: “blackbody”

absorbed energy $\rightarrow$ heats up

re-emits according to T

“blackbody radiation” $=$ thermal radiation

Thermal Spectrum: Light as Thermometer!

peak λ is color seen: $\lambda_{\text{peak}} \propto 1/T$

where T is *absolute* temperature in Kelvin

recall: $T_{\text{Kelvin}} = 273 + T_{\text{Celsius}}$

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

"Wien's Law"

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

$$T = 3000 \text{ K} \left(\frac{10^{-6} \text{ m}}{\lambda_{\text{peak}}} \right) \tag{1}$$

so: can find T just from light!

$\Rightarrow$ spectrum as **thermometer**

color measures temperature

example: the Sun

`www: solar spectrum`

Sun's spectrum peaks in middle visible wavelengths:

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

$$T_{\text{Sun}} = 3000 \text{ K} \left(\frac{10^{-6} \text{ m}}{\lambda_{\text{peak,Sun}}} \right) = 3000 \text{ K} \left(\frac{10^{-6} \text{ m}}{5 \times 10^{-7} \text{m}} \right) \quad (2)$$

$$= 6000\text{K} \approx 10,000^{\circ} \text{ F} \quad (3)$$

toasty!

Q: but the Sun is not all at one temperature–what has this T?

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 $T_{\text{Sun,surfac}}$ $\rightarrow$ 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?

Blackbody Spectrum

useful* to define an ideal substance:
a perfect absorber of light: **"blackbody"**
absorbs all λ, reflects none
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?

blackbody absorbs radiation $\rightarrow$ heats $\rightarrow$ re-emits according to T
"blackbody radiation" = thermal radiation
spectrum depends only on T
diagram: Flux F vs λ

perfect absorber of light: "blackbody"
absorbed energy $\rightarrow$ heats up
re-emits according to temperature T
"blackbody radiation" = thermal radiation

Aside: Temperature Scales

everyday temperature scales:

• Farenheit: water freezes at 32°F, boils at 212°F

• Celcius/Centigrade: water freezes at 0°C, boils at 100°C

connection:

$$T(\mathrm{F}) = \frac{9}{5} T(\mathrm{C}) + 32^\circ \tag{4}$$

In both scales, negative temperatures exist, not mysterious

Turns out: there is a *lowest possible temperature*

→ "**absolute zero**" at −273°C = −459°F

define **Kelvin** scale

$$T(\mathrm{K}) = T(\mathrm{C}) + 273^\circ \tag{5}$$

so $T(\mathrm{K}) = 0$ at absolute zero

room temperature ≈ 30°]C ≈ 300 K