Astro 350

Lecture 8

Sept. 14, 2012

Announcements:

- *Homework 2* due
- *Homework 3* out, due at start of class next Friday
- *Discussion 3* on Compass, due next Wednesday

Last time: our Milky Way galaxy

Q: what would it look like from outside?

Q: how big is it?

Q: where do we live?

Weighing the Milky Way from its Starlight

Big question: *What is the mass of our Galaxy?*

Method I: Look!

We can observe stars and gas clouds throughout the Milky Way

- stars: give most of the light we see in the MW
  and can find a star's mass using its emitted spectrum
  summing up all starlight: total $M_{\rm star} \approx 10^{11} M_\odot$ ($\odot$ =Sun)
- gas: total $M_{\rm gas} \approx 10^{10} M_\odot$, about 1/10 of mass in stars

total mas in stars & gas: $M_{\rm luminous} = M_\star + M_{\rm gas} \simeq 10^{11} M_\odot$

Q: Where is the luminous mass? How distributed in space?
Q: if sum up mass, starting outward from center, what's the result?

Where is the Mass We See?

the Galaxy's mass in stars and gas
traces the light from stars and gas

visible Galaxy is mostly in flattened disk
stars and gas extend from center ($R = 0$ kpc)
to outer edge (15 kpc)

so the mass in stars and gas should trace this shape

- if add up mass inside radius R = "enclosed mass"
  at $R = 0$: enclosed mass = 0 (duh!)
  then increases as we go outward
- and at outer edge $R = 15$ kpc, enclosed visible mass
  "tops out" to constant = total mass of stars+gas: $10^{11} M_\odot$

Weighing the Milky Way from its Gravity

Method II: Find how much gravity there is

- Galaxy is rotating = accelerating, stars not free bodies
- acceleration requires force
- only important force on galaxy scales is **gravity**
  $\rightarrow$ Gravity binds the Galaxy together
- source of gravity is mass

So: study motions of stars and gas in the Galaxy

and ask: how much gravity needed cause accelerations we see

i.e., how much mass needed to keep Galaxy from flying apart?

Milky Way Rotation Curve

`www: Milky Way rotation curve data`

find $v \sim const$ beyond $R \sim 2$ kpc

"flat rotation curve"

speed stays constant (still flat) out to largest R

even when there are no more stars/gas/dust!

compare/contrast: solar system rotation curve

Q: what does the MW/SS difference mean?

recall (HW2): orbits provide measure of gravity
stronger gravity $\rightarrow$ larger accel $\rightarrow$ faster orbits
and stronger gravity $\rightarrow$ more mass
$\Rightarrow$ orbits measure mass interior to motion

in detail (HW2): circular velocity
$v_{\rm circ} = \sqrt{GM_{\rm enclosed}/R}$: use to get mass interior to R
$\rightarrow$ $M(R) = v_{\rm circ}^2 R/G$

Solar System: $M(R) = M_\odot = const$ for all orbits
$\rightarrow$ so $v \propto 1/\sqrt{R}$: rotation curve *decreases* with R
i.e., Mercury is speedy, Pluto slowpoke

But for outer Milky Way: $v(R) = const$
Q: what does this mean for $M(R)$*?*

Milky Way Rotation Curve

disk stars: $\sim$ circular orbit $\rightarrow$ disk rotates

plot **rotation curve:** orbit speed vs distance

find $v \sim const$ beyond $R \sim 2$ kpc

"flat rotation curve"

Newton's gravity and Newton's laws of motion say

$$M_{\text{enclosed}}(R) = \frac{v_{\text{circ}}(R)^2 \; R}{G} \propto v^2 R \qquad (1)$$

for flat rotation curves $v = const$, so

$M(R) \propto R$: Galaxy mass keeps *increasing* with R

...even when there's no more stars/gas/dust!

MW mass estimate (rot curves): $M_{\rm MW} = 5 - 10 \times 10^{11} M_\odot$ total
but stars & gas: $M_\star \simeq 10^{11} M_\odot$
$\rightarrow$ only $10 - 20\%$ of total!

Forced to conclude: a large amount of mass is unseen!
most (80-90%) of Galaxy mass
is in the form of **dark matter**!

Notice: dark matter detected by its *gravity*

- to explain motions (accelerations) of stars
  requires much more mass than meets the eye
  if only visible matter were there, rotation would be slower
- and since gravity is the force holding the Galaxy together
  visible matter alone has too little gravity
  to keep stars in circular trajectories with their observed speeds
  most stars moving fast enough to fling themselves away!

$\Rightarrow$ Without dark matter our Galaxy would fly apart!

Q: how does this revise our view of how the galaxy is built?

Dark Matter and the Structure of the Galaxy

Revised view of Milky Way structure:

- disk: most stars, all gas/dust $R_{\rm disk} \approx 15$ kpc
- bulge/stellar halo: older stars, globular clusters
- ...but *most* of Galaxy in dark halo $R_{\rm dark} > 50$ kpc
  Milky Way much more massive, larger, than meets the eye!

Q: what do rot curves say about the nature of dark matter?

Dark Matter

most of MW matter is dark

What is the dark matter? Unknown! (yet!)
rotation curves don't specify details, only:

- **dark**: must not glow
  (i.e., must be very dim in EM radiation)
- **matter**: must have mass (gravity)

We do not know what makes up 80–90% of our own Galaxy!
→ huge embarrassment for cosmologists! but also an opportunity!
→ the nature of dark matter is one of the biggest questions in science today; big payoff for finding the answer

Multiple possibilities exist:
Q: suggestions?
list all logical possibilities you can think of...and no peeking!

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

Q: how do you confirm/refute a candidate?

Searching For Dark Matter

What is dark matter? Don't know!
But whatever form it takes, there is *a lot* of it

Search strategies:
1. look for dark matter in our own Galaxy
- dark matter surrounds us: some should be nearby
  possibly even *in this room!*
  try to detect it
- dark matter halo encloses Milky Way
  when we look at distant objects beyond our Galaxy
  we are looking *through* the dark halo
  can we see it or its effects?

2. look for dark matter elsewhere

- search for evidence for dark matter beyond our Milky Way galaxy?
  Q: what might we look for?

3. look for dark matter evidence in the past

- recall: telescopes are time machines
- if dark matter present now, was present in past look for influences in the evolution of the universe and the formation of galaxies

in next weeks, will see:
we still do not know what dark matter is, but:
we can say a lot about what it *isn't*

most dark matter candidates can now be ruled out!
and the most(?) exotic option–exotic elementary particles
is the most favored!
`www: particle dark matter detection experiment`

actually, another logical explanation can account
for flat rotation curves... *Q: namely?*

Alternative Hypothesis: Gravity's Broke!

rotation curve data are what they are
surprise when compared to theory prediction
but theory based on Newtonian gravity theory

and, looking ahead, Einstein's General Relativity gives same prediction

but *theory & data don't agree*

- maybe like 18th Century observations of Uranus' orbit
  $\rightarrow$ keep theory, but need new matter (Neptune)
- or maybe like Kepler's study of Mars' noncircular orbit
  $\rightarrow$ throw out busted theory, get a better one!

▷ if Newton correct on Galactic scales, then DM needed

alternatively: maybe Newton incorrect for Galaxy!

- new "modified" gravity theories have been proposed
  some already ruled out, but some not (yet?)!
- tricky — have to still accurately predict solar system motions
- and will find DM/alt gravity needed beyond Milky Way
  difficult to explain everything with simple mod grav theory
- also: very recent data may rule out
  most modified gravity theories

For most of the course:
we will assume Newton is correct, dark matter exists
but: remember how science works–humility/open mind essential!

my view: dark matter likely to exist
  but unproven till identified
also view of most cosmologists–but alt gravity gaining popularity!