Astro 350

Lecture 10

February 9, 2022

Announcements:

- **Homework 3** due Friday
- Office Hours after class Wednesday
- No discussion this week! Mea culpa!

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?

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!
$\rightarrow$ 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

What is the Dark Matter?

Multiple possibilities exist!

In groups, think of candidates for dark matter

list all logical possibilities you can think of...and no peeking!

and for now: don't worry about candidates being ruled out
just think of what they might be

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!

$\triangleright$ 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!

Galaxies

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
→ 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 "Cepheids"
$\rightarrow$ 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
as shown by astronomer Henrietta Leavitt

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

Director's Cut Extras

Alternatives to Dark Matter: Modified Gravity

dark matter is an explanation for the behavior of rotation curves assuming Newton's laws of motion and gravity

but explain flat rotation curves *without any dark matter* by *modifying Newton's law of gravity and/or of motion*

modified gravity:
the idea: on the scales of galaxies, gravitational acceleration is *different* from Newton's inverse square law $g_{\rm Newt}(r) \propto 1/r^2$

recall: for circular orbits, acceleration is $a_{\rm circ} = v_{\rm circ}^2/r$
let modified gravity provide the acceleration: $a_{\rm circ} = g_{\rm mod}$:

$$g_{\rm mod}(r) = \frac{v_{\rm circ}^2}{r} \quad \xrightarrow{\text{flat rot}} \quad \frac{1}{r} \tag{1}$$

Living with Modified Gravity

and we see that we need $g_{\mathrm{mod}}(r) \propto 1/r$
when we consider gravity on scales of galaxies

But: *shorter distances r than Galaxy sizes*,
still need $g_{\mathrm{mod}} \propto 1/r^2$
in order to explain motions in the solar system

Thus the *modified gravity theory must be complicated*
changing from $g_{\mathrm{mod}} \propto 1/r^2$ to $1/r$

this is challenging to do while matching to all observations
and will meet new challenges when we look at other galaxies