Astro 406
Lecture 24
Oct. 23, 2013

Announcements:

- **Planetarium Show tomorrow night** `www: course assignments`
  to get credit: bring iClickers!
- **PS 7 out, due next time**
- ASTR 401: draft due next Monday

Next semester: you qualify for advanced cosmology `www: info`

⋆ **ASTR 596 PC: Physical Cosmology**

⋆ **ASTR 596/496 RJF: Supernovae and Dark Energy**

Last time: interacting galaxies
"flyby" collisions with large closest approach

Q: effect on stars in each galaxy? final effect on galaxy?

Q: effect of flyby on the bulk galaxy motions?

Interactions: Direct Hit

slow, head-on encounter:
two galaxies collide, merge
• stars "collisionless" = only grav interactions (PS6)
→ no dissipation, "puffy" distribution
• gas collides, dissipates (cools) → sinks

if colliding masses very unequal
and smaller galaxy has large gas component
(e.g., dwarf spiral, irregular)
accretion: small galaxy's stars, gas tidally stripped
→ added to big galaxy ("cannibalism")

cannibalism begins at home: ongoing in Milky Way
last major merger $\sim 7-8$ Gyr ago (age of MW disk)
`www: Sgr dwarf` eaten as we speak

Q: what if the galaxies ≈ equal mass?

if $\sim$ equal mass gals: major **merger**

gas components collide, shock heated, compressed, radiate

bulk velocities cancel $\rightarrow$ no support against gravity

$\rightarrow$ center $\rightarrow$ rapid star formation

$\rightarrow$ starburst galaxy!

`www: starburst`

when burst exhausted:

- little/no gas: all consumed in starburst
- $\approx$ all ordinary matter in stars
- stars have large random v's
- small rotation

Q: sound familiar?

Ellipticals from Collisions?

Pro:

single gas cloud grav collapse $\rightarrow$ disk (unless ang mom $\equiv 0$)
$\rightarrow$ need mergers to get spherical structure
galaxy collisions lead to lower density final states
...and indeed, high-L E galaxies less dense
`www: NGC 7252: low-res, with 21-cm`
NGC 7252: tidal tails with H I gas
but center smooth like ell., with $R^{1/4}$ profile
spiral + spiral $\rightarrow$ ell

Con:

E colors, L correlated
but colors $\rightarrow$ time since most recent star form
$L \rightarrow$ stellar mass
if collide randomly, why not color spread at fixed $M_\star$?
`www: NGC 7252: high-res HST` core shows spiral structure

Lessons:

- Not a settled issue, but clear that:
- collisions fundamental for galaxy evolution
- gal interactions likely a major trigger for star formation

$\rightarrow$ much higher in early universe

Preview of coming attractions:
accretion and merging continually going on
$\rightarrow$ galaxies evolve, don't exist in isolation
types depend on (possibly complicated) interaction history
$\rightarrow$ e.g., over long times, can evolve S $\rightarrow$ E $\rightarrow$ S!

Facebook.Cosmos: Galaxies in their Social Context

have seen:
galaxy interactions important
$\rightarrow$ galaxies not “island universes”
but change, evolve depending on local and cosmic environment

lesson: to really understand galaxies
- study assemblies of them
- map their distribution, global dynamics in the Universe

The Local Group

we are not alone! Milky Way is one member
the Local Group of galaxies

- a system of ≈ 36 galaxies
- LG is gravitationally bound: not expanding!

Census of ~ 36 Local Group galaxies:

- 3 spiral (M31, MW, M33)
- 1 elliptical (M32)
- rest are *dwarfs*, many being *satellites* of MW, M31

`www: spatial distribution`

Milky Way Satellites

• Magellanic clouds ($\sim$ 50 kpc)
LMC: flat disk, bar, one weak arm, rotates
SMC: no organized motion

Magallanic clouds orbit MW
• gas tidally stripped $\rightarrow$ Magellanic stream
• bulk KE $\rightarrow$ internal KE
$\rightarrow$ *Q: recall–effect on Magellanic clouds?*

Magellanic clouds move in dark halo
leave "gravitational wake" in dark matter
$\rightarrow$ slow due to "dynamical friction"
$\rightarrow$ orbit decay
$\rightarrow$ will fall onto MW
`www: Mag stream images, movie`

dwarf spheriodals (dSph)
most common in LG
little/no gas, low surf brightness $\rightarrow$ hard to find
if virialized $\rightarrow$ get M $\rightarrow$ M/L large $\rightarrow$ mostly DM!

M31: The Great Galaxy in Andromeda

our "big sister" galaxy: bigger because

$$L_{\rm M31} \simeq 1.5 L_{\rm MW} \quad (1)$$

$$\text{disk scale length } h_R({\rm M31}) \simeq 6-7 \text{ kpc} \sim 2h_R({\rm MW}) \quad (2)$$

`www: M31 multiwavelength`

note IR: "ring of fire" at 6-7 kpc

center of mass: *blueshift* $\rightarrow$ approaching us at ~ -120 km/s

a galactic collision awaits our future!

fate of Sun's orbit uncertain and possibly grim

`www: FutureSky simulation movie`

PS7: analyze MW-M31 dynamics $\rightarrow$ estimate total mass!

Rich Clusters of Galaxies

galaxy clusters are:

⋆ rare: $n_{\text{cluster}} \sim 4 \times 10^{-6}\ \text{Mpc}^{-3}$, rarer than groups

⋆ massive: $M_{\text{cl}} \gtrsim 10^{14} M_{\odot}$, more massive than groups

⋆ densely packed with galaxies: $\rho_{\text{cl}} \gtrsim 10^{13} M_{\odot} \text{Mpc}^{-3}$

(cosmic avg: $\rho_{\text{matter,avg}} \sim 10^{11} M_{\odot} \text{Mpc}^{-3}$)

⋆ gravitationally bound:

clusters are the largest bound objects in the Universe today

in **optical**: cluster galaxies dominated by ellipticals

Q: what might this mean?

center $\rightarrow$ vast cD elliptical galaxy

Clusters as Dark Matter Laboratories

clusters are the largest bound systems in the cosmos today

so we expect clusters are "fair samples" of cosmic matter
i.e., the mix (ratios) of dark matter and ordinary matter
should be representative of the matter that formed the cluster
and thus of the Universe as a whole

hard to see how to segregate ordinary and dark matter on Mpc scales

ergo: *clusters are ideal laboratories for dark matter*

- lotsa mass $\rightarrow$ lotsa dark matter to look for
- fair sample $\rightarrow$ clusters give cosmic ratio of dark matter/ordinary matter ("baryons")

Q: what are remaining viable dark matter candidates?
Q: of these, which is the least exotic, most conventional?

Lineup of Dark Matter Suspects

hot gas

~~cold gas~~

~~black holes~~
~~neutron stars~~
~~white dwarfs~~
~~"failed stars" — "Jupiters," brown dwarfs~~

} ~~compact objects~~

neutrinos

exotic relic particles from big bang

Hot gas is only conventional (non-exotic) candidate left!

Q: if this is the dark matter, how could we look for it in clusters? what's signals/signatures does it leave?

Dark Matter: A Bunch of Hot Air?

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

for experts: emission is bremsstrahlung
e + ion scattering in plasma $\rightarrow$ acceleration $\rightarrow$ radiation

galaxy clusters:
- huge mass, many galaxies
- should be X-ray bright if DM is hot gas

iClicker Poll: X-rays in Clusters

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!

clusters are spatially resolved in the X-ray:
- smooth glow out to ~ 2 Mpc
- emission not just from galaxies

Q: what does smoothness tell us?
Q: what does X-ray nature tell us?
Q: X-ray luminosity large: what does this tell us?

Cluster X-ray Emission: Implications

spatially smooth: source not concentrated in cluster galaxies but fills space between them
"intracluster medium" (ICM)

Intracluster emission spectrum: *thermal*

- comes from gas (emission lines also seen)
  $\rightarrow$ ICM made of gas
- if peak in X-ray: **must be hot!**
  temperatures typically $kT \sim 5 - 10$ keV $\rightarrow T \sim 10^8$ K!

Intracluster X-ray luminosity: very high
reflects amount of ICM gas
typically: $M_{\rm gas} \gtrsim 3 M_{\star,gal}$
$\rightarrow$ more (normal) matter in intracluster gas than in galaxies!

X-Rays Reveal "Dark" Intracluster Matter

- *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!

Q: What heated the gas? Probably more than one effect!

Intracluster Medium: Heat Sources

Several heat sources exist

- supernova explosions
  the intracluster gas contains "metals"
  at rather high abundance: $Z \equiv M_{\mathrm{metal}}/M_{\mathrm{gas}} \sim 0.3 Z_{\odot}$
  $\rightarrow$ some supernova ejecta needed to make metals
  also would add heat

- galaxy collisions/stripping
  converts bulk motion KE $\rightarrow$ thermal motions in gas

- compression as cluster formed
  $\rightarrow$ hydrostatic eqilibrium today