Announcements

- quiz Tuesday on Ch. 18-20 and lectures 10-11. Review session Monday evening?
- graded midterms available in back. Mean/median was 60%.
- Let's raise it to 80% with corrections! Due Thursday Nov. 16. Do not cross out or overwrite original answer. Staple additional sheets of paper to the back, with question#, letter answer, and 1-2 sentence explanation.
Lecture 11: Milky Way and Other Galaxies

- our position, star maps and counts
- Shapley-Curtis debate
- structure of our Galaxy
- other galaxies: types and classification
- distance scale
- Hubble's law and the expanding universe
Milky Way

- literally, a milky “cloud” stretching across the sky
- Galileo resolved into stars in early 1600's
Our Position

- Milky Way appears to be a pancake. Counting stars in each direction might reveal our position in it. (Draw on board.)
- Herschels (1700's) and Kapteyn (~1900) concluded we are near the center and pancake's diameter is 5x the thickness.
- Shapley (1910's) mapped globular cluster system. Its center was tens of 1000's of light-years away!
- How did he know the distances to the clusters? Main sequence fitting.
Main Sequence Fitting

The main sequence of the Hyades is 7.5 times as bright as that of the Pleiades...

...so the Pleiades must be \(\sqrt{7.5} \approx 2.75\) times as far away.

relative apparent brightness

Pleiades

Hyades

surface temperature (Kelvin)

100

10

1

0.1
Why Was Kapteyn Wrong?

- Trumpler (1920's) found that apparent brightnesses of stars in plane of Milky Way decline more rapidly than inverse-square law.
- Conclusion: interstellar dust absorbs and scatters light.
- Light from more distant stars hits more dust, so star counts are deceptive.
- Now very well characterized with infrared and other means.
“Spiral Nebulae”

- known since 1700's
- with telescopes of the time, not clearly different from planetary nebulae and star-forming regions
- Kant (1755) suggested they were “island universes” like the Milky Way
Shapley-Curtis Debate (1920)

- **pros** (Curtis) and **cons** (Shapley) of “island universe” hypothesis
- **con**: 1885 nova in Andromeda nebula was so apparently bright that it could not be very distant
- **con**: M101 nebula appears to be rotating (in plane of sky) with period 100,000 years. If M101 is large, then its outer parts are rotating faster than speed of light!
- **pro**: all other novae in Andromeda were much fainter
- **pro**: M101 rotation measurement is bogus
- How would you judge the debate?
Most things known to be nearby are distributed in a pancake. Are the spiral nebulae?
Family Resemblance?
Proof

• Hubble (1920's) measured the distance to Andromeda nebula with Cepheids: a million light-years

• Andromeda is the closest spiral nebula. These are island universes equal to the Milky Way and separated by vast distances!

• Where did Shapley go wrong?
  – The “nova” in Andromeda was actually a ....
  – M101 rotation measurement was bogus.
Milky Way: Modern Picture

- the “pancake” is a disk of stars and gas on circular orbits, i.e. rotating. (Why?)

- we are in the disk, 28,000 light-yrs from the center, orbiting at ~200 km/s, taking 230 Myr to go around.

- disk is ~100,000 l-y across and ~1000 l-y thick

- central bulge is more spherical

- spherical halo of stars on polar/radial orbits (called “high-velocity stars” from our perspective)
Orbits

- Halo star orbits (green)
- Bulge star orbits (red)
- Disk star orbits (yellow)
Mass of Milky Way

- How do we measure mass?
- Result: $10^{11}$ solar masses inside solar orbit!
- Apply this to stars at various galactocentric distances to see mass distribution.
- Result: mass is everywhere, not just concentrated in center.
- But light is concentrated in center.
- This is a clue to what?
Galactic Recycling

Star–Gas–Star Cycle

- returning gas: supernovae and stellar winds
  - Fig. 19.5
- hot bubbles
  - Fig. 19.6
- atomic-hydrogen clouds
  - Fig. 19.12a
- molecular clouds
  - Fig. 19.10
- star formation
  - Fig. 19.11
- stellar lives: nuclear fusion/heavy-element formation
  - Fig. 19.13
Galactic Fountain Model

Why do superbubbles form?

Multiple supernova explosions in a young star cluster blow a superbubble in the galactic disk.

When the superbubble becomes thicker than the disk, hot gas can blow out of it into the halo.

Hot gas in the bubble can cool and form clouds.

Those cool clouds then rain back down onto the galactic disk.
Formation Scenario

- halo stars are very metal-poor: 0.02% vs up to 2% for disk stars
- must have been the first to form
- formed before gas collapsed onto disk
- ongoing star formation in disk but not in halo
- mergers with smaller galaxies/gas clouds explain uneven heavy-element distribution
Galactic Center

- orbits of a handful of stars very close to galactic center now well measured
- why do we want to do this?
Galactic Center

- orbits indicate $3-4 \times 10^6$ Msun within 90 AU ($10^{10}$ km)
- there is no way to pack this many stars into this small a volume without them merging!
- very little light comes from this huge mass
- conclusion: supermassive black hole!
- more evidence: X-ray flares
- usually pretty quiet, though
Galactic Center

- orbits indicate $3-4 \times 10^6$ Msun within 90 AU ($10^{10}$ km)
- Schwarzschild radius for this mass: $\sim 10^7$ km
- so black hole not proven beyond all doubt
- why is it difficult to prove all this mass is inside the Schwarzschild radius?
Fun BH fact: the more mass you have, the less dense it needs to be to form an event horizon.

Examples: 1 Msun BH has mean density $\sim 10^{-2}$ Msun/km$^3$ vs $10^9$ Msun BH with mean density $\sim 10^{-20}$ Msun/km$^3$, less dense than water!

Similarly, SMBH tides do not rip you apart until well after you enter event horizon. But watch out for the singularity!

Thought experiment: could we be in a black hole and not even know it?!
Review Questions

Order the main components of our Galaxy from lowest to highest angular momentum, metallicity, gas content, and star formation rate:

A. disk, bulge, halo
B. bulge, halo, disk
C. halo, bulge, disk
D. halo, disk, bulge
Review Questions

Order the main components of our Galaxy from lowest to highest angular momentum, metallicity, gas content, and star formation rate:

A. disk, bulge, halo
B. bulge, halo, disk
C. halo, bulge, disk
D. halo, disk, bulge
Review Questions

Our Galaxy's disk is about:
A. 10,000 light-yrs thick and 100,000 across
B. 1,000 light-yrs thick and 100,000 across
C. 1,000 light-yrs thick and 10,000 across
D. 100,000 light-yrs thick and 1,000 across
Review Questions

Our Galaxy's disk is about:
A. 10,000 light-yrs thick and 100,000 across
B. 1,000 light-yrs thick and 100,000 across
C. 1,000 light-yrs thick and 10,000 across
D. 100,000 light-yrs thick and 1,000 across

Followup question: where are we?
Our Galaxy contains about how many stars?
A. 100 trillion \((10^{14})\)
B. 100 billion \((10^{11})\)
C. 100 million \((10^8)\)
D. 100,000 \((10^5)\)
Review Questions

Our Galaxy contains about how many stars?
A. 100 trillion \((10^{14})\)
B. 100 billion \((10^{11})\)
C. 100 million \((10^8)\)
D. 100,000 \((10^5)\)
Other Galaxies...Lots of Them!

Hubble Deep Field (HDF)
Zoo of Galaxies: Spirals
Zoo of Galaxies: Ellipticals
Zoo of Galaxies: Irregulars
Hubble's Tuning Fork Diagram

- classifies ellipticals and spirals
- *Is not* a time sequence! *Is* a sequence of angular momentum, gas content, star formation.
- irregulars have even more gas content and star formation
Galaxies Usually Live in Groups/Clusters

Group (common)        Rich cluster (rare)
Our Own Local Group
Large Galaxies Have Satellites
Distances to Galaxies
Hubble Diagram

- galaxies are moving away from us
- more distant ones are moving away faster: \( v = H_0 d \) where \( H_0 \) is Hubble constant, \( \sim 70 \text{ km/s/Mpc} \)
- does this mean we are at the center?
Cosmological Principle

- Assume we do not occupy a special position or time. In fact, assume there is no special position.
- All galaxies are rushing away from all other galaxies!
- Requires no center and no edge, fits all data.
- Galaxies are not expanding into anything. Space itself is getting bigger.
Exceptions to Hubble Flow

- Where mass is concentrated, gravity is strong enough to resist expansion.
- E.g. Local Group galaxies will merge and fall into Virgo Cluster
- We see a blueshift when looking at Andromeda galaxy or Virgo cluster (60 million ly away!)
- Galaxies also have random velocities due to interactions
- Pure Hubble flow seen only on several $\times 10^8$ ly scales
Defining “distance” becomes tricky

One for luminosity, one for angular size, plus others...
Extrapolating Back in Time...

- galaxies must have been closer together in the past
- universe was denser and hotter
- far enough back in time, the mean distance between galaxies must have been zero!

- How far back in time? Assuming constant velocity expansion, answer is just $1/H_0$ or 13.8 billion years!

- lots of interesting things happen if universe was so hot and dense. Subject of future lectures...
Review Questions

How do we know the distance to nearby galaxies?
A. Radar
B. Parallax
C. Main sequence fitting
D. Cepheid variable stars
Review Questions

How do we know the distance to nearby galaxies?

A. Radar
B. Parallax
C. Main sequence fitting
D. Cepheid variable stars
Review Questions

What are the three main types of galaxies?
A. Bulge, halo, spiral
B. Elliptical, spiral, irregular
C. Spherical, spiral, irregular
D. Dwarf, giant, main sequence
Review Questions

What are the three main types of galaxies?
A. Bulge, halo, spiral
B. Elliptical, spiral, irregular
C. Spherical, spiral, irregular
D. Dwarf, giant, main sequence
Review Questions

What is Hubble's law?

A. More distant galaxies move away from us more quickly than nearby galaxies
B. More distant galaxies move toward us more quickly than nearby galaxies
C. More distant galaxies move away from us more slowly than nearby galaxies
D. More distant galaxies move toward us more slowly than nearby galaxies
Review Questions

What is Hubble's law?

A. More distant galaxies move away from us more quickly than nearby galaxies

B. More distant galaxies move toward us more quickly than nearby galaxies

C. More distant galaxies move away from us more slowly than nearby galaxies

D. More distant galaxies move toward us more slowly than nearby galaxies