Astronomy 162, Week 8
Milky Way Galaxy, continued

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Rotation of Galaxy

- How do we know the galaxy is rotating, and how do we measure its rotation?
  - Measure radial velocities of objects at different positions along the plane (disk) of the galaxy
  - Radio astronomy (21-cm line) is main technique - radio waves penetrate dust clouds
    (Review our discussion of HI clouds, the 21-cm line, and how it penetrates the dust clouds)

Fig. 25-9b, 21-cm emission

Fig. 25-10, 21-cm map of sky

Fig. 25-11, Mapping Spiral Structure

Fig. 25-12, HI Map of our Galaxy

Spiral Structure

- Milky Way is a spiral galaxy
  - (see Fig. 25-14, also 25-13 – M83 is similar)
- What are properties of spiral arms? How do they form? and survive?
  - Milky Way does not rotate like a solid body (e.g., a bicycle wheel)
  - Outer parts rotate more slowly than inner, so spiral arms should wind up and disappear

Fig. 25-14, Our Galaxy

Spiral Arms

- Spiral arms are density waves, made visible by star formation
  - wave pattern rotates more slowly than the stars and clouds of gas in the galaxy
  - as gas clouds encounter a spiral arm, star formation is triggered, arms become bright
  - The newly formed stars appear to pass through the spiral arms

Spiral Arms, cont.

- Differential rotation causes stars to string out along spiral arm
  - outer parts of galaxy rotate more slowly than inner parts (like planets in Solar System)

Fig. 25-20, Star Formation and Density Wave

Halo of Galaxy

- Halo
  - much lower density than disk
  - has old stars with low abundance of metals (heavy elements)

Bulge region of galaxy

- Bulge
  - mixture of stars
  - some old with few metals
  - some with more metals than sun
  - result of many generations of stars

Infrared and Radio Views of Galaxy

- COBE satellite used infrared obs.that penetrate dust to make map of galactic plane
  - Result (Fig. 25-6b) clearly shows disk and bulge region of galaxy
- Radio maps indicate spiral structure

Central Region of Galaxy

- Center of galaxy is in direction of Sagittarius
  - direct optical view completely blocked by dust
  - X-rays, infrared, and radio waves can penetrate dust
  - First radio source ever discovered in sky is near center of galaxy

Why is central region so important?

- Remember star formation, evolution of stars
  - Mass concentrates toward center
  - Density increases with time
- It is likely that center of our galaxy is different from solar neighborhood
  - May expect higher density
  - Other galaxies have bright nuclei
  - Radio source near center is a clue

Scale at center

- At center of galaxy
  - 1 arcsec is about 0.04 parsec, or 0.13 light year
  - We can study nucleus in great detail, more than for any other galaxy, if we can penetrate the dust

Geography at Center

- Density of stars is very high
  - Separation of stars as little as 500 - 1000 AU
  - Most stars are red giants
  - Some are supergiants in young clusters
  - Ring of molecular gas and dust surrounds center at distances of 6 to 25 pc
  - Hot stars near center ionize inner part of ring of gas

Motions near center

- Gas clouds at 0.1 pc from center have motions of 700 km/s
  - Imply that a mass of millions of suns lies within 0.1 pc of center
  - Probably not in form of stars
- What is the central mass?

Massive Black Hole

- It appears likely that there is a black hole with a few million solar masses at center of galaxy. It could explain
  - central radio source Sgr A*
  - filaments and trails of radio emission
  - central region being clear of gas except for spiral structure

Black Hole

- As matter falls in towards the black hole
  - it heats up
  - can produce the radio emission and jets of gas seen in radio maps
  - can account for the rapid motions seen so close to center
  - but the black hole is only about 10 times size of sun, so it wouldn't be observable directly

Fig. 25-22, The Galactic Center

Fig. 25-24, The Galactic Nucleus

Results from stellar motions (Eckart, Genzel, Ghez et al.)

- Find projected velocities up to 1500 km/s
- Results agree with Keplerian motion to within 0.01 pc of galactic center
- Implied mass of central black hole is 3 million solar masses
- Strong evidence for existence of black hole
  - nothing else could have the small observed size, high density

- This work is from the Max Planck Inst. for Space Physics in Germany
- See the link http://www.mpe.mpg.de/www_ir/GC/ for more information.

- See also the link to the UCLA group: http://www.astro.ucla.edu/~jlu/gc/

Fig. 25-23, Orbits of Stars at the Galactic Center

Astronomy 162, Dark Matter, Formation of Galaxy

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Mass of Galaxy

- Recall Sun orbits center of galaxy
  - Speed about 220 km/s
  - Distance is about 8000 pc from center
  - Takes about 225 million yrs to complete one orbit
  - From Kepler's law, can estimate mass of galaxy inside Sun's orbit to be about 10^{11} solar masses

- This is mass in galaxy out to distance of sun
- Outer parts of galaxy have fewer stars
- Would expect rotational velocity to decrease
- It doesn't (Fig. 25-15, 25-16)
- What is going on?

Fig. 25-15, Rotation of our Galaxy

Fig. 25-16, Observed Rotation of Galaxy

Dark Matter

- In fact, there is evidence for much unseen mass
  - Can be more than 10 times the visible mass
  - It is called dark matter (is non-luminous)
  - What is it?

Dark Matter, cont

- Observations show dark matter is not
  - neutral hydrogen
  - ionized hydrogen
  - molecular material
  - dust
  - black holes

Dark Matter, cont.

- Could it be
  - low mass stars
  - planets
  - bricks
  - unusual atomic particles?
- This is one of main research problems in astronomy today

How to detect dark matter?

- It’s dark, so we can’t see it
- Make use of its gravity, such as
  - Influence on motions of other objects, e.g., binary stars, rotation curve of galaxy
  - how it bends the light of more distant objects, e.g., gravitational lensing or microlensing

Fig. 25-17, Detecting Dark Matter by Microlensing

Microlensing

- Prof. Andrew Gould of our department is a world expert in this subject
  - He has developed many of the mathematical results for understanding and interpreting microlensing
  - Together with Prof. DePoy and several of our students, a huge OSU effort to study microlensing has been done in the Southern Hemisphere

MACHOs

- MACHO - massive compact halo object
  - could be planets to low mass stars such as brown dwarfs or white dwarfs
  - recent evidence for MACHOs from gravitational lensing surveys
  - white dwarfs might be the source of the dark matter, but not favored at present
  - stay tuned for further results

WIMPs

- Weakly interacting massive particles
  - neutrinos?
  - remember discussion of solar neutrino problem
  - neutrinos or some other basic particle might also account for the dark matter
  - As with MACHOs, stay tuned to see what happens

How did the galaxy form? I. Top-down theory

- General idea is that material fell together from a giant cloud of gas in the early universe
  - Cloud fragmented
  - formed oldest stars (10-15 billion yrs ago)
  - likely formed in halo
  - thus have high velocities,
    low abundances of heavy elements

Formation of Galaxy, cont.

- Similarly, globular clusters formed early in halo
- As with stars, matter falls toward and concentrates at center of galaxy
- High density there
- Recycling of matter via massive stars
- Abundance of heavy elements builds up with time. Current stars at center have greater metal abundance than sun

Formation of disk

- Farther out from center, matter forms disk
  - in analogy with accretion disks around protostars
  - density is lower, recycling slower than at center of galaxy
  - have a normal (solar) abundance of heavy elements

Alternate Theory
II. Bottom-up approach

- Galaxy could have formed from the collision and assembly of smaller clouds of gas
- As they collided and lost energy
  – star formation is triggered
  – a disk can form
  – matter can fall to center, increase density there

Formation of galaxy, cont.

- The later evolution of the galaxy could be similar under both theories
- Summary - at this time, we don't have a definitive theory for how the galaxy formed
- Observations of other galaxies and computer models show both top-down and bottom-up approach can occur
- Stay tuned for more developments

Theories of Galaxy Formation

Galaxies beyond the Milky Way

- We have covered the properties of the Milky Way
- What about other galaxies?
- Indeed, the historical question was,
  Are there other galaxies?

History and Philosophy

- Thomas Wright, 1750, proposed sun is part of flattened system - the Milky Way
- Immanuel Kant, 1755, speculated nebulae were other island universes (Milky Ways)
- Recall the data and observations
  - Messier catalog (we now know) has galaxies
  - Herschels' catalogs also

Wright's Milky Way (1750) But there was no proof

- Basic problem - how to establish distances to the nebulae
  - Were they nearby, like emission nebulae, and part of our Milky Way galaxy?
  - Or, were they distant, separate galaxies in their own right?

Beyond the Milky Way

- 3 milestones in this quest
  - Leavitt - Period-luminosity relation for cepheids in Magellanic Clouds
  - Shapley - establishing size of our galaxy
  - Hubble - use of 100-in telescope to find cepheid variables in nearby galaxies

Quantum jump in our view of the universe

- Hubble's work built on that of Leavitt, Shapley
  - 1923-24 - he showed that the cepheids in the nebulae M31, M33 were so faint that they were well outside our own galaxy
  - M31, M33 are galaxies in their own right
- This work genuinely changed our view of the universe

Types of galaxies

- As with planets, stars, and clusters, there are different types of galaxies:
  - spirals
  - ellipticals
  - irregulars
- As previously, goal of classification of galaxies is to discover underlying order, gain insight into their true nature

- We'll see that our understanding of galaxies is less well advanced than for stars
- Galaxies don't have the advantage of being in equilibrium that most stars do

Spiral galaxies

- Many galaxies, like Milky Way and M31 in Andromeda show:
  - spiral arms
  - disk
  - halo
  - nucleus
  - bulge

- However, there is a range of "spiralness"
  - How conspicuous the arms look
  - Degree of concentration toward center
  - Range of mass
  - Range of size
  - Presence of bars: some have a conspicuous bar in central regions from which the spiral arms emerge

M83, AAT image

Astronomy 162, Week 8
Galaxies, continued

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Galaxies, continued

- We have discussed spiral galaxies
- Next, consider elliptical and irregular galaxies
- Then, classification, distances, and overall properties of galaxies
  - Also see more about the dark matter problem

Elliptical Galaxies

  - Appear round or elliptical in shape
  - Smooth in appearance
  - Red in color
  - Dominated by Population II
  - May have hot gas (X-ray emission)
  - Have globular clusters
  - Great range in luminosity and mass

Irregular Galaxies

- Irregular in shape (not spiral, not elliptical)
- May have:
  - much gas
  - regions of intense star formation
  - Mix of Pop. I and II
  - Nearby examples are Large and Small Magellanic Clouds, nearest galaxies to Milky Way

- Review Figs. 26-4 through 26-10 in text
- Also, see image galleries on the web sites:
  - Anglo-Australian Observatory
  - European Southern Observatory
  - Hubble Space Telescope
  - National Optical Astronomy Observatory
  - (The links are on the class web page)

Galaxy Classification

- Hubble's approach
  - "Tuning fork diagram" (Fig. 26-9)
  - start with roundest ellipticals (class E0)
  - proceed to most elliptical (class E7)
  - use type S0 to mark transition between ellipticals and spirals
  - S0 galaxies have disk shape of spiral, but no spiral arms

Galaxy classification

- Two branches of spirals
  - normal
  - barred
  - types Sa and SBa have large nuclei, tight arms, look smoother
  - types Sc and SBc have small nuclei, open arms, rougher structure, more Pop. I stars

How far away are the galaxies?

- To make progress in mapping the universe and in understanding galaxies, we have to be able to determine their distances
  - Recall parallaxes are only direct measures of distance in astronomy
  - For objects beyond limit of parallaxes, we are always using indirect methods

Measuring distances

- Requires
  - Calibration of indicators
  - Understanding of systematic effects
  - Correction for dust absorption
- Historically, problems in all three points above have caused errors in distance scale

Traditional Distance Ladder

- Use a series of steps
  - parallaxes
  - calibration of variable stars in clusters
  - use variable stars, like Cepheids, in galaxies
  - but each step has a limit in distance
  - need successively brighter distance indicators

Fig. 26-12

Distance ladder, cont.

- For galaxies beyond limit of Cepheids, use
  - brightest stars in galaxies
  - globular clusters
  - supernovae
  - then, the brightest galaxies in clusters of galaxies
  - however, the uncertainty increases at each step

Distance scale

- Continues to be active research subject
  - new indicators are being used
  - rotation curves of galaxies can indicate luminosity
  - planetary nebulae
  - fluctuations of brightness in galaxies

Properties of Galaxies

- Fundamental properties of galaxies are mass, size, and luminosity
  - should tell us about their intrinsic nature
- How to determine mass?
  - Analogy with Milky Way, use orbital speed and distance from center in combination with law of gravity

Masses of galaxies

- For spirals, measure rotation curve
  - note Fig. 26-28
  - as long as we know distance of galaxy, we can estimate its mass
- Ellipticals are a different case
  - may not rotate
  - orbits of stars are more radial (in and out)
  - such motions broaden spectral lines

Fig. 26-28, Rotation Curves

  - use widths of lines and another application of law of gravity to determine masses
  - can also use X-ray observations of hot gas in ellipticals
- Related approaches to estimate mass
  - for double galaxies and galaxies in clusters, can use differences in radial velocities plus law of gravity

Summary of Galaxy Properties (Table 26-1)

Mass to light ratio

- Mass to light (M/L) ratio of a galaxy is an indication of what kind of stars it has
  - recall mass-luminosity relation for main sequence stars
  - compared to sun, low-mass stars are underluminous
  - high-mass stars are overluminous

- The M/L = 1 for sun
- For low-mass stars, M/L > 1
- For high-mass stars, M/L < 1
- Thus, M/L is a population indicator

Dark Matter (again)

- In some galaxies, M/L is about 100
  - this is additional evidence for dark matter
  - in fact, the Milky Way (spiral), M87 (giant elliptical), clusters of galaxies all show evidence for up to 10 times as much dark matter as in luminous matter
  - Total mass of M87 may be as large as 10^{13} solar masses

Dark Matter

- Continues to be one of the most important mysteries in astronomy and physics today