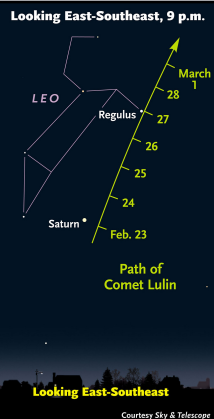## Chapter 15

The Milky Way Galaxy

Agenda

- Project Parts I were due
- Handback tests/labs and go over
- Comet Lulin
- Possible Observation Dates
  - March 3 7pm
  - March 24 7pm
- How do we *know* something?
- Solar Altitude Measurement
- Ch. 15
- Lab@Home:
  - online assignment on dark matter
  - Email a short list of what we could see on the above dates

Labs

- Need original data
- Enough info for someone to duplicate the experiment
- Don't show all calculations
- Quantify error
- Compare error w/ uncertainty:
  - If error<uncertainty, then results consistent w/ theory
  - If error>uncertainty, then results inconsistent w/ theory
    - Bad explanations:
      - Equipment bad (for starters, this would increase unc)
      - Execution bad (then fix it or redo it)
    - Better explanations:
      - Expected value general, not specifically calibrated with *your* equipment
      - A specific source of error that could not be eliminated

Comet Lulin

Looking East-Southeast, 9 p.m.

LEO

March 1
28
Regulus 27
26
25
24
Saturn
Feb. 23

Path of
Comet Lulin

Looking East-Southeast

Courtesy *Sky & Telescope*

How do we know something?

How do we know something?

- Should we stop vaccinations to avoid causing autism?
- Should evolution be taught in schools?
- Did the Holocaust happen?
- Which medicinal practices should insurance pay for:
  - Chiropractor
  - Homeopathic medicine
  - Acupuncture

The Milky Way

- The pale band of light spangled with stars stretching across the sky is the *Milky Way,* a swath of light named by the ancient Greeks
- In the 17th century, Galileo showed the Milky Way is millions of stars too dim to see individually
- Today we know the Milky Way is a slow revolving disk of stars, a galaxy
- We also know today that the Milky Way is filled with stars of various sizes, many of them found in clusters, and clouds of gas and dust
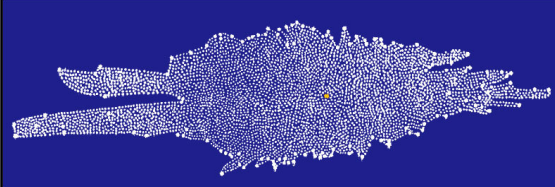
Shape of the Milky Way
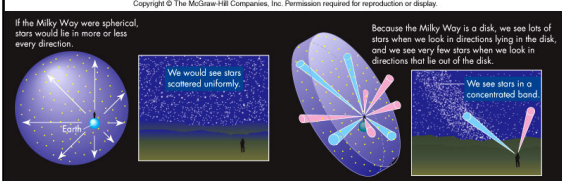
- Uniform distribution of stars in a band across the sky lead Thomas Wright, Immanuel Kant, and William Herschel in the 18th century to suggest the Milky Way is a disc distribution of stars with the Sun near the center
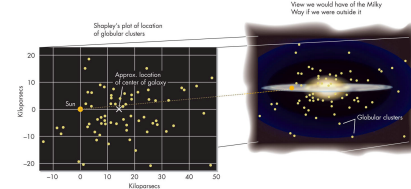
Shape of the Milky Way

- William Herschel's sketch of the Milky Way, from 1748. This sketch led Herschel (and others) to believe the Milky Way was disk-shaped (correct), and that the solar system was near the center of that disk, at the position of the yellow dot (incorrect)
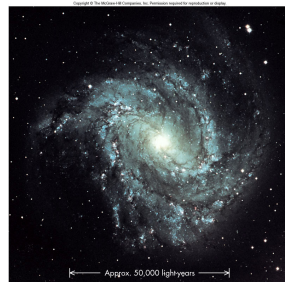
Size of the Milky Way

- Jacobus Kapteyn determined the diameter of the Milky Way to be 20 kpc with the Sun near the center
- Harlow Shapley found the diameter to be 100 kpc with the Sun 2/3 from the center
- Both were not aware of the dimming effects of dust
- Shapley, using globular star clusters for distances, did not distinguish RR Lyrae from Cepheid variables

Size of the Milky Way

- Correcting for dust effects and variable star types, astronomers conclude the disc has a 30 kpc diameter with the Sun 2/3 from the center
- Discovery that nearly all disc-shaped galaxies have spiral arms implied Milky Way is a spiral too.

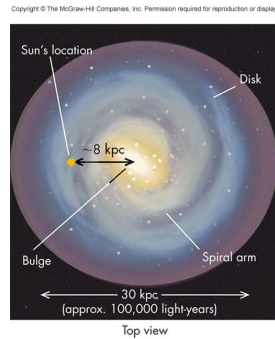Approx. 50,000 light-years

Structure and Contents of the Milky Way

- The *Disk*
  - *Spiral arms* distribution of stars, gas, and dust with a diameter of about 30 kpc (100,000 light-years) and plane tilted with respect to Earth's orbit around Sun
  - Differential rotation with all objects circling in the same direction: 240 million-year period at 220 km/sec at the Sun's orbit (about 8.5 kpc out from center)
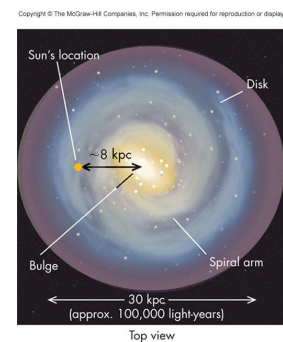
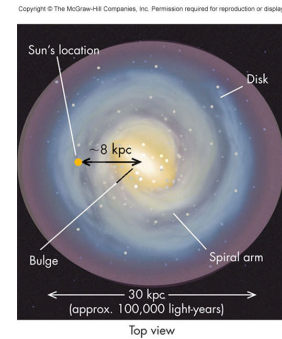## Structure and Contents of the Milky Way

- The *Disk*
  - High density of stars near center (10 million stars per cubic light-year) to low density farther out (0.003 stars per cubic light-year at Sun)
  - Dust and gas is nearly 15% of the disc's mass

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Sun's location
Disk
~8 kpc
Bulge
Spiral arm
30 kpc
(approx. 100,000 light-years)
Top view

Structure and Contents of the Milky Way

- The *Disk*
  - Most of galaxy is hidden from Earth due to dust obscuration including the central *nucleus* with its dense swarm of stars and gas in which a massive black hole may reside
  - Radio and infrared telescopes can "see" entire galaxy: Radio observations suggest larger warped disc of gas (out to nearly 40 kpc)
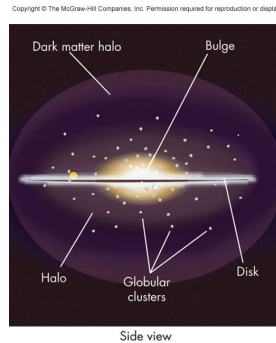

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Sun's location
Disk
~8 kpc
Bulge
Spiral arm
30 kpc
(approx. 100,000 light-years)
Top view

Structure and Contents of the Milky Way

- *Halo*
  - Roughly spherical region with disk embedded
  - Contains mainly old stars, such as globular clusters
  - Large amounts of dark matter may also be present
- *Bulge*
  - Flattened collection of stars surrounding dense core of galaxy
  - About 1/3 the diameter of the galaxy

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Dark matter halo
Bulge
Halo
Globular clusters
Disk
Side view

Mass and Population of the Milky Way

- From its rotation and effects on nearby galaxies, mass of Milky Way is 2×10^{12} M$_\odot$
- From large difference between this mass and what is observed, astronomers conclude Milky Way is embedded in vast halo of material that emits no radiation (at any wavelength) – *dark matter*
- Assuming that the average star has a mass similar to that of the Sun, then based on the Milky Way's mass, there are roughly 100 billion stars

Approx. 50,000 light-years

Age of the Milky Way

- Using stellar aging techniques, astronomers had estimated the galaxy's most ancient stars to be about 15 billion years old
- More recent model calculations and observations suggests the old star ages are more like 13 billion years
- A rough estimate of the Milky Way then is about 13 billion years

Approx. 50,000 light-years

Stars of the Milky Way

- Stellar Censuses
  - Counts that list all known stars of a given type in a region of space is called a stellar census
    - All star types are represented in the Milky Way
    - By analyzing the relative numbers of stars of each type, deducing the galaxy's history is possible
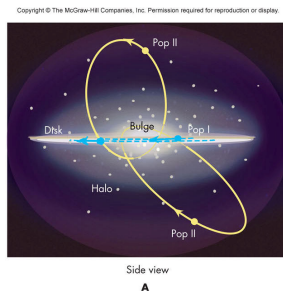
Stars of the Milky Way

- The Mass Function
  - From a stellar census one can derive the number of stars of each mass, technically known as the *mass function*
    - Mass determines the life cycle of a star
    - The evolution of the Milky Way will then depend on:
      - How many stars of each type it contains (A galaxy with only massive stars will evolve quickly)
      - How fast each type is created (Fast creation will quickly deplete gas resources)

Stars of the Milky Way

- Some results:
  - Dividing the number of stars in the Milky Way by its age gives a star creation rate of 3-5 stars per year
  - Most numerous stars turn out to be dim, cool, red dwarfs (mass about 0.5 $M_\odot$)
  - The average mass for Milky Way stars is ~1 $M_\odot$
  - Stars more massive than 100 $M_\odot$ are rare
  - Current research suggests that brown dwarfs ("failed stars" of mass less than 0.08 $M_\odot$) are more numerous than ordinary stars
  - It is important to be aware of "selection effects" when interpreting data: "Absence of evidence is not evidence of absence"; i.e., there may be things there you cannot see)
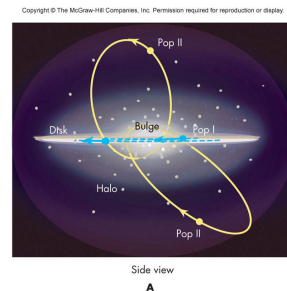
Two Stellar Populations

- *Population I*
  - Age: generally young (10^6 to a few times 10^9) years
  - Color: blue (generally)
  - Location: disk and concentrated in arms
  - Orbit: approximately circular in disk
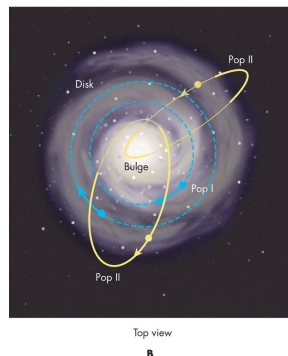 - Heavy-element content: high (similar to Sun)

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Side view

A

Two Stellar Populations

- *Population II*
  - Age: old (about 10^{10}) years
  - Color: red
  - Location: halo and bulge
  - Orbit: plunging through disk
  - Heavy-element content: low (10^{-2} to 10^{-3} Sun)

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Side view

A

Two Stellar Populations

- Division of stars into two groups can be oversimplification
  - Sun does not fit in either category, but is usually considered a Pop I star
  - Inspires creating sub-groups
    - Subdivide each population into *extreme* and *intermediate*
    - *Old-disk population* sometimes used for stars like the Sun

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Top view

B

Two Stellar Populations

- The two populations show that star formation has not occurred continuously
  - Pop II formed in major burst at galaxy's birth during its initial collapse
  - Pop I formed much later and are still forming today
- Pop I stars used to map spiral arms in vicinity around Sun
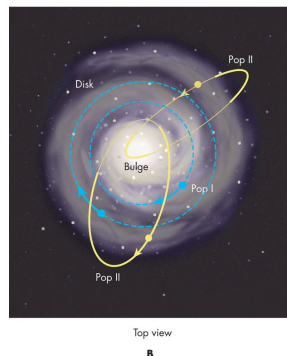
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Top view

B

Star Clusters

- Some of the Milky Way's stars are gravitationally bound together in groups called *star clusters*

- There are two types of star clusters
  - Open Clusters
  - Globular Clusters

Open Clusters

- Contain up to a few hundred members in a volume of typically 7-20 light-years across
- Pleiades (or the Seven Sisters) is an excellent example
- Also called "galactic clusters" since most lie in galactic disk
- Formed when interstellar gas clouds are compressed and collapse upon entering the Milky Way's spiral arm
- About 20,000 open clusters currently exist, many of them obscured by the dust of the galactic disk

Open Clusters

- Within spiral arms, very young stars may group together in loose *associations* a few hundred light-years across
  - Single large open cluster near their center
  - Birthing gas and dust still present
- After hundreds of millions of years, the stars gradually leave and the cluster dissipates

Open Clusters

Globular Clusters

- Contain far more stars than open clusters, from a few hundred thousand to several million per cluster
- Have large radii, 40-60 light-years across
- The strong gravity pulls the stars into a ball denser than that found in open stars
- About 150-200 globular clusters outline the halo and bulge of the Milky Way

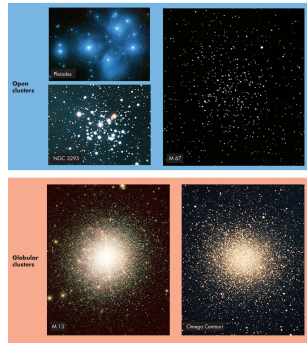## Globular Clusters
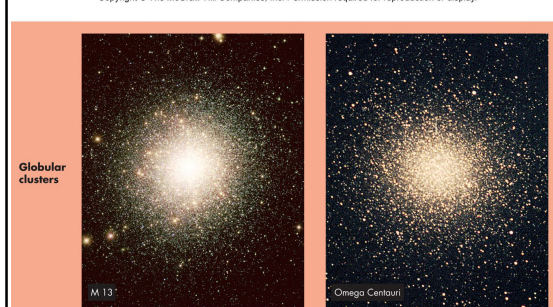
Star Clusters

- Open and globular clusters reflect the properties of Pop I and II stars – Open clusters are generally Pop I and globular clusters are always Pop II


Gas and Dust in the Milky Way

- The space between stars is not empty: it contains *interstellar matter* composed of gas and dust
  - Most of the gas and dust exists in the galactic plane
  - Even here it clumps into clouds a few light-years to a few hundred light-years across
  - Typical densities are a few gas atoms per cubic centimeter (air has 10^{19} atoms per cubic centimeter

Gas and Dust in the Milky Way

- Interstellar clouds seen directly or detected by their effect on light from distant stars
  - Gas and dust imprint narrow absorption lines on starlight passing through interstellar clouds: such lines can give cloud's composition, temperature, density, and speed
  - Gas found to be 71% H, 27% He, 2% heavy elements
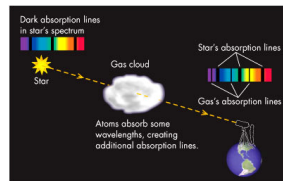
  - Dust is μm to nm in size, made of silicates and carbon compounds, and perhaps coated with ices of water, carbon monoxide, and methyl alcohol
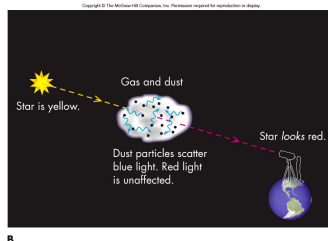
Scattering

- The light from a star dims and reddens as it passes through an interstellar cloud with dust
- Light is randomly reflected from the dust surfaces in a process called *scattering*
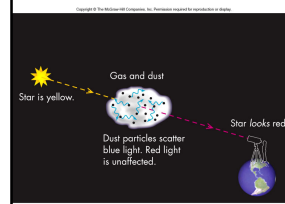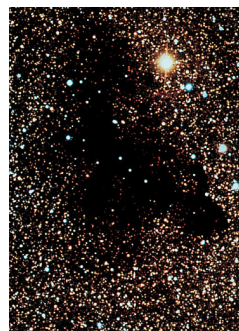
Scattering

- This scattering is most effective when the light's wavelength is smaller than the dust grain
- The optimum scattering for interstellar dust and molecules in the Earth's atmosphere is for blue and ultraviolet light

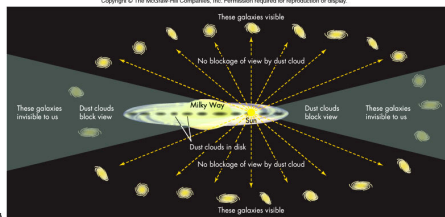- Earth's sky is blue and the setting Sun red because of scattering

Reddening

Dark nebula

- The loss of blue light from a star due to scattering in an intervening cloud is called *reddening*
- An interstellar cloud that completely obscures the stars behind it is called a *dark nebula*

Reddening and Obscuration

- The large amount of dust in the galactic plane reduces almost to zero the number of distant galaxies that can be seen – this region of the sky is called the *zone of avoidance* (the galaxies can still be "seen" in the radio and infrared)

Reflection Nebula

- A nebula may be seen in the visible as the result of starlight reflecting off the dust – such a nebula is called a *reflection nebula*
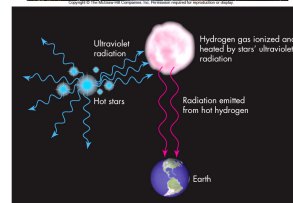
Interstellar Gas

- Interstellar gas plays a crucial role in providing material for creating stars and a repository for matter blown out by dying stars
- Interstellar gas also helps astronomers map the Milky Way since molecules within the clouds emit at wavelengths that can penetrate dust
- And, of course, the visible wavelengths of many gas clouds provide spectacular images
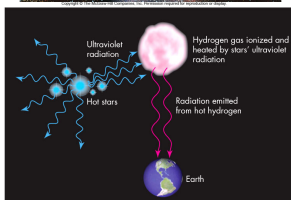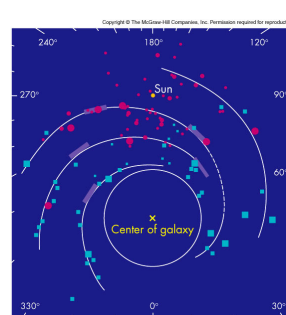
Interstellar Gas

- Interstellar gas clouds that emit visible light are called *emission nebulas*
  - To emit this light, the cloud must have a source of energy, usually a nearby star
  - Hot, blue stars are especially effective at energizing a gas cloud

Interstellar Gas

- Clouds that are hot enough to ionize hydrogen will give off a very characteristic red color as electrons recombine with protons – these clouds are called *HII regions* (the II indicating ionization)

Interstellar Gas

- Maps of radio and optical observations of HII regions are the best evidence we have that the Milky Way is a spiral galaxy

Mapping the Milky Way

- Most interstellar gas clouds are too remote from hot stars to be seen in the visible
  - We detect these clouds by measuring their radio output
  - For hydrogen, the *21-centimeter radiation* is the radio emission that comes from the "spin flip" of the bound electron
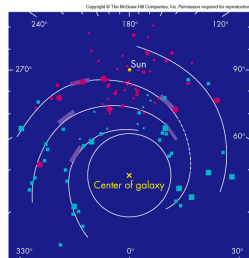
Mapping the Milky Way

- Radio emissions are not only valuable for mapping gas distributions in the galaxy, but also for identifying the types of molecules that exist in space
  - Examples: H_2 (molecular hydrogen), OH (hydroxyl radical), CN (cyanogen radical), CO (carbon monoxide), H_2O (water), NH_3 (ammonia), HCOH, (formaldehyde), HCOOH (formic acid), CH_3CH_2OH (ethyl alcohol or ethanol)
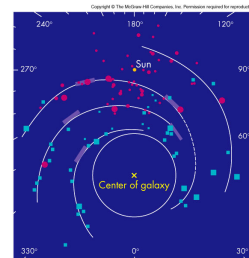
Spiral Arm Models

- *Density-wave model*
  - Stars travel around the center of the galaxy in their own orbits
  - Stars and gas traveling in the disc will bunch up as they enter an arm and will spread out as they leave
  - This bunching is similar to that of cars on a freeway except gravity causes the bunching of the stars
  - Gas entering the arm is compressed initiating star formation
  - The newly created and very luminous O and B stars illuminate the gas and dust in the arms
  - Having very small lifetimes, the O and B stars die before leaving the arm region thus making the spiral arms more conspicuous than surrounding regions
  - Theory has difficult time explaining longevity of spiral arms, but observed aging of O and B stars across the arms is consistent with the theory

Density-Wave Model
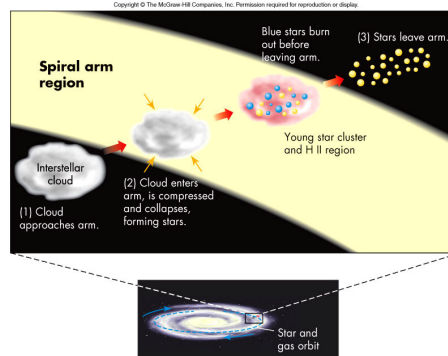
Spiral Arm Models

- *Self-propagating star formation* model
  - This theory proposed to explain ragged-appearing arms of some galaxies
  - Star formation begins at some random location in the galaxy creating a collection of stars
  - As these stars heat the gas around them and the larger ones explode, the disturbance sets off a star formation in an adjoining gas cloud
  - The process continues as long as there are enough large stars and gas to propagate the star formation process
  - Differential rotation of the galaxy then spreads the stars out into a spiral arm
  - The random nature of the triggering star formation should give a spiral galaxy a ragged look and this is observed in some galaxies

## Self-Propagating Star Formation

Diameter of the Milky Way

- All methods to determine the Milky Way's diameter depend on Sun's distance to center
- Red giant maser method
  - Red giant maser radio sources common in inner bulge
  - Stars near galactic center move in random directions
  - Assume in a given volume a star moving radially has the same speed as one moving across the line of sight
  - Use Doppler shift of radial maser source to determine speed and use this with transverse maser angular motion to determine distance
  - Geometric center of masers gives Sun distance of 7 kpc
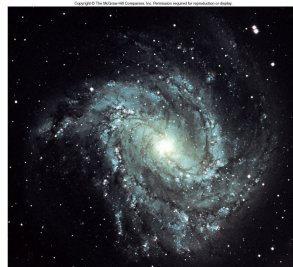
Diameter of the Milky Way

- Globular cluster method
  - Globular cluster distances and directions determined using period-luminosity relation for variable stars
  - Geometric center of globulars then marks the center
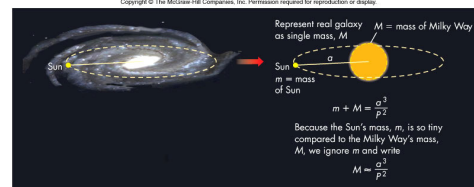 - Distance to center from Sun is then found to be 8.5 kpc
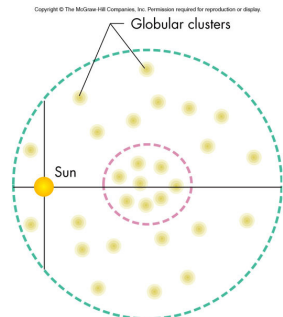
Diameter of the Milky Way

- Once distance to center from Sun found, this is added to distance to outer edge from Sun to arrive at the Milky Way's diameter – a value of about 40 kpc or more


Mass of the Milky Way

Represent real galaxy as single mass, M   M = mass of Milky Way

m = mass of Sun

$$m + M = \frac{a^3}{P^2}$$

Because the Sun's mass, m, is so tiny compared to the Milky Way's mass, M, we ignore m and write

$$M \approx \frac{a^3}{P^2}$$

- The mass of the Milky Way is determined by using Kepler's modified third law
- Using the Sun's distance to the center and its period of revolution, the mass interior to the Sun's orbit is at least 10^{11} M$_\odot$

Mass of the Milky Way
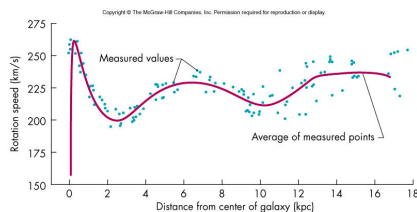
- A more refined technique uses the rotation speeds of stars at a variety of distances from the center (the so-called *rotation curve*)
- This technique can more accurately determine the mass of the entire galaxy – the Sun method only estimates the mass interior to its orbit

Mass of the Milky Way

- In either method, the speed of stars around the galaxy is crucial and there are many ways to do this – two of them are:
  - Use the Local Group of galaxies as a reference frame since the stars on the Milky Way move much faster
  - Use the distribution of randomly moving globular clusters as on average being at rest
- Analysis of the rotation curve also reveals a dark matter halo with a radius exceeding 100 kpc
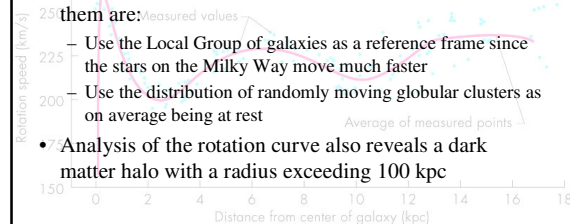
The Galactic Center

- Because the galactic center is not observable in the visible, astronomers must rely on radio, infrared, X-ray, and gamma-ray observations

The Galactic Center

- At a distance of 3 kpc, an arc of cold hydrogen sweeps outward at a speed exceeding 100 km/sec
- A giant swarm of stars, packed in at millions of stars per cubic light-year, are arranged in an elongated structure about 1000 light-years across
- Some energetic event, perhaps a supernova explosion, violently disturbed the center in the not-to-distant past
- Deep within the core lies an incredibly small (10 AU diameter) radio source known as Sgr A*
- A 10^6 $M_\odot$ black hole may occupy the very center of the galaxy, although other explanations have been given

A Black Hole?
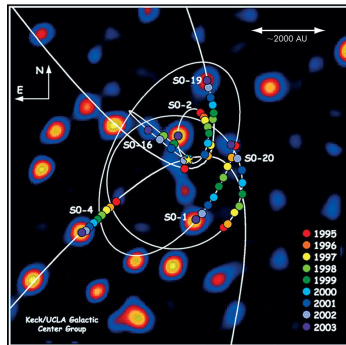
Formation of the Milky Way

- Forming galaxies is still a major unsolved problem
- Currently it is thought that galaxies form like stars, but only on a larger scale
  - Begin with a million-light-year cloud with 100 billion solar masses of material
  - The cloud gravitationally collapses and breaks up into stars
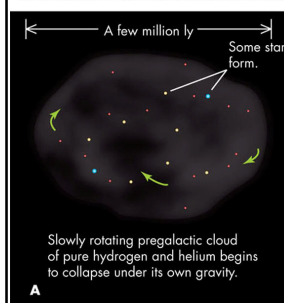- Evidence for this galaxy formation process can be found in the Pop I and Pop II stars

Formation of the Milky Way
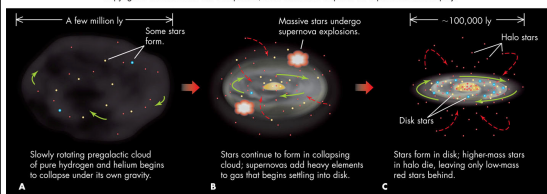
Formation of the Milky Way

- The proto-Milky Way was a giant cloud of pure hydrogen and helium
- The existence of old Pop II stars with very little heavy elements suggests they formed at the onset of collapse and as they did so, they dropped out of the gas collapse
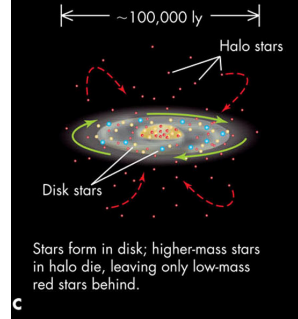
Formation of the Milky Way
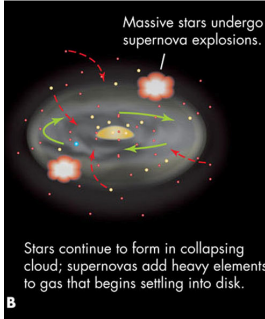
- The massive Pop II stars exploded early on, seeding the galactic cloud with heavy elements
- By the time the cloud collapsed into a disc it was rich enough in heavy elements to generate the Pop I stars we see there today
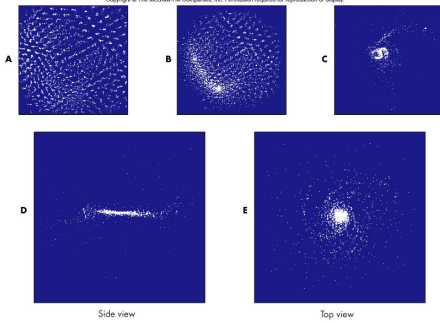
Formation of the Milky Way

Computer Simulation of Galactic Formation

Formation of the Milky Way

- However, the collapse model fails to explain two important properties of stars
  - Pop II stars appear to have formed over a longer time scale than the collapse model allows
  - Some stars should have virtually no heavy elements, but no such stars have ever been observed

Formation of the Milky Way

- Today, astronomers also believe the collapse model fails to include the effects of galactic mergers on galactic and stellar evolution – merging appears to be the rule, not the exception

Population III Stars

- Despite uncertainties, the basic idea of the initial stars being made of pure hydrogen and helium is still true – so where are they
- These *population III stars* may not be observable for three reasons
  - Only short-lived massive population III stars can form – consequently none are left today
  - Population III stars exist, but are masquerading as Pop II since their atmospheres have been contaminated by gas ejected when a more massive star exploded
  - Pop II stars may be rare and hard to find

The Future of the Milky Way

- Eventually all gas finds its way into stars, which in turn will lock up material in stellar remnants
- Hundreds of billions of years from now the Milky Way will fade, slowly spinning in space, a dark disk of stellar cinders