19. Our Galaxy

The infinitude of creation is great enough to make a world, or a Milky Way of worlds, look in comparison with it what a flower or an insect does in comparison with the Earth.

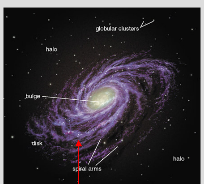
Immanuel Kant (1724 – 1804)
German philosopher

19.1 The Milky Way Revealed

Our goals for learning:

- Describe the general structure of the Milky Way Galaxy.
- Where is the Sun located within our Galaxy?
- Can we see through our Galaxy's interstellar medium?

Regions of the Milky Way Galaxy



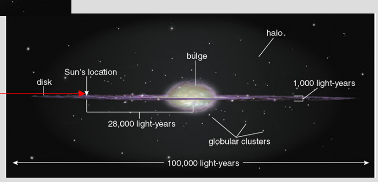
diameter of disk = 100,000 l.y. (30,000 pc)

radius of disk = 50,000 l.y. (15,000 pc)

thickness of disk = 1,000 l.y. (300 pc)

number of stars = 200 billion

Sun is in disk, 28,000 l.y. out from center



Regions of the Milky Way Galaxy

- Disk
  - younger generation of stars
  - contains gas and dust
  - location of the open clusters
- Bulge
  - mixture of both young and old stars
- Halo
  - older generation of stars
  - contains no gas or dust
  - location of the globular clusters

The Interstellar Medium (ISM)

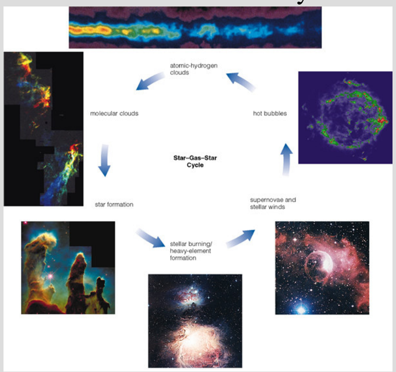
- It is the "stuff" between the stars.
- It is mostly a vacuum (1 atom cm^{-3}).
- It is composed of 90% gas and 10% dust.
  - gas: individual atoms and molecules
  - dust: large grains made of heavier elements
- The ISM effectively absorbs or scatters visible light.
  - it masks most of the Milky Way Galaxy from us
- Radio & infrared light does pass through the ISM.
  - we can study and map the Milk Way Galaxy by making observations at these wavelengths

19.2 Star–Gas–Star Cycle

Our goals for learning:

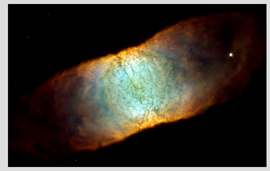
- Briefly describe the Galaxy's star-gas-star cycle.
- What would happen to the heavy elements made by massive stars if there were no interstellar medium?
- What makes a superbubble, what do superbubbles have to do with galactic fountains?
- How does observing in different wavelengths allow us to study different parts of the interstellar medium?

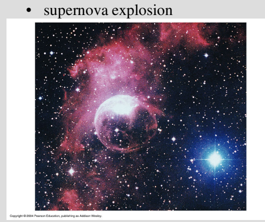
The Star–Gas–Star Cycle



The Star–Gas–Star Cycle

- Stars form heavy elements.
- They return these elements back into space via:
  - stellar winds (mostly as red giants)
  - planetary nebula ejection
  - supernova explosion

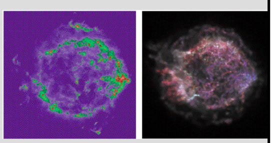




- Supernovae eject high-speed gas
  - it sweeps up the surrounding ISM
  - it excavates a "bubble" of hot gas
  - at temperatures > 10^6 K, the gas is ionized and it emits X-rays
- These bubbles fill 20–50% of the Milky Way's disk.

The Star–Gas–Star Cycle

- Supernovae generate shock waves
  - faster than speed of sound in the ISM
  - compresses, heats, and ionizes ISM
- Particles are accelerated by shock
  - fast electrons emit synchrotron radiation at radio wavelengths
  - cosmic rays are generated



(radio) Tycho's Supernova (X-ray)

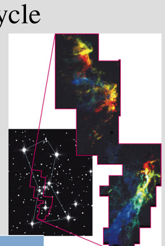
- Older supernova remnants are cooler.
  - they must share their energy with more swept-up matter from the ISM
  - the shocked gas radiates its energy away
  - the shock front slows below the speed of sound and cools
- The new load of heavy elements from the supernova merges with the ISM.

The Star–Gas–Star Cycle

- As the ISM cools, ionized Hydrogen recombines with electrons.
  - neutral, atomic H is formed
- 21-cm emission line of atomic H
  - the electron has two spin states
  - when it flips, a radio photon is emitted at a wavelength of 21-cm
  - we can map the atomic H distribution in the disk with radio telescopes
- The Milky Way contains 5 billion $M_{\odot}$ of atomic H in two states:
  - large, tenuous, warm (10,000 K) clouds
  - small, dense, cool (100 K) clouds
- For warm atomic H to condense into the cooler clouds takes millions of years.
  - gravitational potential energy is quickly radiated away
- The heavy elements are still there!
  - some of them form dust grains

The Star–Gas–Star Cycle

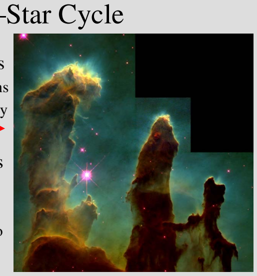
- As atomic H cools to 10 – 30 K
  - it forms molecular H_2
  - a molecular cloud is created
  - but H_2 does not emit at this temperature
- Radio emission lines for many other molecules in the cloud can be observed.
  - H_2O, CO, NH_3, OH, alcohol
- A gravitational push triggers the formation of cloud cores.



State of Gas	Primary Constituent	Approximate Temperature	Approximate Density (atoms per cm^3)	Description
Hot bubbles	Ionized hydrogen	1,000,000 K	0.01	Pockets of gas heated by supernova shock waves
Warm atomic gas	Atomic hydrogen	10,000 K	1	Fills much of galactic disk
Cool atomic clouds	Atomic hydrogen	100 K	100	Intermediate stage of star–gas–star cycle
Molecular clouds	Molecular hydrogen	30 K	300	Regions of star formation
Molecular cloud cores	Molecular hydrogen	60 K	10,000	Star-forming clouds

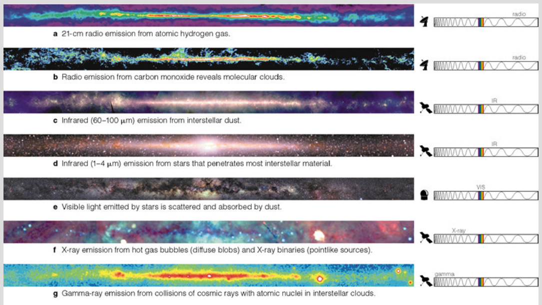
The Star–Gas–Star Cycle

- Cloud cores collapse into protostars
  - the whole star formation process begins
  - the molecular clouds is eroded away by newly formed stars
- This next generation of stars begins life with a greater content of heavy elements.
  - heavy elements which are necessary to form planets in the protostellar disks
- So if there were no ISM:
  - supernovae would blast their matter out of the disk into intergalactic space
  - all generations of stars would lack the heavy elements to form planets



Eagle Nebula's "Pillars of Creation"

The matter in our Galaxy emits different kinds of radiation, depending on what stage of the star–gas–star cycle it is in.



19.3 Galactic Environments

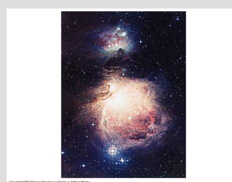
Our goals for learning:

- How do halo stars differ from disk stars?
- What does the environment around hot stars look like?

Halo vs. Disk

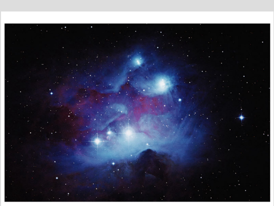
- Stars in the disk are relatively young.
  - fraction of heavy elements same as or greater than the Sun
  - plenty of high- and low-mass stars, blue and red
- Stars in the halo are old.
  - fraction of heavy elements much less than the Sun
  - mostly low-mass, red stars
- Stars in the halo must have formed early in the Milky Way Galaxy's history.
  - they formed at a time when few heavy elements existed
  - there is no ISM in the halo
  - star formation stopped long ago in the halo when all the gas flattened into the disk

Ionization Nebulae



- Found around high-mass stars (OB associations)
- O & B stars (T > 25,000K) make enough UV photons to ionize hydrogen in the nebula
- Gas re-emits Hα line (red)

Reflection Nebulae



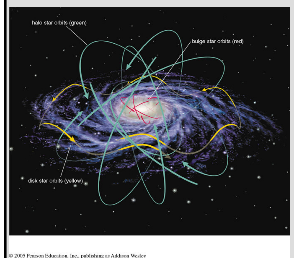
- Light from central star is reflected and scattered by dust
- Blue light is scattered more easily than red
- Similar to our blue sky lit up by a yellow Sun

19.4 The Milky Way in Motion

Our goals for learning:

- How do stellar orbits in the disk differ from those in the halo?
- How long does it take the Sun to orbit the galactic center?
- How do we determine Galactic mass from stellar orbits?
- What is the significance of a rotation curve that is flat at large distances from the Galactic center?
- Why are spiral arms bright?

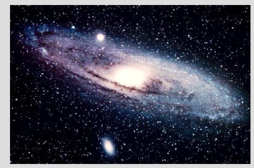
Stellar Orbits in the Galaxy



- Stars in the disk all orbit the Galactic center:
  - in the same direction
  - in the same plane (like planets do)
  - they "bobble" up and down
    - this is due to gravitational pull from the disk
    - this gives the disk its thickness
- Stars in the bulge and halo all orbit the Galactic center:
  - in different directions
  - at various inclinations to the disk
  - they have higher velocities
    - they are not slowed by disk as they plunge through it
    - nearby example: *Barnard's Star*

Mass of the Galaxy

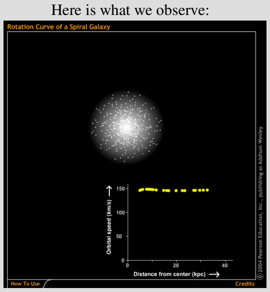
- We can use Kepler's Third Law to estimate the mass
  - Sun's distance from center: 28,000 l.y. = 1.75×10^9 AU
  - Sun's orbital period: 230 million years (2.3×10^8 yr)
  - $P^2 = 4\pi^2/GM\ a^3 \Rightarrow$ mass within Sun's orbit is $10^{11}\ M_\odot$
- Total mass of MW Galaxy : $10^{12}\ M_\odot$
- Total number of stars in MW Galaxy $\approx 2 \times 10^{11}$



Orbital Velocities in the Disk

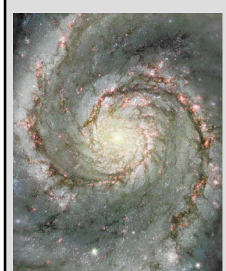
Stars in the Galactic disk should orbit according to Kepler's Laws

Here is what we observe:



- The flat rotation curve of our Galaxy implies that:
  - its mass in **not** concentrated in the center
  - its mass extends far out into the halo
- But we do not "see" this mass
  - we do not detect light from most of this mass in the halo
  - so we refer to it as **dark matter**

Spiral Structure

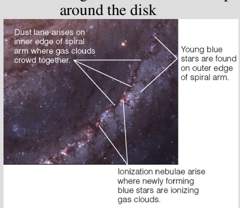


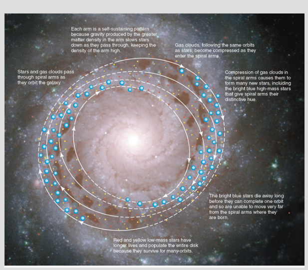
M 51

- The Galactic disk does not appear solid.
  - it has spiral arms, much like we see in other galaxies like M51
- These arms are <u>not</u> fixed strings of stars which revolve like the fins of a fan.
- They are caused by compression waves which propagate around the disk.
  - such waves increase the density of matter at their crests
  - we call them **density waves**
  - they revolve at a different speed than individual stars orbit the Galactic center
- Note how the spiral arms appear bluer compared to the bulge or the gaps between the arms.

Spiral Arms

- The compression caused by density waves triggers star formation.
  - molecular clouds are concentrated in arms…plenty of source matter for stars
  - short-lived O & B stars delineate the arms and make them blue & bright
  - long-lived low-mass stars pass through several spiral arms in their orbits around the disk



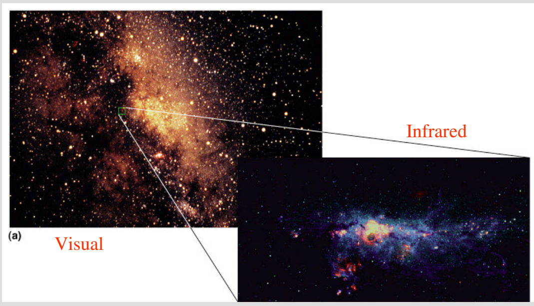


19.5 The Mysterious Galactic Center

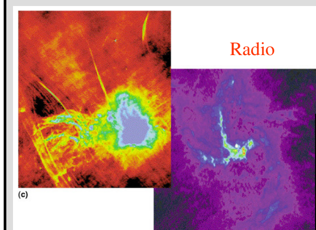
Our goals for learning:

- What lies in the center of our Galaxy?

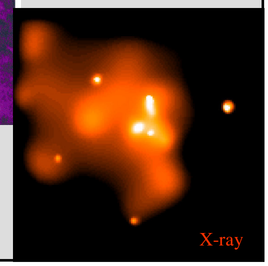
Center of the Galaxy
in *Sagittarius*



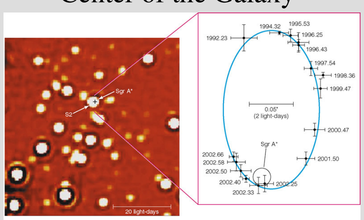
Center of the Galaxy



Although dark in visual light, there are bright radio, IR, and X-ray sources at the center of the Galaxy, known as Sgr A*.

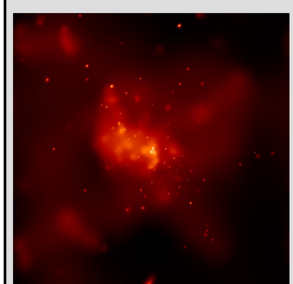


Center of the Galaxy



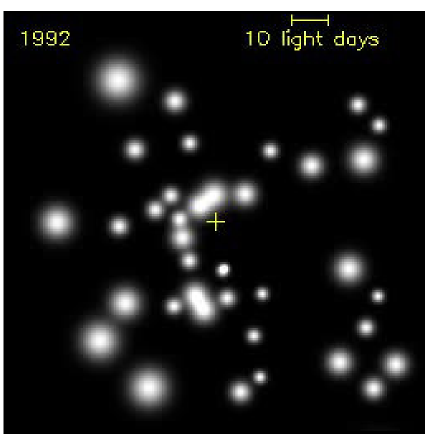
- We measure the orbits of fast-moving stars near the Galactic center.
  - these measurements must be made in the infrared
  - in particular, this star passed within 1 light-day of Sgr A*
  - using Kepler's Law, we infer a mass of 2.6 million $M_{\odot}$ for Sgr A*
- What can be so small, yet be so massive?

X-ray Flare from Sgr A*



*Chandra image of Sgr A**

- The rapid flare rise/drop time (< 10 min) implied that the emission region is only 20 times the size of the event horizon of the 2.6 million $M_{\odot}$ black hole.
- Observations are consistent with the existence of a supermassive black hole at the center of our Galaxy.
- Energy from flare probably came from a comet-sized lump of matter…torn apart before falling beneath the event horizon!



What have we learned?

- Describe the general structure of the Milky Way Galaxy.
  - The Milky Way Galaxy consists of a thin disk about 100,000 light-years in diameter with a central bulge. The spherical region surrounding the entire disk is called the halo.
- Where is the Sun located within our galaxy?
  - The Sun is located in the disk, about 28,000 light years from the galactic center.
- Can we see through our galaxy's interstellar medium?
  - The gas and dust that make up the interstellar medium absorb visible light, preventing us from seeing most of the galaxy's disk in these wavelengths. However, some other wavelengths of light, notably infrared and radio, can pass through the gas and dust, allowing us to study regions of the galaxy whose visible light is blocked.

What have we learned?

- Briefly describe the galaxy's star-gas-star cycle.
  - Stars are born from the gravitational collapse of gas clumps in molecular clouds. Near the ends of their lives, stars more massive than our Sun create elements heavier than hydrogen and helium and expel them into space through supernovae and stellar winds. The supernovae and winds create hot bubbles in the interstellar medium, but the gas moving outward with these bubbles gradually slows and cools. Eventually this gas cools enough to condense into clouds of atomic hydrogen. Further cooling allows atoms of hydrogen and other elements to collect into molecules, producing molecular clouds. These molecular clouds then form stars, completing the star-gas-star cycle. With each generation of stars, the proportion of heavy elements in the galaxy gradually increases.

What have we learned?

- What would happen to the heavy elements made by massive stars if there were no interstellar medium?
  - Supernovae would still blow the heavy elements into space, but without an interstellar medium to slow them down, these heavy elements would simply fly out of the galaxy into intergalactic space. Thus, there would be no star-gas-star cycle to recycle these elements into subsequent generations of stars.
- What makes a superbubble, what do superbubbles have to do with galactic fountains?
  - When numerous supernovae occur relatively near each other and within a few million years of each other, the shock waves from the individual events may merge to form an enormous superbubble. In some places, superbubbles may blow through the galactic disk, creating a fountain of hot, ionized gas that rises high above the galactic disk before the material cools and rains back down to the disk.

What have we learned?

- How does observing in different wavelengths allow us to study different parts of the interstellar medium?
  - Although all the Milky Way's interstellar gas has roughly the same composition — about 70% hydrogen, 28% helium, and 2% heavy elements (by mass) — gas in different stages of the star-gas-star cycle produces different kinds of radiation. Molecules in molecular clouds and hydrogen atoms in atomic gas emit radiation at radio wavelengths. Interstellar dust absorbs visible light and converts the absorbed energy into infrared light. Hot gas in bubbles and superbubbles emits X rays. Gamma rays come from collisions of cosmic rays with atomic nuclei.

What have we learned?

- How do halo stars differ from disk stars?
  - The halo generally contains only old, low-mass stars, while the disk is home to stars of all ages. In addition, halo stars have a much smaller proportion of heavy elements than stars in the disk.
- What does the environment around hot stars look like?
  - High-mass, hot stars energize spectacular ionization and reflection nebulae in the gas and dust around them. High-mass stars tend to be clustered together, so their neighborhoods are likely to have gas bubbles and shock waves from the winds and supernovae produced by nearby stars.

What have we learned?

- How do stellar orbits in the disk differ from those in the halo?
  - Stars in the disk all orbit the galactic center in about the same plane and in the same direction. Halo stars also orbit the center of the galaxy, but with orbits randomly inclined to the disk of the galaxy.
- How long does it take the Sun to orbit the galactic center?
  - Each orbit takes about 230 million years.
- How do we determine galactic mass from stellar orbits?
  - By using a star's orbital speed and distance from the galactic center in the orbital velocity law ($M_r = (r \times v^2)/G$), we can calculate the mass of the galaxy that lies within the region enclosed by the star's orbit.

What have we learned?

- What is the significance of a rotation curve that is flat at large distances from the galactic center?
  - The Milky Way's flat rotation curve implies that the matter associated with our galaxy extends to large distances from the center. A rotation curve is a plot of the orbital speed of stars or gas clouds against distance from the center of the galaxy. If most of the galaxy's mass were concentrated toward the center, orbital speed would decline as distance from the center increased, as in the solar system. Because the rotation curve of the Milky Way is flat, orbital speed in the Milky Way does not decline at great distances. Thus, the Milky Way's mass is not concentrated toward the center but instead extends far into the halo. Because we do not detect light from all this mass in the halo, we call it dark matter.

What have we learned?

- Why are spiral arms bright?
  - Spiral arms mark places in the disk where star formation is especially active. The arms are probably caused by disturbances known as spiral density waves that move through the galaxy's disk. The enhanced gravity in these waves compresses gas clouds that pass through them, causing the clouds to form many new stars. Bright but short-lived massive stars are therefore more common in spiral arms than elsewhere in the disk.

What have we learned?

- What lies in the center of our galaxy?
  - Motions of stars near the center of our galaxy suggest that it contains a black hole about 2.6 million times more massive than the Sun. The black hole appears to be powering a bright source of radio emission known as Sgr A*. However, the gas thought to be falling into this black hole does not emit as much X ray light as expected.

Based on the idea of chemical enrichment, which types of stars contain a higher proportion of heavy elements: stars in globular clusters or stars in open clusters?

1. Stars in globular clusters because they are younger and therefore formed from more enriched material.
2. Stars in globular clusters because they are older and therefore formed from more enriched material.
3. Stars in open clusters because they are younger and therefore formed from more enriched material.
4. Stars in open clusters because they are older and therefore formed from more enriched material.
5. They have, on average, the same proportion of heavy elements.

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How does the halo of our galaxy resemble the distant future fate of the galactic disk?

1. Stars migrate toward the center of the galaxy so in the distant future, all the stars that we see now in the disk will be in the halo.
2. After the gas in the galactic disk is all used up, it will no longer form stars as in the halo.
3. As the stars in the disk get older, they will lose mass and become red and dim, like the stars in the halo.
4. The heavy element proportion in the disk is gradually decreasing with time so in the distant future, the stars in the disk will have low heavy element proportions, as in the halo.
5. Because the disk is younger than the halo and will always be so, it can never resemble the halo.

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What causes the blue and red colors to come out in a photograph of a typical nebula (e.g. Figures 19.16/17)?

1. The ionizing photons from a hot star cause hydrogen gas to glow red and helium to glow blue.
2. Dust grains scatter blue light and let red light pass through, similar to the blue sky and red sunsets in our atmosphere.
3. The blue color is due to the scattering of light by interstellar dust grains and the red color arises from a hydrogen emission line.
4. The blue light comes from young, hot stars and the red light from older, cooler stars.
5. The blue color comes from gas moving toward us and the red color from gas moving away from us.

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Many spectacular ionization nebulae are seen throughout the Milky Way's halo.

1. Yes, they are the sites of new star formation as in the Orion cloud.
2. Yes, but they are concentrated in the spiral arms.
3. No, there are no young, hot stars that cause ionization nebulae in the halo.
4. No, there are very few stars in the halo.
5. No, there is very little mass in the halo.

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The Sun's velocity around the Milky Way tells us that most of our galaxy's dark matter lies within the solar circle.

1. Yes, the Sun's motion in the galaxy shows that we are near the edge of the Milky Way disk and therefore exterior to most of the mass of the galaxy.
2. Yes, the Milky Way's rotation curve stops increasing well before the orbit of the Sun, indicating that the majority of the Milky Way's mass lies within the Sun's orbit.
3. No, the Milky Way's rotation curve remains flat well beyond the orbit of the Sun, indicating that the majority of the Milky Way's mass lies beyond the Sun's orbit.
4. No, the Milky Way's rotation curve looks similar to the rotation curve of planets in our solar system where most of the mass lies near the center.

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