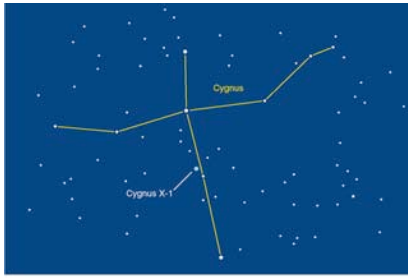
Announcement

- Mid-term exam **Next Tuesday**.
- Any questions about review questions? Please come to the help session at 5:30pm today.
  - Just in case you don't know about this --- we are having help sessions every Tuesday from 5:30pm to 6:30pm at RLM 15.210B.
  - Elizabeth Jeffery (TA) answers your questions.

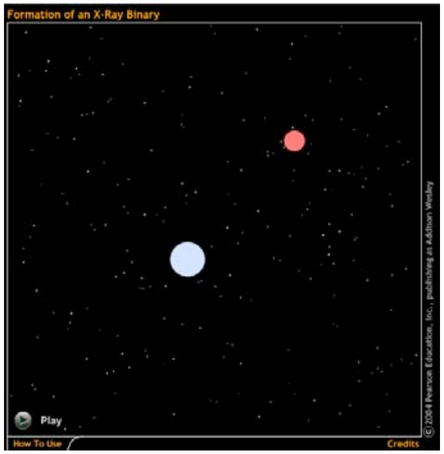
Finding Black Holes

- We can see the effect that a black hole has on its stellar companion in an X-ray binary:
  - Cygnus X-1 was the first good candidate for a black hole
  - Newton's Law gives a mass > 3 $M_\odot$ for unseen companion
  - it can not be a neutron star
  - the only thing that massive, yet small enough to be invisible is a black hole



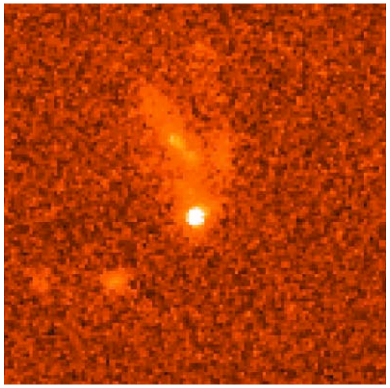
Finding Black Holes

- Then how do we know black holes exist?
  - we detect them in **X-RAY BINARY STARS**



Gamma Ray Bursts (GRB): The Biggest Explosion in the Universe

- Mysterious Gamma Rays Detected
  - since the 1960s, satellites have detected strong bursts of γ-rays
  - U.S. Military satellites discovered them first: cheating! nuclear experiments somewhere?!
  - they occur daily, for a few minutes
  - γ-rays are hard to focus, so determining their direction is tough
  - After all, they came from deep in the Universe.
- Since 1997, we have detected the afterglows of GRBs at other wavelengths.
  - we can pinpoint their sources to distant galaxies
- What they are is still a mystery.
  - best theory: they are hypernovae … gigantic supernovae which form black holes
  - most luminous events since the Big Bang



Hubble ST image of GRB afterglow in a distant galaxy

Now you are familiar with Orion

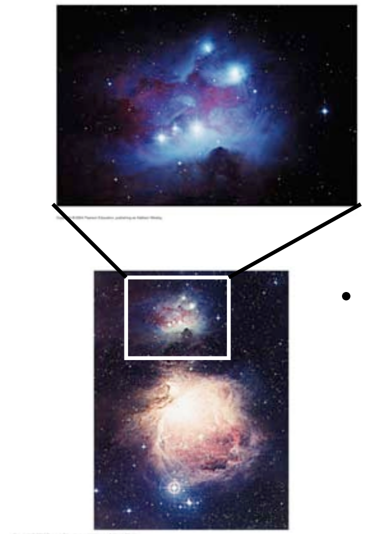
•Betelgeuse is a red supergiant. (therefore, it's red and bright.) It may die anytime soon (or, it may have already died!) So watch out, IF it died 425 years ago, it would appear to explode as a brilliant supernova even tomorrow! (it can be seen in full day light.)

•Rigel is a blue supergiant, and is on its way to become a red supergiant. Still blue, but it will become as red as Betelgeuse as its surface expands and cools.

•Orion's belt (tristars): Main sequence O stars.

•Orion nebula (a.k.a. M42): new stars are born (star-forming region)

Colors of Nebulae (Example: Orion)



- "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
- "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)

Station #4, "The Milky Way"

Lecture 15

Our Galaxy

Reading: Chapter 19

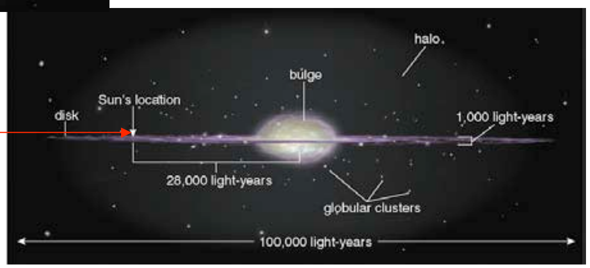
Regions of the Milky Way Galaxy

diameter of disk = 100,000 l.y.

thickness of disk = 1,000 l.y.

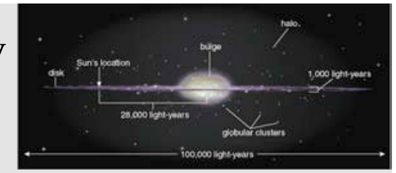
thickness/diameter = 1/100 (thin disk)

number of stars = 200 billion



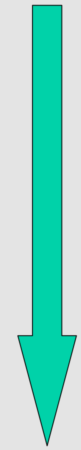
Sun is in disk, 28,000 l.y. out from center

Regions of the Milky Way



- 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

Young Stars



Old Stars

What is out there between stars?

The Interstellar Medium (ISM)

- It is the "stuff" between the stars.
- It is mostly a vacuum (1 atom cm^{-3}).
  - So, yes, it's almost "empty" between stars.
  - But the ISM plays a very important role in our Galaxy.
- It is composed of 90% gas and 10% dust.
  - gas: individual atoms and molecules
  - dust: large grains made of heavier elements
- Visible Light vs ISM:
  - the ISM effectively absorbs or scatters visible light.
  - it masks most of the Milky Way Galaxy from us
- Radio & infrared light vs ISM:
  - radio and infrared light does pass through the ISM.
  - we can study and map the Milk Way Galaxy by making observations at these wavelengths

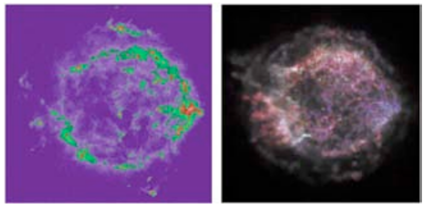
The Star–Gas–Star Cycle: Explosion!

- Stars form heavy elements by fusion.
  - Carbon, Oxygen, …
- 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
- Bubbles are common -- These bubbles fill 20–50% of the Milky Way's disk.

The Star–Gas–Star Cycle: Gas from stars merges with the ISM

- ISM stops high-speed ejecta from the supernovae
  - Supernovae generate **shock waves**
  - faster than speed of sound in the ISM
  - compresses, heats, and ionizes ISM
- Older supernova remnants are cooler.
  - they must share their energy with more swept-up matter from the ISM
- The new load of heavy elements from the supernova merges with the ISM.



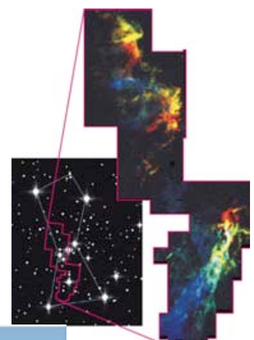
(radio) Cassiopeia-A Supernova (X-ray)

The Star–Gas–Star Cycle: Cool Down

- As the ISM cools, ionized Hydrogen (I.e., protons) recombines with electrons.
  - neutral, atomic H is formed
  - We can observe the neutral hydrogen using radio waves
- 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: Sites of next star formation!
- For warm atomic H to condense into the cooler clouds takes millions of years.
  - Hot hydrogen clouds → Cool down → Collapse → Gravitational potential energy heats it up → Cool down→ Collapse … this process takes millions of years.
- The heavy elements are still there.

The Star–Gas–Star Cycle: Condense

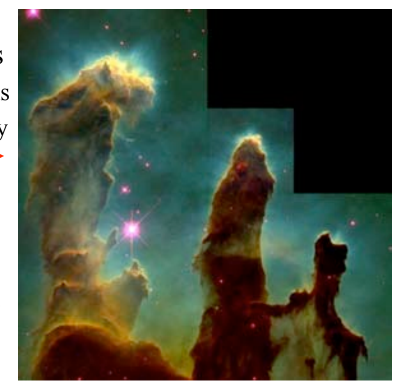
- As atomic H cools to 10 – 30 K
  - it forms molecular H_2
  - a molecular cloud is created
- A gravitational push triggers the formation of cloud VERY DENSE cores. (~10,000 molecules per cm^3) (c.f., the mean ISM is 1 atom per cm^3)



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

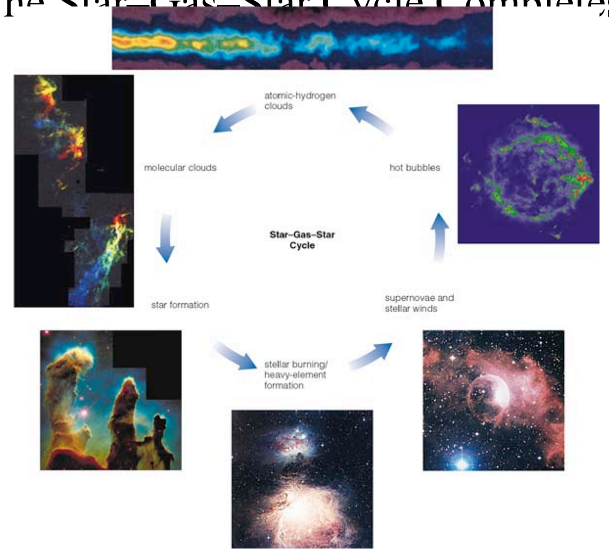
The Star–Gas–Star Cycle: Star Formation!

- 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:
  - **No Stopping**: supernovae would blast their matter out of the disk into intergalactic space
  - **No Life!** all generations of stars would lack the heavy elements to form planets

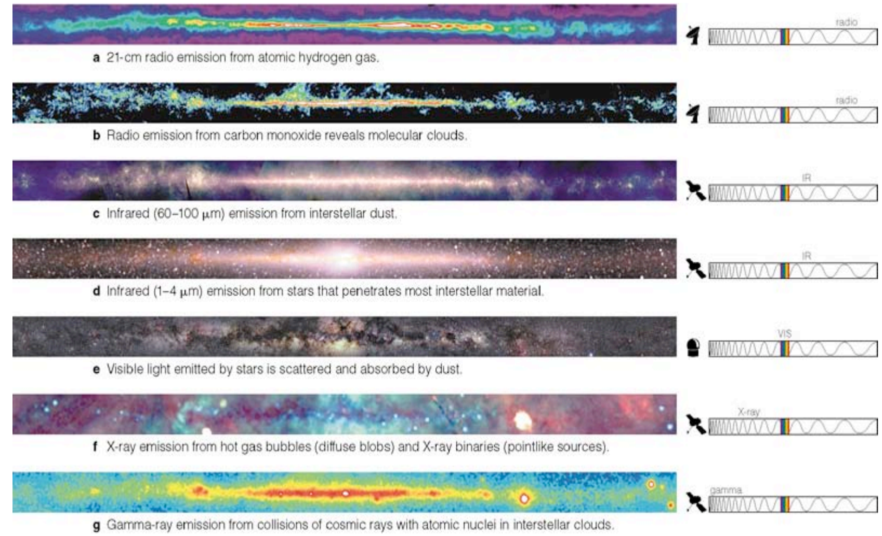


Eagle Nebula's "Pillars of Creation"

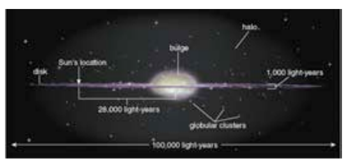
The ISM maintains Galaxy Echo System: The Star–Gas–Star Cycle Completes



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



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 (not "polluted" or "enriched" much)
  - mostly low-mass, red stars (heavy stars, if any, already died)
- 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 → no further star formation**
  - star formation stopped long ago in the halo when all the gas flattened into the disk

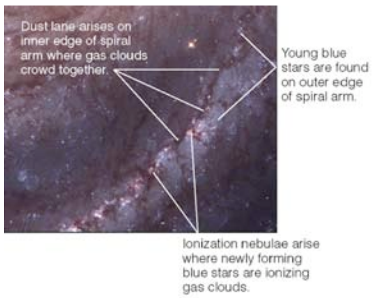
Spiral Structure

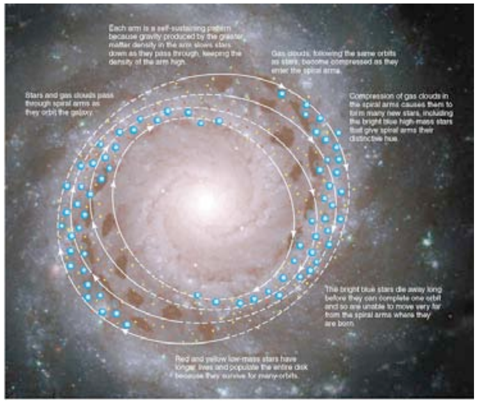
M 51

- The Galactic disk does not appear solid.
  - it has spiral arms, much like we see in other galaxies like M51
- These arms are not fixed strings of stars which revolve like the fins of a fan.
- They are caused by "waves" (much like waves in ocean) 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 star orbit the Galactic center
- Note how the spiral arms appear bluer compared to the bulge or the gaps between the arms. WHY?

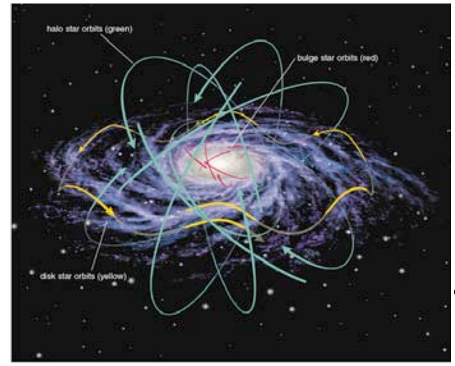
Spiral Arms

- A: 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





Motion in the Galaxy: Stellar Orbits



- 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 its

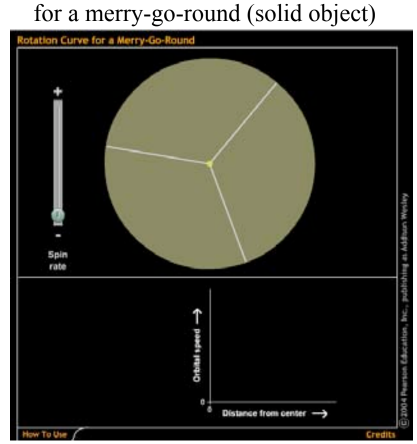
Mass of the Galaxy

- We can use Newton's Law of Gravitation 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 $\approx 2 \times 10^{11}$

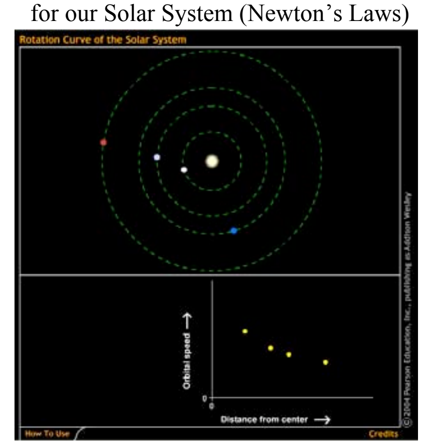
Orbital Velocities in the Disk

rotation curve – a plot of rotational (orbital) speed vs. distance from the center

for a merry-go-round (solid object)



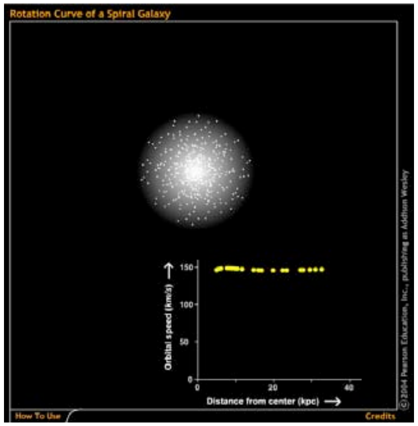
for our Solar System (Newton's Laws)



Mystery Revealed

Stars in the Galactic disk should orbit according to Newton's Laws, but…

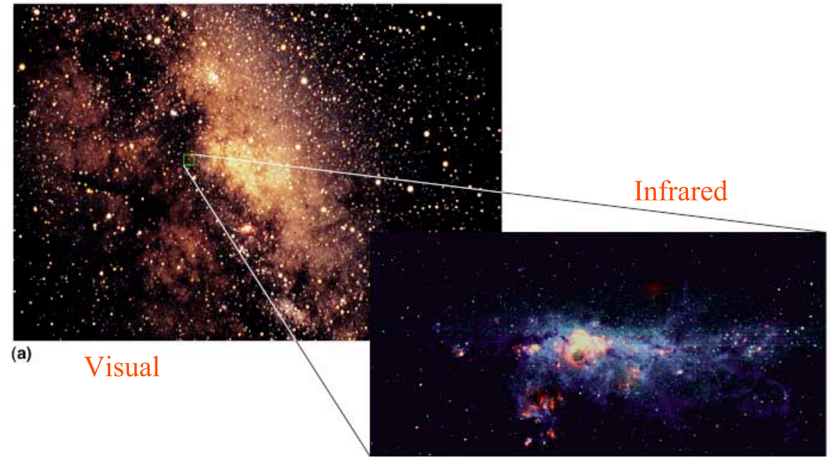
Here is what we observe:



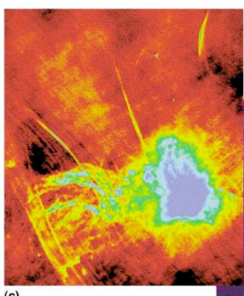
- The flat rotation curve of our Galaxy implies that:
  - its mass in **not** concentrated in the center
  - its mass extends far out into the halo
- **But we do not "see" this mass**
  - we do not detect light from most of this mass in the halo
  - so we refer to it as ***dark matter***

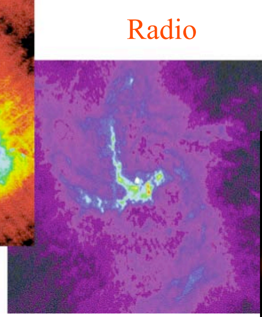
Center of the Galaxy

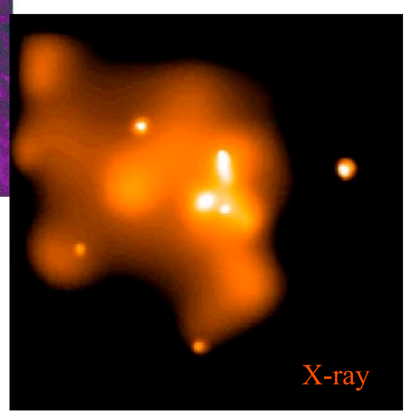
in *Sagittarius*



Center of the Galaxy

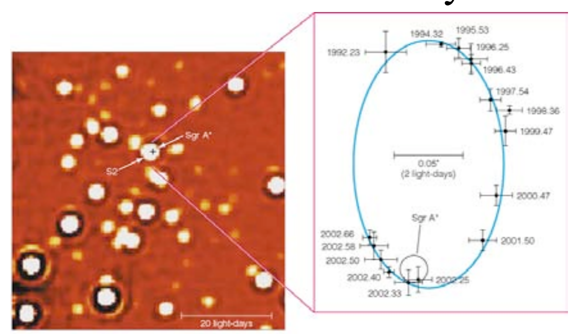






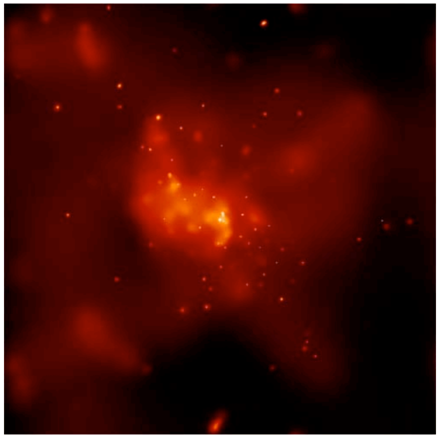
Although dark in visual light, there are bright radio, IR, and X-ray sources at the center of the Galaxy, known as **Sgr A***.

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 Newton's Law, we infer a mass of 2.6 million $M_{\odot}$ for Sgr A*
- What can be so small, yet be so massive?

A super-massive blackhole in Sgr A*



*Chandra image of Sgr A**

- Observations are consistent with the existence of a supermassive (~3 million solar masses) black hole at the center of our Galaxy.

Next Station: “Galaxies” Reading: Chapter 20

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