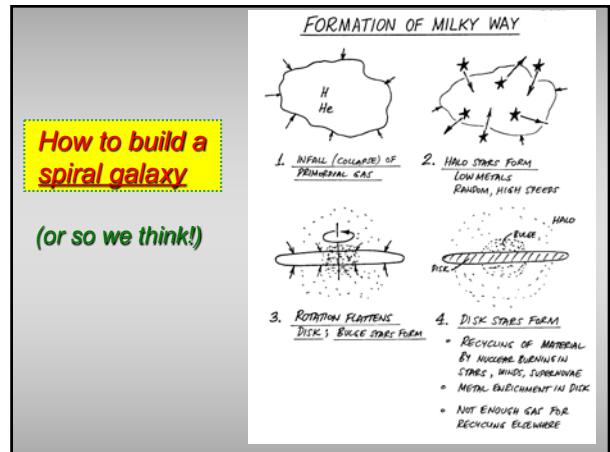
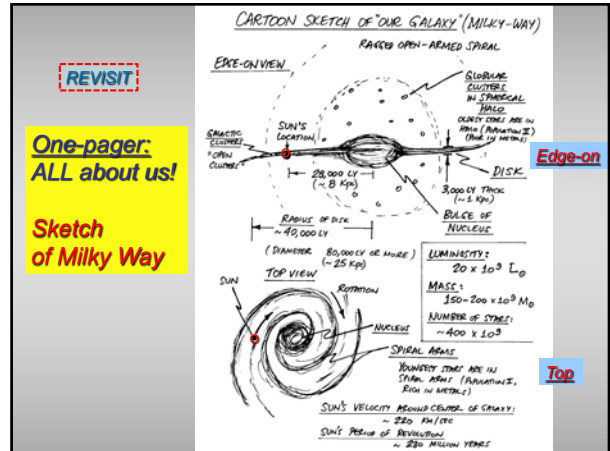


- Today+ in Our Galaxy (Chap 19)
- Visit “inventory” of our galaxy: **stars, gas, dust**, and all in constant motion and recycling
- Look at **dust** in absorbing / reddening light
- Why **spiral patterns are made in the disk** of galaxies, including our own
- **Mr. Einstein’s work** S.2 (special relativity), S.3 (general relativity) **in recitation**
- **HW #9** now graded, **answer sheet** on canvas

- How we will be zoom-interactive**
- “**Raise Hand**” (Max monitors “Participants”)
 - “**Send Chat**” Message (Max will act)
 - In both cases, Juri will get to your question or comment within at most a few minutes
 - Or if pressing, Unmute your mike and ask question
 - We can adjust “how to interact”, with your advice and experience





INVENTORY OF MILKY WAY

Inventory of "stuff" making up our galaxy

+ "dark matter"

1. STARS FEW HUNDRED BILLION, $\approx 10^{11} M_{\odot}$

BULGE MEDIUM OLD, "METAL POOR"

DISK YOUNG, "METAL RICH" INCLUDES OPEN CLUSTERS, OB ASTEROIDS

HALO OLDEST, METAL POOR INCLUDES GLOBULAR CLUSTERS

2. GAS 10% MASS OF STARS

INTERSTELLAR MEDIUM

A. VERY COLD GAS IN THIN SHEET
SITE OF STAR FORMATION (MOLECULAR CLOUDS)

B. WARM ATOMIC AND IONIZED H CLOUDS
EMISSION NEBULAE (BRIGHT NEBULAE)

C. HOT GAS
HEATED BY STELLAR WINDS, SUPERNOVAE

HALO VERY HOT GAS BLOWING OUT OF GALAXY

3. DUST 1% MASS OF GAS, 0.1% MASS OF STARS
MOSTLY IN CLOUDS IN DISK

Stars

Gas

Dust

COMPONENTS OF INTERSTELLAR MEDIUM

Ingredients of Interstellar Medium (ISM) (stuff between the stars)

1. GIANT MOLECULAR CLOUDS $\sim 10^5 M_{\odot}$

- SITES OF INTENSE STAR FORMATION
- NEARLY 50 MOLECULES DISCOVERED BY EMISSION LINES OBSERVED IN RADIO
- COMBINATIONS OF H, C, N, O FORM MOLECULES (AS MANY AS 11 ATOMS!)
- ⇒ AMMONIA, WATER, FORMALDEHYDE, METHYL & ETHYL ALCOHOL, CYANIDE, CARBON MONOXIDE (CO) ...
- CO IMPORTANT FOR DOPPLER MAPS OF CLOUDS WITH RADIO OBSERVATIONS

2. DIFFUSE CLOUDS OF GAS (AND SOME DUST)

H I REGIONS : CLOUDS OF COOL, NEUTRAL HYDROGEN ATOMS (REFLECTIVE NEBULAE)
21 cm RADIO EMISSION

H II REGIONS (EMISSION NEBULAE):
GLOWING, IONIZED HYDROGEN SURROUNDING YOUNG HOT STARS (O & B ASTEROIDS)

Very cold gas: star birth

Cool gas: neutral H

Hot H

INTERSTELLAR MEDIUM ...

More stuff in ISM inventory

Now let us look at them in turn

3. HOT INTERCLOUD GAS $> 10^6 K$

- HEATED BY SUPERNOVAE, STELLAR WINDS
- FILLS HALO, GALACTIC WIND?
- HIGHLY IONIZED GAS, NO DUST
- EMITS X-RAYS, YIELDS UV EMISSION ... LIKE OXYGEN III (OXYGEN STRONG OF S ELECTRONIC)

4. COSMIC RAYS
VERY ENERGETIC ATOMIC NUCLEI (PARTICLES)

5. INTERSTELLAR DUST
NOT MADE BY MASS, BUT ...
REFLECTS STARLIGHT, ABSORBS SOME OF IT, POLARIZES THE LIGHT

Really hot gas

Dust

States of gas in ISM

State of Gas	Primary Constituent	Approximate Temperature	Approximate Density (atoms per cm ³)
Hot bubbles	Ionized hydrogen	1,000,000 K	0.01
Warm atomic gas	Atomic hydrogen	10,000 K	1
Cool atomic clouds	Atomic hydrogen	100 K	100
Molecular clouds	Molecular hydrogen	30 K	300
Molecular cloud cores	Molecular hydrogen	60 K	10,000

Questions or Comments

Cold Stuff



Dark Molecular clouds (10's of Kelvin)

Horsehead in close-up

Warm Stuff

- **Gas & Dust**
 - Heated by stars to 100s-1000s Kelvin
- **Absorbs** visible and UV light
- **Transparent** to longer wavelengths
 - Infrared, radio
- **Emits** its own infrared light



Horsehead Nebula

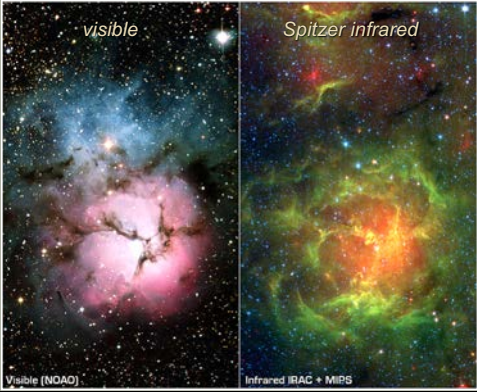
Hot Stuff

- Ionization nebulae
- Hot (young) stars ionize hydrogen and other elements in the gas
- **T~ 10,000 K near hot young stars**



Trifid Nebula

Trifid Nebula (M20)




visible Spitzer infrared

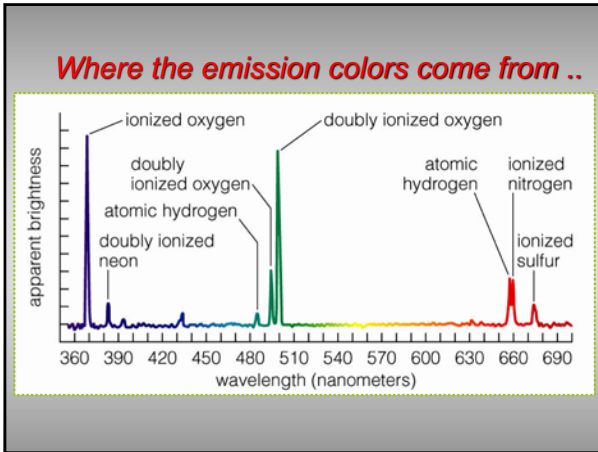
Visible (NOAO) Infrared IRAC + MIPS

Emission nebulae "O & B star associations"

- Emission lines from hydrogen and other ionized elements
- **T~ 10,000 K near hot young stars**



Lagoon



Really Hot Stuff

- **Bubbles of hot gas** blown out by **SUPERNOVAE**
- **T = millions of degrees K**
- Mixing with rest of galactic gas → enrichment with heavy elements

Cass A SN remnant Flamsteed ~1680

Fast electrons & magnetic fields

REALLY HOT STUFF

- **Synchrotron emission from SNR**
- **X-ray and radio**
- **Traces very hot gas bubbles (SNR)**

Chandra X-ray image of Tycho Brahe 1572 supernova remnant

Questions or Comments

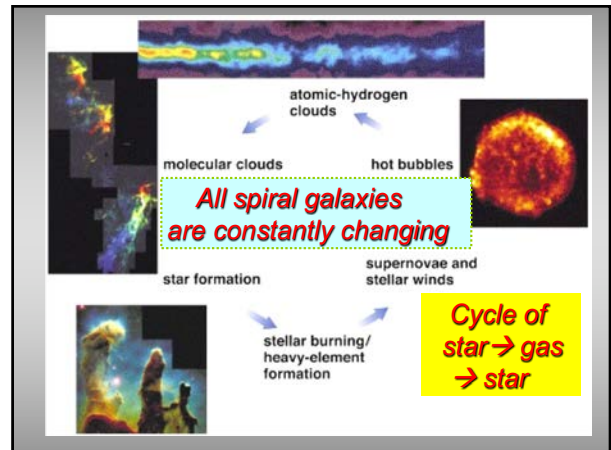
For Break-Out Room:

Meet & Greet with video/sound on

Why was it so difficult to figure out where in the Milky Way are the Sun and Earth located, and if ours is the only "nebula" (galaxy) ?

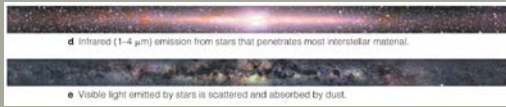
Poll 1 – Where are we?

- Why was it so difficult to figure out where in the Milky Way are the Sun and Earth located, and if ours is the only "nebula" (galaxy) ?
- **A.** We are immersed in a soup of stars, gas and dust, so hard to see far
- **B.** In a middle of city of stars, hard to figure shape of overall 'metropolitan area'
- **C.** Gas and dust can absorb light, making distance estimates uncertain
- **D.** All of the above



Infrared light reveals stars whose visible light is blocked by gas clouds

Infrared



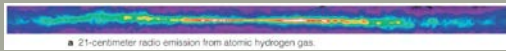
Visible

X-rays are observed from hot gas above and below the Milky Way's disk

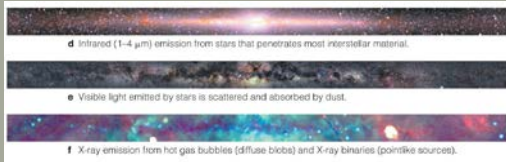


We also see "point" sources – these are binaries X-rays

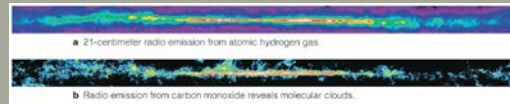
21 cm radio waves emitted by atomic hydrogen show where gas has cooled and settled into disk



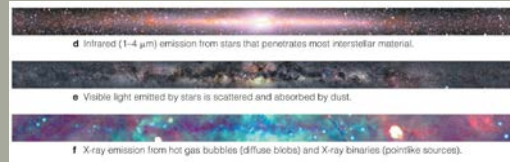
Radio (21cm)



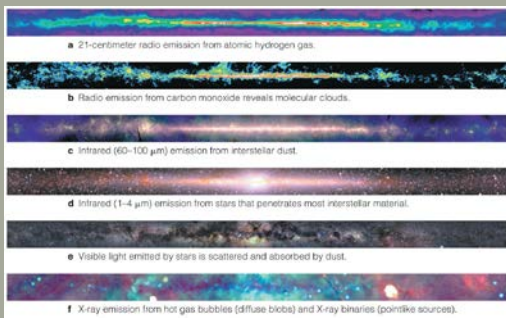
Radio waves from carbon monoxide (CO) show locations of molecular clouds



Radio (CO)

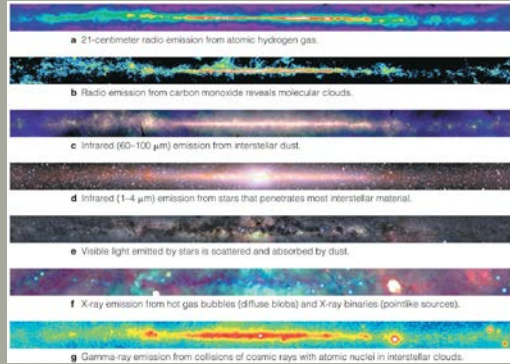


Long-wavelength infrared emission shows where young stars are heating the dust



IR (dust)

Gamma rays show where cosmic rays from supernovae collide with atoms in gas clouds



Gamma Rays

Many views of our galaxy disk

- a) 21-cm radio emission from atomic hydrogen gas.
- b) Radio emission from carbon monoxide reveals molecular clouds.
- c) Infrared (60-100 μm) emission from interstellar dust.
- d) Infrared (1-4 μm) emission from stars that penetrates most interstellar material.
- e) Visible light emitted by stars is scattered and absorbed by dust.
- f) X-ray emission from hot gas bubbles (diffuse blobs) and X-ray binaries (pointlike sources).
- g) Gamma-ray emission from collisions of cosmic rays with atomic nuclei in interstellar clouds.

INTERSTELLAR DUST

... MINOR COMPONENT, BUT BIG EFFECTS!

ISM:
A little **DUST** goes a long way!

1. **REDDENING OF LIGHT** "INTERSTELLAR REDDING"
PREVENTING SCATTERING OF BLUER PHOTONS BY DUST PARTICLES OR GRAINIE

"Reddens the light"

2. **GENERAL EXTINCTION OR DIMMING OF LIGHT**
SOME AREAS APPEAR OPAQUE TO STARLIGHT

Absorbs the light

3. **POLARIZATION OF LIGHT**
MAGNETIC FIELDS CAN TEND TO ALIGN DUST GRAINE WHICH MAY BE ELONGATED IN SHAPE AND SELECTIVE ABSORPTION OF LIGHT OF ONE ORIENTATION

SEMI-WARM stuff: dust

- **DUST:** absorbs visible and UV light
- **Transparent to long wavelengths** (red, IR, radio)
- **Emits IR light**

Horsehead Nebula

Questions or Comments

Motion of stars in spiral galaxy

Halo & bulge: swarming in and out

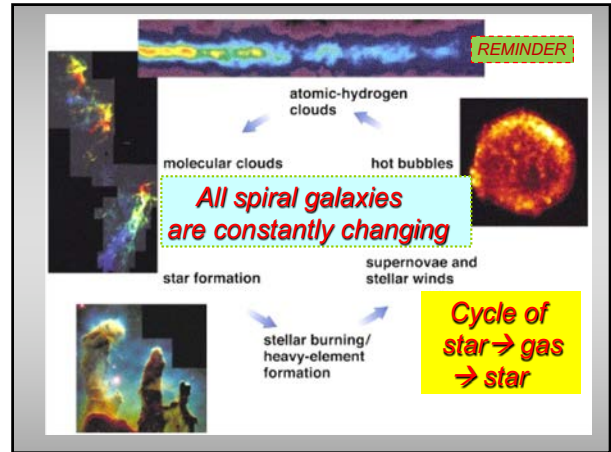
Disk: circular + bit up/down

Poll 2 – stars and "heavy metals"

- The ages of stars suggest that the bulge and halo of the Milky Way formed before many of the stars in the disk. Which would you expect to have **more heavy metals** (higher metallicity)?

- **A.** Halo and bulge stars
- **B.** Disk stars
- **C.** No difference

- **B. Disk stars** are continually forming out of gas that is more and more "polluted" by heavy metals.
- The **OLD globular clusters in the halo** were formed a long time ago before the galaxy was so polluted – they have very low "metallicities"

Why spiral arms?

"Density waves" – stars move in and out of denser regions

More like ripples in a pond than arms of a pinwheel

In dense regions, **star formation is more intense**, so "arms" are brighter



M51 - Whirlpool

Push and pull of gravity in disk

Gas/stars are pulled a little forward or backward toward the high density regions

Such clumping helps **create a spiral pattern "traffic jam"**




Gas clouds, following the same orbits as stars, become compressed as they enter the spiral arms.

Compression of clouds causes them to form new stars, including the blue high-mass stars that give spiral arms their distinctive hue.

Blue stars die away long before they complete one orbit, and thus tend to remain close to the spiral arms where they were born.

Red and yellow low-mass stars have longer lives and survive for many orbits, populating the entire disk.

Read with care

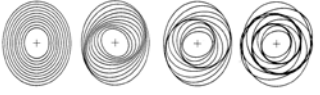
"Density wave" story – how spiral structure is built

Gravitational instability of disks (gentle)

THEORY OF SPIRAL STRUCTURE ...

DENSITY - WAVE THEORY

1. "SPIRAL ARMS ARE STELLAR TRAFFIC JAMS"
2. STARS SLOW DOWN (DUE TO GRAVITY), THEREFORE BUNCH UP
3. SLOWDOWN PATTERN HAS SPIRAL SHAPE, PERPETUATES ITSELF (ROTATES LIKE A PINWHEEL)
4. EFFECT ON GAS IN DISK IS MOST PRONOUNCED, SINCE STRONG COMPRESSION AND TRIGGERS STAR FORMATION
5. SPIRAL TRACERS: YOUNG MASSIVE STARS (O & B) BRIGHT EMISSION NEBULAE COLD GAS CLOUDS
6. STARS AND GAS CLOUDS CAN OVERTAKE SPIRAL ARMS AND PASS THROUGH THEM



Stars and gas move through spiral wave

Star birth strongly enhanced by shock

DENSITY WAVES AND SPIRAL ARMS
 FASTER MOVING GAS AND STARS OVERTAKE A DENSITY WAVE (COMPRESSION SHOCK WAVE)
 STRONGLY ENHANCING STAR FORMATION AFTER SHOCK

The diagram illustrates a cross-section of a spiral density wave. A dashed line represents the wave, with an arrow labeled 'GAS FLOW' pointing towards it. On the left side of the wave, there are labels for 'OUTER EDGE OF SPIRAL ARM' and 'INNER EDGE'. Various symbols represent different components: a cross for 'Gas & star streamlines', a circle with a cross for 'Dark molecular cloud', a circle with a plus sign for 'Star formation', and a circle with a dot for 'Star cluster'. The diagram shows that as gas and stars move through the wave, they are compressed, leading to star formation.

SPIRAL DENSITY WAVE IS A ROTATING (FIXED) PATTERN
 WITH STARS & GAS MOVING THROUGH IT

Crash/bang of star birth and recycling: rotating through the spiral arms in the disk

The image shows the M51 Whirlpool Galaxy, a classic example of a spiral galaxy. The central region is bright yellow, surrounded by several distinct spiral arms. The arms are composed of stars and gas, with some regions appearing reddish, indicating star formation. The overall structure is a rotating disk with a fixed pattern of spiral arms.

Bright O & B stars mark the spiral pattern

M51 Whirlpool Galaxy HST