ASTR 1040: Stars & Galaxies

Edge-on spiral galaxy NGC 4013

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Lecture 22 Tues 4 Apr 2017

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Today in Our Galaxy

- Why *spiral patterns are made in the disk* of galaxies, including our own
- Consider *rotation curve* of our galaxy, and the unseen mass *(dark matter)* that it implies
- Look at *dust* in absorbing / reddening light
- How *21-cm radio emission* works, and used to map our galaxy (and its spiral structure)
- Overview read *Chap 20 "Galaxies and Foundations of Modern Cosmology"*
- *Observatory Night #7 tomorrow Wed Apr 5*

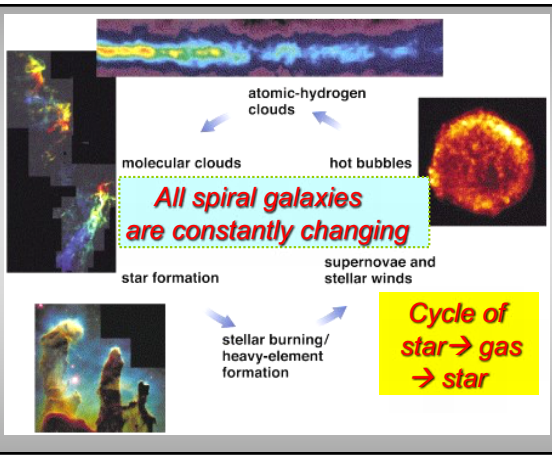
REVIEW

Inventory of "stuff" making up our galaxy

+ "dark matter"

INVENTORY OF MILKY WAY

1. STARS — FEW HUNDRED BILLION, $\geq 10^{11} M_\odot$ — **Stars**
   - BULGE — MEDIUM TO OLD, "METAL POOR"
   - DISK — YOUNG, "METAL RICH" — INCLUDES OPEN CLUSTERS, OB ASSOCIATIONS
   - HALO — OLDEST, METAL POOR — INCLUDES GLOBULAR CLUSTERS
2. GAS — 10% MASS OF STARS — **Gas**
   - MOSTLY IN DISK — 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 — **Dust**
   - MOSTLY IN CLOUDS IN DISK



REVIEW

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

COMPONENTS OF INTERSTELLAR MEDIUM

1. GIANT MOLECULAR CLOUDS — $\sim 10^5 M_\odot$ — **Very cold gas: star birth**
   - 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 13 ATOMS!)
     - → AMMONIA, WATER, FORMALDEHYDE, METHYL & ETHYL ALCOHOL, CYANOGEN, CARBON MONOXIDE (CO) ...
     - CO IMPORTANT FOR DOPPLER MAPPING OF CLOUDS WITH RADIO OBSERVATIONS
2. DIFFUSE CLOUDS OF GAS (AND SOME DUST)
   - HI REGIONS: CLOUDS OF COOL, NEUTRAL HYDROGEN ATOMS (REFLECTION NEBULAE) — 21 cm RADIO EMISSION — **Cool gas: neutral H**
   - HII REGIONS (EMISSION NEBULAE): GLOWING, IONIZED HYDROGEN SURROUNDING YOUNG HOT STARS (O & B ASSOCIATIONS) — **Hot H**

More stuff in ISM inventory

INTERSTELLAR MEDIUM ...

3. HOT INTERCLOUD GAS — $> 10^6$ K — **Really hot gas**
   - HEATED BY SUPERNOVAE, STELLAR WINDS
   - FILLS HALO, GALACTIC WIND?
   - HIGHLY IONIZED GAS, NO DUST
     - EMITS X-RAYS, YIELDS UV EMISSION ... LIKE OXYGEN VI (OXYGEN STRIPPED OF 5 ELECTRONS!)
4. COSMIC RAYS
   - VERY ENERGETIC ATOMIC NUCLEI (PARTICLES)
5. INTERSTELLAR DUST — **Dust**
   - NOT MUCH BY MASS, BUT ....
     - REDDENS STARLIGHT, ABSORBS SOME OF IT, POLARIZES THE LIGHT

Now let us look at them in turn ....

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

Reading ahead clicker – mapping our galaxy

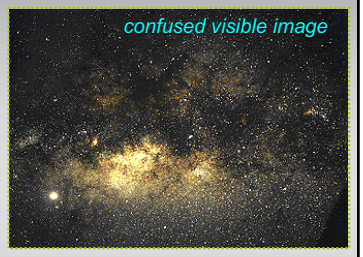
- *We want to map the structures of very cold gas within the dusty disk of the Milky Way. What wavelengths should we be using, and why?*

A.

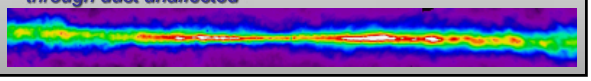
- *A.* radio
- *B.* visible light
- *C.* x-rays

A. Radio

- *Dust obscures our vision of much of the galaxy in visible and UV light.*
- *X-rays only highlight the hottest and weirdest places*
- *21 cm radio waves map normal hydrogen gas -- these pass through dust unaffected*



MW disk in radio



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

Infrared

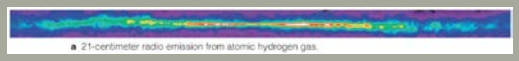
Visible

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

We also see "point" sources – these are binaries

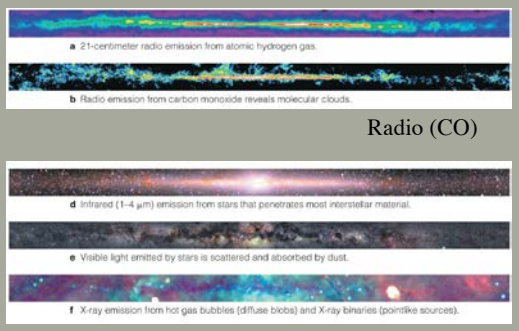
X-rays

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



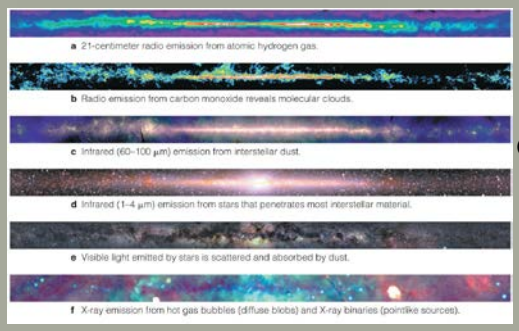
Radio (21cm)

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



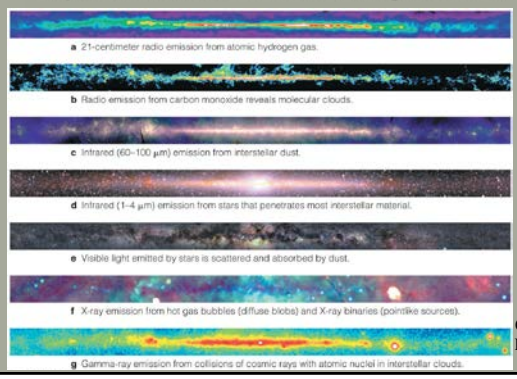
Radio (CO)

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



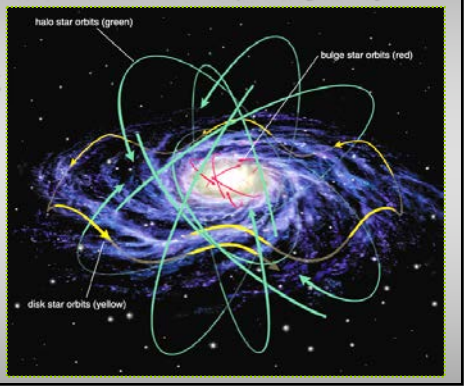
Gamma-Rays

Many views of our galaxy disk

Motion of stars in spiral galaxy

Halo & bulge: swarming in and out

Disk: circular + bit up/down



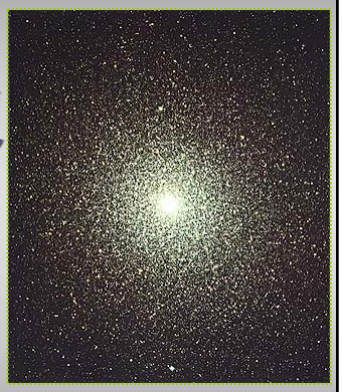
Clicker – stars and "heavy metals"

- 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)?

B.

- 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

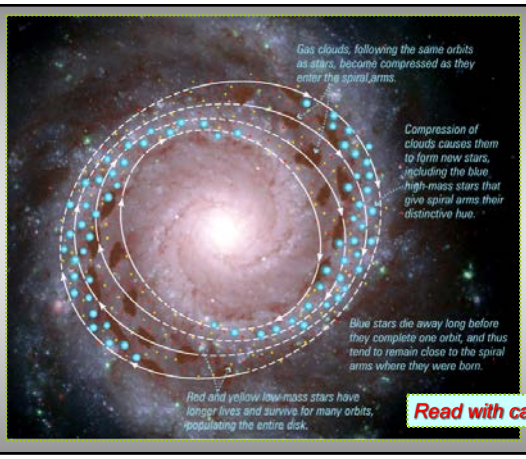
More like ripples in a pond than arms of a pinwheel

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

Push and pull of gravity in disk

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

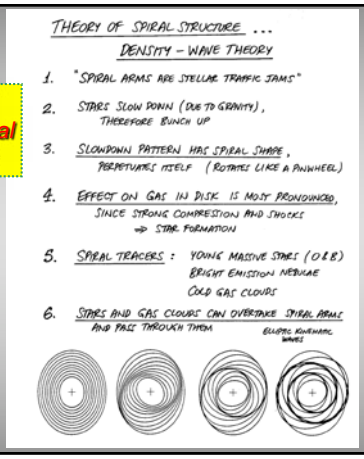
Such clumping helps create a spiral pattern "traffic jam"



Read with care

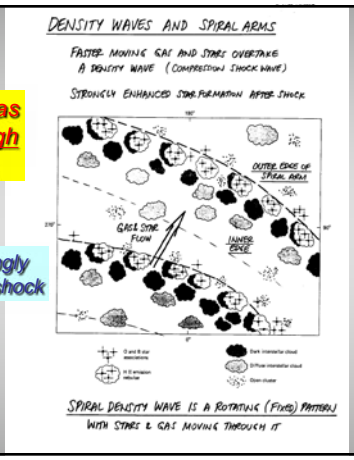
"Density wave" story – how spiral structure is built

Gravitational instability of disks (gentle)



Stars and gas move through spiral wave

Star birth strongly enhanced by shock

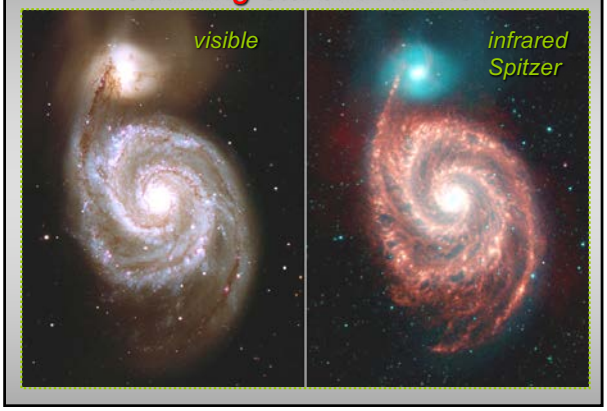


Crash/bang of star birth and recycling: rotating through the spiral arms in the disk

Bright O & B stars mark the spiral pattern

M51 Whirlpool Galaxy HST

Outlining starbirth in M51



Q: Why does "M51 – Whirlpool" have open spiral structure, and ours is pretty ragged?

A: Collision with companion galaxy enhanced its spiral wave

Clicker on deductions about Milky Way's stars

C.

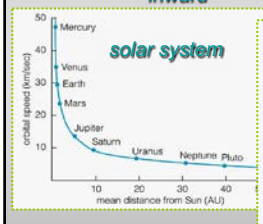
- Why are stars in the halo poor in the common elements carbon, nitrogen and oxygen?

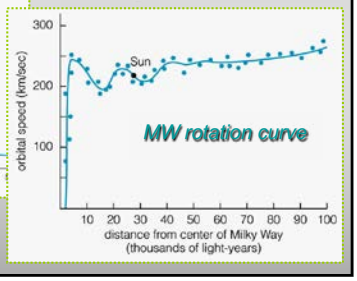
- A. Those elements have been used up in halo stars
- B. C, N and O are biological elements, and there is no life out there to make them
- C. The halo stars formed before these elements were made in abundance
- D. Making C, N and O requires massive stars, and these have been absent in the halo

Stars moving in circles: orbital velocity law

$$M_R = R \times V^2 / G$$

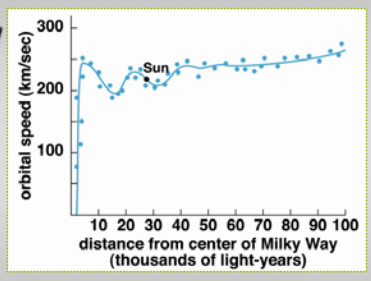
mass inward | radius | orbital velocity | ...faster orbit, more mass





Reality for the Milky Way

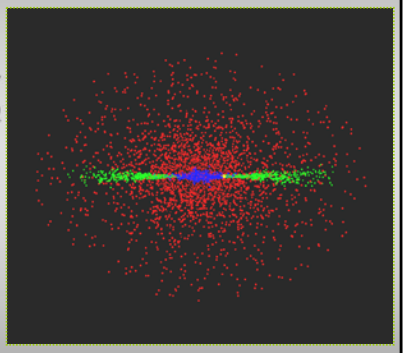
- Rotation curve is flat or even rising!
- Most of the mass of the galaxy is outside the solar circle!
- But few stars, little gas there…



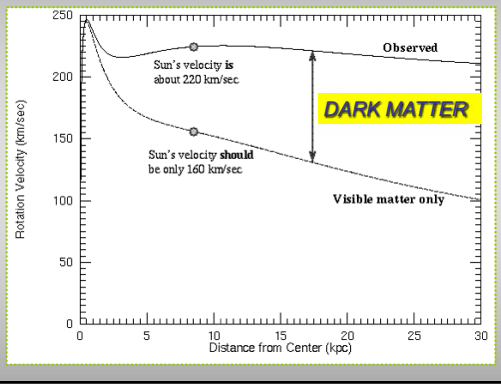
DARK MATTER ! probably in large halo -- outweights stars+gas by factor of about 10

Massive dark matter halo for MW

- Stars and gas are embedded in a much larger dark matter halo
- Don't know what dark matter is … probably not baryonic (usual protons, neutrons, electrons)

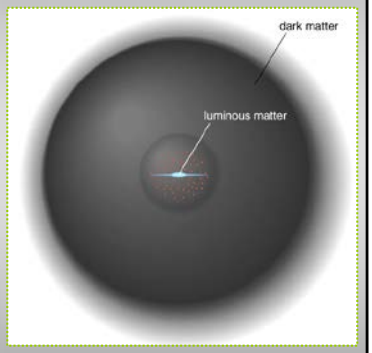


Role of dark matter on rotation profile



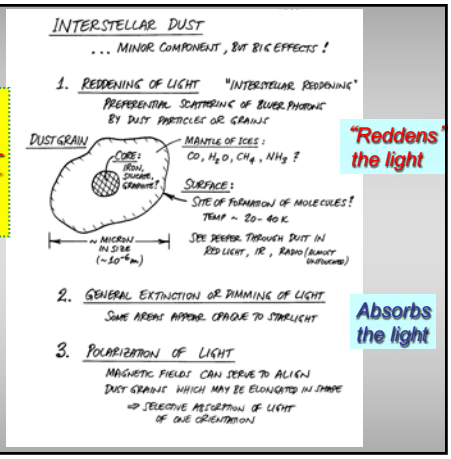
Dark matter halos for all galaxies

- Presence revealed by rotation curves (motions of stars in galaxy)
- Dark matter extends beyond visible part of the galaxy -- mass is ~10x stars and gas !
- Most likely subatomic particles, as yet unidentified (weakly interacting massive particles – WIMPs ?)



ISM:

A little DUST goes a long way!



"Reddens" the light

Absorbs the light

SEMI-WARM stuff: dust

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