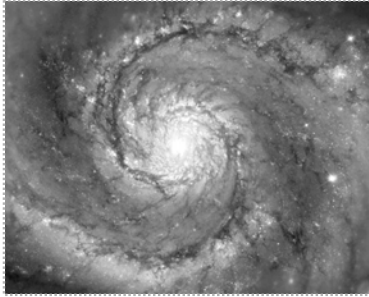


ASTR 1120: Stars & Galaxies



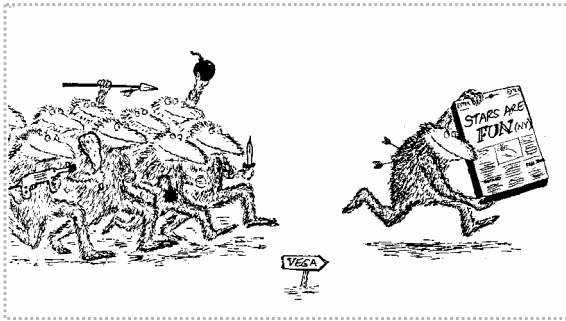
M51
Whirlpool

Prof. Juri Toomre TA: Ben Brown
Lecture 28 Wed 16 Mar 05
zeus.colorado.edu/astr1120-toomre

Today in Our Galaxy

- Look at why *spiral patterns* are made in the disk of galaxies, including our own
- Examine the *rotation curve* of our galaxy, and the unseen mass (*dark matter*) that it implies
- Complete your reading of 19.2 *Star-Gas-Star Cycle* -- Ben covers this in Friday lecture
- *Second Mid-Term Exam* returned today (plus answers) – mapping of grades next
- *Problem Set 7* due in class on Friday (or turn in earlier to Ben)

So did we really love this exam?



RESULTS FROM SECOND MID-TERM EXAM

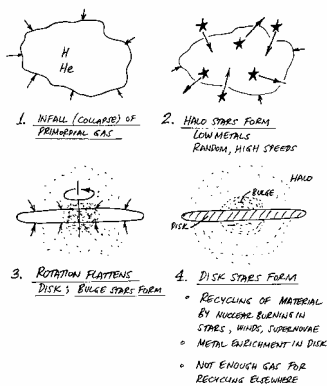
SECOND MID-TERM EXAM

- Grade boundaries, based on 135 points:
 - If 123/145 (85%) or over, A's [24%]
 - 110/145 (76%) or over, B's [29%]
 - 85/145 (59%) or over, C's [37%]
 - 72/145 (50%) or over, D's [6%]
- Also +, plain, and – within these ranges
Median grade 77%; highest 99,98% (2)!
- Go through answer sheet – and talk to us if do not understand our choices. Keep exam + answers for future review (comp final)

How to build a spiral galaxy

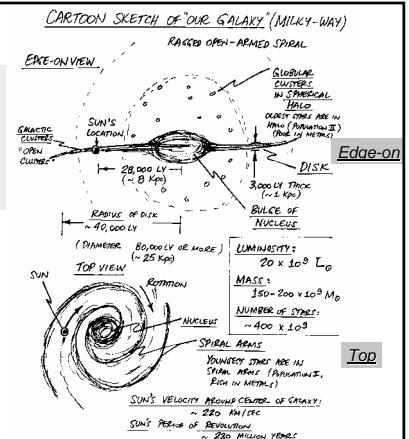
(or so we think!)

FORMATION OF MILKY WAY

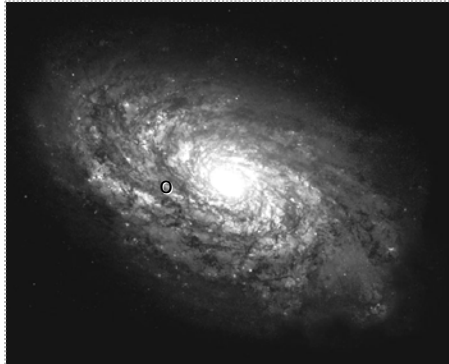


Review: One-page story

Cartoon sketch of Milky Way

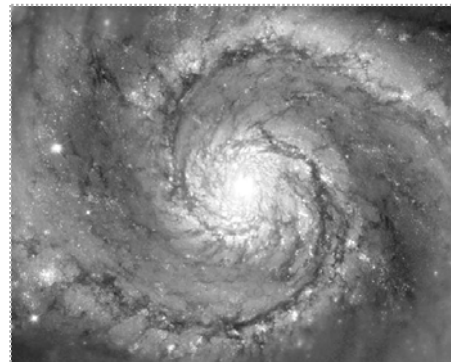


If we might see Milky Way from outside



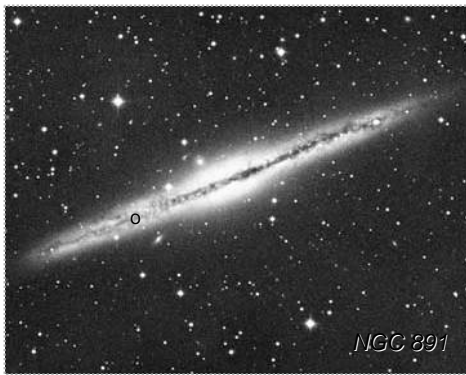
Spiral Sb galaxy
NGC 4414

Magnificent spiral galaxy – M51 Whirlpool



Why the two-armed SPIRAL PATTERN?

Stars, gas and dust in disk



NGC 891

INVENTORY OF MILKY WAY

1. STARS FEW HUNDRED BILLION, $\approx 10^{11} M_{\odot}$
- BULGE MEDIUM TO OLD, "METAL POOR"
 - DISK YOUNG, "METAL RICH" INCLUDES OPEN CLUSTERS, OB ASCIATING
 - HALO OLDEST, METAL POOR INCLUDES GLOBULAR CLUSTERS

Stars

Inventory of "stuff" making up our galaxy

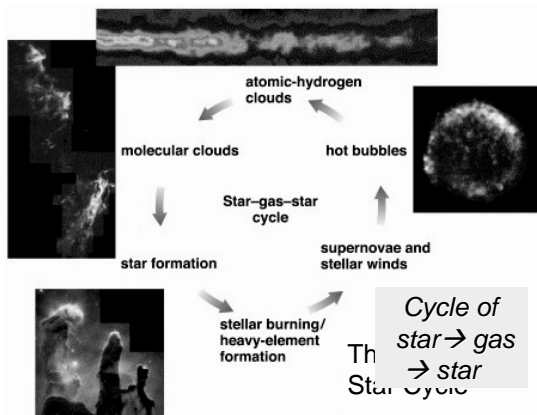
2. GAS 10% MASS OF STARS
- MOSTLY IN DISK INTERSTELLAR MEDIUM
- A. VERY COLD GAS IN THIN SHEET SITE OF STAR FORMATION (MOLECULAR CLOUDS)
 - B. WARM ATOMIC AND IONIZED H CLOUDS EMISSION NEBULAE (BRIGHT NEBULAE)
 - C. HOT GAS HERDED BY STELLAR WINDS, SUPERNOVAE

Gas

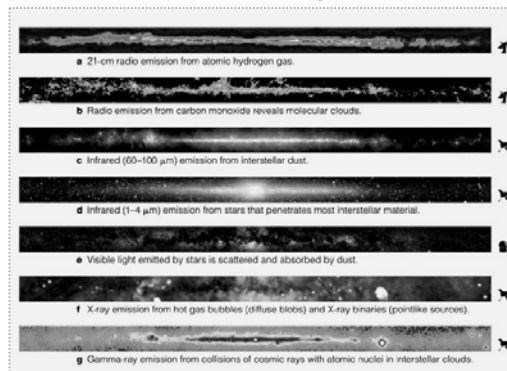
+ "dark matter"

Dust

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



Many views of our galaxy disk



Reading 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.

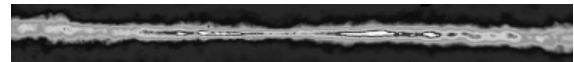
- A. radio
- B. visible light
- C. x-rays

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



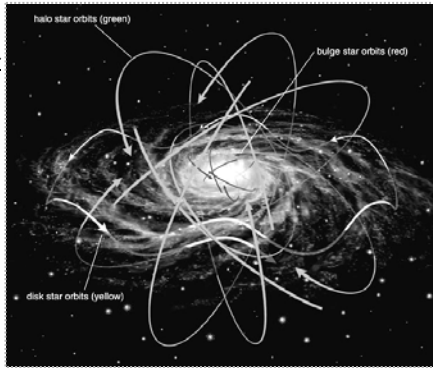
MW disk in radio



Motion of stars in spiral galaxy

Halo & bulge:
swarming in and out

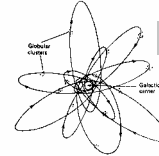
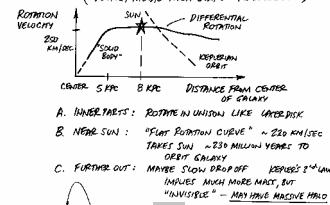
Disk:
circular + bit up/down



SUMMARY OF STAR MOTIONS

Different star motions in disk & halo

1. DISK POPULATION OF STARS (& GAS & DUST) ROTATING IN NEARLY CIRCULAR ORBITS (YOUNG, METAL-RICH STARS "POPULATION I")



2. SPHERICAL POPULATION IN BULGE AND HALO STARS IN RANDOM, HIGH-SPEED ORBITS (INCLUDE STARBURST CORES) OLDER, METAL-POOR STARS "POPULATION II"

Song dedicated to the Milky Way

THE GALAXY --
LIGHTEN UP!

Whenever life gets you down, Mrs. Brown,
And things are hard and tough,
And people are stupid, obnoxious and down,
And you feel that you've had quite enough...
Just remember that you're standing on a planet that's evolving
And revolving at 900 miles an hour.
It's orbiting at 90 miles a second, so it's reckoned,
From the sun that is the source for all our power.
The sun and you and me and all the stars that we can see
Are moving at a million miles a day
In an outer spiral arm at 40 thousand miles an hour
In the Galaxy we call the Milky Way.

Now the Galaxy itself contains a hundred billion stars.
It's a hundred thousand light-years side from side.
It bulges in the middle 16 thousand light-years thick,
But out by us it's just 3 thousand light-years wide.
We're 30 thousand light-years from galactic central point.
It'll go round every 200 million years.
And our galaxy is only one of millions and billions
In this amazing and expanding Universe.

Now the Universe itself is still expanding and expanding
In every direction it could wish
As fast as it can go, the speed of light we know,
12 million miles a minute and that's the fastest speed there is.
So remember when you're feeling very small and insecure
How amazingly unlikely was your birth,
And pray that there is intelligent life somewhere up above,
For there isn't any down here on Earth.

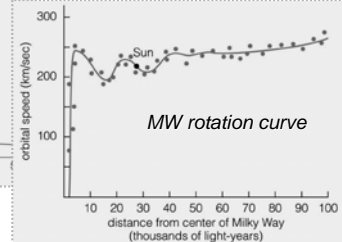
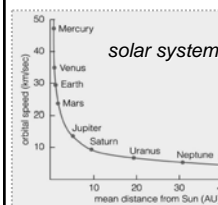
Lighten up, there are stars in the sky,
Lighten up, it's a good question why,
But you don't know the answer and neither do I,
So meanwhile let's just all lighten up.

And remember that you're standing on a planet that's evolving ...

Stars moving in circles: orbital velocity law

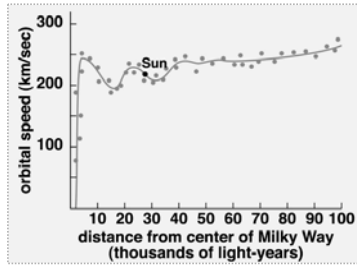
$$M_R = R \times V^2 / G$$

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

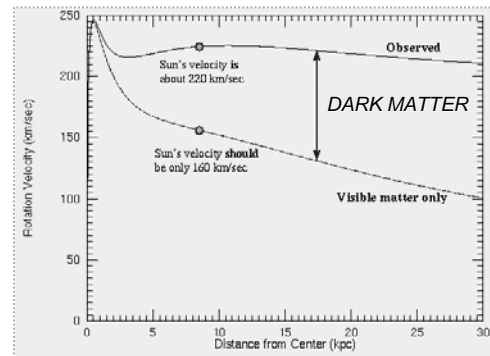


Reality for the Milky Way

- 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 -- outweighs stars+gas by factor of 3 to 10

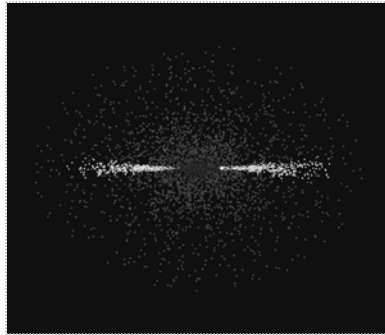


Role of dark matter on rotation profile



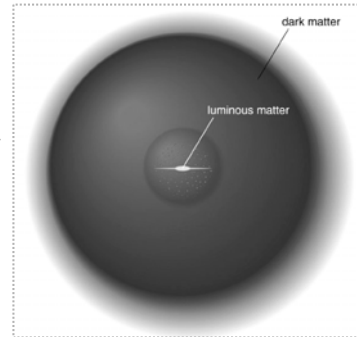
Massive dark matter halo for MW

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



Dark matter halo for 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 ?)

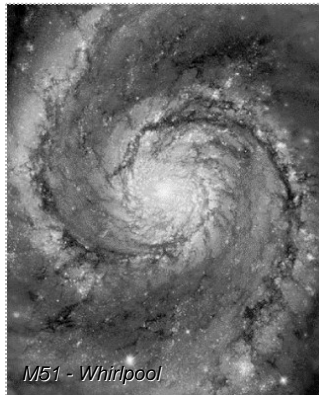


Why spiral arms?

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

More like ripples in a pond than arms of a pinwheel

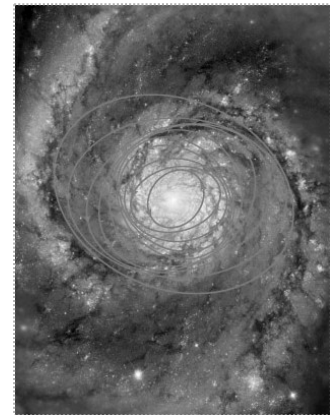
In dense regions, star formation is more intense, so "arms" are brighter

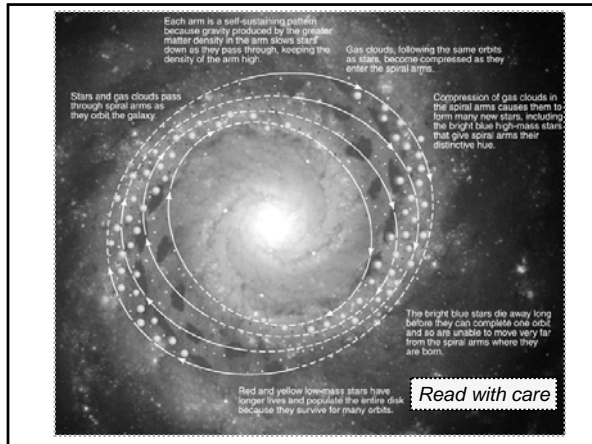


Push and pull of gravity in disk

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

Such clumping helps create a spiral pattern





"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 PINNACLES)
4. EFFECT ON GAS IN DISK IS MOST PRONOUNCED, SINCE STRONG COMPRESSIONS AND SHOCKS \Rightarrow 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

DENSITY WAVES AND SPIRAL ARMS

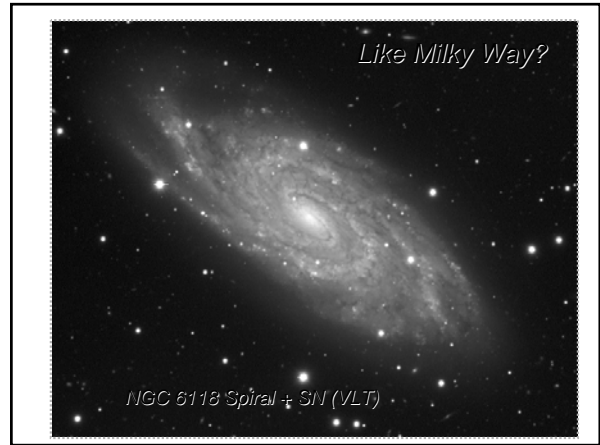
FASTER MOVING GAS AND STARS OVERTAKE A DENSITY WAVE (COMPRESSION SHOCK WAVE)

STRONGLY ENHANCED STAR FORMATION AFTER SHOCK

Stars and gas move through spiral wave

Star birth strongly enhanced by shock

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



"Grand design spiral" – M51 Whirlpool

Bright O & B stars mark the spiral pattern

Outlining starbirth in M51

visible

infrared Spitzer