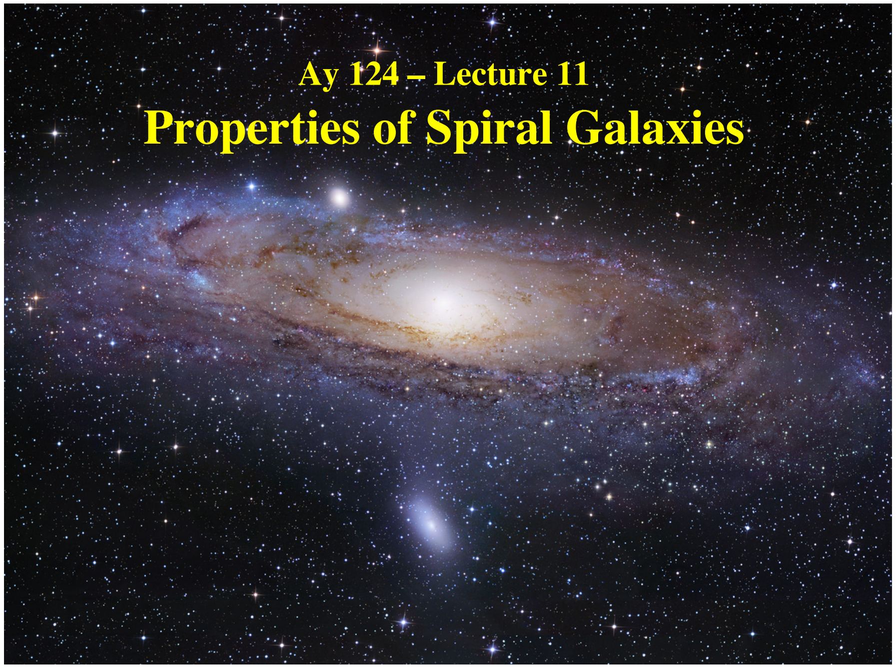


Spiral Galaxies

Named for their bright spiral arms, which are prominent due either to bright O and B stars (evidence for recent star formation), or to dust lanes.

Define two parallel sequences of spiral galaxies:

Sa **Sb** **Sc** **Sd**

→

Central bulge becomes less important
Disk becomes more important
Spiral arms become more open and ragged

Sb **SBb** **SBc** **SBd**

As above, except that these galaxies also have a central, linear **bar**, while the Sa, Sb… are unbarred

Barred Galaxies

- Half of all disk galaxies - Milky Way included - show a central bar which contains up to 1/3 of the total light
- Bars are a form of dynamical instability in differentially rotating stellar disks
- S0 galaxies also have bars – a bar can persist in the absence of gas
- Bar patterns are not static, they rotate with a pattern speed, but unlike spiral arms they are not density waves. Stars in the bar stay in the bar
- The asymmetric gravitational forces of a disk allow gas to lose angular momentum (via shocks) compressing the gas along the edge of the bar. The gas loses energy (dissipation) and moves closer to the center of the galaxy

NGC 1300, Barred Spiral Galaxy

Variation of Galaxy Properties Along the Hubble Sequence

	E	S0	Sa	Sb	Sc	Sd	Irr
Color	Red	→					Blue
Stellar Pop.	Old	Old + Intermediate		Old + Intermediate + Young		Intermediate + Young	
SFR	zero	low →		higher →			high
HI (gas)	Zero/ low	low →		modest →		high	highest
dust	Zero/ low	Higher		highest			Lower (less metals)
Dyn.	Bulge/halo dom.		Disk dominated, so rotation				

Galaxy Properties and the Hubble Sequence

Hubble sequence turned out to be surprisingly robust: many, but not all, physical properties of galaxies correlate with the classification morphology:

E S0 Sa Sb Sc Sdm/Irr →

Pressure support → Rotational support
Passive → Actively star forming
Red colors → Blue colors
Hot gas → Cold gas and dust
Old → Still forming
High luminosity density → Low lum. dens.
… etc.

But, for example, masses, luminosities, sizes, etc., do not correlate well with the Hubble type: at every type there is a large spread in these fundamental properties.

Global Properties of Spiral Galaxies

Spirals are complex systems, generally more complex and diverse than ellipticals:

- Wide range in morphological appearance
- Fine scale details – bulge/disk ratios, structure of spiral arms, resolution into knots, HII regions, etc.
- Wide range in stellar populations – old, intermediate, young, and currently forming
- Wide range in stellar dynamics:
  - "cold" rotationally supported disk stars
  - "hot" mainly dispersion supported bulge & halo stars
- Significant amounts of cold interstellar medium (ISM)

Spirals tend to avoid high-density regions (e.g., clusters) as they are dynamically fragile, and can be merged and turned into E's

Spiral Galaxies: Trends Along the Hubble Sequence

	S0-Sa	**Sb-Sc**	**Sd-Sm**
Spiral Arms	Absent or tight		Open spiral
Color	Red; late G star	Early G star	Blue; late F star
B-V color	0.7-0.9	0.6-0.9	0.4-0.8
Young stars	few		many
HII regions	Few, small		More, brighter
Gas	Little gas		Much gas
Blue luminosity	1-4 x $10^{10} L_\odot$		<0.1-2 x$10^{10} L_\odot$
Central SB	high		low
mass	0.5-3 x $10^{11} M_\odot$		<0.2-1 x 10^{11} $M_\odot$
rotation	Fast rising		Slow rising

Spiral Galaxies: Basic Components

- **Disks:** generally metal rich stars and ISM, nearly circular orbits with little random motion, spiral patterns
  - Thin disks: younger, star forming, dynamically very cold
  - Thick disks: older, passive, slower rotation and more random motions
- **Bulge:** metal poor to super-metal-rich stars, high stellar densities, mostly random motion – similar to ellipticals
- **Bar:** present in ~ 50 % of disk galaxies, mostly older stars, some random motions and a ~ solid body rotation?
- **Nucleus:** central (<10pc) region of very high mass density, massive black hole or starburst or nuclear star cluster
- **Stellar halo:** very low density (few % of the total light), metal poor stars, globular clusters, low density hot gas, little or no rotation
- **Dark halo:** dominates mass (and gravitational potential) outside a few kpc, probably triaxial ellipsoids, radial profile ~ singular isothermal sphere, DM nature unknown

Photometric Properties of Galaxies

Empirically, the surface brightness declines with distance from the center of the galaxy in a characteristic way for spiral and elliptical galaxies

For spiral galaxies, need first to correct for:

- Inclination of the disk
- Dust obscuration
- Average over spiral arms to obtain a mean profile

Corrected disk surface brightness drops off as:

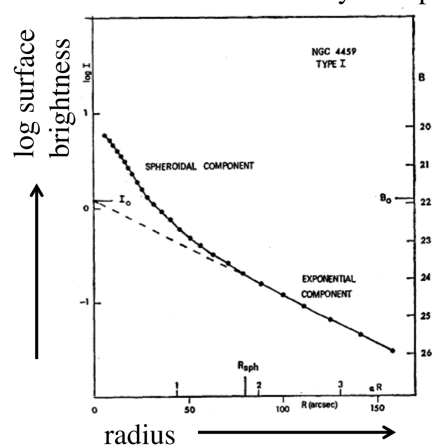
$$I(R) = I(0)\, e^{-R/h_R}$$

where ***I(0)*** is the central surface brightness of the disk, with a broad range of values, but typically ~ 21 - 22 mag/arcsec^2, and h_R is a characteristic **scale length**, with typical values:

$$1 \text{ kpc} < h_R < 10 \text{ kpc}$$

Bulge-Disk Decomposition

In practice, surface brightness at the center of many spiral galaxies is dominated by stars in a central bulge. Central surface brightness of disk must be estimated by extrapolating inward from larger radii



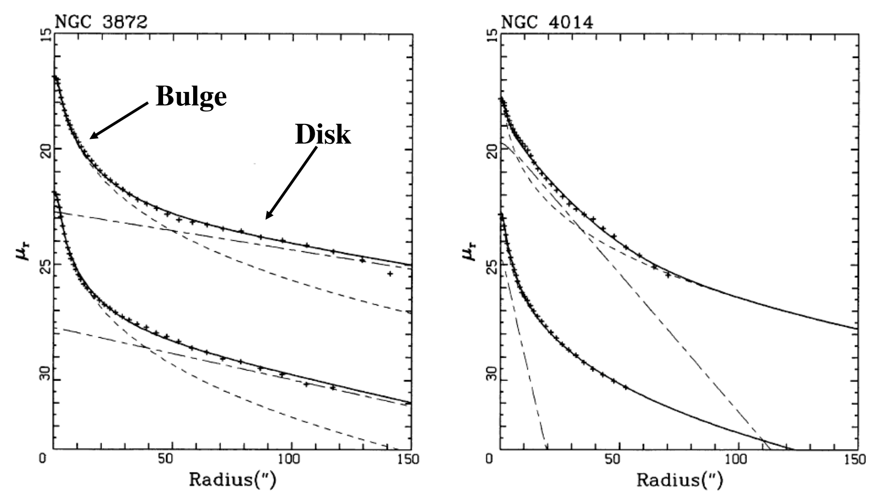
Component profiles (μ is the logarithmic surface brightness in mags/arcsec2):

$$\mu_{\text{bulge}} = \mu_e + 8.325\left[(r/r_e)^{1/4} - 1\right]$$

$$\mu_{\text{disk}} = \mu_0 + 1.082(r/h).$$

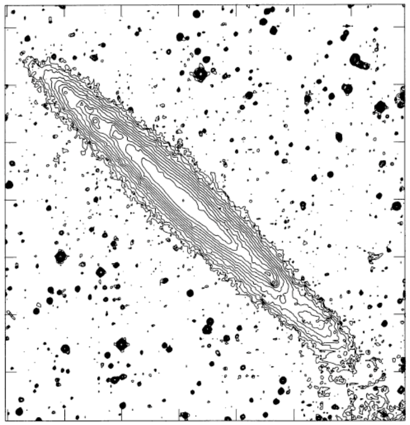
Radial Surface Brightness Profiles of Spiral Galaxies

Note: semi-log profiles

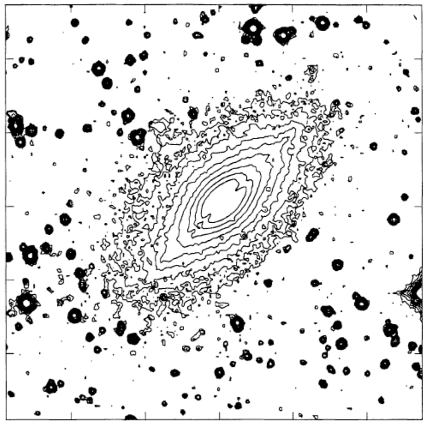


(from S. Kent)

Edge-On Spirals: Contour Maps

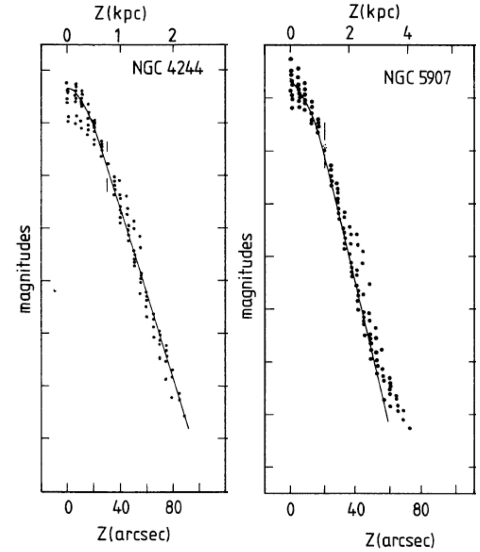


Nearly a pure disk:
NGC 4244



Bulge dominated:
NGC 7814

Vertical Structure of Galaxy Disks



Stellar density $\sim exp(-z/z_0)$

[Actually, more like sech ^{2} $(-z/z_0)^2$ …]

Also seen in star counts in our Galaxy

Typical values of z_0 range from ~ 0.1 kpc (young disk) to ~ 1 kpc (old thick disk)

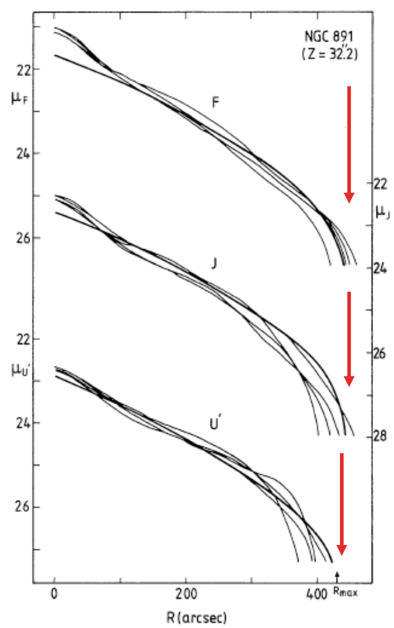
Disks Have Cutoffs

Stellar disks have finite radii, R_{max}, typically 3 - 5 h_R

This is not seen in ellipticals: we have never seen their edges

Note that the H I gas extends well beyond the visible cutoff, and of course so does the dark matter

There is a trend that the stars are younger at large radii in disks: inside-out formation?



Inclination Effects

- We can integrate surface brightness to obtain a total apparent magnitude (in a given filter), but we need to correct for:
- Inclination – face-on ($i = 0^o$), edge-on ($i = 90^o$)
  - To first order, $cos\ i = b/a$ where a and b are the observed major and minor axes (assume disk is intrinsically circular)
  - But disks also have an intrinsic thickness, c, so we find

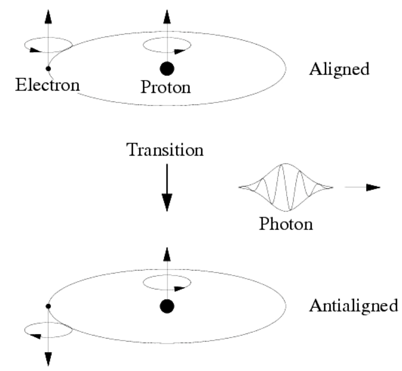
$$cos^2\ i = \{(b/a)^2 - q^2\}/1 - q^2$$

    where q^2 is the intrinsic ratio of c/a ~ 0.13
- Dust (both in the MW, and internal absorption)
  - Internal absorption is corrected for using empirical formulae, e.g. in the B band: $A_B(i) = 0.70\ log[sec(i)]$ (in mags), or in the I band, $A_I = 1.12(\pm 0.05)\ log\ (a/b)$

Spiral Galaxies: Gas Content

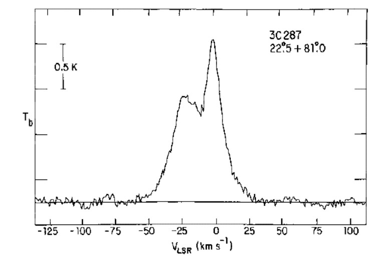
- Gas in spirals
  - Cool atomic HI gas
  - Molecular hydrogen H_2, CO, many other molecules
  - Need gas to form stars! Star formation associated with dense ISM
  - Can observe ionized hydrogen via optical emission-lines (Hα)
  - Observe HI via radio emission – 21 cm line due to hyperfine structure – a hydrogen atom that collides with another particle can undergo a spin-flip transition
- Spirals show HI disks (amount of HI depends on Hubble type)
- HI gas is optically thin, 21 cm line suffers little absorption, so we can measure gas mass directly from line intensity
- HI is much more extended than optical light
- Can use radial motion of 21 cm line to measure rotation in spiral galaxies

A Basic Tool: Spin-Flip (21 cm) Line of H I

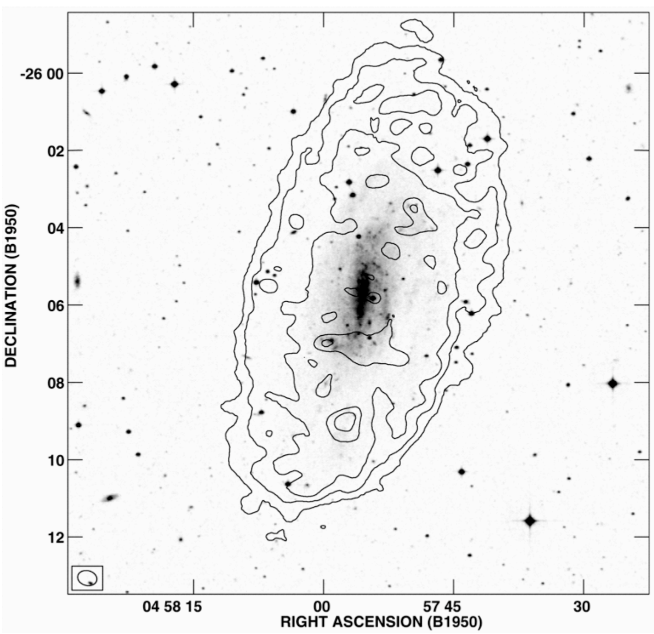


In emission generally originates from warm (T ~ 100 - 6000 K) ISM, which accounts for ~ 30 - 65% of the total ISM volume in the Galactic disk. In absorption, it probes a cooler ISM (can be also self-absorbed).

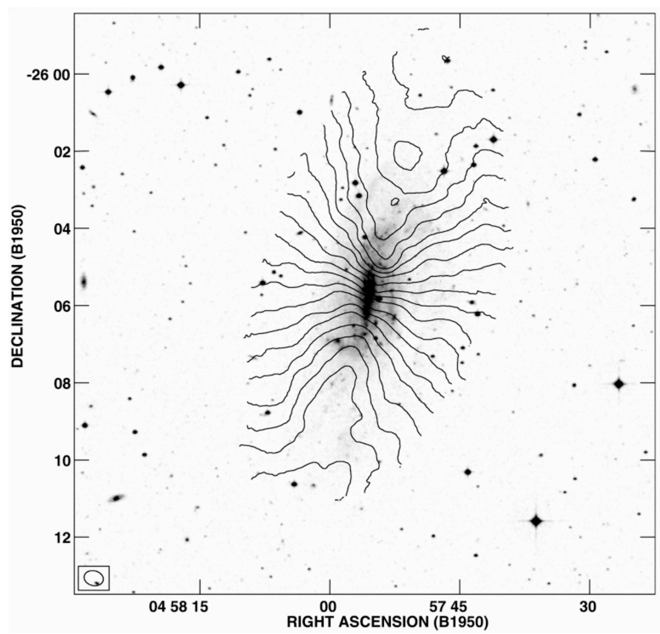
Typical line profile →



A major advantage: it is not affected by the dust absorption!

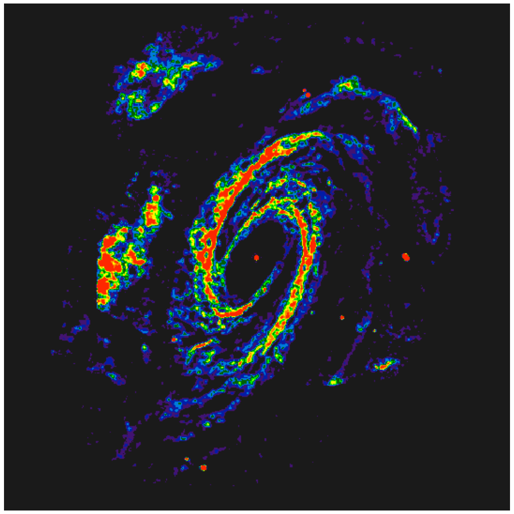


NGC 1744 Optical and HI contours

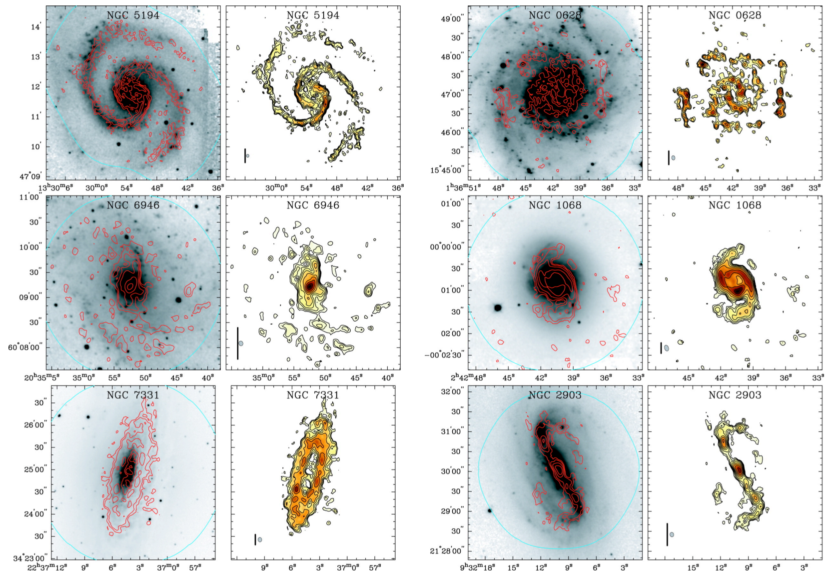


NGC 1744 Optical contours and H I radial velocities

M81: Optical and H I



Optical and CO

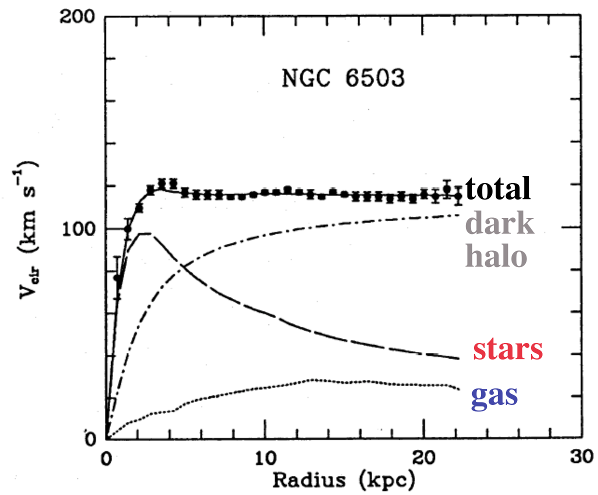


Multi-Phase ISM

The ISM has a complex structure with 3 major components:

1. **Cold** (T ~ 30 - 100 K), dense ($n_{HI} > 10$ cm^{-3}) atomic (H I) and molecular (H_2, CO, …) gas and dust clouds
   - ☆ Only ~ 1 - 5 % of the total volume, but most of the mass
   - ☆ Confined to the thin disk
   - ☆ Low ionization fraction ($x_{HII} < 10^{-3}$)
   - ☆ Stars are born in cold, dense clouds
2. **Warm** (T~10^3-10^4 K) neutral & ionized gas, n ~ 1 cm^{-3}
   - ☆ Energized mainly by UV starlight
   - ☆ Most of the total ISM volume in the disk
3. **Hot** (T ~ 10^5 - 10^6 K), low density (n ~ 10^{-3} cm^{-3}) gas
   - ☆ Galactic corona
   - ☆ Almost fully ionized, energized mainly by SN shocks

Disk Galaxy Rotation Curves: Mass Component Contributions

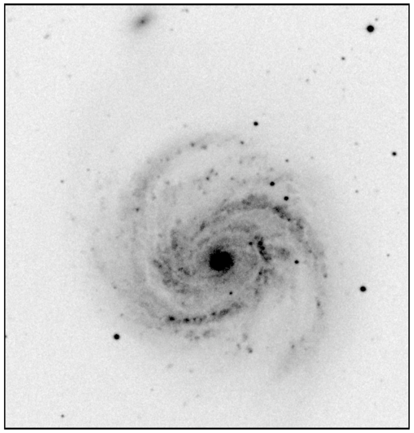


Dark Matter dominates at large radii

It cannot be concentrated in the disk, as it would make the velocity dispersion of stars too high

Spiral Arms

Defining feature of spiral galaxies - what causes them?



Observational clues:

Seen in disks that contain gas, but not in gas poor S0 galaxy disks.

Defined mainly by blue light from hot massive stars, thus lifetime is << galactic rotation period

When the sense of the galactic rotation is known, the spiral arms almost always trail the rotation

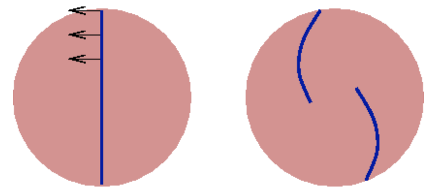
Differential Rotation of Galaxian Disks

First ingredient for producing spiral arms is differential rotation. For galaxy with flat rotation curve:

$$V(R) = \text{constant}$$

Angular velocity $\longrightarrow$ $\Omega(R) = \frac{V}{R} \propto R^{-1}$

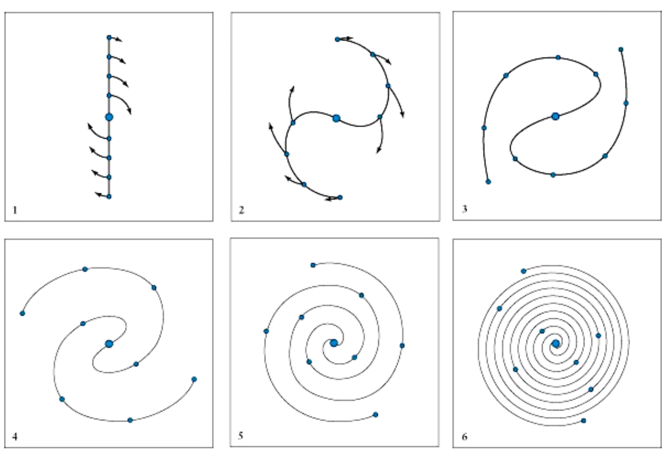
Any feature in the disk will be wrapped into a trailing spiral pattern due to differential rotation:



Tips of spiral arms point *away* from direction of rotation

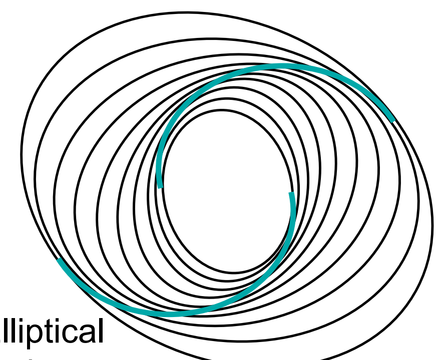
The Winding Dilemma

Due to differential rotation, stars near the galactic center don't need to travel far to circle the galaxy, but stars further out can take a long time to go around. An initial line of stars will be drawn out into a spiral:



But this is <u>not</u> why galaxies have spiral arms!

Orbit Crowding Schematic



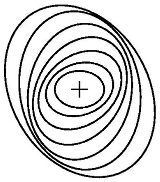
Nested Elliptical Orbits, each one slightly rotated.

Density Wave Theory

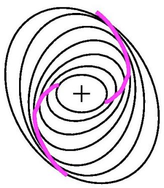
- Spiral arm patterns muct be persistent. Density wave theory provides an explanation: the arms are desity waves propagating in differentially rotating disks
- Spiral arm pattern is amplified by resonances between the epicyclic frequencies of the stars (deviations from circular orbits) and the angular frequency of the spiral pattern
  - Spiral waves can only grow between the inner and outer *Linblad resonances* ($\Omega_p = \Omega - \kappa/m$; $\Omega_p = \Omega + \kappa/m$) where κ is the epicyclic frequency and m is an integer (the # of spiral arms)
  - Stars outside this region find that the periodic pull of the spiral is faster than their epicyclic frequency, they don't respond to the spiral and the wave dies out
  - Resonance can explain why 2 arm spirals are more prominent
- We observe resonance patterns in spirals

Spiral Density Waves

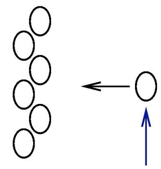
- The orbits in spiral galaxies are not quite circles – they are ellipses. These ellipses are slightly tilted with respect to each other.



- Thus there are regions of slightly higher density than their surroundings. The higher density means higher gravity.

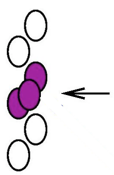


- Objects (such as a gas cloud) will be attracted to these regions and will drift towards them.

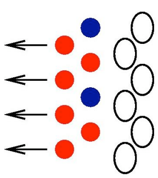


Spiral Density Waves

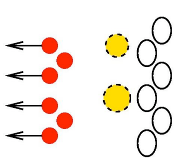
- When the gas cloud collides with other gas clouds, stars will be formed. (This is where most of the galaxy's star formation takes place.)



- Many of the stars will be faint, red main sequence stars, but some will be bright blue OB stars. These stars will continue to drift through the region.

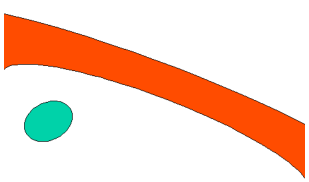


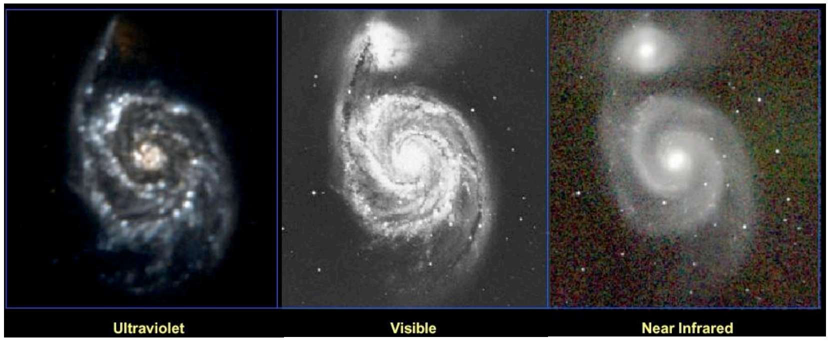
- The OB stars don't go far before they explode. The brightest (and bluest) of a galaxy's stars will never be far from the spiral arm where they were born.



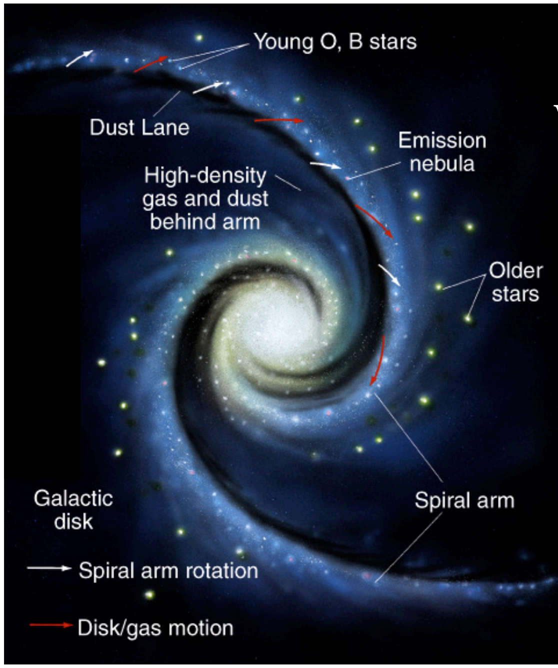
Spiral Density Waves

Since all the bright blue stars die before leaving the spiral arm, the **spiral density waves** must show up better at ultraviolet wavelengths.





The Density Wave Theory



Density Wave Theory Summary

- Spiral arms are waves of compression that move around the galaxy and trigger star formation
- Star formation will occur where the gas clouds are compressed
- Stars pass through the spiral arms unaffected
- This theory is successful in explaining the properties of spiral galaxies
- Two outstanding problems with it:
  1. What stimulates the formation of the spiral pattern?
     Tidal interactions?
  2. What accounts for the branches and spurs in the spiral arms?

Star Formation in Spiral Arms

- Spiral density wave creates spiral arms by the gravitational attraction of the stars and gas flowing through the arms
- Even if there was no star formation, there would be spiral arms - but star formation makes them more prominent
- This can explain the so-called ***"grand design" spirals***
- Star formation can ***self-propagate*** in a differentially rotating disk, e.g., as supernova shocks compress neighboring molecular clouds
- Self-propagating star formation may be responsible for the branches and spurs in the spiral arms, or disks without evident spiral density waves (the so-called ***flocculent spirals***)