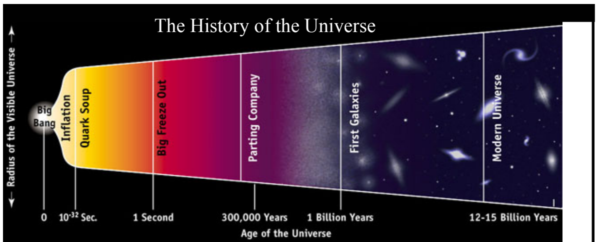


Planck time

Inflation

Nucleosynthesis of H, He, Li

Decoupling of CMB

Galaxy Formation

Now

Hot → Cool

High density → Low density

Astronomy in 1936

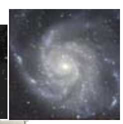
100 inch telescope
Completed 1918

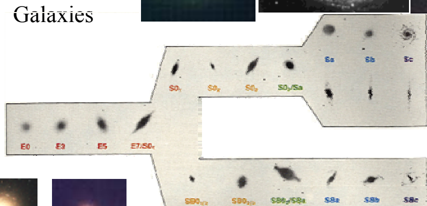
Edwin Hubble

- ~1770: Messier catalogue
- 1888: NGC, IC catalogues
- Van Maanen's "contribution"
- 1920: Curtis-Shapley debate
- 1923: Hubble measured distance to M31
- 1929: Expanding universe
- 1936: *Realm of the Nebulae* described Hubble classification system.

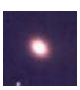
The Types of Galaxies

Spirals





Also… Irregulars



Ellipticals

Barred Spirals

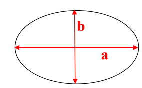
Usual classes used at current time:

- E0-E7
- S0, Sa, Sab, Sb, Sbc, Sc, Scd, Sd, Sdm, Sm, Im, Ir (or amorphous)
- SB0, SBa, SBab, SBb, SBbc, SBc, SBcd, SBd, SBdm, SBm

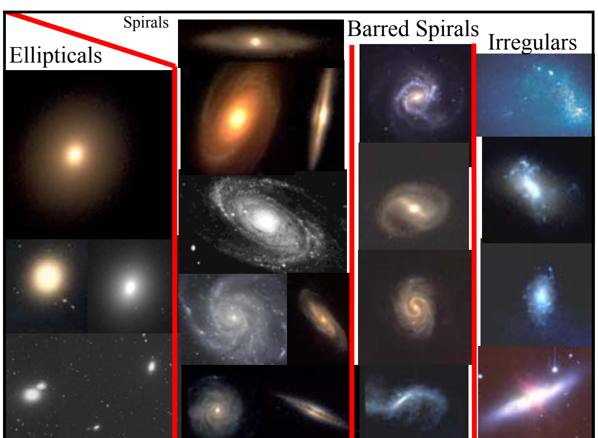
General Properties of Galaxy Types

- **E**
  - M_B = -8 to less than –23
  - Mass = $10^7 - 10^{13}\ M_\odot$
  - diameters <1 kpc – hundreds of kpc
- **S**
  - M_B = -16 to –23
  - Mass = $10^9 - 10^{12}\ M_\odot$
  - luminous diameters 5-100 kpc
- **Irr**
  - M_B = -13 to –20
  - Mass = $10^8 - 10^{10}\ M_\odot$
  - luminous diameters 1–10 kpc

E0→E7
10*(1-b/a)



Sa→Sc
- Bulge:disk ratio
- Tightness of winding
- Resolution of arms into star clusters & H II regions.



Morphological Types of Local Galaxies

(images taken from Frei, Guhathakurta, Gunn & Tyson 1996)

Homework Assignment No. 1
Due Jan 16 (Friday)

Classifying Galaxies

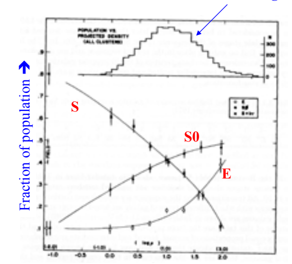
Good news, Professor Hubble! Even though it is 1936, you have been awarded access to the internet (at only $39.95/month, directly chargeable to your VISA card). So you don't have to waste any more time freezing at telescopes in order to classify galaxies. You can just look at them over the web! Here's how:

- Find a computer with decent bandwidth over the internet.
- Point your web browser to www. stsci.edu
- Click on "Digitized sky survey" on the side-bar.
- Now click on "retrieve image data" buried in the middle of the text.
- Set "File Format" to GIF. (You may have to reset this each time you get a new image).
- Leave the other defaults alone: "First Generation Survey", etc.
- Look at the images of the galaxies at the coordinates listed below.
- Write down your best guess at the Hubble class of each galaxy, with a brief description of the galaxy and of why you gave it whatever Hubble class you picked.

RA	Dec	Epoch
12 20 07	29 16 50	J2000
12 48 36	-05 48 00	J2000

Distribution of galaxy types

- Dense regions (cluster centers) predominantly ellipticals.
- Field galaxies predominantly spirals.
- On average, roghly even split between E and S.



Dressler 1980

Spiral galaxies

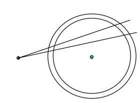
- Holmberg radius r_H
  - Length of semi-major axis down to 26.5 B-mag arcsec $^{-2}$
- Effective radius r_e
  - Radius within which ½ of light is emitted.

USE TRANSPARENCY

- Disks follow exponential law
- Freeman's law
  - Most disks have about same surface brightness at their centers
  - Reason not clear
  - This observational result is now in dispute

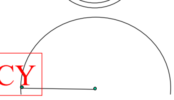
Rotation Curves

- Spherical mass shell, uniform density:



- $F_{centripital} = F_{gravity}$

USE TRANSPARENCY



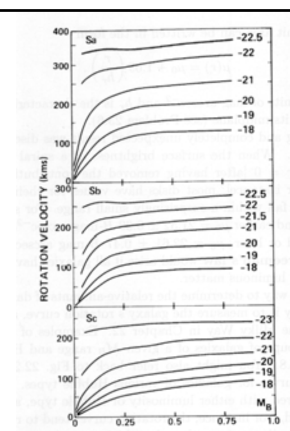
- Inside spherical mass distribution:
- Outside mass distribution:
- Sph. Distr. + exponential disk

Show spectrograph slit positions

Mass Determinations for Spiral Galaxies

Rotation Curves

- Flat rotation curves ➔ dark matter

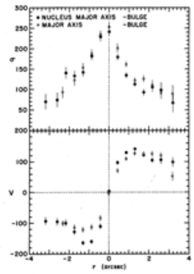


M33 Rotation curve

Density Distribution of Dark Matter halo

Mass determinations from absorption line widths

- Virial Theorem
  $2K = -U$
  $\langle v^2 \rangle = 3 \langle v_r^2 \rangle$
  ➔ $\sigma^2_r = GM/(5R)$
- See pp. 1005-1008, + Sect. 2.4
- Applied to nuclei of spirals ➔ presence of massive black holes
- Also applied to
  - E galaxies
  - Galaxy clusters



The Virial Theorem [CO 2.4]

- For gravitationally bound systems *in equilibrium*
  - Total energy = ½ time-averaged potential energy.

  E = total energy
  U = potential energy.
  K = kinetic energy.

  $E = K + U$

- Can show from Newton's 3 laws + law of gravity:
  - $\frac{1}{2}(d^2I/dt^2) - 2K = U$ where $I = \Sigma m_i r_i^2$ = moment of inertia.
  - Time average $\langle d^2I/dt^2 \rangle = 0$, or at least ~ 0.
  - Virial theorem ➔ $-2\langle K \rangle = \langle U \rangle$
    $\langle K \rangle = -\frac{1}{2}\langle U \rangle$
    $\langle E \rangle = \langle K \rangle + \langle U \rangle$ ➔
    $\langle E \rangle = \frac{1}{2}\langle U \rangle$

Mass to Light Ratios: Evidence for Dark Matter

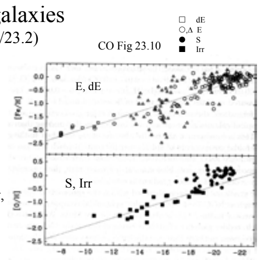
Tuning-Fork Diagram

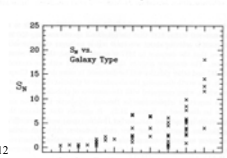
Trends in spiral galaxies

(see CO Tables 23.1/23.2)

- Mass/Light ratios
  - Sa ➔ Sc : $M/L_B = 6.2$ ➔ 2.6
  - Sc's dominated by younger, hotter, more massive stars.
- Colors
  - Sa ➔ Sc : B-V = 0.75 ➔ 0.52
  - Bluer colors ➔ Sc's dominated by younger, hotter stars.
- M_{gas}/M_{total}
  - Sa ➔ Sd: $M_{gas}/M_{total} = 0.04$ ➔ 0.25
- Molecular/atomic hydrogen
  - Sa ➔ Sd: $M_{H2}/M_{HI} = 2.2$ ➔ 0.3
- Metallicity
  - Depends on absolute magnitude
- No. of Globular Clusters/Total Luminosity

CO Fig 23.10

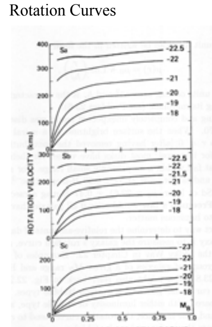


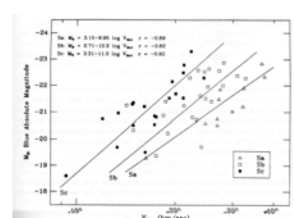


CO Fig 23.12

Tully-Fisher Relation

Rotation Curves





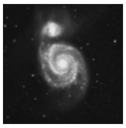
- Maxiumum rotation velocity-Luminosity relation [FIG 23.8]
  - **Tully-Fisher** relation [FIG 23.9]
    - $M_B = -9.95 \log_{10} V_{Max} + 3.15$ (Sa)
    - $M_B = -10.2 \log_{10} V_{Max} + 2.71$ (Sb)
    - $M_B = -11.0 \log_{10} V_{Max} + 3.31$ (Sc)

CO Semi-Derivation

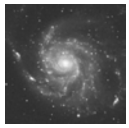
- Follows from $M(r) = v^2 r/G$

Spiral Structure

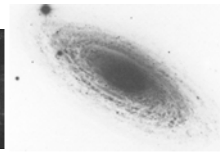
[CO 23.3]



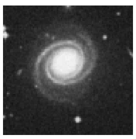
Grand design (10%)
M51



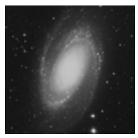
Multi-arm (60%)
M101



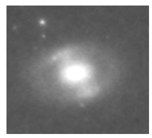
Flocculent (30%)
NGC 2841



NGC 7096



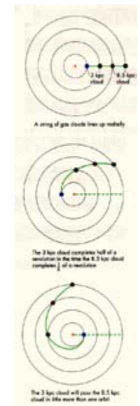
Inner rings
M81



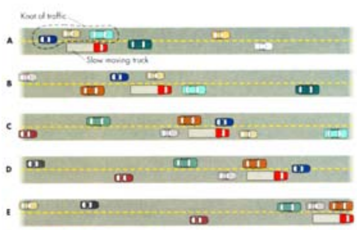
Outer Ring
NGC 4340

What causes spiral structure?

- Winding up of arms
  - Due to differential rotation
- Stochastic, Self-Propagating Star Formation
  - Chain-reaction star formation
  - SN shells ➔ shock fronts ➔ density enhancements ➔ star formation ➔ more SN
  - Differential rotation then winds these regions up into spiral patterns
- Density Waves
  - Wave in gravitational potential
  - Orbital velocity of stars different than pattern speed
    - Stars, gas bunch up at position of spiral arms
    - Causes higher grav. Potential
  - Unclear if self-sustaining or forced.



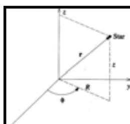
Spiral Arms & the Interstate Highway



- Density wave
  - Spiral arms have higher density than space between arms
  - Excess gravitational attraction slows down gas, stars when they pass through spiral arm in course of their orbits.
  - ➔ spiral arms are a traffic jam

Epicycles… the short form.

For lurid details, see [CO pp.1018-1030]



Ptolemy
Alexandria, 140AD

$$M\frac{d^2\mathbf{r}}{dt^2} = -\nabla U(R,z) = -\frac{\partial U}{\partial R}\hat{\mathbf{e}}_R - \frac{1}{R}\frac{\partial U}{\partial \phi}\hat{\mathbf{e}}_\phi - \frac{\partial U}{\partial z}\hat{\mathbf{e}}_z$$

Circular symmetry ➔ independent of ϕ

$$\frac{d^2\mathbf{r}}{dt^2} = -\frac{\partial \Phi}{\partial R}\hat{\mathbf{e}}_R - \frac{\partial \Phi}{\partial z}\hat{\mathbf{e}}_z \qquad (23.11)$$

$$\frac{d^2\mathbf{r}}{dt^2} = \left(\ddot{R} - R\dot{\phi}^2\right)\hat{\mathbf{e}}_R + \frac{1}{R}\frac{\partial\left(R^2\dot{\phi}\right)}{\partial t}\hat{\mathbf{e}}_\phi + \ddot{z}\hat{\mathbf{e}}_z$$

Separate d^2r/dt^2 into R, ϕ, z components ➔ 3 equations. (23.13-23.15)

$$\ddot{R} - R\dot{\phi}^2 = -\frac{\partial \Phi}{\partial R},$$

$$\frac{1}{R}\frac{\partial\left(R^2\dot{\phi}\right)}{\partial t} = 0,$$

$$\ddot{z} = -\frac{\partial \Phi}{\partial z}.$$

Conservation of specific angular momentum $J_Z = R^2\, d\phi/dt$

Define an effective potential:

$$\Phi_{\rm eff}(R,z) \equiv \Phi(R,z) + \frac{J_z^2}{2R^2}$$

$$\ddot{R} = -\frac{\partial \Phi_{\rm eff}}{\partial R}$$

$$\ddot{z} = -\frac{\partial \Phi_{\rm eff}}{\partial z}$$

Conservation of J_Z ➔ acceleration in ϕ direction when r changes.

Taylor series expansion around position of minimum $\Phi_{\rm eff}$ (circular orbit):

$$\Phi_{\rm eff}(R,z) = \Phi_{{\rm eff},m} + \left.\frac{\partial \Phi_{\rm eff}}{\partial R}\right|_m \rho + \left.\frac{\partial \Phi_{\rm eff}}{\partial z}\right|_m z + \frac{1}{2}\left.\frac{\partial^2 \Phi_{\rm eff}}{\partial R\partial z}\right|_m \rho z + \frac{1}{2}\left.\frac{\partial^2 \Phi_{\rm eff}}{\partial R^2}\right|_m \rho^2 + \frac{1}{2}\left.\frac{\partial^2 \Phi_{\rm eff}}{\partial z^2}\right|_m z^2 + \cdots$$

$$\Phi_{\rm eff}(R,z) \simeq \Phi_{{\rm eff},m} + \frac{1}{2}\kappa^2\rho^2 + \frac{1}{2}\nu^2 z^2. \qquad (23.24)$$

$$\ddot{\rho} \simeq -\kappa^2\rho \qquad \kappa^2 \equiv \left.\frac{\partial^2 \Phi_{\rm eff}}{\partial R^2}\right|_m$$

$$\ddot{z} \simeq -\nu^2 z \qquad \nu^2 \equiv \left.\frac{\partial^2 \Phi_{\rm eff}}{\partial z^2}\right|_m$$

(23.25-23.26)

Harmonic oscillation in R, ϕ, z about circular orbit (Epicycles)

$$\ddot{\rho} \simeq -\kappa^2\rho$$

$$\ddot{z} \simeq -\nu^2 z$$

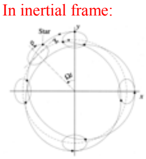
$$\rho(t) = R(t) - R_m = A_R \sin\kappa t$$

$$z(t) = A_z \sin(\nu t + \zeta)$$

$$\phi(t) = \phi_0 + \frac{J_z}{R_m^2}t + \frac{2J_z}{\kappa R_m^3}A_R\cos\kappa t = \phi_0 + \Omega t + \frac{2\Omega}{\kappa R_m}A_R\cos\kappa t$$

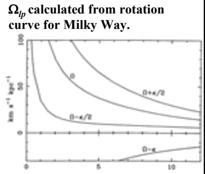
$R_m = R$ at min. $\Phi_{\rm eff}$
Ω = circular ang. vel.

In inertial frame:

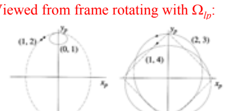


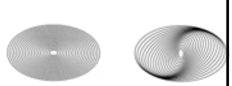
Orbits closed if:
$m\,(\Omega - \Omega_{lp}) = n\kappa$
$$\Omega_{lp}(R) = \Omega(R) - \frac{n}{m}\kappa(R)$$

Ω_{lp} calculated from rotation curve for Milky Way.



Viewed from frame rotating with Ω_{lp}:





Two ways to line up closed elliptical orbits (as seen from frame rotating with Ω_{lp})

Basic nature of a density wave

From: Toomre, Annual Review of Astronomy & Astrophysics, 1977 Vol. 15, 437.

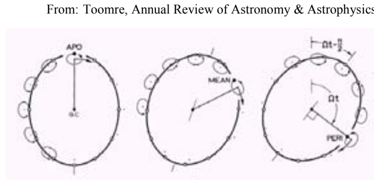
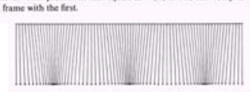
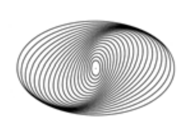


Figure 2 Slow $m = 2$ kinematic wave on a ring of test particles, all revolving clockwise (like the 12 shown) with mean angular speed Ω in strictly similar and nearly circular orbits. The small elliptical "epicycles," traversed counterclockwise in the above sequence of snapshots separated in time by exactly one-quarter of the period $2\pi/\kappa$ of radial travel along each orbit, depict the apparent motions of these particles relative to their mean orbital positions or "guiding centers." Drawn for the case $\kappa = \sqrt{2}\Omega$—or one where the rotation speed $V(r) = r\Omega(r)$ = const at neighboring radii—the diagram emphasizes that the oval locus of such independent orbiters advances in longitude considerably more slowly than the particles themselves. That precession rate equals $\Omega - \kappa/2$, as one can verify at once by comparing the last frame with the first.

Pendulum example



- At each R_m, stars' positions in epicycles are forced into a specific pattern by gravitational potential of spiral arm.
- Sum of positions of stars at this R_m forms an ellipse rotating at pattern speed.



- Spiral density pattern is sum of many ellipses, all rotating at same pattern speed.

Lin & Shu's theory

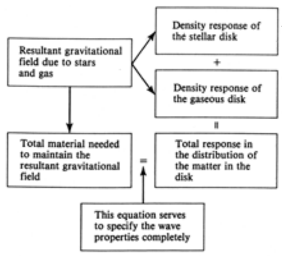
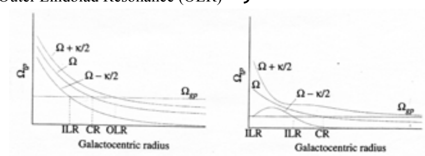


Figure 12.26. The calculational scheme used to calculate the normal modes of oscillation of a disk galaxy. (After C. C. Lin.)

Figure 12.27. Contours of equal density excesses above the average value around a circle in a typical spiral mode. The dashed circle gives the radius where the material rotates at the same speed as the wave pattern.

Inner Lindblad Resonance (ILR)
Co-rotation Radius
Outer Lindblad Resonance (OLR)

} Important in all disk galaxies

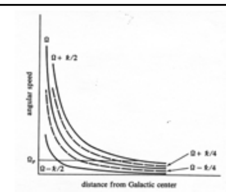


Density waves cannot propagate across ILR or OLR

Density wave theory interprets most spirals as 2-armed

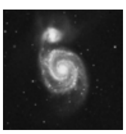
- 4-armed pattern is n / m = 1 / 4
- exists over a narrow range of radius.
  - ➔ less likely to be seen.

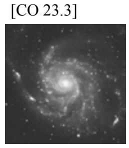
•Actual 4-armed spirals are superposition of two 2-armed patterns

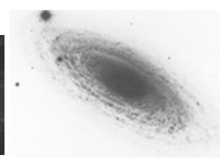


Spiral Structure

[CO 23.3]

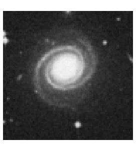


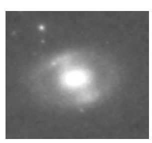




Grand design (10%) Multi-arm (60%) Flocculent (30%)

M51 M101 NGC 2841



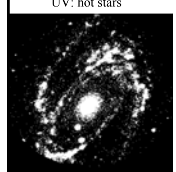


Inner rings Outer Ring

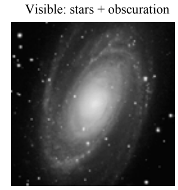
NGC 7096 M81 NGC 4340

M81 spiral structure at different wavelengths

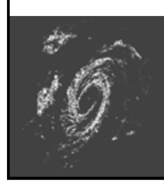
UV: hot stars



Visible: stars + obscuration



Near IR: late-type stars



21 cm: HI

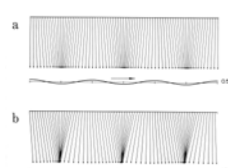
Old red population shows small but real spiral density enhancement.

Passage of gas through spiral arms

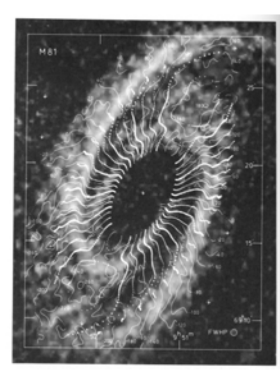
Figure 12.33. The streamlines of gas from a theoretical model of the spiral galaxy M81 (NGC3031, type Sb). (From H. Visser, *Astr. Ap.*, **88**, 1980, 159.)

Calculated streamlines for gas

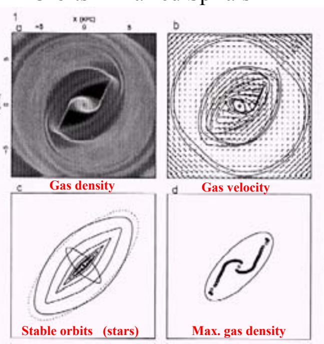
Response of gas to density waves



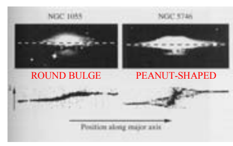
- Simple pendulum model
  - Each pendulum = 1 gas cloud
  - For large amplitude forcing, pendulums collide.
  - ➔ shock fronts in spiral arms
- HI map (right) shows velocity jumps at spiral arms.

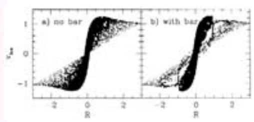


Orbits in Barred Spirals



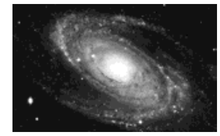
Kinematics of gas, in [NII]
[BM] Fig 4.60

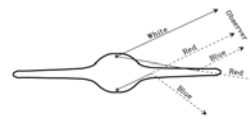




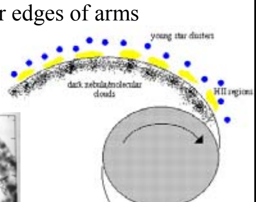
- Gas avoids "co-rotation" radius in barred potential.
- Causes "Fig-8" shape in rotation curve.

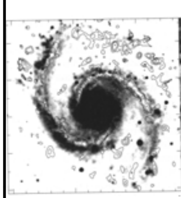
Trailing vs. leading spirals
Which is the near side of the galaxy?



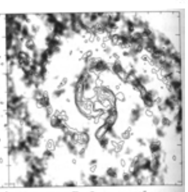


Molecular clouds on inner edges of arms

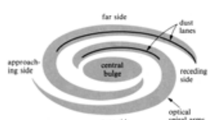




CO contours over red image

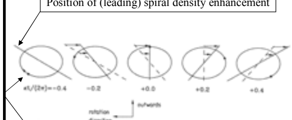


CO contours over 21 cm map



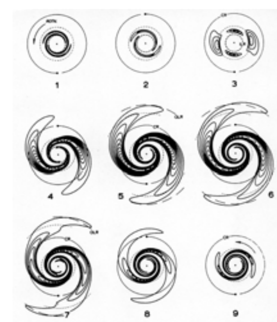
Swing Amplification

Position of (leading) spiral density enhancement



Epicyclic orbit of star

Automatically converts any leading spirals into much stronger trailing spirals.

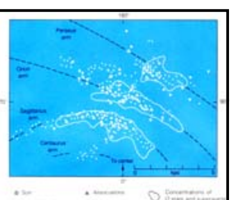


Spiral Structure of the Milky Way

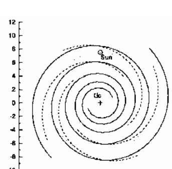
From HI (21 cm observations) assuming circular rotation.

Hard to measure, because we are inside it.

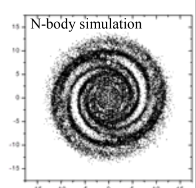
Map of nearby young objects



- New model
  - Lepine et al (2001) ApJ 546, 234.
- → mix of
  - 2-armed mode
  - 4-armed mode
- Sun at ~ co-rotation radius.



N-body simulation



Summary: Density Waves?

- Evidence showing density waves *do* occur.
  - Old, red stars show spiral density perturbation.
  - Molecular clouds form on inner edges of spiral arms.
  - HI gas flow shows discontinuity due to shocks at inner edges of spiral arms.
  - Bright young stars also in narrow arms.
    - Observed width $\Delta\theta \sim t_*(\Omega - \Omega_p)$, as predicted.
- Are these waves self-sustaining over 10^{10} years? Problems:
  - Lin-Shu theory is linear; does not predict whether waves will grow or decay.
  - How are density waves initially formed?
- The usual interpretation
  - Density waves need a driving force
    - Satellite galaxy at co-rotation radius (M51)
    - Bars
  - Otherwise, act to prolong life of transitory phenomena.
  - Other mechanisms probably also important.
    - Swing-amplification efficiently builds up temporary trailing spirals.