Spiral Structure in Galaxies

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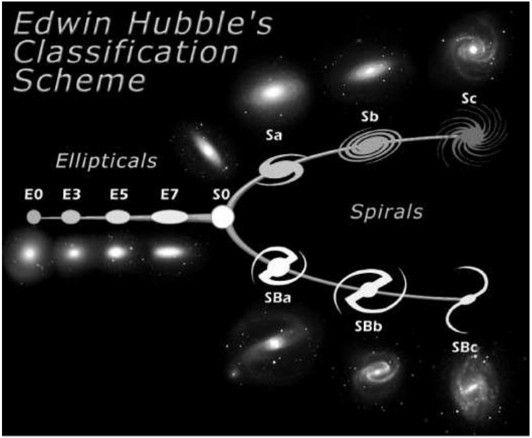
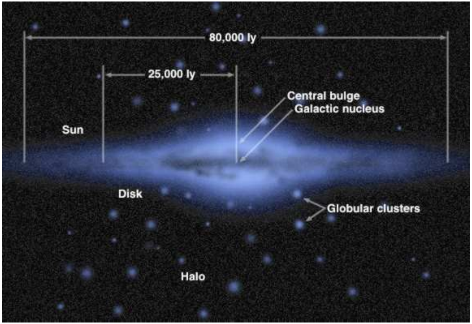
Morphological classification scheme of galaxies

- Galaxies: a rich variety of shapes
- In 1926: Edwin Hubble's morphological classification scheme
- Elliptical galaxies
- Spiral galaxies
    - 'Normal'
    - Barred (60 %)
- Lenticulars and irregulars



Face-on view of the Whirlpool Galaxy (M51)

Edge-on view



- Multi-component disk plane: $5 - 100$ kpc in diameter
- Vertical scale heights of the disk: only a few percents of its radii

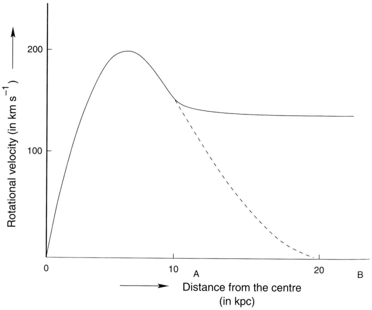
- Thin disk: young stars, gas and dust
- Central bulge: mostly old stars
- Spherical halo ($r \sim 100$ kpc): old stars, globular clusters
- Dark matter halo ($r \sim 230$ kpc)
- Mass: $10^9 - 10^{12}\ \mathrm{M}_\odot$
- Number of stars: $10^9 - 10^{12}$

Rotational curve

- A circular Keplerian orbit:

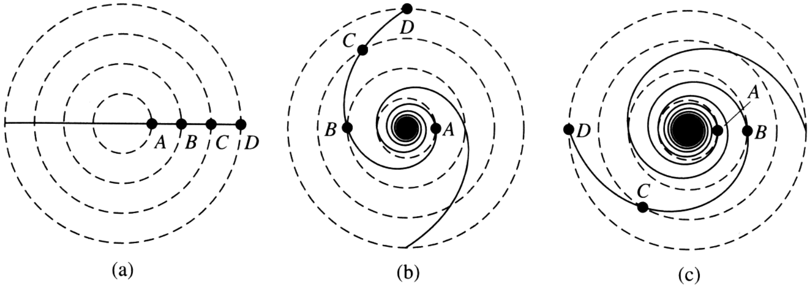
$$v = \sqrt{\frac{GM(r)}{r}}$$

- A: extension of a visible mass
- But: Rotation curve for $r > R$ is constant!
- B: extension of a dark matter
- Rotational velocities vary with the morphology.



- $v_{min} = 50 - 100\ \mathrm{km\ s^{-1}}$ for the development of a well-organized spiral pattern.

The Winding Problem

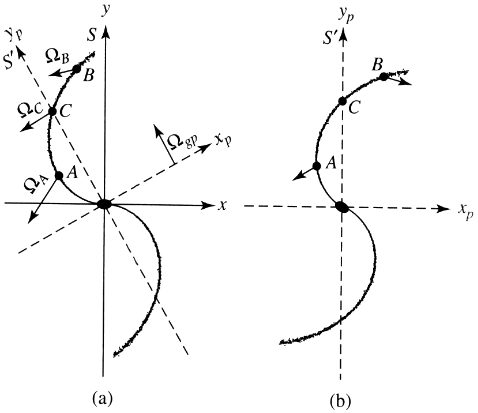


- Material arms
- Differential rotation of the disk
- After only a few periods: arms wound too tightly to be observed

Density Waves

- 1960's: C. C. Lin and Frank Shu: *long-lived quasistatic density waves*
- Enhanced density by $10 - 20$ %
- Frame of reference
- Stars, gas and dust travel on their orbits through the waves, triggering star formation
- Jeans criterion $M_c > \left(\frac{5k_B T}{G\mu m_H}\right)^{3/2} \left(\frac{3}{4\pi\rho_0}\right)^{1/2}$
- The hypothesis: only large-scale regular structure

Frame of reference



Inertial frame (S):

- Velocity of a quasistatic density wave: Ω_{gp}
- $\Omega_C = \Omega_{gp}$ - corotation with a density wave

Noninertial frame (S'):

- Galaxy is rotating with Ω_{gp}
- The spiral pattern seems to be stationary
- Star C corotates with the wave

Axial Symmetric Gravitational Potential

- Inertial frame, the potential is stationary
- Only collisionless stellar component ($N = 10^{11}$ stars)
- We neglect the potential of the spiral waves.
- An effective gravitational potential (cylindrical coordinates (r, φ, z)):

$$\Phi_{eff}(r,z) = \Phi(r,z) + \frac{J_z^2}{2r^2},$$

$$\Phi(r,z) = U/m, \quad m\frac{d^2\mathbf{r}}{dt^2} = -\nabla U(r,z)$$

- The minimum Φ^0_{eff}: orbit of the star is perfectly circular, $(r = R_m, z = 0)$

The perturbation analysis

- Only the first order of perturbation
- $\rho = r - R_m$

$$\Phi_{eff}(r, z) \simeq \Phi^0_{eff} + \frac{1}{2}\kappa^2\rho^2 + \frac{1}{2}\nu^2 z^2$$

$$\kappa^2 \equiv \frac{\partial^2\Phi_{eff}}{\partial r^2}\Big|_m, \qquad \nu^2 \equiv \frac{\partial^2\Phi_{eff}}{\partial z^2}\Big|_m$$

- κ: the *epicycle frequency*, ν: the *oscillation frequency*
- Equations of harmonic motion:

$$\ddot{\rho} \simeq -\kappa^2\rho, \qquad \ddot{z} \simeq -\nu^2 z$$

- Solution:

$$\begin{aligned} \rho(t) &= A_R \sin \kappa t, \\ z(t) &= A_z \sin(\nu t + \zeta) \end{aligned}$$

The perturbation analysis

- The difference between the azimuthal position of the star and the equilibrium point: $\chi(t)$

$$\begin{aligned}\dot{\varphi} &= \frac{v_\varphi}{r(t)} = \frac{J_z}{r(t)^2} \\ r(t) &= R_m + \rho(t) = R_m(1 + \rho(t)/R_m)\end{aligned}$$

For $\rho(t) \ll R_m$:

$$\dot{\varphi} \approx \frac{J_z}{R_m^2}\left(1 - 2\frac{\rho(t)}{R_m}\right)$$

$$\chi(t) \equiv (\varphi(t) - (\varphi_0 + \Omega t))\, R_m$$

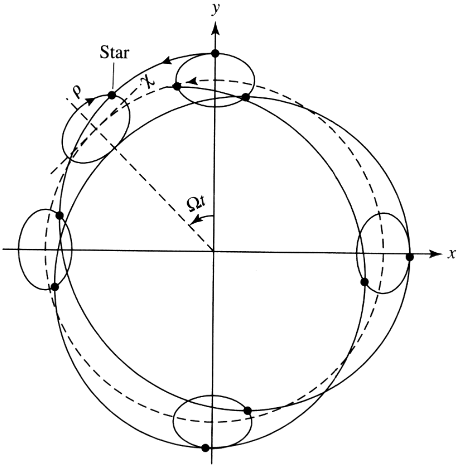
$$\rightarrow \quad \chi(t) = \frac{2\Omega}{\kappa} A_R \cos \kappa t$$

Epicycles

- Oscillation around the equilibrium position $(R_m, 0)$

$$\begin{aligned}\rho(t) &= A_R \sin \kappa t, \\ \chi(t) &= \frac{2\Omega}{\kappa} A_R \cos \kappa t\end{aligned}$$

- Inertial frame: most stellar orbits are not closed; the rosette pattern → epicycles
- Center of the epicycle: the equilibrium position, rotating around the center of the galaxy with Ω



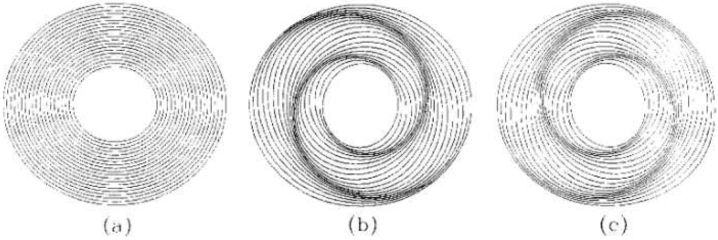
Closed Orbits in Noninertial Frames

- Number of oscillations per orbit in inertial frame: $N = \frac{\kappa}{\Omega}$
- If N is an integer, orbit is closed
- Closed orbit in noninertial frame (Ω_{lp} relative to the inertial frame): We choose frame in which star completes n orbits and m epicycle oscillations (m and n are integers)
- We choose $m(\Omega - \Omega_{lp}) = n\kappa$ or

$$\Omega_{lp}(r) = \Omega(r) - \frac{n}{m}\kappa(r)$$

- Only selected modes ($(n, m) = (1, 2)$) are most common to be observed

The Spiral Pattern

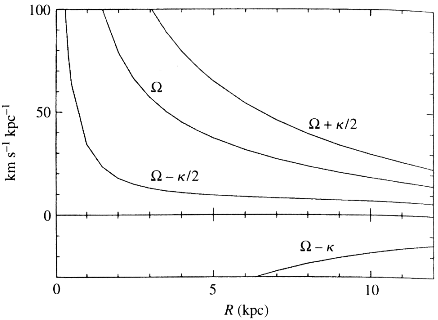


- A large number of stars at various distances r: Ω_{gp}
- If $\Omega_{lp} \neq \Omega_{lp}(r)$, then we can set $\Omega_{gp} = \Omega_{lp}$.
- From the Earth: patterns could be nested with their major axis aligned

- Rotation of the major axis: trailing two-armed grand-design spiral wave pattern
- Rotation in the opposite sense: leading arms

The Stability of the Spiral Structure

- For $(n, m) = (1, 2)$: $\Omega_{lp}(r) = \Omega(r) - \frac{\kappa(r)}{2}$; $\Omega_{lp} \neq ?\Omega_{lp}(r)$, $\exists ?$ appropriate Ω_{gp}
- The most frequent systems: two-armed with $m = 2$, flat rotation velocity, just like the Ω_{lp}
- Observations: large-scale, regular spiral structure should be quasistationary if the dynamics of the disk is dominated by one mode or by a very small number of modes

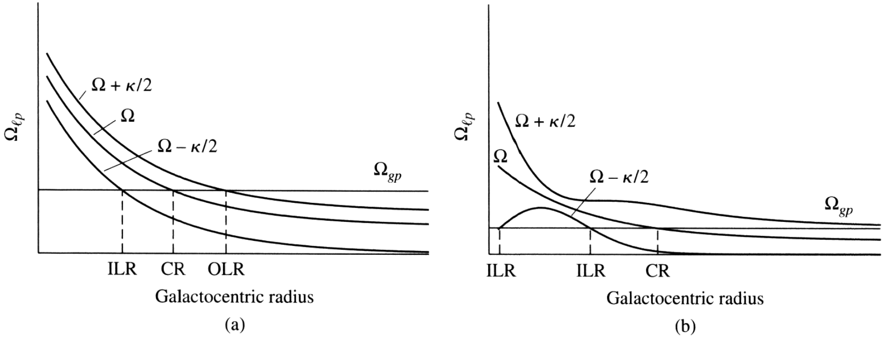


- Presence of gas is essential for spiral structure (star formation)

Lindblad Resonances

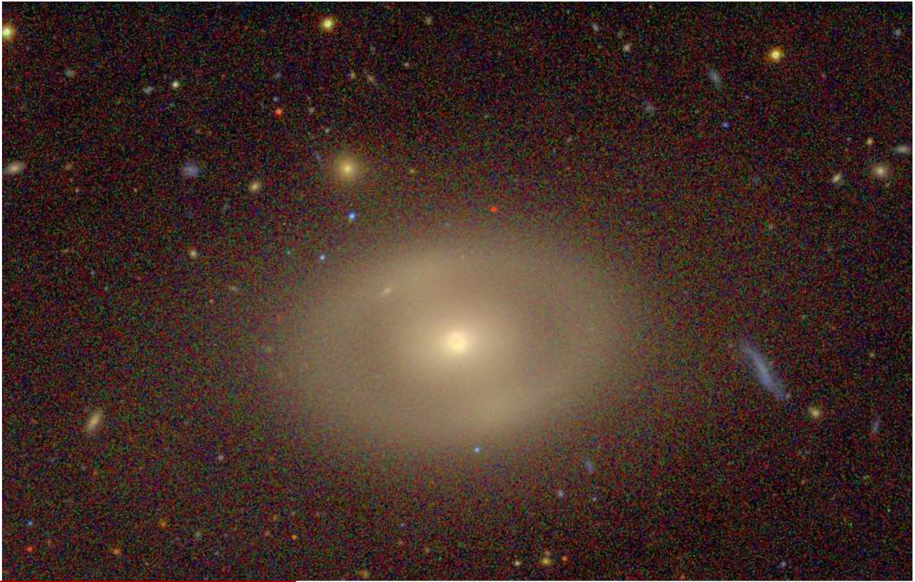
- The potential of the arms
- When star encounters a density wave with χ_{max}: resonance
- A_R and A_z are considerably increased
- Perturbations acumulate, if star enters the density wave with χ_{max} each time
- Analogy with the spring oscillation
- In resonance: more likely for gas clouds to collide and for the dissipation of the energy $\rightarrow$ damping in spiral waves
- $\Omega = \Omega(r) \rightarrow$ only certain radii with a resonance:

Lindblad Resonances



- $\Omega_{lp} = \Omega - \kappa/2 = \Omega_{gp}$ $(n/m = 1/2)$: *inner Lindblad resonance* at several radii
- $\Omega = \Omega_{gp}$: a *corotation resonance*
- $\Omega + \kappa/2 = \Omega_{gp}$: an *outer Lindblad resonance*

Lindblad Resonances (NGC 4340)



Spiral Arms

- Variation in number and shape of galactic arms
- Grand-design spirals: only two very symmetric arms
- 10 % of grand-design spirals, 60 % of multiple-armed galaxies and 30 % of flocculent galaxies
- Visible wavelengths: domination by spiral pattern due to very luminous O and B main-sequence stars and HII regions
- $t_\star = 10^7$ yr $< t_{gx} = 23 \cdot 10^7$ yr $\rightarrow$ spiral pattern: regions of **active star formation**
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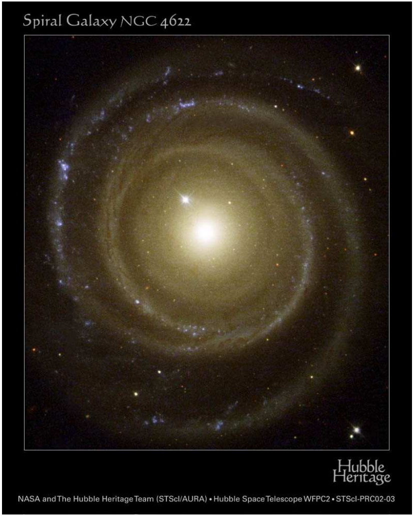
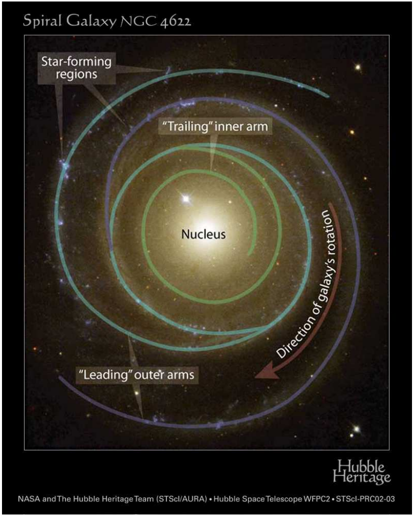
Spiral Arms - NGC 4622: one leading arm



Spiral Arms - NGC 4622: one leading arm



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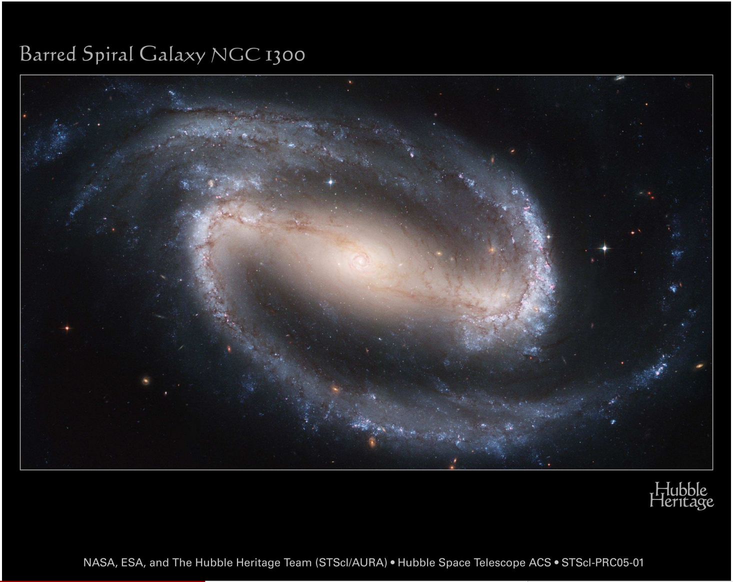
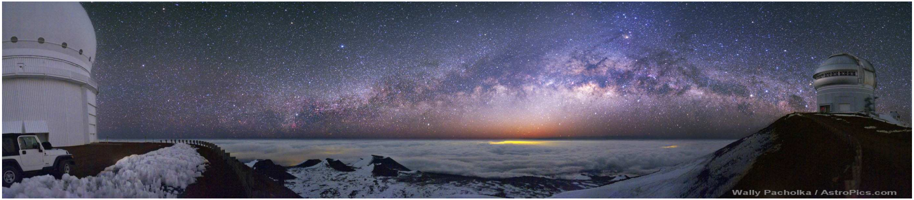
- Trailing spiral arms in most cases; but in galaxy NGC 4622: one leading spiral arm
- An important role in galactic evolution: galactic **bar**

Spiral Arms - Barred Spiral Galaxy NGC 1300

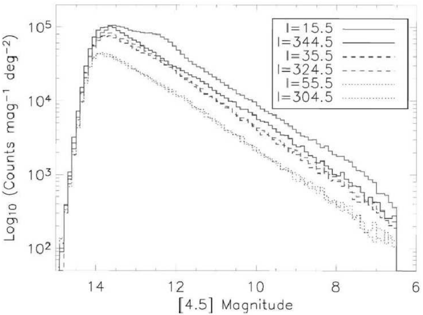


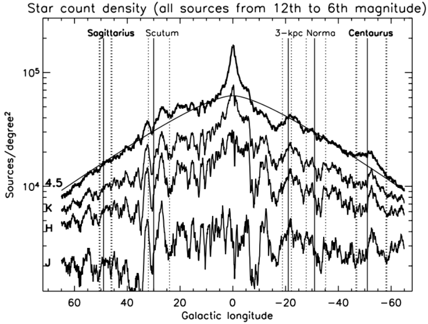
Mapping the Milky Way Galaxy



- The large-scale structure: somehow misterious
- We are positioned inside the galactic plane
- Obscurity of the extensive dust clouds
- GLIMPSE surveys: archived over 100 million stars

Mapping the Milky Way Galaxy

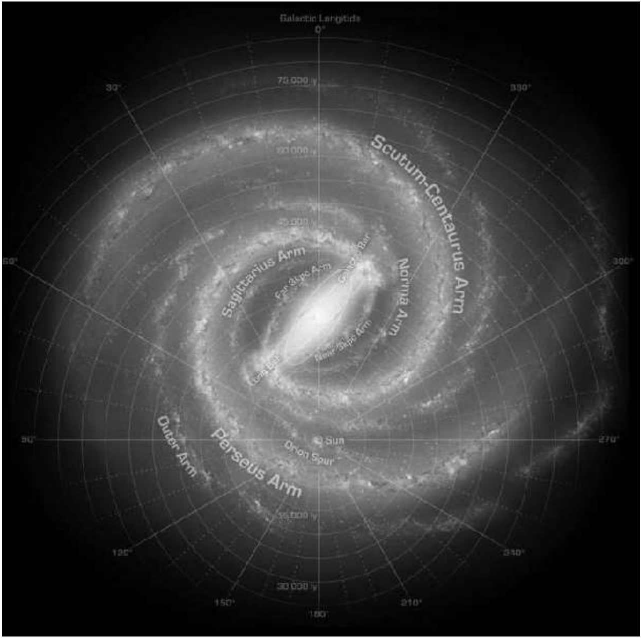




- Power-law exponent of stars per magnitude per square degree versus magnitude: **bump:** a northern arm of a central bar
- An enhancement of stars along the Galactic midplane toward the Scutum-Centaurus arm; no increase towards the Sagittarius arm

Some of the most fundamental physical parameters of our Galaxy

- Number of stars: $\sim 10^{11}$
- Stellar mass of the thin disk: $10^{10} - 10^{11}\ \mathrm{M_\odot}$
- Multi-component disk plane: 50 kpc in diameter
- Sun's distance to the Galactic center: $8 - 8.5\ \mathrm{kpc}$ $(7.62 \pm 0.32\ \mathrm{kpc})$
- Vertical scale height (thin disk): $\sim 350\ \mathrm{pc}$ (1.4 % of its radii); thick disk: (1 kpc or 4 % of disk's radii)
- Radius of dark-matter halo: 230 kpc
- Type SBbc, grand-designed two-armed barred spiral



Scutum-Centaurus Arm
Norma Arm
Sagittarius Arm
Perseus Arm
Outer Arm
Sun

Conclusion

- Arms are not material (winding problem)
- The Lin-Shu density wave theory
- Small-amplitude orbital perturbations
- In the first order: epicycles
- Nested and rotated oval-shaped orbits, spiral pattern
- Several resonant radii
- Spiral pattern is associated with the star-forming regions
- Difficulties with revealing the spiral pattern of our Galaxy
- The Milky Way Galaxy: SBbc