Whittle : EXTRAGALACTIC ASTRONOMY

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5. SPIRAL GALAXIES

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(1) Introduction

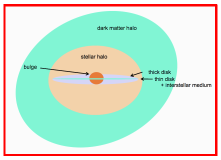
(a) Spiral Galaxies are Complex Systems

Disk galaxies appear to be more complex than ellipticals

- Wide range in morphological **appearance**:
  eg classification bins : simple E0-6 compared with all the spiral types
  not just smooth, considerable fine-scale details
- Wide range in stellar **populations**:
  old, intermediate, young and currently forming
  → ongoing chemical enrichment
- Wide range in stellar **dynamics**:
  "cold" rotationally supported disk stars
  "hot" mainly dispersion supported bulge and halo stars
- Significant **cold ISM**:
  note : the cold and warm components are **dissipative**, and therefore :
  → influences dynamical evolution (eg helps spiral formation)
  → influences stellar density distribution (eg creates dense cores & black holes)

(b) Review of Basic Components [image]

- **Disks :**
  Metal rich stars and ISM
  Nearly circular orbits with little (~5%) random motion & spiral patterns
  Both thin and thick components
- **Bulge :**
  Metal poor to super-rich stars
  High stellar densities with steep profile
  V(rot)/σ ~ 1, so dispersion support important.
- **Bar :**
  Flat, linear distribution of stars
  Associated rings and spiral pattern
- **Nucleus :**
  Central (< 10pc) region of very high density (~10^6 $M_\odot pc^{-3}$)
  Dense ISM &/or starburst &/or star cluster
  Massive black hole



- **Stellar Halo :**
  Very low SB; ~few % total light; little/no rotation
  Metal poor stars; GCs, dwarfs; low-density hot gas
- **Dark Halo :**
  Dark matter dominates mass (and potential) outside ~10 kpc
  Mildly flattened &/or triaxial

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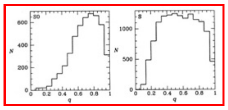
(2) 3-D Shapes

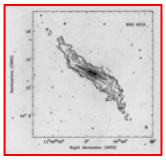
(a) Disks

- Distribution of (projected) b/a : [image]
  Approximately **flat** over wide range, from 0.3 to 0.8
  Rapid rise at b/a ~ 0.1 - 0.3; and rapid fall at b/a > 0.8



- Interpretation :
  - Randomly oriented thin circular disks give N(b/a) = const
    → observed N(b/a) consistent with **mostly flat circular disks**
  - Drop at low b/a due to bulge. Note: slower rise for big bulge S0s, and faster rise for small bulge Scs.
  - Minimum b/a ~ 0.05 - 0.1 for ~bulgeless Sdm → **disks can be highly flattened**
  - drop at high b/a ~ 0.8 caused by **non-circular disks**
    → dark matter potentials slightly oblate/triaxial ($<\epsilon(\phi)> \sim 0.045$)

- Warps: [image]
  - starlight almost always flat (if undisturbed)
  - however, HI is often **warped**, with warp starting beyond D_{25}
  - 180 degree symmetry: "integral sign" when seen edge-on.
  - 75% of warped galaxies have **no** significant companion
    → probably response to non-spherical halo potential misaligned with disk



(b) Bulges

Not as easy as ellipticals because of other components
Study edge-on spirals to minimise contamination
Results :

- oblate spheroids, flattened by rotation
  → probably similar to low-luminosity ellipticals

(c) Bars

- Axis ratios from 2.5 to 5.
- Probably **flat**, since they aren't visible in edge-on spirals
- However, "peanut" bulges thought to be thickened (unstable) bars seen edge-on [image]

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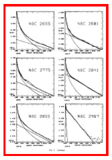
(3) Surface Photometry

Model as two components: bulge and disk [image]



- 1-D fits to elliptically-azimuthally averaged light profile
- 2-D fits to full image: better, since bulge & disk have different ellipticities

(a) Radial Profiles

(i) Bulge

deVaucouleurs $R^{1/4}$ Law, first in flux units:

$$\boxed{\begin{aligned} I(R) &= I(0)\, exp\left(-7.67\,(R/R_e)^{1/4}\right) \\ &= I(R_e)\, exp\left(-7.67\left[\,(R/R_e)^{1/4}-1\,\right]\right) \end{aligned}} \qquad \begin{aligned}&(5.1a)\\&(5.1b)\end{aligned}$$

or in magnitudes per square arcsec:

$$\boxed{\begin{aligned} \mu(R) &= \mu(0) + 8.325\,(R/R_e)^{1/4} \\ &= \mu(R_e) + 8.325\left[\,(R/R_e)^{1/4}-1\,\right] \end{aligned}} \qquad \begin{aligned}&(5.2a)\\&(5.2b)\end{aligned}$$

where

- Effective radius, R_e, contains half the light; [Note: $I(R_e) \equiv I_e$, etc]
- $R_e \sim 0.5$ - 4 kpc (larger for early Hubble types)
- $I(0) = 2140\, I(R_e)$
- Integrating to infinity: $L_{tot} = 7.22\,\pi\, R_e^2\, I_e$

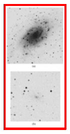
(ii) Disk

Exponential fits well (first flux units, then mag/ss):

$$\boxed{\begin{aligned} I(R) &= I(0)\, exp\,(-R/R_d) \\ \mu(R) &= \mu(0) + 1.086\,(R/R_d) \end{aligned}} \qquad \begin{aligned}&(5.3a)\\&(5.3b)\end{aligned}$$

where

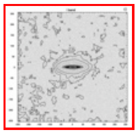
- R_d is the disk **scale length**, ie $I(R_d) = 1/e\ I(0)$
- Typically, $R_d \sim 0.25\, R_{25} \sim 2$ - 5 kpc   (R_{25} is 25th mag/ss isophote)
- In practice, disk light falls sharply beyond 3 - 5 R_d
- $R_d > R_e$ always (eg MW : $R_d \sim 5$ kpc, $R_e \sim 2.7$ kpc)
- Integrating to infinity: $L_{tot} = 2\,\pi\, R_d^2\, I(0)$
- $\mu_B(0) \sim 21.65 \pm 0.3$ mag/ss (Freeman 1970 "Law" of ~const $\mu(0)$ for normal spirals)
  However, a few Low Surface Brightness (LSB) galaxies have much fainter $\mu(0)$ [image]



(iii) Stellar Halos

- MW and M31 have **resolved** halos with metal poor stars, and globular clusters
  Both of these systems contain significant **substructure** [image]
  → tidally stripped dwarf galaxies and globular clusters.
  However, M33 does **not** have a significant stellar halo

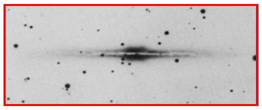
- Extremely difficult to see as integrated light in other galaxies [image]
  Stacking ~1000 SDSS edge on galaxies shows extended red light out to $\mu_i \sim 29$ mag/ss:
  Implied density: $\rho(r) \propto r^{-\alpha}$ with $\alpha \sim 3$.
  Consistent with moderately flattened spheroid: c/a ~ 0.6



- Overall, still unclear yet:
  How much of stellar halo is in form of tidal streams
  How many galaxies have stellar halos .

(b) Vertical Disk Structure

Studies of edge on disks suggests **exponential** distribution: [image]



$$\boxed{I(z) = I(0)\, exp\,(-|z|/z_o)} \qquad (5.4)$$

Where z_o is the **scale height** of the disk, ie $I(z_o) = I(0)\,/\,e$

At large z, excess light sometimes reveals a second "Thick Disk" of larger z_0
(see 4d(ii) below for further discussion of vertical disk structure)

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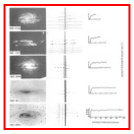
(4) Disk Velocity Field

(a) Gas Rotation Curves

Typical rotation curve comprises [image]

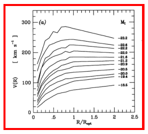
- rise from zero at the nucleus
- V_{max} peak at R_{max}
- extended region close to flat



Many rotation curves have now been measured
Some systematic trends are noticable :

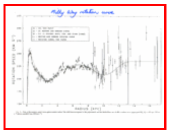
(i) At Large Radius

- V_{max} increases as L increases (T-F relation, see below)
- Outer slope increases as L decreases [image]
  for $V(r) \propto R^m$ we find m in the range -0.2 to 0.2 ($m = 0$, flat, for $M_B \sim -22.5$)
  Drop in massive early types caused, in part, by high V_{max} from bulge



(ii) At Small Radius

- For luminous early type spirals, V(r) rises **very rapidly** (often unresolved)
  → dense bulge core(&/or black hole?) [see Milky Way rotation curve: image]



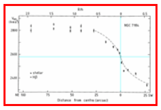
- For low luminosity later type spirals, V(r) rises **more slowly**
  often $V(r) \propto r$ → "solid body"
  However: sometimes, when V(r) drops, $\sigma(r)$ **increases**, so V(r) is **not** the full V_c
  i.e. rotation **and dispersion** both provide support

(b) Stellar Velocities in the Disk

Disks are **faint** → stellar LOSVD (Line Of Sight Velocity Dispersion) is difficult to measure
Also, brighter central regions are confused by bulge component
Nevertheless, some results are emerging.

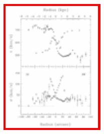
(i) Rotation

For disk stars, $V_{los} >> \sigma_{los}$ so stars are **cold** and have ~ circular orbits
Usually, V_{stars} follows V_{gas} which is close to V_c [image]



- Sometimes, star orbital rotation velocity can be **slower** than the gas
  this is called **asymmetric drift** and indicates a higher stellar dispersion
  → support beginning to be shared with dispersion
  → stars at r likely to be at apogee, so have $V < V_c$

- In S0s, ~30% have **counter-rotating** gas disks [image]
  a few spirals even have two counter-rotating **stellar** disks
  → both indicate external origin postdating primary disk formation



(ii) Vertical Dispersion

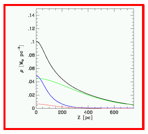
Face-on galaxies yield σ_z : the vertical stellar dispersion

- As a function of radius, σ_z decreases exponentially, with scale length $2R_d$
  This agrees with simple stellar dynamics theory:
  An isothermal disk gives $\sigma_z^2 = 2\pi G z_o \Sigma_M$
  where Σ_M is the surface mass density and z_o is the scale height
  Hence $\sigma_z \propto \Sigma_M^{1/2} \propto I(r)^{1/2} \propto \exp(-R/2R_d)$, as found.

- Consider the Milky Way disk: observations near the solar neighborhood:

  The inferred mass density within the disk suggests dark matter does **not** dominate the disk.

  It turns out there are **several components** of different z_o and σ_z [image]



  - gas and dust, $z_o \sim$ 50 pc ; $\sigma_z \sim$ 10 km/s
  - young thin disk, $z_o \sim$ 200 pc ; $\sigma_z \sim$ 25 km/s
  - old thick disk, $z_o \sim$ 1.5 kpc ; $\sigma_z \sim$ 50 km/s

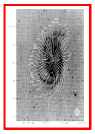
  The astrophysical origin of this is thought to be σ_z increasing with **age**

  - stars born "cold" from molecular clouds with $\sigma_z \sim$ sound speed, and corresponding small z_0
  - stars gradually "heated" by scattering off DMCs and spiral arms, and/or
  - heating of the disk over time by satellite passage and/or minor mergers

(c) 2-D Velocity Fields: Spider Diagrams

A circular disk tilted by angle i (0 = pole on) projects to an ellipse.
The photometric major axis (PMA) of this ellipse is called the **line of nodes**

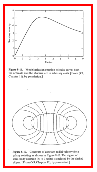
Contours of projected velocity, V_{los}, give a **spider diagram** [image]



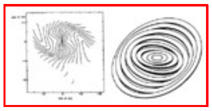
Kinematic Major Axis (KMA): line through nucleus **perpendicular** to velocity contours
Kinematic Minor Axis (KMI): V_{los} contour at V_{sys} through the nucleus

These spider diagrams reveal much about the detailed form of the disk velocity field:

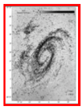
- **Circular velocity** in an inclined circular disk: [image]
  KMA aligned with photometric major axis (PMA)
  KMI aligned with photometric minor axis (PMI)



- **Flat** V(r) (beyond initial rise) gives:
  V_{los} contours are approximately **radial** at large R
  If V(r) **declines** past V_{max}, then V_{los} contours close in a loop.
- **Solid body** i.e. $V_c(r) \propto r$ in near-nuclear regions, gives:
  equally spaced contours across nuclear KMA, with spacing $\propto$ 1/slope
- **Warped** disks have: [image]
  Twisted V_{los} contours in outer parts
  Note: model galaxies as a set of rings with different V(r), PA(r), i(r)



- **Bars** often show:
  evidence of **radial motion** over bar region
- **Oval disks** (e.g. arising from non-axisymmetric halo)
  KMI and KMA not perpendicular
  KMA not aligned with PMA, and KMI not aligned with PMI
- **Spiral arms** yield: [image]
  small perturbations to V_{los} contours near arm positions



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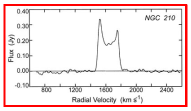
(5) Scaling Relations

There are a number of correlations between the global parameters of galaxies:
Luminosity; Size; Surface Brightness; Rotation Velocity;
Such relations are called "Scaling Relations".
They are important for several reasons:
They reveal the internal properties of galaxies
They must arise naturally in theories of galaxy formation.

In the case of disk galaxies, the most important is between V_{rot} and Luminosity:

(a) V_{max} and the Tully-Fisher Relation



- V_{max} = maximum rotation velocity (inclination corrected), derived from: [image]
  - Major axis optical (often Hα) rotation curves (**half** the full amplitude)
  - HI 21 cm integrated (single dish) profile width, W_{20}: $W_{20} / \sin i \;=\; 2V_{max}$

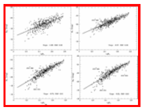
- Tully & Fisher (1977) recognised that V_{max} correlates with galaxy luminosity
  - $L \;\propto V_{max}{}^{\alpha} \quad \alpha \sim 3 - 4$

- As for the Faber-Jackson relation, the T-F relation stems from virial equilibrium:

  $V_c{}^2 \propto M/R$ and $L \propto I(0)\, R^2$

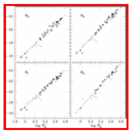
  $\rightarrow L \propto (M/L)^{-2}\, I(0)^{-1}\, V_c{}^4$

  $\rightarrow$ T-F relation holds if $(M/L)^{-2}\, I(0)^{-1} \sim$ const (roughly true)



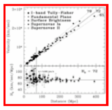
- Usually, choose **longer** wavelengths (eg I & H bands rather than B & V): [image]
  - smaller scatter on the T-F relation, and slightly steeper gradient (α larger)

  This is because, at ~1-2μm :
  - $L_{1\mu}$ is less sensitive to star formation and dust
  - $L_{1\mu}$ tracks older population which dominates mass and has a more homogeneous M/L ratio



- The T-F relation is one of the key methods of **distance determination**
  - First calibrate on nearby galaxies with Cepheid distances [image]
    this yields the following relations :

$$\begin{aligned} M_B^{0,i} &= -7.41\ (\log W_R^i - 2.5) - 20.04\ \pm 0.04 \\ M_R^{0,i} &= -8.09\ (\log W_R^i - 2.5) - 21.05\ \pm 0.04 \\ M_I^{0,i} &= -8.55\ (\log W_R^i - 2.5) - 21.51\ \pm 0.04 \\ M_H^{0,i} &= -10.39\ (\log W_R^i - 2.5) - 22.22\ \pm 0.08 \end{aligned} \tag{5.5}$$



  - Then for more distant galaxies, measure V, inclination, and apparent magnitude:
    V_{max} and TF relation gives M, which gives m - M, which gives <u>distance</u>.
  - These greater distances can now be used with redshifts to derive H_o [image]

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(6) Mass Estimates and Dark Matter Halos

(a) Deriving M(r) from V_c(r)

For centrifugally supported circular motion, V_c(r) yields the mass distributions.
In general (**not** assuming spherical symmetry):

$$M(<r) \;=\; \beta\, \frac{R V_c^2(r)}{G} \tag{5.6}$$

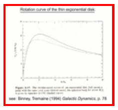
where β is a geometry factor $0.7 < \beta < 1.2$
Sphere: $\beta \;=\; 1.0$, Flattened : $\beta \;\sim\; 0.7$

For an exponential, thin disk, one can show that :

$$\boxed{\begin{aligned} V_c^2(R) &= R\frac{\partial\Phi}{\partial R} \\ &= 2\frac{GM_d}{R_d}y^2\left[I_0(y)K_0(y)-I_1(y)K_1(y)\right] \quad \left(y=\frac{R}{2R_d}\right) \\ &\simeq 0.767\,\frac{GM_d}{R_d}\,\frac{0.44(R/R_d)^{1.3}}{1+0.235(R/R_d)^{2.3}} \qquad R<4R_d \end{aligned}} \tag{5.7}$$

Where I_n and K_n are modified Bessel functions of the first and second kind.

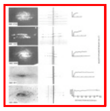
This rotation curve has peak: V_{max} at $R_{max} \sim 2.2\ R_d$ [image]
for $R\ >\ 3\ R_{max}$ $V_c(R)$ falls $\sim R^{-½}$ (Keplerian)



see: Binney, Tremaine (1994) *Galactic Dynamics*, p. 78

(b) Results from Optical Rotation Curves

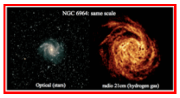
- 1960s (Burbidge's) gathered Hα rotation curves and **assumed** Keplerian fall-off beyond their data.
  → quote well defined galaxy "masses"
- 1970s & 80s (Rubin et al) went deeper : **~ flat** out to ~ 2 - 3 R_d [image]
  → conclude dark matter (**careful** : exponential disk still ~flat here)



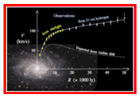
- Kent (1986) images **same** galaxies and derives rotation curves directly from light profile
  they **match** the observed rotation curves !
  → dark matter **not required**; bulge + disk with normal M/L suffices

(c) Results from HI mapping

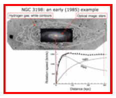
- Fortunately, HI extends **well beyond** the optical disk [image]
  while Hα goes to 2-3 R_d (~0.75 R_{25}), HI often goes to > 5 R_d



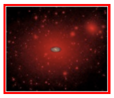
- V_{rot} rarely declines; still flat or rising **well beyond the disk** [image]
  It is necessary to invoke an invisible **halo**
  Since $\Phi = \Phi_d + \Phi_h$ and $V_c^2 = r\ d\Phi/dr$, then:
  $V_c^2 = V_d^2 + V_h^2$
  Use the observed rotation, V_c, and the (predicted) disk rotation, V_d, to
  → infer the halo contribution, V_h, and its potential.



- Typically, bulge + disk accounts for inner rotation curve with reasonable $M/L_B \sim 3 - 5$
  If this is forced to fit the inner rotation, it is a called "maximum disk" model
  Dark matter **halo** needed at larger radii, giving total $M/L_B \sim 30$
  → ~5 times more dark matter than normal matter in stars + gas
  This is a **lower limit** since V_{rot} still constant/rising!
- Historically important paper: van Albada et al (1985) analysis of NGC 3198 : [image]



- It is now generally accepted that galaxies reside within large halos of dark matter. [image]



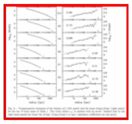
(d) Dark Matter Halo Structure

- At largest measured radii V_{rot} is ~flat, so $\rho(r)\ \sim\ r^{-2}$ in this region
  Unknown beyond this, but must drop faster to keep total mass finite.
- Difficult to constrain the **inner** parts
  Bulge + "maximum disk" fits yield plausible M/L (~ 3-5), suggesting DM not important here
  Halo contribution clearly drops at small radii, but functional form not well constrained.
- N-body codes which follow hierarchical assembly of DM halos yield a particular form:
  The Navarro-Frenk-White (NFW) 2-parameter broken power-law profile:

$$\boxed{\rho(r) = \frac{\rho_0}{(r/a)(1+r/a)^2}} \tag{5.8}$$

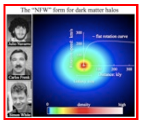
This has $\rho(r) \sim r^{-1}$ in the center and $\rho(r) \sim r^{-3}$ at r >> a.

Or a slightly better 3-parameter fit is the "Einasto Profile": [image]



$$\boxed{\begin{aligned}\rho(r) &= \rho_0 \exp[-d_n (r/r_e)^{1/n}] \\ &= \rho_e \exp[-d_n [(r/r_e)^{1/n} - 1]\,]\end{aligned}} \qquad (5.9)$$

In this case, $d_n \approx 3n - 1/3 + 0.0079/n$, ensures that r_e contains half the total mass.
n ~ 7 → 4, decreasing systematically with halo mass (cluster → galaxy halos).
[See Merritt et al (2006 o-link) for a detailed discussion of halo fitting functions]



Both these give rotation curves that rise to a peak and slowly decline [image]
They are approximately flat in the regions measured by optical or HI rotation curves.

(e) Disk-Halo Conspiracy

There is an intriguing property of these rotation curves:

- After a rapid rise, most rotation curves are ~flat **at all radii** :
  - → in regions where V_c is determined by disk matter, **and**
  - → in regions where V_c is determined by dark matter
- How do these two **different** regions know they should have the **same** rotation amplitude ??
- This is not currently understood, but indicates something important about galaxy formation

- Notice that a related puzzle also underlies the Tully-Fisher relation
  V_{max} is set by the halo, while
  M_I is set by the luminous matter
- Indeed, the theoretical origin of the TF relation is not yet fully understood.

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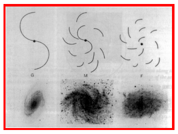
(7) Spiral and Bar Structures

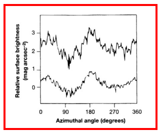
(a) Spirals

(i) Spiral Classes



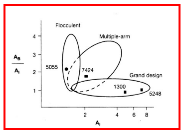
- recall, two types (extremes) of spiral structure [image]
  - Grand Design (AC 12), two strong arms (~10%)
  - Flocculent (AC 1), more chaotic (~90%)
  - Multiple Arm (intermediate), strong inner arms, outer ratty

(ii) Arm Prominence



- Arm / Inter-arm contrast is useful [image]
  - for contrast Δm magnitudes (typically 1-2 in B), define A = dex(0.4 Δm)

- A depends on color:
  - Grand Design : $A_B \sim A_I \sim$ large (1.5 - 8)
  - Flocculent : $A_B >> A_I \sim 1.0$
    → a plot of A_B / A_I vs A_I separates the classes well. [image]

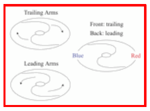


- Clearly:
  - spiral arms are **bluer** than the underlying (red) disk
  - sprial arms are **younger** than the disk
  - the old disk in Grand design has **spiral pattern**
  - the old disk in flocculents is **uniform**

- Interpretation:
  - Grand design is a **density wave**: it involves a spiral in the underlying mass distribution
    global coherence implies **global** process generates structure

  - Flocculent spirals are **not** density waves
    lack of coherence implies **local** process generates structure

(iii) Leading or Trailing ?

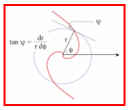


- Consider orientation of spiral w.r.t. direction of disk rotation: [image]
  - arm ends point **forward** → **leading** spiral
  - arm ends point **backwards** → **trailing** spiral

- To decide: need to know which side is nearest:
  - Difficult, but try to identify the least obscured by dust (near side)
    → arms are almost always **trailing**

- Many arms have dust lanes & HII regions on **inside** (concave) edge
  → gas runs into arms on concave side; compressed; star formation
  → HI and CO distribution is narrow and focussed on inner edge [image]

(iv) Pitch Angle



- ψ Defined as the angle between the tangents of arm and circle [image]
  e.g. tight spiral has **small** ψ
  clearly: $\tan\psi = dr / r\,d\phi$ (where ϕ is azimuth)

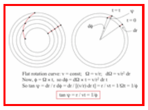
- Most spirals have $\psi \sim$ const throughout disk
  → logarithmic spiral : $r(\phi) = r_o \exp[(\phi - \phi_o) \tan\psi]$
  with $r = r_o$ at ϕ_o

- This is, in fact, predicted by density wave theory.

(v) The Winding Problem

- If arms were "fixed" w.r.t. the disk (e.g. like leaves on water)
  With flat rotation (V ~ const), inner parts rotate many times compared to outer parts
  E.g. for one rotation at R, two rotations at R/2, four at R/4, 8 at R/8.
  This leads to very tightly wound arms.

  More precisely: with $\Omega = V_c / R$ and V_c = constant we find [image]



  $$\tan\psi = R / V t = 1 / \Omega t = 1 / \phi$$
  so after 1 rotation: $\tan\psi = 1 / 2\pi$ or $\psi = 9°$; after 2 rotations: $\psi \sim 4.5°$.
  This quickly becomes a **very tight** spiral in which ψ **decreases** with radius

- In reality: for Sa: $< \psi > \sim 5°$; for Sc: $< \psi > \sim 10°$-$30°$
  This suggests we might have two types of condition

- **Long lived** spiral arms are **not** material features in the disk
  they are a **pattern**, through which stars and gas move
  these might be the grand design spirals

- **Short lived** spiral arms can arise from temporary patches pulled out by differential rotation
  the patches might arise from **local** disk instabilities, leading to star formation
  these might be the flocculent spirals

(b) Bars

- Barred galaxies are common (~50%): [image]

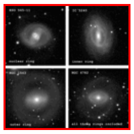
- Isophotes not fit by ellipses; more **rectangular**
  Probably **flat** in disk plane
  K (2.2μm) images can show bars within bars (inner bar ~independent)

- Bars are **straight**, and stars **stay in the bar** → rigid rotation of pattern with well defined Ω_b
  Bars are **not** density waves:
  Stars **move along the bar** on closed orbits in frame rotating at Ω_b

Such orbits only occur for $\Omega_b < \Omega_{stars} \rightarrow$ bars occur **inside co-rotation** (CR)

Bars can drive a density wave in disk → helps maintain spiral structure.

- **Gas motions** important and interesting :
  <u>Observations</u>:
    Star formation occurs at bar ends
    Dust lanes seen down leading edge of bar
    Velocity fields suggest strong non-circular motion, including radial inflow.
  <u>Simulations</u> :
    Orbits mildly self-intersecting → weak shocks → compression where dust lanes seen
    Inner gas loses angular momentum and **moves inwards**
    May collect in disk/ring near ILR, or continue to fuel AGN & build black hole mass.
    Outer gas stored in **ring** near bar ends (CR)
    Gas beyond the bar can be stored in an outer ring at OLR
    → may explain inner and outer rings seen in many barred galaxies [image]



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