Whittle : EXTRAGALACTIC ASTRONOMY

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 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

- **Disks :**
  metal rich stars and ISM
  nearly circular orbits with little (~5%) random motion
  spiral patterns

- **Bulge :**
  metal poor to super-rich stars
  high stellar densities with steep profile
  V(rot)/σ ~ 1
- **Bar :**
  long lived, flat, linear distribution of stars
  associated dust lanes and star formation
  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
  metal poor stars, GCs, dwarfs, low-density hot gas
  little/no rotation
- **Dark Halo :**
  dominates mass (and potential) outside ~10 kpc
  mildly flattened &/or triaxial
  nature unknown

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(2) 3-D Shapes

(a) Disks

- Distribution of (projected) b/a : [images]
  ~ flat over wide range, from 0.3 to 0.8
  rapid rise from zero at b/a ~ 0.1 to max at b/a ~ 0.3
  rapid fall from max at b/a ~ 0.8 to about 0.5 at b/a = 1

- 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 : much slower rise for S0s (bigger bulges)
    much faster rise for Scs (smaller bulge)
  - minimum for bulgeless Sdm : b/a ~ 0.05 - 0.1
    → disks can be highly flattened
  - drop at high b/a ~ 0.8 caused by non-circular disks
    more careful analysis confirms this, and suggests :
    → dark matter potentials slightly oblate/triaxial
    $< \epsilon(\Phi) > \sim 0.045$ with range $\sigma \sim 0.025$

- Warps :
  - starlight almost always flat (if undisturbed)
  - however, HI is often **warped** (either visibly or kinematically inferred)
  - 180 degree symmetry : "integral sign", with warp starting between R_{25} and R_H
  - 75% of warped galaxies have **no** significant companion
  - origin poorly understood (see B&T § 6.6) :
    self-sustaining bending modes dont seem viable
    probably response to halo potential misaligned with disk
    example of warp : NGC 4013

(b) Bulges

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

- probably similar to low-luminosity ellipticals
- $0 < \epsilon < 0.7$
- ~ oblate spheroids, flattened by rotation
- ~ 25% have very boxy isophotes
  $\rightarrow$ "peanut" (double lobed) shape (unshelled !)
  however, this may also be associated with presence of a bar

(c) Bars

- axis ratios plane range from 2.5 to 5.
- isophote twists suggest nested bars common : bars within bars
- are probably **flat**, since they aren't visible in edge-on spirals
- however, "peanut" bulges may in fact be bars seen edge-on
  note : theory suggests flat bars are unstable

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(3) Surface Photometry

Two components : bulge and disk
Typically, use $R^{1/4}$ plus exponential fits to : [images]

- 1-D elliptically-azimuthally averaged light profile
- 2-D image
  this is better, since bulge & disk have different ellipticities

Note : it is important to fit **both** together, since $R^{1/4}$ still contributes at large R, under the disk.
An exponential fit alone to the outer parts yields a **steeper** profile.

(a) Radial Profiles

(i) Bulge

as for ellipticals, we have :

$$I(R) = I_e \, exp\left(-b \left[(R/R_e)^{1/n} - 1 \right]\right) \quad (5.1)$$

where

- R_e contains half the light
- $L_{tot} = 7.22 \pi R_e^2 I_e$
- $I(0) = 2000 I_e$
- $R_e \sim 0.5 - 4$ kpc (larger for early Hubble types)
- Bulges follow the 2 & 3 parameter relations for ellipticals
  eg I_e decreases for R_e increasing

(ii) Disk

A simple exponential fits well :

$$I(R) \;=\; I_0 \, exp\,(-R/R_d) \qquad (\text{for } \; R < R_{max}) \tag{5.2}$$

where

- equivalently : $\sigma(R) = \sigma_o + 1.086\ R/R_d$ (in terms of mag/ss)
- 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
- $R_d > R_e$ always (eg MW : $R_d \sim 5$ kpc, $R_e \sim 2.7$ kpc)
- $L_{tot} = 2\ \pi\ R_d^2\ I(0)$
- In practice, disk light falls sharply beyond $R_{max} \sim 3 - 5\ R_d$
- analogous relations to bulges : ie I_d decreases as R_d increases
  ie larger disks have, statistically, **lower** surface brightness
- $I_B(0) \sim 21.65$ +/-± 0.3 mag/ss (Freeman 1970, "Law" of ~const I(0) for all spirals)
  However, low Surface Brightness (LSB) galaxies have now been discovered (**figure**)
  Freeman "Law" is now thought to be largely a selection effect (**figure**)

(iii) Bulge to Disk Ratio

Integrating the $R^{1/4}$ and exponential laws gives flux ratios :

- $B/D = 3.57\ (R_e/R_d)^2\ (I_e/I_d)$
  or, equivalently
- $B/T = R_e^2 I_e\ /\ (R_e^2 I_e + 0.28\ R_d^2 I_d\ )$
  where $I_e = I(R_e)$ for the bulge component only
  where $I_d = I(R_d)$ for the disk component only
- along the Hubble sequence, B/D decreases monotonically

Type	**< B / T >**	**< D / B >**
E	1.0	0.0
S0	0.57	0.7
Sa	0.39	1.5
Sab	0.32	2
Sb	0.24	3
Sbc	0.16	5
Sc	0.10	10
Scd	0.05	20
Sd	0.02	50

the data are presented here

Note there is considerable scatter :
some is intrinsic but much depends on fitting method

(b) Vertical Disk Structure

Study edge on disks (eg figure of Sd)
Two forms have been used :

$$I(z) = I(0)\ exp\,(-|z|/z_o) \tag{5.3a}$$

$$I(z) = I(0)\ sech^2\,(-|z|/2z_o) \tag{5.3b}$$

recall, sech(z) = 2 / [exp(z) + exp(-z)]

- z_o is the **scale height** of the disk, ie $I(z_o) = 1/e\ I(0)$
  (see 4d(ii) below for further discussion of vertical disk structure)

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(4) Disk Velocity Field

In general, self-gravitating systems are supported by both **rotation** and **dispersion**
Disks are **cold** (low dispersion) so $V_{rot} \sim V_c$, where V_c = ideal circular velocity
Note : V_c (& geometry) yeild M(< R) unambiguously
$\rightarrow$ disk rotation is a very important probe of M(R)

(a) 2-D Velocity Fields : Spider Diagrams

Consider circular rotation $V_c(r)$ in a planar circular disk
disk tilted by angle i to los (i=0 : pole on)
the major axis of the projected ellipse is the **line of nodes**

In projected (sky) plane : s, α = distance to nuc; angle from major axis
In unprojected (galaxy) plane : r, θ = equivalent location
For measured Doppler velocity field : $V_{los}(s,\alpha)$, we have

$$V_c(r,\theta) = \frac{V_{los}(s,\alpha)\ \sqrt{\cos^2 i + \tan^2 \alpha}}{\sin i \cos i} \tag{5.4a}$$

with $\tan\theta = \tan\alpha / \cos i$ and $r = s\,(1 + \sin^2\alpha \tan^2 i)^{1/2}$

Conversely, if we want to project $V_c(r,\theta)$ onto the sky, we have

$$V_{los}(s,\alpha) = V_c(r)\ \cos\theta \sin i \tag{5.4b}$$

with $\tan \alpha = \tan \theta \cos i$ and $s = r (\cos^2\theta + \sin^2\theta \cos^2 i)^{1/2}$

Contours of V_{los} on the projected disk give a "spider diagram" [images]
Kinematic Major Axis (KMA) : line through nucleus **perpendicular** to velocity contours
Kinematic Minor Axis (KMI) : V_{los} contour at V_{sys} through the nucleus

There are various forms for $V_{los}(s,\alpha)$:

- Circular velocity in inclined plane :
  KMA aligned with photometric major axis (PMA)
  KMI aligned with photometric minor axis (PMI)
- if V(r) is approximately **flat** (ie indep of r beyond initial rise)
  V_{los} contours approx radial at large R
  V_{los} contours close in loop if V(r) declines past V_{max}
- solid body nuclear rise in $V_c(r)$
  equally spaced contours across nuclear KMA, spacing $\propto$ 1/slope
- if disk is **warped**
  twisted V_{los} contours in outer parts
- Bars
  evidence of **radial motion** over bar region
- oval disk (eg defined by non-axisymmetric halo)
  KMI and KMA not perpendicular
  KMA not aligned with PMA
  KMI not aligned with PMI
- spiral arms
  small perturbations to V_{los} contours near arm positions (viewgraph)

Full datasets can be analysed as a set of independent rings, each with different V_c, PA, i [images]
Eg : here is an analysis of the circinus galaxy (Jones et al 2001) :
HI intensity, velocity and dispersion maps
inferred run of V(r), PA(r), i(r)
3-D model of warped disk

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

V_{max} = maximum rotation velocity (inclination corrected), derived from :

- Major axis optical (often Hα) rotation curves (**figure**)
- HI 21 cm integrated (single dish) profile width, W_{20} (**figure**)

$$2V_{max} = (W_{20} - W_{disp}) / \sin i$$

where $W_{disp} = 3.6\, \sigma_{HI}$ and $\sigma_{HI} \sim 10$ km/s = random component
and $\cos i = [(b/a)^2 - u^2] / (1 - u^2)$ where u is b/a for edge-on system (defines i)

Tully & Fisher (1977) recognised that V_{max} correlates with galaxy luminosity

- $L \propto V_{max}^{\alpha}$ $\alpha \sim 3 - 4$

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

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

→ 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)

- smaller scatter on the T-F relation
- slightly steeper gradient (α larger) (**figure**)

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
- this population has a more homogeneous M/L ratio

The T-F relation is one of the key methods of distance determination

- first calibrate on galaxies with Cepheid distances (**figure**)
  this yields the following relations :

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

- then : V_{max} → M → m - M → distance
- these distances can then be used with redshifts to derive H_o
  eg this figure yields H_o = 80 km/s/Mpc
  (here is a simple cartoon illustrating the TF relation)

(c) Rotation Curve Shapes and Systematics

Typical rotation curve comprises

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

Many rotation curves have now been measured (**figure**)
Some systematic trends are noticable :

(i) At Large Radius

- V_{max} increases as L increases (T-F relation)[images]
- R_{max} increases as L decreases (slower rising curves)
- R_{max} increases as T increases (later Hubble types)
- outer slope increases as L decreases (viewgraph)
  for $V(r) \propto R^{\delta}$ we find δ in the range -0.2 to 0.2

specifically :

$10^{½\delta}$ = $[2.32 + 0.096(M_B + 21.5)] / [2.056 - 0.11(M_B + 21.5)]$

flat ($\delta = 0$) occurs for $M_B \sim -22.5$

- drop in massive early types caused, in part, by high V_{max} from bulge
- Galaxies in dense environments have **falling** V(r)
  → consistent with removing/disturbing some of the halo
- Galaxies in dense environments have high fraction of anomalies in V(r)
  asymmetries across nucleus
  dips in disk region and inner peculiarities
  → consistent with tidal disturbance

(ii) At Small Radius

- For luminous early type spirals, V(r) rises very rapidly (often **unresolved**)
  dense bulge core (& black hole ?)
  cf Milky Way rotation curve : figure
- for low luminosity later type spirals, V(r) rises more slowly
  slow rise often : $V(r) \propto r$ → "solid body"
  careful, however : sometimes, when V(r) drops, $\sigma(r)$ **increases**
  so V(r) is **not** V_c (ie rotation and dispersion **both** provide support)
  in general : $V(r) < V_c(r)$ (this is called **asymmetric drift**)

(d) Stellar Velocities in the Disk

Disks are **faint** → stellar LOSVD 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

sometimes, star rotation can be **slower** than 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 [images]
< 10% spirals may even have two counter-rotating **stellar** disks (figure)

→ both indicate external origin postdating galaxy formation

(ii) Dispersion

Face-on galaxies yield σ_z : the vertical stellar dispersion

- measurements indicate σ_z decreases exponentially with scale length $2R_d$
  this agrees with simple theory :
  stellar dynamics for isothermal disk gives $\sigma_z^2 = 2 \pi G z_o \zeta$
  where ζ is the **surface** mass density and z_o is the scale height
  hence $\sigma_z \propto \zeta^{½} \propto I(r)^{½} \propto \exp(-R/2R_d)$, as found.
- combining major and minor axis observations of σ_{los} yields σ_z σ_ϕ σ_r

for NGC 488 we find ratios σ_z : σ_ϕ : σ_r = 0.7 : 0.8 : 1.0
which is similar to the velocity ellipsoid in the solar neighborhood.

- consider, now, the interdependence of σ_z and the vertical density distribution
  for an **isothermal** disk (σ_z = const) stellar dynamics gives :
  → **volume** density $\rho(z) = \rho(0)\ \mathrm{sech}^2(z/2z_o)$
  which nicely fits the observed light distribution (cf Eq 6.3b)
  we also find for the scale height : $z_o^2 = \sigma_z^2 / 8 \pi G \rho(0)$
  so we can use measured values of σ_z and z_o to calculate $\rho(0)$
  → dark matter **doesn't** dominate in the MW disk near the sun
- turning now to consider the **exponential** vertical law (Eq 6.3a)
  this in fact fits edge on galaxies better at 2μm
  for $\rho(z) = \rho(0) \exp(-|z| / z_o)$ stellar dynamics gives :
  $\sigma_z^2 = 4 \pi G \rho(0) z_o^2 [1 - ½ \exp(-z/z_o)]$
  → for $z >> z_o$ we recover an isothermal distribution : σ_z = const
  plane, z = 0, we have : $\sigma_z(0) \sim \sigma_z(\mathrm{high}) / \mathrm{sqrt}(2)$
  → disk plane is **cooler** than above by a factor sqrt(2)

Returning to compare with observations of the Milky Way :

- there are several components of different z_o and σ_z
  - 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
- we may view this as either
  - superposition of several isothermal components
  - cooler nearer the equatorial plane
- the astrophysical origin of this is thought to be :
  - σ_z increases with **age**
  - stars born "cold" from molecular clouds
    dissipation ensures $\sigma_z \sim$ sound speed and z_o is correspondingly small
  - stars gradually "heated" by scattering off DMCs and spiral arms

  or...
  - heating of the disk over time by satellite passage and/or minor mergers
- Here is a MW disk model : red=young stars; blue=gas; green=old stars; black=total

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(5) Mass Estimates and Dark Matter Halos

$V_c(r)$ gives important and unambiguous access to mass distributions

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

In general :

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

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 :

$$V_c^2(r) \simeq 0.767 \frac{GM}{R_d} \frac{0.44(R/R_d)^{1.3}}{1+0.235(R/R_d)^{2.3}} \qquad R < 4R_d \tag{5.7}$$

This has peak : V_{max} at $R_{max} \sim 2.2\ R_d$

for $R > 3\ R_{max}$ $V_c(R)$ falls $\sim R^{-1/2}$ (Keplerian)

This figure shows $V_c(R)$ for exp disk, point mass, and sphere [all with same $M(<R_d)$]

(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 (figure)
  → 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
  while Hα goes to 2-3 R_d (~0.75 R_{25}), HI often goes to > 5 R_d (~1.5 R_H)
- V_{rot} **rarely** declines; still flat or **rising** well beyond the disk (sometimes out to 50-100kpc !)
- fits to V_{rot} **must** have dark matter, especially in outer regions (eg beyond ~1% sky)
- Typically, bulge + disk accounts for inner rotation curve (see above) with reasonable $M/L_B \sim 3 - 5$
- dark matter **halo** needed, giving total $M/L_B \sim 30$
  → in general, 5 times more Dark Matter than mass in stars + gas
- still only a **lower limit** since $V_{rot} \sim$ const implies $M(<R) \propto R$
  → currently, Dark Matter Halos have **divergent** masses

- Nice example from van Albada et al (1985) :
  image of NGC 3198 with HI distribution
  rotation curve of NGC 3198 with disk + halo fit
  abstract of paper summarizing results

(d) Dark Matter Halo Structure

- obviously, $\rho(r) \propto r^{-2}$ at **large** radii (since V_{rot} is flat)
- unfortunately, difficult to constrain the **inner** parts
  usually, bulge & disk are made to fit inner V_{rot} (the "maximum" disk fit)
  this still only yields a modest M/L (~ 3-5), suggesting DM not important here
  clearly, the halo contribution drops at small radii, but functional form not known

- simple model assumes "isothermal" sphere with a core :

$$\rho_0$$

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

which has the correct asymptotic behaviour for r >> a : $\rho(r) \propto r^{-2}$
integrating the mass profile gives a rotation curve :

$$V_c(r) = \sqrt{4\pi G \rho_0 a^2 \left(1 - \frac{a}{r}\arctan\frac{r}{a}\right)} \quad (5.9)$$

which has : V_c = sqrt[4 π G ρ(0) a^2] for r >> a

and V_c = sqrt[4/3 π G ρ(0) a^2] × (r/a) for r << a

Here is a model halo with a core radius of 1 kpc : **figure**

(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

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(6) 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
  - for contrast δm magnitudes (typically 1-2 in B), define A = dex(0.4 δm)
  - (note : arms poorly visible in azimuthally averaged radial profile)

- A depends on color :
  - Grand Design : A_B ~ A_I ~ large (1.5 - 8)
  - Flocculent : A_B >> A_I ~ 1.0

→ a plot of A_B / A_I vs A_I separates the classes well.

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

- 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 direction of rotation :
  - 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]

- trailing arms exert a torque on the disk : matter inwards, AM outwards
  rotation energy transferred into random motions (disk heats)
  this would halt arm formation (see below), but.....
  new stars form from "cold" gas, so disk kept unstable to arm formation
  note : S0 galaxies have no arms : no gas to keep disk "cool"
  → gas is necessary to the formation of spiral arms

(iv) Pitch Angle

- ψ defined as the angle between the tangents of arm and circle
  eg tight spiral has **small** ψ
  clearly : $\tan\psi = dr / r\, d\phi$ (where ϕ is azimuth)

- Most spirals have ψ ~ 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 (eg like leaves on water)
  → for typical V_c ~ const, so $\omega \propto R^{-1}$ and we predict **very tight** spiral (ψ ~ 2°)
  eg two points at R and R+dR are separated azimuthally after time dt by Vdtdr/R
  so $\tan\psi$ = R/(Vdt) and taking V = 200 km/s, R = 8 kpc, dt = 1Gyr we have
  $\tan\psi \sim \psi$ ~ 8/200 ~ 2° (¼° for 8Gyr)

- in reality : for Sa : $\langle\psi\rangle \sim 5°$; for Sc : $\langle\psi\rangle \sim 10°-30°$

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%)
  NGC 1300 is a nice example : **figure**

- axis ratio up to 1:5
  they can be **strong** : up to ~30% of the galaxy light
  not fit by elliptical isophotes --- more rectangular
  probably flat in disk plane
  K (2.2μm) images can show bars within bars (inner bar ~independent)

- light profile : I(R) along bar :
  Early Hubble types and Grand design :
  $\rightarrow$ I(R) ~ const; strong bar; helps drive spiral pattern
  Later Hubble types and Flocculant :
  $\rightarrow$ I(R) exponential [R_d(bar) ~ R_d(disk)]; weaker bar

- Bars are **straight** $\rightarrow$ rigid rotation of pattern with well defined ω_b
  stars **stay in the bar** --- bars are **not** density waves
  closed orbits in frame rotating at ω_b
  stars move **along** the bar (in the rotating frame)
  such orbits only occur for $\omega_b < \omega_{stars}$ [= $V_c(r) / r$]
  $\rightarrow$ bars dont extend beyond **co-rotation** (CR)
  (typically they extend out to ~80% of CR)

- <u>simulations</u> suggest bars form (too!) easily (see Topic 8) :
  they are long lived
  they slow with age & lengthen (CR moves out as ω_b drops)
  angular momentum is transferred to disk and halo stars :
  $\rightarrow$ bars may be important in long term AM redistribution in galaxies
  $\rightarrow$ bars can drive density wave in disk

- gas motions important and interesting :
  <u>observationally</u> :
  star formation occurs at bar ends
  dust lanes seen down leading edge of bar
  velocity fields suggest strong non-circular motion
  <u>simulations</u> :
  orbits mildly self-intersecting >> weak shocks >> compression where dust lanes seen
  inner gas loses AM and goes inwards
  this gas may go to the nucleus (feed AGN?), or collect in disk near ILR
  outer gas in bar stored in **ring** near bar ends (CR)
  gas beyond this is stored in ring at OLR
  $\rightarrow$ may explain inner and outer rings seen in many barred galaxies

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