Physics of Galaxies, 2015
10 credits
Lecture 4: Disks and ellipticals

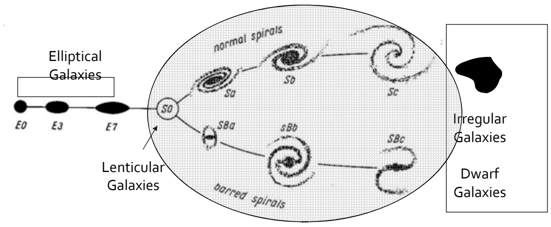
Outline I

- Disk galaxies
  - Surface brightness profiles
  - Stars and gas
  - Rotation curves
  - The Tully-Fisher relation
  - Spirals and bars

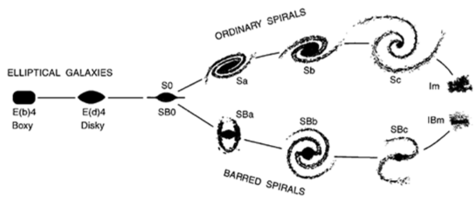
Outline II

- Elliptical galaxies
  - Surface Brightness Profiles
  - Stars
  - cD-Galaxies
  - Triaxiality
  - Stellar Motions
  - The Faber-Jackson Relation
  - Masses

Recall the Hubble Tuning Fork

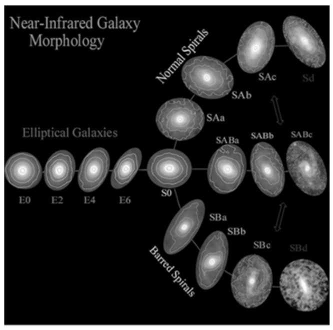


Alternative version: More elliptical subclasses



Kormendy & Bender (1996)
Featured in Schneider's book

Alternative version: More spiral subclasses



Disk galaxies

- Sequence:

  S0-Sa-Sb-Sc-Sd-Sm

  SB0-SBa-SBb-SBc-SBd-SBm

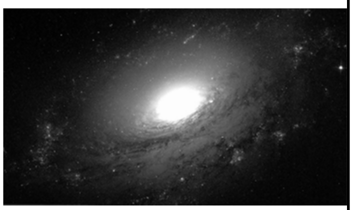
  Early-type disks Late-type disks

- Outside the original Hubble Tuning fork:
  - Sd-galaxies: Bulgeless disks
  - Sm-galaxies: Magellanic spirals (almost irregular, prototype LMC)

Disk galaxies

	S0-Sa	Sd-Sm
Spiral arms:	Absent or tight	Open spiral
Bulges:	Big	Small
Color (B-V):	Red (0.7-0.9)	Blue (0.4-0.8)
Young stars:	Few	Many
HII-regions:	Few, faint	Many, bright
Surface brightness:	High	Low
Mass:	High	Low
Rotation:	Fast rising	Slow rising

Intermission: Which of these disks is the most "early-type"?



Surface Brightness

$$\alpha \approx \frac{D}{d}$$

Size of object

Distance to object

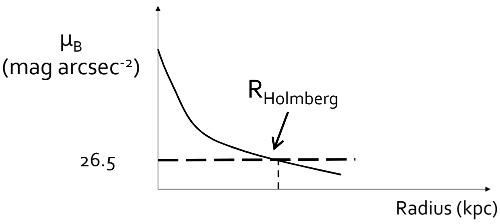
$$I(r) = \frac{F}{\alpha^2} = \frac{L/4\pi d^2}{D^2/d^2} = \frac{L}{4\pi D^2}$$

$$\mu(r) \propto -2.5\log_{10} I(r)$$

- *I(r)* usually $L_\odot$ kpc^{-2}, but *μ(r)* in mag arcsec^{-2}
- Determines observability of extended objects (e.g. galaxies)
- *I(x)* independent of distance(!) in local universe…
- … but subject to factor $(1+z)^{-4}$ of redshift dimming → One reason why high-redshift objects are extremely difficult to detect

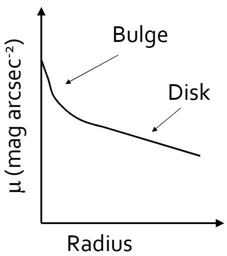
Surface Brightness

- Sizes of galaxies often given out to a specified isophote:
  - R_{25}: Radius at 25 mag arcsec^{-2} in B-band
  - Holmberg radius: Radius at 26.5 mag arcsec^{-2} in B-band



Surface Brightness Profiles I

Isophotes
(constant surface brightness)



Surface Brightness Profiles II

- Radial direction — Sérsic formula:

$$I(R) = I(0)\exp\left(-(R/h_{\mathrm{R}})^{1/n}\right)$$

h_R: Scale length
$I(0)$: Central surface brightness
n=4 → de Vaucoleur formula (for bulges & ellipticals)
n=1 → Exponential disk (for the disks of disk galaxies)

Surface Brightness Profiles III

- Profiles of exponential disks (n=1):

$$I(R) = I(0)\exp\left(-R/h_{\mathrm{R}}\right) \quad (L_{\odot}\ \mathrm{kpc}^{-2})$$

- Alternative formulation (3.14 in Schneider):

$$\mu(R) = \mu_0 + 1.09\frac{R}{h_{\mathrm{R}}} \quad (\mathrm{mag\ arcsec}^{-2})$$

μ_o: central surface brightness

Surface Brightness Profiles IV

- Alternative formulation of Sérsic formula (3.39 in Schneider)

$$I(R) = I_{\mathrm{e}}\exp\left(-b_n\left[(R/R_{\mathrm{e}})^{1/n} - 1\right]\right)$$

R_e: effective radius
(radius inside which half of the light is emitted)
I_e: Surface brightness at R_e
b_n: coefficient given by $b_n \approx 1.999n$-0.327

Stars and Spectra of Disk Galaxies

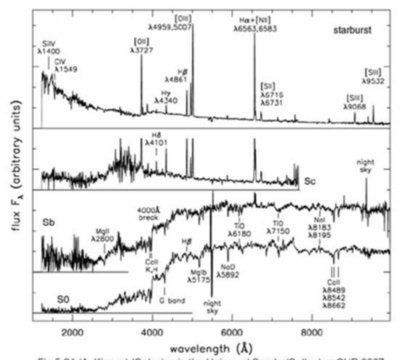
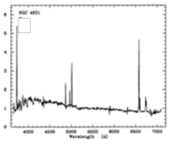
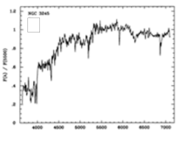


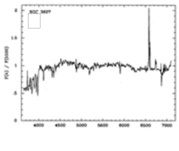
Fig 5.24 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

- Sc: Young stars
- So: Old stars

Intermission:
Order these disk-galaxy spectra from early-type to late-type


A


B


C

Neutral hydrogen

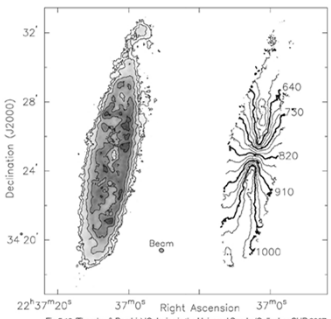


Fig 5.13 (Thornley & Bambic) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Neutral hydrogen

- Flux in 21 cm line → HI mass:

$$\frac{M(\mathrm{HI})}{M_{\mathrm{solar}}} = 2.356\times10^{5} D^{2} \underbrace{\int F_{\nu}\, dV_{r}}_{\text{Integration over line profile}}$$

Distance
In Mpc

Molecular hydrogen

- H_2 most abundant molecule, but difficult to observe in emission
- 2.6 mm line of CO can be used as tracer:
  - $M(H_2)/F(Co)=X$
  - However: the conversion factor X depends on metallicity; very uncertain in metal-poor galaxies

Gaseous and stellar motions

In disks:

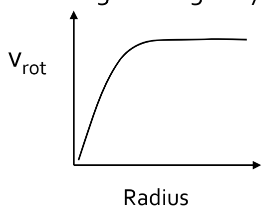
Average rotational velocity

Typical velocity dispersion

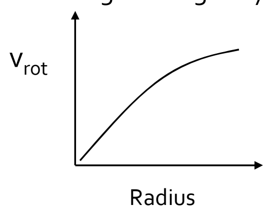
$$\frac{v_{\mathrm{rot}}}{\sigma_{\mathrm{v}}} \sim 10$$

Rotation curves

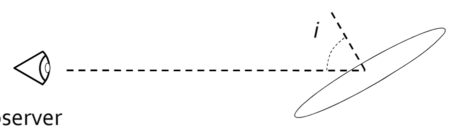
Typical
high surface
brightness galaxy



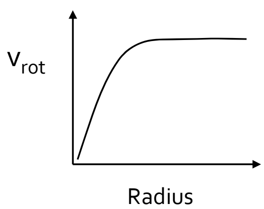
Typical
low surface
brightness galaxy



Rotation curves



$$v_{\mathrm{rot}} = \frac{v_{\mathrm{obs}}}{\sin(i)}$$

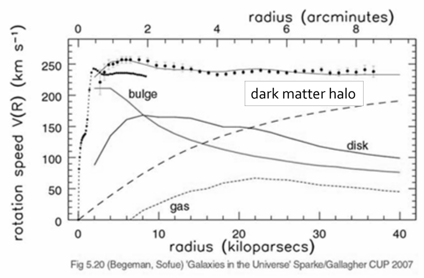


Rotation curves

Recall from lecture 3:

$$M(<R) = \frac{v_{\mathrm{rot}}(R)^{2} R}{G}$$

Rotation curve decomposition

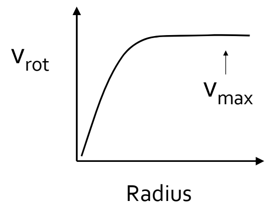


Typical global M/L~10-100

The Tully-Fisher relation

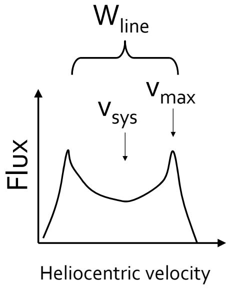
$L \propto V_{max}^4$

Example: $$\frac{L_H}{3\times10^{10}\, L_{H\text{solar}}} = \left(\frac{v_{\max}}{196\ \text{km/s}}\right)^{3.8}$$



The Tully-Fisher relation II

Don´t need rotation curve — you can also use HI spectral line profile



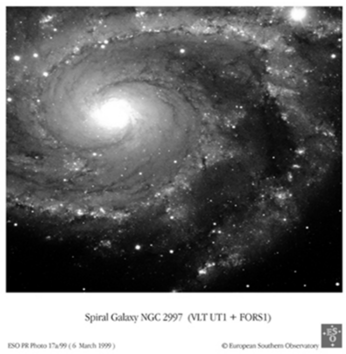
$$V_{max} \approx \frac{W_{line}}{2}$$

In one of the exercises, we use the following form of the TF relation:

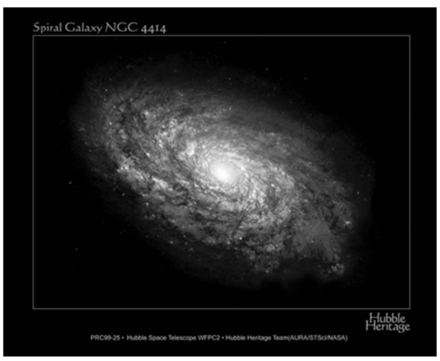
$$M_H \approx -9.50(\log_{10} W - 2.50) - 21.67,$$

W_{line}

Spiral patterns I: A "Grand Design" Spiral

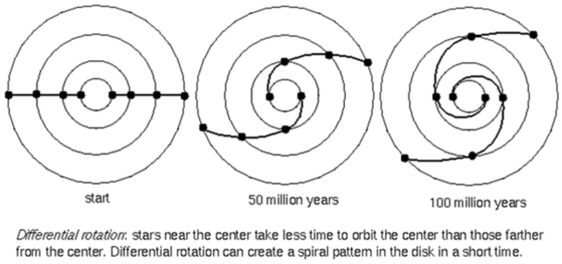


Spiral patterns II: A Flocculent Spiral

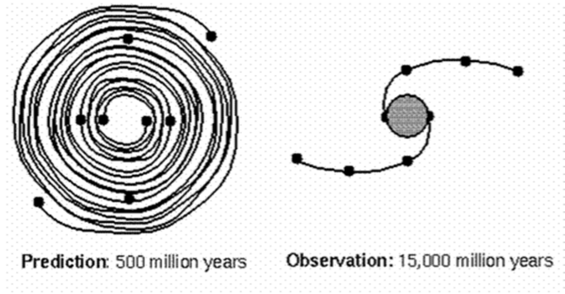


Intermission: What type of spiral is this?

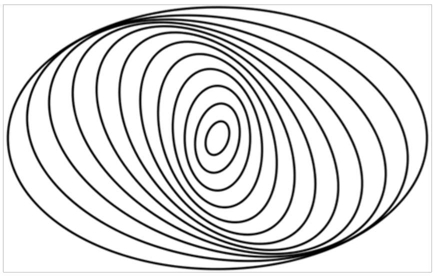
Spiral patterns III: Differential rotation



Spiral patterns IV: The winding-up dilemma

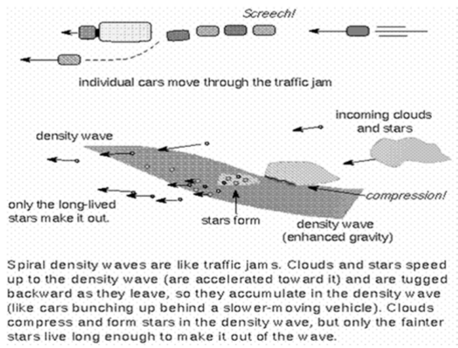


Spiral patterns V: Density waves



Stars on elliptical orbits with different orientations → stars in piral arms continuously replaced

Spiral patterns VI: Density-wave theory



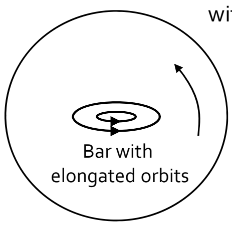
Spiral patterns VII: Problems with density waves

- From where does the density wave get its energy?
  - From the rotation of the disk?
  - From a companion galaxy?
  - Internal forces from a central bar?
- Spiral patterns remain mysterious…

Bars

- At least 50% of all disk galaxies have bars
- Bars are not density waves!
- Elongated orbits

Face-on disk with bar



Bulges

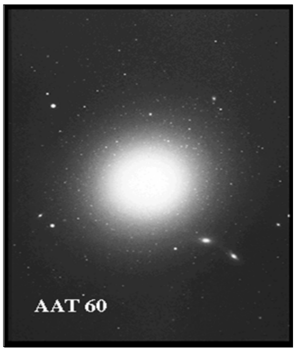
- In bulges:

$$\frac{v_{\mathrm{rot}}}{\sigma_{\mathrm{v}}} \sim 1$$

Intermission:
The Galaxy Zoo Project

http://zoo1.galaxyzoo.org/

Elliptical Galaxies



Surface Brightness Profiles of Ellipticals I

$R^{1/4}$ or De Vaucoleurs law ($n \approx 4$)

$$I(R) = I(0)\exp\left(-(R/h_{\mathrm{R}})^{1/n}\right)$$

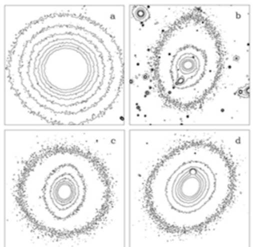
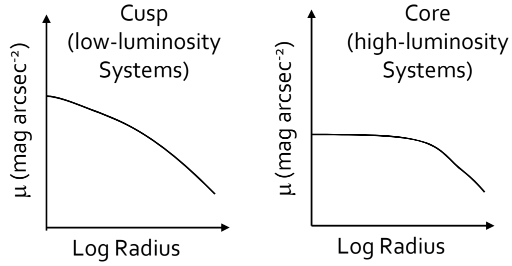


Fig 6.1 (R. de Jong) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Surface Brightness Profiles of Ellipticals II



Stars and Spectra of Ellipticals I

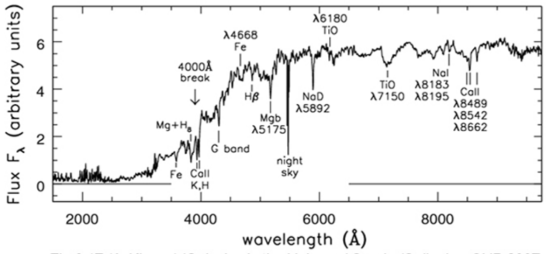
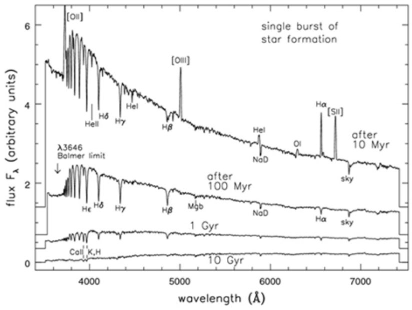


Fig 6.17 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

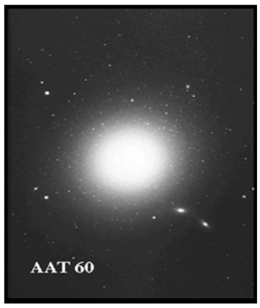
Stars and Spectra of Ellipticals II

'E+A'-systems: Ellipticals with spectral signatures of recent star formation



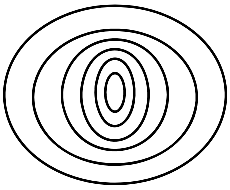
cD-Galaxies

- The most luminous, non-active galaxies
- "Cannibal-galaxies", found only in centres of galaxy groups and clusters
- Brighter than $R^{1/4}$-law prediction at large radii



Triaxiality

- $X \neq Y \neq Z$
- Isophote twisting: a tell-tale sign of triaxiality



Stellar Motions in Ellipticals

- Flattening of ellipticals not always due to rotation, but rather velocity anisotropy ($\sigma_x \neq \sigma_y$)

$$\frac{v_{\max}}{\sigma_v} \approx 0.01 - 1$$

The Faber-Jackson Relation

$L \propto \sigma_o^4$, e.g.

$$\frac{L_V}{2\times 10^{10} L_{V\mathrm{solar}}} = \left(\frac{\sigma_0}{200\ \mathrm{km/s}}\right)^4$$

which is a projection of the "fundamental plane" of elliptical galaxies:

$$R_e \propto \sigma_0^{1.4} \langle I \rangle_e^{-0.85}$$

where R_e is the effective radius, σ_o is the central velocity dispersion and $\langle I \rangle_e$ is the average surface brightness within R_e

Mass Determinations for Ellipticals

- More difficult than for disk galaxies
- A few methods:
  - For gas-rich Es: HI rotation curves
  - X-ray gas: $M=f(\rho_{gas}, r, T)$
  - Virial theorem: $M=f(\sigma, r)$ with
    - Stellar $\sigma(r)$ from absorption lines
    - Stellar $\sigma(r)$ and v_{rot} from planetary nebula emission lines