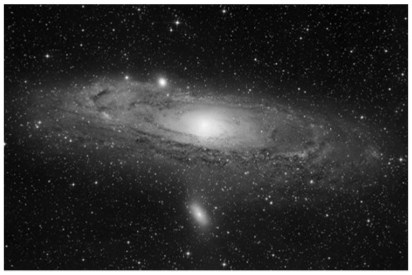
Physics of Galaxies 2018
10 credits
Lecture 4: Disks and ellipticals



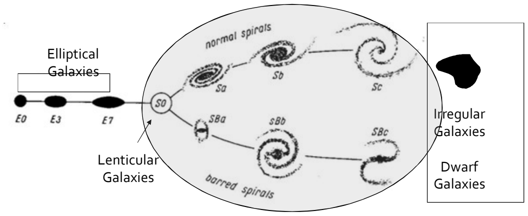
Outline I

- 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



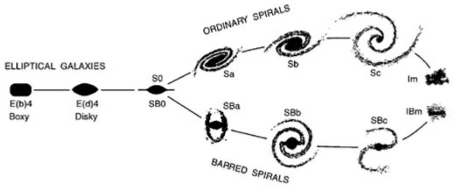
Elliptical Galaxies

Lenticular Galaxies

Irregular Galaxies

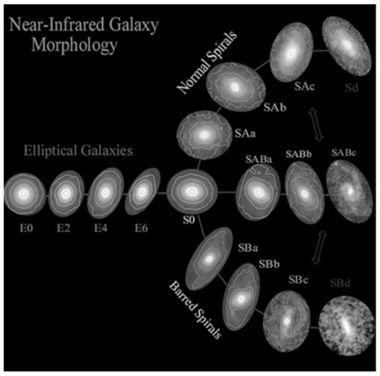
Dwarf Galaxies

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

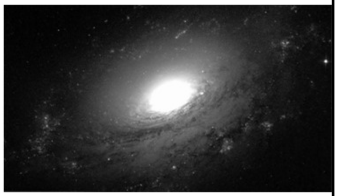
  Early-type disks Late-type disks

- 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

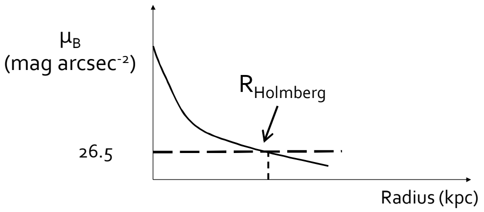
$$I(r) = \frac{F}{\alpha^2} = \frac{L/4\pi d^2}{D^2/d^2} = \frac{L}{4\pi D^2}$$

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

- *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

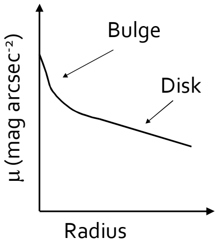
Surface Brightness

- 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

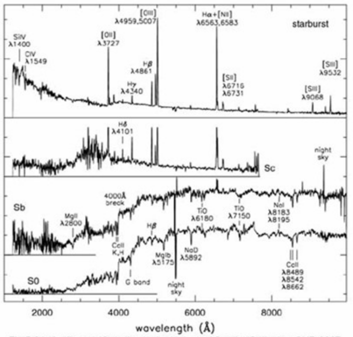
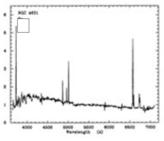
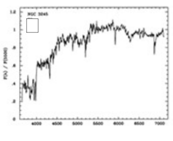


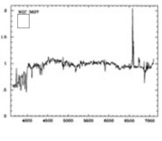
Fig 5.24 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

- Sc: Young stars
- So: Old stars

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


A


B


C

Neutral hydrogen

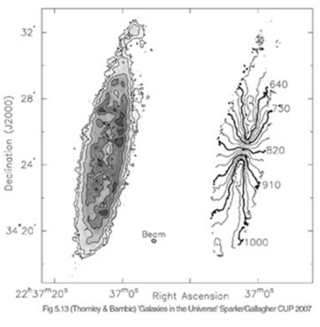


Fig 5.13 (Thornley & Bambic) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Neutral hydrogen

- Flux in 21 cm line → HI mass:

$$\frac{M(\mathrm{HI})}{M_{\mathrm{solar}}} = 2.356\times10^{5} D^{2} \underbrace{\int F_{\nu} dV_{\mathrm{r}}}$$

Distance
In Mpc

Integration
over line profile

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

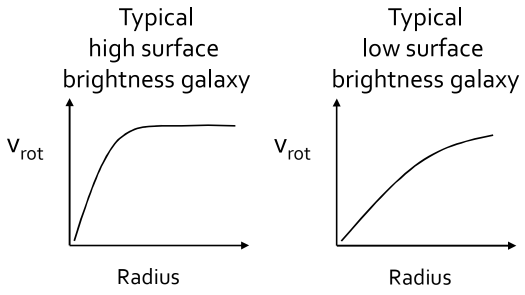
In disks:

Average rotational velocity

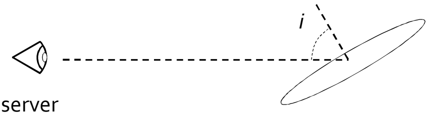
Typical velocity dispersion

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

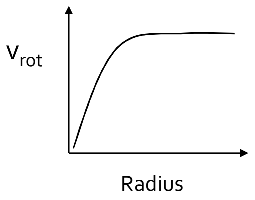
Rotation curves



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

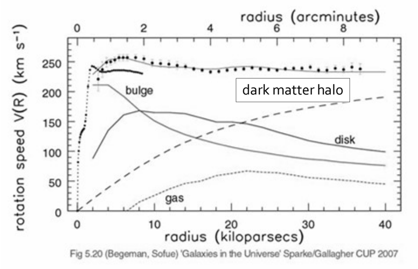
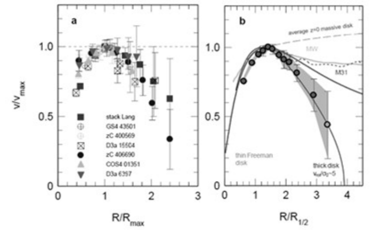


Fig 5.20 (Begeman, Sofue) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Typical global M/L~10-100

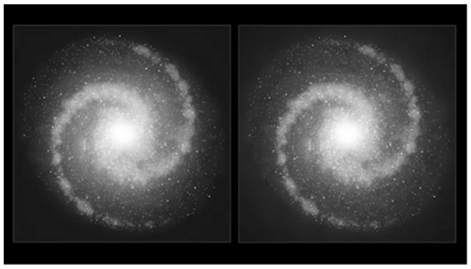
New results 2017: Galaxies at earlier epochs less dominated by dark matter?



Dropping rotational velocities in z=0.6-2.6 galaxies ⇒ Less need for dark matter

Genzel et al. 2017 , Nature 543, 397

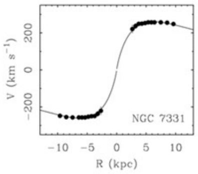
New results 2017: Galaxies at earlier epochs less dominated by dark matter?



z = 0 disk

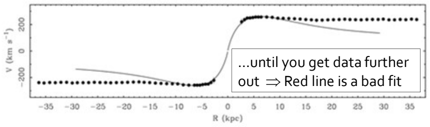
z = 0.6-2.6 disk

New results 2017: Galaxies at earlier epochs less dominated by dark matter?



Stacy McGaugh: This may be an artefact of having data on the inner regions of galaxies only

Example: The turnover in the rotation curve sure makes it seem like there's a drop in the outskirts...



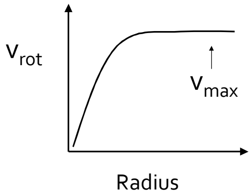
...until you get data further out ⇒ Red line is a bad fit

The Tully-Fisher relation

$L \propto V_{max}^4$

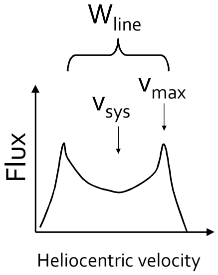
Example:

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



The Tully-Fisher relation II

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

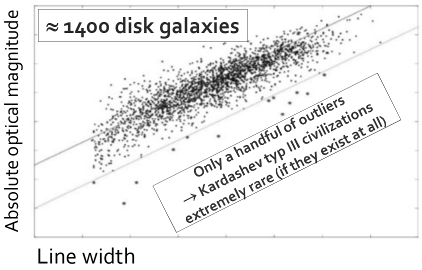


$$\boxed{V_{\max} \approx \frac{W_{\mathrm{line}}}{2}}$$

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

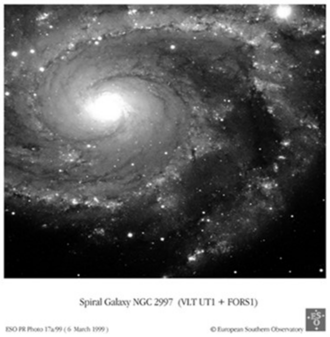
$$M_H \approx -9.50(\log_{10} \underset{\nwarrow W_{line}}{W} - 2.50) - 21.67,$$

Weird stuff: The Tully-Fisher relation as a tool to search for extraterrestrial intelligence

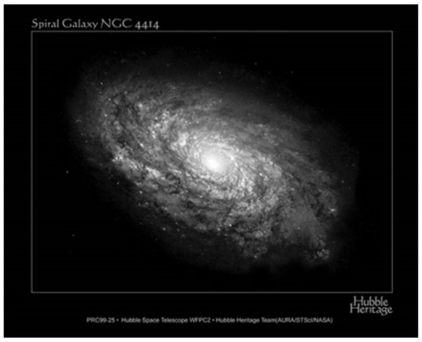


Shameless self-promotion: Zackrisson, E., Calissendorff, P., Asadi, S., Nyholm, A. 2015, Astrophysical Journal, 810, 23

Spiral patterns I: A "Grand Design" Spiral

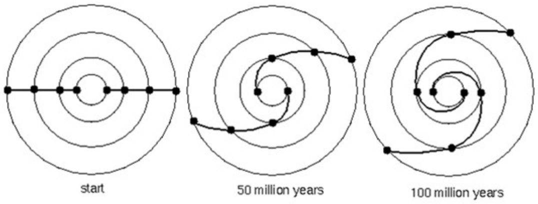


Spiral patterns II: A Flocculent Spiral



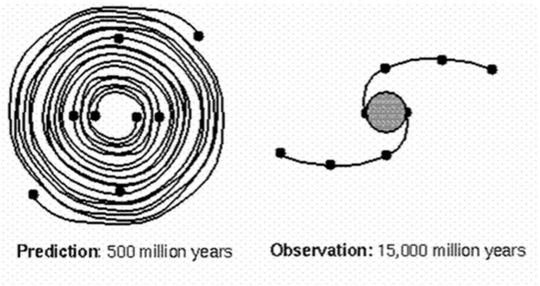
Intermission:
What type of spiral is this?

Spiral patterns III:
Differential rotation

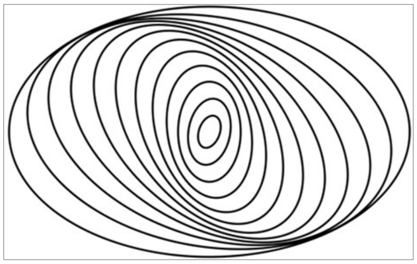


Differential rotation: stars near the center take less time to orbit the center than those farther from the center. Differential rotation can create a spiral pattern in the disk in a short time.

Spiral patterns IV:
The winding-up dilemma

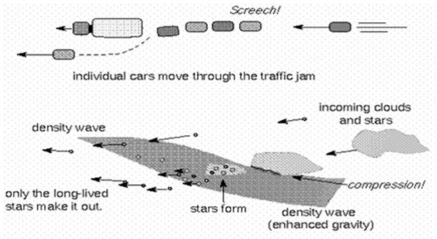


Spiral patterns V: Density waves



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

Spiral patterns VI: Density-wave theory



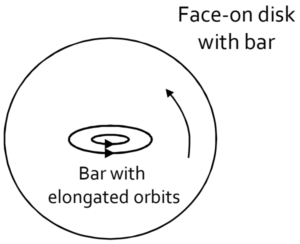
Spiral density waves are like traffic jams. Clouds and stars speed up to the density wave (are accelerated toward it) and are tugged backward as they leave, so they accumulate in the density wave (like cars bunching up behind a slower-moving vehicle). Clouds compress and form stars in the density wave, but only the fainter stars live long enough to make it out of the wave.

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



Bulges

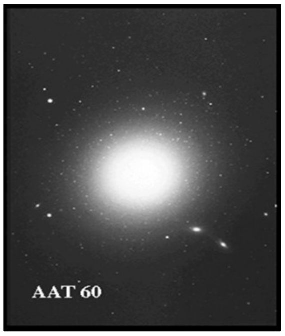
- In bulges:

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

Intermission: The Galaxy Zoo Project

https://www.galaxyzoo.org/

Elliptical Galaxies



Surface Brightness Profiles of Ellipticals I

$R^{1/4}$ or De Vaucoleurs law (n≈4)

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

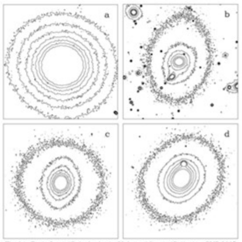
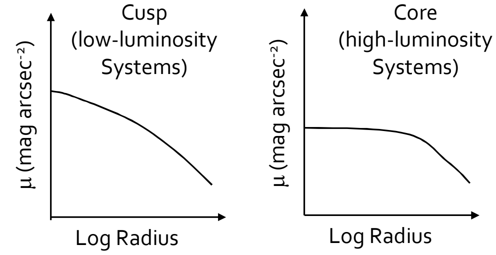


Fig 6.1 (R. de Jong) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Surface Brightness Profiles of Ellipticals II



Late-breaking news: The core is due to influence from the central supermassive black hole. The radius of the core correlates strongly with the black hole mass (Thomas et al. 2016, Nature)!

Stars and Spectra of Ellipticals I

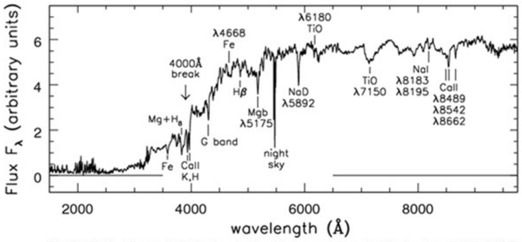
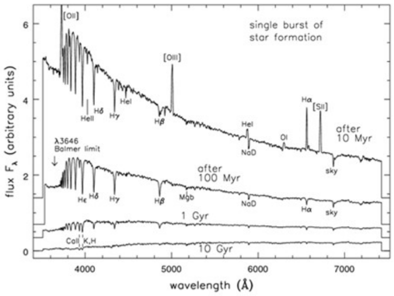


Fig 6.17 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

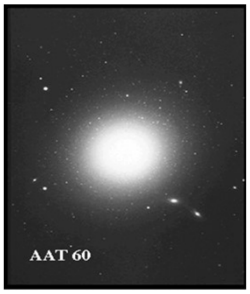
Stars and Spectra of Ellipticals II

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



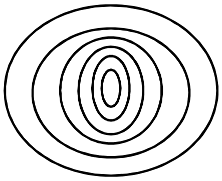
cD-Galaxies

- 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 ($\sigma_x \neq \sigma_y$)

$$\frac{v_{\max}}{\sigma_{\mathrm{v}}} \approx 0.01-1$$

The Faber-Jackson Relation

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

$$\frac{L_V}{2\times10^{10}\,L_{V\mathrm{solar}}} = \left(\frac{\sigma_0}{200\ \mathrm{km/s}}\right)^4$$

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

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

where R_e is the effective radius, σ_o is the central velocity dispersion and $<I>_e$ 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