Physics of Galaxies 2016 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



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

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

- I(r) usually L_{\odot} kpc⁻², but $\mu(r)$ 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:

- R₂₅: 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:

$$I(R) = I(0) \exp(-(R/h_R)^{1/n})$$

 h_R : Scale length I(o): Central surface brightness $n=4 \rightarrow$ de Vaucoleur formula (for bulges & ellipticals) $n=1 \rightarrow$ Exponential disk (for the disks of disk galaxies) Surface Brightness Profiles III
Profiles of exponential disks (n=1):

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

•Alternative formulation (3.14 in Schneider):

$$\mu(R) = \mu_0 + 1.09 \frac{R}{h_{\rm R}}$$

(mag arcsec⁻²)

 μ_o : central surface brightness

Surface Brightness Profiles IV

Alternative formulation of Sérsic formula (3.39 in Schneider)

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

 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



Sc: Young stars
So: Old stars

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









Neutral hydrogen



Neutral hydrogen

• Flux in 21 cm line \rightarrow HI mass:

 $\frac{M(\mathrm{HI})}{M_{\mathrm{solar}}} = 2.356 \times 10^5 D^2 \int F_{\nu} dV_{\mathrm{r}}$

Distance In Mpc Integration over line profile

Molecular hydrogen

•H₂ most abundant molecule, but difficult to observe in emission

- •2.6 mm line of CO can be used as tracer:
 - M(H₂)/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

rot ~10

Rotation curves

Typical high surface brightness galaxy Typical low surface brightness galaxy

V_{rot}

V_{rot}

Radius

Radius





Rotation curves

Recall from lecture 3:

 $M(\langle R) = \frac{v_{\rm rot}(R)^2 R}{G}$

Rotation curve decomposition



Typical global M/L~10-100

The Tully-Fisher relation

 $L \propto V_{max}^{4}$ Example:

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



Radius

The Tully-Fisher relation II Don't need rotation curve — you can also use HI spectral line profile



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

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

Wline

Heliocentric velocity

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



Line width

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

Spiral patterns I: A "Grand Design" Spiral



Spiral Galaxy NGC 2997 (VLT UT1 + FORS1)



ESO PR Photo 17a/99 (6 March 1999)

Spiral patterns II: A Flocculent Spiral

Spiral Galaxy NGC 4414



PRC99-25 • Hubble Space Telescope WFPC2 • Hubble Heritage Team(AURA/STScI/NASA)

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 \rightarrow stars in piral 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

Face-on disk with bar

Bar with elongated orbits

Bulges

• In bulges:

 $\mathcal{V}_{\rm rot}$ ~ 1 $\sigma_{
m v}$



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)

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



Surface Brightness Profiles of Ellipticals II

μ (mag arcsec⁻²)



Log Radius

Log Radius

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



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

$\bullet X \neq Y \neq Z$

Isophote twisting: a tell-tale sign of triaxiality



Stellar Motions in Ellipticals

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

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

The Faber-Jackson Relation

 $L \propto \sigma_0^4$, e.g.

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

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

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

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(p_{gas},r,T)
 - Virial theorem: M=f(σ,r) with
 - Stellar $\sigma(r)$ from absorption lines
 - Stellar $\sigma(r)$ and v_{rot} from planetary nebula emission lines