Astro 358/Spring 2009

(48540)

Galaxies and the Universe

Figures for Lecture 3-5 (Th Jan 29 to Tu Feb 7)

Do external galaxies exist ?

1) 1920s : The Great Debate": Harlow Shapley vs Heber Curtis

Are spiral nebulae large distant systems like the Milky Way or nearby small objects associated with our own Galaxy?

→Shapley: Milky Way is huge (diameter ~100 kpc, Sun off center) and spiral nebulae are small nearby companions

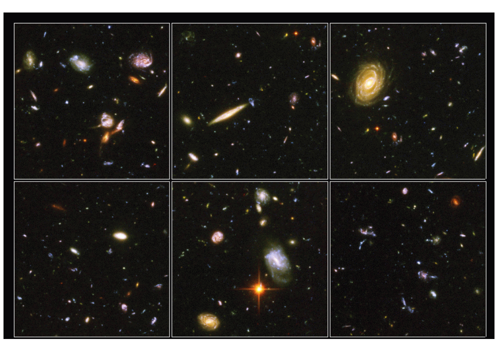
→ Curtis: Milky Way is small (d~18 kpc, Sun at center) and spiral nebulae are external stellar systems (galaxies) comparable to the Milky Way, but very distant from us

2) Progress: Accurate distances + realization that galaxies have dust

3) 1927: Edwin Hubble use Cepheids to show M31 distance = 770 kpc
M31 and other spiral nebulae are external galaxies

Do external galaxies exist ?

Today we know : over a billion galaxies exist beyond our Milky Way



Fundamental Stellar components of Galaxies
Stellar disks and Spherical/Spheroidal/Triaxial components

There are 2 fundamental stellar components of galaxies

a) Flattened component = stellar disk
b) Puffed-up Spherical/Spheroidal/Triaxial (SST) stellar components (e.g, classical bulges, massive Ellipticals)

These 2 components differ fundamentally in
---> 3-D structure and ratio V_c/σ of ordered to random motion
---> formation pathways

See in class notes

Galaxies types based on total mass and morphology

Galaxies types based on total mass and morphology

1) High mass
- Elliptical galaxies (E, cE)
- Lenticular galaxies (S0)
- Spiral galaxies (Sa to Sd)

2) Low mass
- Irregular galaxies (Sm, Im Irr)
- Dwarf galaxies (dIrr, dE, dSph)

3) Mixed
- Peculiar/Interacting

See in class notes

Properties of E, Spirals, Irregulars and Dwarfs

Table 1. Properties of E, Spirals (Sa-Sd), Irregulars (Sm,Im,Irr) & Dwarfs (dIrr,dE, dSph)

	E	Sa to Sc	Sd/Sm	Im/Irr	Dwarfs (dE,dIrr,dSph +BCD)
Dynamical Mass M_d ($M_\odot$)	$10^8 - 10^{13}$	$10^9 - 10^{12}$	$10^8 - 10^{10}$	$10^8 - 10^{10}$	$10^7 - 10^9$
D_{25} (kpc)	1-200	5-100	0.5-50	0.5-50	dE: 1-10 dIrr: 1-10 dSph: 0.1-0.5 BCD: < 3
M_B	-15 to -23 (mostly -17 to -23) -15 to -19 for cE -19 to -23 for rest	Sa: -17 to -23 Sb: -17 to -23 Sc: -16 to -22	-15 to -20	-13 to -18	dIrr: -15 to -18 BCD: -14 to -17 dE: -13 to -19 dSph: -1.5 to -15
L_B ($L_\odot$)	$(0.3 - 4) \times 10^{10}$ for intermediate and giant E but lower for low luminosity E	Sa: $(1 - 3) \times 10^{10}$	$(< 0.1 - 2) \times 10^{10}$	$\cdots$	$\cdots$
Mass-to-light ratio M_d/L_B ($M_\odot/L_\odot$)	10 - 100	Sa: 6.2 Sb: 4.5 Sc: 2.6	~ 1	~ 1	dSph: ~ 5 to ~ 3500
B - V	0.7-1.2	Sa: 0.75 Sb: 0.64 Sc: 0.52	0.47	0.37	$\cdots$
M_{gas}/M_*	$\cdots$	Sa: 0.04 Sb: 0.08 Sc: 0.16	0.25	$\cdots$	dIrr: > 0.25
M(HI)/L_B	< 0.1	Sa: 0.05 - 0.1	0.25 to > 1	$\cdots$	$\cdots$
Peak V_c (km s^{-1})	0-100	Sa: 163-367 Sb: 144-330 Sc: 99-304	$\cdots$	50-70	$\cdots$

Properties of E, Spirals, Irregulars and Dwarfs

Table 1—Continued

	E	Sa to Sc	Sd/Sm	Im/Irr	Dwarfs (dE,dIrr,dSph +BCD)
Velocity dispersion $\langle\sigma_*\rangle$ (km s^{-1})	50 - 400	5 - 50	~ 10	~ 10	dSph: $3.5 - 20$
V_c/σ_*		10 - 40	$\cdots$	~ 5	$\cdots$
Stars dominating color	G/K	$\cdots$	$\cdots$	$\cdots$	$\cdots$

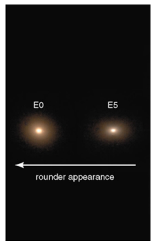
Note. — References: Tables 3.1/EAC, 3.2/EAC, 5.1/GU. dSph data references from 1998, ARA&A, 36, 435 and 2011, ApJ, 733, 46.

Terms used in table refer to the following:

D_{25} = Diameter where B-band surface brightness reaches 25 mag $arcsec^{-2}$
M_B = Absolute blue magnitude
L_B = Blue luminosity
M_d = dynamical mass = mass of visible matter (gas+stars) + mass of dark matter
M_* = mass of stars
M_{gas} = mass of atomic and molecular gas
M(HI) = mass of atomic hydrogen
V_c = peak circular speed of stars
σ_*= velocity dispersion of stars

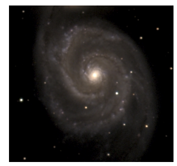
Elliptical Galaxies

Giant elliptical M87



Spiral Galaxies

Spirals have extended outer stellar disk with spiral arms and central stellar bulge

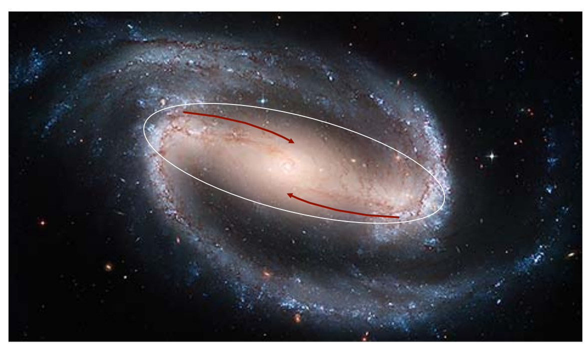


Spiral Galaxies: Edge-on view

Typical spiral, where outer disk is more massive and luminous than central bulge (Bulge/Disk luminosity ratio well below 1)

NGC 4594 or M104 (Sombrero)
An unusual spiral, with an unusually large bulge and a dusty disk, seen edge-on (Bulge/Disk luminosity ratio > 2)

Strongly Barred spiral (SBbc) NGC 1300



A stellar bar drives gas (via shocks+ torques) from the disk into the central kpc where

→ it ignites powerful central bursts of star formation:.. 10 billions L_{sun}!
→ It may help to feed the central monster (black **hole)**

Weakly barred and unbarred spirals

Weaky barred spiral
(SABc) NGC 674

Unbarred spiral (SAab) NGC 4622

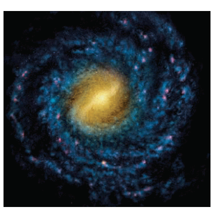
Spirals divided into Hubble type Sa to Sd

Unbarred (SA) spirals SAa SAb SAc

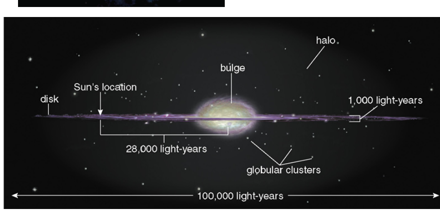
Strongly Barred (SB) spirals SBa SBb SBc

Our Milky Way

Milky Way = a barred (SBbc) çgalaxy



Face-on view
(Artist's conception)



Edge-on view
(Artist's conception)
Qualitatively ok but missing stellar bar and wrong shape for bulge

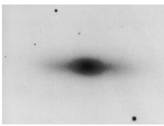
Properties of Spiral (Sa to Sd) & Irregular (Irr, Sm, Im) galaxies

Table 3.2. Characteristic values for spiral galaxies. V_{max} is the maximum rotation velocity, thus characterizing the flat part of the rotation curve. The opening angle is the angle under which the spiral arms branch off, i.e., the angle between the tangent to the spiral arms and the circle around the center of the galaxy running through this tangential point. S_N is the specific abundance of globular clusters as defined in (3.13). The values in this table are taken from the book by Carroll & Ostlie (1996)

	Sa	Sb	Sc	Sd/Sm	Im/Ir
M_B	−17 to −23	−17 to −23	−16 to −22	−15 to −20	−13 to −18
$M\ (M_\odot)$	10^9–10^{12}	10^9–10^{12}	10^9–10^{12}	10^8–10^{10}	10^8–10^{10}
$\langle L_{bulge}/L_{tot}\rangle_B$	0.3	0.13	0.05	–	–
Diam. (D_{25}, kpc)	5–100	5–100	5–100	0.5–50	0.5–50
$\langle M/L_B\rangle\ (M_\odot/L_\odot)$	6.2 ± 0.6	4.5 ± 0.4	2.6 ± 0.2	∼ 1	∼ 1
$\langle V_{max}\rangle$ (km s^{-1})	299	222	175	–	–
V_{max} range (km s^{-1})	163–367	144–330	99–304	–	50–70
Opening angle	∼ 6°	∼ 12°	∼ 18°	–	–
$\mu_{0,B}$ (mag $arcsec^{-2}$)	21.52 ± 0.39	21.52 ± 0.39	21.52 ± 0.39	22.61 ± 0.47	22.61 ± 0.47
$\langle B-V\rangle$	0.75	0.64	0.52	0.47	0.37
$\langle M_{gas}/M_{tot}\rangle$	0.04	0.08	0.16	0.25 (Scd)	–
$\langle M_{H_2}/M_{HI}\rangle$	2.2 ± 0.6 (Sab)	1.8 ± 0.3	0.73 ± 0.13	0.19 ± 0.10	–
$\langle S_N\rangle$	1.2 ± 0.2	1.2 ± 0.2	0.5 ± 0.2	0.5 ± 0.2	–

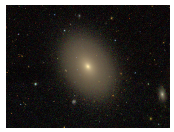
Table 3.2, EAC

Lenticular (S0) galaxies



NGC 4417

NGC 4382

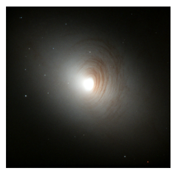


NGC 4578

Moderately inclined S0S:
Is outer structure really
a disk?

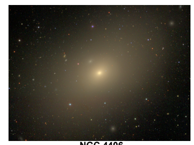
NGC 5866

Edge-on and highly
inclined SO: outer disk
is clearly visible

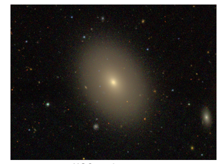


NGC 2787

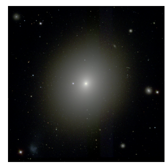
Hard to separate moderately inclined unbarred S0s from Es



NGC 4406



NGC 4578



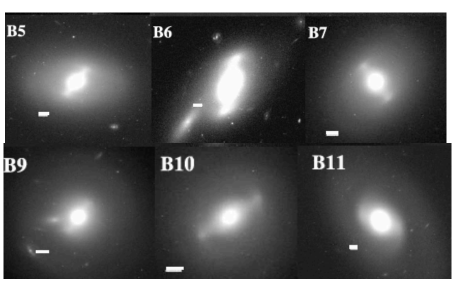
NGC 4472

NGC 4382

Elliptical galaxies

Moderately inclined SOs

Some S0s are barred and must thus have outer disks



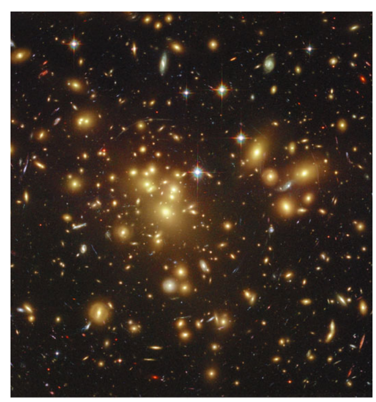
Barred S0 galaxies in the Coma cluster
(Credit Marinova, Jogee, & Coma ACS Team, 2012, ApJ, in press)

Since bars only form in disks, the presence of barred S0s implies that at least
some S0s harbor extended outer disks

Why are S0s important?

Morphology-density relation: the frequency of (E+S0) galaxies relative to spiral galaxies is much higher in high density environments (e.g., galaxy clusters) than in low density environments (e.g., field)

Frequency of E+S0:Sp
= 40%+50% :10% in cluster
= 10%+10%: 80% in field



Core of Abell 1689 cluster

Transition in color and luminosity from S0 to Scs

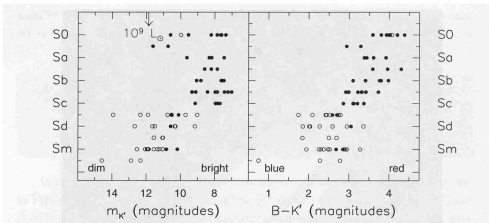


Figure 5.6 Apparent magnitude $m_{K'}$ and $B-K'$ color of galaxies in the Ursa Major group, plotted by galaxy type. Galaxies to the right of the arrow have $L > 10^9 L_{\odot}$ at the group's distance of 15.5 Mpc. Open circles show galaxies where the disk has lower central brightness: $I_{K'}(0) > 19.5$. On average, S0 galaxies are luminous and red, while the Sd and Sm systems are fainter and bluer – M. Verheijen.

There is a (fairly smooth) trend of higher luminosity and redder colors from Sa-Sc to S0s

Irregular Galaxies (Sm, Im, Irr)

Low mass, gas-rich; Irregular visual morphology ; Stellar (V_c/σ) > 1

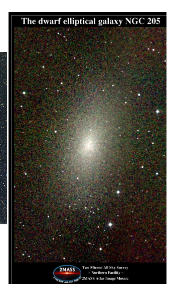
Large Magellanic Cloud or LMC
Type (SB(s)m)
Distance = 50 kpc
Image diameter = 10 kpc

Small Magellanic Cloud or SMC
Type = SB(s)m pec or Im
Distance = 63 kpc
Image diameter = 6 kpc

Dwarf Galaxies (dIrr, dSph, dEs)

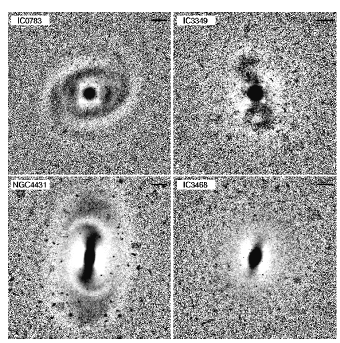
NGC 1705 (dIrr)
(Credit: NASA, ESA, Hubble Heritage)

Leo I (dSph), satellite of M Way



NGC 205 (dE)
(Credit: NASA, ESA, Hubble Heritage)

Some dEs show disk features (bar, spiral arms)



(Barazza et al .2002, A&A)

Specially processed images (unsharp masked images) of bright dE and dS0s reveal:

-IC3468 (dE) ; short bar in a nearly face-on disk or small disk seen edge-on in a spheroid

- IC3349 (dE) ; show a weak bar-like elongated central structure

-NGC 4431 (dS0) ; strong long bar
- IC0783 dS0); spirals

Difference between (dSh + bright dEs) and (bright E+bulges)

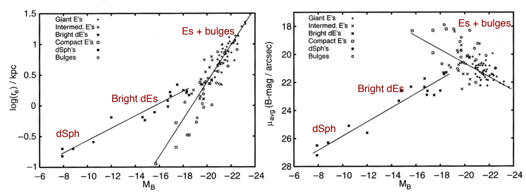


Fig. 3.7. Left panel: effective radius R_e versus absolute magnitude M_B; the correlation for normal ellipticals is different from that of dwarfs. Right panel: average surface brightness μ_{ave} versus M_B; for normal ellipticals, the surface brightness decreases with increasing luminosity while for dwarfs it increases

- dSph → low blue luminosities (overlapping with those of globular clusters)
  → very low mean surface brightness (25-27 mag arcsec^{-2} in B) → visible only in the local Group
- (dSph + bright dEs) → Half-light radius r_e rises only slowly with luminosity causing their mean surface brightness to rise with luminosity.

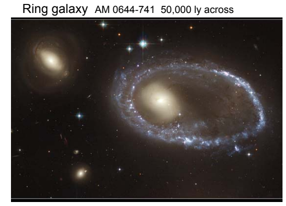
(Bright Es and bulges) → Half-light radius r_e rises steeply with luminosity, causing their mean surface brightness to fall at higher luminosities

Peculiar/Interacting Galaxies

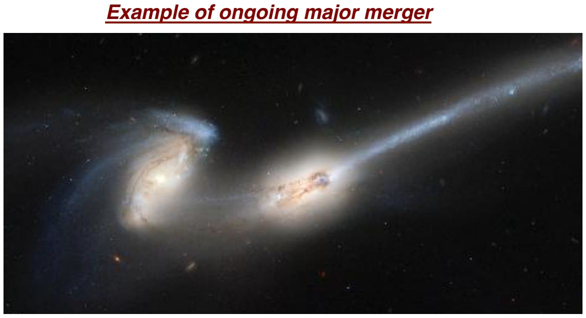
Polar ring galaxy NGC 4650

Cartwheel galaxy
Head-on collision

Ring galaxy AM 0644-741 50,000 ly across



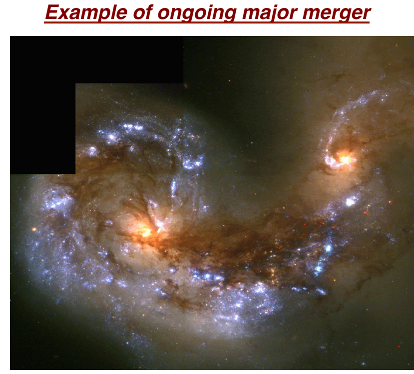
Example of ongoing major merger

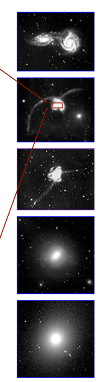


NGC 4736 / The Mice (Credit: NASA/STScI/Hubble Heritage

HST image shows details of a collision between 2 spiral galaxies 30 kpc apart.
Example of a nearby ongoing major merger

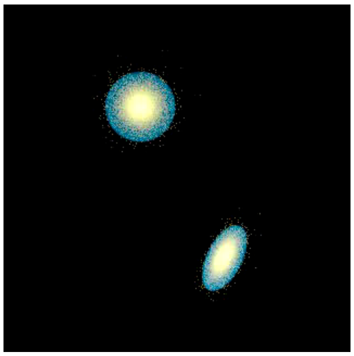
Example of ongoing major merger





The Antennae system is believed to be an ongoing major merger of 2 spirals
The HST image of the central region of the merger: shows stripped gas and dust lying between the 2 disks

Simulation of a major merger between 2 spirals

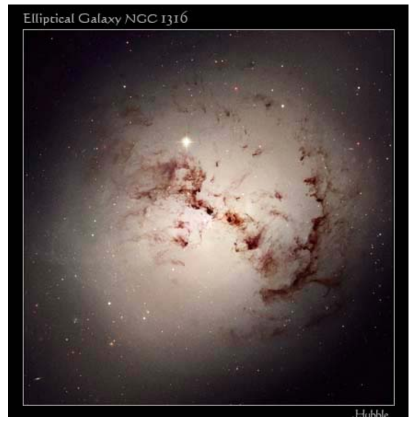


(Mihos & Hernquist; DM halo + Stars =yellow, gas= blue, Duration = 1 Gyr)

Major mergers: gas inflows, conversion of gas to stars, violent relaxation of stars converting disk configuration into spheroidal distribution of stars

Data The Toomre Sequence

Example of a minor merger



The Elliptical/Peculiar galaxy (NGC 1316)
→ recently accreted small gas-rich galaxies

2 fundamental groups of galaxies dominated by disks versus puffed-up SST components

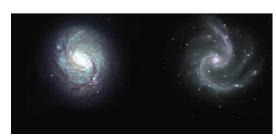
SST = Spherical/Spheroidal/Triaxial components

2 fundamental groups of galaxies dominated by disks versus puffed-up SST components

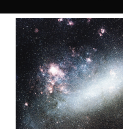
Can divide galaxies into 2 groups where the stellar mass is dominated

By puffed-up SST	versus	By disks
(supported by velocity dispersion)		(supported by rotation)
- Massive Es - Some S0s + rare spirals dominated by classical bulges		- Most spiral galaxies , Irrs, dIrr - Some S0s dominated by outer disks - Under debate: Some dE, low mass E

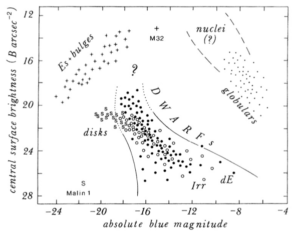
Massive Elliptical



Spirals



Irr (LMC)



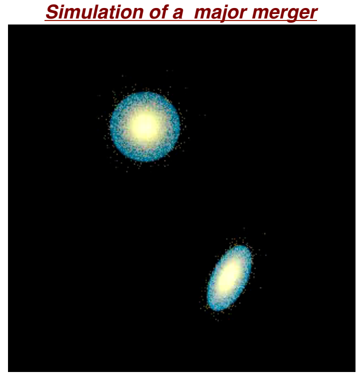
Difference between (dIrr + dEs + disk of spirals) versus (bright Es+ bulges)

Figure 4.18 Dwarf and giant galaxies occupy different regions in a plot of absolute V-magnitude and measured central surface brightness; because of 'seeing', the true peak brightness may be higher. At left, luminous elliptical galaxies and the bulges of disk systems have very high surface brightness at their centers. The rightmost of the 'dE' points (filled circles) represent what this text calls dwarf spheroidals; open circles mark irregular and dwarf irregular galaxies. Disks of spiral galaxies are marked 'S'. Malin 1 is a low-surface-brightness galaxy; see Section 5.1 – B. Binggeli.

In plane of central SB vs absolute blue magnitude (Es + bulges of spirals) follow a radically different relation from (dIrr, dE, and disk of spirals). Do the two groups represent

- galaxies dominated by disks vs puffed-up SST components
- different sources of support from gravity (random velocity of stars vs ordered rotation or stars)
- different formation pathways?

Simulation of a major merger

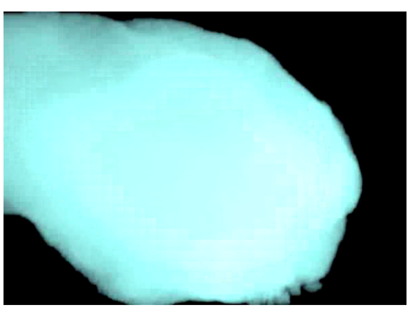


(Mihos & Hernquist; DM halo + Stars =yellow, gas= blue, Duration = 1 Gyr)

Major mergers: gas inflows, conversion of gas to stars, violent relaxation of stars converting disk configuration into spheroidal distribution of stars

Data The Toomre Sequence

Building a spiral galaxy (with a classical bulge and disk) starting from mini proto-disk galaxies over 13 billion years



Caroon movie (courtesy: Frank Governato)

Galaxy grows via smooth accretion, minor mergers and major mergers

B/D ratio as a proxy for Ratio of stellar mass in (SST/Disk)

Ideally, we want to measure

R = (Stellar mass in Spherical/Spheroidal/Triaxial components / Stellar mass in disk)
= (M_* in SST)/(M_* in Disk)
= (M_* in classical bulge or massive Elliptical)/ (M_* in disk)

In practice, we measure in (spiral, S0s, E), the bulge-to-disk (B/D) ratio

B/D = (M_* in bulge)/ (M_* in disk)
= 1 for massive E, 0 for pure disk galaxy, intermediate for Spirals and S0

where bulge is defined as central component containing excess light over outer disk

SAa SAb SAc

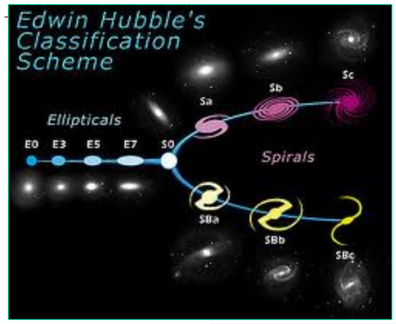
<---

B/D ratio rises from Sc to Sa

One problem in using B/D as a proxy for R is that "bulges" defined in the above way include not just puffed-up classical bulges, but also disky bulges, peanut bulges

Galaxy Classification Schemes

Hubble-Sandage Classification System (1961) extended from Hubble (1936)



Limitations of Hubble-Sandage classification scheme

1) Assumes B/D, smoothness, of disk and tightness of spiral arms are correlated.
→ Where does a spiral with low B/D and smooth disk fit in?

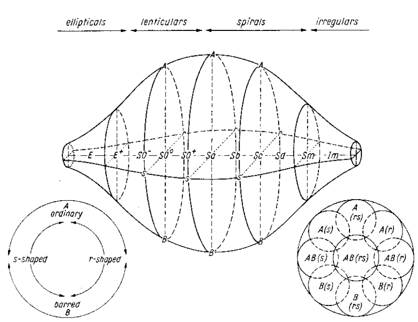
2) Low mass (Sd, Irr, Dwarf) and Pec/Interacting galaxies do not fit in

3) Weakly barred galaxies do not fit in

4) Based on optical images. But need multi-wavelength images and kinematics for a more complete view

------------> Ellipticals E0 to E7 have rising ellipticity e =1-b/a = 0 to 0.75	S0	---------------------------------> Spirals from types Sa to Sc have (lower B/D, less smooth disk, more open spiral arms). Letter B denotes Barred

De Vaucouleurs's extension of the Hubble Classfication system (1959)



Example: NGC 2782 is typed as SAB(rs)a in the RC3 catalog:

→SAB(rs) means it is a weakly barred spiral, with a ring and spiral arm

→ Sa means it has high B/D, tight and smooth spiral arms

a) added low mass galaxies (Sd, Sm, Im) , "Pec" notation,

b) added bar strength : SB= strongly barred, SAB=weakly barred, SA=unbarred

c) added dimensions for ring (r) and spiral arms (s)

d) fine-tuned transition from E to S0 as (E+ S0- S0+}