Galaxies

• Known since 18th century as fuzzy, distended objects => “spiral nebulae”

• Recognized only recently (1923) as independent stellar systems

• A great diversity of shapes and sizes (~10^5- 10^{13} M_{Sun})

• Normal vs. Active Galaxies - latter are most energetic observed objects in the universe

True Nature of Spirals

"Spiral nebulae" or "Island universes" ?

What are the distances to these objects?

Why do they seem to avoid the plane of our Galaxy?

Why large recession velocities from plane of our Galaxy?

Shapley - Curtis debate (1920)

Shapley	Curtis
Distances small	Distances large
Spirals avoid disk and have recession speeds due to an unknown repulsive force	Spirals avoid disk because of obscuring material No explanation for recession speeds

True Nature of Spirals

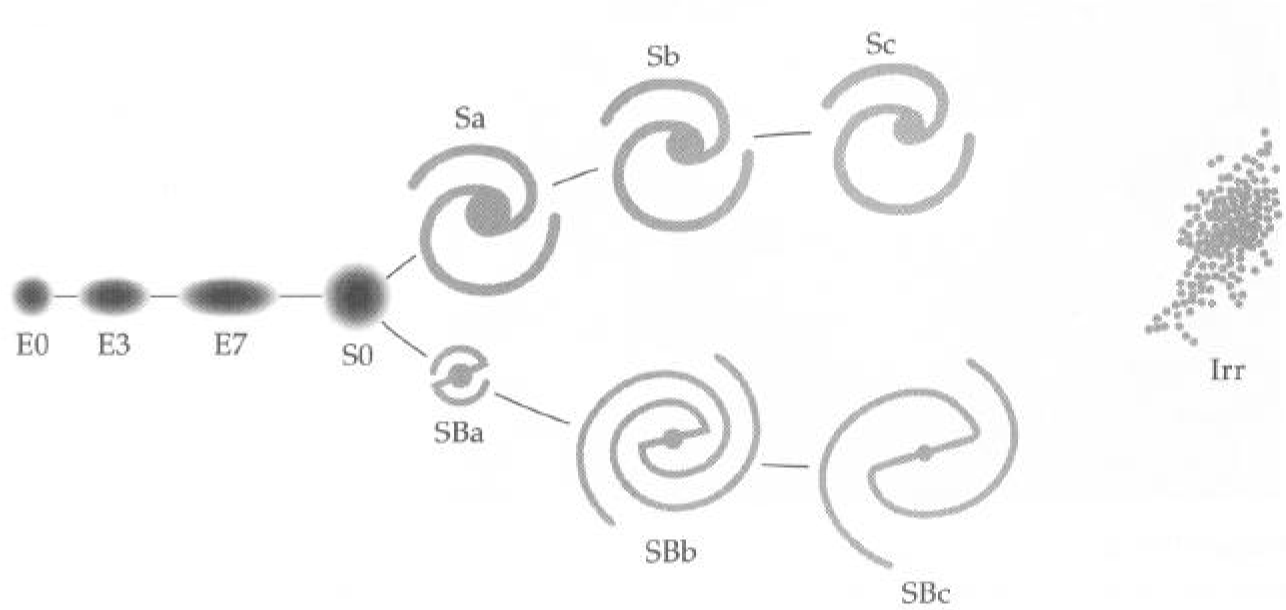
Resolution of controversy:

Hubble (1923) identifies a Cepheid variable in M31 (Andromeda Galaxy) .

P-*L* relation yields $d \approx 6 \times 10^5 \,\mathrm{pc}$.

M31 must be an external galaxy!

Hubble's Classification Scheme



Hubble thought (incorrectly) that this was an evolutionary sequence.

Ellipticals: E0 - E7

Spirals: normal spirals (Sa - Sc) or barred spirals (SBa -SBc)

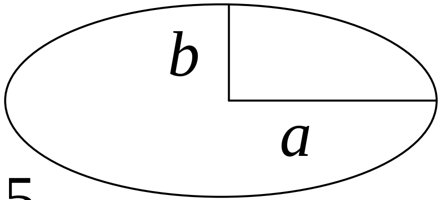
Irregulars

Dwarfs

Also, Peculiars and cD galaxies.

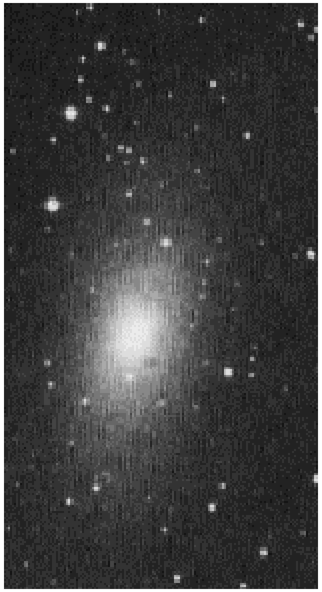
Ellipticals

E0 (circular) - E7 (most flattened)



Ellipticity is 10 (*1 - b*/*a)*, e.g., *a/b* = 2 => E5

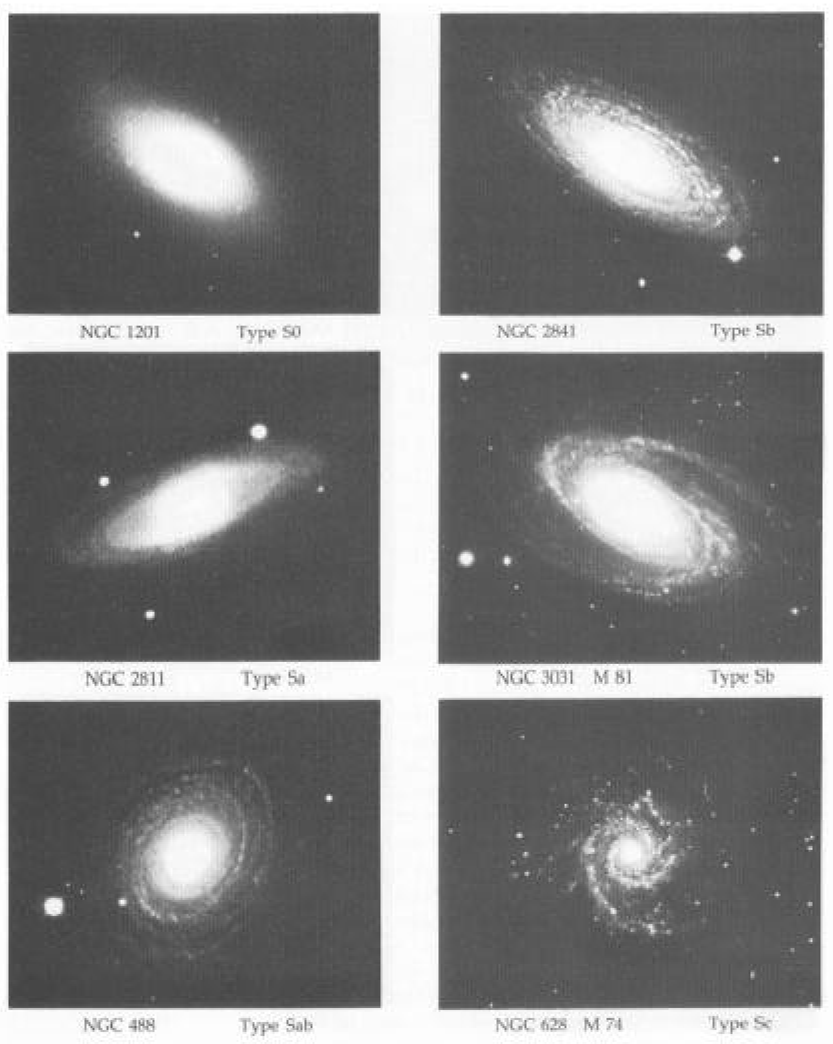
- See a smooth distribution of light, typically $I(r) \propto \exp[-(r/r_0)^{1/4}]$.
- No large scale rotation
- Very old stars, little dust and gas, and no current star formation

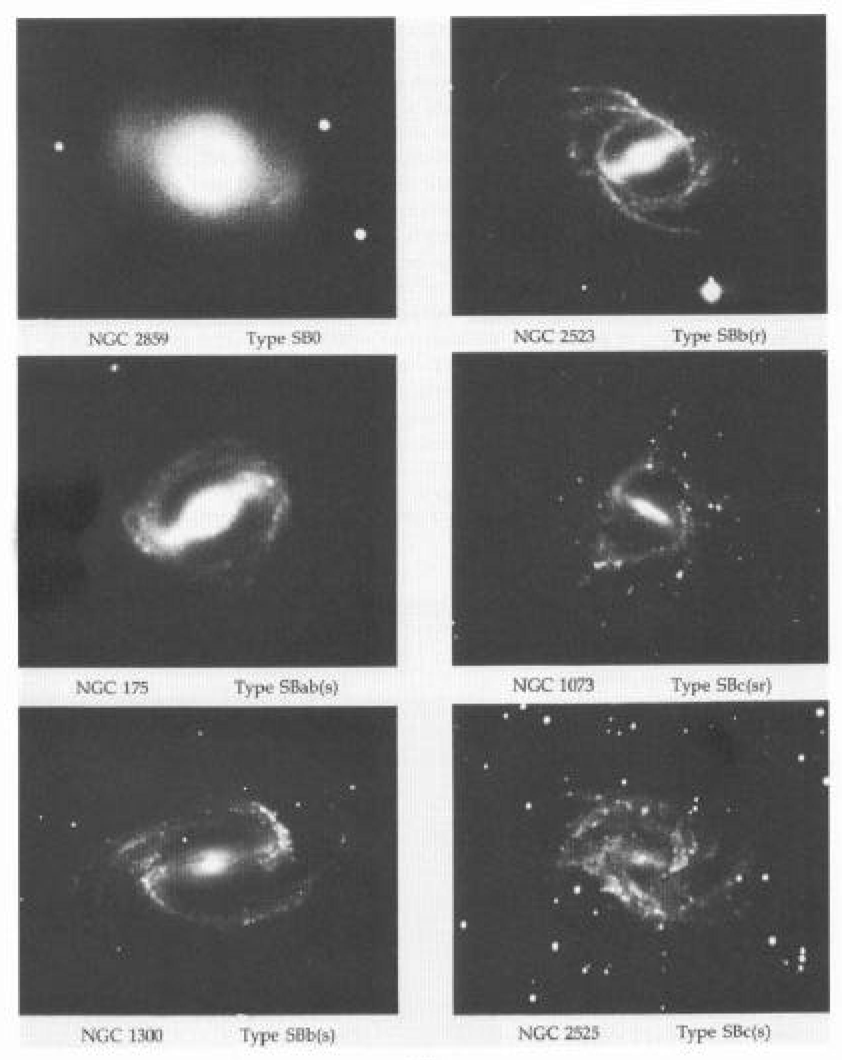


Also, cD galaxies are supergiant ellipticals in the centers of galaxy clusters. Have multiple nuclei, and are likely formed by merger of many galaxies.

M110, an E6 elliptical

Spiral Galaxies





Normal spirals

Barred spirals

Spiral Galaxies

Spiral arms emerge from central region or a bar:

<u>Sa (SBa), …, Sb (SBb), …, Sc (SBc)</u>

most tightly bound $\longrightarrow$ least tightly bound

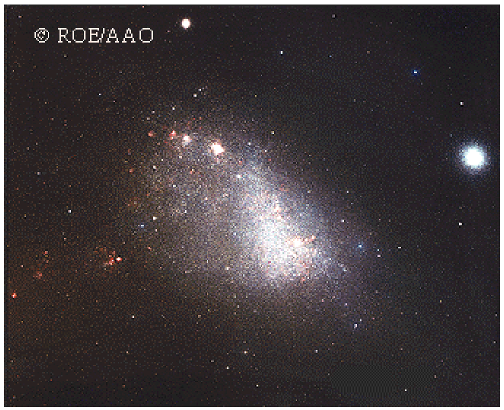
brightest nucleus $\longrightarrow$ dimmest nucleus

- Rotational motions dominate
- Contain old and young stars, 20-30% mass in gas and dust, ongoing star formation, mainly in spiral arms
- Intensity $I(r) \propto \exp[-(r/r_0)^{1/4}]$ in nuclear bulge, just like ellipticals, but $I(r) \propto \exp[-(r/r_0)]$ in disk.

Irregulars

No symmetrical or regular structure

Lots of gas and dust and ongoing star formation.



The Small Magellanic Cloud (SMC), a satellite of the Milky Way

Dwarfs

Leo I, an E3 dE in the Local Group of galaxies.

Account for most galaxies in the universe! Have < 10^9 stars.

Mostly dwarf ellipticals (dE) or dwarf irregulars (dI)

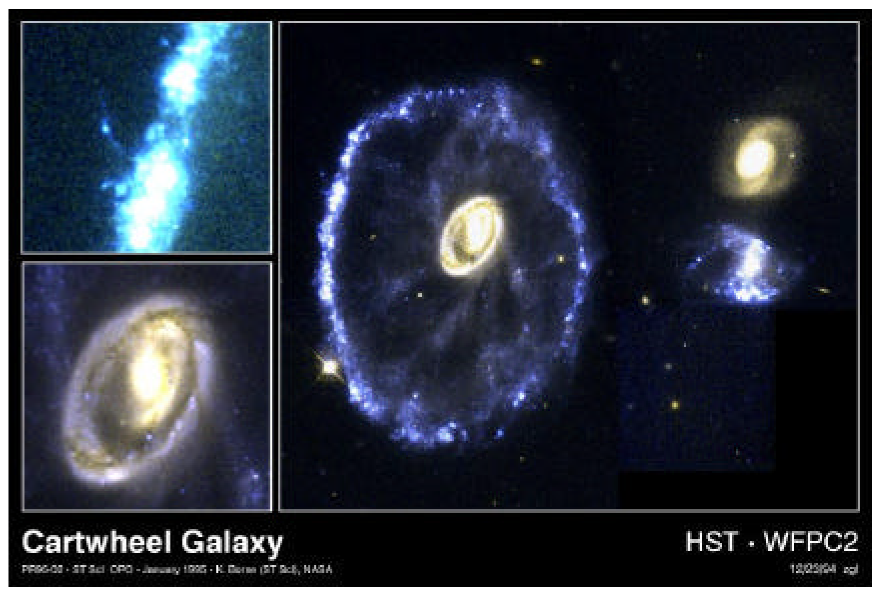
S0 Galaxies

Intermediate between ellipticals and spirals. Flatter than E7 and has a noticeable disk, but no spiral arms.

NGC 4594 - The Sombrero Galaxy. Actually an Sa galaxy, but close to S0 type.

Peculiars

Do not fall into any of the above categories. May have undergone interaction with another galaxy => tidal effects.



Other Properties

Ellipticals	-	Spirals	-	Irregulars
		Sa-Sb-Sc		
reddest (greatest *B*-*V*'s)	→		→	bluest (lowest *B*-*V*'s)
old pop I, pop II stars	→	pop I in arms, old pop I in bulge, pop II in halo	→	pop I, some popII
almost no gas and dust	→		→	most gas and dust

The Morphological Mix

Most galaxies are dwarfs (mainly dE’s). However, large galaxies contain most of the mass.

Among large galaxies:

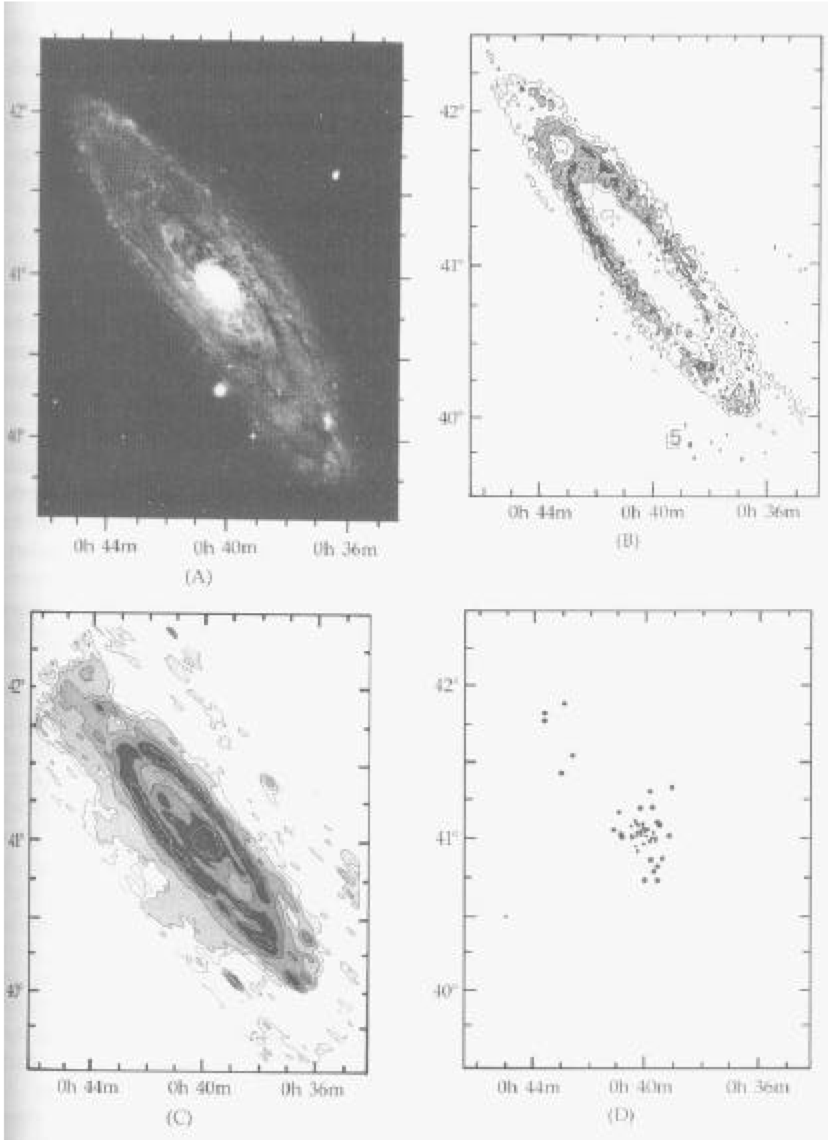
Observed galaxies -	77% spirals, 20% ellipticals, 3% irregulars

But only brightest distant galaxies are observed.
Look for a more complete sample.

Within 9.1 Mpc -	33% spirals, 13% ellipticals, 54% irregulars

although many irregulars are small, nearly like dwarfs.

Galaxies at Other Wavelengths



M31 at four wavelengths

(A) Optical (blue band): Stars

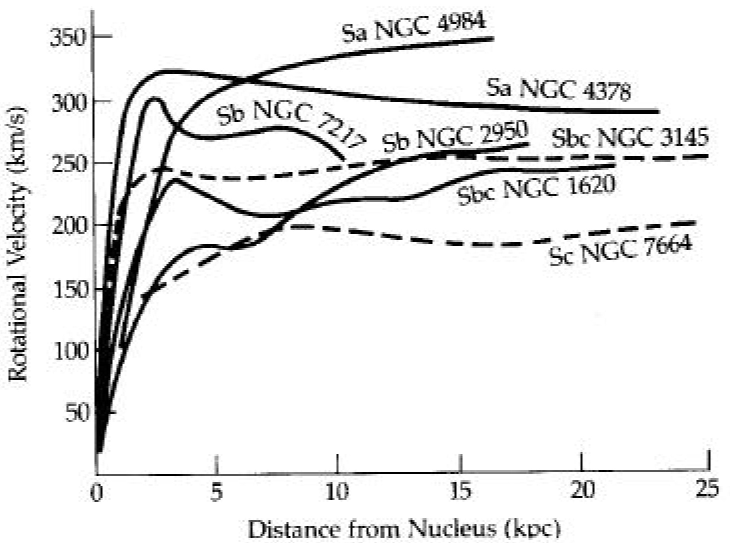
(B) Radio: 21 cm line emission. Also, see synchrotron emission at continuum radio wavelengths.

(C) Infrared 60 μm: Thermal radiation from dust grains.

(D) X-ray: Discrete sources. Hot gas around compact objects.

Masses of Galaxies

Spiral galaxies: measure Doppler shifts at different radii, using optical and H I measurements => get rotation velocities.



Rotation curves for several spirals - do not decrease in any galaxy!

Predicted Keplerian motion $v \propto r^{-1/2}$ at large radii not observed!

$$v \approx \text{constant} \quad \Rightarrow \quad m(r) \propto r.$$

Mass-to-light ratio of stellar matter is $\dfrac{M}{L} \sim 1 \dfrac{M_{Sun}}{L_{Sun}}.$

Measured rotation curves at outer radii require $\dfrac{M}{L} \sim (5-30) \dfrac{M_{Sun}}{L_{Sun}}.$

What can account for the missing dark matter?