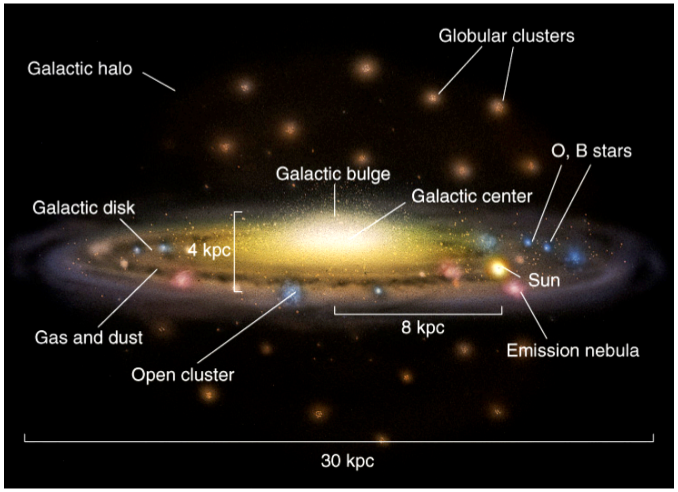
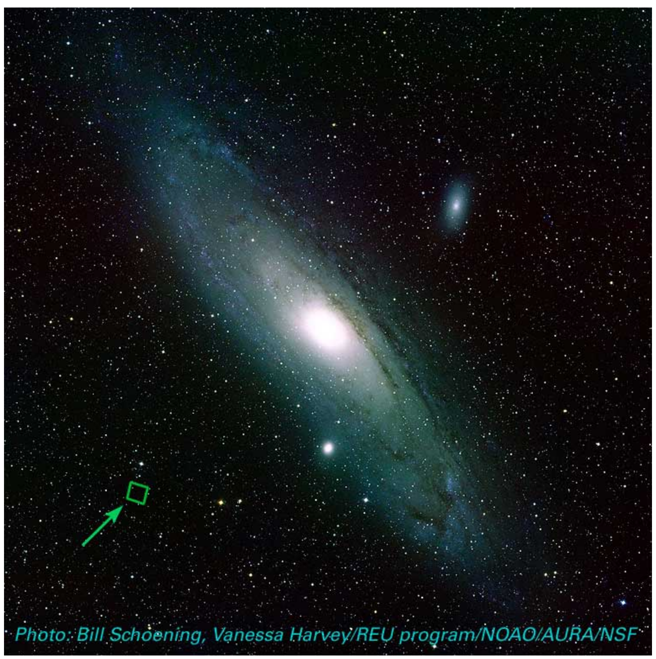
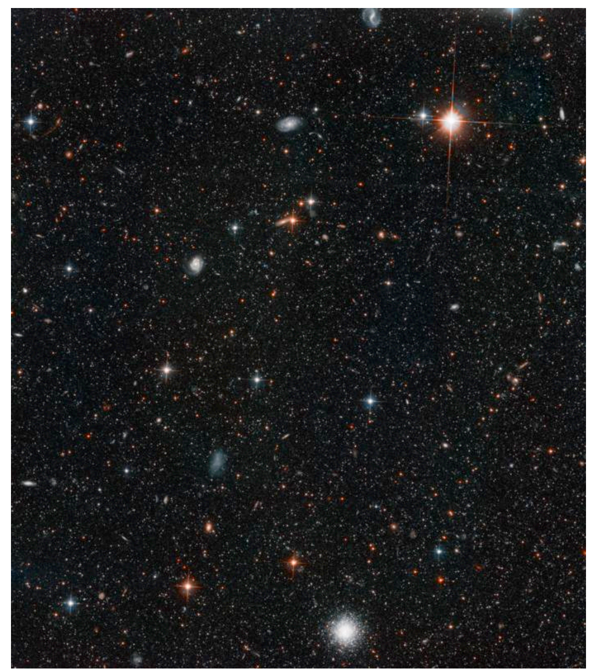
The Milky Way:



Spiral galaxies:

- Basic components:
  - Disks: metal rich stars and ISM, nearly circular orbits with little random motion, spiral patterns
  - Bulge: metal poor to super-rich stars, high stellar densities, mostly random motion – similar to ellipticals
  - Bar: present in 50 % of disk galaxies, long lived, flat, linear distribution of stars
  - Nucleus: central (<10pc) region of very high mass density, massive black hole or starburst or nuclear star cluster
  - Stellar halo: very low surface brightness (few % of the total light), metal poor stars, GCs, low-density hot gas, little/no rotation
  - Dark halo: dominates mass (and gravitational potential) outside ~10kpc, nature unknown?





Spiral galaxies:

- Luminosity profiles (1D):
  - Exponential disk: $I(r) = I_0\ e^{-r/rd}$ or in magnitudes per square arcsec: $\mu(r) = \mu_0 + 1.09(r/r_d)$
  - r_d= disk scale length, typically ~2-6 kpc
  - Light falls off sharply beyond R_{max} ~3-5r_d
  - In the central regions, also see light from the bulge
  - Bulge follows the $r^{1/4}$-law, like ellipticals

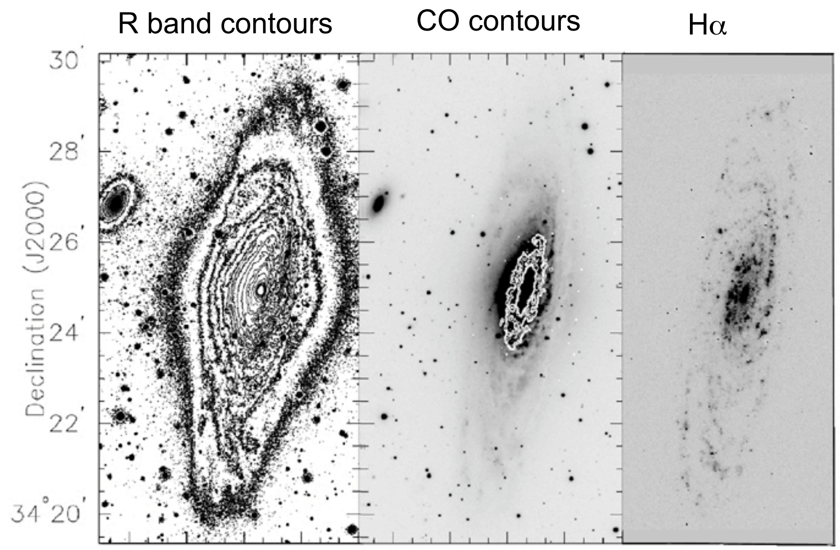


Fig 5.3 (Ferguson, Thornley) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

NGC 7731 -- Sb

Spiral galaxies:

- We can perform a bulge/disk decomposition.
- And calculate bulge to disk and bulge to total ratios (by integrating exponential and $r^{1/4}$-laws as in the problem set!)
- We find that B/D decreases along the Hubble sequence
  - Note there is lots of scatter!

Bulge to disk decomposition:

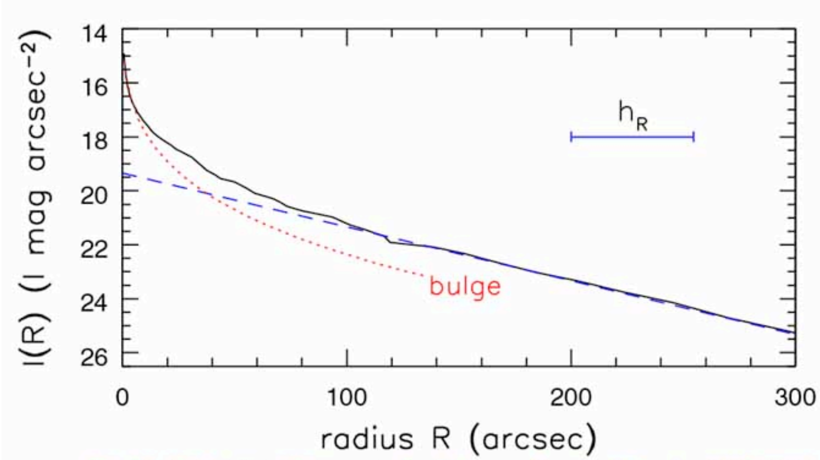
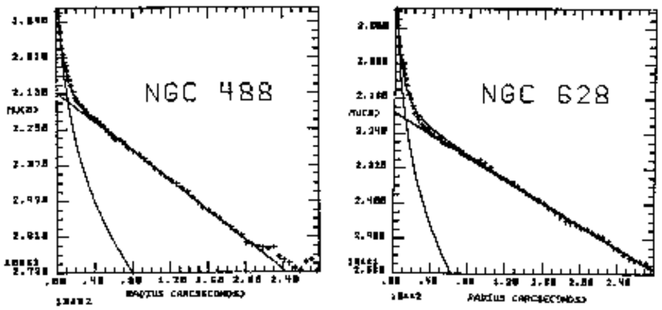


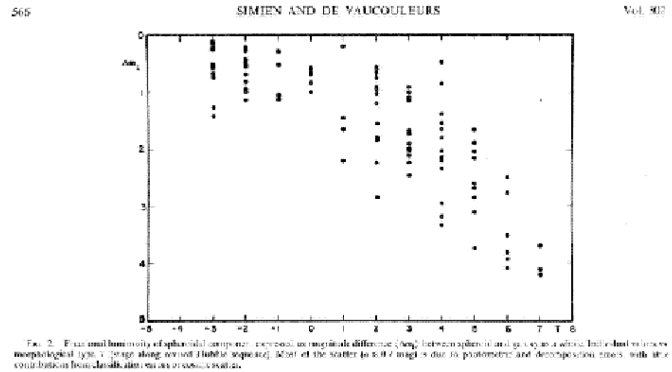
Fig 5.4 (R. Peletier) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Bulge to disk decomposition:



Boroson (1981)

Bulge to total ratio vs T-type:



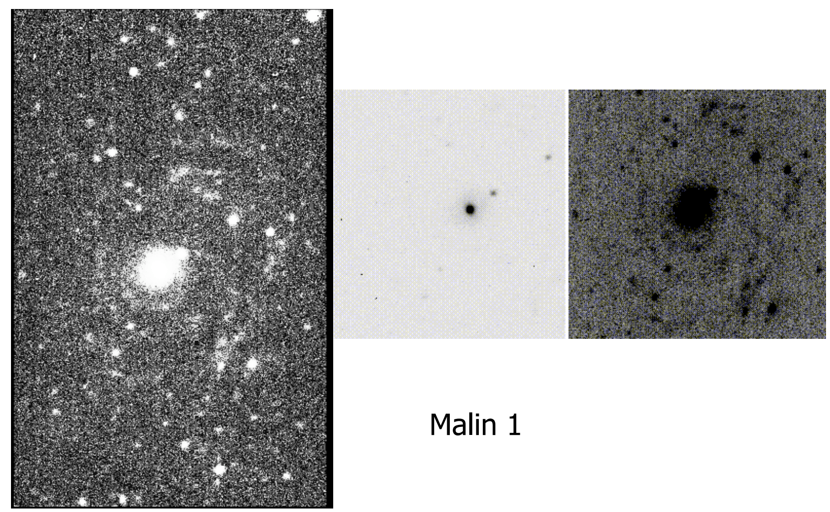
see: Simien, de Vaucouleurs (1986) *ApJ*, **302**, 564

Y-axis is difference in magnitudes

Spiral galaxies:

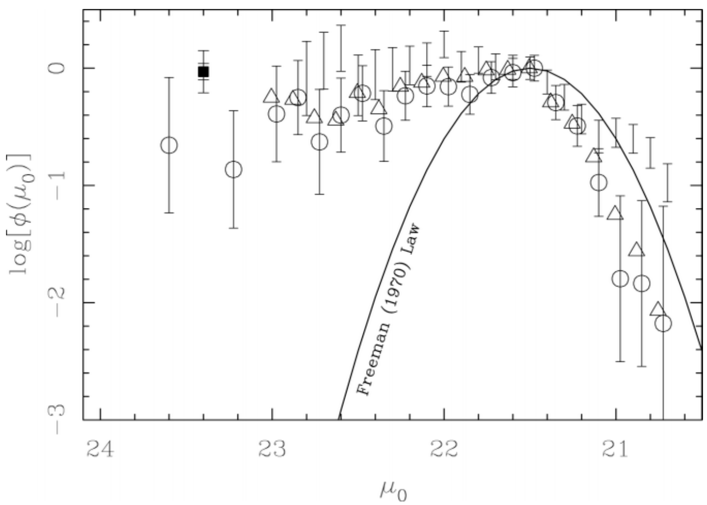
- Freeman’s Law:
  - Freeman (1970) found that all disks reach a central surface brightness of $\mu_B(0)$ = 21.7±0.3 mag per square arcsec
  - This is now known to be a *selection effect* !
  - Freeman’s value is an upper limit, but there are plenty of low surface brightness galaxies (LSBs)

Low Surface Brightness Galaxy



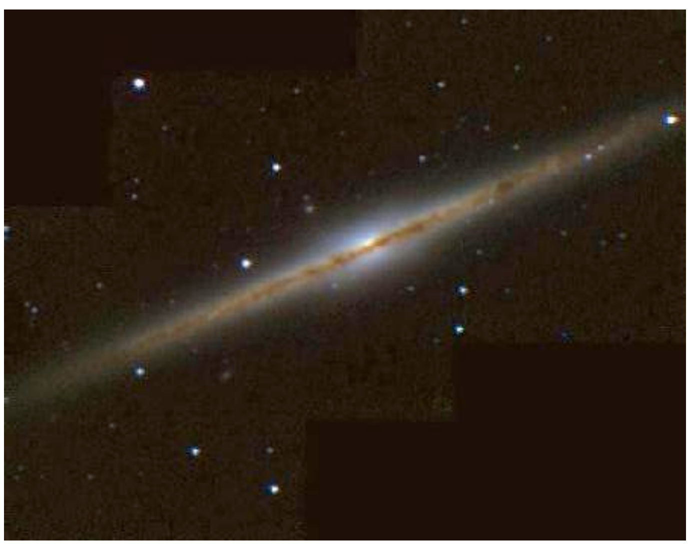
Malin 1

Low Surface Brightness Galaxies:



Spiral galaxies:

- Vertical disk structure:
  - The surface brightness perpendicular to the disk is also described by a exponential or sech law
    - $I(z) = I(0) \exp(-|z|/z_0)$
    - $I(z) = I(0) \text{sech}^2(-|z|/2z_0)$ recall $\text{sech}(z)=2/[\exp(z)+\exp(-z)]$
    - z_0 is the scale height of the vertical disk
  - Different populations have different scale heights. In the Milky Way:
    - Young stars & gas ~50pc
    - Old thin disk ~300-400 pc (older stars, like the sun)
    - Thick disk ~1 – 1.5 kpc (older, metal-poor stars)



NGC 891

Spiral galaxies:

- Inclination effects:
  - We can integrate surface brightness to obtain a total apparent magnitude (in a given filter)
  - But we need to correct for:
    - Dust (both in the MW, and internal absorption)
    - And inclination – face-on(i=0), edge-on (i=90)
    - Corrected total magnitudes are quoted as B^0_T
    - Corrected color quote as $(B-V)^0$

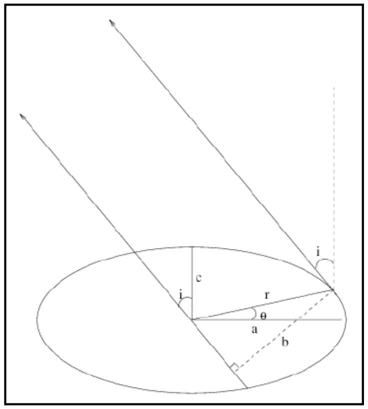
Spiral galaxies: Inclination

Inclination: face-on(i=0°), edge-on (i=90°)

- To first order, cos i = b/a where a & b are the *observed* major and minor axes (assume disk is intrinsically circular)
- But this implies galaxies have zero thickness at i = 90°! Better to assume that spirals are oblate ellipsoids with *intrinsic* axis ratios *a*:*a*:*c*. If $q = c/a$, then after a bit a simple geometry

$$\cos^2 i = \frac{(b/a)^2 - q^2}{1 - q^2}$$

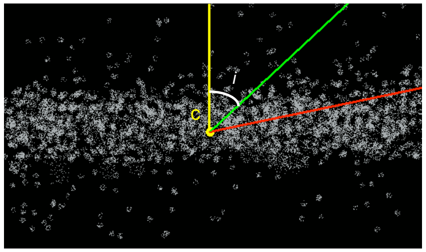
- The best fit to observed spirals yields q = 0.13 for Sc galaxies.



- All things being equal, the mean surface brightness of a spiral will increase with increasing inclination. (The same luminosity will be squeezed into a smaller area.) But internal extinction works in the other direction.

Spiral galaxies: Internal Extinction

The higher the inclination, the longer the path length through the galaxy, and the greater the extinction. For a slab of thickness c, the path length is p = c / cos i = c sec i. An inclined spiral will suffer more internal extinction than a face-on spiral by A_i-$A_{i=0}$ = c (sec i - sec(0)) = c (sec i - 1)



- In RC3, de Vaucouleurs corrected the observed B-magnitude of spiral galaxies for internal extinction by $A_B(i)$ = 0.70 log[sec(i)]
- By looking at the surface brightnesses of ~1200 spiral galaxies, Giovanelli et al. (1994) empirically estimated the I-band internal extinction to be A_I = 1.12(±0.05) log (a/b)

Internal Extinction:

log(a/b)

Ave. SB

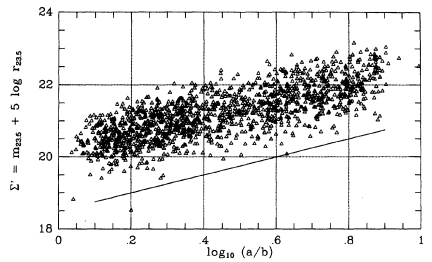
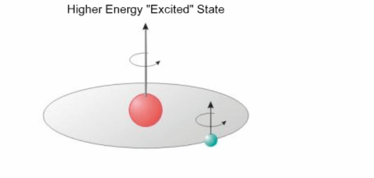


FIG. 8. Surface magnitude averaged over a circular aperture of radius $r_{23.5}$ vs log of the axial ratio, for our sample of 1235 objects. The solid line is an arbitrary linear law of slope 2.5.

Giovanelli et al. (1994)

Spiral galaxies: Gas Content

- Gas in spirals
  - Cool atomic HI gas
  - Molecular hydrogen H_2
  - Need gas to form stars!
  - Can observe ionized hydrogen via optical emission-lines (Hα)
  - Observe HI via radio emission – 21 cm line due to hyperfine structure – a hydrogen atom that collides with another particle can undergo a spin-flip transition



Spiral galaxies:

- Spirals show HI disks (amount of HI depends on Hubble type)
- HI gas is optically thin: the 21 cm line suffers almost no absorption. Note that spin flips are classically “forbidden”: on average, a single hydrogen atom will take 10^7 years to decay!   The probability of an absorption is even rarer.
- HI gas mass is directly proportional to 21 cm line intensity
- HI disk is much more extended than optical light, typically out to $2R_{25}$ sometimes farther
- The radial motion of the 21 cm line can be used to measure rotation in spiral galaxies

Galaxies in Ursa Major -- HI gas fraction is larger for fainter galaxies

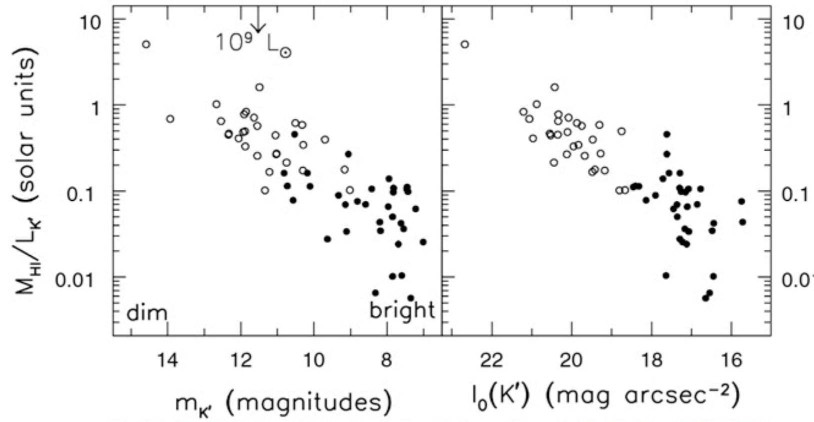
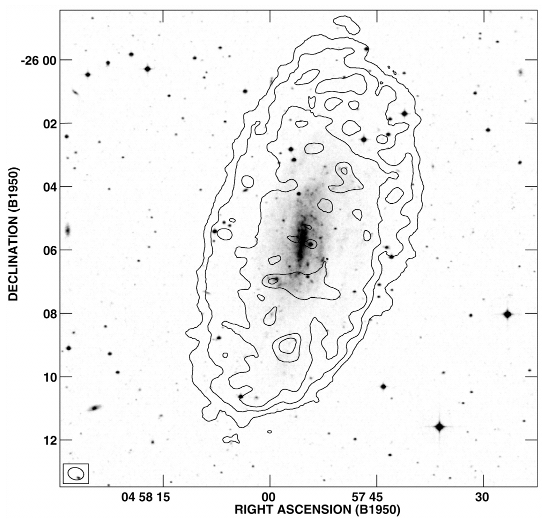
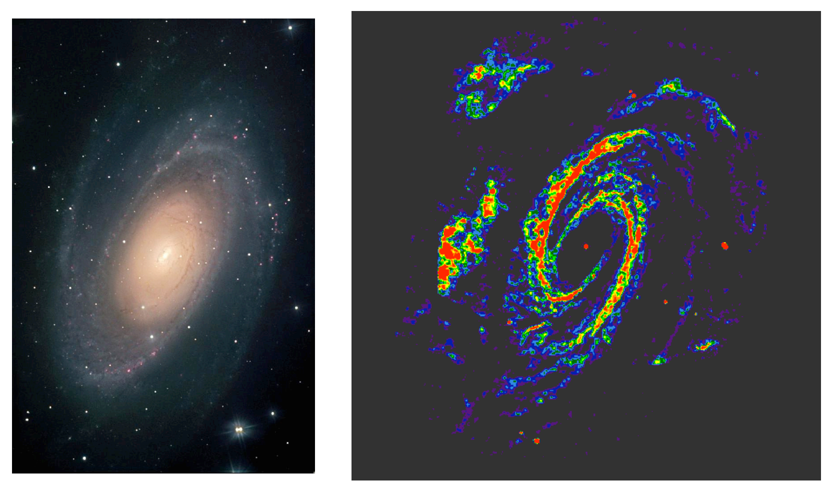


Fig 5.8 (M. Verheijen) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



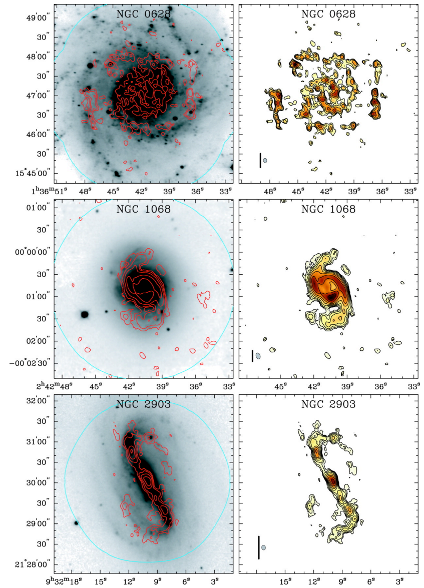
NGC 1744 Optical & HI contours



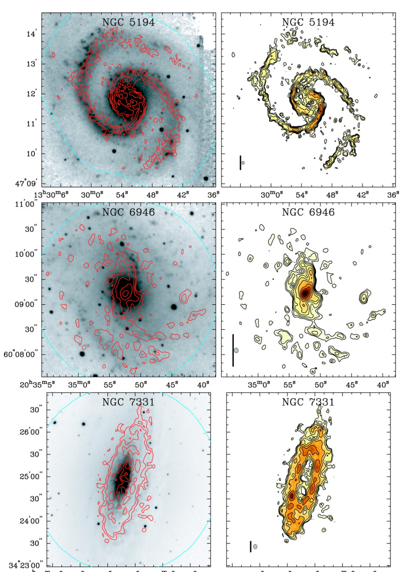
M81 – optical and HI

Spiral galaxies:

- In denser regions of the ISM, collisions between atoms become frequent enough to form molecules.
- The most common molecule is H_2, but since H_2 is a symmetric molecule, it has no rotational quantum transitions. It is therefore *extremely* difficult to detect.
- As a tracer of H_2, astronomers usually use CO
- Ratio of CO/H_2 is ~6 x 10^{-5}
- CO is generally most intense in a galaxy's inner regions, some spirals have inner rings, others have peaks in the center
- CO is generally not detected beyond the stellar disk



BIMA SONG survey
Regan et al. (2001)



BIMA SONG survey
Regan et al. (2001)

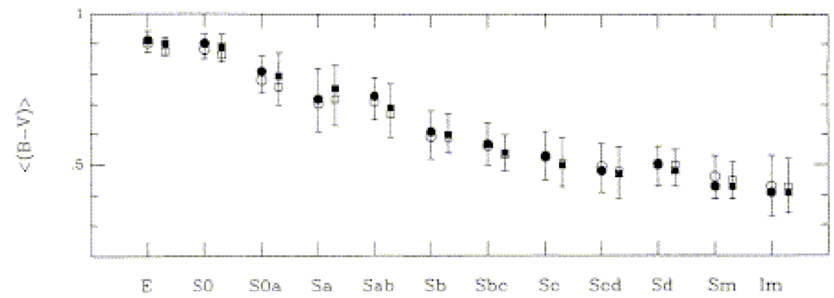
Spiral galaxies – trends with the Hubble Sequence:

- There are many trends with galaxy luminosity and with Hubble type
  - Tightness of spiral arms
  - Bright spirals are more metal rich than faint spirals
  - Early-type spirals are more metal rich than late-type spirals
  - Later type galaxies are bluer
  - Later type galaxies have more gas

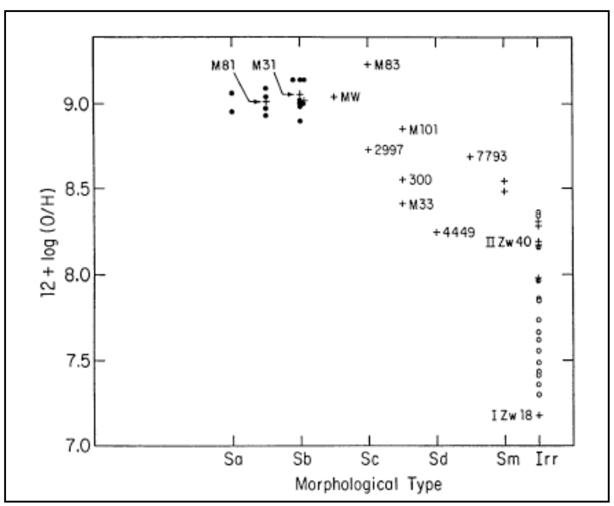
Spiral galaxies – trends with the Hubble Sequence:

	S0-Sa	Sb-Sc	Sd-Sm
Spiral Arms	Absent or tight		Open spiral
Color	Red; late G star	Early G star	Blue; late F star
B-V	0.7-0.9	0.6-0.9	0.4-0.8
Young stars	few		many
HII regions	Few, small		More, brighter
Gas	Little gas		Much gas
Blue luminosity	1-4 x $10^{10} L_\odot$		<0.1-2 x$10^{10} L_\odot$
Central SB	high		low
mass	0.5-3 x $10^{11} M_\odot$		<0.2-1 x 10^{11} $M_\odot$
rotation	Fast rising		Slow rising

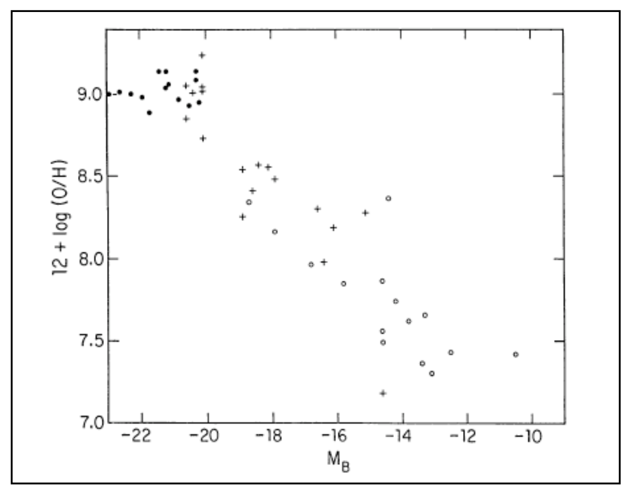
Later type galaxies are bluer:



Roberts & Haynes (1994)



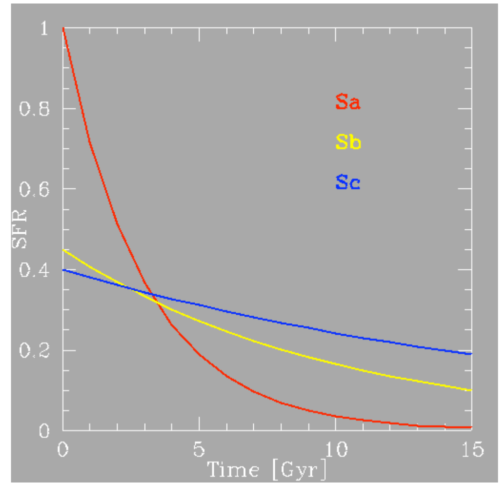
Roberts & Haynes (1994)



Spiral galaxies – trends with the Hubble Sequence:

- Best interpretation of many of these is a trend in star formation history
  - Early type spirals formed most of their stars early on (used up their gas, have older/redder stars)
  - Late type spirals have substantial on-going star-formation, didn't form as many stars early-on (and thus lots of gas left)
  - Spirals are forming stars at a few $M_\odot$ per year, and we know that there is a few x $10^9\,M_\odot$ of HI mass in a typical spiral
    - How long can spirals keep forming stars??

SFR history vs Hubble type:



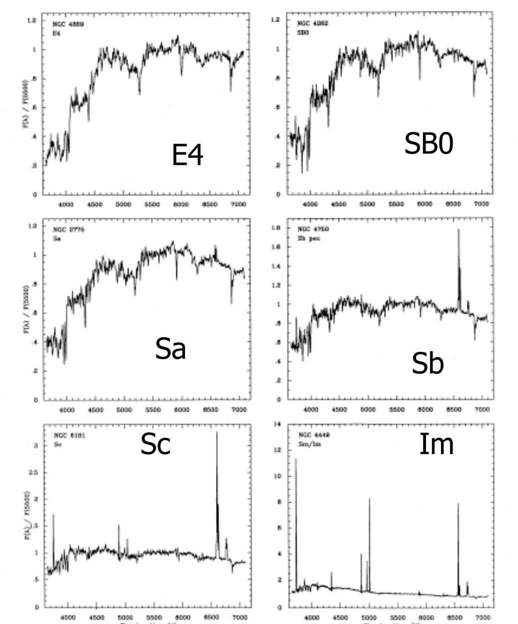


Fig. 2a

FIG. 2.—(a) The spectral Hubble sequence. Galaxies are shown in order of increasing Hubble type from top to bottom. See Table 3 for data on the galaxies. (b) Same spectra as in (a), but expanded in the blue to show the properties of the absorption-line spectra.

Kennicutt (1992)

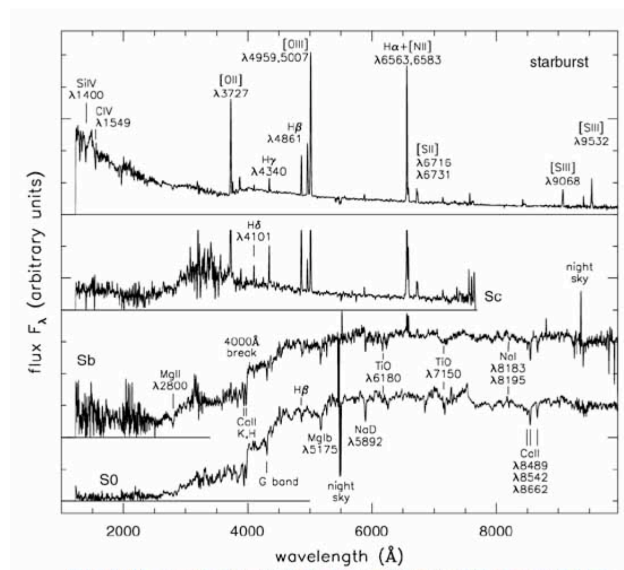


Fig 5.24 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Rotation Curves:

- We can measure rotation curves via:
  - HI mapping
  - Via optical spectroscopy Hα
  - What are the advantages/disadvantages of each?
  - For HI mapping, we observe the radial velocity $V_r(r,i)$. We can convert this to true rotation speed V(r) via the equation $V_r(r,i) = V_{sys} + V(r) \sin i \cos \varphi$ where i is the inclination, φ the azimuthal angle, and V_{sys} is the systemic velocity
  - Contours of constant V_r connect points of equal $V(r) \cos \varphi$, producing the spider diagram

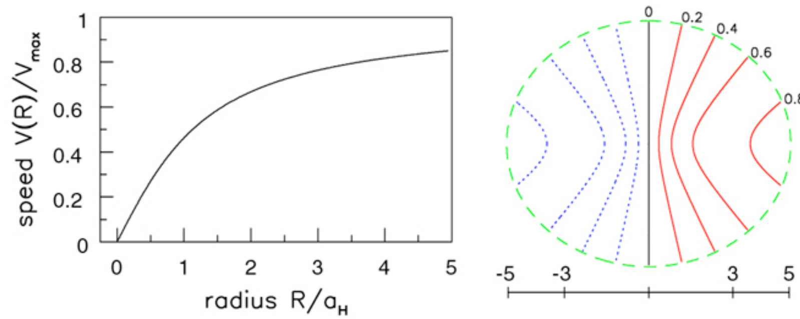
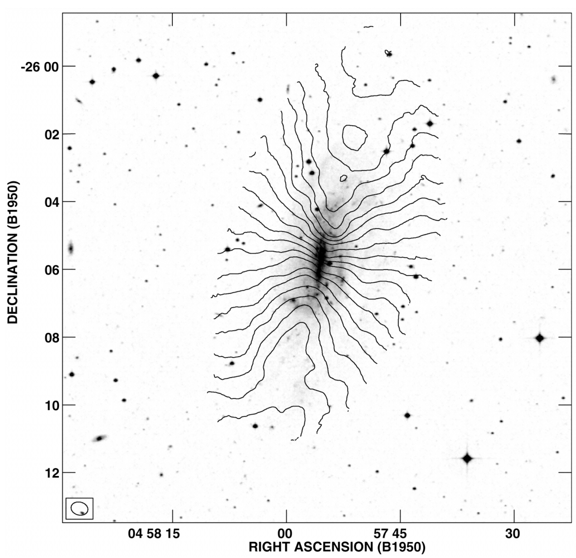


Fig 5.19 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



NGC 1744
Optical light and radial velocity contours (a "spider" diagram)

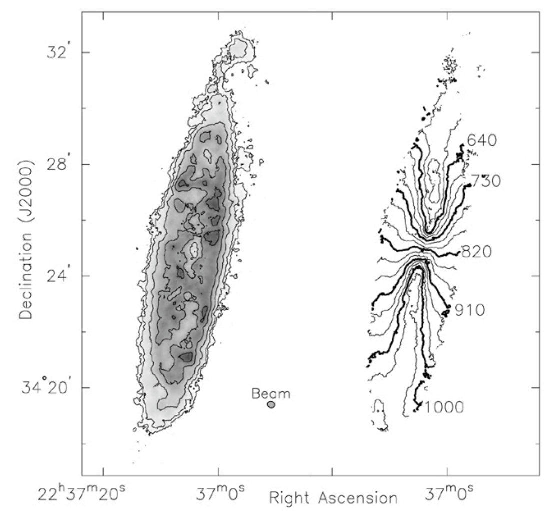


Fig 5.13 (Thornley & Bambic) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

NGC 7731

HI rotation curve NGC 3918

No. 2, 1985 DISTRIBUTION OF DARK MATTER IN NGC 3198 309

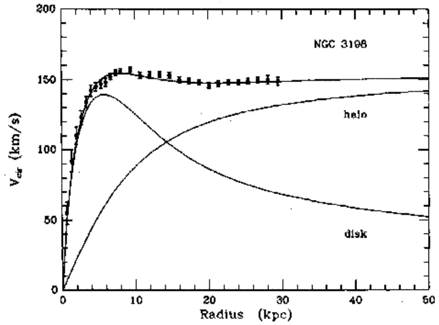


FIG. 4.—Fit of exponential disk with maximum mass and halo to observed rotation curve (*dots with error bars*). The scale length of the disk has been taken equal to that of the light distribution (60", corresponding to 2.68 kpc). The halo curve is based on eq. (1), a 8.5 kpc, γ 2.1, $\rho(R_0)$ 0.0040 $M_\odot$ pc^{-3}.

see: van Albada et al. (1985) *ApJ*, **295**, 305

$$\Phi = \Phi_{halo} + \Phi_{disc} \Rightarrow v_{circ}^2 = v_{c,halo}^2 + v_{c,disc}^2 \left(v_{circ}^2 = r\frac{\partial\Phi}{\partial r} \right)$$

Hα rotation curves

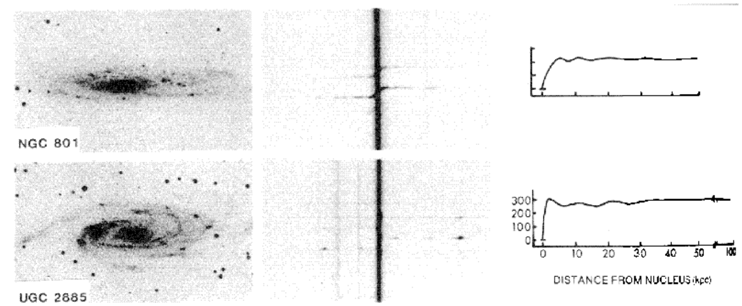
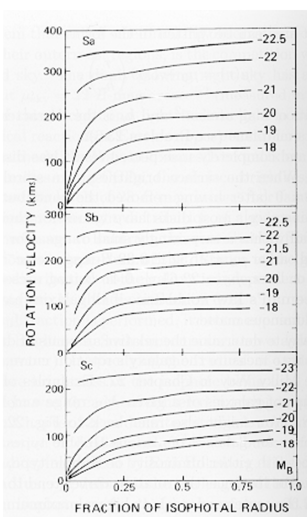


Figure 10-1. Photographs, spectra, and rotation curves for ~~five~~ two Sc galaxies, arranged in order of increasing luminosity from top to bottom. The top three images are television pictures, in which the spectrograph slit appears as a dark line crossing the center of the galaxy. The vertical line in each spectrum is continuum emission from the nucleus. The distance scales are based on a Hubble constant $h = 0.5$. Reproduced from Rubin (1983), by permission of *Science*.

see: Binney, Tremaine (1994) *Galactic Dynamics* p.600



% of R_{25}

Rotation Curves vs
Hubble type & luminosity
Rubin et al. 1985

More luminous galaxies have higher rotation velocities, later type galaxies have slower rise in velocity

Typical spiral galaxies have peak rotation velocities of ~150-300 km/s

Rotation Curves:

For circular orbits,

$$\frac{mV^2}{r} = \frac{GM(r)m}{r^2} \quad \Rightarrow \quad M(r) = \frac{V^2 r}{G}$$

where V is the velocity, and $M(r)$ is the mass contained inside an orbit of radius r. If there is no mass outside this radius, then as r increases, $M(r)$ remains constant, and $V \propto r^{-1/2}$ (in other words, simple Keplerian motion).

However, since a spiral galaxy's rotational velocity is roughly constant with radius, that means $M(r) \propto r$ beyond limits of stellar disks. (But recall that the stellar luminosity is declining exponentially!)

Rotation Curves:

- For rotational velocity to remain constant:
  - $M(r) \propto r$
  - Since the amount of visible matter is declining exponentially, the mass must be coming from a "dark halo" that extends out to ~100 – 200 kpc
  - Since there is no visible matter to see, it is hard to measure total masses of spirals!
  - What does this imply for the density profile of the dark halo? To first order:

$$\frac{dM}{dr} = 4\pi r^2 \rho(r) \quad \text{(assuming spherical symmetry)}$$

$$M(r) = \frac{V^2 r}{G} \quad \Rightarrow \quad \frac{dM}{dr} = \frac{V^2}{G}$$

$$\frac{V^2}{G} = 4\pi r^2 \rho(r) \quad \Rightarrow \quad \rho(r) = \frac{V^2}{4\pi G r^2} \quad \Rightarrow \quad \rho(r) \propto r^{-2}$$

This looks like the outer regions of an isothermal sphere

Rotation Curves:

- The rotation curves of the inner regions of spirals can be explained by the visible mass, But in the outer regions of spirals, dark matter is needed. So the dark halo is often modeled via an approximation to an isothermal sphere:

$$\rho(r) = \frac{\rho_0}{1 + (r/r_c)^2}$$

$$\text{so } \rho \propto r^{-2} \text{ for } r >> r_c \text{ but } \rho \propto \rho_0 \text{ for } r << r_c$$

- So rotation curves can be modeled using 3 components:
  - an exponential disk (with constant M/L)
  - a bulge
  - a dark halo
- But how does the dark halo know when to start balancing out the contribution from the disk?? Disk-halo conspiracy!!

HI rotation curve NGC 7731

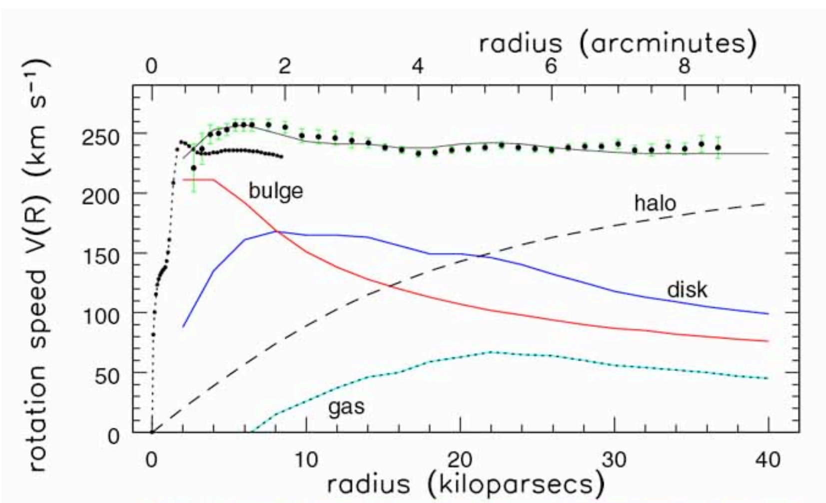
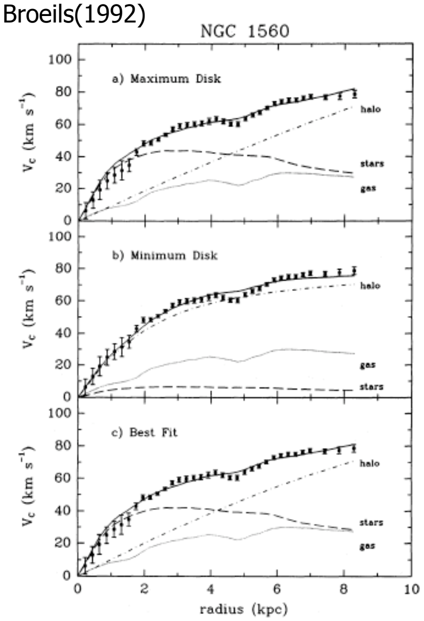


Fig 5.20 (Begeman, Sofue) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Broeils(1992)



Allocate as much mass to the visible disk as possible (assuming constant disk M/L)

Make disk M/L as small as possible, by allocating as much mass as possible to the dark halo.

Allow program to find the "best fit")

Rotation Curves:

- In the inner regions of spirals, the rotation velocity often increases as $V \propto r$. This implies that the angular velocity, V/r = constant. This is solid body rotation!
- But in the outer regions, where V is constant, the angular velocity falls off as $1/r$, *i.e.,* there is differential rotation! In other words, two stars starting out right next to each other on adjacent orbits will move apart with time.