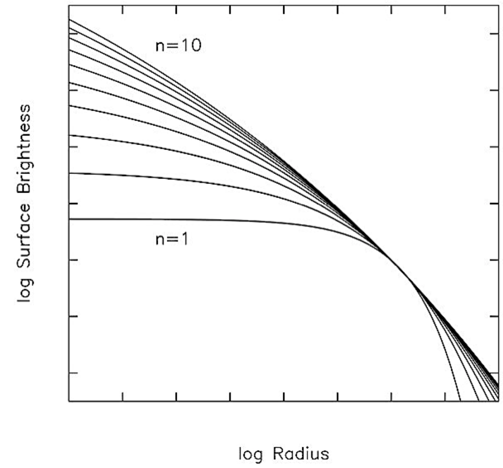
Descriptions of Galaxy Optical Surface Brightness

- For most massive galaxies a two component description of the surface brightness is a reasonable approximation to the azimuthally averaged data
  - Bulges/spheroids
  - Disks
- The ratio of these two components has wide variation
- <u>Both</u> can be described by a radially symmetric 'Sersic' profile

  $\Sigma(r)=\Sigma(0)\exp(-k\,[(r/r_e)^{1/n}-1]$;

k ~2n-0.331 (who called for that!) where r_e is the half light radius



$$L = 2\pi \int_0^\infty I(R)\, R\, dR = \frac{2\pi n \Gamma(2n)}{(\beta_n)^{2n}} I_0 R_e^2,$$

total luminosity of Sersic profile- Γ is the gamma function

Galaxy Optical Surface Brightness

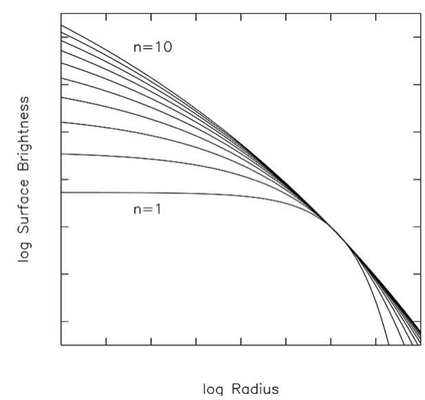
'Sersic' profile (S&G eq 5.13)

$\Sigma(r)=\Sigma(e)\exp(-k\,[(r/r_e)^{1/n}-1]$

k ~2n-0.331 where r_e is a characteristic scale length and

$\Sigma(e)$ is the intensity at the effective radius r_e that encloses half the total light

- **Disks have n~1 (exponential profile) while spheroids have n~2-5** (a special value is n=4, the DeVacouleurs profile)
- Most spirals have a bulge and thus **the surface brightness is the sum of 2 Sersic profiles** (the bulge usualy dominates for small r)

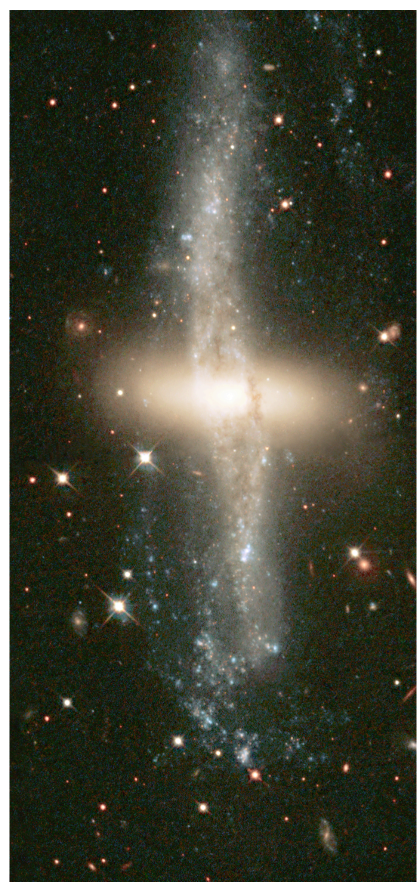


$$L = 2\pi \int_0^\infty I(R)\, R\, dR = \frac{2\pi n \Gamma(2n)}{(\beta_n)^{2n}} I_0 R_e^2$$

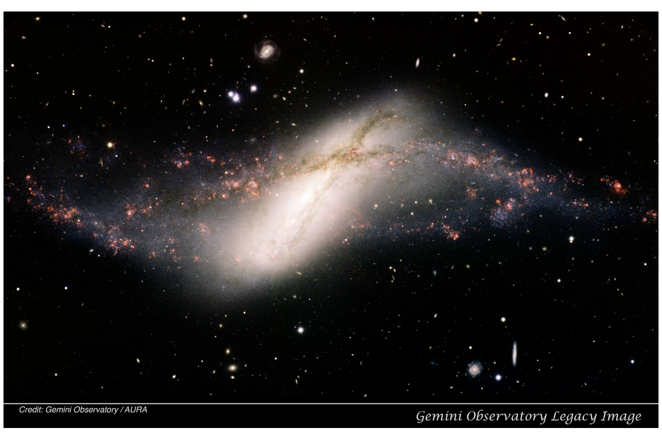
total luminosity of Sersic profile- Γ is the gamma function $\Gamma(2n) = (2n-1)!$

Total Luminosity

- $L(< R) = \int_0^R I(R) 2\pi R dR$
- $L(< R) = I(o) R^2 e 2\pi n e^{b/}(b)^{2n} \Gamma(2n, x)$
- $\Gamma(2n, x)$ Gamma function
- $\Gamma(2n) = (2n-1)!$
- see https://arxiv.org/pdf/astro-ph/0503176.pdf for lots of details
- For an exponential (n= 1) profile, 99.1% of the flux resides within the inner $4R_e$
- For an n= 4 profile, 84.7% of the flux resides with the inner 4 R_e
- For large values of n the S ´ersic model tends to a power–law with slope equal to 5.



- If one express the surface brightness in magnitudes, $\mu \propto -2.5\log(I)$, the Sersic profile can be expressed as
- $\mu(R) = \mu_e + 1.086k[(r/r_e)^{1/n} - 1]$
- .



Stellar Distribution-radial average

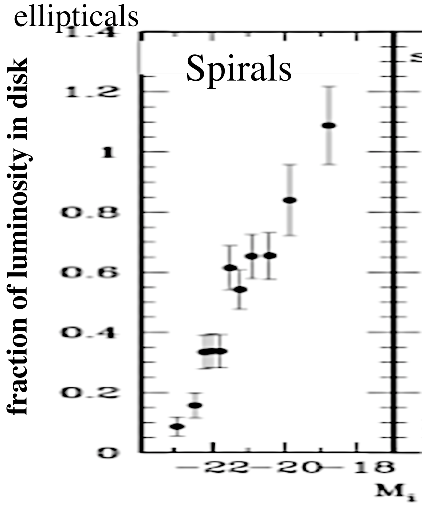
- Massive galaxies (spirals and ellipticals) can be described by a '2' component radial profile model:
  - disk; n~1
  - bulge; n~2-5 (n~4 for giant ellipticals

$$\Sigma(r) = \Sigma_e e^{-\kappa[(r/r_e)^{1/n}-1]}$$

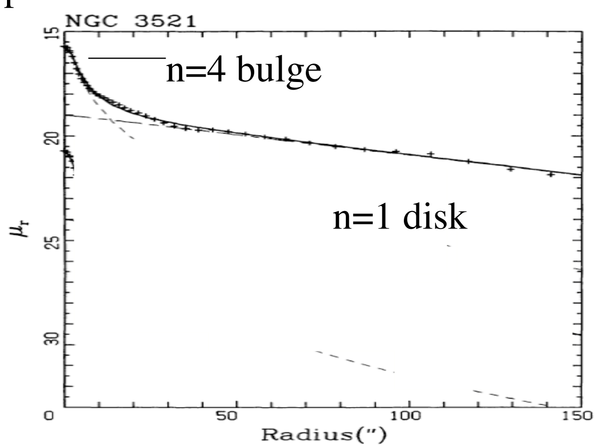
$$\kappa \approx 2n - 0.331$$

Sersic(1968) profile S+G eq 3.13

More massive galaxies have a higher fraction of their light (mass) in the bulge (and by defintion 'earlier' type

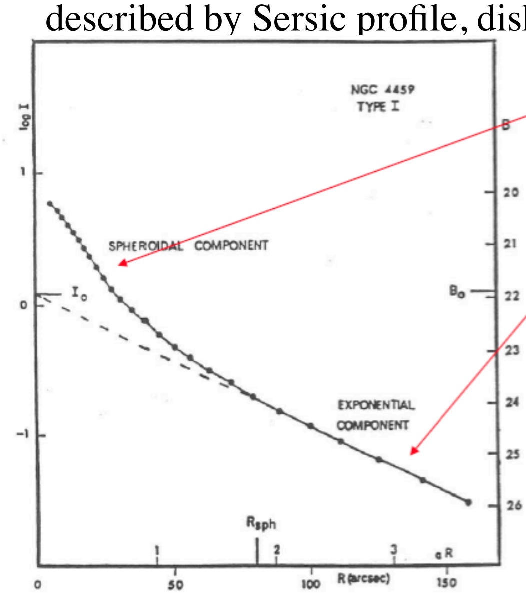


absolute mag



Azimuthally Averaged Light Profiles

- Bulge is more concentrated than the disk: bulge is described by Sersic profile, disk by an exponential profile



$$logI \propto R^{1/4} \quad \text{(inner)};$$

$$I(R) = I_0 e^{-\alpha r} \quad \text{(outer)}$$

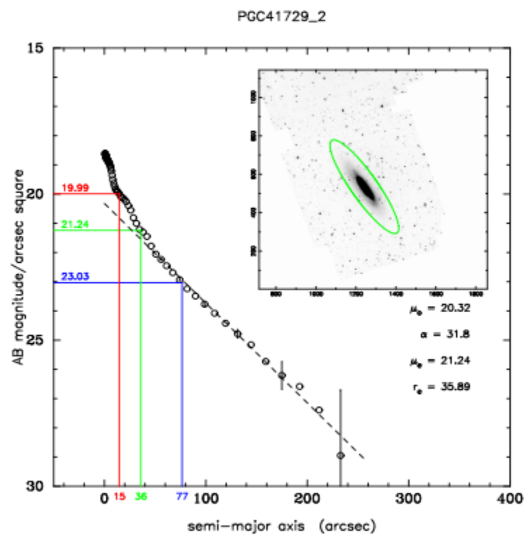
α is the inverse scale height

(Freeman 1970)

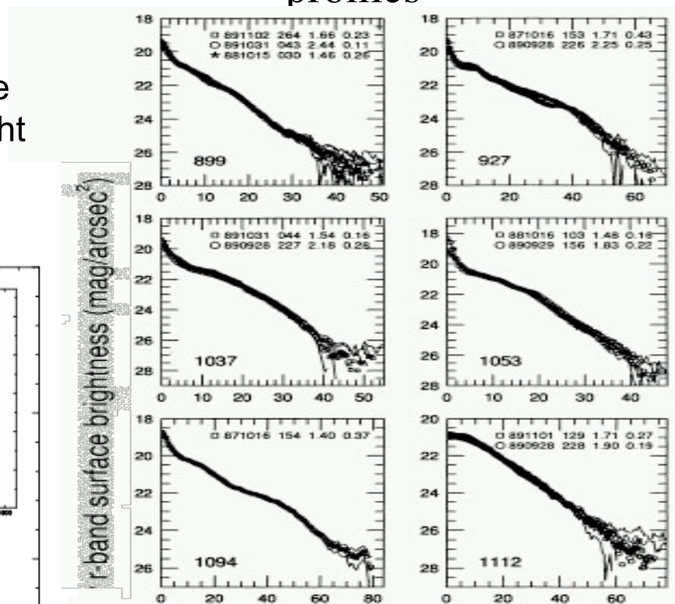
This is an approximation, galaxies with strong bars or other non-azimuthally symmetric features will clearly change this

Pure exponentials would be straight lines.

The exponential scale length is a measure of the size of the baryonic disk.- Most of the light is inside 2 scale lengths



Typical disk surface brightness profiles



Courteau, ApJS, 103, 363, 1996

Typical values for the scale length are:
$1<h_R<10$kpc
$h_R \sim M_*^{1/3}$

In many, but not all, spiral galaxies the exponential part of the disk seems to "end" at some radius R_{max},~ 3 - 5 h_R.

Beyond R_{max} the surface brightness of the **stars** decreases more rapidly – "edge" of the optically visible galaxy.

The central surface brightness of many spirals is ~ constant, irrespective of the absolute magnitude of the galaxy!

Presumably this arises from physics of galaxy and /or star formation.

What's Important So Far

- The class of galaxies called spirals (based on morphology in the optical) has a set of strongly correlated properties (mass, star formation, dust, gas, color) - so there is physics in morphology

- The big bifurcation between color, mass, morphology classification by color,mass, morphology gives similar but NOT identical results
  - At one lower level (e.g sub-divisions in morphology (Sa,Sb,Sc etc) there are also trends.
  - the luminosity function of galaxies is fit by a simple function (Schechter function) which is different for ellipticals and spirals but sums together into a smooth form
  - spirals tend to 'live in the field' low density regions
  - ellipticals in denser regions

  (morphology density relation- Dressler 1978)

Summary of Surface Brightness Profiles

- Most galaxies can be well fit with the Sersic profile, spirals have lower values of 'n' for the disk and 2 components to the profile (bulge, disk)
  - Sersic profile 2 asymptotic forms
    - low n ~exponential:$I(R)=I(0)(\exp-[(R/R_d)]$ where R_d is the disk scale length $I(R)=(1/e)I(0)$; total flux $I_{tot}=2\pi R^2_d I(0)$
    - high n - $R^{1/4}$ profile
  - deVacouleurs profile (n=4) $I(R)=I(R_e)(\exp-7.67[(R/R_e)^{1/4}-1]))$
  - R_e is the half light radius

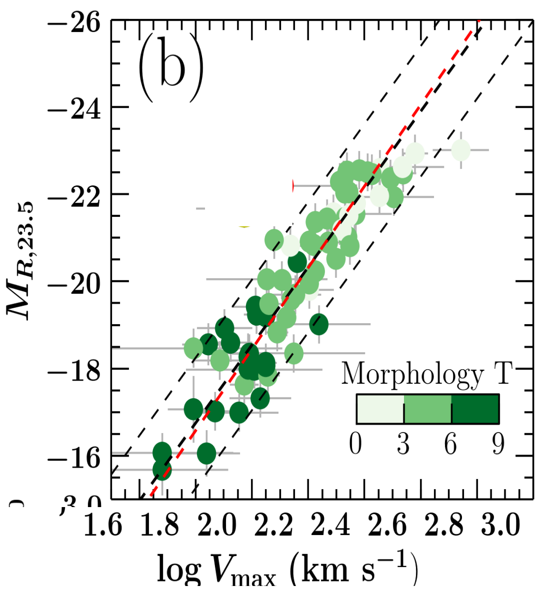
ESO510-G13

- Beautiful but complex

Tully-Fisher for Spiral Galaxies:S&G **5.3.3**

- Relationship between the speed at which a galaxy rotates,V, and its optical luminosity L_{opt}: (the normalization depends on the band in which one measures the luminosity and the radius at which the velocity is measured)
  - $L_{opt} \sim A v_{max}^4$
- Connects galaxy dynamics to optical luminosity
- Since luminosity depends on distance^2 while rotational velocity does not, this is a way of inferring distances

Absolute luminosity measured in magnitudes



log rotational velocity

arXiv:1508.03004v1
Barbosa et al

Figure shows the **T-F relation R band**

Tully-Fisher
Back of the envelope derivation

- System in equilibrium: centripetal force balances gravity
- $GM(r)/r^2=v_c^2/r$; so $M(r)=v_c^2r/G$; definition of surface density $\Sigma=L/r$

- If all galaxies are alike and have the same surface densities $L\sim r^2$
- Further if M/L is constant M~L
- a little algebra gives $L\sim v_c^2L^{1/2}\sim v_c^4$
- If galaxies contained no dark matter, we could understand the Tully–Fisher relation fairly easily
- But, since the rotation speed V_{max}

is set largely by dark matter, while the luminosity comes from stars Somehow, the amount of dark matter is coordinated with the luminous mass.

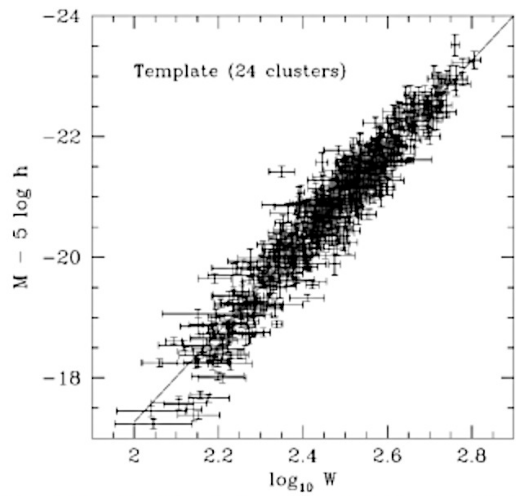


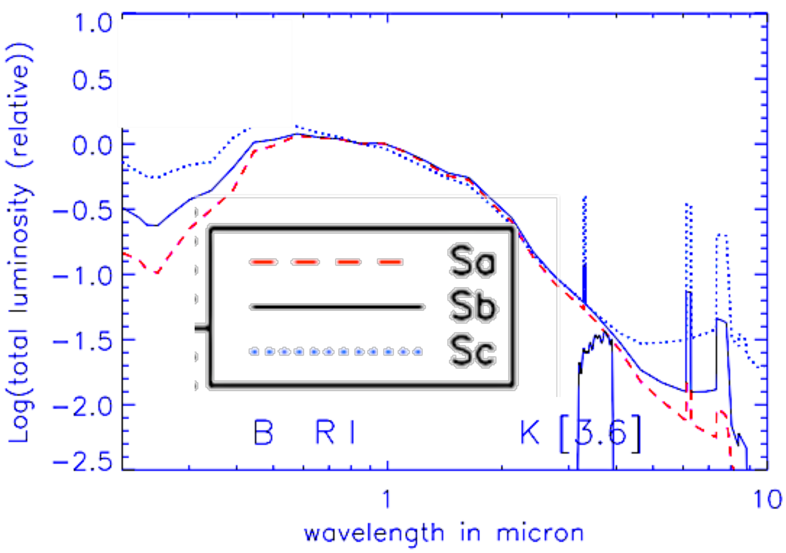
FIG. 1.—Template relation based on 555 galaxies in 24 clusters. The fit is −21.00 ± 0.02–7.68 ± 0.13 (log W − 2.5).

Giovanelli et al 1997

New Topic- Galaxy Optical-IR Spectra

Spiral Galaxy spectra

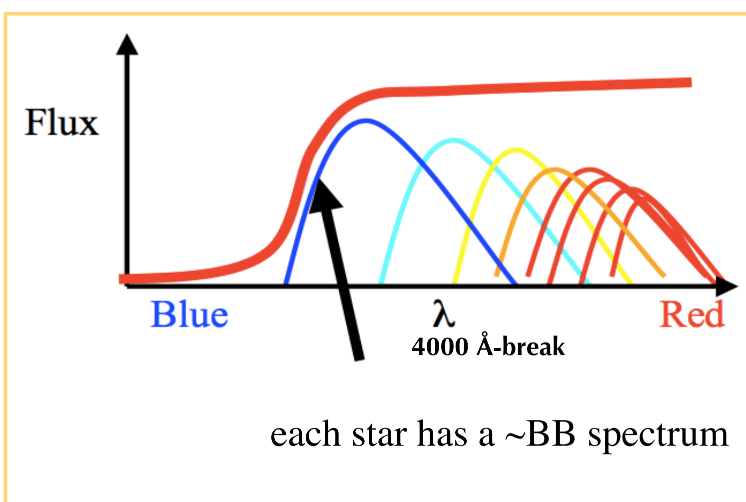
- Galaxies have composite spectra. They integrate contributions from different stars of different stellar populations, gas and the effects of dust
- The overall continuum shape is modulated by the gas, the stars, as well as by the presence of dust.



Spiral SEDs normalized at 8000Å with emphasis on near IR spectral features (PAHs)

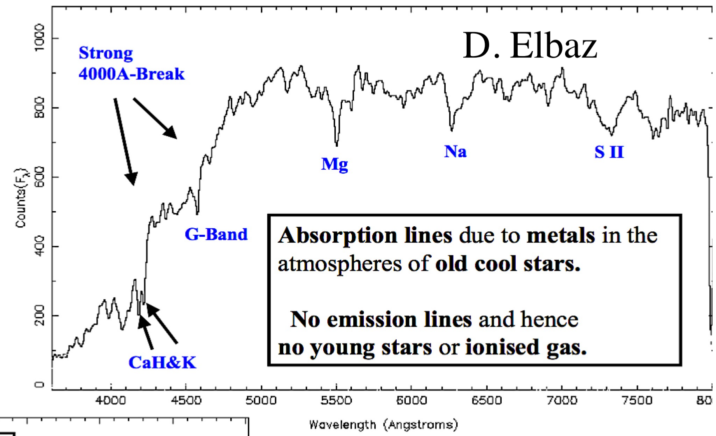
Galaxy Spectra The Simple Picture

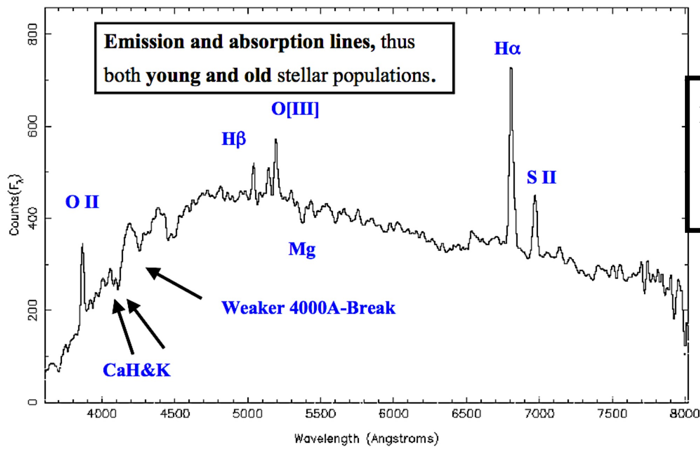
- Continuum: the combination of many Black-Body spectra (from a wide range of stellar types, spanning a range in temperatures, weighted by the IMF) *just happens* to produce a fairly flat overall spectrum



One Step Beyond Simple

Little star formation, little ionized gas





moderate star formation, strong lines from ionized gas

A Sequence

- Connection between morphology and spectrum (S&G fig5.24)

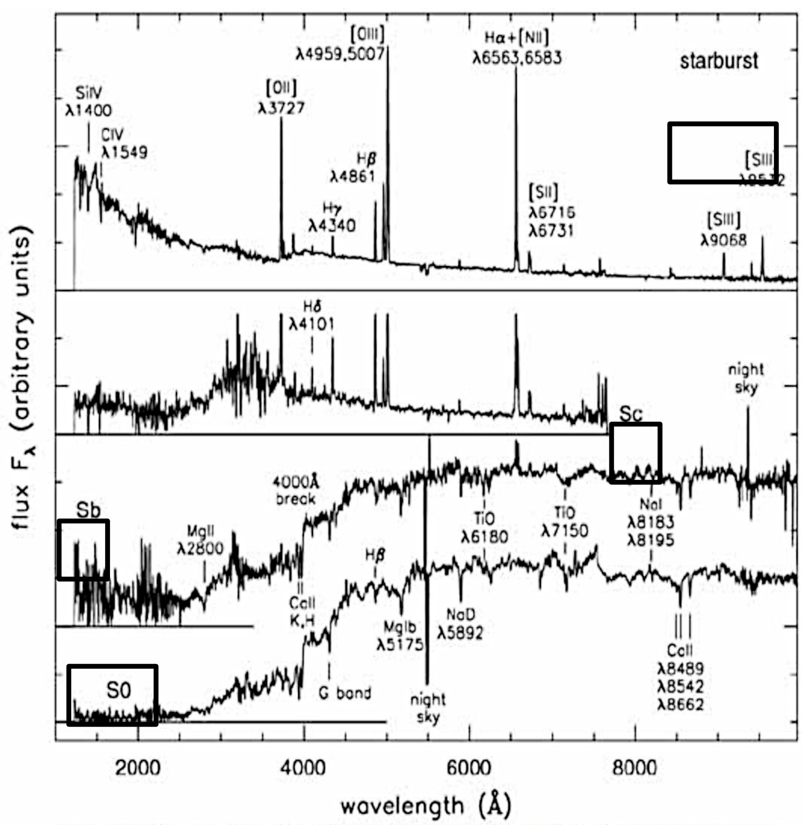


Fig 5.24 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Galaxy spectra

- Galaxies have composite spectra. They integrate contributions from different stars of different stellar populations, gas and the effects of dust
- The emission lines trace the ionized gas and its excitation mechanism.
- The absorption lines trace the stellar populations, their ages and metallicities.
- The overall continuum shape is modulated by the gas, the stars, as well as by the presence of dust.
  - color of line is based on g-r color

continuum mostly from stars

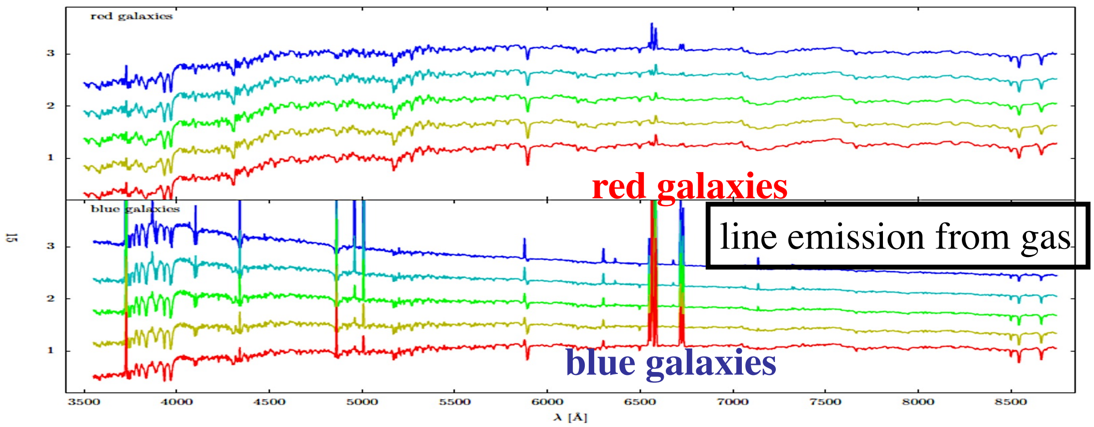
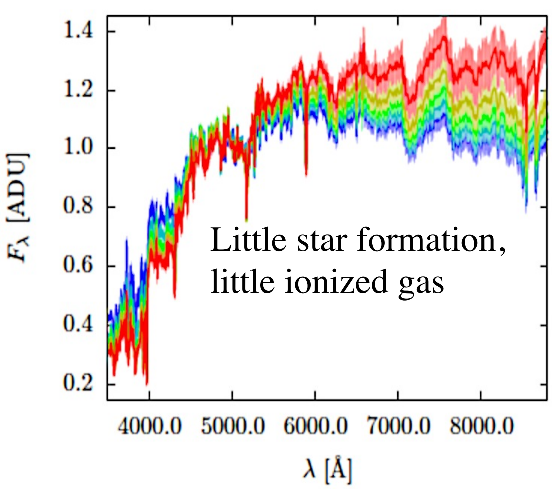


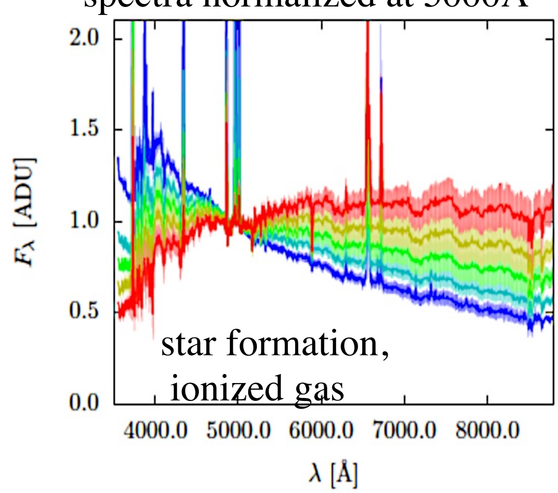
Figure 12: Composite spectra of the refined colour classes as described in Sec. 3.4. The curves are colour-coded from blue (top) to red (bottom) based on the $g - r$ colour of the galaxies. See the online edition for a colour version of this plot.

Galaxy spectra

- Sequence of ages of a composite SSP population (star forming-spiral population)
- bulges are dominated by stellar absorption lines and have little 'blue' light
- The star forming galaxies- *almost all spirals at low redshift*, show emission lines (from ionized gas) and much more blue light (especially when they are young)

spectra normalized at 5000Å

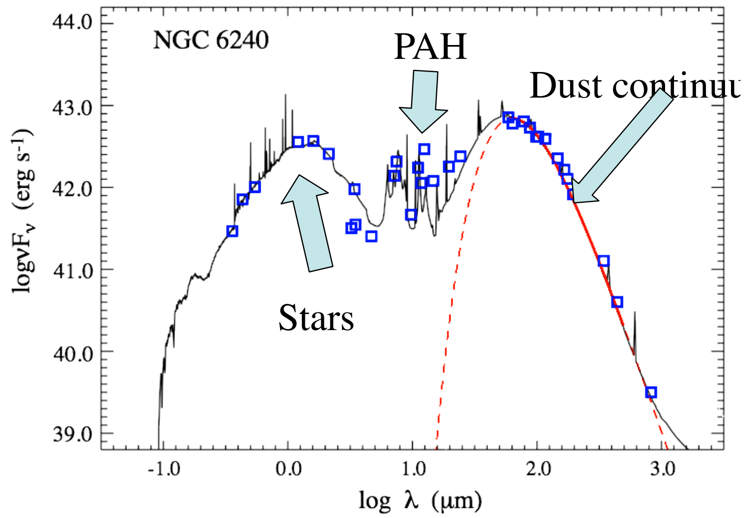




Galaxy Spectra -IR

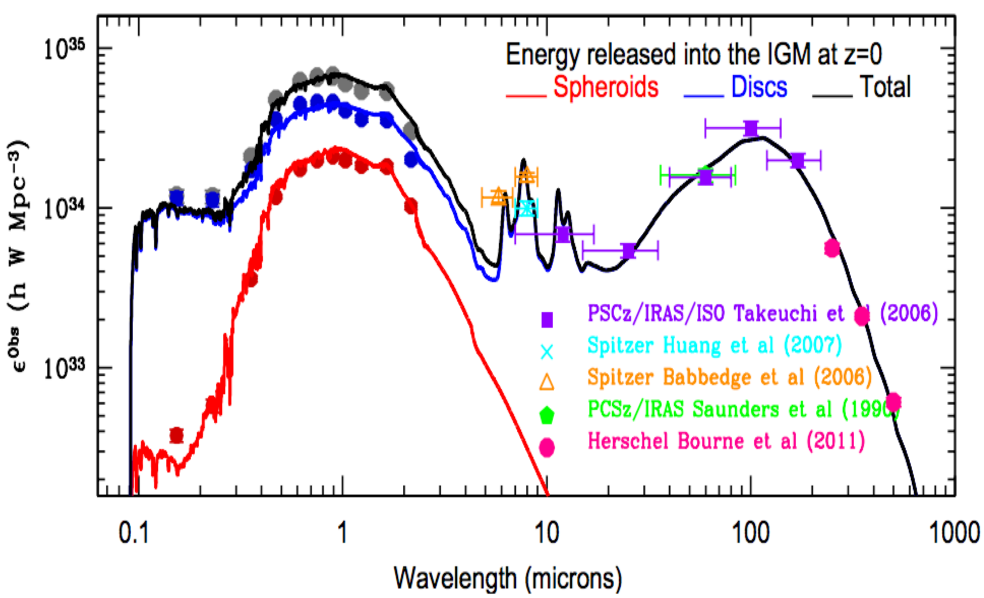
- At λ>5μ in most spiral galaxies continuum dominated by emission from dust -there are atomic and molecular features as well
- In many spiral galaxies L(opt)~L(IR)
  - dust heated by star light - temperature to which it is heated depends on geometry and the nature of the stars

Dust emission spectrum is a grey body $L_\lambda = (\varepsilon(\lambda))\, F_{BB}$ where F_{BB} is the black body function



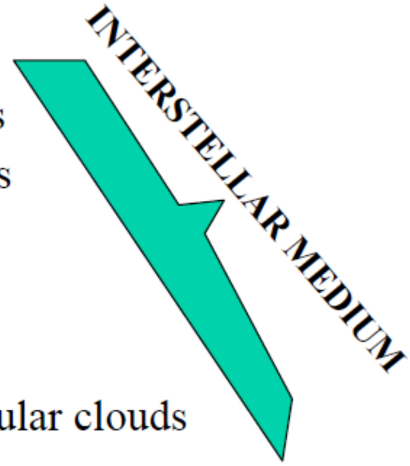
Energy Released By Galaxies

- Extensive galaxy surveys have allowed the measurement of the total energy released by all low z galaxies across the UV-far IR spectrum 1.3×10^{35} W/Mpc^3(Driver 20120; 35-45% of energy generated by stars is absorbed by dust and re-radiated in IR- this occurs predominately in spirals



Composition of 'Average' Spiral

- Stars ~80% of mass
  - DISK ~80% of stars
  - BULGE ~20% of stars
- Gas ~20% of mass
  - atomic gas (“H I”) ~2/3 of gas
  - molecular gas (H_2) ~1/3 of gas
  - hot, ionized gas (“H II”)
- Dust
  - between stars
  - mostly in spiral arms & molecular clouds



Reminder of Big Picture See S&G table 5.1

- Disks :

Metal rich stars and ISM

Nearly circular orbits with little (~5%) random motion & spiral patterns

Both thin and thick components

- Bulge :

Wide range of metals; poor to super-rich stars (only in nuclear regions)

  - V(rot)/σ ~ 1, so dispersion (random velocity-hot systems) support important.

- Bar/Spiral Patterns/rings :
- Dense'cold' ISM +star formation
- Stellar Halo :

  Very low surface brightness; ~few % total light; little/no rotation

  Metal poor stars; GCs, dwarfs; low-density hot gas

- Dark Halo :

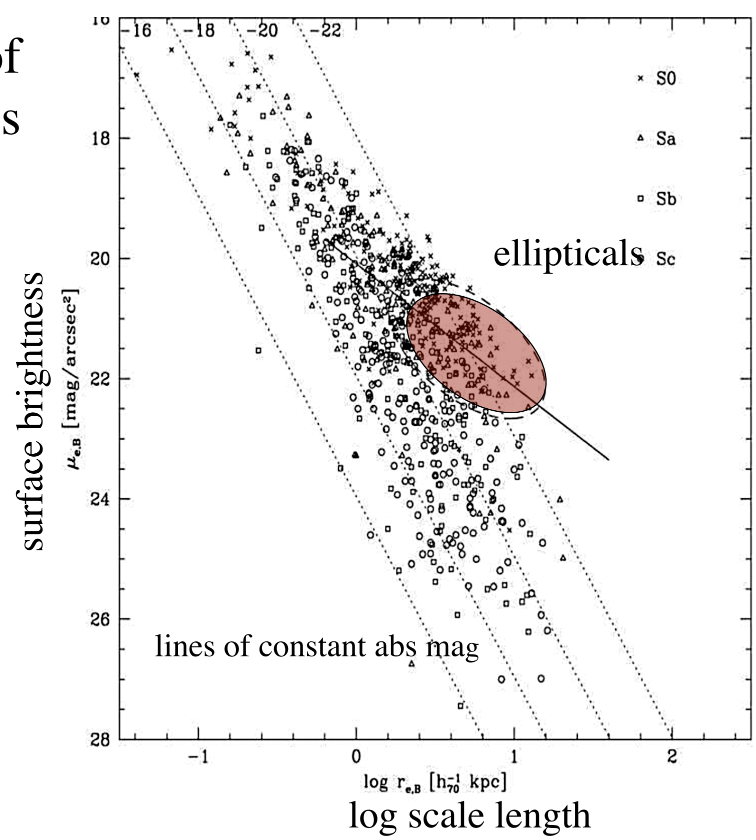
Dark matter dominates mass (and potential) outside ~a few scale lengths

General Patterns- reminder, please review

- Relationship of 'class' (e.g. S0,Sa,Sb..) to physical properties -
- Correlations of surface brightness, size, color, star formation etc etc
- 'Later' types, lower mass, more of baryons in gas, higher specific star formation rates (today):
- Sa -> Sb -> Sc -> Sd in order of decreasing bulge size.
- Patterns
  - More luminous galaxies have larger V_{max}
  - Earlier Hubble-type galaxies rotate faster for the same L
  - Fraction of DM inside optical radius increases with decreasing V_{max}
- Large fraction of energy radiated in the IR due to dust
- Spectroscopic signature of gas in spirals in form of emission lines from hydrogen, oxygen etc; gives information about physical conditions (temperature, density, velocity field)

The properties of Bulges of Spirals

- The bulges of all Hubble types show similar pattern (surface brightness, size, total luminosity) but ellipticals have a smaller range of parameters than spiral bulges.
  - Dwarfs have different bulges (large n values, scale lengths and higher surface brightness)



Gas Motions

- If there is a well defined disk, inclined at some angle i to the plane of the sky (inclination) and rotating perpendicular to this angle (fig 5.18 in text)
- 2 sets of coordinates
  - disk of galaxy (R, ϕ)
  - plane of sky (ρ, θ)
  - When $\theta=\phi$ line of nodes
- The measured radial velocity of gas in circular orbits is

$v_R(\rho, \theta)=v_{system}+v_R(R, \phi)$ $\sin\phi\sin\mathbf{i}+v_\phi(R,\phi)\cos\phi\sin\mathbf{i}+v_z$ $(R,\phi)\cos\mathbf{i}$

v_R velocity in radial direction

v_ϕ angular speed

v_z vertical speed

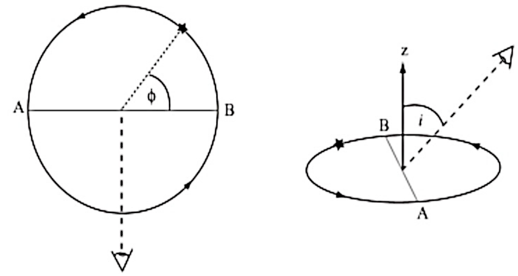


Fig. 5.18. Left, a rotating disk viewed from above. Azimuth ϕ, measured in the disk plane, gives a star's position in its orbit; an observer looks from above the disk, perpendicular to diameter AB. Right, the observer's line of sight makes angle i with the disk's rotation axis z.

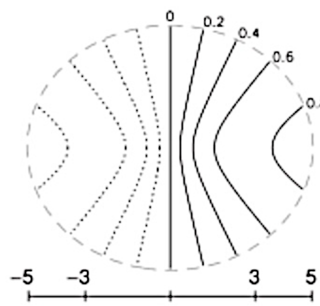


Fig 5.19

contours of constant v_r, velocity pattern disk observed at i=30

negative velocities ----

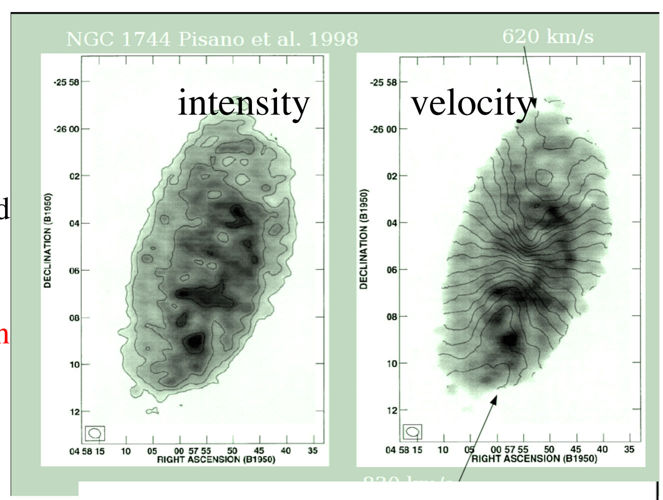
HI

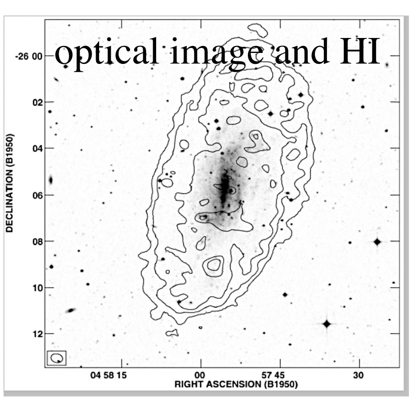
- Spirals have large HI disks

– This gas is optically thin

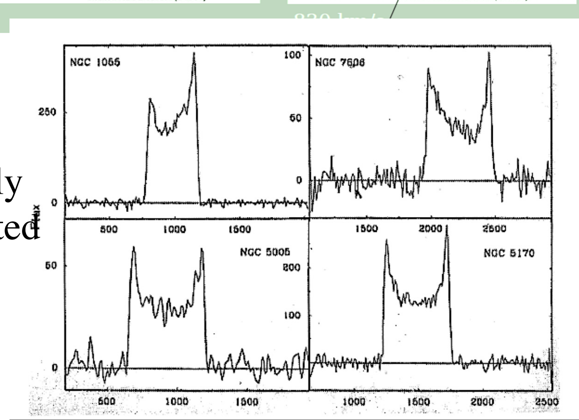
This means that we see all the gas and can measure the amount directly from the line intensity

- HI gas is much more extended than the optical light,
- – Gives a unique tracer for the velocity in spiral galaxies





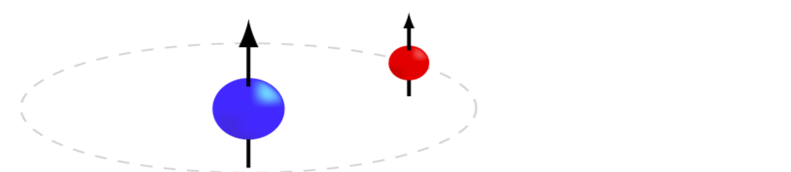
Spatially integrated



Physics of 21cm Line

- While Hydrogen is the most abundant element in the ISM, but the symmetric H_2 molecule has no dipole moment and hence does not emit a spectral line at radio frequencies.
- But it is detectable in the 21 cm (λ=1420.405751 MHz) hyperfine line, a transition between two energy levels due to the magnetic interaction between the quantized electron and proton spins. When the relative spins change from parallel to antiparallel, a photon is emitted. Collisions excite the line.
  - The equilibrium temperature of cool interstellar HI is determined by the balance of heating and cooling. The primary heat sources are cosmic rays and ionizing photons from hot stars.

http://www.cv.nrao.edu/course/astr534



One λ = 21 *cm photon is emitted when the spins flip from parallel to antiparallel.*

Gas Motions- continued

- Circular disk tilted by an angle i, projects to an ellipse
- What to look for in the 'spider' plot (see figure C.4 in text)
  - Kinematic major axis - line through nucleus perpendicular to velocity contours- should be aligned to photometric axis if mass is traced by light
  - If V(r) is flat at large radii outer contours are radial
  - if V(r) is declining at large radii contours close in a loop
  - spiral arms give perturbations to pattern near arms
  - warped disk (see figure)

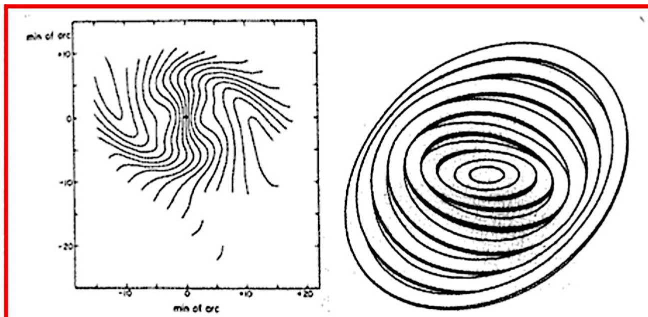


Figure 8.36 A tilted ring model of M83 (right) and the spider diagram predicted by this model (left). [After Rogstad, Lockhart & Wright (1974)]

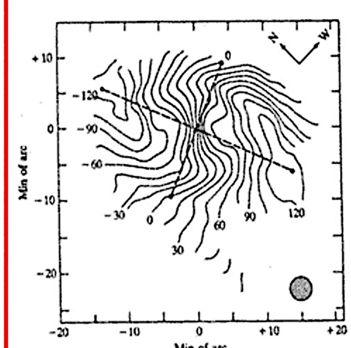
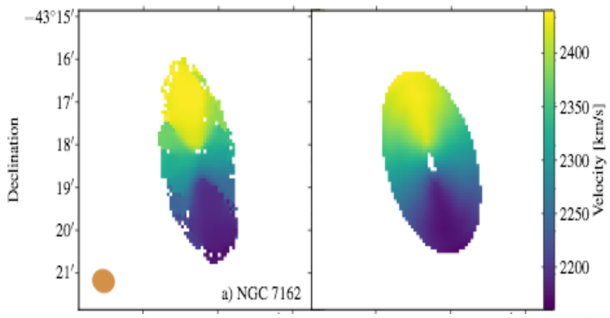


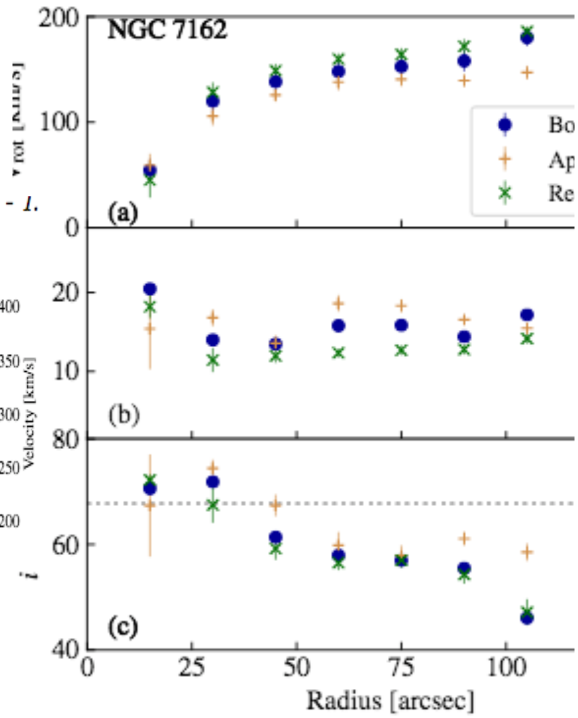
Figure 8.37 The observed spider diagram of M83. [After Rogstad, Lockhart & Wright (1974)]

Tilted Ring Modeling

- Data left panel- model right panel T.N. Reynolds, et al. 2018

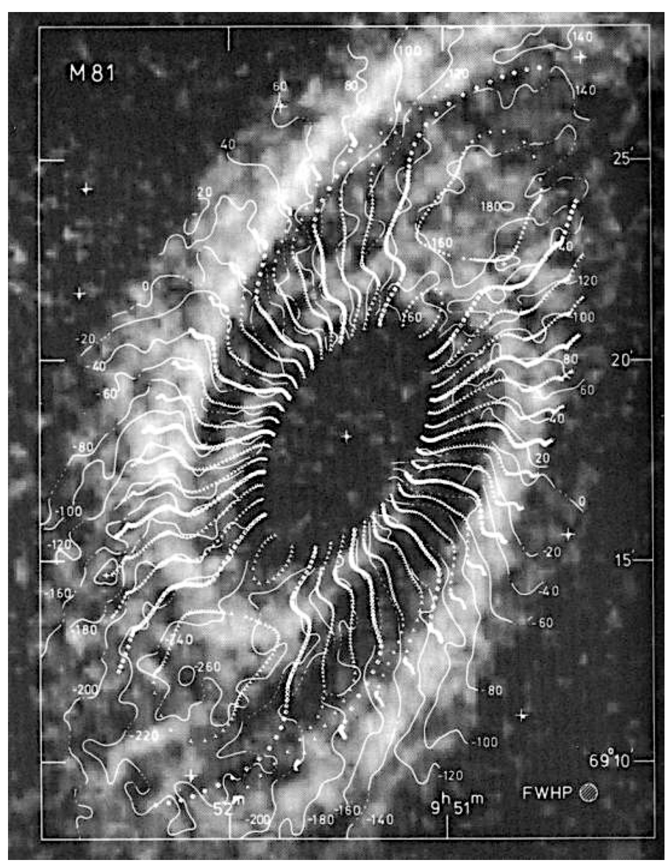
WALLABY ES - I.





Gas Motions

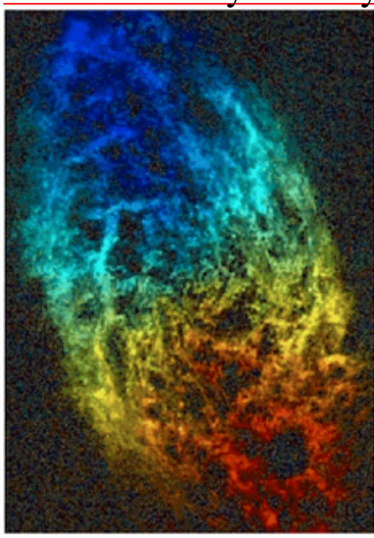
- This is what is seen in 'real' galaxies in the motion of HI (fig 5.13 S=G)
- e.g spider diagram is 'A diagram that gives the equations for lines of constant radial velocities as seen for a rotating galaxy inclined to the observer's line of sight."
- - Deviation from Spider plot in M81 shows influence of spiral arms (real density increases- not just light increases)



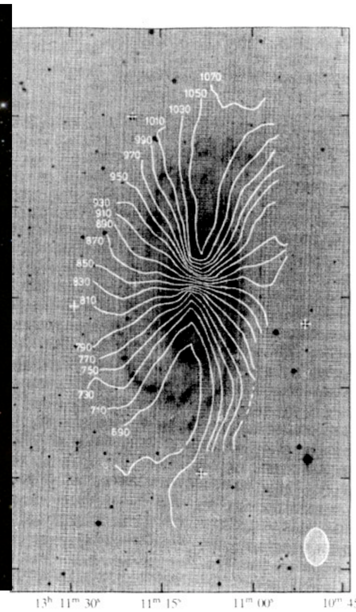
Optical Image and Velocity Field of NGC5033

- Spider plot is the contours of the velocity field

color coded by velocity



hydrogen velocity



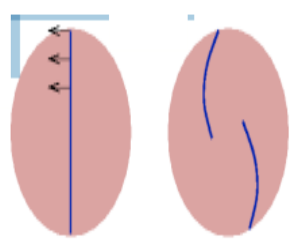
Spiral Arms (sec 11.6 in MBW- sec 5.5.2 in S+G)

- Defining feature of spiral galaxies - what causes them?

- Observational clues

Seen in disks that contain gas, but not in gas poor S0 galaxy disks.

- Defined by blue light from hot massive stars. Lifetime is << galactic rotation period.
- When the sense of the galactic rotation is known, the spiral arms trail the rotation.
  - First ingredient for producing spiral arms is differential rotation.



ps of spiral arms point away from direction of rotation.

(From P. Armitage)