Next Presentation

- Structure & Kinematics of Early-Type Galaxies from Integral-Field Spectroscopy

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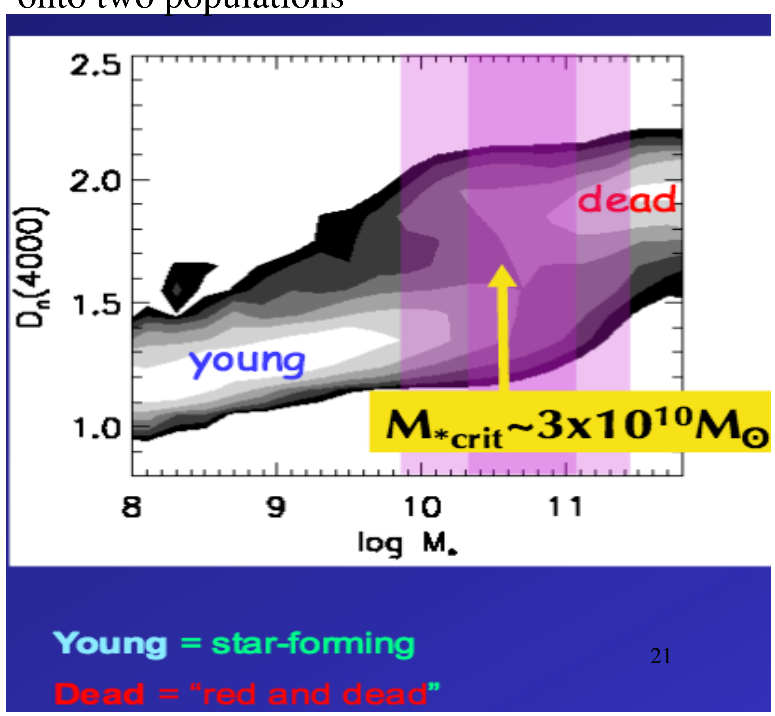
- Annu. Rev. Astron. Astrophys. 2016.54:1–67

- Liz T. Nov 27
- This is a **huge** paper, please do only sec 1,4.1-4.3,6.

Spirals

- This stellar critical mass corresponds to a halo mass of ~10^{12}M,
- Divides galaxies into two populations
- theoretically at this mass accretion switches from cold to hot accretion (cold at lower masses)

Characteristic stellar mass divides galaxies onto two populations

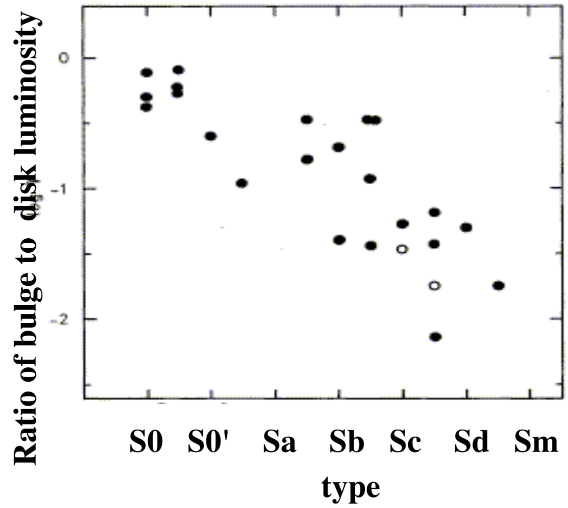


Kauffmann 2003

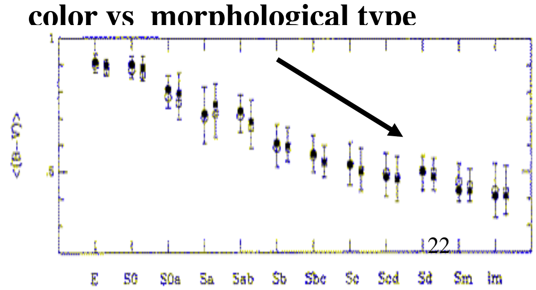
Spirals

The Hubble type of a spiral correlates with

- bulge/disk luminosity ratio
- relative content of cool gas (H I)
- mass concentration
- stellar population (how many young/ old stars)
- nuclear properties-AGN
- chemical abundances in the ISM
- star formation history and integrated stellar spectrum
- bulges of spirals tend to have old stars, disks younger stars
- *A lot of the detail depends on what wavelength one observes in (e.g. the UV favors hot young stars, the IR dust, x-rays hot gas and binaries)*



color vs morphological type



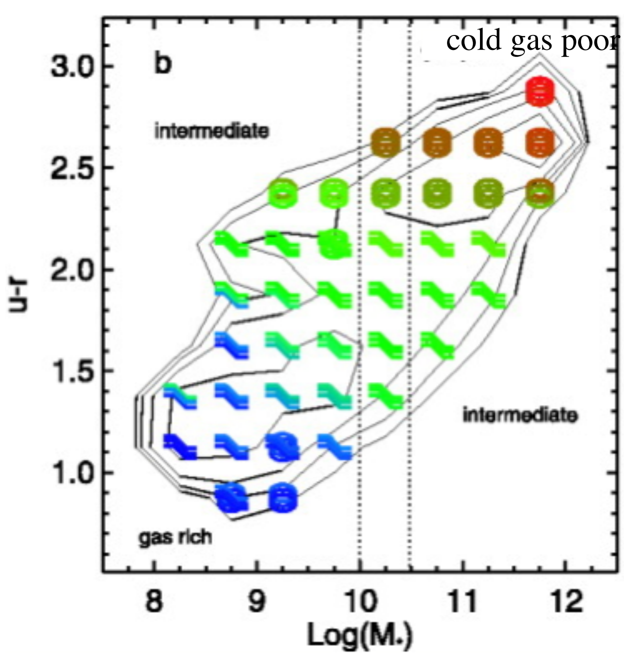
Spirals and Gas

- The ISM of spiral galaxies is quite complex and show wide variations with position

Trends - the lower the mass and the 'bluer' the galaxy the higher is the baryonic fraction in cool/cold gas.-

characteristic stellar mass ~$3x10^{10}M$ where things change.

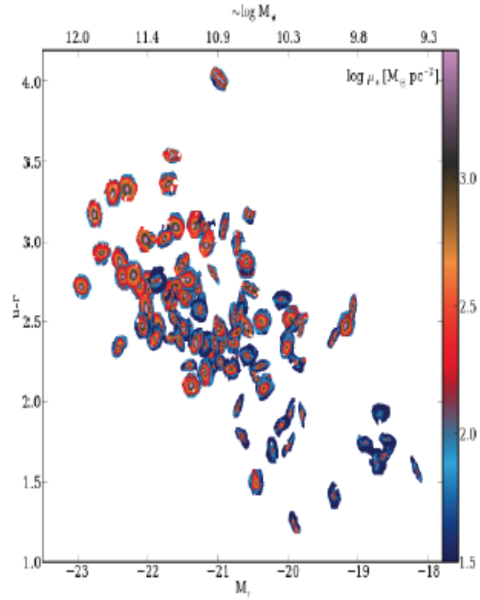
color symbols gas to light ratio in log scale



Spirals- More Trends with Morphology (Sd ⇨ Sa)

- Total luminosity decreases
- M / L_B rises
- M (HI) / M $_{(total)}$ rises
- Bulge / Disk decrease
- Tightness of the spiral arms decreases
- Scale length drops
- color reddens- star formation history
- The question is what are the primary eigenvectors of the correlations... it seems to be mass

The stress on 'B' band comes from history- before CCDs photographic plates were used and they were most sensitive in the 'B' band.

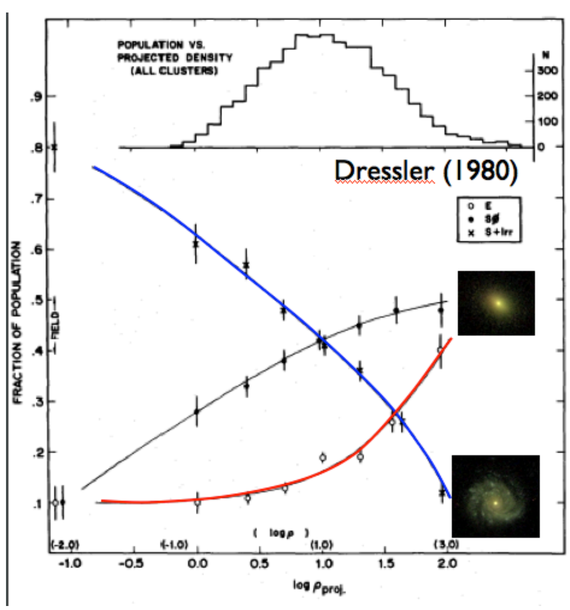


CALIFA collaboration-arxiv 1310.5517

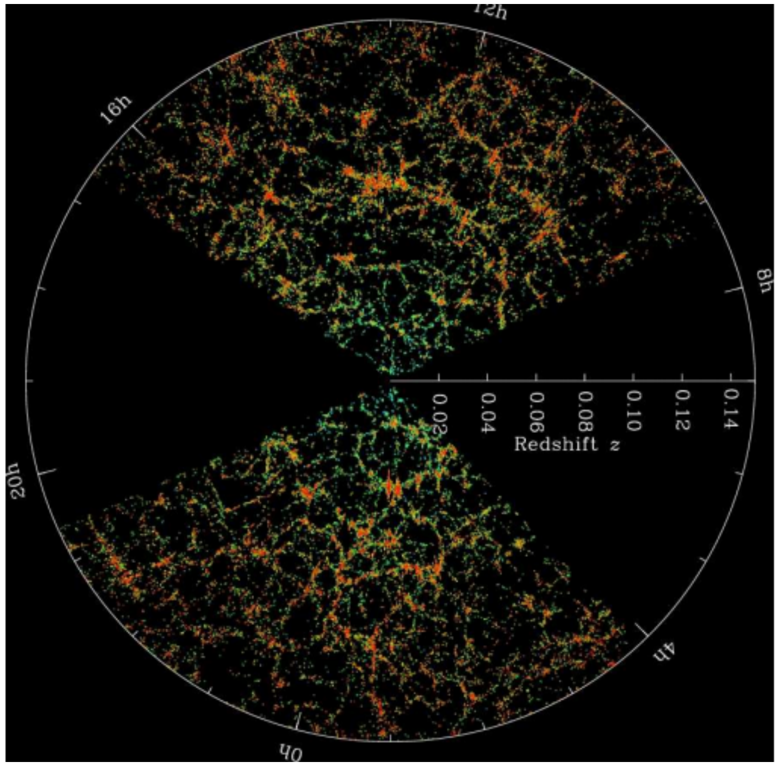
2-D map of stellar density

"Where" Do Galaxies of a Given Type Reside

- In low density regions most of the galaxies are spirals (blue line)
- As the density of galaxies increases the fraction which are S0(black) and E (red) increase dramatically- this reaches it limit in massive clusters of galaxies whose cores have almost no spirals
- **Thus the morphology of galaxies 'knows' about the environment- not clear if this is nature (formed that way) or nuture (spirals converted into S0's)**

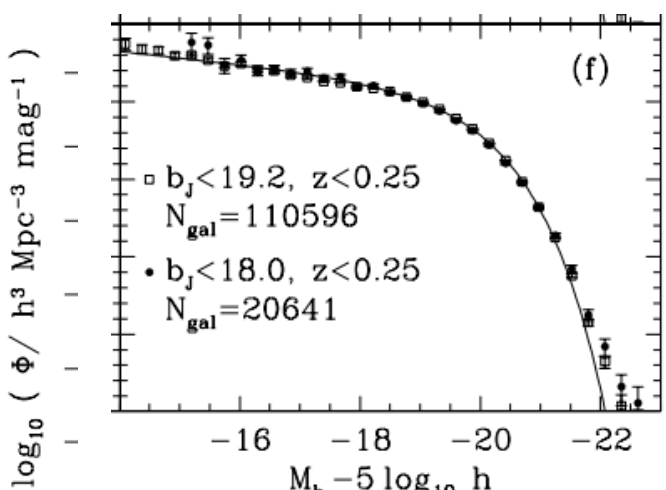


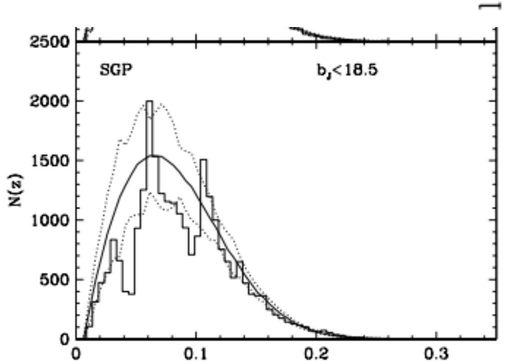
- Distribution of red and blue galaxies out to z-0.15 from the SDSS (M. Blanton)
- Notice that **red** galaxies are highly concentrated in dense regions while **blue** galaxies are in the filaments



Luminosity Function

- The combined luminosity function of **all** galaxies is fitted by the **Schecter function**- a power law at low L and an exponential cutoff at high L





Redshift

Redshift distribution is not uniform (e.g. large scale structure makes derivation of f(L) unstable at high L where objects are rare)

Schecter Function (eq 2.34 MBW)

- $\phi(L)dL = \phi_0 * (L/L_*)^{-\alpha} \exp(-L/L_*)\, dL/L_*$

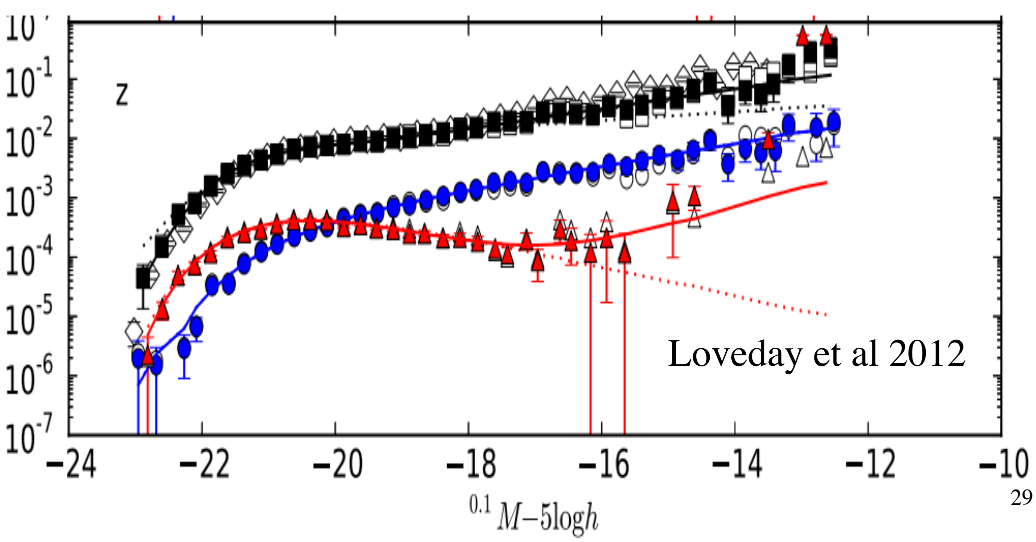
L_* is a characteristic luminosity, α is the faint-end slope, and ϕ_0 is an overall normalization.

Integral over all luminosities to get total number of galaxies is

- $n_g \equiv \int_0^\infty \phi(L)dL = \phi_0 * \Gamma(\alpha+1)$, *incomplete gamma function*
- Total luminosity is $\phi_0 * L_* \Gamma(\alpha+2)$
- number density is dominated by faint galaxies while the luminosity density is dominated by bright ones

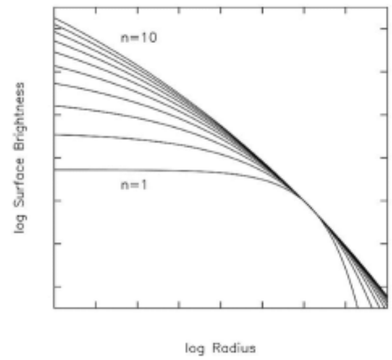
Red and Blue Luminosity Functions

Despite differences in populations the red (mostly ellipticals) and **blue** (mostly spiral) galaxy luminosity functions add smoothly together and are well fit with a Schechter function



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
- Both can be described by a '**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 a characteristic (scale length-$\Sigma(r)$ is the surface brightness profile S+G eq 3.13, MBW 2.22
- **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 usually dominates for small r)

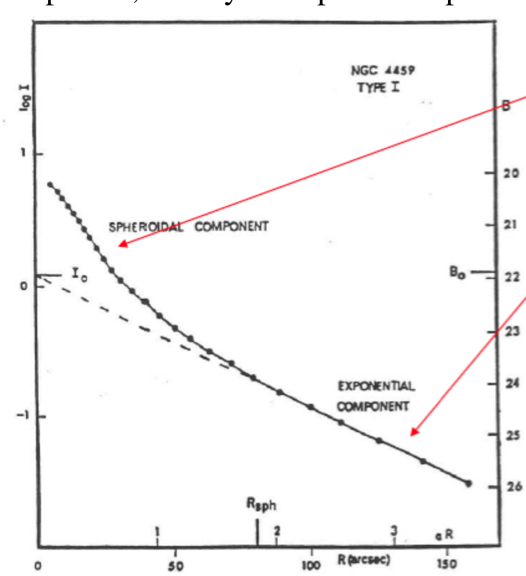


$$L = 2\pi\int_0^\infty I(R)\,R\,dR = \frac{2\pi n\,\Gamma(2n)}{(\beta_n)^{2n}} I_0 R_e^2,$$

total luminosity of Sersic profile- *Γ is the gamma function*

Azimuthally Averaged Light Profiles

- Bulge is more concentrated than the disk: bulge is described by Sersic profile, disk by an exponential profile (Sersic with n=1)



$\log I \propto R^{1/4}$ (inner);

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

α is the inverse scale height

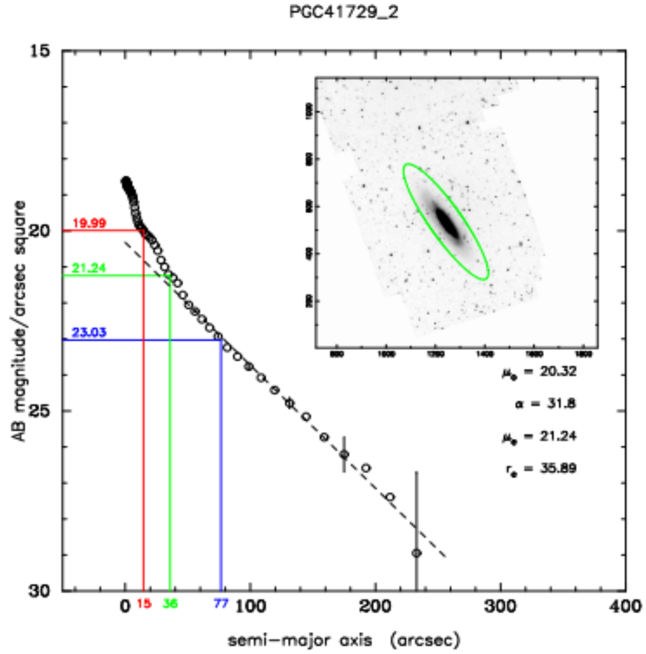
(Freeman 1970)

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

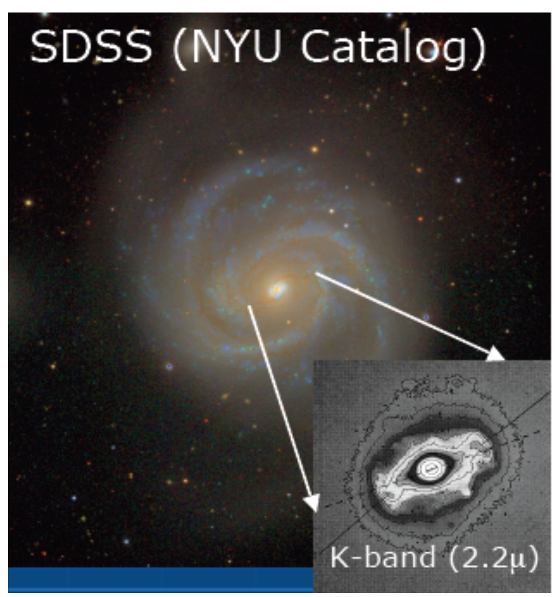
Typical disk surface brightness profiles



Courteau, ApJS, 103, 363, 1996

Other Complications - Disk Components

- Stellar **bars** are common
  - Often only recognized in near-IR images (less dust)
  - Consequence of disk instability
    - Effective means of angular momentum transport
- Spiral **arms** are common and coherent features– even after accounting for young stars (while often spiral arms are the locations of star formation they are also seen in the light of older stars).



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 total flux$I_{tot}=2\pi R^2{}_d I(0)$
    - high n - $R^{1/4}$ profile
  - deVacouleurs profile $I(R)=I(R_e)(\exp-7.67[(R/R_e)^{1/4}-1]))$
    - R_e is the half light radius

Spirals- Summary

- have cold gas and dust
- present day star formation
- many have internal structure (spiral arms and bars)
- a bulge and disk (large range in relative importance)
- host **radio quiet AGN**
- x-ray luminosity is dominated by binaries
- ISM is highly structured

Summary - Continues

- Spirals 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)

- Surface brightness can be well modeled by Sersic Law ;

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

Tully-Fisher Relation MBW 11.3 S&G 5.3.3

Giovanelli et al 1997

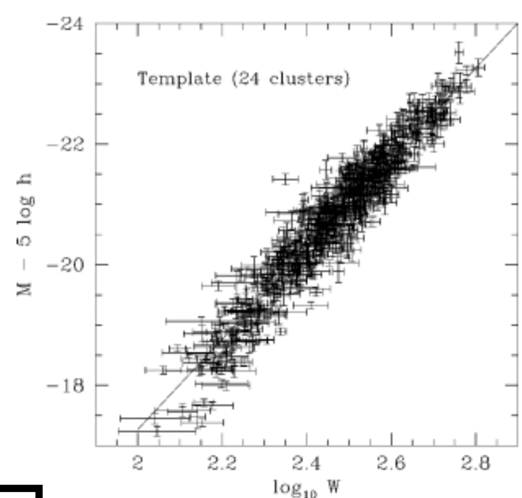
- $L \sim v_c^4$
- If galaxies contained no dark matter, we could understand the Tully–Fisher

relation fairly easily; see next page

But, since the rotation speed Vmax is set largely by dark matter, while the luminosity comes from stars, the link between them is puzzling.

Somehow, the amount of dark matter is coordinated with the luminous mass.

Since luminosity depends on d^2xflux can get distance to object from measuring its circular velocity and apparent brightness!



Fi[illegible] 1.—Template relation based on 555 galaxies in 24 clusters. The fit is −21.0[illegible] ± 0.02−7.68 ± 0.13 (log W − 2.5).

Tully-Fisher Relation MBW 11.3

- Relates circular velocity of test particles (gas, stars) to total **luminosity** of system

(circular velocity is related to mass, $v^2_{circ}(r) = r\, d\Phi/dr = GM(r)/r$)

- Back of the envelope derivation of it
- System in equilibrium: centripetal force balances gravity
  - $GM(r)/r^2 = v_c^2/r$; so $M(r) = v_c^2 r/G$; 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 $L \sim v_c^2 L^{1/2} \sim v_c^4$

Giovanelli et al 1997

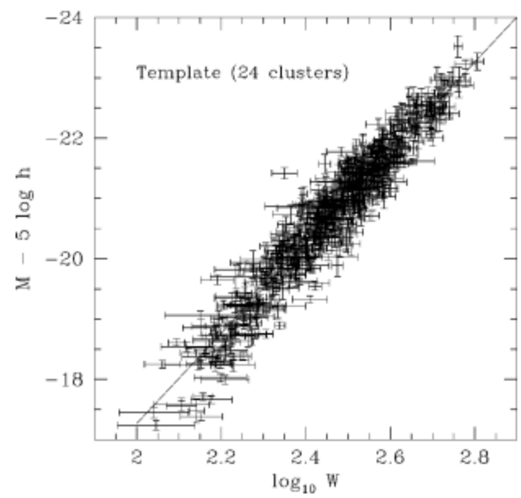


FIG. 1.—Template relation based on 555 galaxies in 24 clusters. The fit is −21.00 ± 0.02−7.68 ± 0.13 (log W − 2.5).

Since luminosity depends on d^2xflux can get distance to object from measuring its circular velocity and apparent brightness!

Implications of T-F

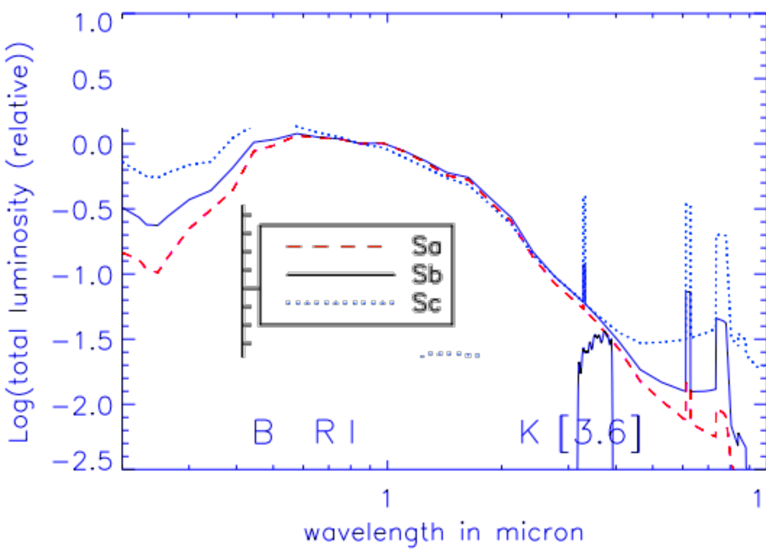
- M/L~constant from galaxy to galaxy?
- But
  - Mass is dominated by dark halo
  - Luminosity is dominated by disk
- Total mass: $M \sim [V^2_{max} h_R]$
- Total luminosity: $L \sim [I_0 h_R^2]$
- $L \sim [V^4_{max} (M/L)^{-2} I_0^{-1}]$
- A universal M/L implies remarkable constancy of the ratio of dark to luminous matter

Or worse, a fine-tuning of the dark-to-luminous mass ratio as the stellar M/L varies.

Adapted from M.Bershady lecture notes

Spiral Galaxy spectra

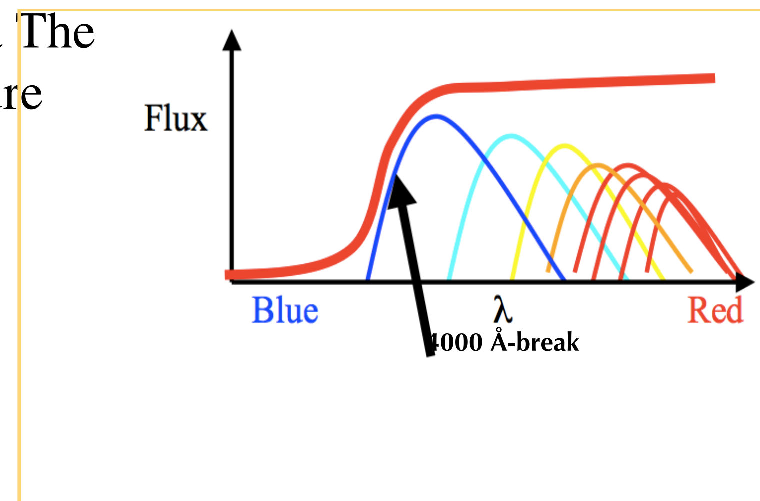
- Galaxies have composite spectra. They integrate contributions from different stars of different stellar populations, gas and the effects of dust
- The overall continuum shape is modulated by the gas, the stars, as well as by the presence of dust.



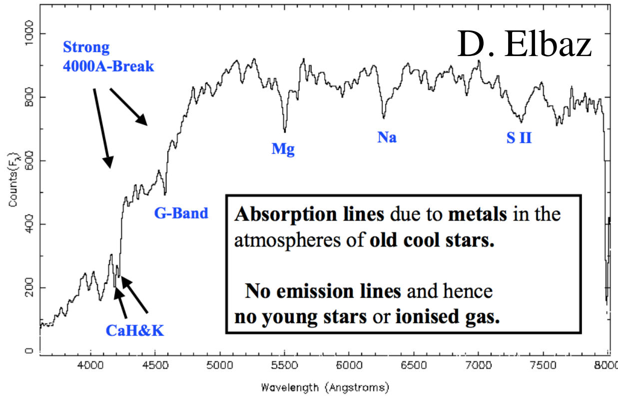
Spiral SED normalized at 8000A with emphasis on near IR spectral features (PAHs)

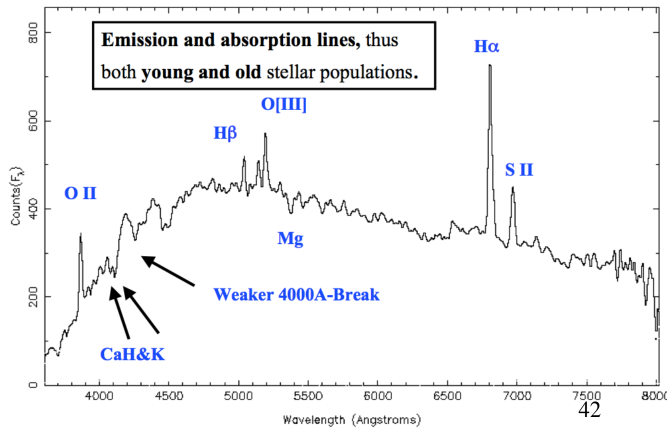
Galaxy Spectra The Simple Picture

- 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





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

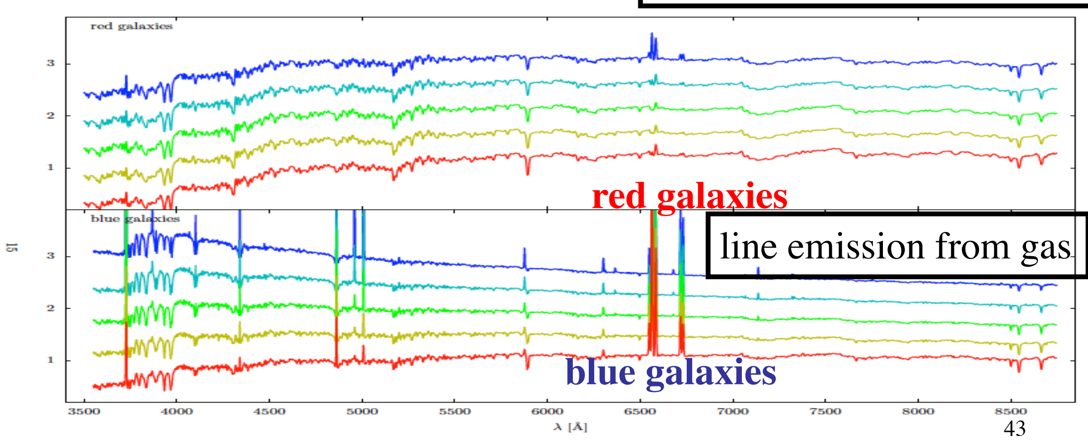
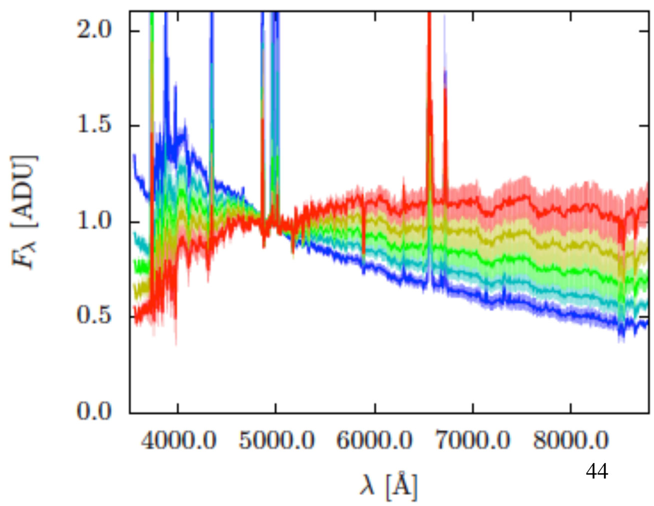


Figure 12: Composite spectra of the refined colour classes as described in Sec. 3.4. The curves are colour-coded from blue (top) to red (bottom) based on the $g - r$ colour of the galaxies. See the online edition for a colour version of this plot.

Galaxy spectra

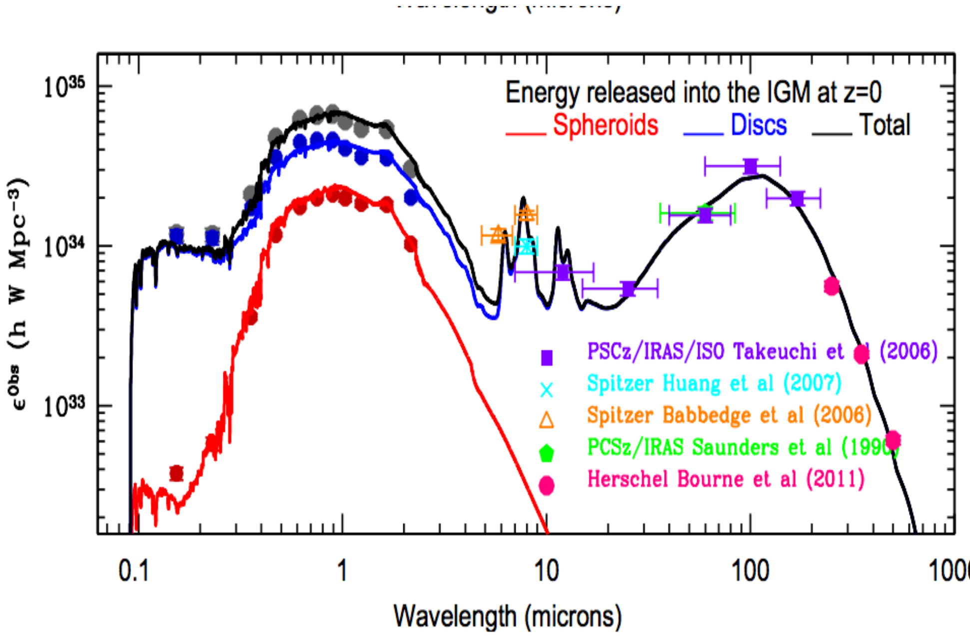
- Sequence of ages of a composite SSP population (star forming- spiral population)
- bulges are dominated by stellar absorption lines and have little 'blue' light

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)



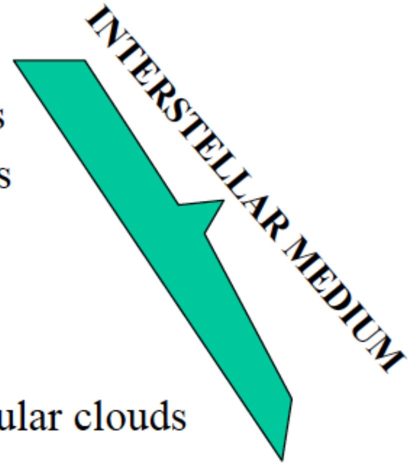
Energy Released By Galaxies

- Extensive galaxy surveys have allowed the measurement of the total energy released by all low z galaxies across the UV-far IR spectrum 1.3x10^{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

- 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

- 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)

Gas Motions

- If there is a well defined disk, inclined at some angle i to the plane of the sky 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

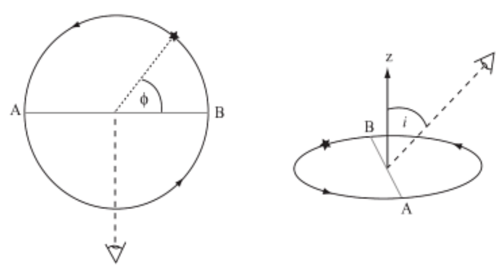
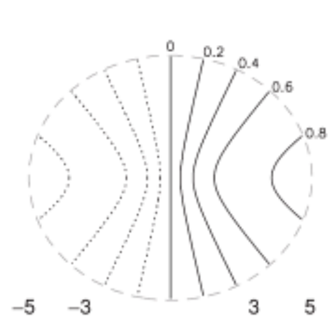


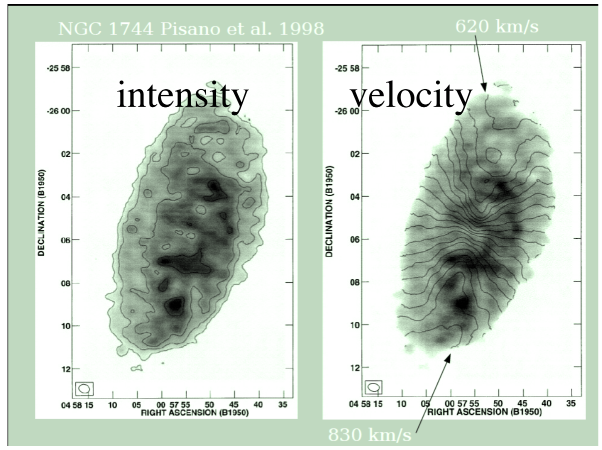
Fig. 5.18. Left, a rotating disk viewed from above. Azimuth ϕ, measured in the disk plane, gives a star's position in its orbit; an observer looks from above the disk, perpendicular to diameter AB. Right, the observer's line of sight makes angle i with the disk's rotation axis z.

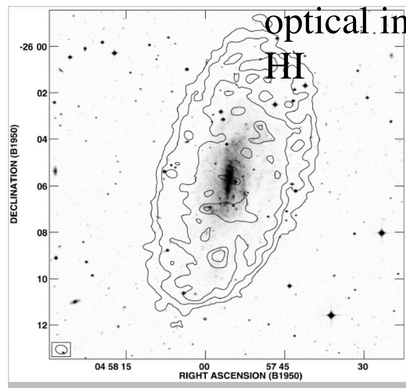


contours of constant v_r, velocity pattern disk observed at i=30
negative velocities ----

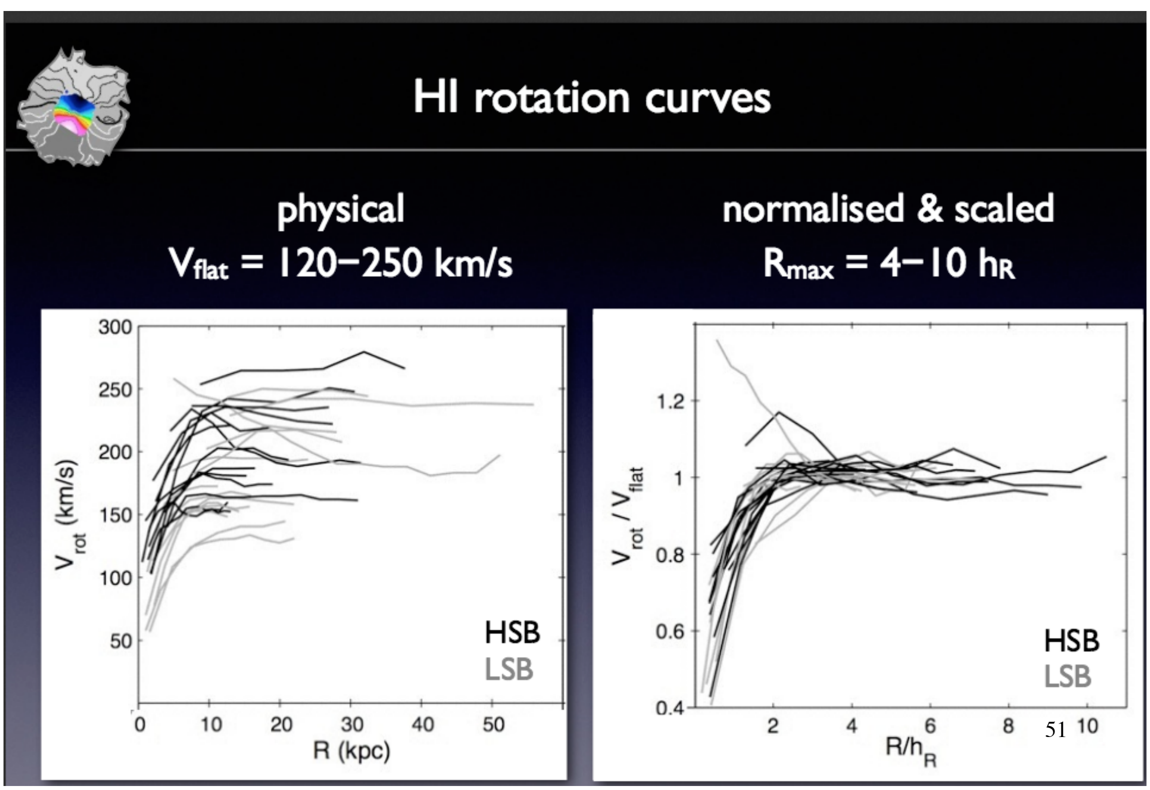
HI

- 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, $r_{HI} > 2.5\, R_{25}$
- – Gives a unique tracer for the velocity in spiral galaxies





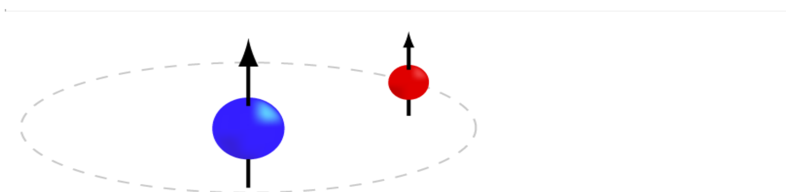
Verheijen IAU 311



Physics of 21cm Line

- 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. The main coolant in the cool ISM is radiation from the fine-structure line of singly ionized carbon, CII, at =157.7 μ.

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
  - 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)

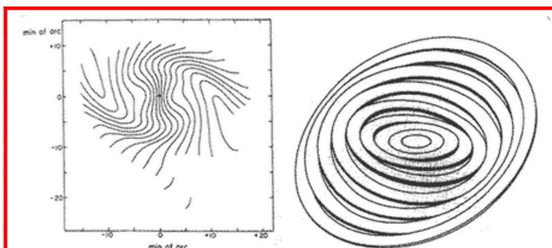


Figure 8.36 A tilted ring model of M83 (right) and the spider diagram predicted by this model (left). [After Rogstad, Lockhart & Wright (1974)]

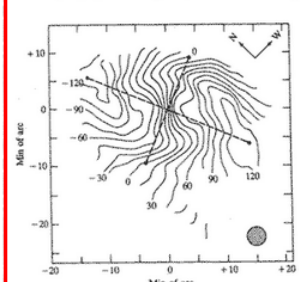
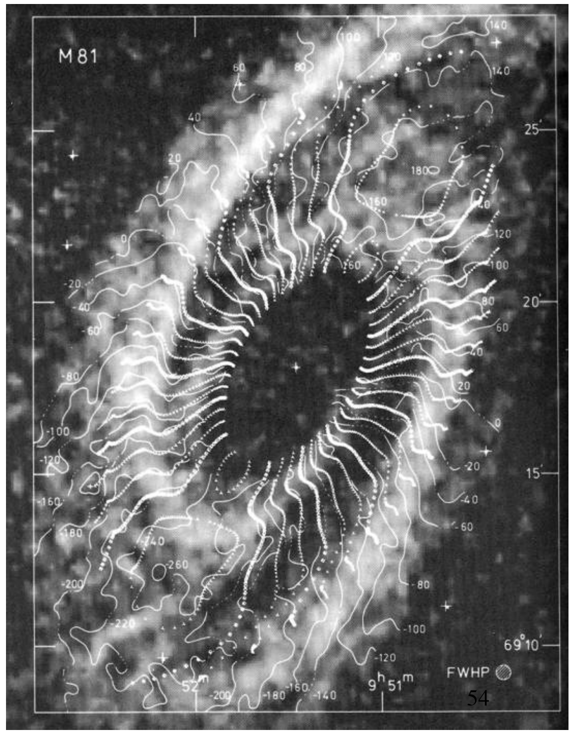


Figure 8.37 The observed spider diagram of M83. [After Rogstad, Lockhart & Wright (1974)]

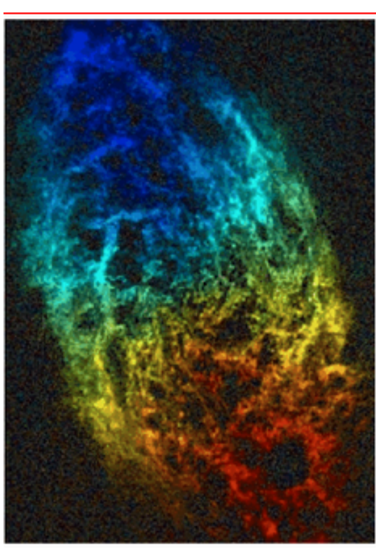
Gas Motions

- 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."
- Gas sees all the matter- deviation from Spider plot in M81 shows influence of spiral arms (real density increases- not just light increases)

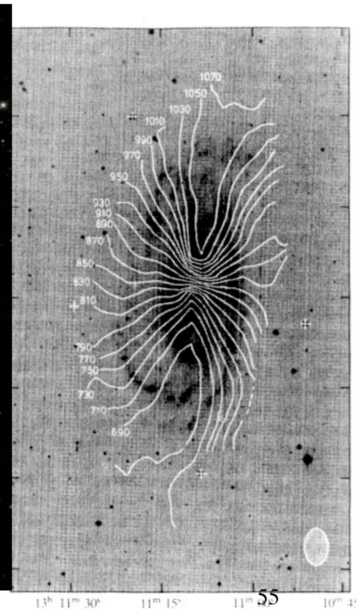


Optical Image and Velocity Field of NGC5033

- Spider plot is the contours of the velocity field



hydrogen velocity



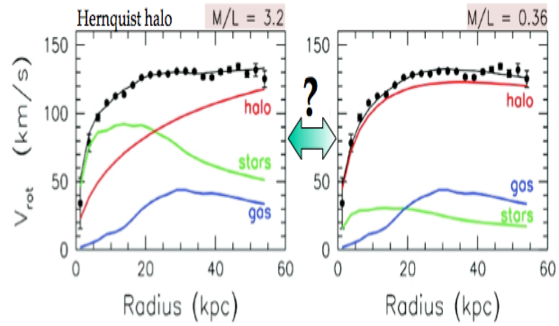
Spirals and Dark Matter- Review of Dynamics

- Rotation-curve decomposition - primary tool for measuring the distribution of dark matter in spiral galaxy halos, **but** uncertainties in the mass-to-light ratio of the luminous disk and bulge make accurate estimates difficult (IMF-mass degeneracy)
- Disk-halo conspiracy- there is no 'feature' in the rotation curve indicating where dark matter starts to dominate- smooth transition!

- Disks in equilibrium

  Rotation provides total mass within a given radius.

Bershady et al 2011ApJ...739L..47B
http://hipacc.ucsc.edu/Lecture%20Slides/GalaxyWorkshopSlides/bershady.pd



Solution is that disks have less mass than the maximum allowed by IMF, colors-
At the radius where the velocity curve flattens ~15-30% of the mass is in baryons
Build your own rotation curve (!)
http://burro.astr.cwru.edu/JavaLab/RotcurveWeb/main.html

Spiral Arms in Spirals (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. 'Visually' spiral arms are associated with star formation/molecular gas.Lifetime is << galactic rotation period.

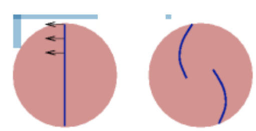
When the sense of the galactic rotation is known, the spiral arms almost always trail the rotation.

- First ingredient for producing spiral arms is differential rotation.
- For galaxy with flat rotation curve:

V(R) = constant

Ω(R) =V/R Angular velocity~1/R

- Any feature in the disk will be *wrapped* into a trailing spiral pattern due to differential rotation:



Tips of spiral arms point away from direction of rotation.

(From P. Armitage)

However this is NOT SOLELY why spiral galaxies have spiral arms- they would wrap up into a tight spiral in time scale $\Delta R/R=2\pi R/vt$
putting in values near the sun $\Delta R/R=0.25\ (t/\mathrm{Gyr})^{-1}$
e.g. The Winding Problem

If arms were "fixed" w.r.t. the disk
With flat rotation (V ~ const), **inner parts rotate many times compared to outer parts**
E.g. for one rotation at R, two rotations at R/2, four at R/4, 8 at R/8.
This leads to very tightly wound arms.

- Angular frequency $\omega = V_c/R$- spirals have flat rotation curve V_c= constant

$d\omega/dr = v/r^2$ angle $\phi = \omega t$ $d\phi = t d\omega = v/r^2\, t dr$

so $\tan\psi = dr/r\, d\phi = r/vt = 1/\phi$

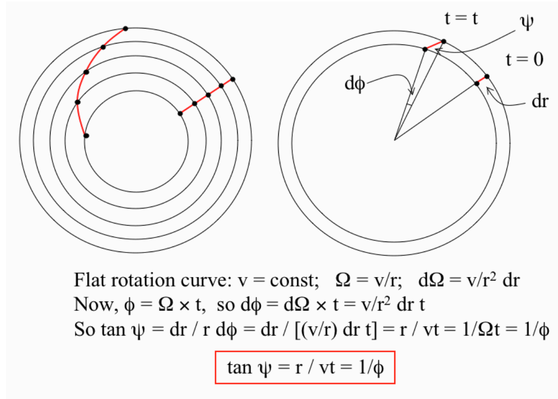
pitch angle,ψ , steadily decreases as the pattern rotates- after 1 rotation $\tan \psi = 1/2\pi$ ($\psi = 9^{\circ}$) e.g winds up! - 2 rotations 4.5° etc

In Sa's $\psi \sim 5^{\circ}$ while in Scs $\psi \sim 10\text{-}30^{\circ}$

SO since galaxies have been around for >> 2 orbital times

- Long lived spiral arms are **not** material features in the disk they are a pattern, through which stars and gas move

Winding?



M. Whittle's web site

Winding

- Thought experiment: paint a stripe on a galactic disk along $\varphi = \varphi_0$
- Disk is in differential rotation with an angular speed $\Omega(R)$
- So the equation of the strip as a function of time is

$$\varphi(R,t) = \varphi_0 + \Omega(R)t$$

For a typical spiral galaxy with a flat rotation curve

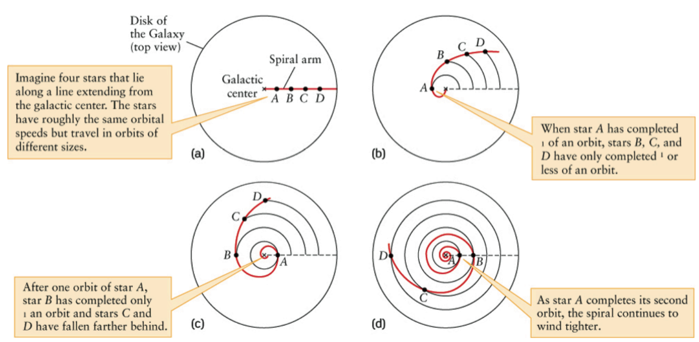
$\Omega(R) = v_{circularr}/R$; so

$d\Omega(R)/dR = v_{circular}/R^2$

near the sun =220km/sec at R~10kpc, at $t = 10^{10}$yrs $\alpha = 0.25$deg !

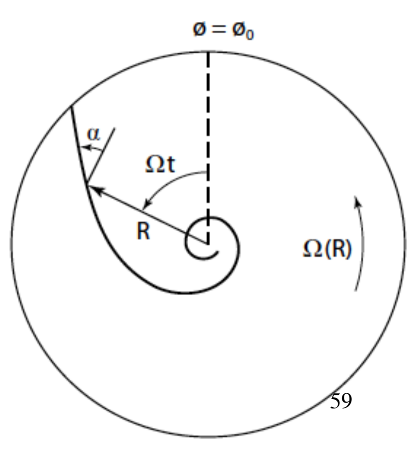
Real galaxies have $\alpha \sim 5\text{-}25$ deg

From http://www.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect24/lecture24.h



In the diagram

$\cot\alpha \sim R t d\Omega(R)/dr$



Spiral Density Waves- One Possible Answer

- Properties of spiral arms can be explained if they are continuously generated and destroyed
- density waves provide the perturbation which gets sheared :

Spiral arms are where the stellar orbits are such that stars are more densely packed-waves of compression that move around the galaxy

Gas is also compressed, triggering star formation and young stars.

Stars pass through the spiral arms unaffected

Arms rotate with a pattern speed which is not equal to the circular velocity - i.e. long lived stars enter and leave spiral arms repeatedly.

Pattern speed is less than the circular velocity - partially alleviating the winding up problem.

• In isolated disk, creation of a density wave requires an instability. Self-gravity of the stars and / or the gas can provide this.

Simplest case to consider is gas. Imagine a small perturbation which slightly compresses part of the disk:

• Self-gravity of the compressed clump will tend to compress it further.

• Extra pressure will resist compression. If the disk is massive (strong self-gravity) and cold (less pressure support) first effect wins and develop spiral wave pattern.

Spiral Arm Formation

The fundamental cause of spiral arm formation is not well understood.

- To quote from https://www.cfa.harvard.edu/~edonghia/Site/Spiral_Arms.html

  'The precise nature of spiral structure in galaxies remains uncertain. Recent studies suggest that spirals may result from interactions between disks and satellite galaxies...., here we consider the possibility that the multi-armed spiral features originate from density inhomogeneities orbiting within disks.'
- In this movie spiral arms are formed due to mergers (http://www.nature.com/news/galaxy-formation-the-new-milky-way-1.11517)

The *Eris* N-body simulation of a massive late-type spiral galaxy in a WMAP3 cosmology (Guedes, Callegari, Madau, & Mayer 2011. The simulation was performed with the GASOLINE code on NASA's *Pleiades* supercomputer and used 1.5 million cpu hours.

M_{vir}=7.9 x 10^{11} M_{sun}

$N_{DM}+N_{gas}+N_{star}$=7M+3M+8.6M within the final R_{vir}

force resolution=120 pc

RESEARCH FUNDED BY NASA, NSF, AND SNF

New Results on Arms (arxiv1411.5792 Kendall et al and 1507.07000 Choi et al)

- In general, spiral morphology correlates only weakly with morphological parameters such as stellar mass, gas fraction, disc/bulge ratio, and v_{flat}.

In contrast a strong link is found between the strength of the spiral arms and tidal forcing from nearby companion galaxies.

This appears to support the longstanding suggestion that either a tidal interaction or strong bar is a necessary condition for driving grand-design spiral structure.

- Stationary density waves rotating at a constant pattern speed P would produce age gradients across spiral arms.
  - however there is no evidence of star formation propagation across the spiral arm
  - thus no convincing evidence for a stationary density wave with a single pattern speed in M81, and instead favor the scenario of kinematic spiral patterns that are likely driven by tidal interactions

- Star forming disk galaxies have an IMF consistent with that of the MilkyWay
  - bulges might have different IMF
  - Origin of Tully-Fisher is not clear
- disks are 'sub-maximal' e.g.
  - A disk contributing maximally to the gravitational potential sets a lower limit on the amount of halo dark matter in the inner regions of disk galaxies. Maximum-diskdecompositions find the disk mass produces 85±10% ofthe observed rotation velocity at 2.2 disk scale-lengths
  -

Next Set of Lectures

- Elliptical galaxies