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

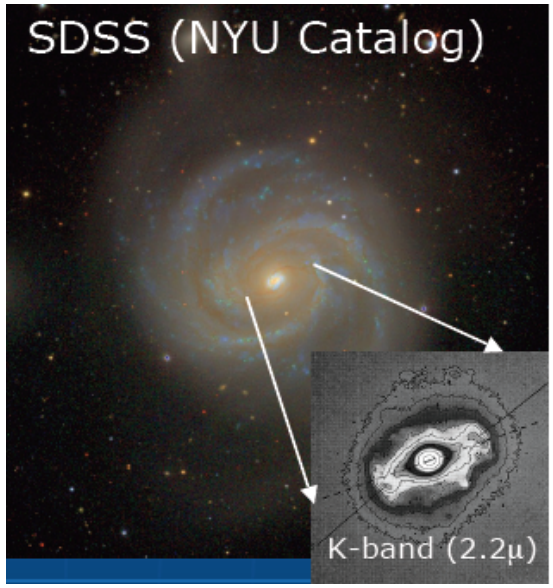
  (morphology density relation- Dressler 1978)

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 $I(R)=I(R_e)(\exp-7.67[(R/R_e)^{1/4}-1]))$
  – R_e is the half light radius

Spirals- 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).



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 measures)
  - $L_{opt} \sim A v_{max}^4$
- Connects galaxy dynamics to optical luminosity
- Since luminosity depends on distance^2 while rotational velocity does not, this is a way of inferring distances

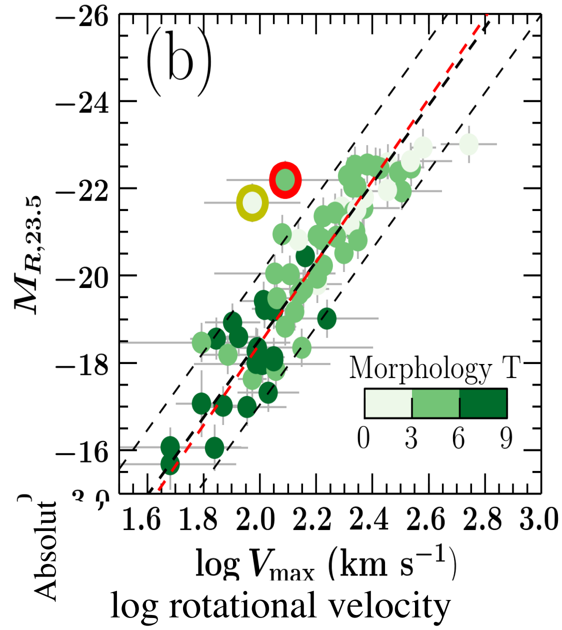


Figure shows the **T-F relation R band**

arXiv:1508.03004v1
Barbosa et al

Tully-Fisher
Back of the envelope derivation

- System in equilibrium: centripetal force balances gravity
- $GM(r)/r^2 = v_c^2/r$; so $M(r) = v_c^2 r/G$; definition of surface density $\Sigma = L/r$
- If all galaxies are alike and have the <u>same surface densities</u> $L \sim r^2$
- Further if M/L is constant M~L
- a little algebra gives $L \sim v_c^2 L^{1/2} \sim v_c^4$
- 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.

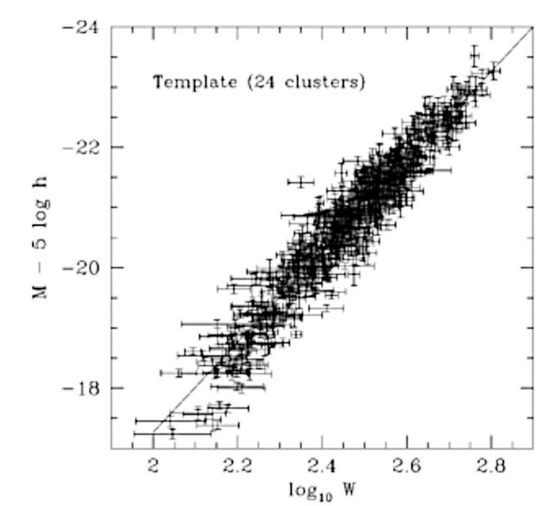
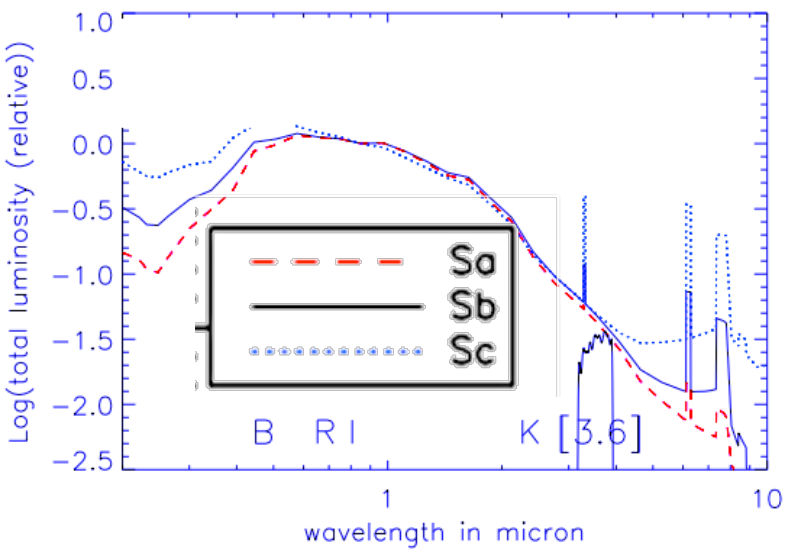


Fig. 1.—Template relation based on 555 galaxies in 24 clusters. The fit is −21.00 ± 0.02−7.68 ± 0.13 (log *W* − 2.5).

Giovanelli et al 1997

Spiral Galaxy spectra

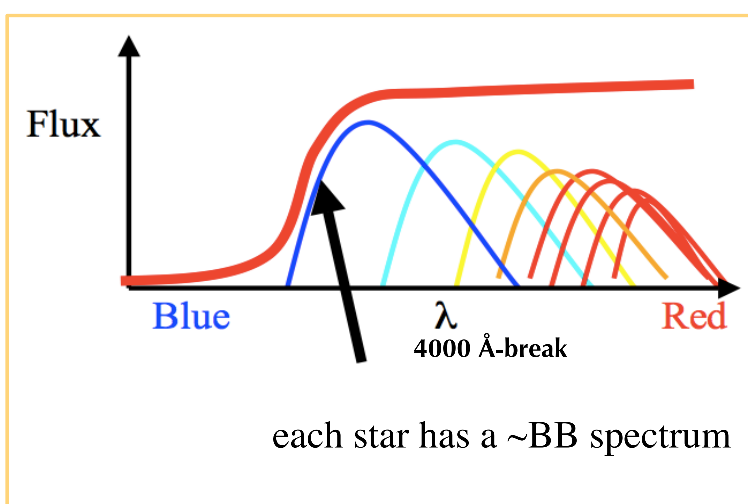
- Galaxies have composite spectra. They integrate contributions from different stars of different stellar populations, gas and the effects of dust
- The overall continuum shape is modulated by the gas, the stars, as well as by the presence of dust.



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

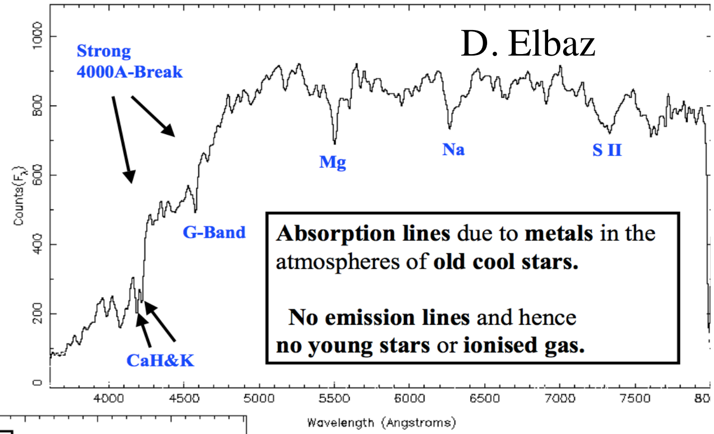
Galaxy Spectra The Simple Picture

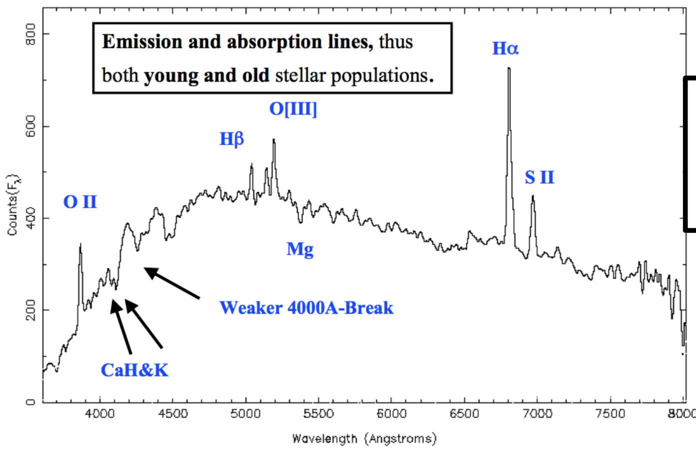
- Continuum: the combination of many Black-Body spectra (from a wide range of stellar types, spanning a range in temperatures, weighted by the IMF) *just happens* to produce a fairly flat overall spectrum



One Step Beyond Simple

Little star formation, little ionized gas





moderate star formation, strong lines from ionized gas

A Sequence

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

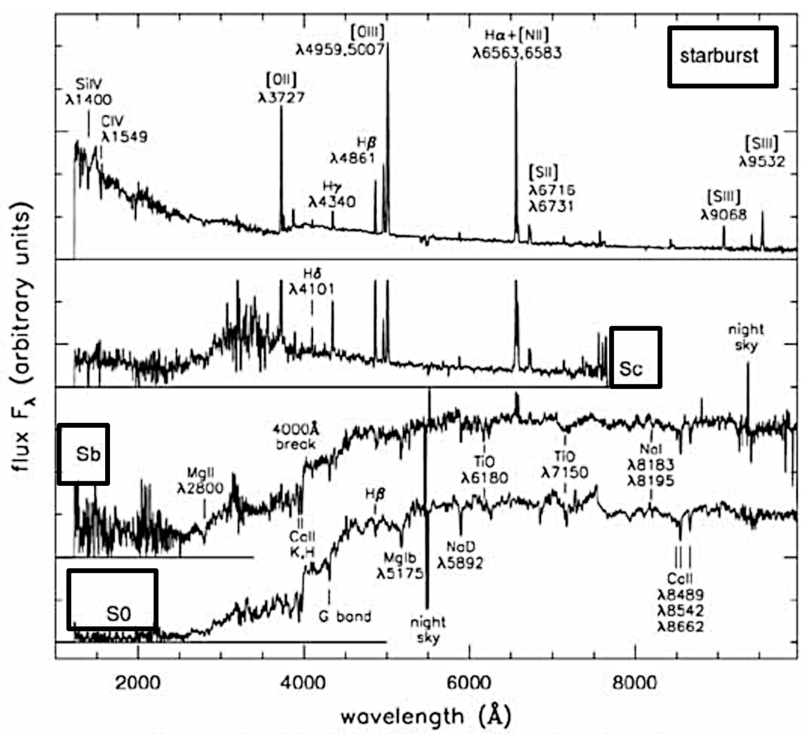


Fig 5.24 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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

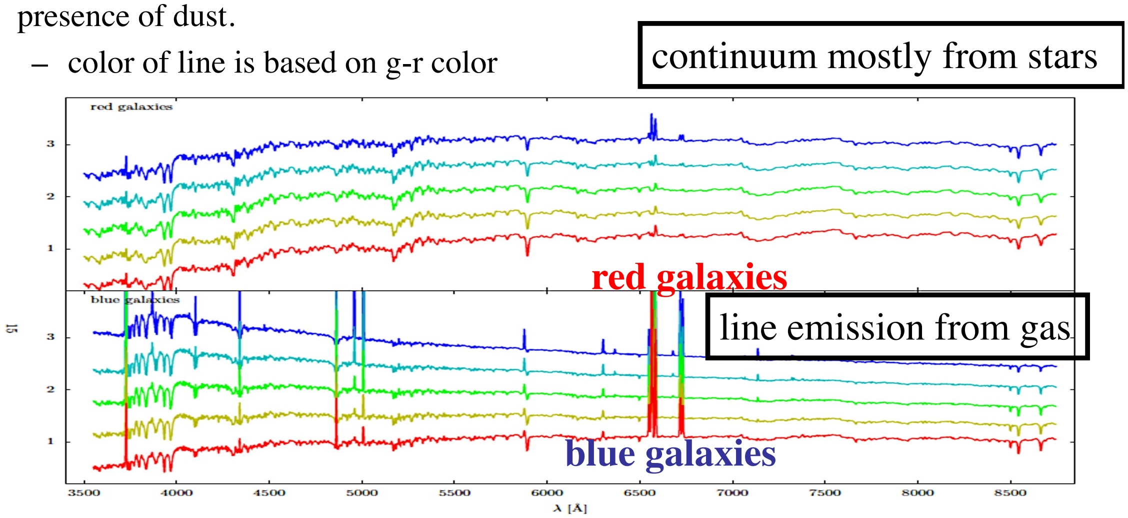
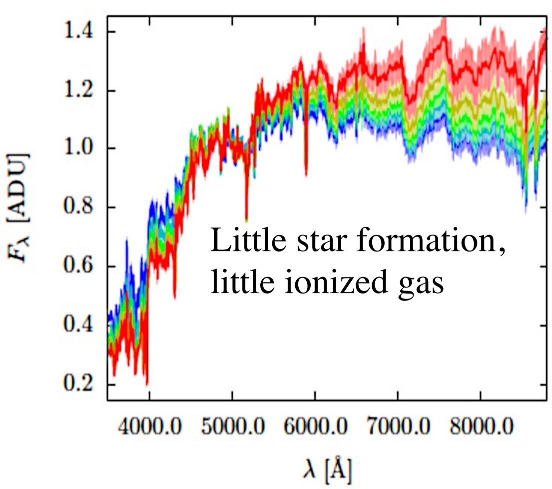
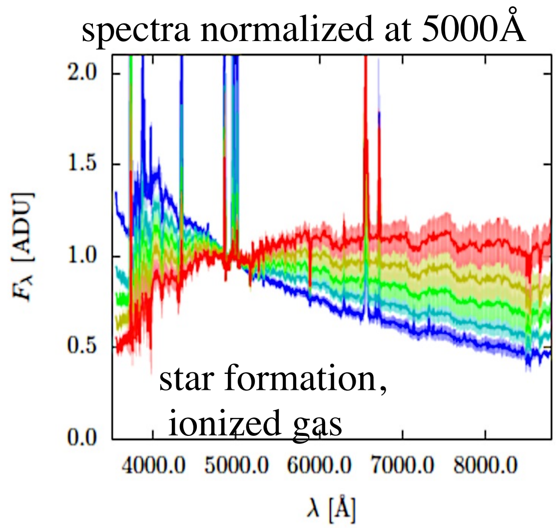


Figure 12: Composite spectra of the refined colour classes as described in Sec. 3.4. The curves are colour-coded from blue (top) to red (bottom) based on the $g - r$ colour of the galaxies. See the online edition for a colour version of this plot.

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)

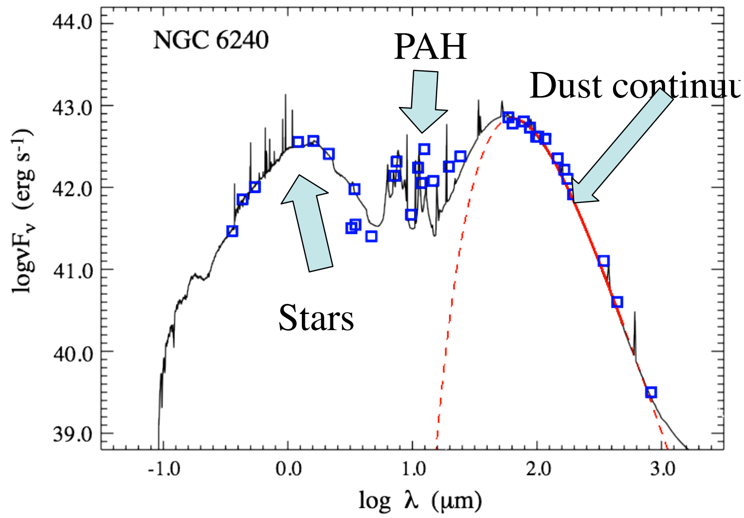




Galaxy Spectra -IR

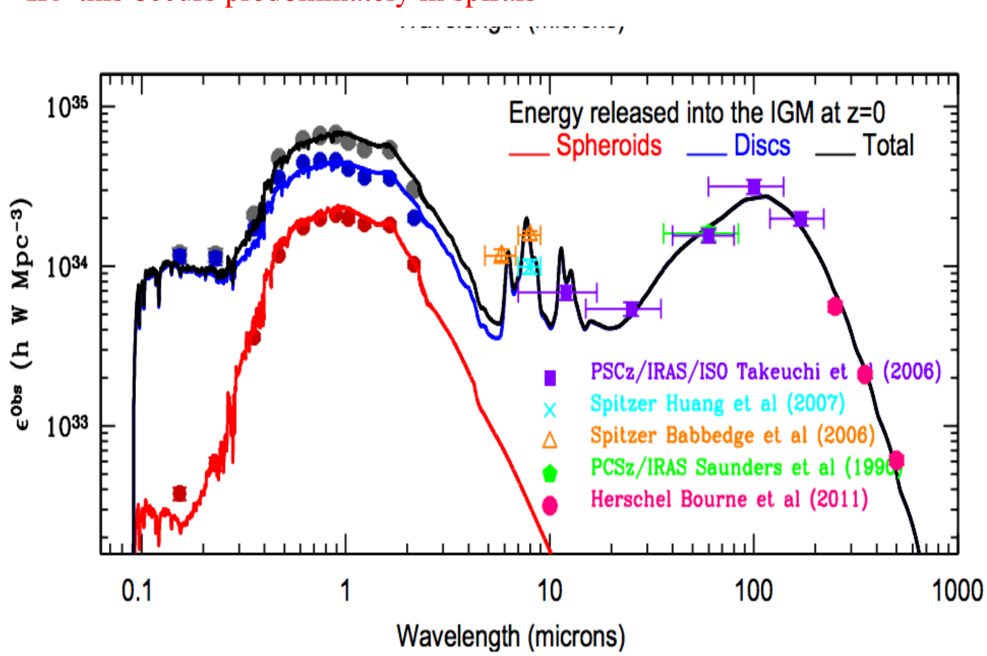
- At λ>5μ in most spiral galaxies continuum dominated by emission from dust -there are atomic and molecular features as well
- In many spiral galaxies L(opt)~L(IR)
  - dust heated by star light - temperature to which it is heated depends on geometry and the nature of the stars

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



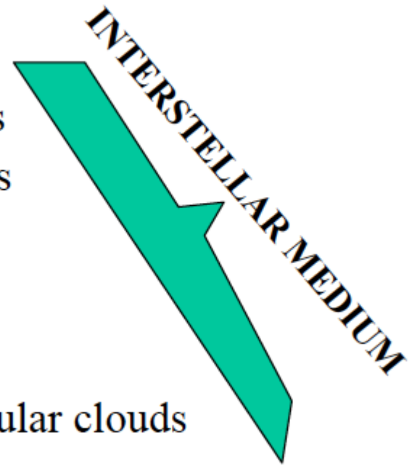
Energy Released By Galaxies

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

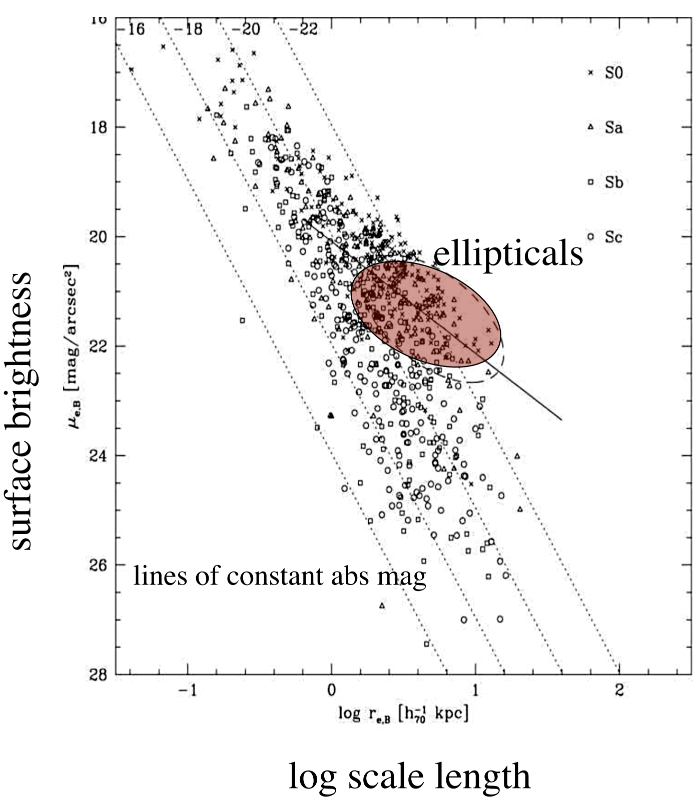
Dark matter dominates mass (and potential) outside ~a few scale lengths

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 spiral

- 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

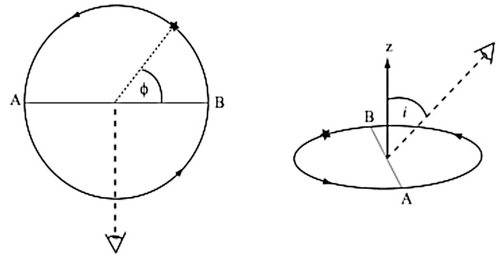
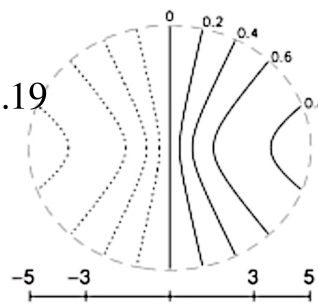


Fig. 5.18. Left, a rotating disk viewed from above. Azimuth ϕ, measured in the disk plane, gives a star's position in its orbit; an observer looks from above the disk, perpendicular to diameter AB. Right, the observer's line of sight makes angle i with the disk's rotation axis z.

Fig 5.19



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

negative velocities ----

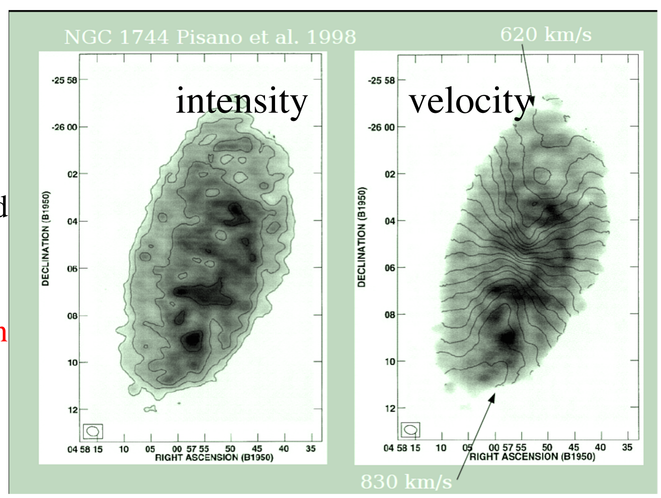
HI

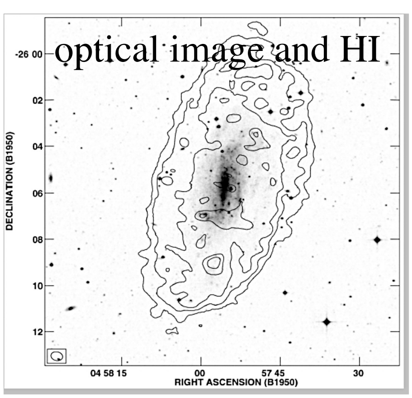
- Spirals have large HI disks

– This gas is optically thin

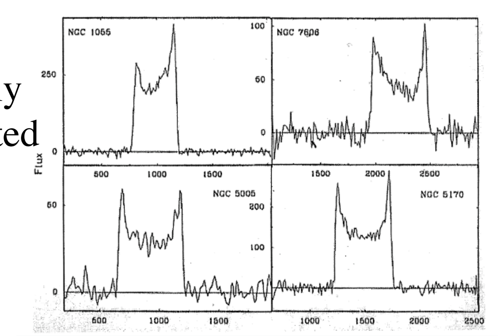
This means that we see all the gas and can measure the amount directly from the line intensity

- HI gas is much more extended than the optical light, $r_{HI} > 2.5\ R_{25}$
- – Gives a unique tracer for the velocity in spiral galaxies





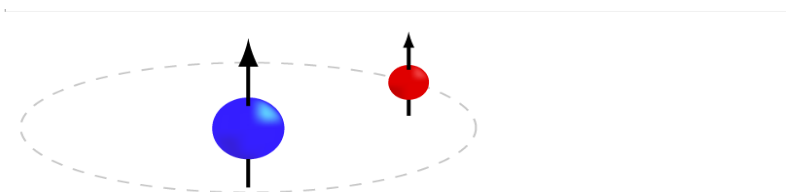
Spatially integrated



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
  - 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)

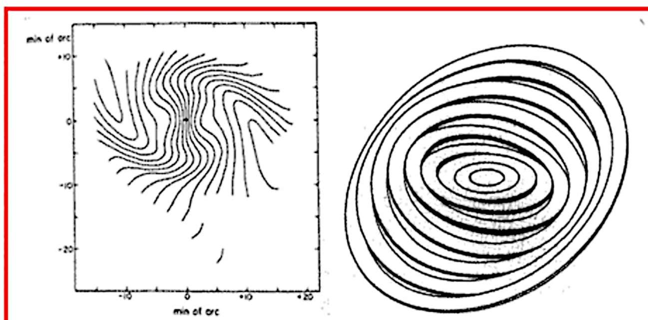


Figure 8.36 A tilted ring model of M83 (right) and the spider diagram predicted by this model (left). [After Rogstad, Lockhart & Wright (1974)]

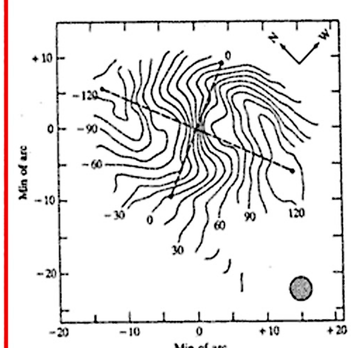
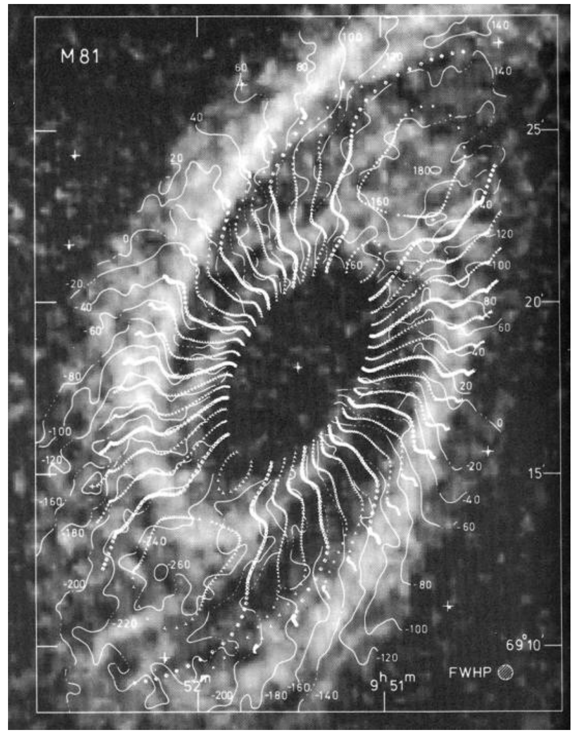


Figure 8.37 The observed spider diagram of M83. [After Rogstad, Lockhart & Wright (1974)]

Gas Motions

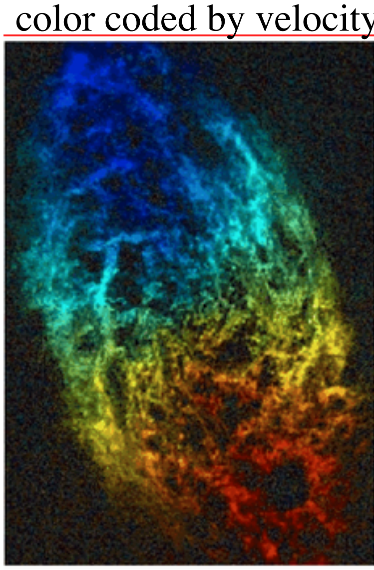
- This is what is seen in 'real' galaxies in the motion of HI (fig 5.13 S=G)
- e.g spider diagram is 'A diagram that gives the equations for lines of constant radial velocities as seen for a rotating galaxy inclined to the observer's line of sight."
- - Deviation from Spider plot in M81 shows influence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



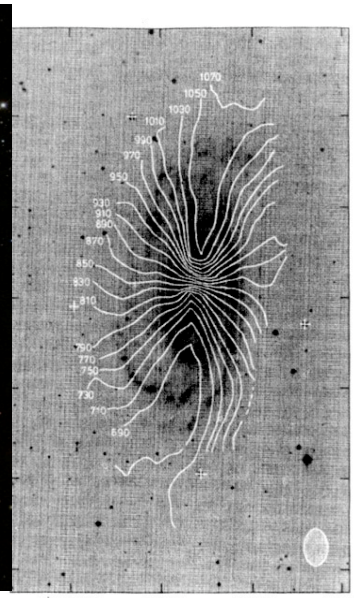
Optical Image and Velocity Field of NGC5033

- Spider plot is the contours of the velocity field

color coded by velocity



hydrogen velocity



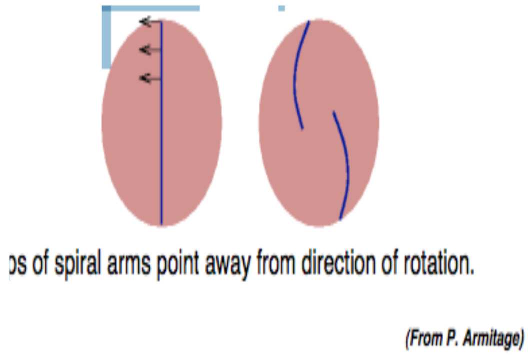
Spiral Arms (sec 11.6 in MBW- sec 5.5.2 in S+G)

- Defining feature of spiral galaxies - what causes them?

- Observational clues

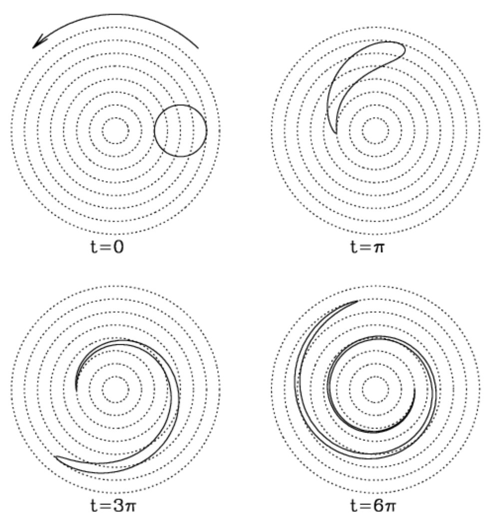
Seen in disks that contain gas, but not in gas poor S0 galaxy disks.

- 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.



Spiral Arms

- 'Visually' spiral arms are associated with star formation/molecular gas.
- How to describe: if the arms are 'sinusoidal' $\Sigma(R,\phi)=\Sigma_0(R)+\Sigma_1(R)\cos[m\phi+f(r)]$
  - f(r) shape function of the spiral- if spiral is tightly wound $\partial f/\partial r$ is large
- Differential rotation of disk - for V(r)=constant, $\Omega=V/R$ must vary with R.
  - So a line with a constant azimuthal angle $\phi=\phi_0$ will be sheared into a spiral curve $\phi(R,t)=\phi_0+Vt/R$ at time t.
  - thus a 'blob' will be sheared into a spiral structure



MBW, fig 11.3)

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

- For galaxy with flat rotation curve:

$V(R)$ = constant

$\Omega(R) = V/R$ Angular velocity~$1/R$

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

However this is NOT SOLELY why spiral galaxies have spiral arms- if so 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

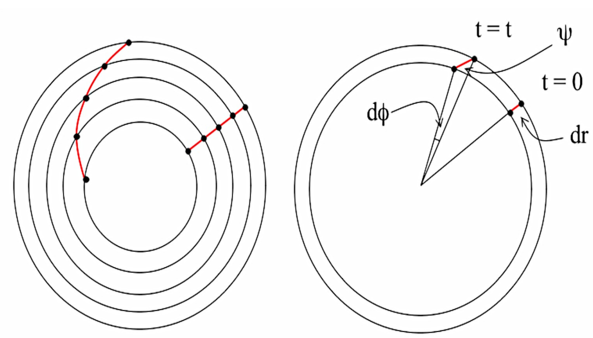
$d\omega/dr = v/r^2$ angle $\phi = \omega t$, $d\phi = t d\omega = v/r^2\ t dr$
so $\tan\psi = dr/r\ d\phi = r/vt = 1/\phi$

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
- Short lived spiral arms can arise from temporary patches pulled out by differential rotation

Winding?



Flat rotation curve: v = const; $\Omega = v/r$; $d\Omega = v/r^2\ dr$
Now, $\phi = \Omega \times t$, so $d\phi = d\Omega \times t = v/r^2\ dr\ t$
So $\tan\psi = dr / r\ d\phi = dr / [(v/r)\ dr\ t] = r / vt = 1/\Omega t = 1/\phi$

$\tan\psi = r / vt = 1/\phi$

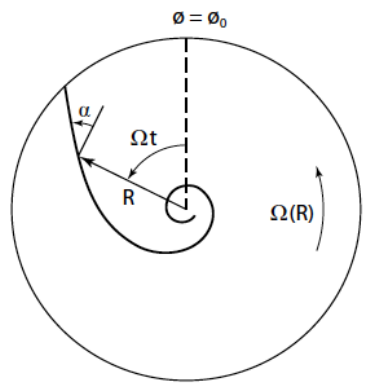
M. Whittle's web site

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

In the diagram

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



For a typical spiral galaxy with a flat rotation curve

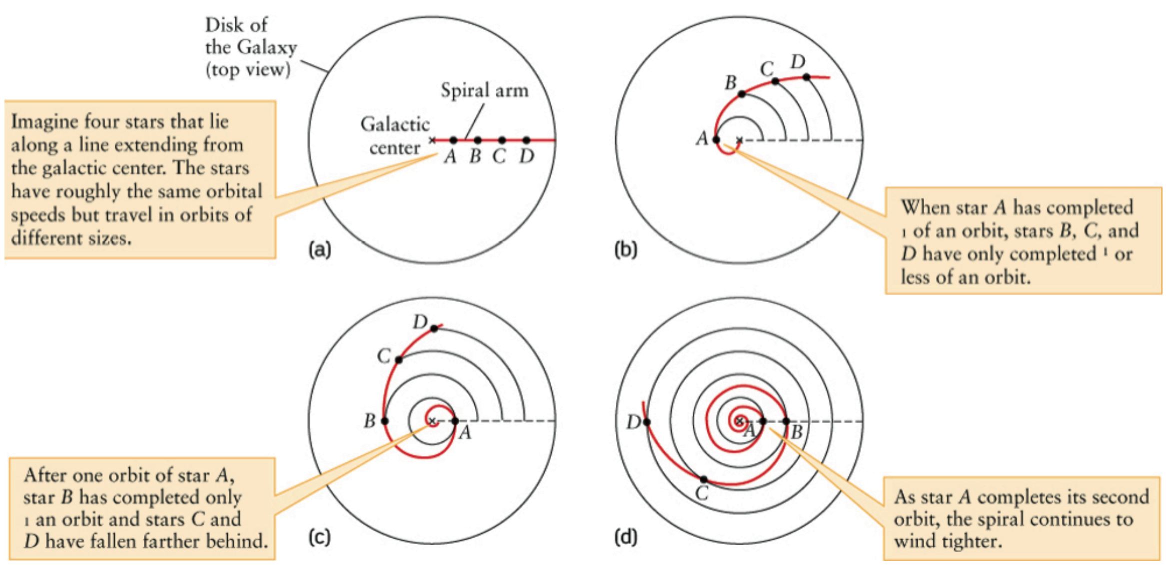
$\Omega(R) = v_{circularr}/R$; so

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

near the sun $v_{circular}$ =220km/sec at R~10kpc, for $t=10^{10}$yrs
   α=0.25deg !

Real galaxies have α ~5-25 deg

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



Spiral Density Waves- One Possible Answer –see notes "Theory of Spiral Structure"

- 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.

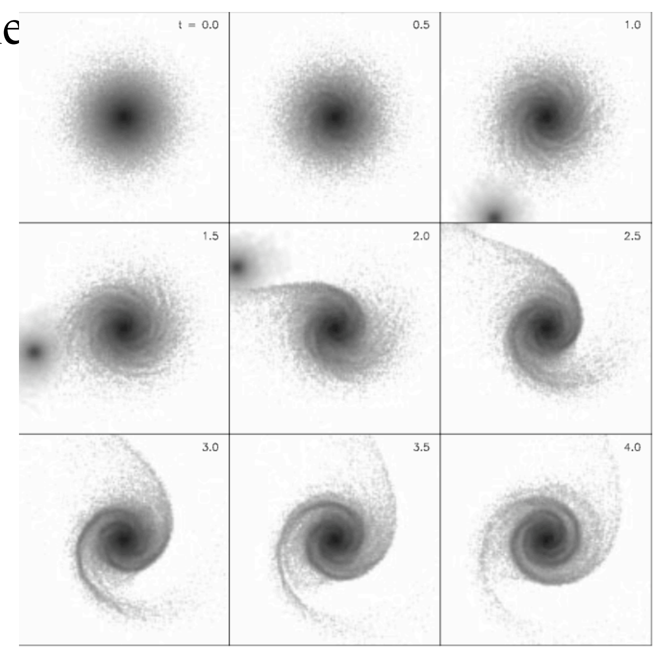
Simplest case to consider is gas. Imagine a small perturbation which slightly compresses part of the disk:

• 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.

Another Possible Origin

- Tides between galaxies provoke a two-sided response, like the ocean's response to the tidal pull of the Moon.
- Since the classic two-armed 'grand-design' spiral galaxies M51 and M81 are clearly interacting with close companions, it's very likely that these galaxies owe their symmetric spirals to tidal interactions (J. Barnes)



Tidal encounter between disk and a companion of 1/10th the mass- times in rotation units at 3 scale lengths

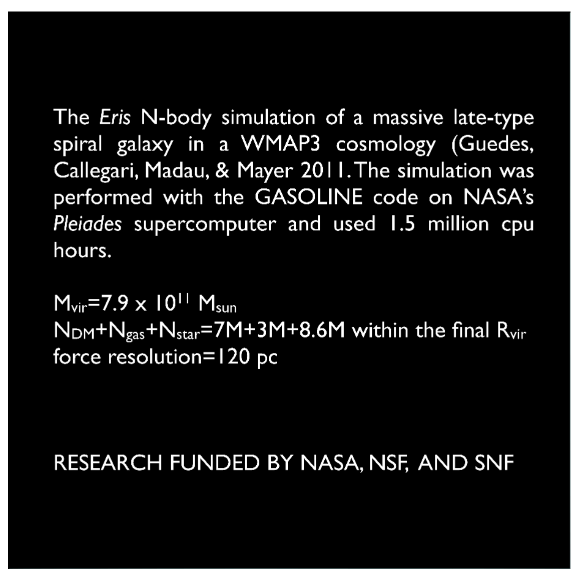
Formation of Spiral Galaxies

- Recent numerical models (Somerville and Dave 2015) show that several general conditions must be met to produce realistic disk galaxies
- First, stellar feedback must be effective at keeping galaxy-wide star formation efficiencies low, and stellar winds must preferentially remove low-angular momentum material.
- Second, star formation should occur only in very dense, highly clustered environments like those that are expected to form GMCs, not smoothly distributed over the whole disk, which helps to make stellar feedback more efficient because the star formation is highly clustered.
- Third – the ISM must be highly pressured to stabilize disks against fragmentation

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 a merger (http://www.nature.com/news/galaxy-formation-the-new-milky-way-1.11517)



End of Spirals

- Now a bit on star formation
  (Not in S&G)

Another take on spiral arm formation- see web page for paper

- For another take on the formation of spiral arms see
- https://www.youtube.com/watch?v=-ii0nksV2lY
- https://www.cfa.harvard.edu/~edonghia/Site/Spiral_Arms.html
- The authors E. D'onghia et al say

  "mass concentrations with properties similar to those of giant molecular clouds can encourage the formation of spiral arms through a process termed swing amplification. ... the response of the disk can be highly non-linear, significantly modifying the development and longevity of the resulting patterns. Contrary to expectation, ragged spiral structures can survive at least in a statistical sense long after the original perturbing influence has been removed, motivating a new interpretation of various phenomena, including disk heating, radial migration, and galaxy pattern speeds."