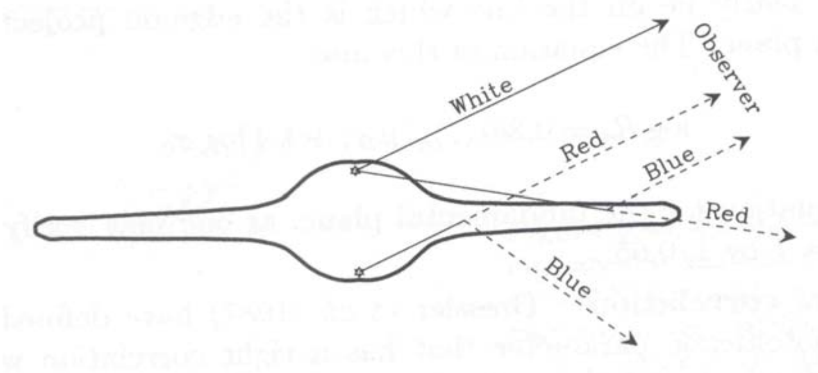
Photometry of disk galaxies

The surface brightness profiles of disk galaxies are complex:
•they contain more than one component (central bulge, disk, bar, spiral arms, rings…),
•disk galaxies contain large amounts of dust, and hence they are not transparent.

Besides the contribution from stars, their appearance will depend on the distribution of gas and dust, and from the angle from which we observe them.



When the galaxy is edge-on, light has to pass through longer columns of the galaxy's interstellar material.

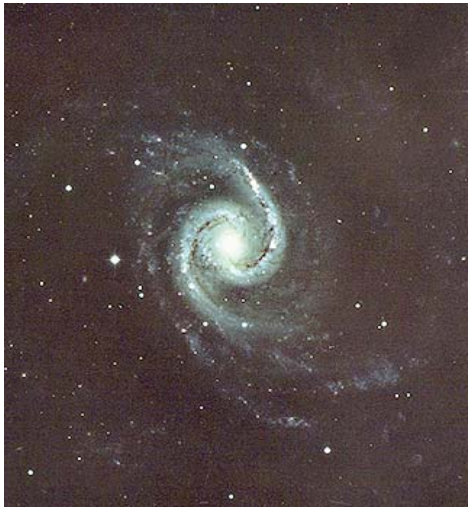
Self-absorption in the galaxy

The elliptical galaxies contain little or no gas and dust (there is no ongoing star formation). This means that the intrinsic absorption in this type of galaxies is not important.

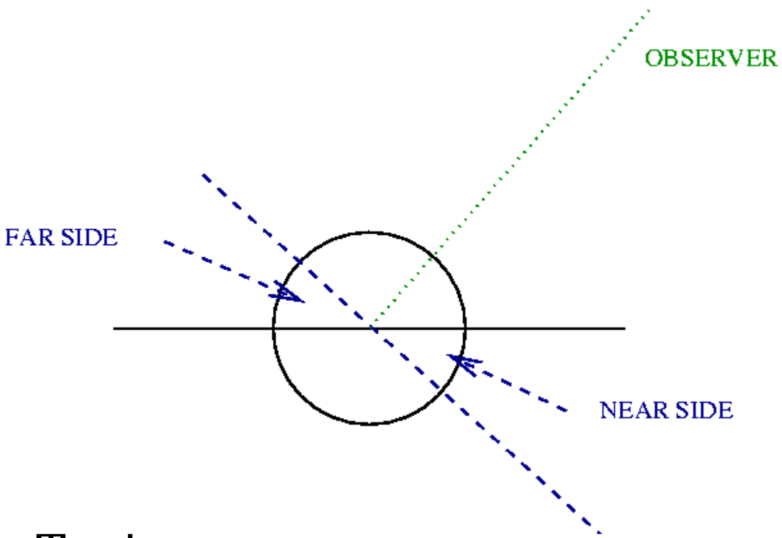
In disk galaxies, however, there are large amounts of gas and dust. These affect their surface brightness (flux per sq.arcsec), depending on the angle from which the galaxy is viewed:

Edge on

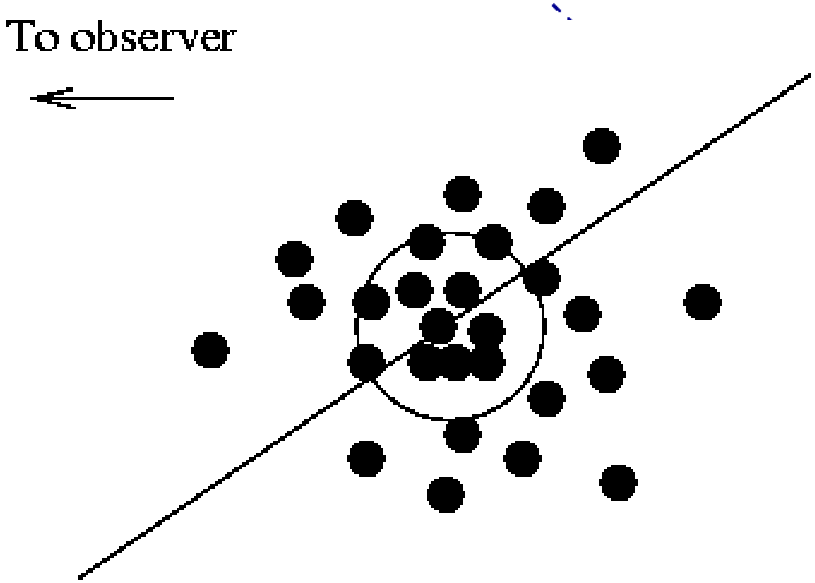
Face on

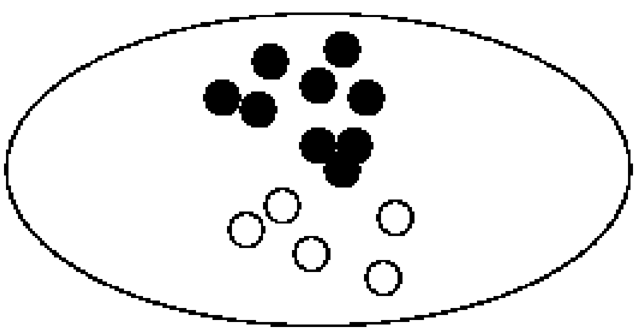


Photometry of disk galaxies



The light coming from the near side of the bulge (along the major axis) is absorbed by the dust in the disk, becoming redder than that on the far side (on the disk major axis).





Photometry of disk galaxies

On the other hand, dust preferentially scatters blue light. Thus, since light from the near side is more scattered than that on the far side, the near side would appear bluer.

Scattering is not isotropic; it is produced by dust grains that are not round. They are more efficient in scattering light through small angles (forward scattering).

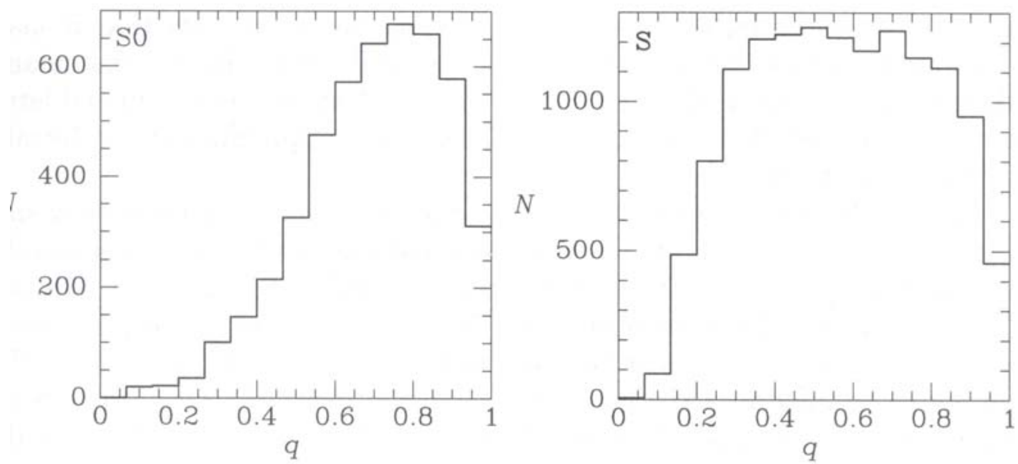
Thus scattering and absorption have competing effects. Which dominates depends on the inclination of the galaxy:

- at small inclinations (nearly face on) absorption dominates, the near side appears dimmer and redder.
- At intermediate inclinations, (forward) scattering dominates.
- At very large inclinations, the near side is very heavily obscured.

NOTE: The inclination is measured by the tilt of the disk with respect to the plane of the sky (edge-on: 90 deg; face-on: 0 deg)

Shapes of disk galaxies

The following figures show the distribution of apparent axis ratio of a sample of ~5000 S0 galaxies (left) and ~13000 spiral galaxies (right)



In S0 galaxies the distribution of q rises and has a sharp peak at q ~0.7, whereas the distribution of spirals rises fast, but remains more or less constant above q ~ 0.3.

Shapes of disk galaxies: spirals

We may assume that spiral galaxies are axisymmetric oblate bodies. We can then use the equation derived in the lecture on elliptical galaxies:

$$f(q) = q \int_0^q \frac{d\beta N(\beta)}{[(1-\beta^2)(q^2-\beta^2)^{1/2}}$$

where β is the true axis ratio, and q the observed ellipticity.

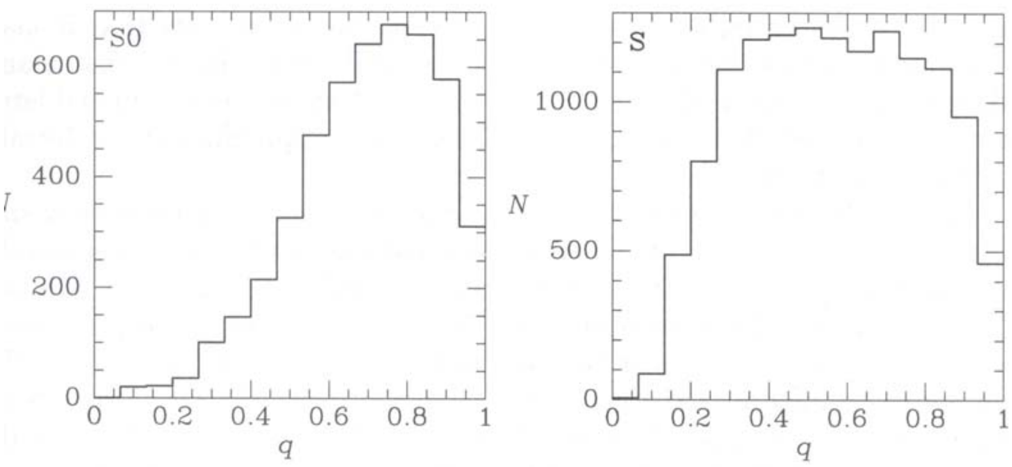
Note that a distribution of β that peaks at some value $\beta_0 << 1$ will produce an apparent distribution of q that is approximately independent of q for $q >> \beta_0$. (e.g. assume $N(\beta) = \delta(\beta - \beta_0)$).

Such a distribution would then explain the previous figures.

This provides quantitative support to the subjective impression that spiral galaxies are intrinsically quite thin.

Shapes of disk galaxies: S0

In contrast, the sharp rise in the distribution of q for S0 galaxies implies that the true axis ratios have to be more or less uniformly distributed from $q \sim 0.25$ to $q \sim 0.85$.



This is probably related to the fact that S0s have prominent bulges, in which case the axis ratio will be close to unity independently of inclination.

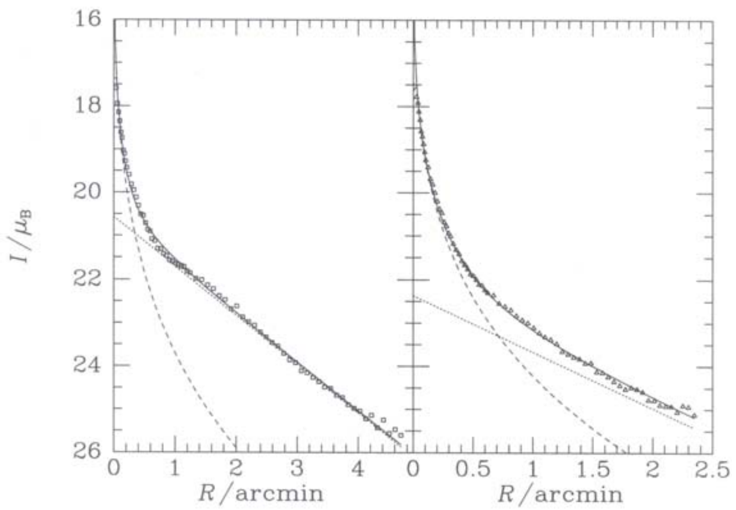
Photometry of disk galaxies

•To a good approximation, at large distances from the center, the surface brightness profile of disk galaxies are straight lines in a log-log plot (log intensity vs. log radius).

•This implies that the profiles there decay exponentially.

•In many cases there are deviations from this behavior, which are often attributed to the presence of other components in the disk (e.g., bars and rings).

•The following Figure shows the surface brightness profile of the two spirals NGC 2841 and NGC 3898.



The dotted line shows the exponential fits to the disk; the dashed curve is an $R^{-1/4}$ profile fitted to the central bulge of these galaxies. The full curve is the sum of both components.

Photometry of disk galaxies

Studies of edge-on galaxies also allow us to derive the light profile perpendicular to the plane of the disk (z-direction). Commonly used profiles are:

$$j(R,z) = j_0 \exp(-R/R_d)\exp(-|z|/z_0)$$

$$j(R,z) = j_0 \exp(-R/R_d)\,\mathrm{sech}^2(z/2z_0)$$

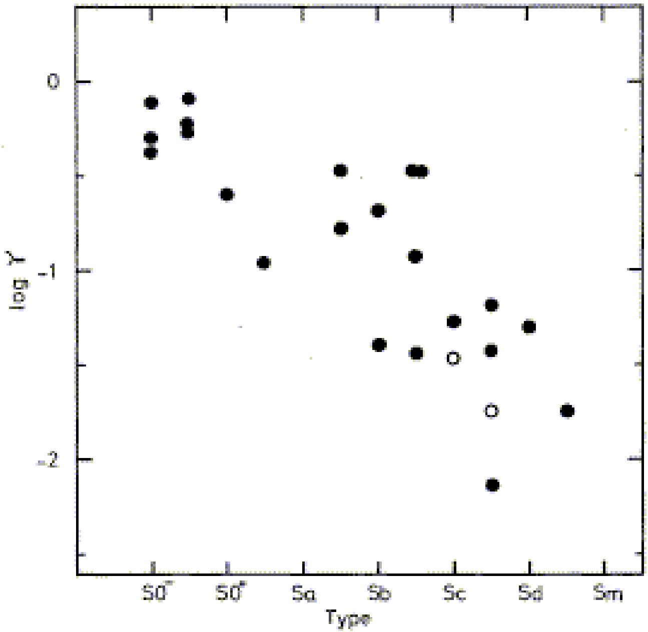
Both descriptions are often used, and it is not clear whether one should be preferred over the other (There are no clear theoretical arguments that favour either of the two).

Just like in the Milky Way, a second exponential component can sometimes be fitted to the observed light distribution of edge-on galaxies. This would be the equivalent of our thick disk. But it is much more difficult to establish the reality of thick disks, because of inclination effects, a very flattened stellar halo, etc, which would mimic a thick disk.

In the general case, the total surface brightness profile can be expressed as a combination of an $R^{-1/4}$ (the bulge) and an exponential (the disk) profile.

The relative contribution of the bulge to the total luminosity is known as the bulge fraction:

$$B/T = \frac{R_e^{\,2} I_e}{R_e^{\,2} I_e + 0.28 R_d^{\,2} I_d}$$

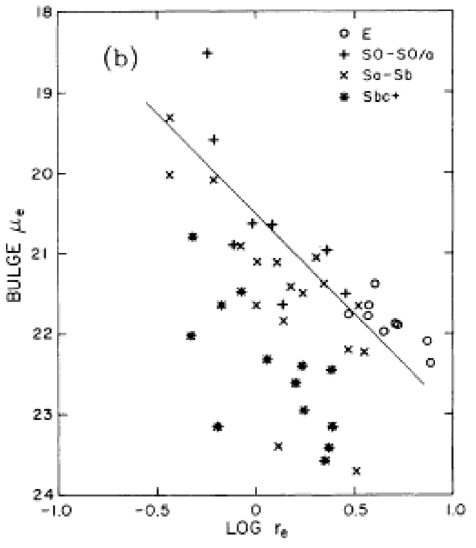


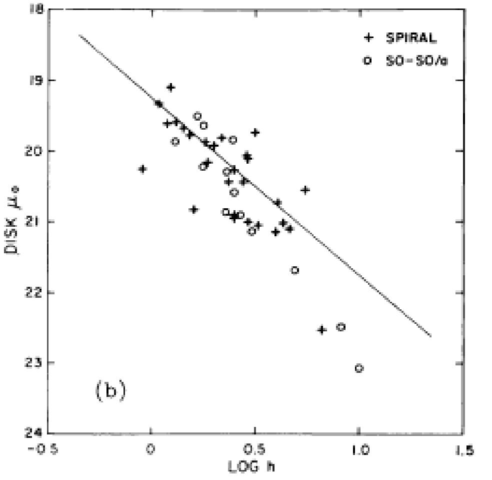
This ratio is computed from the total luminosity of the bulge (for a de Vaucouleurs) and the disk (for an exponential in R).

This is often related to the disk-to-bulge ratio: $D/B = (B/T)^{-1} - 1$

The figure on the left shows that B/T (or γ = B/D) correlates Hubble type.

Correlations between parameters





•Bulges of Sb and earlier type disks follow a similar relation between central surface brightness and effective radius as E galaxies.
•Bulges of later types (Sc…) tend to lie systematically lower.

•The disks also show that physically larger systems have lower central surface brightness.

•It has been suggested that the central surface brightnesses cluster around I ~ 21.7$\mu_{B,}$ (Freeman's law) but this is at least partly due to selection effects. It is easier to measure large and bright galaxies; but there are large numbers of disk galaxies of very low surface brightness (LSBs).

The properties of bulges

Bulges are some of the densest stellar systems. They can be flattened, ellipsoidal or bar-like. The surface brightness of a bulge is often approximated by the Sersic law:

$$I(R) = I(0) \exp\{-(R/R_0)^{1/n}\}$$

Recall that n=1 corresponds to an exponential decline, whereas n=4 is the de Vaucouleurs law.

About half of all disk galaxies contain a central bar-like structure. The long to short axis ratio can be as large as 5:1.

When viewed edge-on, the presence of a bar can be noticed from the boxy shape of the light distribution. In some cases the isophotes are squashed, and the bulge/bar has a peanut-like shape.

Colour and metallicity of disk galaxies

Let us consider the case of M31:

• Interior to 6 kpc, the bulge dominates the light profile; the colours are similar to an E galaxy.

•Slightly further out, young stars begin to contribute substantially to the surface brightness, and colour of the galaxy.

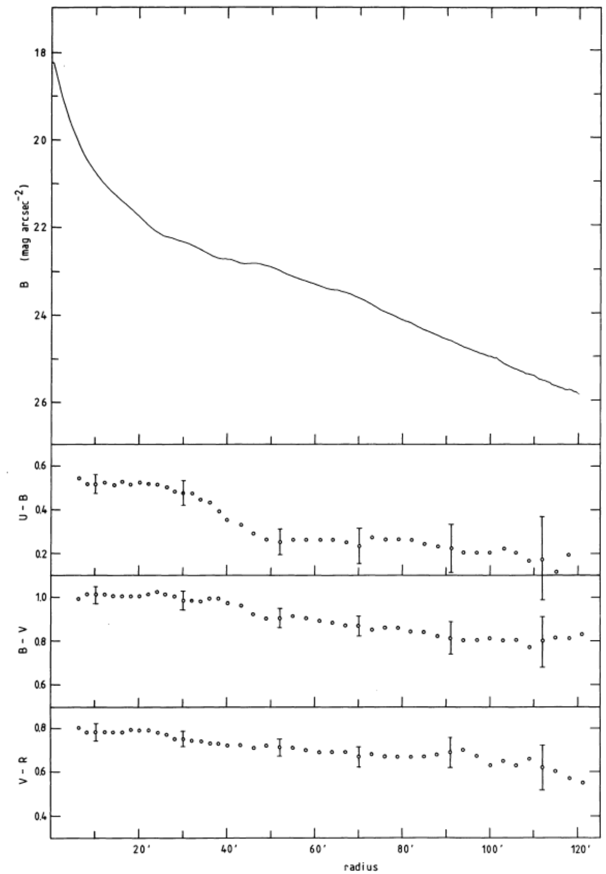


FIGURE 12. — The global light and color profiles of M31 obtained from the data by averaging the intensity distributions in ellipses centred on the nucleus of the galaxy. Foreground stars were removed from the data beforehand. The uncertainties were estimated from comparisons of the global profiles derived from different plates in the same color band.

For other disk galaxies, there is no conclusive answer with respect to the presence or absence of colour-gradients (they are very hard to measure).

There are competing reasons for colour-gradients:

- the degree of internal extinction by dust
- the mean ages of stars
- metallicity gradients

All of these effects could produce colour-gradients, as well as destroy these.

Cool gas in the disk

•Since the gas in the disk is moving, the emission of the HI 21 cm line will be Doppler shifted according to its radial velocity.

•The HI is optically thin (the 21 cm line suffers little absorption). This means that the mass of gas is simply proportional to the intensity of its emission.

•The HI gas is often spread out more uniformly than the stars (peak is only a few times larger than average, in comparison to the 10,000 contrast in stellar disks). It can also be more extended.

•The ratio $M(HI)/L_B$ is often used as an indicator of how gas rich a system is: for S0/Sa this quantity ranges between 0.05 – 0.1 $M_{sun}/L_{B,sun}$. For Sc/Sd it is about ten times larger.

Gas motions and the masses of disk galaxies

In the case of the Milky Way, we saw that the stars and gas account only for a fraction of its mass (and we introduced the concept of dark-matter).

The same is true for most spiral galaxies.

The acceleration of a particle moving on a circular orbit is related to the gravitational potential $\Phi(R,z)$ acting on it:

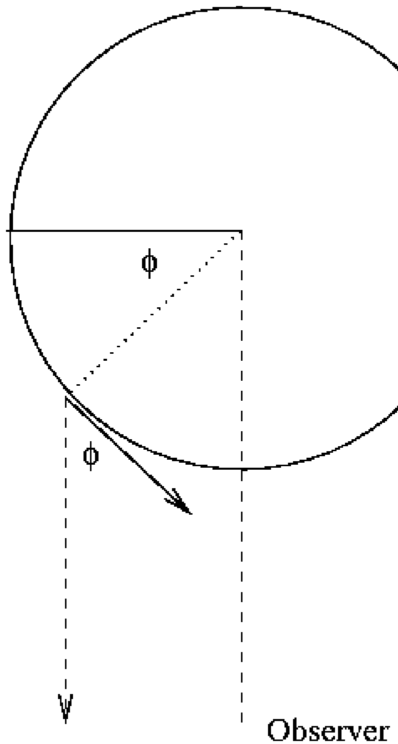
$$\frac{V^2(R)}{R} = \left| \frac{\partial \Phi}{\partial R} \right|_{z=0}$$

- The quantity V(R) is the circular velocity (defined as in the Milky Way)
- Measurements of V(R) give an estimate of how the gravitational potential (and hence mass) varies as function of distance from the centre.
- V(R) is often referred to as the rotation curve.

Rotation curves

Just like in our Galaxy, the dominant motion in a disk galaxy is rotation, HI gas random motions are typically of the order of 10 km/s or smaller. This implies that we may assume that the gas clouds follow nearly circular orbits with velocity V(R).

The question now is how to derive V(R) from the observed radial velocity toward or away from us.



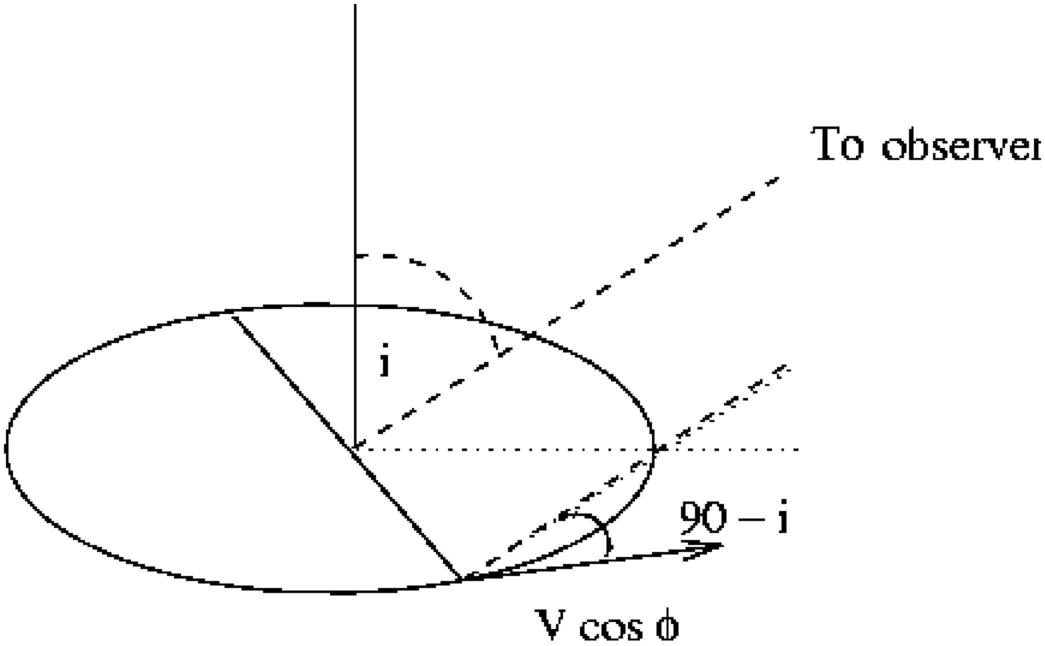
Viewed edge-on, the radial velocity measured $V_r(R,i=90)$ is

$$V_r(R,i=90) = V_{sys} + V(R)\cos\phi$$

V_{sys} is the systemic velocity of the Galaxy wrt the observer.

When the galaxy is tilted an angle *i*, we have to project the circular velocity V(R) one additional time. Then the measured radial velocity $V_r(R,i)$ is

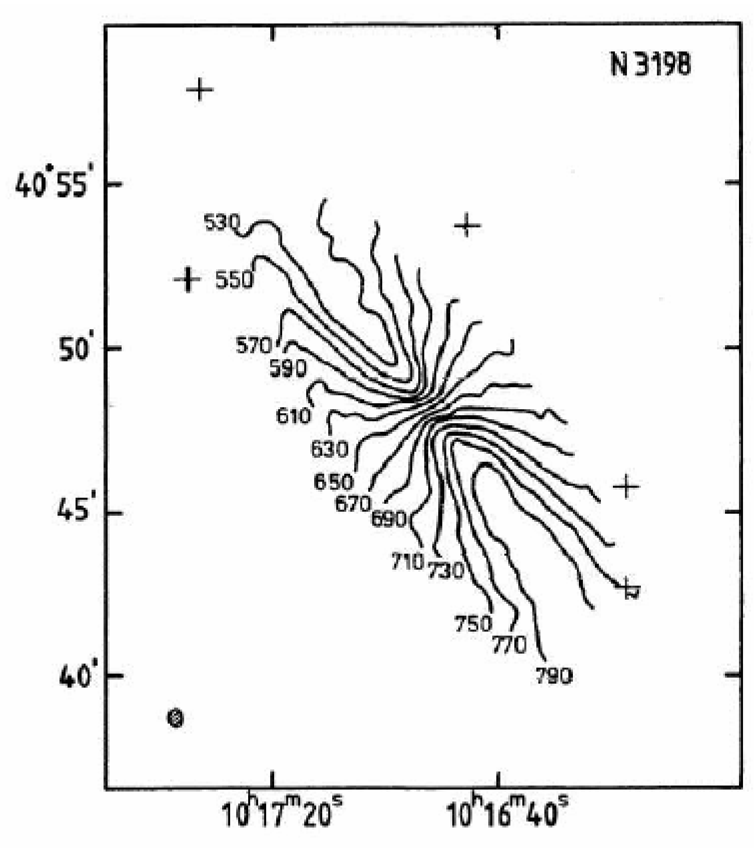
$$V_r(R,i) = V_{sys} + V(R) \cos\phi \sin i$$



Spider diagrams

Contours of constant V_r connect points with the same value of $V(R) \cos\phi$ forming a spider diagram like that shown here.

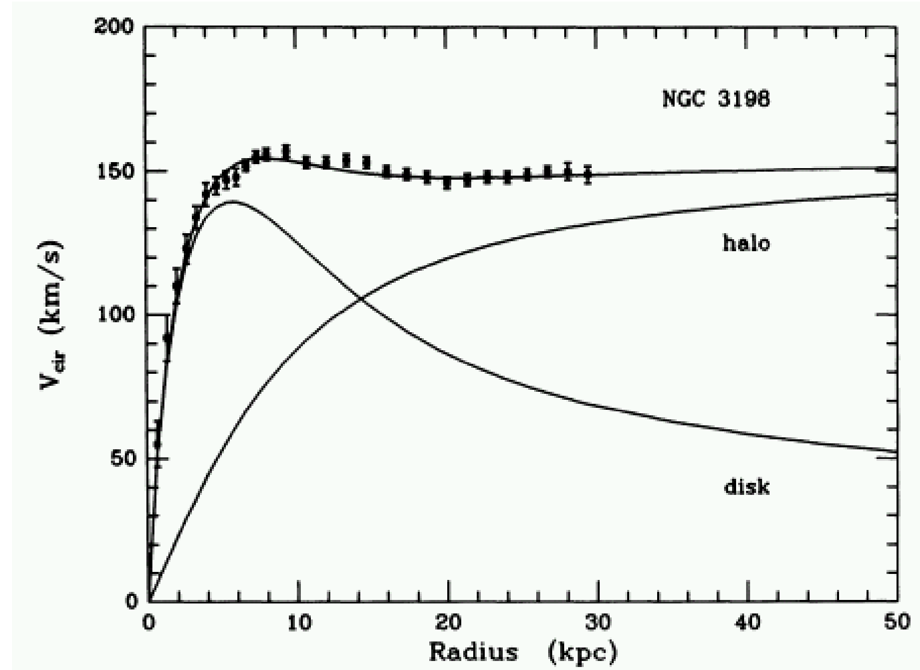
- In the central regions, the contours run parallel to the minor axis.
- Further out, (i.e. larger values of ϕ), they run radially away from the centre.
- The directions where the radial velocity deviates most from the systemic velocity of the galaxy, define the kinematic major axis (i.e ϕ=0,180 deg)
- Note that the shape of the contours, and in particular, how closely packed they are, tells us about how rapidly the V(R) is changing with R.



This is the rotation curve for the previous galaxy.

It is shown as function of radius R along the (photometric) major axis.

This axis is generally (but not always) coincident with the kinematic major axis.



We can compare this rotation curve to that provided by the luminous mass in the galaxy (its disk and bulge).

To calculate the predicted circular velocity (i.e. the mass or the gravitational potential), we use the observed surface brightness distribution of gas and of stars (preferably in the R-band to be sensitive to older stellar populations which trace mass better).

Fitting rotation curves

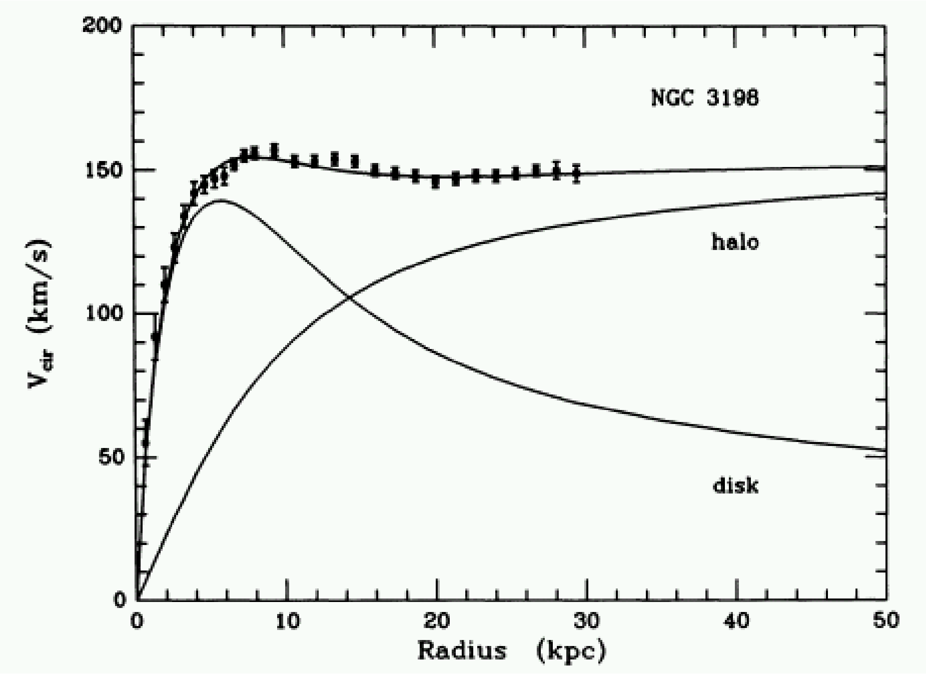
Because V(R) depends on mass (and not on luminosity or brightness), we need to transform surface brightness into surface density: we also need to assume a M/L (mass-to-light ratio).

Typically, one uses values of M/L found in the Solar neighbourhood. M/L ~ 1-3 $(M/L)_{\odot}$.

We then add the contribution of the bulge and disk:

$$V^2(R) = V^2_{disk}(R) + V^2_{bulge}(R)$$

since the potentials (or the forces) can be added linearly.



Dark matter in disk galaxies

The previous plot shows that it is necessary to add a third component to the galaxy, a “dark halo”.

This component is more extended and often dominates at large radii.

The dark halo generally accounts for a large fraction of the total mass of a galaxy; in the example it is ~75%. In Sa/Sb galaxies, the proportion of dark-matter needed to explain the rotation curves is ~ 50%, while in Sd and later, this increases to 90%.

Note that the rotation curve as measured by HI kinematics, can only probe regions of the galaxy where there is an HI disk. Thus the mass derived from rotation curves, is necessarily a lower limit. It is likely that a fair fraction of the dark matter is located at larger radii. To measure its gravitational influence requires tracers that probe those regions, such as satellite galaxies, binary pairs, planetary nebulae etc.

Uncertainties and degeneracies. I

Given a certain rotation curve, more than one functional form for the distribution of dark matter can be consistent with the data (see below).

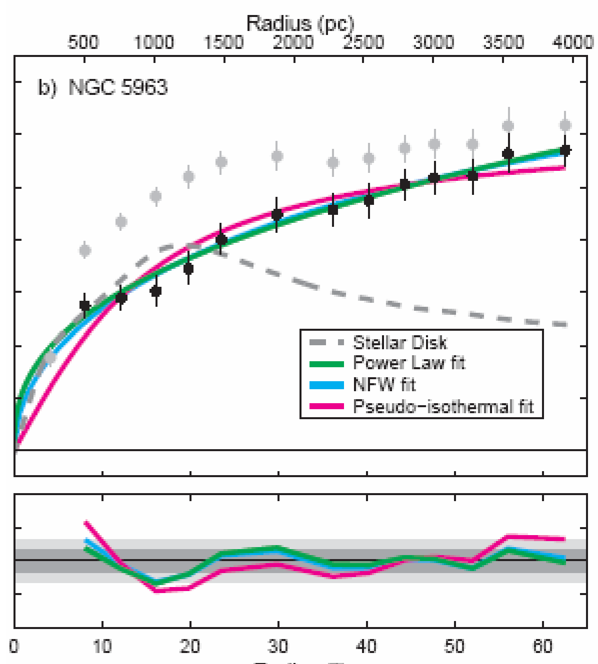
Some examples are:

- isothermal profile: $\rho(r) = \rho_0 \, (r_0/r)^2$

- Navarro, Frenk & White profile: $\rho(r) = \rho_0 \, r_s^3 / [r \, (r + r_s)^2]$
  This profile fits the density distribution found in cosmological simulations of the formation of dark halos.

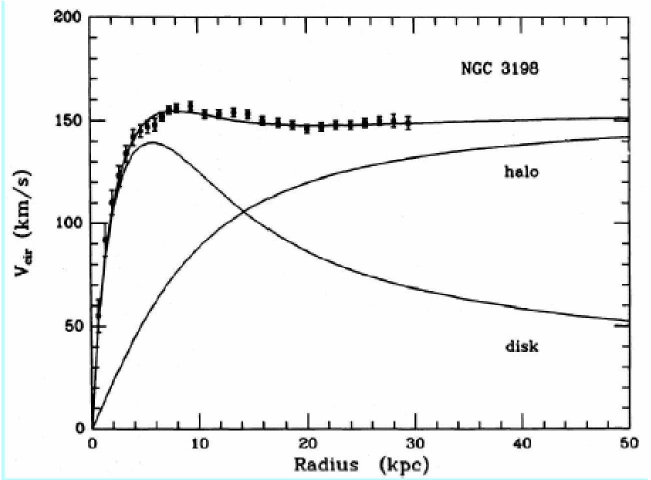
- power-law: $\rho(r) = \rho_0 \, (r_0/r)^\alpha$

- In the first two cases, the total mass is infinite (diverges with radius linearly or in the log).

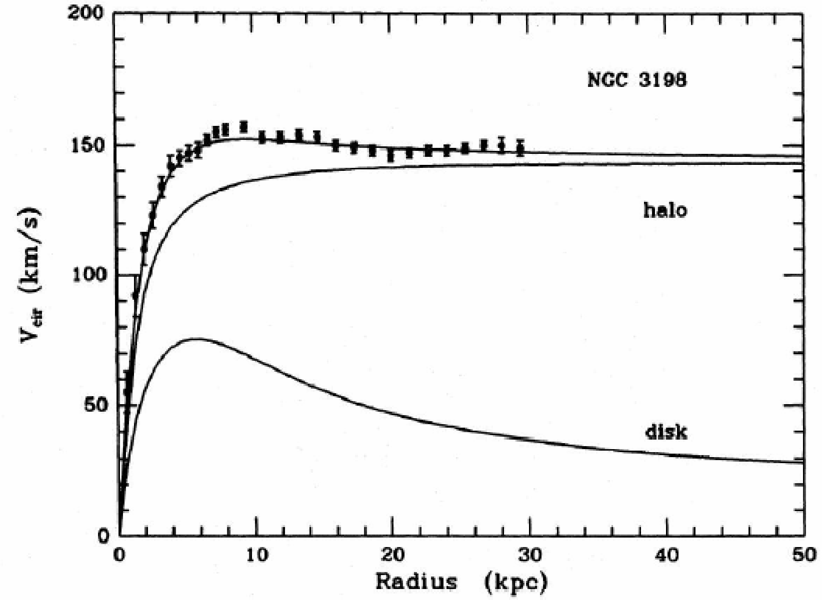


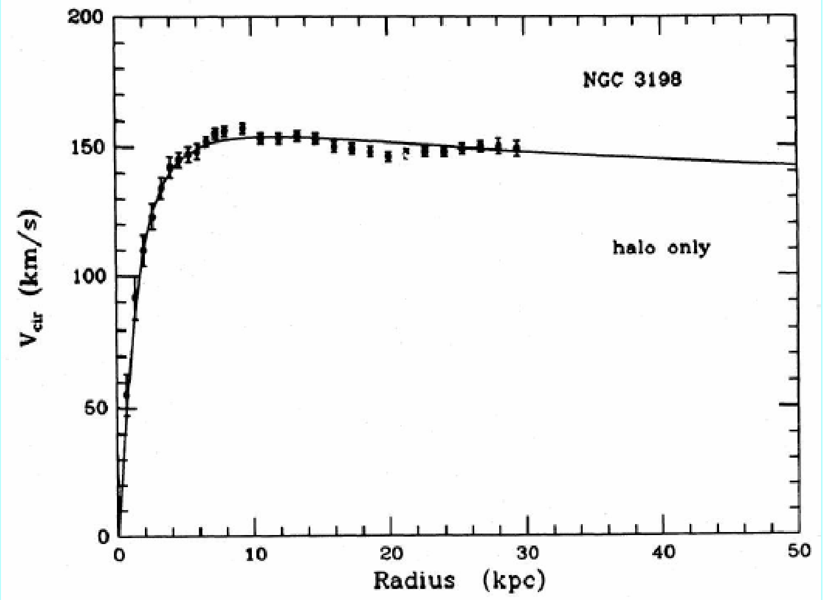
Uncertainties and degeneracies. II

Generally, the M/L used is the one that gives the maximum amplitude to disk contribution (and still consistent with observations) to the given rotation curve. This is known as the maximum disk.



But is not the only option…
The values of the model parameters of the dark halo can be changed to have a minimum disk (left), or no disk at all (right)





Scaling relations: Tully-Fisher

When studying the distance ladder, we discussed a relation between the luminosity of spiral galaxies and their peak circular velocity:

$$\frac{L_H}{3\times 10^{10} L_{sun}} = \left(\frac{V_{\max}}{196 km/s}\right)^{3.8}$$

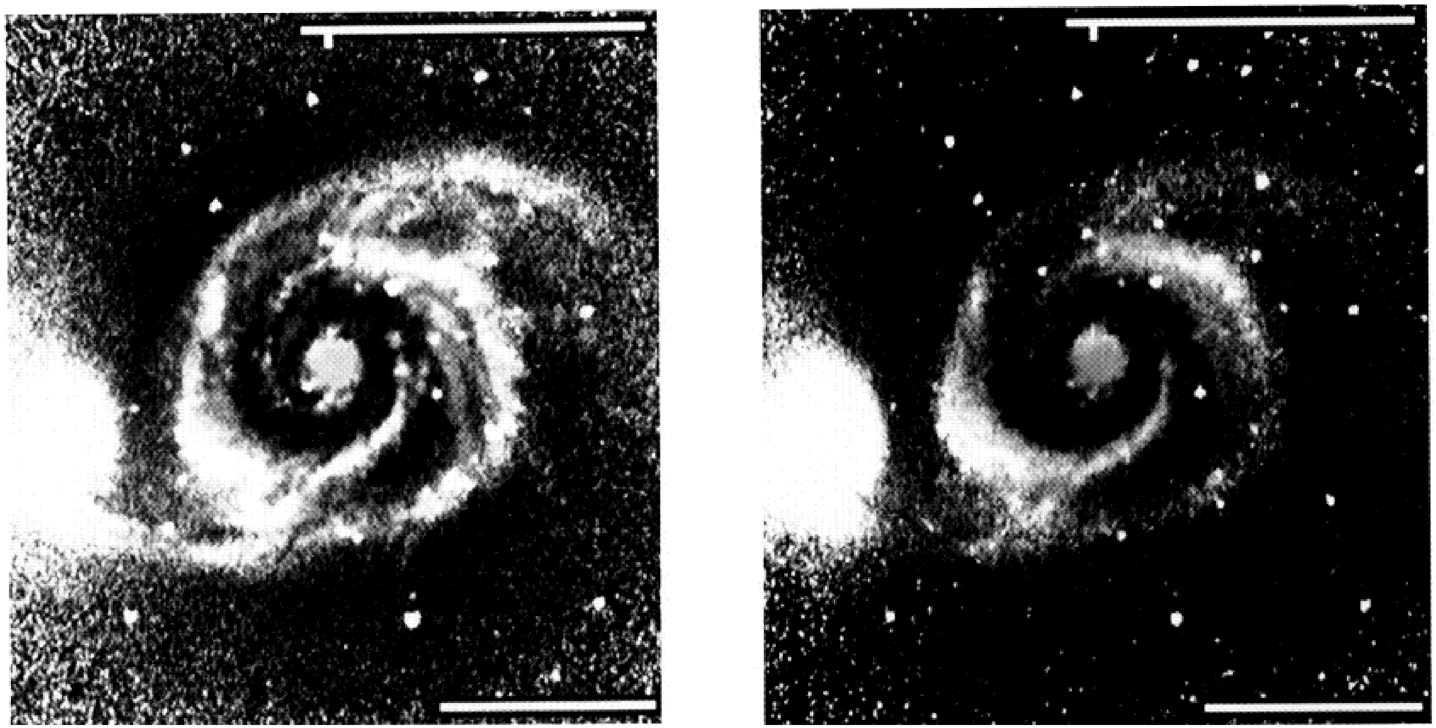
This relation implies that more luminous galaxies rotate faster. Let us try to understand how such a relation arises.

From the equation for the circular velocity, we can write $M \propto V^2{}_{\max} R_d$ and $L = 2\pi I(0) R^2{}_d$.
Combining the two, and assuming that M/L and I(0) are constant, then

$$L \propto V^4{}_{\max}$$

Spiral structure

To analyse the spiral structure one can study an image from which the azimuthally smooth component has been subtracted. An example is shown for M51 (left panel in the B band, right panel in the I-band)



These images show that

(i) spiral structure is present in both bands, but it has larger amplitude in the B band;

(ii) spiral structure is smoother in I than in the B band

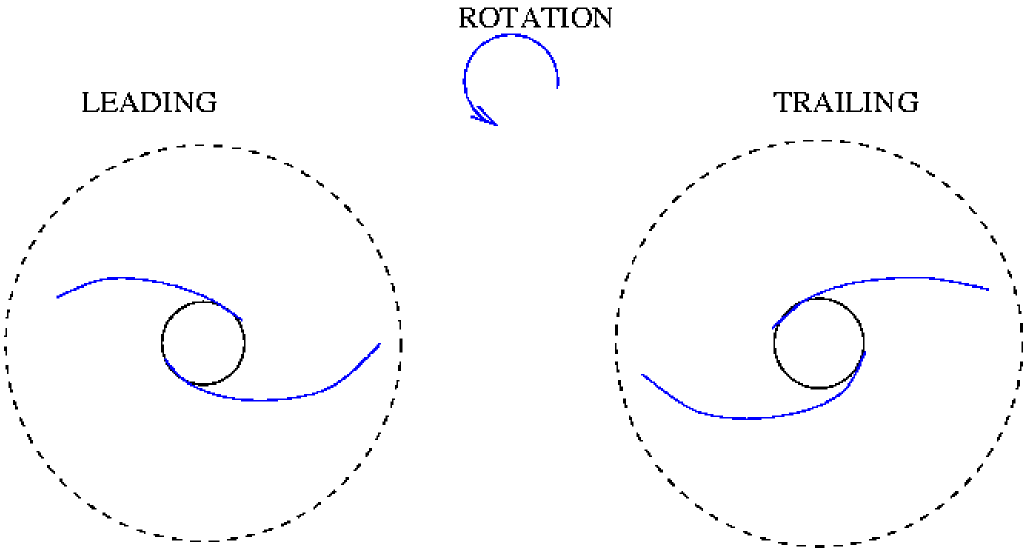
Spiral structure and patterns

Often, the shapes of spiral galaxies are approximately invariant under a rotation around their centres. A galaxy that looks identical after a rotation of an angle 2π/m is said to have an m-fold symmetry.

A galaxy with an m-fold symmetry usually has m-spiral arms. Most spirals have 2 arms, hence they have a twofold symmetry (if their image is rotated by an angle π, the image remains unchanged).

Spiral arms can be classified according to their orientation with respect to the direction of rotation of the galaxy:

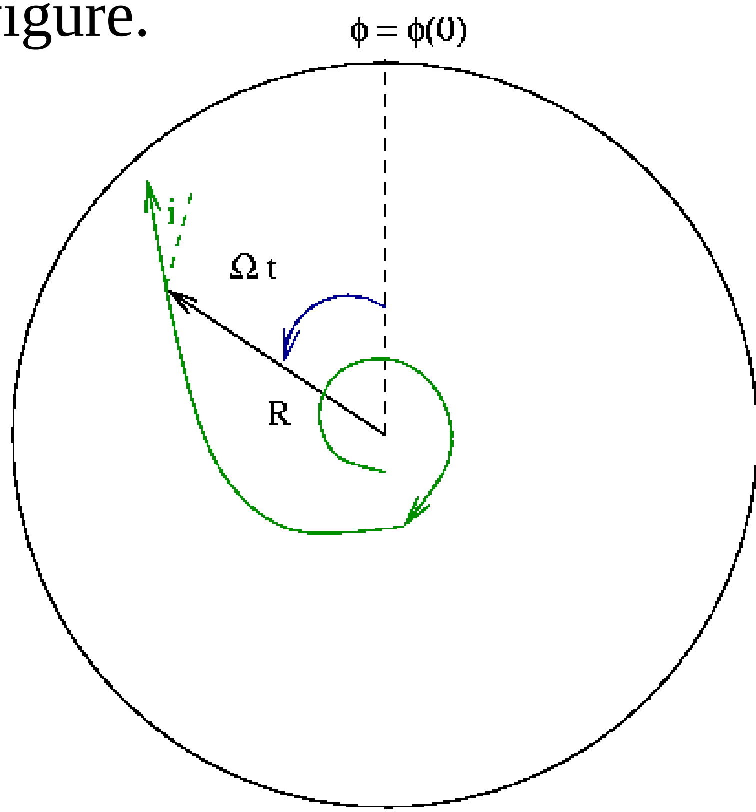
- trailing: outer tip points opposite to the direction of rotation
- leading: arm tip points in the direction of rotation



The nature of spiral arms

Spiral structure is a complex phenomenon, and is probably the result of several mechanisms.

Let us study what happens to a “stripe” of material located in a differentially rotating disk, as shown in the figure.



The initial equation of the stripe is $\phi = \phi_{0.}$

Since the disk rotates with an angular speed $\Omega(R)$, the equation of the stripe at a later time t is

$$\phi(R,t) = \phi_0 + \Omega(R)\, t$$

This shows that the stripe distorts into a spiral pattern, because the angular speed is a function of R.

The winding problem

The pitch angle i of the arm is the angle between the tangent to the arm and the circle R = constant. Thus

$$\cot i = \left| R \frac{\partial \phi}{\partial R} \right| = Rt \left| \frac{d\Omega}{dR} \right|$$

Therefore the pitch angle becomes smaller with time. For example, for the Milky Way, we can approximate near the Sun, Ω=V/R, and if we take V = constant = 220 km/s, then

$$\cot i = Rt \left| \frac{d\Omega}{dR} \right| = \frac{220}{8} \frac{t}{1Gyr}, \longrightarrow i \approx 2^\circ \times \frac{1Gyr}{t}$$

After 1 Gyr, the spiral should be much tighter than actually observed.

Any initial spiral pattern would suffer a similar winding up; this would require that the spiral arm pattern be constantly renewed.

In the case of gas rich galaxies, with flocculent spiral arms, it is possible that the spiral arms are simply being recreated every few orbital periods.

The idea is that the gas collapses to form stars, it is stretched by the differential rotation of the disk and it forms a spiral arm. After a while the gas will be used, all hot stars died and the region blends back into the disk. If the pace of star formation can be self-regulated (the gas is not completely exhausted, supernovae explosions compress the ISM and trigger new star formation in a different place), this could work.

A spiral pattern can last longer if the stars are not on circular orbits, but can be arranged in a "kinematic spiral".

We saw that the motions of stars in a disk can be described as an oscillation with an epicyclic frequency around a guiding centre that moves on a circular orbit. The star's location varies as $R = R_g + X_0 \cos(\kappa t + \Psi)$

If we place the stars with their guiding centres spread around a circle of radius R_g, and set $\Psi = 2\,\phi_g(0)$, they will lie on an oval, with the long axis pointing to $\phi=0$.

At a later time t, the guiding centres move according to $\phi_g(t) = \phi_g(0)+\Omega\, t$

The stars advance on their epicycles and are located at $R = R_g + x$, where

$$x = X_0 \cos(\kappa t + 2(\phi_g(t) - \Omega t)) = X_0 \cos((\kappa - 2\Omega) t + 2\phi_g(t))$$

The long axis of the oval now points in the direction where

$$(\kappa - 2\Omega) t + 2\phi_g = 0 \quad \text{or} \quad \phi_g = (-\kappa/2 + \Omega) t = \Omega_p t$$

We have defined the pattern speed Ω_p so that the pattern made up by stars with guiding centre R_g will return to its original state after a time $2\pi/\Omega_p$.

Note, however, that it still takes individual stars $2\pi/\Omega$ to complete their orbits around the centre of the galaxy (but this period is shorter than that of the pattern).

A two-armed spiral arm can be made of nested ovals of stars with different guiding centres R_g.

Since Ω_p also depends on radius, this pattern will also suffer from the winding problem, but it will do so more slowly by a factor Ω_p/Ω (0.3 for a galaxy with a flat rotation curve).

5 Spiral and S0 galaxies

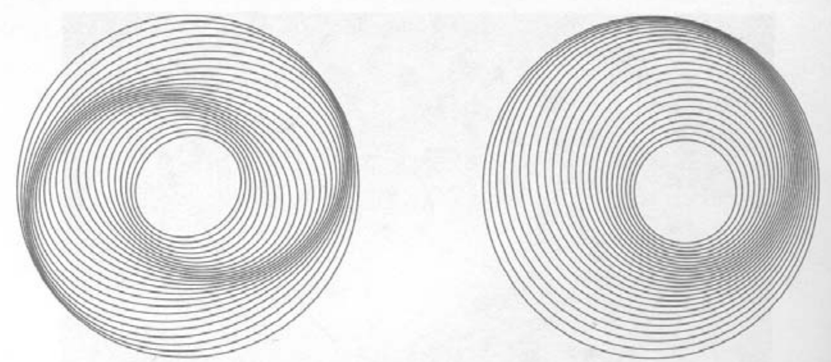


Figure 5.28 Left, oval orbits nested to form a two-armed spiral; the equation of the pattern is $R = R_g\{1 + 0.075\cos[2(5 - 5R_g + \phi)]\}^{-1}$, and $0.3 < R_g < 1$. Right, a one-armed spiral, with $R = R_g\{1 + 0.15\cos[(5 - 5R_g + \phi)]\}^{-1}$.

The star's radius varies as

One possible solution to the winding problem is probably to consider that spiral arms are density waves.

The premise is that the mutual gravitational attraction of stars and gas clouds at different radii can offset the tendency of the kinematic spiral to wind up, and will cause a pattern to grow which rotates rigidly with a single pattern speed.

To some extent, the stars located in the disk will respond to a wave that propagates through the disk with a certain speed, and a spiral arm will be sustained if the stars move to reinforce the pattern.

Stars have characteristic frequencies of motion, and this can resonate or not with the pattern speed of the wave. If it does, then the spiral arm will be maintained, if it does not, it will be damped.