Lecture 17
Spiral structure

Lecturer: Jeremy Heyl
(Notes by Paul Hickson)
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M100

Spiral arms

The spiral arms are regions of enhanced star formation. They are more prominent in blue or UV light due to the presence of short-lived massive stars.

HII regions, produced by ionization from hot stars, are also concentrated in the arms. Such stars have lives of ~ 10 Myr, so the arms must be regions of active star formation.

Spiral arms are found to be trailing rather than leading: the tips point away from the direction of rotation.

If the spiral arms are physical features, they would quickly be wound up by differential rotation. The fact that we see them today indicates that either they are constantly being created, or they are some kind of persistent wave pattern.

Spiral arms

One often sees dust lanes tracing the inner side of the arms, suggesting that the gas is being compressed there. This is consistent with the arms being **density waves** - regions of enhanced gas density propagating in the disk.

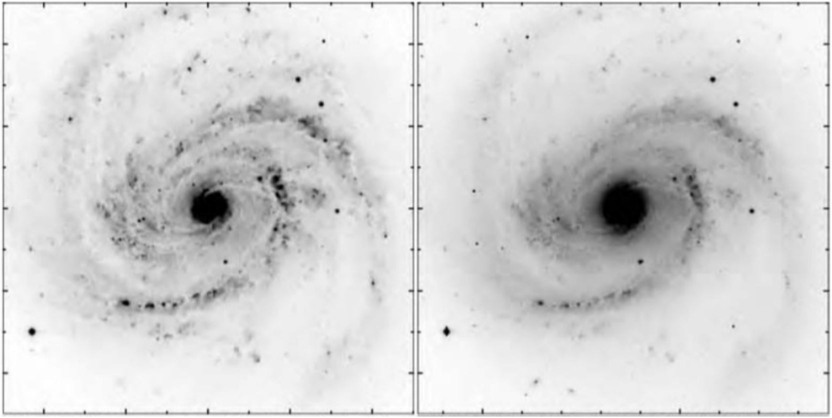
In this picture, the spiral pattern rotates with an angular velocity Ω_p, that generally differs from the angular velocity $\Omega(R)$ of the stars and gas.

Gas, dust and stars therefore move through the arms as they orbit the galaxy.

As molecular clouds enter the spiral arm they is compressed, which triggers star formation.

Eventually, these stars move out of the spiral arm. By then, the most massive luminous blue stars have already died.

M100



Sbc galaxy M100: $26'' = 2$ kpc. Top, B band (left) and I band (right); in these negative images, dark dust lanes just inside the bright spiral arms appear as thin light filaments.

Spiral shape

The shapes of spiral arms can be approximated by the equation

$$\phi = \frac{2\pi n}{m} - f(R,t), \quad n = 0, 1, 2, \ldots$$

where m is the number of arms and $f(R,t)$ describes the shape and rate of rotation of the spiral pattern.

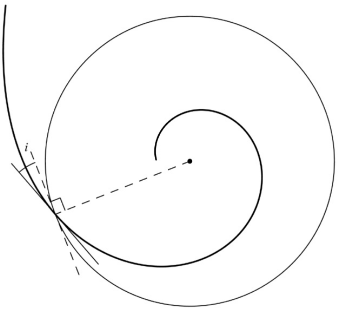


Fig 5.28 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The **pitch angle** i is given by

$$\cot i = \left| R \frac{\partial \phi}{\partial R} \right| = \left| R \frac{\partial f}{\partial R} \right|$$

Typically $i \sim 5^\circ$ for Sa and $i \sim 10 - 30^\circ$ for Sc galaxies.

Kinematic spiral patterns

A region of enhanced density, with a spiral shape, can be created by arranging slightly eccentric orbits as shown below.

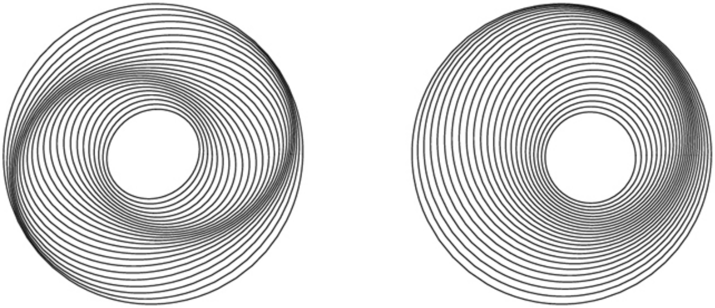


Fig 5.29 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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 $R = R_g[1 + 0.15\cos(5 - 5R_g + \phi)]^{-1}$.

Density wave theory

In the 1960's, Lin and Shu showed how gravitational interaction between stars and the enhanced density in the spiral arms can result in persistent spiral patterns.

A star moving with angular velocity Ω will pass through a spiral arm with a frequency $m(\Omega_{\mathsf{p}} - \Omega)$. If this is an integer fraction of the epicyclic frequency, the small gravitational pull produced by the spiral pattern will be repeated over and over when the star is at the same place in its epicycle, leading to a **resonance** condition.

Over time, this modifies the stellar orbits, setting up a kinematic spiral pattern.

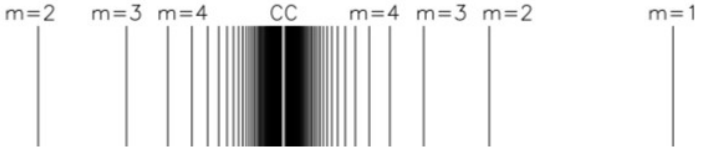
These are called **Lindblad resonances**, and occur whenever

$$mn(\Omega_{\mathsf{p}} - \Omega) = \pm\kappa, \quad n = 1, 2, 3, \cdots,$$

where m is the number of arms in the pattern.

Lindblad resonances

These resonances occur between the inner and outer Lindblad resonances corresponding to $m(\Omega_{\rm p} - \Omega) = -\kappa$ and $m(\Omega_{\rm p} - \Omega) = \kappa$, respectively. They are centred on the radius of **corotation** $(\Omega_{\rm p} = \Omega)$.



Vertical lines indicate the radii of the nth inner and outer Lindblad resonances shown relative to the corotation circle (CC). Radial distance r increases to the right. Only the $n \leqslant 4$ Lindblad resonances are labelled. Not shown is the $n = 1$ inner Lindblad resonance (from gemelli.cororado.edu/ hahnjm/book/chap6.pdf, here n is labelled as m).

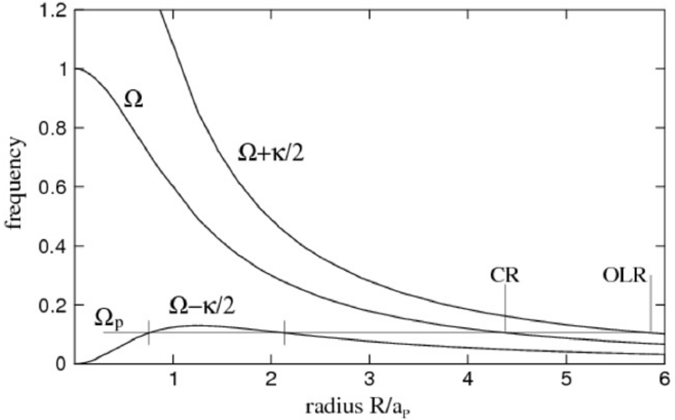


Fig 5.30 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Frequencies $\Omega(R)$ and $\Omega \pm \kappa/2$ in the Plummer potential. For pattern speed Ω_p, the $m = 2$ inner Lindblad resonances are marked by vertical ticks, the corotation radius is labelled 'CR', and the outer Lindblad resonance 'OLR'. If the pattern speed were twice as large, the inner Lindblad resonances would be absent.

The Toomre criterion

In the 1960's, Alar Toomre at MIT began using computer "n-body" simulations to investigate the dynamics or rotating disks.

He found that structure could only grow if the random component of the stellar velocities was not too high.

In other words, the disks must be sufficiently **cold**.

Empirically, structure can grow only if

$$Q \equiv \frac{\kappa \sigma_R}{3.36 G \Sigma} \lesssim 1,$$

where σ_R is the velocity dispersion in the R direction and Σ is the mass surface density in the disk.

Once a spiral pattern develops, it increases the radial velocity dispersion, and Q increases.

In the solar neighbourhood, $Q \sim 1.4$.

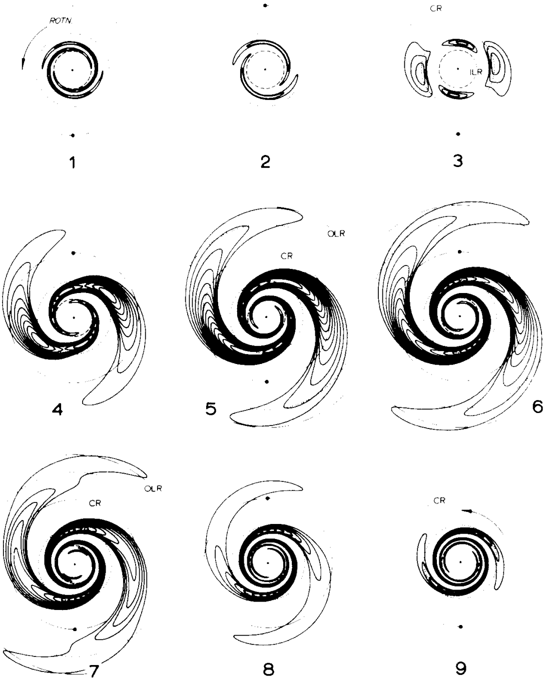
Toomre's swing amplifier

In order for a spiral pattern to be sustained, a mechanism is needed to transfer rotational energy of the disk into the spiral pattern.

Spiral arms can also be generated by gravitational interactions with close neighbouring galaxies, but even isolated galaxies can have spiral structure.

If the galaxy has no inner Lindblad radius, then spiral waves can propagate inwards to the centre of the galaxy. There they pass through the centre, emerging as *leading* spirals.

Differential rotation then turns the leading spirals into trailing spirals, greatly amplifying them in the process. This is the **swing amplifier**.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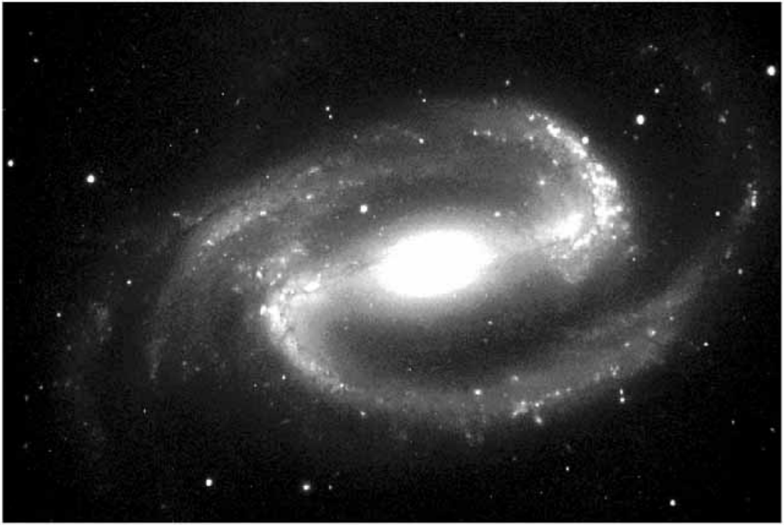


Fig 5.32 (WIYN) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The barred galaxy NGC 1300, classified as SBb or SBbc. The spiral arms trail; note the dust lanes on the leading edge of the bar.

Bars

About half of all disk galaxies have a central linear bar, which can contain up to a third of the total light.

These bars are not static, but rotate with some pattern speed Ω_P.

However, they are not waves, but physical structures. Stars move on elongated orbits within the bar.

The gravitational potential of a rotating bar can compress gas clouds along its leading edge. The gas can then form shock waves that dissipate energy allowing it to flow inwards and form a central ring.

The rotating bar prevents spiral structure forming in the inner part of the galaxy, but spiral arms can form beyond the bar, often appearing to be attached to its ends.

Ostriker-Peebles criterion

Using numerical simulations, Hohl, and then Peebles and Ostriker, found that cold rotating self-gravitating disks are unstable and quickly form dominant bars.

To avoid this instability it is necessary to add a spherical distribution of mass - a *dark halo* is required.

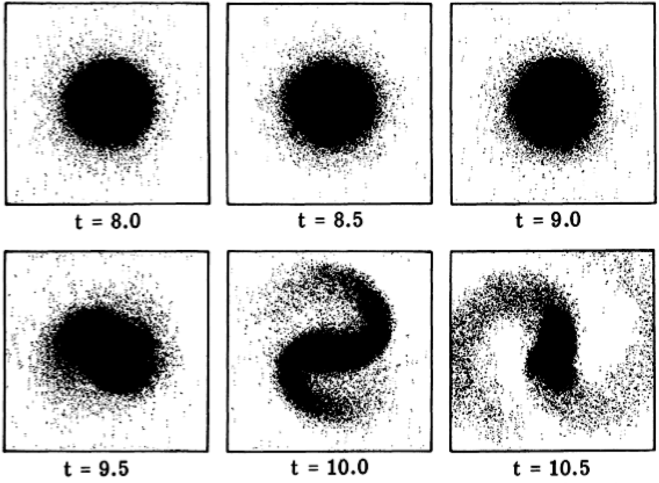
The Ostriker-Peebles stability criterion is

$$\frac{K}{|U|} < 0.14 \pm 0.02,$$

where K is the kinetic energy of rotation and U the total potential energy.

This was an early indication of the presence of dark matter in galaxies.

The bar instability



Numerical simulations of a rotating disk of 100,000 stars. Although stable on small scales, the system is globally unstable, creating a rotating bar after a few rotation times (Hohl 1971).

Bulges

Some bulges appear to be flattened ellipsoids (oblate). Others are triaxial. About 20% are peanut-shaped.

Bulge stars tend to be metal-rich. Star-formation, and metal enrichment of the ISM, likely proceeded rapidly due to the high density. Most bulges now have little gas, except at the very centre.

Their intensity profiles are not exponential, but can be fit with a **Sersic law**

$$I(R) = I(0)\exp[-(r/r_0)^{1/n}]$$

with $n \sim 2 - 4$.

The **half-light radius** (also called the "effective radius") R_e is the radius that contains half the light seen in two-dimensional images. Typically, $R_e/h_R \simeq 0.1$.

Nuclei

In the central region of a disk galaxy, the rotation velocity increases linearly, $V(R)/R \simeq const$. There is little differential rotation to shear gas clouds. Gas in this region is probably rapidly converted into stars.

Nuclear star clusters are often seen. These are more massive than globular clusters, and grow if more gas falls into the centre.

Most galaxies have a central black hole, whose mass may exceed $10^7 M_\odot$. The mass of the black hole is found to be correlated with the luminosity of the bulge - bigger galaxies tend to have more massive black holes.

If gas falls into this black hole, an **active nucleus** results. A wide range of phenomena, ranging from X-ray flares to relativistic jets of matter, can result.