Galaxies: Structure, formation and evolution

Lecture 6

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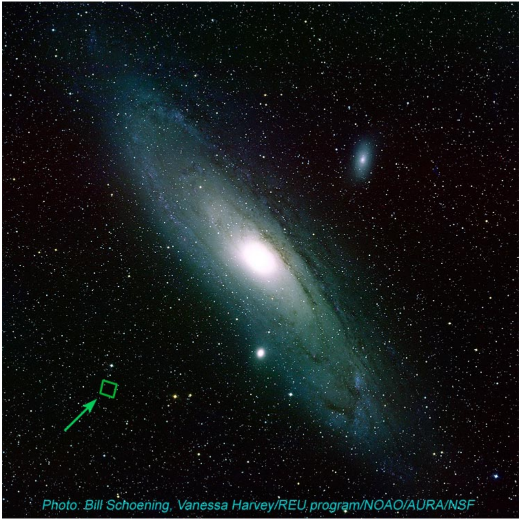
The stellar halo

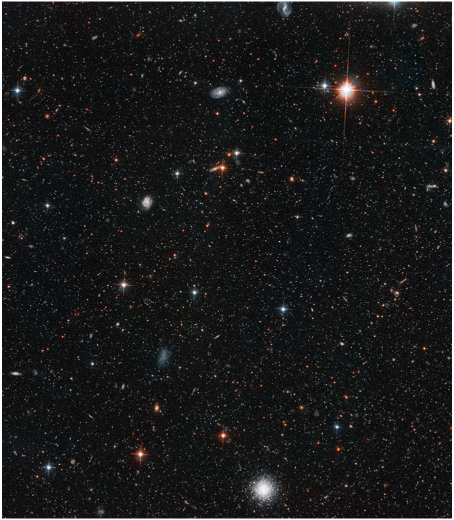
MW and M31 have resolved halos with metal poor stars, and globular clusters. Both of these systems contain significant substructure tidally stripped dwarf galaxies and globular clusters. However, M33 does not have a significant stellar halo.

The stellar halo of M31



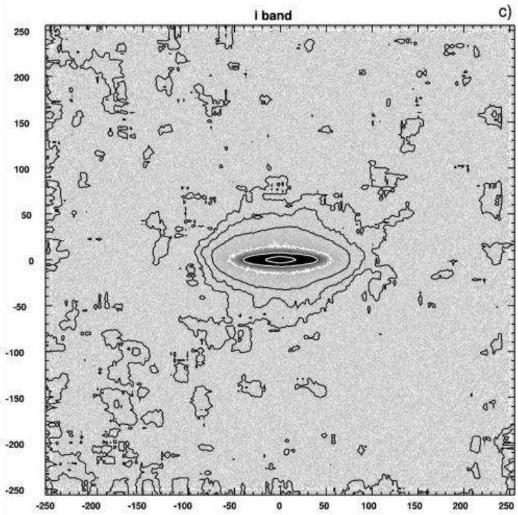
Brown et al. (2003)

The stellar halo of M31



Open questions: How much of stellar halo is in form of tidal streams
How many galaxies have stellar halos?

Stacking of 1000 SDSS edge-on spiral galaxies



Zibetti et al. (2003)

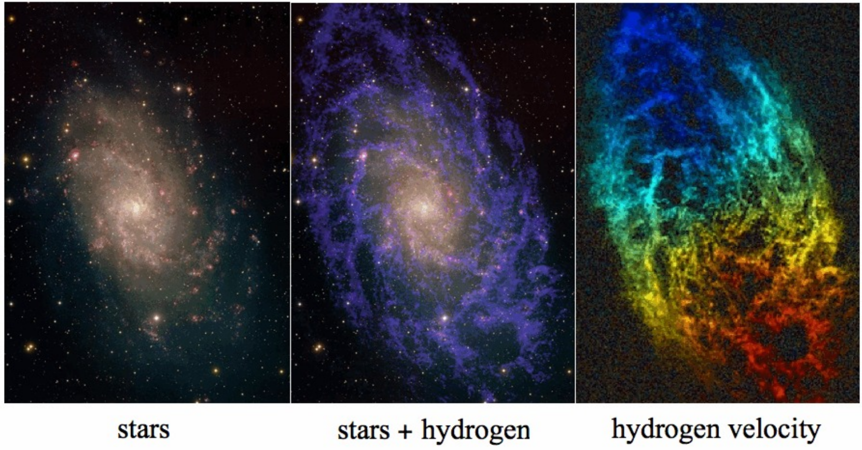
Seminar topics and mid-term exam

Seminar topics due next week on 23 Jan.

Stellar Velocities in the disk

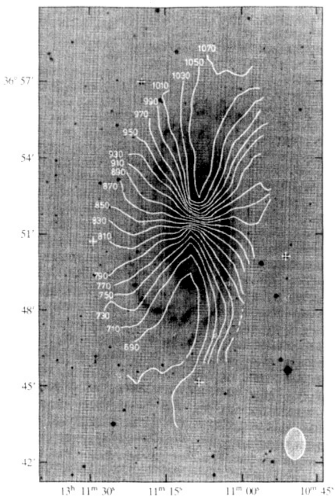
For disk stars, $V_{\rm los} >> \sigma_{\rm los}$ so stars are cold and have approximately circular orbits. Usually, $V_{stars} \sim V_{gas}$.
Sometimes, star orbital rotation velocity can be slower than the gas this is called **asymmetric drift** and indicates a higher stellar dispersion.
In S0s, ~30% have counter-rotating gas disks. How do you think this is possible?

Galaxy rotation



Contours of the last image are **spider diagrams**

Spider diagram



Spider diagram diagnostics

- **Kinematic Major Axis (KMA)**: line through nucleus perpendicular to velocity contours
- **Kinematic Minor Axis (KMI)**: $V_{\rm los}$ contour at $V_{\rm sys}$ through the nucleus
- KMA aligned with photometric major axis (PMA) and KMI aligned with photometric minor axis (PMI) $\rightarrow$ Circular velocity in an inclined circular disk
- equally spaced contours across nuclear KMA

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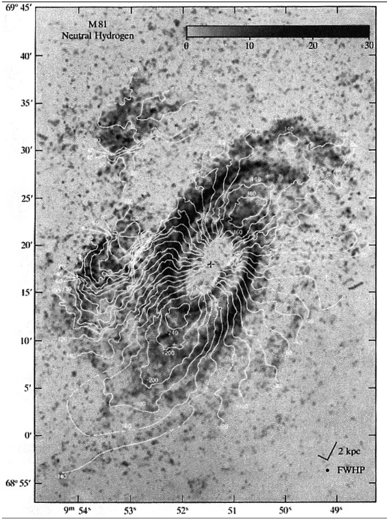
- KMA aligned with photometric major axis (PMA) and KMI aligned with photometric minor axis (PMI) $\rightarrow$ Circular velocity in an inclined circular disk
- equally spaced contours across nuclear KMA $\rightarrow$ Solid body rotation.
- Bars often show: evidence of radial motion over bar region. Warped disks have twisted contours in outer parts.

Spiral arm kinematics



Spiral arms yield small perturbations to $V_{\rm los}$ contours near arm positions, although photometrically they are large perturbations.

Kinematics modeling of spider diagrams

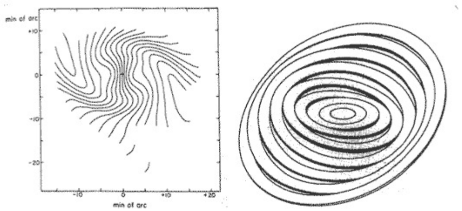


Figure 8.36 A tilted ring model of M83 (right) and the spider diagram predicted by this model (left). [After Rogstad, Lockhart & Wright (1974)]

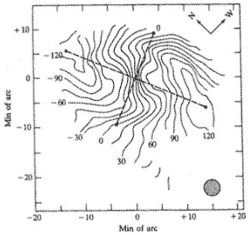


Figure 8.37 The observed spider diagram of M83. [After Rogstad, Lockhart & Wright (1974)]

Scaling relations

There are a number of correlations between the global parameters of galaxies: **Luminosity; Size; Surface Brightness; Rotation Velocity**. Such relations are called **Scaling Relations**.

They are important for several reasons:

- They reveal the internal properties of galaxies
- They must arise naturally in theories of galaxy formation.

In the case of disk galaxies, the most important is between $V_{\rm rot}$ and Luminosity

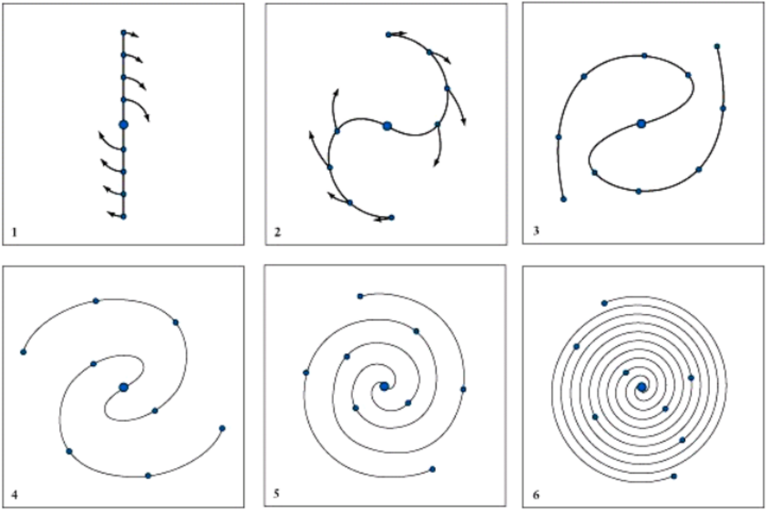
Tully Fisher relation

Tully & Fisher (1977) recognised that $V_{\max}$ correlates with galaxy luminosity $L \propto V_{\max}^{\alpha}$ where $\alpha \sim 3-4$
Scatter in T-F relation smaller at longer wavelengths.
Tully Fisher relation is an important distance indicator. How to measure distance with TF relation?

The winding problem

Why do flat rotation curves lead to winding of spiral arms?

Winding of spiral arms



Show winding video and Star Orbit Video

Another issue

Spiral arms are defined mainly by blue light from hot massive stars, thus lifetime is $<<$ galactic rotation period.
Should'nt spiral arms just fade away?

A cryptic observation

For galaxies where the galactic rotation has been measured, the spiral arms almost always **trail the rotation of the underlying disc.** Relative to the disk they seem to be rotating in a direction opposite to the disk.

Spiral arms

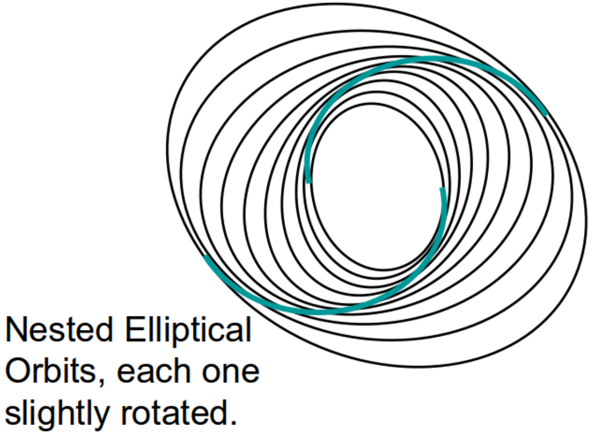
Long lived spiral arms are not material features in the disk, they are a pattern, through which stars and gas move as in the **grand design** spirals

Short lived spiral arms can arise from temporary patches pulled out by differential rotation; the patches might arise from local disk instabilities, leading to star formation as in **flocculent** spirals. Formation in one place may lead to further star-formation in nearby regions - **detonation wave.**

Grand Design Spirals

Flocculent Spiral NGC 2775

Orbit winding



Density wave theory by Lin and Shu

Spiral arm patterns must be persistent. Why? Density wave theory provides an explanation: the arms are density waves propagating in differentially rotating disks. Spiral arm pattern is amplified by resonances between the epicyclic frequencies of the stars (deviations from circular orbits) and the angular frequency of the spiral pattern. More specifically, for an m-armed spiral, a star at radius R will move through the spiral structure with a frequency $m(\Omega_p - \Omega(R))$. Stars have a epicyclic frequency $\kappa(R)$. It can be shown that the spiral pattern is maintained only for those R that lie between $\Omega(R) = \Omega_p + \kappa(R)/m$ and $\Omega_p - \kappa(R)/m$, the inner and outer Lindblad resonance points. Where will the **corotation radius** – where stars take the same time to rotate around the centre as the spiral arms – be?

Density Wave theory

The Sun is approximately at the corotation radius. κ/Ω for the sun is $\sim$ 1.3. So the Sun makes 1.3 radial oscillations in the time it takes to complete an oscillation around the centre.
also explains why the rings of Saturn are long lived. For more details see Hedman et al. (2019)

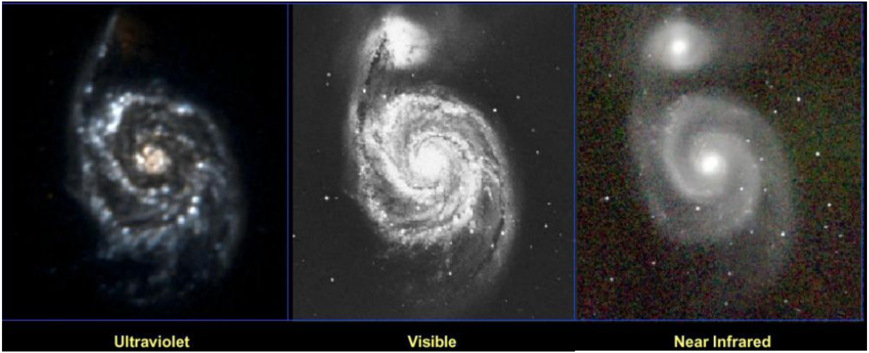
Density wave triggers star formation

In the density wave, there are regions of slightly higher density than their surroundings. The higher density means higher gravity. Objects (such as a gas cloud) will be attracted to these regions and will drift towards them.

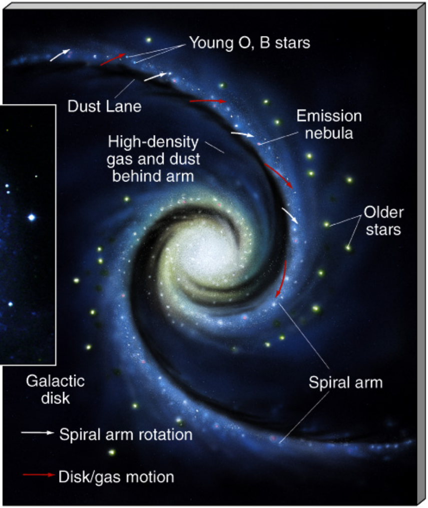
When the gas cloud collides with other gas clouds, stars will be formed. (This is where most of the galaxy's star formation takes place.) Many of the stars will be faint, red main sequence stars, but some will be bright blue OB stars. All stars will continue to drift through the region.

The OB stars don't go far before they explode. The brightest (and bluest) of a galaxy's stars will never be far from the spiral arm where they were born. Show video

M51 in 3 wavebands



Spiral density wave



Motion of the Sun

Can you say if the sun is in a spiral arm?

Motion of the Sun

Can you say if the sun is in a spiral arm?

U = 10 km/s (radially inwards)

V = 5 km/s (in the direction of Galactic rotation)

W = 7 km/s (northwards out of the plane of the Galaxy)

Sun is in the Orion Spur between Perseus and Sagittarius arms. It passes through a spiral arm for about 10 million years every 100 million years.

Density Wave theory - a summary

Spiral arms are waves of compression that move around the galaxy and trigger star formation

- Star formation will occur where the gas clouds are compressed
- Stars pass through the spiral arms unaffected
- theory predicts the geometry of dust lanes and star formation.
- Two outstanding problems with it:
  1. What stimulates the formation of the spiral pattern? Tidal interactions?
  2. What accounts for the branches and spurs in the spiral arms?

Star formation in spiral arms

- Spiral density wave creates spiral arms by the gravitational attraction of the stars and gas flowing through the arms
- Even if there was no star formation, there would be spiral arms - but star formation makes them more prominent
- This can explain the **grand design** spirals
- Star formation can self-propagate in a differentially rotating disk, e.g., as supernova shocks compress neighboring molecular clouds
- Self-propagating star formation may be responsible for the branches and spurs in the spiral arms, or disks without evident spiral density waves (the **flocculent spirals**)

A Flocculent Spiral galaxy

Some definitions

Spectral velocity $u \equiv c \ln \lambda \rightarrow \Delta u = c\Delta\lambda/\lambda = v_{\rm los}$. Hence light received at spectral velocity u was emitted at spectral velocity $u - v_{\rm los}$ Observed galaxy spectrum is the sum of individual spectra of many stars, each with a slightly different $\Delta u = v_{\rm los}$. Hence spectrum is **Doppler broadened.**

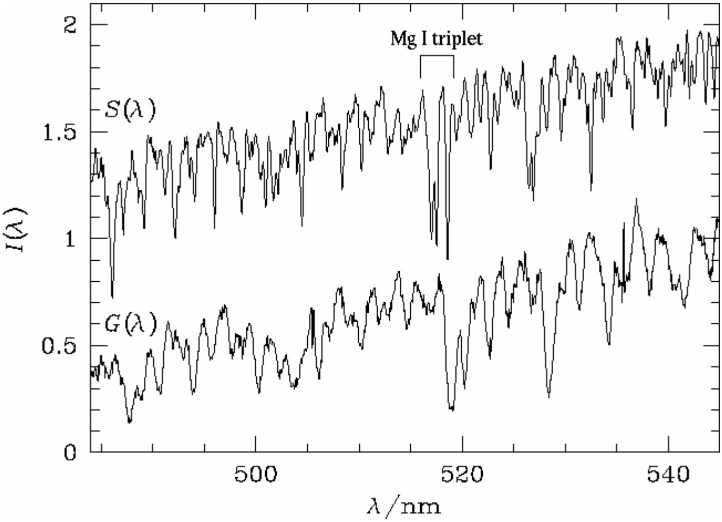
The LOSVD

Define a Line of sight velocity distribution (LOSVD) $F(v_{\rm los})$. If all stars have identical spectra $S(u)$, then the intensity received at spectral velocity u from a star with velocity $v_{\rm los}$ is $S(u - v_{\rm los})$ Summing over all stars we obtain the galaxy spectrum.

$$G(u) = \int dv_{\rm los} F(v_{\rm los}) S(u - v_{\rm los})$$

Can we use Fourier transforms to measure $F(v_{\rm los})$

Star galaxy spectrum



How are the star and galaxy spectra different?

Some properties of the LOSVD

Mean

$$\overline{v}_{\rm los} = \int dv_{\rm los} v_{\rm los} F(v_{\rm los})$$

and standard deviation $\sigma_{\rm los}$

$$\sigma^2_{\rm los} = \int dv_{\rm los} (v_{\rm los} - \overline{v}_{\rm los})^2 F(v_{\rm los})$$

How to calculate $\overline{v}_{\mathrm{los}}$ and σ_{los}

$$\mathrm{CCF}(v_{\mathrm{los}}) = \int du G(u) S(u - v_{\mathrm{los}})$$

When $v_{\mathrm{los}} = \overline{v_{\mathrm{los}}}$, then the two functions line up and the cross correlation peaks. So $\overline{v_{\mathrm{los}}}$ simply by determining the maximum of the CCF. Similarly one can derive σ_{los} by measuring the width of the peak in the CCF.

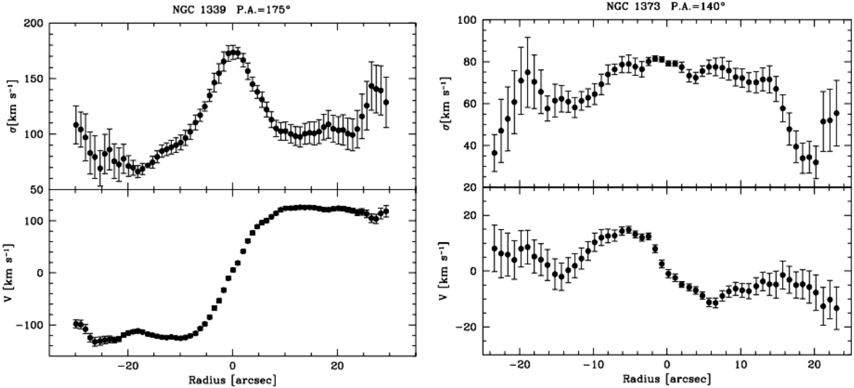
Simplifying assumptions we made and their impact

- all stars have the same spectrum $S(u)$
- LOSVD is Gaussian; this assumption is OK for ellipticals but not otherwise. Also if the mean velocity and standard deviation are not the same along the LOS, the overall LOSVD will not be Gaussian even if each individual distribution is Gaussian.

Stars in elliptical galaxies

Stars in E galaxies have some ordered motions (e.g., rotation), but most of their kinetic energy is in the form of random orbits. Thus, we say that ellipticals are **pressure-supported** systems To measure the kinematics within galaxies we use absorption lines. Each star emits a spectrum which is Doppler shifted in wavelength according to its motion. Random distribution of velocities then broadens the spectral lines relative to those of an individual star. Systemic motions (rotation) shift the line centroids.

Rotation and dispersion in elliptical galaxies



Gaia Astrometric Accuracy and sample size