The Milky Way & Normal Galaxies

Spiral arms
The Hubble sequence

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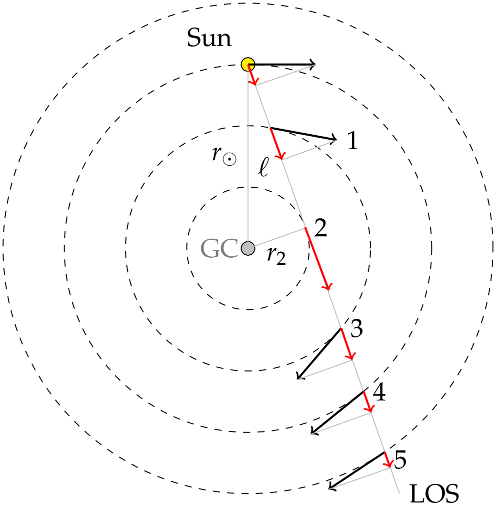
The Milky Way & Normal Galaxies

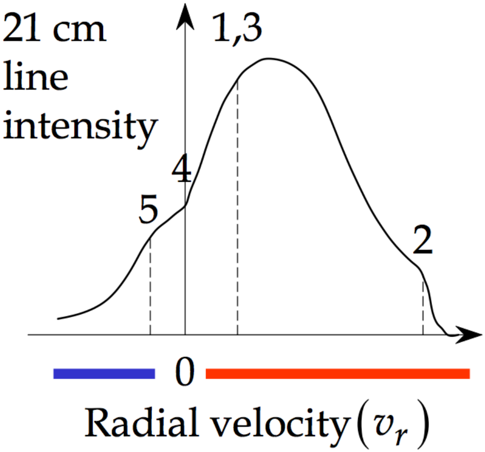
- Spiral structure in the Galaxy
- The Hubble sequence for the shapes of normal galaxies

Reading: Kutner Ch. 17.1–17.2, Ryden Sec. 20.1

M101 (NGC 5457), the "Pinwheel" Galaxy (Kuntz et al. 2006).

Interpretation of HI line profiles





Rotation curves from HI and CO lines

The resolution of the distance ambiguity usually involves information other than velocities:

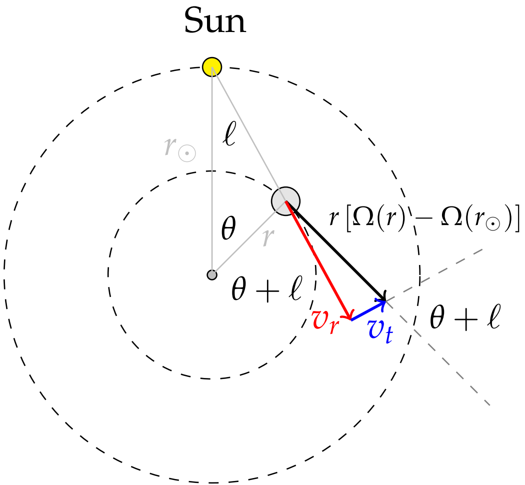
- Association (or lack thereof) with visible wavelength nebulosity; less extinction $\Longrightarrow$ closer.
- Cloud angular size; bigger size $\Longrightarrow$ closer.
- Height above the Galactic plane; clouds that appear higher are closer.

It is much harder to determine the distance to clouds in the outer Galaxy, so the uncertainties are larger.

- Best method so far: association of clouds with HII regions or star clusters. Cluster distances are determined by **main sequence fitting**.

If *only* the rotation curve is desired (not the 3D distribution of the clouds), then the distance ambiguity can be bypassed, as follows.

Measurement of (inner) Galaxy rotation curve



For the HI cloud at (r, ℓ), note from the law of sines that

$$\frac{\sin \ell}{r} = \frac{\sin\left[\pi - (\theta + \ell)\right]}{r_\odot} = \frac{\sin(\theta + \ell)}{r_\odot}$$

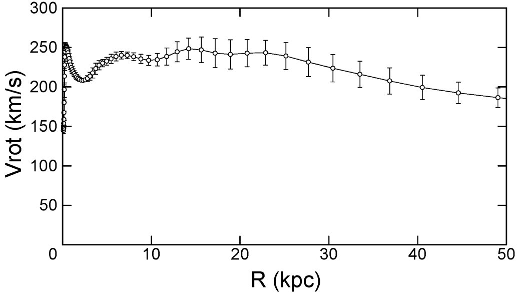
In the homework, you will show that its velocity relative to us is

$$\begin{aligned} v_r &= r\left[\Omega(r) - \Omega(r_\odot)\right]\sin(\theta + \ell) \\ &= r_\odot\left[\Omega(r) - \Omega(r_\odot)\right]\sin \ell \\ &= v_{r,\max}\sin \ell \end{aligned}$$

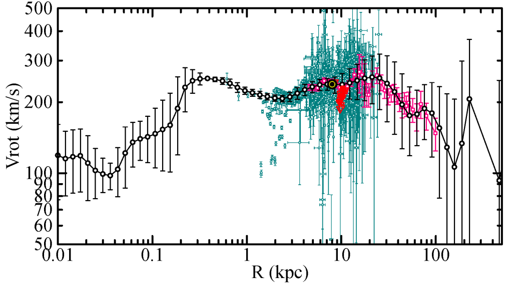
and its orbital speed is

$$v(r) = r\Omega(r) = v_{r,\max} + r_\odot\Omega(r_\odot)\sin \ell$$

Galactic rotation curve



Compilation of rotation curves from HI, CO, and *Gaia* (red symbols). Keplerian revolution is not seen beyond 10 pc (Sofue 2020).



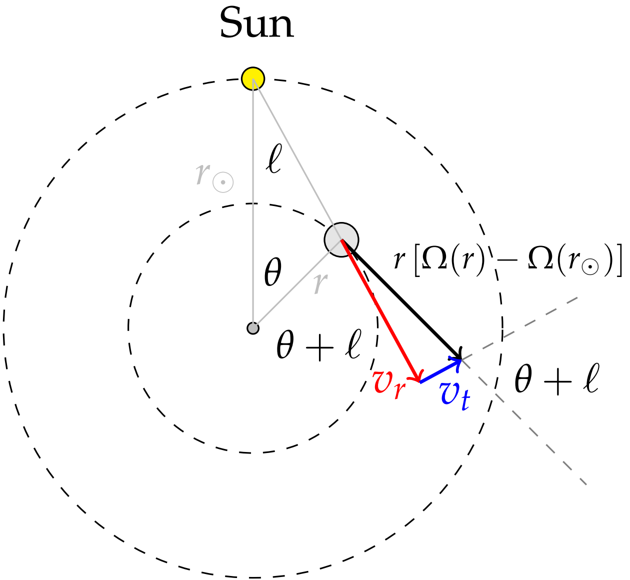
Notable features of the Galactic rotation curve

- The central region of the Galaxy has v increasing linearly with r, as occurs with the rotation of a solid sphere.
- Most of the disk has a "flat" rotation curve (differential rotation), meaning the **enclosed mass increases linearly with increasing radius**, as if the mass were dominated by a spherical $1/r^2$ density out to the **largest density at which interstellar gas is detected**.
- This is the case in spite of the fact that the **observed stellar density decreases more sharply than** $1/r^2$.
- Keplerian rotation is expected eventually at sufficiently large distances, but is not seen.
- Effect of **dark matter**? Yes!

Structure of the Galactic ISM

Once the rotation curve is known, the positions (subject to distance ambiguity) can be determined:

$$r = r_{\odot} \frac{v \sin \ell}{v_r + v \sin \ell}$$



The Milky Way

Milky Way viewed from Galactic North Pole:

- Barred spiral with four major arms: Scutum-Centaurus-OSC, Sagittarius-Carina, Perseus, and Norma
- Molecular ring is superposition of these four spiral arms
- The 3-kpc expanding arms represent flows closer to the bar

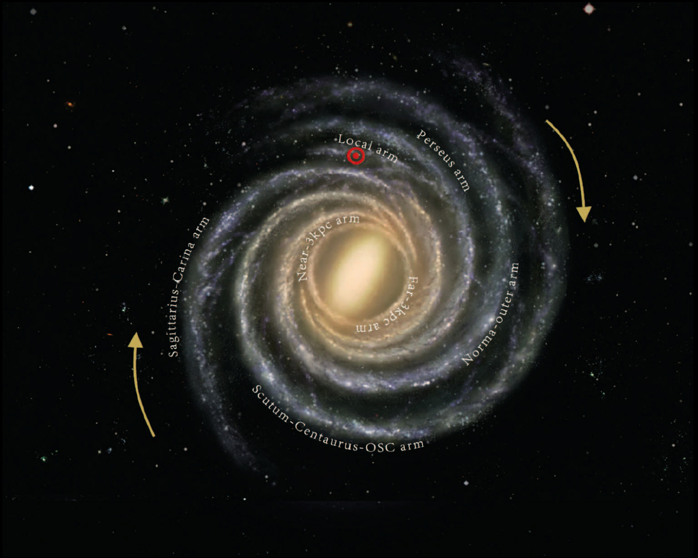


Image from Shen & Zheng (2020)

Why are there spiral arms?

The arms are due to **spiral density waves** (Lin & Shu 1964).

By analogy, consider a road crew painting line stripes on a highway. They move along at 10 mph. A traffic jam forms behind them and moves along with them. Cars before and after the jam move at 65 mph and are much further apart than in the jam. Cars enter the jam from behind, slow as they move through it, and resume speed as they leave.

From a helicopter, it appears that a dense concentration of cars moves along with the road work, though it is composed of different cars at different times.

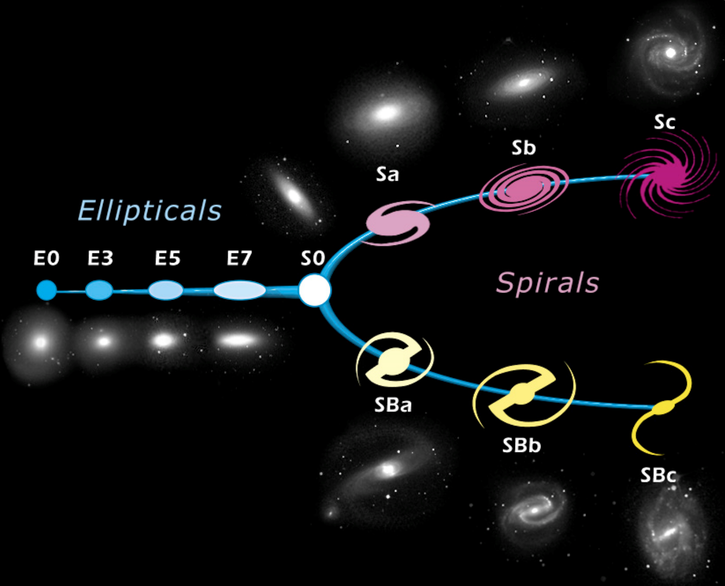
Normal traffic speed	$\Longleftrightarrow$	normal stellar orbit speed
Road crew speed	$\Longleftrightarrow$	spiral-wave **pattern speed**
Traffic jam	$\Longleftrightarrow$	density wave (spiral arm)

The Hubble sequence

Galaxies are classified by shape into the Hubble types listed in the "tuning fork" diagram on the right (from SDSS).

Different spiral galaxy types are distinguished by the shapes of their disks and bulges; ellipticals by their ellipticity.

Hubble thought galactic shape was related to evolutionary status and the tuning fork was the evolutionary sequence. (Not true.)



Overview of galaxy features

Ellipticals: smooth, dustless, featureless, ellipse-shaped light distributions. Defined by ellipticity $e = 1 - b/a$, where a and b are the semimajor and semiminor axes of the ellipse. Examples:

- E0 circular shape ($e = 0$)
- E7 ellipse with $e = 0.7$

Lenticulars: "lens-shaped" galaxies

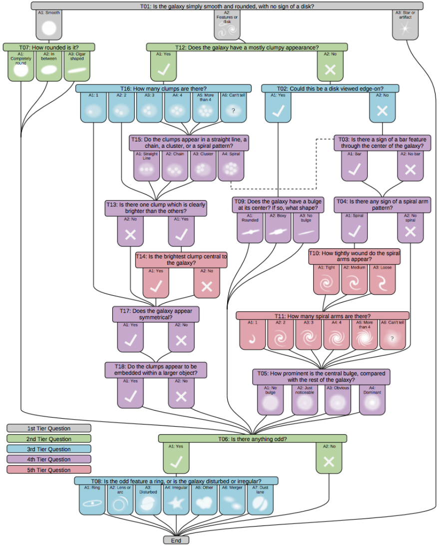
- S0 bright central bulge plus an extended disk-like structure

Spirals: Galaxies with a central bulge and spiral arms within a rotating disk that contains dust, gas, and stars.

- Sa / SBa large bulge, small arms, modest ISM + star formation
- Sb / SBb medium bulge, moderate ISM + star formation
- Sc / SBc small bulge, strong arms, major ISM + star formation

“Modern” galaxy classification techniques

- Until large-scale digital surveys like SDSS, galaxies were manually classified by experts.
- Ideally, classification would occur automatically using machine-learning techniques.
- Current approach: **crowd sourcing** using apps like Galaxy Zoo.
- Right: question flowchart for galaxy classification in HST legacy data (Willett et al. 2017).



Example Sc galaxy

Color composite image of M74 (NGC 628) from the Gemini North 8 m telescope.

Note the relatively small bulge, very strong spiral structure, very blue color of the spiral arms, and the dust lanes on the trailing edges of the arms.

Another example Sc galaxy

Photograph of M33 (NGC 598) by the ESO.

Note the diffuse spiral structure as compared to M74.

- M74 is a grand design spiral galaxy with two prominent and well-defined spiral arms.
- M33 is a flocculent (“fluffy”) spiral galaxy with less well-defined features.

About 10% of spiral galaxies are grand design, 30% are flocculent spirals, and 60% are **multiple-armed**.

Example Sb galaxy

grz color composite image of NGC 1288 from the DESI Imaging Legacy Surveys.

Sb galaxies are distinguished from Sc galaxies by less-open spiral structure and by a more prominent bulge.

Another example Sb galaxy

M81 (NGC 3031), an Sb galaxy. HST/ACS image from the Hubble Heritage Team, NASA/STScI.

Example Sa galaxy

NGC 2681 is an Sa galaxy. This is a *gri* image by D. Hogg and M. Blanton (SDSS).

Sa galaxies have even tighter spiral patterns and yet more prominent bulges.

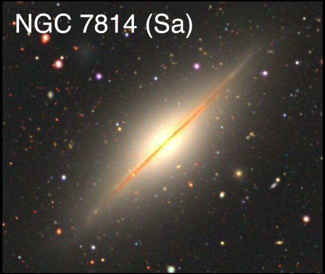
NGC 2681 has two major spiral arms, seen by their extinction, with little evidence for star formation within them.

Another example Sa galaxy

A *gri* image of NGC 3898 by D. Hogg and M. Blanton (SDSS).

The spiral arms are still faint but have more HII regions to delineate them than NGC 2681.

Bulge/disk size in edge-on disk galaxies



An SBc(s) galaxy

A *BRI* image of NGC 1365 from VLT Antu (ESO).

The (s) means the arms and bar form a letter S, rather than a closed (r)ing.

Note that the galaxy has at least two concentric bars oriented in different directions.

An SBb(s) galaxy

NGC 1300, an SBb(s) galaxy. HST/ACS image from the Hubble Heritage Team, NASA/STScI.

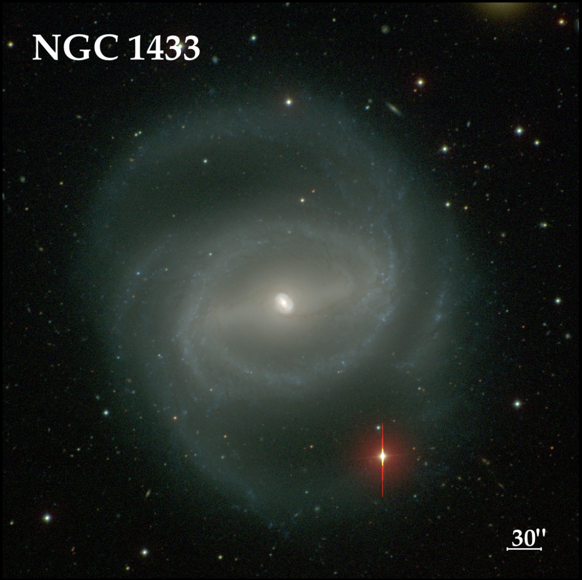
An SBc(r) galaxy

A *BVRI* image of NGC 1433 from the GCS.

The ring around the end of the bar gives rise to the (r), but there is another much smaller ring in the nucleus.

There is also a point-symmetric bridge of material connecting the two rings, appearing here as dust lanes.

The Milky Way has this sort of nuclear disk, too, evident in the central couple of degrees of the HI or CO ℓ–v diagrams.



An SBb(r) galaxy

An *LRGB* image of M95 by Adam Block.

The galaxy has a continuous ring, with two spiral arms.

This is another good example of dust lanes delineating a bridge of material between the ring and another, inner ring within the bulge.

- The M95 image on the Mees website shows the inner ring better.

The bright blue star in the spiral arm on the right is SN 2012aw, a type II supernova.

Spiral structure

- Spiral arms generally trail rotation.
- Spiral arms never wind much more than once around a galaxy.
- Concentration of HII regions and young blue stars is higher in the arms than elsewhere; the star formation rate is higher there.
- Dust lanes lie on the trailing edges of arms.
- Molecular cloud complexes tend to be more massive in the arms than elsewhere.

M100 (Sc). C. King, S. King, and A. Block, NSF/NOAO/AURA. The disk rotates clockwise.

Spiral structure

- The central bulges in nearby spirals usually (65% of the time; Sheth et al. 2008) look at least slightly **oval or elliptical** rather than axisymmetric.
- Less commonly (30% of the time) the bulge is strongly **barred**. These are the SB galaxies.
- This is in harmony with computer simulations. Initially axisymmetric stellar disks always develop quickly (within a few rotation periods) into stable, oval/elliptical or barred, shapes (Hohl 1971).

NGC 1398, SBb(r), from S. Stecker, R. Stecker, A. Block, NSF/NOAO/AURA.

Elliptical galaxies

Elliptical galaxies are the other Hubble type, given as En.

- Rotation is often not evident; random motions dominate the stellar velocity distribution.
- There is very little interstellar matter compared to the mass in stars. Consequently, there is not much star formation.
- There is a variety of shapes ranging from round (E0) to an **ellipticity** of 0.7 (E7).
  - In terms of semimajor and semiminor axes a and b, the ellipticity is $e = 1 - b/a$. The notation En with $n = 10e$ is used to denote the shape.
- Ellipticals may be prolate (football-shaped) or oblate (pill-shaped) in 3D. In general they are probably **triaxial**, i.e., all the principal axes have different lengths.

Example of an E0 galaxy

M87 (NGC 4486) has a bright core and jet (which we will discuss when we cover active galactic nuclei). From Adam Block, NSF/NOAO/AURA.

Example of an E7 galaxy

NGC 1332 is an E7 galaxy about 24.5 Mpc from Earth.

To the southwest is a smaller (or more distant) E1.

Image from the Carnegie-Irvine Galaxy Survey.