X-RAY



Galactic Rotation Curves The Hubble Sequence Galaxy spectra Distribution of mass and light Dark matter

April 1, 2025

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# The Milky Way & Normal Galaxies

- Spiral structure in the Milky Way
- The Hubble sequence for the shapes of normal galaxies
- Characteristics of galaxy spectra
- Distribution of mass and light in normal galaxies
- Dark matter in spiral galaxies





Spectral energy distribution (SED) of the starburst galaxy M82 (Viewspace.org).

#### 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 closer.
- Cloud angular size; bigger size  $\implies$  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.

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#### Measurement of (inner) Galaxy rotation curve



For the HI cloud at  $(r, \ell)$ , note from the law of sines that

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

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

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

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<sup>2</sup> 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 faster** than  $1/r^2$ .
- Keplerian rotation is expected eventually at sufficiently large distances, but is not seen.
- Effect of dark matter? Yes!

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#### 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

ESA / Gaia / DPAC / Stefan Payne-Wardenaar

#### 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	$\Leftarrow$
Road crew speed	$\Leftarrow$
Traffic jam	$\Leftarrow$

- normal stellar orbit speed  $\Rightarrow$  $\Rightarrow$ 
  - spiral-wave pattern speed
- density wave (spiral arm)  $\Rightarrow$

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## 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, respectively. 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 SB0 same as S0, but with a bar feature in the center

**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

# 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.



## 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.





April 1, 2025 (UR)

## 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 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  $\ell$ –v diagrams.



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

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## 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 main 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 E*n* with *n* = 10*e* 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.

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### 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.



### Lenticular galaxies

Lenticular galaxies are Hubble types S0 or SB0.

- Like ellipticals, they have very little interstellar matter and very little star formation.
- Like spirals, they have disks in which rotation dominates the stellar velocity distribution.
- The central bulges tend to dominate the mass in lenticulars; no spiral structure is observed in the disks.
- Lenticulars are components of polar ring galaxies, an important class of "interacting" galaxies. More on that later.
- They got their name from their lens-like shape in photographs, as for NGC 5866 at right (Sandage & Bedke 1994).



### NGC 5866, a S0 galaxy

S0 galaxies tend not to look so obviously lens-like when observed with CCD cameras and presented with a non-photographic stretch.

The dust disk may in fact have some spiral structure. It is not easy to tell because of our edge-on view of the galaxy.

Image: HST image of NGC 5866, NASA/ESA.

#### The differences between E7 and S0

E7 (NGC 1332): smooth variation in brightness in all directions from the center. Round nucleus. Nothing disk-like at all.



S0 (NGC 4526): definite bulge and extended disk; brighter disk 1 kpc diameter in nucleus. Both disks inclined at  $i = 76^{\circ}$ .



#### Lenticular galaxies viewed nearly face-on

Left: HST/WFC3 image (NASA/STScI). Right: gri image by D. Hogg and M. Blanton (SDSS).





#### Irregular galaxies

Usually set between the tines of the fork are the irregular galaxies, types Irr I and Irr II.

- These galaxies are supposed to be amorphous. They have a wide range of masses and luminosities, though they are small compared to typical spirals.
- They tend to be rich in ISM and have respectable star formation rates, though most have very small abundances of heavy elements.
- ▶ Irr I: hints of regular structure, e.g., the "bar" in the Large Magellanic Cloud.
- Irr II: no regular structure at all. However, note that the archetype Irr II, M82, looks amorphous just because of extinction. Underneath, it is a spiral galaxy!

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# Example of an Irr I

The Large Magellanic Cloud (LMC) is an Irr I.

The LMC is located 50 kpc from Earth and is easily visible to the naked eye from the Southern Hemisphere.

Photograph by Wei-Hao Wang, NRAO.



# Archetype of Irr II

M82 (NGC 3034), the "Cigar" Galaxy, is the archetype Irr II.

Its rotation curve reveals that M82 is a nearly edge-on spiral with heavy foreground extinction.

*BVI-Hα image from NASA, ESA, and the Hubble Heritage Team.* 



#### Dwarf galaxies

Due to technical limitations at the time, the Hubble sequence is only comprised of (and therefore only applies to) luminous galaxies with high surface brightness. This excludes dwarf galaxies, the most numerous galaxy type that exists.

Dwarf galaxies have low surface brightness and low luminosity. They also come in various shapes:

- dE Dwarf ellipticals ( $L < 10^9 L_{\odot}$ ) are elliptical in shape and contain little gas or dust
- dSph Dwarf spheroidals ( $L < 3 \times 10^7 L_{\odot}$ ) are extremely faint dwarf ellipticals with small ellipticity

dIrr Dwarf irregulars have major ISM & star formation

There are very few dwarf spiral galaxies; the spiral structure is an apparent attribute of massive, luminous galaxies.

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### Example dE galaxy

Commonly found in galaxy clusters, dEs are thought to be primordial objects. Larger galaxies are believed to have formed as a result of the merging of many smaller dEs over time.

A dE member of the Virgo Cluster (The Extended Virgo Cluster Catalog, Kim et al. 2014)



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## Example dSph galaxy

Dwarf spheroidals are named after the constellation in which they are found. Because they are so faint, most that have been identified are satellites of the Milky Way. There are currently  $\sim$ 25 dSph that have been identified.

dSph are distinguished from globular clusters by the presence of a **dark matter halo**.

The Fornax dwarf galaxy, a dSph of the Milky Way (ESO/Digitized Sky Survey 2)



### Example dIrr galaxies

About 90% of the dwarf galaxy population are characterized as dIrrs.

Similar to the dEs, dIrrs are also thought to be the predecessors of the more massive galaxies we see today. These objects typically have a significant amount of gas and a low metallicity, indicating that they are relatively young in their evolution.

Top: blue compact dIrr galaxy (ESA/Hubble & NASA) Bottom: dIrr galaxy in the Local Group (ESA/Hubble & NASA)



#### Hubble – de Vaucouleurs sequence

Modified version of the original Hubble sequence commonly used today

