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Chapter 1 • A brief history of galaxies

§1.1 • Early attempts to understand the nebulae

Galileo Galilei (1564-1642)

- Born in Pisa; worked as professor of mathematics
- Built one of the **first telescopes** in 1609
- Some of his telescopic observations:
 - Saw craters and mountains on the **Moon** (not a perfectly round body)
 - Identified four **satellites of Jupiter** ("Galilean moons")
 - Observed **phases of Venus** (killing the geocentric solar system model)
 - Resolved the **diffuse Milky Way** into many faint stars
 - Found the same for other known "nebulae" (which were star clusters)



Andromeda

- Andromeda was first described by Persian astronomer Abd al-Rahman al-Sufi as a "little cloud" in 964
- Simon Marius first looked at it with a telescope and found that it did not resolve into stars



Marius:

Among them the first is that with the spy-glass, from 15 December 1612 I discovered and observed a fixed star with a certain wonderful shape that I cannot find in the entire heavens. It is near the third and northernmost [star] in the belt of Andromeda. Without the instrument the same is seen as some sort of little cloud; and with the instrument no distinct stars are seen as in the nebular star in Cancer and other nebular stars, but rather only white rays, which the closer to the centre the brighter they come out; in the centre there is a dull and pale light; and its diameter is about a quarter of a degree. About the same brilliance appears when a bright candle is observed through a clear lantern from a long distance.

Charles Messier (1730 - 1817)

- Identified many **nebulae** (fuzzy patches of light)
- Published Messier Catalogue in 1780
- Intended as aids to **comet hunters** to reject "uninteresting" objects





Globular clusters (29)



Open clusters (26)



Lefty's Astrophotography

Gas clouds (7)



Planetary nebulae (4)



Supernova remnant (1)



Double star (1)



Galaxies (40)













Modern, scientific categories

- Globular cluster (round, compact star cluster)
- Open cluster (less compact cluster of stars)
- Gas cloud (diffuse nebula)
- Planetary nebula (gas cloud around single star)
- Supernova remnant (leftovers of stellar explosion)
- Double star (two stars that happen to appear close)
- Galaxy (the only objects not in MW)

In the Milky Way

Immanuel Kant and the Island Universe

- Philosopher but also interested in astronomy
- Heard about the "nebulae" and postulated that they are separate "worlds" similar to Milky Way
- Called them "Island Universes" (1775)
- Thomas Wright had proposed similar theory
- Views did not take hold becaues there was no direct evidence yet of other galaxies



William & Caroline Herschel

- Discovered thousands of new nebulae
- Thought they could be star collections like MW
- Concluded Milky Way was a disk with the Sun at the center (map from 1785)



John Herschel (son of William)



• Observed nebulae in greater detail, made lots of sketches



Whirlpool Galaxy (M51 a/b)





Drawing by Lord Rosse (1845)

Spectroscopy: William & Lindsay Huggins



- Huggins took spectra of celestial objects (about 1860 1900)
- First to distinguish star-like spectra of Andromeda galaxy from emission line spectra of gas clouds in the Milky Way

§1.2 • The Great Debate and the 20th century



"Spiral nebula" Messier 51 by George Ritchey, 1910





Harlow Shapley

Heber Curtis

What are the nebulae?

- Heber Curtis (1917) observed novae (strong flares in stars' light) in three spiral nebulae; much fainter than in MW, suggesting **great distance**
- Harlow Shapley showed that Sun is far out in disk of Milky Way (but overestimated MW size by factor of three)





The Great Debate

• Shapley

- If Andromeda not in the MW, must be extremely far away
- Pinwheel galaxy seen to be rotating (wrong)
- Curtis
 - More novae in Andromeda than in MW
 - Novae appear faint in Andromeda (and other nebulae)



What is the distance to Andromeda?

The distance to Andromeda



- In 1924, Edwin Hubble first observed a variable star with properties of a Cepheid in Andromeda
- Determined that Andromeda must be well outside MW, settling the Great Debate!

MW

Hubble-Lemaitre law

- Edwin Hubble and his collaborators (Slipher and Humason) systematically measured the spectra of galaxies
- Hubble and Humason combined redshifts (velocities) from spectra and distances from Cepheids
- They found a linear relationship (in 1929): recession velocity is distance times the "Hubble constant" H₀
- Lemaitre had published same result in 1927 (in low-impact journal)





Milton Humason



Vesto Slipher



Edwin Hubble

 $v = H_0 \times d$



Georges Lemaitre

Cosmological redshift



Redshift is caused by the expansion of space!

Galaxies vs. nebulae

- Roughly in the 1930's, the understanding of what galaxies are manifested in using the term "galaxy" rather than "nebula"
- The word comes from Greek γαλαξιαζ, meaning "milky"



Hubble 1936

History of the Universe

Dark Energy Accelerated Expansion





How are galaxies distributed on the sky?



Proctor 1869 • Inspired by a slide by Andrey Kravtsov

Sky surveys

- Issue with catalogs like those of Messier or the Herschels: we do not know...
 - How much sky they searched
 - How they selected the "nebulae" to look at
 - How good their telescope was (meaning how dim a galaxy they could see)
- This makes it hard to quantify the galaxy population: how many galaxies are there per volume? How bright are they?

Sky surveys

TABLE I. AREA III, UNCORRECTED COUNTS OF NEBULAE PER SQUARE DEGREE

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Sky surveys



Figure 2. Equal surface density contours for nebulae in Area III, based on smoothed counts by 1° squares.

Redshift surveys

- Observing galaxies on the sky gives us two dimensions, but how do we know how far away a galaxy is?
- We measure each galaxy's redshift and use Hubble's law
- Distance is expressed as redshift or velocity (only valid at low z!)



First redshift surveys



- CfA surveys obtained redshifts for about 20,000 galaxies
- Slice in z-RA space (projected through some width in DEC)
- Shows large-scale structure, e.g. long filament known as the "CfA Great Wall"

Sloan Digital Sky Survey (SDSS)

- The key is the word **digital**
- Most data taken at Apache Point Observatory in New Mexico (one of the darkest places in the US)
- Umbrella for multiple surveys of "phases," but we will mostly be concerned with Phases I and II:
 - **Step 1:** Photograph ~15,000 square degrees with powerful digital camera in multiple filter bands
 - **Step 2:** Identify objects and classify as stars, galaxies, quasars, etc.
 - Step 3: Define a sample of galaxies (m_r < 17.77) for which to measure spectra
 - **Step 4:** Create metal plates with pre-drilled holes at positions of galaxies; place individual fibers on holes; feed to a spectrograph









Images: SDSS Collaboration

SDSS Telescope Operations



SDSS Collaboration (youtube)

Reading

- CFN §2.1-2.3
- MvdBW §1.4, §3.1-3.2