ASTR 505

Galactic Astronomy

Course Notes

HCG59. NASA/ESA HST

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1 Introduction

Figure 1.1: NGC 3370, a spiral galaxy that resembles the Milky Way. NASA, Hubble Heritage Project.

1.1 Why study galaxies?

Galaxies are the largest stellar systems in the Universe. They contain the vast majority of luminous matter. Galaxies are the primary sites of star formation activity and element production. They trace the large-scale structure of the Universe, and cosmic history over ~ 13 Gyr. They are the site of a wide variety of interesting phenomena, including supernovae, gamma-ray bursts, supermassive black holes, and relativistic jets to name a few.

There are many questions. Some of the biggest are: Why are there galaxies? Why do they have such varied structure? Why are there such large variations in mass and size? How do they form and evolve? What do they tell us about the Universe?

At the same time one must ask the question, "What is a galaxy?" They come in such a wide range of shapes, sizes, masses and luminosities that one may wonder what distinguishes a galaxy from its satellites, or what distinguishes a galaxy from a star cluster? We shall approach this by examining the properties of these objects in some detail.

1.2 A brief history

Here we provide just a very brief summary. For more-detailed accounts see for example

- https://ned.ipac.caltech.edu/level5/March02/Gordon/Gordon2.html
- http://apod.nasa.gov/diamond_jubilee/papers/trimble.html
- Berendzen, Hart and Seeley, *Man Discovers the Galaxies*, Columbia Univ. Press 1984.

The brightest galaxies were seen as "diffuse nebulae" by 18th-century observers such as Thomas Wright and Sir William Herschel. The Andromeda galaxy (M31) can even be seen with the naked eye, but only as a fuzzy luminous patch of light.

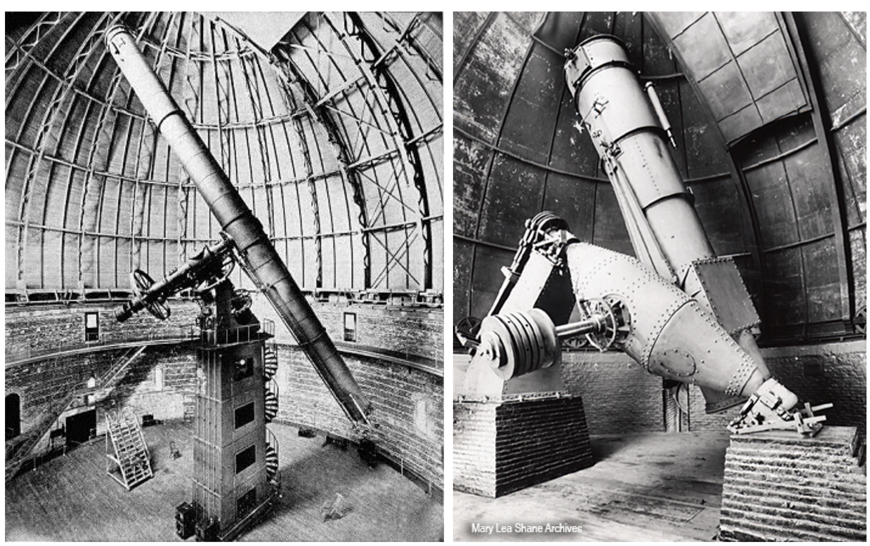
The nature of these objects was long a subject of debate. The philosopher Immanuel Kant first suggested that they were "island universes". Herschel, on the contrary, was led to the conclusion that they were small object within the Milky Way since some "planetary nebulae" were clearly associated with stars.

Spiral structure was first noted (in M51) in 1845 by William Parsons (the 3rd Earl of Rosse) observing with his 72-inch telescope. Although large for the time, its performance, and that of earlier reflecting telescopes, was limited by the low efficiency of its primary mirror made from "speculum" metal.

Figure 1.2: Lord Rosse's 72-inch telescope (the "Leviathan of Parsonstown"), used by Rosse and Dreyer to observe spiral nebulae.

Figure 1.3: Early photograph of M31 taken by Issac Roberts (from *A Selection of Photographs of Stars, Star-clusters and Nebuae, Volume II*, The Universal Press, London, 1899)

The introduction of photography in the mid 19th century provided a powerful new tool. The first photograph of a nebula (the Orion Nebula) was obtained in 1880 by the American doctor and amateur astronomer Henry Draper using an 11-inch refractor built by Alvan Clark. Early photographs by Welsh engineer and amateur astronomer Issac Roberts and American astronomer James Keeler allowed classification into knotty (M33) and smooth (M31) types. Keeler and Heber Curtis, working at Lick Observatory, made extensive photographic studies of nebulae starting around 1900 using the 36-inch Crossley reflector.



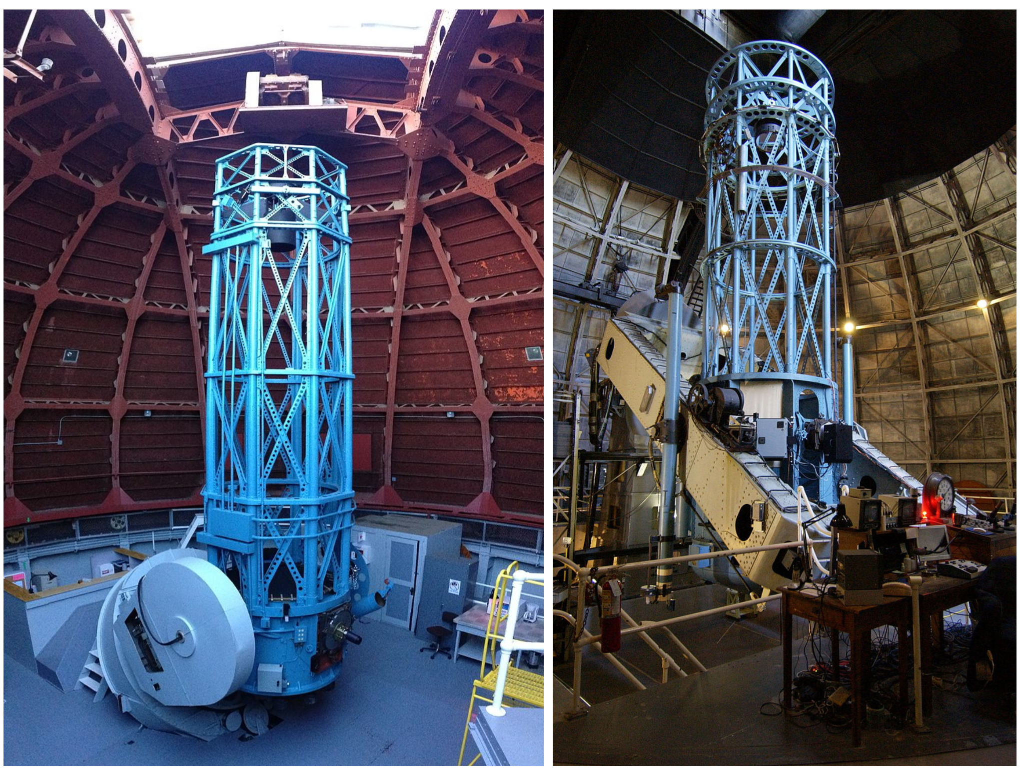
(a) (b)

Figure 1.4: (a) The 40-inch Alvan Clark refractor at Yerkes Observatory. (b) The 36-inch Crossley reflector at Lick Observatory circa 1905 (Mary Lee Shane Archives).

Evidence was mounting for the extragalactic nature of at least some nebulae, which clearly resembled a miniature version of the Milky Way. However, the central surface brighness of some of these exceeded that of the centre of the Milky Way, which argued against this hypothesis. (We now know that the bright centre of our galaxy is obscured by dust.)

Another breakthrough came with the application of photographic spectroscopy. Spectroscopy of M31 showed it to have a continuous spectrum, unlike the emission spectrum seen for gaseous nebula. In 1914 Vesto Slipher measured the radial velocity of M31 and Wolf measured internal rotational velocities in M81. It soon became evident that the radial velocities of some nebulae are too large for them to be bound to the Milky Way. However their distances were still unknown.

Measurements made by van Mannen of photographic plates taken with the Hale 60-inch telescope at Mount Wilson seemed to indicate motion in M81. He interpreted this as either rotation or expansion, which would support the local hypothesis. However, independent measurements of his plates by Lundmark found proper motions that were an order of magnitude smaller!



(a) (b)

Figure 1.5: The 60-inch Hale reflector (a) and 100-inch Hooker telescope (b) at Mt. Wilson.

Measuring thousands of stars in the Large Magellanic Cloud (LMC), Henrietta Leavitt found a relationship between the period and luminosity of a certain type of pulsating star called a Cepheid variable. Published in 1908, the period-lumnosity relation formed the basis for distance measurements using the inverse square flux law.

In 1917 George Ritchey discovered a nova in M31, supporting the extragalactic theory. More novae discoveries followed. Debate over the nature of these objects reached a peak in 1920, with the Curtiss-Shapley debate.

The spiral nebulae were firmly identified as extragalactic with the discovery of Cepheid variables in M31 by Hubble in 1925. New plates taken with the Mt. Wilson 100-inch Hooker telescope also ruled out van Mannan's proper motions in M81.

1.3 Catalogues

A necessary starting point for the study of galaxies is a sample of objects. Many catalogues have been compiled over nearly three centuries. Some of the most significant are listed below.

It is important to realize that all of these catalogues are largely heterogeneous samples of objects. Some contain other objects in addition to galaxies, and none have uniform quantitative selection criteria.

In fact, the very nature of galaxies makes identification difficult. Low-surface-brightness (LSB) galaxies may be lost in the noise of the light of the night sky. Typically one can detect and measure only to an intensity level that is about 1% of the sky "background" intensity.

High-redshift galaxies are subject to numerous biases, due to cosmological surface-brightness dimming, small angular size, redshift of their spectra, etc.

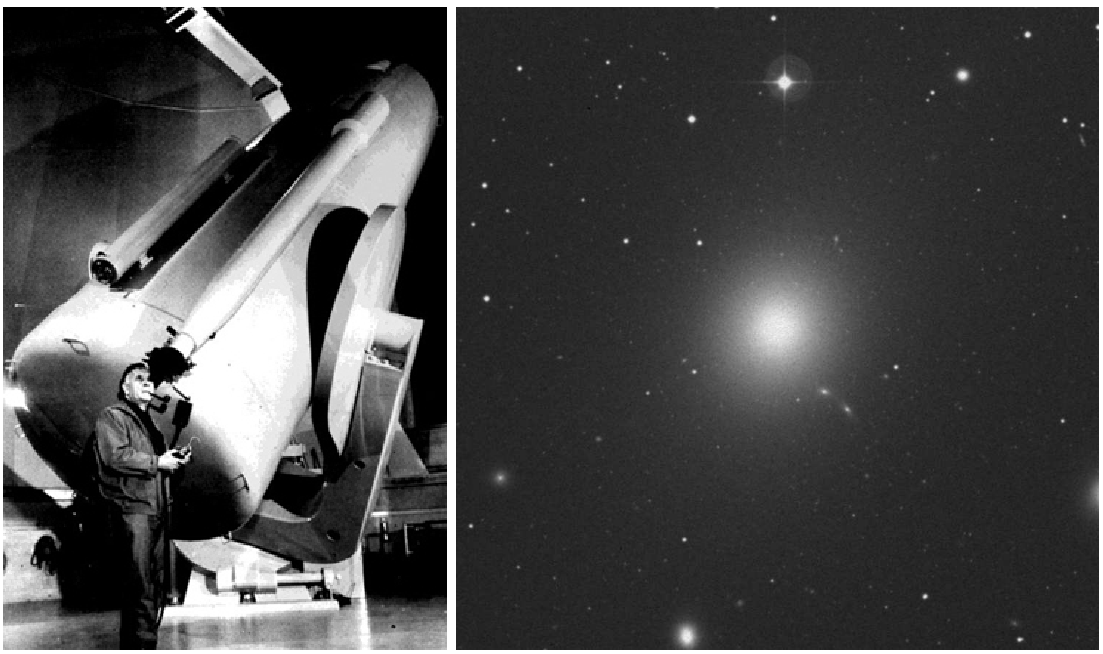
Nevertheless, the catalogs form a starting point for many studies, and also serve to identify the brightest galaxies. Many such galaxies have Messier or NGC identifications that are frequently used.

- ***Messier Catalogue*** (Messier, circa 1758) contains 110 nebulae, galaxies and star clusters.
- ***General Catalog of Nebulae*** (GC: John Herschel 1864) contains 5079 non-stellar objects.
- ***New General Catalog*** (NGC: Dreyer, circa 1880) was compiled from the GC and results of many observers. Dreyer observed many of these objects using Lord Rosses 72 reflector. The catalogue lists 13,226 non-stellar objects, including those in the Index Catalogs.
- ***Revised NGC*** corrected many errors in the original NGC.
- ***Index Catalogs*** (IC) are two expansions to the NGC (IC I and IC II).

- ***Shapley-Ames Catalog*** (SA: Shapley & Ames, 1932) contains 1200 galaxies brighter than 13th magnitude.

- ***Revised Shapley-Ames Catalog*** (RSA: Sandage & Tammann 1981) provides data on magnitudes, types and redshifts for the SA. It also added some additional galaxies.

- ***Palomar Observatory Sky Survey*** (POSS) consists of complete photographic imaging of the northern sky to ~ 30 deg declination in red and blue wavelength bands. The limiting magnitude is ~ 19. Digitized images available at http://archive.stsci.edu/cgi-bin/dss_form



(a) (b)

Figure 1.6: (a) Edwin Hubble with the 48-inch Schmidt telescope at Mt. Palomar. (b) The elliptical galaxy M87, from the Digitized Palomar Observatory Sky Survey.

- ***Reference Catalog of Bright Galaxies*** (de Vaucouleurs and collaborators). There are three editions. The RC (1964) provided photometric data for 2594 galaxies. The RC2 (1976) lists 4362 galaxies, and the RC3 (1993) lists 23012 galaxies.

- ***Zwicky Catalogue*** (Zwicky et al 1961-1967) is a catalogue of galaxies and clusters of galaxies (CGCG) that contains $\sim 20,000$ galaxies found on Palomar 18-inch Schmidt plates, to a limiting magnitude of ~ 15.5. From this galaxy sample, 1931 clusters of galaxies were identified. Zwicky also published a Catalog of Compact Galaxies (1971)

- ***Updated Zwicky Catalogue*** (Falco et al 1999) provides better positions and redshifts for Zwicky catalogue.

- ***Uppsala General Catalogue*** (UGC: Nilson 1973) is an essentially complete catalogue of $\sim 13,000$ galaxies to limiting diameter of 1.0 arcmin and limiting magnitude of 14.5

on blue POSS plates.

Third Cambridge Catalogue of radio sources (2C: Bennett et al. 1962) contains 328 radio sources.

- ***CFA Redshift Survey*** (Centre for Astrophysics) (1982 - 1987) obtained reshifts for about 18,000 galaxies to a magnitude of 15.5.
- ***IRAS*** (Infrared Astronomy Satellite) all-sky mid-infrared survey (1982).
- ***Automatic Plate Measuring Machine*** (APM) survey of more than 2 million galaxies (1990) found on POSS and UK Schmidt plates.
- ***Two-Micron All Sky Survey*** (2MASS, 2003) infrared all-sky survey
- ***Two Degree Field Redshift Survey*** (2DF, 2002) provided spectra and redshifts for more than 200,000 galaxies over 1500 square degrees of sky.
- ***Sloan Digital Sky Survey*** (SDSS, 2003-2013) provides photometry for 500 million objects and spectra for a million objects.

1.4 Electronic archives

Electronic archives have become indispensable tools in astronomy. Here are some of the most useful:

- Many catalogues are available in digital form from the CDS Data Centre in Strasbourg, ***cdsweb.u-strasbg.fr***
- Digital images of any region of the sky can be downloaded from the Digitized Sky Survey at
  archive.stsci.edu/cgi-bin/dss_form
- The NASA Extragalactic Database (NED), maintained at Caltech's Infrared Processing and Analysis Center (IPAC) has extensive data and tools,
  ned.ipac.caltech.edu
- The Lyon Extragalactic Data Archive (LEDA) has an extensive galaxy database and useful search tool, HyperLeda,
  leda.univ-lyon1.fr
- The most extensive and useful archive of scientific literature is the NASA Astrophysics Data System (ADS) and search engine,
  adsabs.harvard.edu