Stars and **Galaxies**

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Aim

The *Hubble Deep Field* shows how even a tiny patch of sky contains thousands of galaxies of different sizes and shapes, lighting-up the Universe in a dazzling display of colours. When did they form? Which physical processes shaped them? How do they evolve? Which types are there, and whence the huge variety? How does the Milky Way galaxy fit in? What can we learn from them?

11 lectures are too few to answer any of these fundamental questions in detail. In addition, galaxy formation and evolution require a cosmological setting, see the later lecture courses on cosmology (L3) and Galaxy Formation (L4). The more modest aim of these lectures is to give an overview of the properties of galaxies (galaxy types, properties of spiral galaxies in general and the Milky Way galaxy in particular, properties of elliptical galaxies), look at some of the more spectacular phenomena (quasars, gravitational lensing), and investigate the extent to which all this can be described with simple physics. These lectures will *use* the physics you've learned in other lectures (in particular classical mechanics, electricity and magnetism, quantum mechanics, and of course the earlier parts of this course on Observational Techniques and Stars) to galaxies, rather than teach new physics.

The beauty of galaxies is for most people enough to warrant their study, but of course astronomy and cosmology enable one to study physics in situations which cannot be realised in a laboratory. Examples of fundamental physics made possible by astronomy and cosmology are tests of general relativity (Mercury's orbit, dynamics of pulsars, growth of structure in the Universe, detection of gravitational waves, study of black holes), investigations whether the fine-structure constant evolves (from quasar absorption spectra), the discovery of dark matter (from the motions of galaxies and from the growth of structure), the discovery of dark energy (from the expansion of the Universe), and even estimating the masses of neutrinos (from the

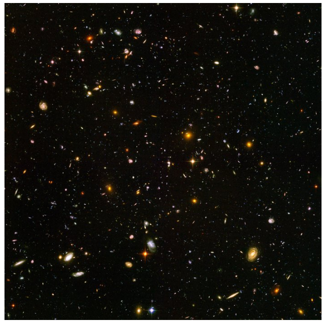

Figure 1: The Hubble Ultra Deep Field

growth of structure). Several of these fundamental discoveries rely on a basic understanding of galaxies, the building blocks of the visible Universe.

Learning outcomes:

- ability to classify galaxies and state defining properties of spiral, elliptical and irregular galaxies
- explain observational basis for discovery of the Milky Way
- explain observational basis of the modern view of the Milky Way
- apply classical mechanics to dynamics of galactic discs, including arguments for the presence of dark matter
- apply classical mechanics and other basic physics to the properties of the interstellar medium in spirals (properties of gas and dust, 21-cm radiation, concept and application of Jeans mass)
- apply mechanics and hydrostatics to describe elliptical galaxies and clusters of galaxies
- understanding of galaxy scaling relations and statistical properties of galaxies
- observational manifestations of active galactic nuclei, and the connection to central supermassive black holes
- basics of gravitational lensing, and its applications

Additional information

There are many excellent sites with images of galaxies, and explanations of some of the issues discussed below. The latest version of *Google Earth* has the option to look at the night sky, with images of galaxies taken from the *Sloan Digital Sky Survey* and the *Hubble Space Telescope*.

Most of the images shown during the lectures come from one of

- http://www.seds.org/
- http://www.aao.gov.au/images.html/
- http://hubblesite.org/newscenter/archive/
- http://teacherlink.ed.usu.edu/tlnasa/pictures/picture.html

- http://astro.estec.esa.nl
- http://space.gsfc.nasa.gov/astro/cobe/cobe_home.html
- http://astro.estec.esa.nl/Hipparcos/
- http://astro.estec.esa.nl/GAIA/

Much of what is discussed in the notes can be found often with additional explanations and diagrams in several text books. The lectures here will refer very often to Carroll & Ostlie: paragraphs refer to the corresponding section in that reference book (*e.g.* CO 6.2 refers to Section 6.2 of that text book, CO p. 310 to page 310.)

Additional explanations can be found in

1 Carroll & Ostlie, *Modern Astrophysics*, Addison-Wesley, second edition, 2007

2 Zeilik & Gregory, *Astronomy & Astrophysics*, Saunders College Publishing, 1998

3 Binney & Merrifield, *Galactic Astronomy*, Princeton, 1998

4 Binney & Tremaine, *Galactic Dynamics*, Princeton, 1987

(These are referred to as CO, ZG, BM, and BT in these notes) The first two are general and basic texts on astronomy, which, together with the web pages, should be your first source for more information. [3] is a much more advanced text on galaxies, and [4] is a superb and detailed discussion of the dynamics of galaxies. Chris Mihos maintains an excellent web site where you'll find additional material on what is discussed in these lectures, and several images in these notes originate from there.

About your lecturer

I research how galaxies form and evolve using numerical cosmological simulations. The aim of these simulations is to try to understand which are the main physical processes that shape galaxies and how, starting from the nearly uniform Universe that we see in the cosmic microwave background, the different types of galaxies emerge over cosmic time. If you are interested, please take a look at the website of the Eagle simulations. I was one of the main contributors to the simulation code that was used to perform these cosmological hydrodynamical simulations. The simulations themselves were performed on the Curie supercomputer in Paris , part of the European PRACE supercomputing consortium, as well as on the Cosma supercomputer that is part of the Dirac infrastructure, here in Durham.

The Eagle project has resulted in several hundred scientific publications, one of which is the most cited paper in the whole of astronomy in 2015. (I am a little bit proud of that!) The simulation data are available to anyone, and you can play with the results using a database. If you're keen to try this and want some suggestions of what you might want to look into, do not hesitate to ask me. The database has several python examples to get you started.

Summary

Chapters 1-6: spiral galaxies

Galaxies come in a range of colours and sizes. In **spiral** galaxies such as the Milky Way, most stars are in a thin disc. The disc of the Milky Way has a radius of about 15 kpc, and contains $\sim 6\times 10^{10}M_\odot$ of stars. The disc stars rotate around the centre of the galaxy on nearly circular orbits, with rotation speed $v_c\sim 220$ km s^{-1} almost independent of radius r (unlike the motion of planets in the solar system where $v_c\propto 1/r^{1/2}$). Such *flat rotation curves* require a very extended mass distribution, much more extended than the *observed* light distribution, indicating the presence of large amounts of invisible *dark matter*. Curiously, the spiral arms do not rotate with the same speed as the stars, hence stars may move in and out of spiral arms.

Stars are born in the large molecular gas clouds that are concentrated in spiral arms. Massive short-lived stars light-up their natal gas with their ionising radiation, and such 'HII' regions of ionised hydrogen follow the arms as beads on a string. The blue light from these massive and hot stars affects the colour of the whole galaxy, one reason why spirals are blue. Remember that the luminosity L of a star is a strong function of its mass M, with approximately $L\propto M^3$ on the main sequence, hence a single $100M_\odot$ star outshines nearly 10^6 solar-mass stars: the colour of a galaxy may be affected by how many massive (hence young) stars it harbours.

The stars in the central region of the Milky Way (and most spirals) are in a nearly spherical *bulge*, a stellar system separate from the spiral disc, with mass $\approx 10^{10}M_\odot$. Dust in the interstellar medium of the disc prevents us from seeing the Milky Way's bulge on the night sky. disc and bulge are embedded in a much more extended yet very low-density nearly spherical *halo*, consisting mostly of dark matter. The stellar halo contains a sprinkling of 'halo' stars, but also globular clusters, very dense groups of 10^5-10^6

stars of which the Milky Way has ~ 150. The total mass of the Milky Way is $\sim 10^{12} M_\odot$, but stars and gas make-up only $\sim 7 \times 10^{10} M_\odot$ with the rest in dark matter.

Chapter 7: elliptical galaxies

Elliptical galaxies are roundish objects which appear yellow. The redder colour as compared to spiral galaxies is mostly due to the absence of massive (blue) stars: elliptical galaxies have much lower star formation rates than spirals of the same mass (and massive stars are short lived, so can only be present in a galaxy that is forming stars). We suspect that the low star formation rate is because the central super massive black hole prevents star formation.

The stars move at high velocities but with little ordered motion: it is these random motions, not rotation, that provides the support against gravity. This is similar to how the velocities of atoms in a gas generate a pressure, $p \sim \rho v^2 \sim \rho T$. However, unlike the atoms in a gas, the stellar velocities are in general *not* isotropic, meaning that also the pressure is not isotropic. The result is that, whereas stars are round, elliptical galaxies are in general flattened, *i.e.* elliptical in shape (tri-axial in 3 dimension).

The observed stellar motions, but also the hot X-ray emitting gas detected in them, both suggest the presence of dark matter in elliptical galaxies.

Chapters 8-9: galaxy statistics

Roughly half of all stars in the Universe are in spirals, and half are in ellipticals. Spiral galaxies tend to live in region of low galaxy density. The Milky Way is part of a 'local group' of galaxies, containing in addition to Andromeda a swarm of smaller galaxies. Ellipticals in contrast tend to cluster in groups of tens to hundreds of galaxies, called clusters of galaxies. Such clusters contain large amounts of hot, X-ray emitting gas. Together with the large observed speeds of the galaxies, this hot gas provides evidence that a large fraction of the cluster's mass is invisible dark matter.

Chapter 10: Active Galactic Nuclei

A small fraction of galaxies contains an active nucleus, which may generate as much or even more energy than all the galaxy's stars combined. The observational manifestations of such active galactic nuclei, or AGN, are quite diverse, with energy being emitted from visible light in quasars, to immensely power full radio lobes, to X-rays and even gamma-rays. Some fraction of energy may even be released in the form of a powerful jet.

The energy source is thought to be accretion onto a supermassive black hole, with masses from 10^6 to as high as $10^9 M_\odot$. It is thought that most, if not all, massive galaxies contain such a supermassive black hole in their centres. The evidence is particularly convincing for the presence of a $\sim 10^6 M_\odot$ black hole in the centre of the Milky Way.

Clearly, if most galaxies contain the engine but have little or no observational AGN manifestations, it must imply that the majority of black holes is dormant - starved of fuel.

Chapter 11: Gravitational lensing

A gravitational field bends light. In general this is only a small effect and our view of the distant universe is not significantly deformed by the gravitational lensing caused by the intervening potentials generated by stars, galaxies or clusters of galaxies. The phenomenon has been used to test Einstein's theory of relativity, to constrain the nature of dark matter in the Milky Way, to determine the masses of galaxies and clusters, and even to enable astronomers to use clusters of galaxies as truly giant telescopes enabling the detailed study of distant galaxies.

Chapter 1

Introduction

CO §25.1 & 25.2

1.1 Historical perspective (*CO §24.1*)

Galaxies are extended on the night sky as can be seen even without using a telescope[1]. *Andromeda* is similar in size to the Milky Way and extends over several degrees, whereas the *Large Magellanic Cloud* or LMC, visible from the Southern hemisphere on a clear night, extends over six degrees (diameter of full moon is 1/2 a degree). The Sagittarius dwarf galaxy, a small galaxy gravitationally bound to the Milky Way, extends over a large fraction of the sky.

The Milky Way galaxy is a spiral galaxy, in which most of its $\sim 200\times 10^9$ stars lie in a thin ($\sim$ 1/2kpc) disc of radius $\sim$ 15 kpc, with the Sun at a distance $\sim$ 8kpc from the centre. The Milky Way's disc can be seen as a faint trail of light on the night sky, while the other visible stars are not obviously part of a disc simply because they are nearby.

Other extra-solar objects which appear extended on the night sky include planetary nebulae, supernova remnants, and star clusters. Before intergalactic distances were first measured in the 1920s it was not realised that galaxies were a separate class, and both Messier's catalogue (1780, in which Andromeda is M31) and Dryers (1988) *New General Catalogue* (in which it

[1]The discs of stars on the sky can only be resolved with special techniques, and even then only for very nearby stars.

is NGC 224) make no distinction between galaxies and these other 'nebulae'. Emmanuel Kant was one of the first to suggest that galaxies were other Milky Ways. The study of galaxies therefore only started in the 20th century, and we now know that the observable Universe contains $\sim 10^{11}$ galaxies more massive than the Milky Way. Surveys of galaxies routinely catalogue properties of millions of galaxies, with the planned EUCLID mission aiming at detecting 2 billion galaxies.

1.2 Galaxy classification (*CO §25.1*)

Optical light from normal galaxies is produced predominantly by stars. Luminosities of stars vary widely. The luminosity, L, of a main sequence star depends on its mass, M, approximately as $L \propto M^\alpha$, with $\alpha \approx 3$, hence a single $100M_\odot$ star outshines $\sim 10^6$ solar-mass stars. For given M, L depends strongly on the phase of stellar evolution, with giant and asymptotic giant branch stars *much* more luminous than their main sequence progenitors. In conclusion, we expect that the observed luminosity of a galaxy will be dominated by giants and massive main sequence stars.

1.2.1 Galaxy observables

- *Luminosity, L* Total luminosity of all stars combined.
- *Spectrum* The spectrum of a galaxy is the combined spectrum of all of its stars, weighted by their luminosity.
- *Colour* A measure of the fraction of light emitted in long versus short wavelengths. *True colour* images of galaxies[2] are made by combining photographs of the galaxy taken through standard broad-band filters (see observational techniques), and mapping these to RGB colours of screen/projector or printer. Since massive stars are young, hot and blue, galaxies which contain massive stars will tend to be bluer than those without them.
- *Extent* The angle the galaxy extends on the sky.

[2]Sometimes narrow-band filters are used to stress the presence of particular emission lines, for example the Hα hydrogen emission line produced in star-forming regions.

- *Flux, F* Just as for stars, the flux F of a galaxy with luminosity L at distance d is $F = L/4\pi d^2$, and is usually expressed using a system of magnitudes. Whereas L is an intrinsic property of the galaxy, F additionally depends on the distance to the observer.

- *Surface brightness and intensity* Approximate a galaxy as a slab of stars, with surface density σ (in stars per unit area), each of identical luminosity L. The total luminosity $d\mathcal{L}$ of an area dS of this galaxy is $d\mathcal{L} = \sigma L\, dS$. The *intensity* I is the luminosity per unit area, therefore $I = d\mathcal{L}/dS = \sigma L$ for a slab. It is an intrinsic quantity, *i.e.* it does not depend on the distance to the observer. The flux dF an observer at distance d receives from this surface area is

$$\begin{aligned} dF &= \frac{d\mathcal{L}}{4\pi d^2} \\ &= \frac{\sigma L dS}{4\pi d^2} \\ &= \frac{I}{4\pi}\, d\Omega\,. \end{aligned} \tag{1.1}$$

Here, $d\Omega = dS/d^2$ is the solid angle the surface area dS extends on the sky. The quantity $dF/d\Omega = I/4\pi$, the flux received per unit solid angle, is called the *surface brightness*,

$$\text{Surface brightness} = \frac{dF}{d\Omega} = \frac{I}{4\pi}\,. \tag{1.2}$$

Note that it is independent of distance[3]. Since σ decreases with radius r from the centre, surface brightness is higher in the centre than in the outskirts. Surface brightness is usually expressed in magnitudes per square arc seconds but this is not correct. What is meant is that one has converted the flux dF, measured in a solid angle of 1 square arc seconds, into magnitudes.

1.2.2 Galaxy types

Images of galaxies immediately show there are two types, called *elliptical* (E, also called early type, or spheroidal) and *spiral* S, also called disc type, or

[3]This is only true for nearby galaxies with redshift $z \ll 1$. When z is not $\ll 1$, surface brightness dims with redshift $\propto 1/(1+z)^4$ (see my cosmology lecture notes), but this falls outside the scope of this course on nearby galaxies.

late type. Large galaxies that do not fit into either category have usually undergone a recent violent collision, and most small galaxies are of type *irregular*.

Defining characteristics for E and S galaxies are

	Elliptical	Spiral
Shape	spheroidal	most stars in a disc
Colour	red	blue
Stars	old stars	old and young stars
ISM	little gas or dust	gas and dust
Stellar Dynamics	large random motions (hot)	circular orbits (cold)
Environment	dense (clusters)	low density (groups and field)

Ellipticals Isophotes (lines of constant surface brightness) of Es are smooth and elliptical and are further classified as En, where $n = 10(1 - b/a)$, where a and b are the major and minor axis of the isophotes, respectively. A round elliptical ($a = b$) is type E0, whereas the most flattened ellipticals, E7, have $b = 0.3a$. There is little evidence for rotation in elliptical galaxies (except may be small ellipticals), so their flattening is not due to angular momentum. The intrinsic (as opposed to projected) shapes of Es are thought to be triaxial, with iso-density contours $a > b > c$.

Spirals The very thin flattened disc of spirals galaxies is due to rotation, and the stars in the disc are on nearly circular orbits around the galaxy's centre. Gas collects in Giant Molecular Clouds in the spiral arms of discss, where some fraction collapses into new stars. The massive, newly formed stars ionise their natal gas, and such HII regions of ionised hydrogen follow the arms as beads on a string. Once the cloud is dispersed, the blue light of these stars contributes to making the whole spiral appear blue, in contrast to the yellow/red light emitted by the older stars in Es. Spirals also contain dust which causes dark bands across the disc as the dust obscures background stars. The presence of dust prevents us from seeing the Milky Way's central bulge in visible light. The *bulge* is the central spheroidal stellar system, with many properties in common with elliptical galaxies. Spirals are further divides as Sa to Sc, where along the sequence the ratio of bulge-to-disc luminosity decreases, and the spiral arms become more loosely wound.

Some spirals also contain a *bar*, an almost rectangular stellar system in the disc, sticking-out of the bulge. These are designated as SB. So for example, an SBc galaxy is a barred (B) spiral (S), with loosely wound spiral arms and a small bulge (c), where an Sa has no bar, and a big bulge. The Milky Way is between types SBb and SBc, Andromeda is type Sb.

Hubble's classification

Hubble used the above classification ordering galaxies in a tuning fork diagram called the Hubble Sequence (Fig. 1.1). The commonly used nomenclature of early types (for Es) and late types (for Ss) comes from the mistaken belief that Es evolve in Ss.

The range in physical scales of Es is huge, from masses as little[4] as $10^7 M_\odot$ to as much as $10^{13} M_\odot$, with linear sizes ranging from a a fraction of a kpc to hundreds of kpc. In contrast, spirals tend to be more homogeneous, with masses 10^9–$10^{12} M_\odot$, and disc diameters from 5 to 30 kpc or so.

cDs and S0s are unusual types of Es and Ss, respectively. cDs are very large ellipticals, found in the centres of clusters, with a faint but very large outer halo of stars[5]. S0s (or SB0 when barred) or lenticulars are the divide in Hubble's sequence between E and S, they have discs without gas or dust, and no recent star formation.

Most small galaxies like *e.g.* one of our nearest neighbours, the Small Magellanic Cloud or SMC, have no well defined disc, nor a spheroidal distribution of stars, and hence are neither of type E nor S, they are classified as type *Irregular*. The two main types of galaxies are then elliptical and spiral, with most small galaxies being irregulars.

1.3 Summary

After having studied this lecture, you should be able to

- Describe the Hubble Sequence
- Describe the main galaxy types, Es and Ss, and list five defining characteristics

[4]It has been suggested that globular clusters are small ellipticals and should represent the low-mass end.

[5]cD refers to properties of the spectrum, but think of it as standing for **c**entral **D**ominant.

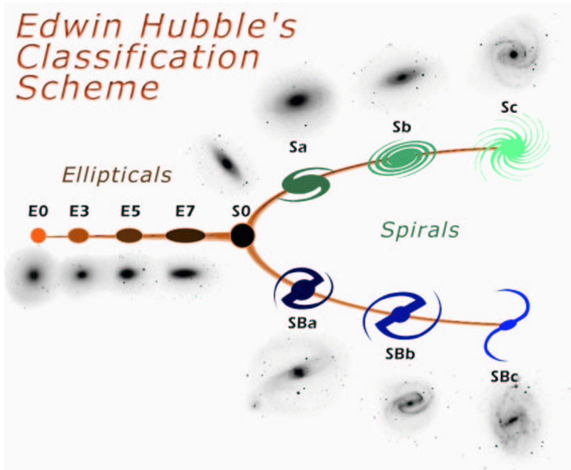

Figure 1.1: The Hubble sequence.

- Define surface brightness, and show it to be independent of distance
- Derive the relation between the surface density of stars in a galaxy, and its surface brightness

Chapter 2

The discovery of the Milky Way and of other galaxies

CO §25.1

Before distances to galaxies were measured, their nature and that of the Milky Way itself, was unclear. One suggestion was that nebulae were related to stellar evolution - maybe proto-stellar systems? Observations gave contradictory results, with star counts suggesting the Sun was near the centre of the Milky Way, while globular clusters observations suggested it was not. This chapter discussed the reasons of the confusion and how all was finally resolved.

2.1 The main observables

Star clusters

- *Globular clusters* (GCs) are small ($\sim$1pc) dense concentrations of $10^5 - 10^6$ stars of low-mass, old stars. Most galaxies contain 10s to 1000s of GCs, spherically distributed around their centres; the MW galaxy has about 150 GCs. How and where these systems form is not well known, even today.
- *Open clusters* contain typically 10^4 stars, are much less dense than GCs, and are restricted to the galactic plane. They are gravitationally bound systems left-over after star formation has ceased in a Giant Molecular

Cloud, and the remaining gas has been dispersed. They are of crucial importance for testing theories of stellar evolution: since their stars are thought to be coeval, any differences in properties should be a consequence of differences in initial mass.

Star counts (CO p.878)

Star counts can probe the number density of stars in a stellar system, as a function of position. William and Caroline Herschel, brother and sister, counted the numbers of stars as function of their magnitude in $\sim$ 700 directions in the sky. Such counts can tell us about the distribution of stars around the Sun - and hence the shape of the MW galaxy, as follows.

Suppose for simplicity that all stars have the same luminosity, L. The flux of a star, $F = L/4\pi r^2$. Because we assumed L is the same for every star, the flux received from a star only depends on its distance - hence counting the number of stars as a function of flux is equivalent to counting the number of stars as a function of distance.

Let the number density of stars at distance r in direction $\hat{\Omega}$ be $n(r, \hat{\Omega})$. Using the relation between F and r, means that the the number of stars with flux between F and $F + dF$ in that direction, is

$$\begin{aligned} dN(F, \hat{\Omega}) &= n(r, \hat{\Omega}) r^2 dr\, d\Omega \\ &= -\frac{1}{2}\, n(F, \hat{\Omega})\, (\frac{L}{4\pi})^{3/2}\, F^{-5/2}\, dF\, d\Omega\,. \end{aligned} \tag{2.1}$$

Therefore counting $dN(F)$ allows one to infer the density $n(r)$. Curiously - the answer the Herschel's found for $n(r, \hat{\Omega})$ was (very) wrong.

Parallax

Nearby stars appear to move with respect to more distant stars as Earth moves around the Sun. The angular extent of the excursion, θ, depends on the Earth-Sun distance and the distance to the star. Measuring θ gives a *parallax* distance to the star. A star at 1pc distance has by definition a yearly parallax of 2 arcsec. The name 'parsec' (pc) derives from **par**allax of one **sec**ond of arc.

Standard candles

Standard candles are objects with a known intrinsic property, for example a known size, or known luminosity. If the luminosity L is know, measuring the flux F yields the distance to the object. If the (physical) size is known, measuring the angular extent yields the distance to the object.

Cepheid variables are an important example. Henrietta Leavitt studied variable stars in the Magellanic Cloud in 1912. She recognised that the flux of some of the variable stars varied with a very characteristic pattern which was periodic in time. She realised that there was a simple relation between the (mean) flux of these stars and this period. Since all these stars are at (nearly) the same distance (namely the distance Earth-LMC), she realised that such 'Cepheid variables' follow a period-luminosity relation. The importance of her discovery for astronomy can hardly be overstated. They are *standard candles* because observationally we can measure P as well as F. The $P - L$ relation yields L from the emasured P, and the combination of L and F yields r, the distance. Parallax measurements to nearby Cepheids are required to calibrate the relation.

Parallax and Cepheid variables are therefore the first two steps in establishing the *distance ladder*, which use one method (e.g. parallax) to calibrate another distance measure (e.g. Cepheids), that then can be used to calibrate another distance indicator, and so on to ever greater distances. One of the key science goals for the *Hubble Space Telescope* was to detected the periods and fluxes of Cepheid variables in the nearby Virgo cluster (see the later chapter on clusters), in order to get an accurate measurement of the local Hubble constant (even today one of the most accurate measurements of H_0)

2.2 Discovery of the structure of the Milky Way (CO p 875)

Star counts

Jacobus Kapteyn confirmed in the beginning of the 20th century using photographic plates the star count results obtained by peering by eye through a telescope by the Herschels. The conclusion from these counts is that the MW is a flattened elliptical system, with stellar density n decreasing away from the centre. n drops to half its central value at 150pc perpendicular to the MW plane, and 800pc in the galactic plane. The Sun is at 650pc from the centre. Although the star counts are correct, the interpretation to the shape of the MW and the position of the Sun are wrong.

The conversion from F to r, for given L, assumes $F \propto 1/r^2$, which neglects possible absorption of the light on route (think of a grey day, when clouds absorb a lot of Sun light). Kapteyn realised this, but how can one test whether absorption is important? A plausible source of absorption is light scattering off atoms or molecules along the line of sight (Rayleigh scattering). The strength of scattering is colour dependent (stronger for shorter wavelengths): scattering of Sun light off molecules in the atmosphere makes the sky appear blue. Therefore if this were important, distant (hence fainter) stars should appear redder than more nearby stars. Kapteyn did measure such 'reddening' yet the amount was too small for dimming due to absorption to strongly affect the interpretation of the star counts.

However the reddening is not due to scattering off atoms, but due to scattering off *dust* (Tyndall scattering). Although this *also* reddens the light (because more blue light is absorbed by dust than red light) the amount of reddening is less than for Rayleigh scattering. Therefore the small amount of reddening detected implies a *large* amount of dimming of distant stars - and hence the interpretation of the star counts was significantly wrong.

Globular clusters

Harlow Shapley estimated the distances to the MW's brightest globular clusters using their RR Lyrae variables, and found they were not centred around the Sun, but around a point 15kpc away in the direction of Sagittarius. This implied a much bigger MW than Kapteyn's, and relegated the Sun to the MW outskirts. But who was right?

Other nebulae

Another famous Dutch astronomer, *van Maanen*, observed galaxies over several years, and decided he could see them move with respect to the stars. This must mean they are relatively nearby, certainly within the MW.

But another astronomer Slipher measured large (1000s km s^{-1}) velocities for some Nebulae, and found evidence for rotation. He also claims the light is produced by stars, not by gas. This suggests the nebulae are galaxies,

and outside of the MW, in conflict with van Maanen's and Kapteyn's MW picture.

The conflicting interpretations of data (Kapteyn: small elliptical MW with Sun near the centre, Shapley: very large system of globular clusters, with Sun far from the centre; van Maanen: nebulae are nearby, Slipher: nebulae are far away) culminated in a 'Great Debate' to try to settle the issue once and for all.

Hubble's discovery

Hubble used the 100-inch Hooker Telescope on Mount Wilson in 1919 to identify Cepheid variables in other nebulae, including Andromeda. He inferred[1] a distance of ~ 0.3 Mpc, much larger than even Shapleys size for the MW. This decisively proved that nebulae were other galaxies outside of the MW, and that the size of the MW is very large (Shapley and Slipher were right!). Hubble went on to discover that the more distant galaxies move away from us, with speed proportional to distance (Hubble's law). It is difficult to overstate the importance of this discovery. In one fell swoop, the size of the Universe increased dramatically. The Sun got relegated to the outskirts of the MW, and the MW itself was found to be just one out of billions of other galaxies. And the Universe was found to be expanding, making Einstein's attempts to build a static cosmological model out of his theory of relatively irrelevant.

Epilogue

Trumpler discovered only later, in the 1930s, what was wrong with Kapteyn's interpretation, by studying MW Open Clusters. He assumed the size of Open Clusters to be a standard candle, and hence assumed you could infer their distance from their angular size. Using this distance indicator, he found that the stars in the more distant clusters (as inferred from cluster size) were invariable much fainter than stars in more nearby clusters. He concluded that the light from distant stars was attenuated much more than expected from scattering off atoms. It had to be absorption by dust, and Kapteyn's neglect of this lead to his error in interpretation.

[1] The modern value is ~ 0.7Mpc.

Time-line

1610 Galileo resolves the MW into stars

1750 Immanual Kant suggests that some of the other Nebulae are other galaxies, similar to the MW.

end of 1700s Messier and Herschel catalogue hundreds of Nebulae. Herschel counts stars, and deduces that the Sun lies near the centre of an elliptical distribution with axes ratio 5:5:1

1900-1920 Kapteyn counts stars, decides wrongly that extinction is unimportant, and deduces the MW to be 5kpc $\times$ 5kpc $\times$ 1kpc big, with the Sun at 650pc from the centre.

1912 Leavitt discovers the $P(L)$ relation for Cepheids.

1914 Slipher measures large (1000s km s^{-1}) velocities for some Nebulae, and finds evidence for rotation. The spectra he takes suggests presence of stars, not of gas. A clear indication these are not proto-planetary structures in the MW, but other galaxies.

1915 Shapley finds the centre of the MW's globular cluster system to be far away from Kapteyn's MW centre.

1920 van Maanen claims (erroneously) that some spiral nebulae have a large proper motion, suggesting they are within the MW.

1920 Shapley and Curtis debate publicly over the size of the MW, but the matter is not settled.

1923 Hubble resolves M31 (Andromeda) into stars, using the newly commissioned 100-inch telescope. Given the large inferred distance means that M31 must be outside the MW. He also discovers Cepheids, and the distance to M31 is estimated at 300kpc. So Andromeda is indeed another galaxy.

1926 Lindblad computes that Kapteyn's MW is so small, it cannot gravitationally bind its Globular Clusters. But Shapley's much bigger MW could.

1927 Jan Oort shows that several aspects of the local motion of stars can nicely be explained if the Sun (and the other nearby stars), is on a nearly circular motion around a position 12kpc away in the direction of Sagittarius. Nearly the same position as found by Shapley, and implying a much larger MW than Kapteyn's.

1927 larger MW picture, where many of the nebulae are extra-galactic MWs, gains general acceptance.

1929 Hubble discovers his expansion law. His derived value is a factor of 10 too large!

1930 Trumpler uses open clusters to show the importance of extinction, and explains why Kapteyn's measurement were faulty

1930-35 Hubble's new data confirm the modern picture of galaxies, and demonstrates van Maanen's measurements must have been wrong.

2.3 Absorption and reddening (CO p.878)

Consider a light ray of intensity I traversing a space containing very large dust grains (bricks). The bricks will absorb a fraction of the incoming light, and the intensity of the ray will decrease as

$$\frac{dI}{dr} = -A\, I\,, \tag{2.2}$$

which expresses the fact that each distance dr will absorb a constant *fraction* $dI/I = -A\, dr$ of the light. The constant A depends on the number density of bricks, and their size.

The solution to this equation is

$$I(r) = I_0\, \exp(-Ar)\,. \tag{2.3}$$

In terms of magnitudes, $\Delta m = -2.5 \log(I/I_0) = \hat{A}\, r$, where the relation between $\hat{A}$ and A is left to the reader (you!). $\hat{A}$ therefore has units of magnitude per unit length. Absorption therefore changes the usual relation $(m - M) = 5\log(r) - 5$ between apparent and absolute magnitude to $(m - M) = 5\log(r) - 5 + \hat{A}\, r$.

If the size of the particles is of order of the wavelength λ of the light, then the value of A will be wavelength dependent. This leads to reddening of the star, since smaller wavelengths (blue light) will be absorbed more strongly than longer wavelengths (red light).

If we apply this reasoning to light in the B versus V band, for example, we obtain

$$\begin{aligned}
(m-M)_\mathrm{B} &= 5\log(r) - 5 + A_\mathrm{B}\, r \\
(m-M)_\mathrm{V} &= 5\log(r) - 5 + A_\mathrm{V}\, r \\
E_\mathrm{B-V} &\equiv (m_\mathrm{B} - m_\mathrm{V}) - (M_\mathrm{B} - M_\mathrm{V}) = (A_\mathrm{B} - A_\mathrm{V})\, r\,. \qquad (2.4)
\end{aligned}$$

The quantity $E_\mathrm{B-V}$ is called the *colour excess*, note that it is the difference between the observed and intrinsic colour of the star,

$$E_\mathrm{B-V} = (\mathrm{B}-\mathrm{V})_\mathrm{observed} - (\mathrm{B}-\mathrm{V})_\mathrm{intrinsic}\,. \qquad (2.5)$$

Trumpler's measurements, and also laboratory measurements, show that for interstellar dust grains

$$E_\mathrm{B-V} \approx \frac{1}{3} A_\mathrm{V}\, r\,. \qquad (2.6)$$

This is a crucial result. Reddening and hence $E_\mathrm{B-V}$, is easy to measure, and so if we do this for stars of known distance, we find[2] $A_\mathrm{V} \approx 1\mathrm{mag\,kpc}^{-1}$. If we now measure $E_\mathrm{B-V}$ for another star of *known* colour (from stellar evolutionary models say) we can estimate r.

[2]The amount of dust is not the same everywhere: there are regions where the absorption is much stronger, not surprisingly called dark clouds, and some directions along which the absorption is much less, a well known direction is called Baade's window.