Lecture 1:
Historical Introduction

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1 The dawn of Extragalactic research

While galaxies external to our own Milky Way have been observed for many centuries – the Magellenic Clouds and the Andromeda Galaxy are all easily observable with the naked eye – it wasn't until the bulding of the 100-inch telescope (i.e., ≈ 2.5 m diameter aperture) on Mt Wilson in 1917 that they were systematically studied. This was the first fully steerable large telescope and was immediately put to use to study galaxies external to our own.

At the time the 100-inch was built, debate still raged over whether galaxies – then referred to as "spiral nebulae" – were internal or extenal to the Milky Way. Edwin Hubble used the 100-inch to make the first distance measurements to these galaxies. He did this by using Cepheid variables, whose peak intrinsic luminosities are known to be tightly related to the period of their variation. By measuring the period of Cepheid variables, Hubble was able to calculate their intrinsic luminosity (L), and by measuring their peak flux (F) was able to determine their distance (r) using:

$$F = \frac{L}{4\pi d^2} \tag{1}$$

In 1924, Hubble published his results which demonstrated that the galaxy NGC 6822 lies at a distance of 214 kpc (7×10^5 light years; it is now known to be even more distant: 500 kpc) – well beyond the most distant of stars in our Milky Way – thus confirming its extragalactic nature.

Hubble continued his study of these (now confirmed) external galaxies, calculating the distances to many others. He also measured the velocity (v) at which these galaxies are moving away or toward the Milky Way by measuring the shift of emission/absorption lines in their spectra. In his 1929 study, Hubble reported that:

1. the vast majority of the galaxies he studied are *receding* from the Milky Way, i.e., have *redshifted* spectral lines; and

2. their velocity is proportional to their distance from us.

These two points have profound implications when combined with the Extended Copernican Principle (i.e., we – here meaning the Milky Way – hold no special place in the Universe). They imply that, no matter where you are in the Universe, (almost) all other galaxies will be receding from you at a velocity that is proportional to its distance from you. The only way this can be the case is if the Universe is expanding in all directions. Thus, this was the first clear sign that the Universe originated in a Big Bang (although it's not conclusive proof).

A further, perhaps more practical (but no less important) use of Hubble's 1929 result is that we no longer have to tediously measure the periods of Cepheids to measure distances to galaxies. Instead, we can make the far easier measurement of the galaxy's receding velocity (v) from its redshift (recall redshift: $z \approx v/c$ when $v \ll c$) and use Hubble's relation calculate the distance (r):

$$d = H_0 v \tag{2}$$

where H_0 is Hubble's constant, which is currently measured to be $67.6^{+0.7}_{-0.6}$ km s^{-1} Mpc^{-1}.

2 Extragalactic research today

Hubble conducted his groundbreaking research by studying just a handful of galaxies. Today, telescope surveys of the night sky have identified hundreds of millions of galaxies (of the trillions that are contained within the observable Universe). These galaxies display a vast diversity of shapes, masses, luminosities, stellar ages, metallicities etc. and reside in environments ranging from dense superclusters to isolated voids. The main goal of extragalactic research is to explain this huge diversity in galaxy parameters and the correlations between them.

3 What we need to explain

While a glance at a field of galaxies may give the impression that their properties are randomly distributed, there is, in fact, quite a lot of underlying order and a number of correlations between their various physical parameters. Much of extragalactic research is focussed on explaining what causes this order. Below, I briefly highlight some of the key properties of galaxies that we need to explain. We will consider each of these in more detail throughout the course.

- **Morphologies:** Perhaps the most obvious feature of galaxies is their shape, whether spiral, elliptical or irregular. But, why do galaxies have different shapes? Why aren't they all the same shape? And why those particular shapes? Why not cubes, pyramids, or dog-shaped?

- **Luminosity function:** Not all galaxies have the same luminosities. When we produce a histogram of galaxy luminosities – known as the galaxy *luminosity function* – we find that there are far more low luminosity galaxies than high luminosity galaxies. Furthermore, the galaxy luminosity function follows a characteristic shape, known as a Schechter function. Why don't all galaxies have the same luminosity? Why are there more low luminosity galaxies than high luminosity galaxies? And what causes the specific shape of the luminosity function?

- **Stellar populations:** Different galaxies are made up of different mixes of stellar populations. Furthermore, the mix of stellar populations depends strongly on the type of galaxy, with elliptical galaxies tending to have old, metal-rich populations, while spiral galaxies typically having younger stellar populations. Why don't all galaxies have the same mix of old and yound stars? And why do different types of galaxy contain different proportions of old and young stars?

- **Scaling relations:** As well as the link between stellar populations and galaxy morphologies, a number of other correlations exist between various galaxy properties. For example, there exists a tight correlation between the rotational velocity and the luminosity of spiral galaxies

(Tully-Fisher relation). There is a similar relationship between luminosity and velocity dispersion for Elliptical galaxies. Also, the colour of ellipticals (literally, whether they are bluer or redder) is also correlated with luminosity. There even exists a tight correlation between mass of the supermassive black hole that reside at the centres of galaxies, and the mass of their host bulges. Why aren't the various properies of galaxies simply randomly distributed amongst each other? What causes these correlations to exists?

- **Clustering:** Galaxies are not distributed evenly in space. Instead, they clump together in superclusters, clusters and groups. Furthermore, various galaxy properties are related to their cluster environment with, for example, large ellipticals preferring high density regions. Why do galaxies clump together? Why are they distributed in the way they are? And why do their various physical properties correlate with environment?

And all that is simply for today's galaxies! We can also ask how all of these different properties and correlations were different at different epochs of the Universe, to almost 13.6 billion years ago.

4 Studying galaxy evolution

If we wish to explain the physical properties of today's galaxies, it is important that we understand how they have evolved to their present state. There are two key means of achieving this:

- **The fossil approach:** Examining the detailed structures, stellar populations, abundance patterns of galaxies in the local Universe. For example, piecing together the star-formation histories of different galaxies to determine when their stars were put in place.

- **The high redshift approach:** Examining the properties of distant galaxies as a function of redshift/lookback time.

The high redshift approach works because of the finite speed of light. As we look to increasingly distant objects, the light from those objects has been travelling for longer and longer times. We therefore see those objects as they were when they emitted their light. For example, we see the Sun as it was about 8 minutes ago; the nearest star as it was about 4 years ago; the most distant stars in our galaxy at they were a few 10,000 years ago; the Andromeda galaxy as it was about 2.5 million years ago; the most distant galaxies as they were about 13 billion years ago.

If we can find galaxies in the distant Universe that we *believe* will evolve into the types of galaxies that we see today, then by studying those distant galaxies we gain insights into what today's galaxies likely looked like at earlier times. For example, we see that galaxies in the distant (and therefore early) Universe tend to form stars more rapidly than nearby (i.e., today's) galaxies. So, unless we live in a very peculiar region of the Universe, it is highly likely that nearby galaxies – including the Milky Way – went through an episode of rapid star-formation at earlier times. As it turns out, this is backed-up by the fossil record of nearby galaxies.

5 Evidence of galaxy evolution

There are a number of key pieces of evidence indicating that galaxies have evolved significantly over the past 13 billion years. Most of these have been established over the past half-century or so, and I briefly describe some of them below. First, however, we'll consider a philosophical argument that has been offered as evidence of an evolving Universe for almost 200 years.

5.1 Olber's paradox

Olber's paradox concerns the question of why the sky is dark. At first, it may seem obvious why the sky is dark. However, if the Universe is infinite in both size and age (and contains a roughly constant density of stars/galaxies), then the night sky should be bright.

This can be explained if we consider a square patch of sky say, 1 degree-by-1 degree. There will be very few "nearby" stars – at, say distance r – in this small patch, but because they are nearby, they will appear bright. As we increase r, the number of stars within that patch increases as r^2, but their individual brightness drops off as r^2. So, the sum of the light ($F_{\rm Tot}$) from all the N ($\propto r^2$) stars in the patch at a given r is constant:

$$F_{\rm Tot} = \sum_{i=0}^{N} \frac{L_i}{4\pi r^2} = N\frac{\bar{L}}{4\pi r^2} = Cr^2\frac{\bar{L}}{4\pi r^2} = k\bar{L} \tag{3}$$

where C is a constant of proportionality, $k = C/4\pi$ and $\bar{L}$ is the average luminosity (L) of the stars. Note that the second step comes from the definition of an average:

$$\bar{L} = \frac{\sum_{i=0}^{N} L_i}{N} \tag{4}$$

In theory, if we sum over all r in an *infinite* Universe, then we get an infinite amount of light in the patch. In practice, however, stars will start to block each other out, so in fact the whole sky will have the same surface brightness as a typical star. As such, if the Universe were infinite in age and size, we should expect the night sky to have about as the same surface brightness as the surface of the Sun! This paradox is solved if the Universe is either finite in size, age and/or evolving.[1]

5.2 Quasar number counts

Quasars are extremely bright, point-like astronomical objects. They are the brightest non-transient objects in the observable Universe. They are now known to be powered by matter accreting onto a supermassive black hole at the centre of a galaxy. Because of their extremely high luminosities, we can detect them from across the whole of the observable Universe. Indeed, for a long time, they were the most distant observable objects.

We will cover Quasars in a lot more detail later in the course. For now, it is suffice to say that because of their brightness, they provided our first insights into the very distant – and thus early – Universe. In doing so, they provided the first robust suggestions of an evolving Universe via their *number counts.*

Number counts are the flux equivalent of a luminosity function. Rather than a histogram of luminosities, "number count" is the term we use for a histogram of fluxes. It is somewhat more fundamental than a luminosity function, however, since it doesn't require an distance information (recall, flux, F, is simply what is measured by your telescope, whereas to calculate a luminosity we also require a distance, $L = 4\pi r^2 F$).

If the density of quasars within the Universe has remained constant with time (i.e., a non-evolving Universe), it is fairly easy to predict the numbers of quasars there should be within a given flux range (i.e., their number count). To do this, we'll use calculus to sum the number of

[1] If you're doing PHY406, this is just an alternative way to describe the same Olber's Paradox presented in that module.

quasars with a given observed flux, F, throughout the entire Universe. Consider a thin spherical shell of the Universe with radius r and thickness dr. The number of quasars, dN with *observed* flux F within this shell is:

$$dN = \rho(L) \times 4\pi r^2 dr \tag{5}$$

where $\rho(L)$ is the number of quasars of luminosity L per unit volume (i.e., this is the quasar luminosity function). However, to observe a flux F from a quasar of luminosity L, then r *must* be given by:

$$r = \sqrt{\frac{L}{4\pi F}} \tag{6}$$

Subbing this into Eqn. 5 gives:

$$dN = \rho(L)\frac{L}{F}dr \tag{7}$$

To integrate this to get N – the total number of quasars of observed flux F in *all* shells – we need to re-write dr in terms of dL and F by differentiating Eqn. 6:

$$\frac{dr}{dL} = \frac{1}{2}\frac{1}{\sqrt{4\pi LF}} \tag{8}$$

Subbing dr from Eqn. 8 into Eqn. 7 gives:

$$dN = \frac{1}{2}\frac{1}{\sqrt{4\pi}}\rho(L)\frac{L^{\frac{1}{2}}}{F^{\frac{3}{2}}}dL \tag{9}$$

Integrating both sides from $L = 0$ to $L = \infty$ (corresponding to $r = 0$ to $r = \infty$), and taking all non-L terms out of the integral, gives:

$$N = \frac{1}{4\sqrt{\pi}}F^{-\frac{3}{2}}\int_0^\infty \rho(L)L^{\frac{1}{2}}dL \tag{10}$$

and since it's a definite integral, it just integrates to a constant, irrespective of the form of $\rho(L)$ (provided that $\rho(L)$ is non-evolving, and thus independent of r), leaving:

$$N \propto F^{-\frac{3}{2}} \tag{11}$$

So, if the number density of quasars of a given L (i.e., the *luminosity function*, $\rho(L)$) does not evolve, then the number detected with a given flux, F, is proportional to $F^{-\frac{3}{2}}$. Usually, however, astronomers consider *differential* number counts:

$$\frac{dN}{dF} \propto F^{-\frac{5}{2}} \tag{12}$$

When we plot the actual numbers of *observed* quasars as a function of flux, we find that these numbers deviate significantly from a $F^{-\frac{3}{2}}$ law. The actual interpretation of this is not straight forward without further information (including the redshift distribution of the quasars), but it does imply that the quasar population *must* have evolved over the history of the Universe.

5.3 The "V over V_{Max}" test

Later, more formal methodologies were adopted to test for an evolving galaxy population. One of the first of these was the V/V_{Max} test.

Consider a galaxy of luminosity L, detected in a galaxy survey with flux F and measured to have a distance from us of r (corresponding to a volume $V = \frac{4}{3}\pi r^3$). Lets say that the very lowest flux we can detect with our survey is F_{Min} (so, by definition $F > F_{\mathrm{Min}}$). So, the very furthest away *we could have* detected that galaxy (of luminosity L) is therefore:

$$r_{\mathrm{Max}} = \sqrt{\frac{L}{4\pi F_{\mathrm{Min}}}} \tag{13}$$

corresponding to a limiting volume of:

$$V_{\mathrm{Max}} = \frac{4}{3}\pi r_{\mathrm{Max}}^3 \tag{14}$$

So, for every galaxy in our survey we can calculate a V/V_{Max} value. In a non-evolving Universe, we would expect all galaxies to be evenly distributed, so:

$$\left\langle \frac{V}{V_{\mathrm{Max}}} \right\rangle = 0.5 \tag{15}$$

since, on average, we'd expect half of all galaxies to be within $\frac{V_{\mathrm{max}}}{2}$ and the other half to be between $\frac{V_{\mathrm{max}}}{2}$ and V_{Max}. However, what we actually find is that $V/V_{\mathrm{Max}} > 0.5$ for the most luminous galaxies. This would only happen if there were a higher density of luminous galaxies close to the edge of the survey volume (i.e., close to r_{Max}), meaning their individual V/V_{Max} values are greater than 0.5. This result therefore implies there was a higher density of luminous galaxies in the distant, i.e., early, Universe compared to today.

5.4 Quasar luminosity function

As our ability to measure redshifts improved, we gathered distances for increasing numbers of quasars. With this information, astronomers were able to measure their luminosities and, in turn, determine the quasar luminosity function at different epochs. In doing so, they found that the luminosity function of quasars was, indeed, different at earlier epochs, thereby confirming the results inferred from quasar number counts. Again, it was found that the density of quasars was higher in the early Universe compared to today.

5.5 Butcher-Oemler effect

In 1978, Butcher and Oemler published a paper in which they had measured the colours of galaxies in two distant clusters of galaxies, one at redshift 0.39 (corresponding to 4.2 billion years ago) and another at redshift 0.46 (corresponding to 4.8 billion years ago). What they found was that there were a higher fraction of blue galaxies in the cores of the distant clusters compared to similar clusters in the local Universe (i.e., today). Blue colours in galaxies are normally associated with ongoing star-formation, so this result was interpreted as evidence of increased levels of star-formation in cluster cores in the early Universe compared to today. While at the time, they didn't know why this was the case (we've got a better idea now; see later lectures), it was clear evidence that galaxy clusters were different at earlier times; i.e., they have evolved.

5.6 Galaxy number counts

As telescopes grew in size and detectors became more senstive, astronomers were able to start detecting fainter and fainter *galaxies*, rather than just very bright quasars. As they reached the faintest galaxies – some of which will low luminosity, nearby galaxies, but most will be very distant, luminous galaxies – they found that their number counts were *not* consistent with a non-evolving Universe. Instead, they could only match the observed counts of faint galaxies if the density of blue, star-forming galaxies was higher in the early Universe compared to today.

6 Key learning objectives for L1

- What two groundbreaking discoveries did Hubble make that changed our understanding of galaxies and the Universe?
- List and understand the five key properties of galaxy populations that we need to explain.
- Know what the terms "luminosity function" and "number counts" refer to, and know the difference between them.
- Know, in general terms, what a quasar is and understand their importance to early investigations of galaxy evolution.
- Understand why studying distant galaxies and quasars can provide insights into the early Universe.
- Know what is meant by the "fossil approach" and the "high redshift approach".
- Be able to explain Olber's paradox.
- Know the five key pieces of evidence of galaxy evolution prior to the mid-nineties.