Lecture 2:
Challenges and recent advances

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1 Introduction

In the last lecture, we saw how we could exploit "lookback" time to gain a view of the Universe as it was at earlier times. In other words, using our telescopes effectively as a "time-machine" to look into the Universe's past. Unfortunately, it's not quite as easy as this, and in this lecture we'll cover how observing over such vast distances hampers our attempts to study galaxy evolution.

Unfortunately, the material in this lecture is a bit "dry", but it's really important that you understand it to grasp the caveats of our understanding of galaxy evolution. I'll try my best to make it interesting.

2 The challenges of studying the distant Universe

In this section, we'll cover the main difficulties we face in using observations of the distant Universe to study galaxy evolution. In the following section, we will cover how astronomers are overcoming these problems (although some will never be solved entirely).

2.1 Dimming with redshift

The first, most prominent and most obvious challenge in studying the distant (i.e., high redshift) Universe is that all sources are subject to geometrical dilution. In other words, the more distant an object, the fainter it appears. In a geometrically flat (i.e., Euclidian) Universe, all sources will dim at a rate of $1/d^2$ with increasing distance d. This is because as light travels from a source, it gets "shared-out" over a spherical surface with area $4\pi d^2$, so there's less light per unit area as d increases.

In addition to "classical" geometric dilution, at high redshifts other factors start to have a detrimental effect. Because distant galaxies are travelling away from us at high velocities, their photons are redshifted and thus reduced in energy by a factor of $1/(1+z)$ (where z is the measured redshift). Also, because of time dilation, photons from a distant galaxy arrive more slowly by *another* factor of $1/(1+z)$. So the energy per unit time per unit area (i.e., flux) received by our telescope decreases by a factor of $1/4\pi d^2(1+z)^2$. This means that for a galaxy at $z = 2$, its flux is almost a factor of *9 times* lower than what we'd expect from classical geometric dilution!

Things get even more strange (and worse!) when we consider how the *surface brightness* of a galaxy (i.e., the measured flux per unit area) changes with redshift. This is because angular distance also has a $1/(1+z)$ dependence (proving this within the realm of cosmology, so is beyond the scope of this course). What this ultimately means is that the surface brightness of a galaxy decresease as $1/4\pi d^2(1+z)^4$. This means that the surface brightness of a resolved galaxy at $z = 2$ is *81 times* times lower than what we'd expect from classical geometric dilution of an unresolved source!

Together, this all means that distant galaxies *are even fainter than you'd expect*, which makes studying them in a systematic, robust manner *incredibly* hard.

2.2 The K-correction

Another difficulty associated with observing distant galaxies is literally caused by the redshifting of light due to their high receding velocities.

Imagine you wish to compare the luminosities of two galaxies – one at low redshift, say $z = 0.1$, and another at $z = 2$ – in a given optical filter, let's say the r-band (i.e., around wavelength $\lambda = 658$ nm). You've been really careful to take all the above effects due to redshift dimming into account when converting their observed fluxes into luminosities. However, an additional problem is that, because of redshift, the r-band filter samples two different *rest-frame* wavelengths in the two galaxies: 658 nm$/(1 + 0.1) = 598$ nm for the $z = 0.1$ galaxy, and 658 nm$/(1 + 2) = 219$ nm. In the case of the $z = 0.1$ galaxy, you're measuring the luminosity of the rest-frame red part of its spectrum, and in the case of the $z = 2$ galaxy, you're measuring its rest-frame ultraviolet luminosity. Because galaxies tend to be quite faint in the ultraviolet, this often has the effect of making the $z = 2$ galaxy appear dimmer than if you were measuring the red part of its spectrum.

One way to account for this is to apply a *correction* to the ultraviolet luminosity you measure in the $z = 2$ galaxy – known as a *k-correction*. However, to do this, you must know the ratio of red-to-ultravoilet luminosity for the $z = 2$ galaxy. Today, this is usually achieved by observing the galaxy in multiple bands and using spectral templates to interpolate to the desired band. However, in the past, astronomers had to rely on average K-correction factors for different types of galaxies.

Alternatively, you could observed the $z = 2$ galaxy in a band centred at 598 nm $\times\ (1 + 2) =$ 1794 nm, which is in the near-infrared region of the spectrum, as it would probe the rest-frame 519 nm part of the $z = 2$ spectrum.

2.3 Morphological K-correction

One feature of the K-correction is that it can actually effect the observed *shape* of a galaxy.

Most galaxies, and especially star-forming spirals, do not contain uniforms distributions of stellar populations. Instead, spirals often contain old stellar populations in their cores, and have clumps of star-forming regions containing very young stars in their arms. Between these clumps are older stars.

Imagine we're looking at the same two galaxies as in the previous subsection – one at $z = 0.1$ and another at $z = 2$. By some amazing coincidence, it turns out that they have exactly the same intrinsic structure – spirals with an old bulge at the centre and clumps of star-formation in their arms, with populations of older stars between the clumps. For the $z = 0.1$ galaxy we can see all this structure perfectly in our optical filters: the blue filters pick up the star-forming clumps, while the red filters pick up the central bulge and the "sea" of old stars between the clumps.

For the $z = 2$ galaxy, however, the red light from the bulge and inter-clump regions is shifted into the near-infrared, so we won't see it in our optical bands. Also, because old stellar populations don't emit very strongly in the blue part of the spectrum, there won't be much light from the bulge or inter-clumps shifted into the optical-red filter. Instead, the optical-red filter will be dominated by the shifted blue light from the clumps of young stars. So, all you'll see in your blue and red filters are small clumps of star-formation, which you could mistake as lots of small galaxies (since the inter-clump and bulge are too faint to see).

The way to solve this problem is to try to observe high-redshift galaxies in longer-wavelength filters to compensate for the red-shifting of the light. Ideally, you'd like to use filters which mean you observe the same rest-frame wavelengths at different redshifts, but sometimes this isn't possible (due to technology constraints, or atmospheric absorption).

2.4 Progenitor bias

The primary aim of extragalactic research is to determine how today's galaxies got to look the way they do. The justification behind studying galaxies in the high redshift Universe is that it gives us a chance to "look back in time" at galaxies in earlier stages of development. However, it is important to remember that we aren't literally looking at today's galaxies at earlier times (that would require a time machine!). Instead, we have to try to identify those galaxies in the early Universe that we *think* will evolve into certain types of galaxies today. For example, what type of galaxy observed in the distant, early Universe will eventually evolve into the type of massive, elliptical galaxies we seen in the local Universe today (this is, indeed, a big question in current astronomy research)? This is made more difficult because the Universe (and the galaxies in it) have changed a lot over the past 13 billion years. Making the wrong assumptions about progentior galaxies can strongly bias our interpretation of observations, and thus our conclusions.

As an example, we may *think* that the most massive galaxies at $z = 2$ evolve into the most massive galaxies today. It may, however, instead be lots of smaller galaxies at $z = 2$ that merge together to form the most massive of today's galaxies. If we simply assume the first case is true, we may erroneously focus on the most massive galaxies at $z = 2$ and generate (possibly incorrect) evolution theories about how they evolve.

2.5 Cosmic variance

On very large scales (i.e., Gigaparsec scales) the Universe is very homogeneuous; i.e., a given cube 10^9 pc on its side will look the same as another. On scales of $\lesssim 100$ Mpc (Mpc=Megaparsec), however, the Universe is very much non-homogeneous, clumping into clusters and groups with large voids in between. So, a given cube a few Mpc across may contain a very dense cluster of galaxies, wheres another randomly chosen volume of the same size may contain a void.

With the properties of galaxies known to depend on the density of their environmnent (i.e., cluster, group, void), it is important that we survey large enough volumes of the Universe to ensure that we sample galaxies across a wide range of environments.

For example, if we compared galaxies in the (nearby; $z \approx 0$) Virgo supercluster against those in a small-area survey that focussed on a high-redshift void (mostly including what we call "field" galaxies), then we wouldn't be comparing like-for-like. To ensure we're comparing like-for-like, we'd need to use a larger-area survey that contained at least one high-redshift cluster.

2.6 Assumed cosmological model

This one's a bit of an odd one...

In order to convert measured fluxes into intrinsic galaxy properties such as luminosity, mass or even diameter, we need to assume a cosmological model. These cosmological models include things like the shape of the Universe and how fast it is expanding (due to dark energy).

Cosmological models are described by a set of parameters, such as the Hubble constant (H_0), the matter density parameter (Ω_m; i.e., what fraction of the Universe is mass), the dark energy density parameter (Ω_Λ; i.e., what fraction of the Universe is dark energy). One way these parameters can be determined is by "calibrating" the Hubble diagram; using independent distance measurements and comparing them against redshift. For example, if we know the intrinsic luminosity of an object and measure its flux, we can obtain a redshift-independent distance measurement.

In the past, giant elliptical galaxies were used as "standard candles"; i.e., we assumed that all giant elliptical galaxies all had the same intrinsic luminosity. So measuring their fluxes gave us a distance measurement which could then be used to determine cosmological parameters. However, if other astronomers unknowingly used these cosmological parameters to measure the luminosities of giant elliptical galaxies, then they would measure them as all being the same (i.e., it would be circular). Cue headline:

All giant elliptical galaxies are the same luminosity at all redshifts shocker!!!

This highlights that we need to be very careful in making sure that any results we obtain when comparing distant galaxies to nearby galaxies are not simply a consequence of the cosmological parameters and how they were derived.

2.7 A lack of knowledge of today's galaxies

Finally, a bit of a surprising one...

We don't actually understand today's galaxies (i.e., nearby ones) as well as we'd like to. This represents somewhat of a problem if we're trying to understand how galaxies have evolved to their present state since we don't really fully know what the "present state" is.

Bear in mind that even "local" galaxies are very distant in real terms. We can't pick them up and look at them at different angles. Some parts of them are osbcured by dust. Often we can't resolve individual stars in even nearby galaxies. And many aspects we think we do understand are actually highly dependent on uncertain models (e.g., star-formation).

As such, while we understand local galaxies better than more distant ones, the former certainly don't represent a well-defined "end point" for evolutionary studies. Indeed, should our understanding of local galaxies change dramatically, it could force a consderable rethink of our evolutionary models.

As an example, it was only very recently found that the number of dwarf galaxies around the *Milky Way* and other nearby galaxies is much lower than our evolutionary models predicted there should be. As a consequence, our galaxy-evolution models are being re-thought to try to rectify this inconsistency with the real Universe.

3 Overcoming challenges

As telescope, detector and computing technology has developed, astronomers have increasingly mitigated the above challenges. Some have even been overcome entirely.

3.1 Telescope size

Perhaps the most obviously impressive development has been the dramatic increase in telescope size over the past century, starting with the $100''$ telescope on Mount Wilson in 1919. Today's largest telescopes have mirrors 10m in diameter, and thus have 16 times the collecting area of $100''$. This has helped us to observe more distant galaxies, helping to tackle the challenge of the rapid fall off in flux of galaxies at high redshifts.

3.2 Detector technology

A huge development in astronomy occured when astronomers progressed from taking observations by eye to using photographic plates in the mid 19^{th}. Not only are photographic plates less subjective, but they all allow us to *integrate* (i.e., collect) light over longer periods of time than the eye. Photographic plate are, however, hugely inefficient, so a second revolution occured in the 1980s when astronomers started using CCDs as detectors. Although perhaps not as immediately obvious, CCD technology has had a greater impact on modern astronomy than telescope size. Modern CCDs can be more than 90 times more efficient than photographic plates (compared to a 16 times increase in telescope collecting area in the last $\sim$100 years). As a result, today's top-end *amateur* CCD-equipped telescopes can be more senstive than the $100''$ when it was equipped with photographic plates.

The other key advancement in detector technology has been the development of detectors that can measure light across almost the whole electromagnetic spectrum, from the longest wavelength radio to the highest-energy gamma rays. By being able to observe in many different wavelengths, we mitigate the problem of K-correction, since we can often use a waveband that corresponds to the appropriate rest-frame wavelength we wish to compare. There is the caveat that some wavelengths are blocked by our atmosphere, but space-based missions – while expensive – have opened up those parts of the electromagnetic spectrum.

3.3 Wide-field astronomy

As well as being able to detect fainter galaxies, telescope technology has also developed the ability to observe over wide areas. For example, the SDSS telescope has a field-of-view of about 6 square degrees. This means it can observe a whole hemisphere of the sky in about 3500 pointings. That might seem a lot, but each pointing is only viewed for about 1 minute, meaning it can survey the entire observable sky in 3500×1 minute $= 58$ hours ≈ 8 nights (that's for one filter, it has five filters in total).

Such large fields-of-view help to mitigate the "cosmic variance" problem, as it allows us to sample large volumnes of the Universe in a short time. For example, it takes only about 45 pointings (i.e., 45 minutes) for the SDSS telescope to survey a volume of 1Gpc^3 out to $z = 1$, which, as we have seen, is large enough to sample the full diversity of galaxy environments from superclusters to voids. However, the problem remains that, since the SDSS is a relatively small (2.5 m) telescope by today's standards, it will only detect the brightest galaxies at $z = 1$, and miss the faintest ones. In other words, as with any astronomical survey, it is *incomplete*.

Another major development in wide-field astronomy has been the development of multiplex spectroscopy. Early spectrographs could only take the spectrum of one object at a time by placing a single slit on the object. During the 1990s, however, multi-slit and multi-fiber systems were developed to allow astronomers to take the spectra of lots of different objects in the same field-of-view at the same time. Multi-slit systems work by placing a “slit-mask” in the field-of-view which blocks out the light from most objects, but allows the light from a few to pass through to the spectrograph. Multi-slit systems can typically take the spectra of a few tens of objects at a time, and you have to be careful of “spectral overlap” (where two slits are too close to each other and their spectra overlap). Even more advanced and capable are multi-fiber systems (as used by SDSS for its spectrographic mode), where individual fiber-optics are places at the positions of all the objects you want to take the spectra of. The light then travels down the fiber to the spectrograph. These can typically take the spectra of hundreds of objects at the same time and avoid the problem of spectral overlap by arranging the fibers on the spectrograph-end so they don’t overlap.

3.4 Independent cosmological parameters

Rather than relying on galaxies as standard candles or standard rulers, we now have galaxy-independent standards that we use to deteremine the values of cosmological parameters,

Perhaps the most well-known standard candles are Type-1a supernovae. These occur when a White Dwarf star accretes sufficient mass from an orbiting partner star (in a binary system) to ignite carbon-fusion in its core which rapidly leads to the star going supernova. The reason that we can use Type-1a supernovae as standard candles is that theory strongly suggests that their peak luminosities are always the same since they are always triggered by the same process. The other great benefit of Type-1a supernovae is that they are extremely bright, so can be oberved to high redshifts ($z \sim 2$) and thus provide a long baseline for calibration.

While Type-1a supernovae are a very good way of obtaining independent distance measurements and thus determining cosmological parameters, it is important to have other methods so we can check they are consistent. Another important independent distance measurement comes from “Baryon Acoustic Oscillations”. As the name suggests, these are regular, periodic density fluctuations in baryonic matter of the Universe; a sort of “echo” of the Big Bang. The lengh of these fluctuations is about 500 million light years and, as such, can be used as a standard ruler. We can use surveys of galaxies (since they are, of course, made of baryons) to measure the length of these fluctuations at different redshifts to get an independent distance measurement, which then leads to independent cosmological parameters.

4 Learning objectives from Lecture 2

Well, you made it! Here are the learning objectives:

- Understand the problems associated with studying the high-redshift Universe to investigate galaxy evolution.
- Understand how technological advancements have helped to mitigate some of these problems, and eradicate others.