Lecture 6:
Survey Astronomy

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1 Introduction

In the previous lecture, we learned that by studying nearby galaxies in great detail we can gain insight into how these galaxies were formed. In this lecture we'll consider the opposite approach: how surveys of thousands – or even millions – of galaxies can provide clues to their evolutionary history.

2 The philosophy of galaxy surveys

The guiding principle of extragalactic surveys is that by measuring the properties of whole populations of galaxies, we can gain insight into how they have formed and evolved. You should think of it as an alternative approach, yet highly complementary, to detailed studies of individual galaxies.

An analogy I use is studying the causes of heart disease. One way scientists can study the causes of heart disease is via dissection, i.e., the detailed study of an individual's heart to see what has caused the blockage of arteries, such as fatty build up. However, another way to investigate the causes of heart diease is to survey a large group of people – some with heart disease, others without – to assess what lifestyle choices may cause heart disease. Both are perfectly valid ways of studying the causes of heart disease and give consistent answers: that a poor diet rich in saturated fats (which causes the fatty blockaged) plays a role in causing heart disease.

The principle is the same in astronomy. For example, if the fossil record tells us that a lot of stars were put in place about 10 billion years ago, then we should see lots of strongly star-forming galaxies when we survey the Universe at $z = 2$ (corresponding to about 10 billion years ago). However, one of the great benefits of survey astronomy over the fossil record is that we can study galaxies in a statistical sense, identifying correlations and patterns that we otherwise wouldn't be able to uncover by studying just a few galaxies in detail.

2.1 What are galaxy surveys?

In the loosest terms, a galaxy survey can be described as simply a sample of galaxies that satisfies given selection criteria. For example, we could survey all the galaxies above a given stellar mass within 100 Mpc of the Milky Way. Or, we could survey all galaxies above a given luminosity limit within a given redshift.

For the purposes of this lecture, however, we will focus on "Blank-field surveys". These are samples of galaxies that are detected in flux-limited observations of a contiguous patch of sky. They are obtained by literally pointing a telescope at a blank piece of sky, making a set of obervations to a given integration time, and detecting as many galaxies as possible in that patch of sky. The sensitivity of the telescope plus the total length of integration dictates the *flux limit* of the survey.

How large a patch of sky you choose to observe, and for how long to integrate, is determined by your science goals and is known as your *survey strategy.*

3 Survey design

Due to the large amount of resources required to undertake a galaxy survey, a lot of thought goes into *designing* the survey. Things to consider are: the area and depth of the survey (i.e., the survey strategy); where to survey on the sky; what wavelength you want to survey in; is photometric data sufficient, or do we require spectroscopic information as well?

3.1 Survey strategies

As with any type of survey (election polls, consumer surveys etc), what we are ultimately trying to achieve with a blank field survey is a representative sample of galaxies. The more representative that sample is of the whole galaxy population, the better. Ideally, we'd survey the whole night sky to extremely *deep* (i.e., sensitive, in terms of flux limt) levels. However, such an approach requires an unfeasible amount of resources, especially in terms of oberving time. Thankfully, we're helped-out by the Extended Copernican Principle, since it tells us that (on large scales) "the Universe looks the same in all directions". So, to obtain a representative sample of galaxies doesn't *necessarily* require us to survey the whole sky, just a patch of sky large enough to capture the full diversity of galaxies. This is just the same as polling people: pollsters don't ask the entire voting population of the UK their opinions, but rather aim to survey a sample that is *as representative as possible* of the entire population.

But, how do astronomers decide on what "large enough" is, and how *deep* (i.e., sensitive, in terms of flux limit) their survey needs to be? That depends on what science questions you want your survey to address. Since very luminous galaxies are extremely rare, we have to survey very large *areas* of sky to obtain a representative sample; indeed, some of the most luminous galaxies and quasars are *only* seen in all-sky surveys. However, since they are very luminous, we don't need a very sensitive survey to detect them, so all-sky surveys only need to be relatively shallow to identify lots of very bright galaxies/quasars.

If, by contrast, the aim is to study more typical, less luminous galaxies, then such a large survey area isn't needed since there are lots and lots of "normal" galaxies even within a small patch of the sky. Instead, the problem is now that these galaxies are much less luminous, so require a deeper survey.

An analogy I like to help illustrate the area/depth trade off is that of pebbles on a beach. There are only a handful of very large (say >50 cm diameter) pebbles on a beach, so you'd need to look at the whole beach to get a representative sample of them. However, since they're large, they're easy to spot and study from a distance. By contrast, there are hundreds of thousands of < 1 cm diameter pebbles, so you may only need to survey 1 m^2 of beach to get a representative sample, but you'd only be able to study them in detail from a few centimeters away.

Finally, if you are interested in studying the full range of galaxy environments and large-scale structure (i.e., clusters, voids, etc.), then you'd need a wide-area survey again. This is because the

Universe is only truly homogenous on large scales, so you need a wide-area survey to cover these scales and sample all types of environment.

In summary:

- **Large area, shallow surveys:** Are good for studying rare, luminous galaxies and sampling the full range of scale structure, but less good for studying more typical, fainter galaxies.

- **Small area, deep surveys:** Are good for studying fainter, more typical galaxies, but won't contain many luminous examples, nor span the full range of galaxy environments.

Between these extremes is a wide range of trade-offs between area and depth.

3.2 Where to survey

Since the Universe is homogeneous, we should, in principle, be able to choose any patch of sky to conduct a survey on. Unfortunately, it's not as straightforward as that, and a lot of thought goes into where on the sky extragalactic surveys are conducted.

The first and foremost consideration is that the aim of extragalactic surveys is to obtain samples of galaxies *external* to our own. As such, astronomers must choose regions of the sky that are not impeded by the Milky Way in the foreground. Otherwise, the light from external galaxies would be heavily obscured by the dust (and at X-ray wavelengths, gas) within the Milky Way.

A secondary consideration is observability by our telescopes. For example, some regions of the night sky near the celestial poles can be observed continuously by the Hubble Space Telescope as it orbits the Earth, whereas other regions are, at times, blocked by the Earth. Thus, if the design of your survey requires a lot of Hubble observations, then it may be more efficient to survey a patch within the continuously-observable regions. By contrast, regions of the sky near the celestial equator can be observed by ground-based telescopes in both the Northern and Southern hemispheres, so if the design of your survey requires a lot of ground-based observations, then it may be more efficient to survey a patch closer to the celestial equator.

Over the years, a number of well-observed patches of sky have been surveyed and now there are a selection of "well-surveyed" regions that get repeatedly observed by existing and new telescopes (e.g., COSMOS, Lockman Hole, GOODS-S, GOODS-N). Since these well-observed patches of sky now have a huge amount of multiwavelength data available for them, they are frequently chosen as the go-to patches to re-survey with new telescopes.

3.3 Multiwavelength surveys

A major benefit of having a set of well-surveyed patches of sky is that we can concentrate our attention on building-up data from across the full observable electromagnetic for these regions.

For example, some of the most well-surveyed patches of sky, such as the GOODS and COSMOS fields, have been observed extensively at radio, sub-mm, infrared, optical, ultra-violet and X-ray wavelengths. As such, we can combine all this data to obtain as complete a picture as possible for the galaxies in those fields. It would be far less effective if one patch of the sky had been observed in radio wavelengths, another in the optical, and another at X-rays, for example, since we wouldn't multiwavelength coverage of the same galaxies.

The reason this is important is that different parts of the electromagnetic spectrum provide information on different physical properties of the galaxies. For example:

- *Radio*: Star formation rate (SFR), Active Galactic Nuclei (AGN) power.
- *Sub-mm*: (Obscuration-independent) SFRs, gas content, dust content.
- *Far-infrared*: (Obscuration-independent) SFRs.
- *Mid-infrared*: (Obscuration-independent) SFRs and AGN powers.
- *Near-infrared*: Stellar masses, although these are significantly more precise if we have mass-to-light ratios from the...
- *Optical*: Mass to light ratios for stellar masses, star-forming histories (from spectral synthesis), AGN power (caveat dust obscuration).
- *Ultraviolet*: SFRs (caveat dust obscuration).
- *X-rays*: AGN power (and to a lesser extent SFRs).

Thus, by having full, multiwavelength data available for detected galaxies in a survey, we can investigate how different galaxy properties relate to one another. For example, how does SFR relate to stellar mass, or is there a connection between AGN power and SFR?

The other major benefit of surveying the same patches of sky in multiple wavelengths is to overcome problems associated with k-correction, which we first came across in Lecture 1. As we observe more and more distant galaxies, their spectra get shifted further and further redward. So, by observing two galaxies at different redshifts in the same band (i.e., wavelength), we actually sample different *rest-frame* wavelengths. For example, a v-band observation of a $z = 0$ galaxy samples its rest-frame 5400Å emission, whereas observing a $z = 2$ galaxy in the same band samples rest-frame 1800Å, which complicates comparison. However, if we also survey in the H-band near-infrared wavelengths (centred at 16300Å), then this will sample the $z = 2$ galaxy at $16300/(1+2) = 5433\AA$, which is *very* close to the rest-frame v-band. This therefore allows us to compare like-for-like rest-frame v-band luminosities. By surveying at *all* observable wavelengths, it maximises that likelihood that we will be able to compare galaxies at different redshifts at the same rest-frame wavelengths.

One major drawback of multiwavelength surveys, however, is that they have different spatial resolutions. For example, the Hubble Telescope's point spread function (PSF) at optical wavelengths is < 0.1 arcseconds. By contrast, Spitzer's PSF at infrared wavelengths was as high as tens of arcseconds, meaning potentially tens of sources detected with Hubble could lie within the Spitzer PSF. Trying to figure out which of those tens of Hubble sources corresponds to a single Spitzer source is a major challenge (indeed, there could be more than one Hubble source contributing to the total Spitzer flux).

4 Biases in surveys

As with most types of survey, the goal of a blank-field galaxy surveys is to provide an unbiased sample of galaxies. However, no survey is completely unbiased, and that holds true for galaxy surveys. The dominant bias present in blank-field surveys is the flux limit of the survey. Quite simply, blank field surveys will only identify galaxies that are brighter than (i.e., have fluxes higher than) the flux limit of the survey (which depends, among other things, on the telescope sensitivity and exposure time). As such, astronomers have to be extremely careful to take this "selection bias" into account when interpreting results from blank field surveys. Astronomers often have to ask themselves: "Is that correlation we see between two parameters real, or simpy due to the flux limit of the survey?".

Such selection bias in galaxy surveys is similar to that in election polls. For example, it is well known that if pollsters rely solely on internet polls, then they will disproportionately under-represent older voters, since they tend to use the internet less than younger voters. Similarly, our blank-field surveys under-represent faint galaxies. Just as pollsters attempt to correct for biases to predict election outcomes, astronomers attempt to correct for biases in blank-field surveys.

Correcting for selection bias is particularly challenging when using data from surveys taken at multiple wavelengths. Unfortunately, reaching the same (relative) flux limits at all wavelengths is currently impossible due to cost and technological limitations. For example, today's optical telescopes are extremely sensitive, meaning we have incredibly deep survey data at optical wavelengths. By contrast, our far-infrared surveys are much shallower, largely due to the limitations introduced by requiring space-borne telescopes to observe at these wavelengths. Since infrared emission is produced by star formation, this means we are biased toward detecting strongly star-forming galaxies at infrared wavelengths. If we did not correct for this bias, we might think that *all* galaxies were strongly star-forming (when, in fact, they aren't).

5 Spectroscopic Surveys

To this point, we've only considered *photometric surveys*, i.e., taking an image of the sky in a certain waveband/frequency/photon energy. The majority of extragalactic surveys are, indeed, photometric due to the relative ease of conducting them (i.e., "point your telescope, take a picture, detect the sources"). Photometric surveys have, however, a number of significant drawbacks. In particular:

- **Photometric redshifts**: These are redshifts derived by shifting galaxy tempates (of the type used in spectral synthesis) to broad band photometric data. We'll cover these in more detail in section 6; here, it's suffice to say they're a lot less precise than spectroscopic redshifts.
- **No kinematic information**: Unlike with spectroscopy, photometric data doesn't provide any information on kinematics of galaxies (i.e., how they move, rotate, etc.)
- **Little or no information on gas physics**: Photometric data only really provides information on the combined stellar light of a galaxy (plus some information on the AGN, if a galaxy contains one). It contains very little information on the gas content of the galaxies, which is a crucial ingredient for star-formation (and thus galaxy evolution).

All of these problems can be resolved (to a greater or lesser degree) by taking the spectra of galaxies. However, until about 20 years ago, it was only really possible to take the spectrum of one galaxy at a time, which made obtain the spectra of a large sample of galaxies *very* time consuming and, thus, expensive. Recently, however, we have witnessed the rise of *spectroscopic surveys*. This is where multiple spectra of multiple galaxies (in the same field-of-view) can be obtained simultaneously, dramatically reducing the amount of time needed to obtain spectra for large samples of galaxies.

The most famous spectroscoic survey is the *Sloan Digital Sky Survey*, which has taken the spectra of over a *million* galaxies. It does this by placing fibre-optics at the positions of stars and galaxies in its field-of-fiew which carries the light down to a grating, which then disperses it onto the detector. Today, most large telescopes have some kind of such "multiplexing" capabilities (although not all are fibre-fed), meaning that many of the most well-studied "blank-field" surveys have excellent spectroscopic coverage. The main drawback of spectroscopic surveys, however, is that the targets for spectroscopic follow-up (usually) have to be pre-selected from photometric data. This means it is typically the brightest, or most "interesting", galaxies that are chosen for spectroscopic follow-up. Obviously, this introduces a bias which can be difficult to account-for.

Recently, pre-selection bias has been mitigated (to some degree) by the introduction of large-area (1-arcmin^2) Integral Field Units (IFUs), such as MUSE on the Very Large Telescope. These IFUs take the spectrum at every single point within the field-of-view, irrespective of whether there is a star or galaxy there, or whether it's just blank sky. While the fields-of-view are still quite small, it does offer the prospect of selection-free spectroscopic surveys in small patches of the sky.

6 Photometric redshifts

As we saw in the previous section, one of the key benefits of multiplexed spectroscopic surveys is that they provide highly accurate spectroscopic redshifts for large numbers of galaxies. However, even the most capable multiplexing systems cannot target all galaxies spectroscopically. Why is this the case? Well, firstly, there is the problem of the limited availability of fibers or slits: there are simply too many galaxies to target each one. Secondly, there is the problem of source brightness: you can usually only get the spectra of the brighter galaxies in a survey. This is because when a spectra is taken, the light from the galaxy is *spread out*, and the more it is spread out, the less light there is per pixel on your detector, meaning a lower signal-to-noise per pixel. It's impossible to take meaningful spectra of the faintest galaxies in your survey.

To overcome these problems, astronomers have developed a technique to derive redshifts from photometric data, rather than spectroscopic data. To describe this technique, let's first consider how we obtain a normal spectroscopic redshift. Here, we spread the light from a galaxy over lots of individual wavelength bins, each with a width of, say, $\Delta\lambda = 1$Å. Since $\Delta\lambda$ is small, we're be able to *resolve* individual spectral lines, meaning each line will be covered by lots of individual wavelength bins. Next, by comparing the observed wavelengths of lines to the rest wavelengths of the lines, we can calculate the redshift (i.e., $z = \lambda^{\rm obs}_{\rm Line}/\lambda^{\rm rest}_{\rm Line} - 1$). So far, so familiar. Now, consider we increase $\Delta\lambda$ to 10Å. Each wavelength bin is now 10 times wider, so we'll lose some *spectral resolution*. Now we may not be able to fully resolve individual spectral lines: each spectral line might only be covered by one wavelength bin. We'd still be able to identify the lines, but because they're not well resolved, there will be a larger uncertainty on $\lambda^{\rm obs}_{\rm Line}$, meaning a larger uncertainty on the redshift. If we now increase $\Delta\lambda$ to 100Å, we probably won't resolve *any* individual emission lines. However, we'll still be able to see the overall *shape* of the continuum. In particular, we may even be able to see *breaks* in the continuum caused by the absorption of photons by neutral hydrogen. If we can see the overall shape, then we can try to fit it with a galaxy template, shifting the template to and fro in wavelength until we get a good fit. Once we find a good fit, we the amount we've had to shift the template by gives us the redshift of the galaxy.

If instead of a spectrum with bins of $\Delta\lambda$=100Å we have lots of different *photometric filters* of width $\Delta\lambda = 100$Å, we have exactly the same situation: lots of very wide bins of flux. By fitting the overall *shape* of the spectrum or SED that these photometric points trace out with galaxy templates – shifting the template in wavelength until we get a good fit – we can derive the redshift of the galaxy. Of course, since the wavelength bins are wider, the uncertainty in the shift is larger than if we can resolve individual lines. Also, the precision decreases dramatically with fewer and fewer filters. This explains why photometric redshifts are less precise than spectroscopic redshifts. Having said that, provided we have photometric data from lots of filters (> 10 filters is not uncommon in blank field surveys) today's photometric fitting codes can typically measure photometric redshifts to within an accuracy of $\Delta z/z \sim 0.1$ or better.

The large numbers of accurate photometric redshifts available for galaxies in blank field surveys has had a dramatic effect on statistical studies of galaxies. While an individual photometric may not be particularly accurate, if we have lots and lots of them (and we do), then we can reliably use them to derive statistical properties of galaxies, particularly distributions such as mass and luminosity functions.

7 The future of extragalactic surveys

Because of the huge impact galaxy surveys have had on our understanding of the Universe, they are factored-in as a major component of all new observing facilities. Indeed, some telescopes are built specifically to conduct surveys. As such, they will continue to play an increasingly important role in revealing how galaxies have formed and evolved.

8 The Pros and Cons of galaxy surveys

Finally, I though I'd wrap up with a summary of the pros and cons of galaxy surveys:

Pros:

- Samples of galaxies unbiased by pre-selection (but see "con" about flux bias).
- Because the "blank fields" have been surveyed by lots of different observing facilities, we have a lot of multiwavelength data for the galaxies within those surveys. This helps considerably when determing galaxy properties and overcoming k-corrections.
- Surveys are an excellent sources of targets for more detailed, follow-up studies.
- The deepest surveys provide the most sensitive view of the Universe to-date.

Cons:

- Although less biased than studies of pre-selected galaxies, "blank-field" surveys are biased toward brighter galaxies because of the flux limit of the survey.
- While multiwavelength data often exists, it can be a challenge to match between different wavelengths.
- A major drawback of surveys is that they often lack the "detail" of more targetted observations.
- The smallest-area surveys can be particularly badly affacted by cosmic-variance (which was described in Lecture 2).

9 Key learning objectives for L6

By the end of this lecture you should have an understanding of:

- why we conduct extragalactic surveys;
- , the different survey strategies, and why we use them;
- how survey fields are selected for observations;
- the multi-wavelength aspect of surveys, and what physical propertied are measured by different wavelengths;
- the pros and cons of survey science;
- photometric redshifts.