Lecture 7:
The star-forming history of the Universe & Lyman Break Galaxies

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1 Introduction

In the previous lecture, we covered the general philosophy and techniques of survey astronomy. In this lecture, we will cover two important results that are rooted in data from extragalactic surveys: the cosmic history of star formation, and Lyman Break Galaxies.

2 The cosmic history of star formation

Galaxies are made of stars, so asking "when did today's galaxies form?" is akin to asking "when did today's galaxies form their stars?".[1] In lecture 5, we looked at how we could use the fossil record to determine this: effectively combining the star forming histories of all local galaxies to determine when their stars were put in place. We can also, however, try to answer this question using the redshift approach. We can study galaxies at different redshifts (i.e., at different *lookback times*) and measure how much star formation was taking place at different times throughout the history of the Universe. We do this by combining the methodologies outlines in lectures 4 and 6: using UV or infrared surveys to survey the star formation rates (SFR) of galaxies at different times during the history of the Universe. From this, we can determine – on average – when galaxies formed their stars.

2.1 The Madau diagram

One of the first attempts to systematically measure the star-forming history of the Universe using blank field surveys is described in Madau et al. (1996). As such, the resulting plot of SFR vs. redshift is known as the *Madau diagram* or *Madau plot.* Madau used rest-frame UV emission (from the Hubble space telescope) to measure the average SFRs of galaxies out to a redshift of $z \sim 5 - 6$ (i.e., over the past $\sim$ 12 billion years (or $\sim$ 90% of the age of the Universe). What Madau et al. found was that the *SFR density* – that is, the average SFR per unit volume – appeared to peak at around $z \sim 1 - 2$, corresponding to about 6 to 8 billion years ago. Since that time, the SFR density of the Universe has slowly declined until today when it is about one tenth of what it was at its peak. It's like galaxies in the Universe had a growth spurt around 6-8 billion years ago, and has now settled into middle age. Further, since heavier elements (i.e., remember, in astronomy anything heavier than He is a *metal*) are formed in the cores of stars and when stars go supernova,

[1] We'll leave *how* stars are formed to Simon's Star Formation course.

the peak of SFR at $z = 1 - 2$ also means that the rate of metal production also peaked at these times.

It's interesting to consider just how rapidly galaxies were forming their stars when they were at their peak SFRs. From the Madau plot, we see that the SFR density of the Universe peaked at around 0.1 $M_\odot$ per year per Mpc^3. That may not sound like much, but bear in mind that most of the Universe is empty. As such, some galaxies were producing well over a hundred stars *per cubic kpc* per year.

Because of the impact that Madau et al. (1996) had on the field of SFR history, the terms "Madau diagram" or "Madau plot" have now become synonymous with all subsequent plots of SFR density vs. redshift (no matter who publishes them).

2.2 Uncertainties in the Madau diagram

Of course, as with any measurement – especially first attempts – there were considerable uncertainties associated with the earliest attempts to measure the SFR density of the Universe. In particular, by using rest-frame UV light to measure SFRs, the earliest Madau diagrams suffered significantly from uncertainties due to dust obscuration (recall, the UV is *strongly* attenuated by dust). Furthermore, as we saw in Lecture 2, there are significant difficulties associated with measuring light from high redshift galaxies. In particular, Hubble images are strongly biased toward detecting high surface brightness galaxies (remember the $1/(1 + z)^4$ law for surface brightness from Lecture 2), meaning they could easily miss any diffuse regions of star formation and thus underestimate the SFR density. Finally, we also have the usual problems associated with converting UV fluxes to SFRs: how to convert UV luminosity to numbers of high mass stars (which depends on uncertain models of stellar evolution) and from there to total numbers of stars (which depends on uncertain IMFs, especially in the high redshift Universe).

As our telescopes have become more sensitive at more wavelengths (especially infrared wavelengths), our ability to mitigate these uncertainties has improved (consider material in L2). As such, since its first depiction in 1996, the Madau diagram has evolved somewhat, especially at the high redshift end. While it remains the case that the SFR density of the Universe peaked at around $z = 1 - 2$, the most recent Madau plots show less of a steep decline *at higher redshift* than first thought. In other words, the SFR density of the Universe was fairly constant (if slightly increasing) from between $z = 6$ to about $z = 1 - 2$, after which it has dropped significantly. As we shall see later in the course, the reason for this drop-off in SFR density over the past 6-8 billion years is due to the declining availability of gas – the raw material of star formation – in the Universe as it gets used up to form stars.

3 Lyman Break Galaxies

Identifying galaxies at high redshift – as required if we want to use this approach to study galaxy evolution – can be extremely challenging. Not only do we have to contend with the faintness of these galaxies due to their distance from us (as outlined in Lecture 2), but once you have a sample of galaxies, how do you reliably identify the few that are at the highest redshifts out of the millions of more local galaxies? Even with spectroscopic surveys, it would be highly inefficient to target all galaxies with the hope of finding the small handful that were at the highest redshifts.

One approach we saw in the last lecture was to use photometric redshifts. However, that approach requires observations in *many* different bands and so can be costly (in terms of telescope time). In this section, we'll look at a way we can identify high redshift galaxies using as little as two wavebands. This technique relies on exploiting a "break" in a galaxy's spectrum – typically where the flux lonward of the break is higher than shortward of the break. One of the strongest breaks in the spectra of galaxies is the *Lyman* break, so galaxies that are identified by exploiting this break are known as *Lyman Break Galaxies* (we like to be original in astronomy!).

3.1 Identifying Lyman break galaxies

Before we consider how we actually identify Lyman break galaxies, we'll first look into what the "Lyman break" actually is. Consider a galaxy containing a population of massive, hot stars. Because they are hot, they release a strong continuum of UV light. Usually, these stars will be sitting in a pool of surrounding gas (containing mainly Hydrogen) from which they have been born. This means that, almost immediately after the UV photons leave the surface of the stars, those with wavelengths shorter than 912Å (and thus capable of ionising H) hit a neutral H atom and is *absorbed* by it, producing a H ion. The H ion will (eventually) recombine with an electron but – importantly – it is unlikely to recombine directly into the lowest energy level. It is far more likely that it will recombine to a higher energy level, emitting a lower energy photon than the original ionising photon followed by a series of other transitions. As such, it is *highly unlikely* that the original < 912Å will be re-emitted. What all this means is that, because of the ready absorption of < 912Å photons by Hydrogen, there is a sudden drop in flux shortward of this wavelength – known as a "break". And because it is caused by absorption by the first, or *Lyman*, level of Hydrogen, it is known at the *Lyman Break*.

As mentioned already, astronomers can use this break to identify high redshift galaxies. To explain how this works, however, we'll first consider a galaxy at $z = 0$. In this low redshift example, we'd detect the galaxy at wavelengths *longward* of 912Å, but not *shortward* of 912Å, since these short wavelengths photons are absorbed by the hydrogen gas in the galaxy. For galaxies at higher redshifts, however, the break *shifts* to *longer* wavelengths, from the UV to optical wavelengths. For example, for a galaxy at $z = 3.2$, the break will be at $912 \times (1 + 3) = 3830$ Å. This *redshifted* break at 3830Å now lies between the U and B wavebands (centred at 3650Å and 4450Å), but the same principle still applies. A bright, star-forming galaxy at $z = 3.2$ would be detected in the B band, which samples *longward* of the break, but it would not be detected in the U-band, which samples *shortward* of the break. Such galaxies are referred to as "U-band *dropouts*" because they are said to have *dropped-out* of the shorter-wavelength U-band. Because of the wavelength separation between the U and B filters, these bands are sensitive to dropouts between $z \approx 3650/912 - 1 = 3$ and $z \approx 4450/912 - 1 = 3.9$.

By using longer wavelength bands, astronomers can identify Lyman-break galaxies at higher and higher redshifts. For example, using the B and V (5500Å) bands would identify B-band dropouts between $z \approx 4$ and $z \approx 4.9$, while the V and R (6580Å) bands would identify V-band dropouts between $z \approx 4.9$ and $z \approx 6.1$. As a test, what redshift could an I-band dropout have (centred at 8060Å; the next longest wavelength is the z-band at 9000Å)? What type of dropout would the highest-redshift galaxy, at $z = 11.09$ be? (You'll need to look up the central wavelengths of common telescope filters. *Clue*: Check out the near-infrared)

Since their discovery, a large number of Lyman break galaxies (hereafter, LBG) have had their redshifts confirmed spectroscopically using large (8-10 m class) telescopes. The dropout technique makes this feasible – out of the thousands or even millions of galaxies in the deep field surveys, only a few thousand might be LBGs, which can (relatively) easily be followed-up with multi-fiber or multi-slit spectrographs. However, only the brightest ($m_R < 25.5$ LBGs can have their redshifts confirmed spectroscopically. Most fainter ones will remain unconfirmed until larger, more sensitive telescopes are commissioned.

3.2 The spectral characteristics of Lyman break galaxies

For the LBGs that astronomers *have* been able to obtain spectra for, not only do we know their (confirmed) redshifts, we can also measure some of their physical properties. Typically, the spectra of LBGs show a combination of both nebular emission and absorption lines, as well as (weak) absorption lines associated with stellar photospheres. Some also show strong Lyα (at rest-frame 1216Å) and CIV emission from ionised gas surrounding the hot, young stars in these galaxies. However, these lines often appear asymmetric as the photons in the blue wings of the lines are absorbed by Hydrogen gas in the galaxy (which becomes excited to the $n = 2$ level).

The spectra of LBGs appear similar to galaxies in the local Universe that are undergoing episodes of rapid star formation – known as *starburst* galaxies. However, LBGs tend to have spectra that are metal-poor compared to galaxies in the local Universe, suggesting large amounts of *pristine* gas (i.e., unprocessed by star-formation) in LBGs. This makes sense when considering that we're observing LBGs as they were when the Universe was young before lots of reprocessing in stars had "contaminated" gas with metals.

3.3 The morphological characteristics of Lyman break galaxies

Once astronomers have identified LBGs using the dropout technique, they can also study their morphologies (i.e., shapes) in the bands *longward* of the break. Because of their high redshifts, this typically requires the high spatial resolutions only afforded by the Hubble Space Telescope (or adaptive optics, in which the distorting effects of the atmosphere are counteracted using deformable mirrors placed in your telescope optics.)

Detailed morphological studies of LBGs have reveals that the tend to be physically smaller than local galaxies of the same luminosity, with half-light radii similar to the bulges of local spiral galaxies or small ellipticals (although, as ever, we need to be wary of missing low surface brightness features). While some LBGs appear relatively smooth in structure (like today's disk galaxies), many show signs of being highly clumpy and irregular in nature, which is suggestive of mergers and/or interactions in the high redshift Universe. You will recall from Lecture 2 that we need to be mindful of morphological K-corrections if we see such "clumpy" structures in high redshift galaxies. However, LBGs show little evidence of suffering from this problem, with both the rest frame optical (probed by the near-infrared bands) and rest-frame UV (probed by the optical bands) showing similar morphologies.

3.4 The star-forming properties of Lyman break galaxies

By the very nature of how they are identified, LBGs must have a strong UV continuum. There must be a lot of UV photons just longward 912Å (which is still the UV) in order for a LBG to be seen to drop out of the shorter waveband. Since only massive, hot, *young* stars produce a strong UV continuum, and since these stars only live for a short time, then LBGs must have recently undergone a recent bout of star formation.

While LBGs must be star-forming, actually measuring their star formation rates (SFRs) can be problematic. This is because their SFRs are usually measured via their rest-frame UV flux, or sometimes via their nebular emission (if a spectrum is available), both of which can be strongly affected by dust obscuration. Prior to correction for dust, LBGs are measured to have SFRs of a few tens of solar masses per year. After correcting for the effects of dust, however, we find they have SFRs of around 100 $M_{\odot}yr^{-1}$. This is a very high SFR by today's standards - the SFR of Milky Way is about 1 $M_{\odot}yr^{-1}$; only a handful of galaxies undergoing intense starbursts due to major gas-rich mergers in the local Universe have SFRs even approaching 100 $M_{\odot}yr^{-1}$.

Since LBGs are strongly star-forming, we can include them in our measurements of the star-forming history of the Universe and plot them on the *Madau plot*. Since we have identified lots of LBGs, we have good statistics for them, meaning the average SFR density that we derive for them is well-defined and has comparatively small error bars. When we include (dust corrected) LBG SFRs to the Madau plot, we find that they agree well with SFR densities derived using other techniques: the SFR density of the Universe peaked at around $z = 1-2$, and was relatively constant before that time.

3.5 The masses of Lyman break galaxies

As well as measuring their SFRs from UV observations, we can also measure the stellar masses of LBGs using spectral synthesis (recall spectral synthesis fitting can be performed on photometric data, it doesn't require spectroscopic observations). When we do this, we find that the stellar masses of LBGs are typically between $10^9 - 10^{11}\ M_{\odot}$ (some of the spread is introduced by the uncertainty in the model fits). Interestingly, however, when we measure the *dynamical* mass of LBGs via the (assumed) gravitational motions of their stars, we find that they are about a factor of ten *lower* than the total stellar mass measured from spectral synthesis. Clearly, the gravitational mass can't be lower than the mass of all the stars (if it were *higher* it could simply be explained in terms of dark matter). This suggests that the dynamical masses of LBGs are an underestimate, possibly introduced by their motions having a non-gravitational component (e.g., mergers).

3.6 Evidence of outflows in LBGs

When the spectra of LBGs are obtained, it is often observed that their emission and absorption lines are broadened and/or shifted relative to their rest-frame wavelengths. Since shifts in emission or absorption lines are produced by gas moving at high velocities relative to the galaxy, this is seen as strong evidence of inflowing and outflowing gas in LBGs. While the inflowing gas is likely feeding the star-formation, the outflowing gas is thought to be driven by strong winds, powered either by supernovae or stellar mass loss.

Such winds are thought to be extremely important in shaping galaxies, not least in the early Universe. By expelling gas from the galaxy, such outflowing winds are one of the key feedback mechanisms employed in hydrodynamic and semi-analytic models of galaxy evolution. Indeed, winds driven by stellar mass loss and/or supernovae are widely thought to have suppressed the formation of smaller galaxies. This is why the *galaxy* mass function is less steep than the dark matter halo mass function at low masses (see Lecture 3).

3.7 The volume density and clustering of LBGs

Finally, we will consider the distribution of LBGs in space. Since LBGs are detected in blank field surveys, we can calculate how many there are per unit volume of the Universe. To do this, we measure the *luminosity function* of LBGs which, if you recall, provides the number of galaxies (in this case LBGs) per unit volume in a given luminosity bin.

As with most luminosity functions in astronomy, the LBG luminosity function is well fit by a Schechter function: roughly a broken power law with a break at a given luminosity, L^*. When we measure the luminosity function of LBGs, we find that the volume density of LBGs with luminosities close to L^* is roughly the same as the volume density of L^* galaxies in the local Universe. This similar volume density suggests that LBGs may well have evolved to form many of today's massive galaxies. This is further backed up by observations that LBGs cluster together in a similar way to today's galaxies.

4 Where are LBGs today?

Based on their masses, volume density and clustering properties, there is reasonable evidence that LBGs have evolved to form many of the intermediate to high mass galaxies in the local Universe. However, by now, the stars we see forming in LBGs at $z > 3$ will be over 10 billion years old, so will represent some of the oldest stars in today's galaxies. Further, the characteristic masses and sizes of LBGs are similar to those of the cores and central bulges of local elliptical and spiral galaxies, respectively. However, their morphologies are far more disturbed by mergers than nearby bulges or ellipticals. As such, it is thought that what we are seeing when we observe LBGs are the central bulges of spiral and elliptical galaxies in the process of being formed.

5 Learning objectives for Lecture 7

We've covered a couple of important topics in this lecture. Here are the learning objectives:

- Know what is mean by the star-forming history of the Universe.
- Know what the Madau diagram is, including its shape, how it is affected by extinction due to dust, and other challenges associated with defining it.
- Know what a Lyman Break Galaxy (LBG) is.
- Know how LBGs are identified (i.e., be able to decribe the dropout technique).
- Understand the spectroscopic, morphological, star-forming, mass, and clustering properties of LBGs.
- Have an idea of the importance of LBGs in the build-up of today's galaxies.