The Early Universe
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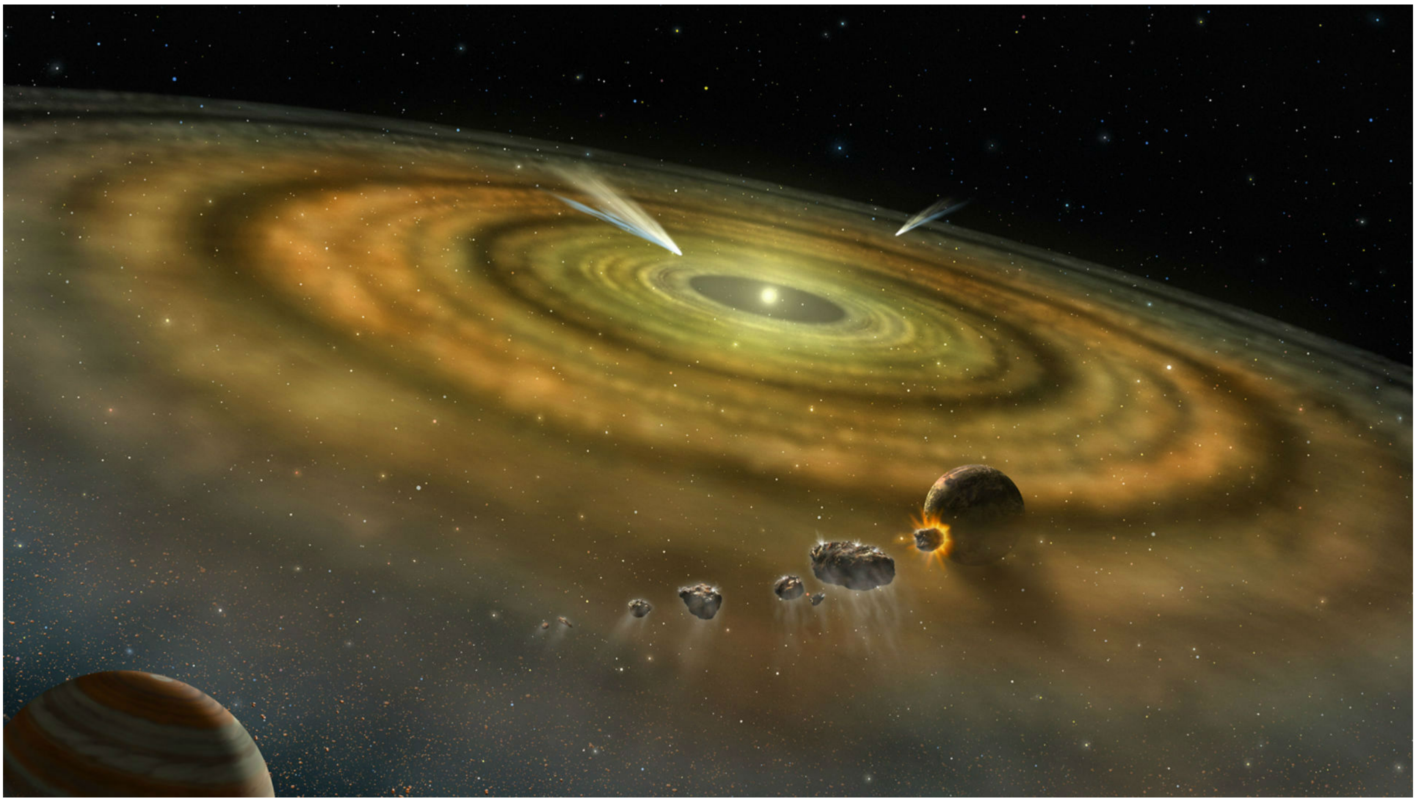

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The Early Universe

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In my previous lectures I have discussed both the earliest glimpse of the Universe available to us, the cosmic microwave background, and the wide variety of astronomical sources that we observe all around us in the present day. Today's talk is an attempt to join the dots between these two extremes: how do we move from an almost completely smooth distribution of matter when Universe was only 380,000 years old, to the complexity of stars, planets, gas clouds, galaxies and even larger scale structure? Galaxies don't just simply appear shortly after the Big Bang, but they take tens of millions of years (at least) to form; and then they continue to change and evolve.

Today's topic is *observational cosmology* – the study of the most remote parts of the cosmos. This is a major growth area in astrophysics, where huge advances in our understanding have been made over the last 15-20 years, primarily due to cutting-edge advances in the design of the telescopes and their adaptive optics. What was this very early Universe like? What happened after the release of the cosmic microwave background light? What did the very first stars and the first galaxies look like? And what do they tell us about the history of galaxies like our own?

Recombination

Immediately after the Big Bang, the Universe was extremely hot and dense. After 380,000 years, it had expanded and cooled sufficiently for the elementary particles to join together and form the very first atoms. This point in history is marked by the light of the Cosmic Microwave Background and it signals the epoch of *recombination.* As the atoms form, the Universe suddenly becomes transparent and neutral, leaving photons free to travel through it (and towards us), without interruption (hesitation or repetition). Space is now full of those energetic photons, the freshly-minted neutral atoms, and most importantly, the dark matter. At the very moment when matter and photons separate out from each other, any tiny fluctuations in density within the cosmic soup (which would originally have been created by sound waves travelling through the plasma) are frozen out, and provide the seeds around which clumps of matter can start to condense. The whole process is driven by the attractive pull of gravity, and it is the dark matter that is first to accumulate around these minute over-enhancements; the ordinary matter is subject to other forces than gravity that resist its concentration, but the dark matter is unaffected by these and can thus contract under gravity much more efficiently. Only later on do these structures accrete ordinary matter from their surroundings in the form of atomic gas.

We can only 'study' these first congregations of matter through cosmological simulations that attempt to model the growth of these structures. They start from the initial conditions we measure at the point of recombination, and let an artificial universe evolve with time, following what we understand about the laws of physics, and hopefully ending up reproducing a Universe similar to that around us today. The simulations demonstrate the importance of the dark matter in getting the process going, as otherwise the over-densities would never grow quickly enough to produce today's galaxies in the time available. The simulations also predict that the growth of matter proceeds in hierarchical fashion, with smaller structures forming merging into larger ones in what's referred to (rather inelegantly) as a 'bottom-up' scenario.

The dark ages

Even though the process of recombination means that the Universe has moved from being opaque to transparent, and that it has photons from the microwave background streaming through it, it is dark. There are no stars and no galaxies yet to give off light. In theory the neutral hydrogen that fills the space will be emitting faint (21cm spin) radio emission, but this remains undetectable with current technology. This part of the Universe's history is known as *the dark ages,* and the darkness will persist until the first luminous objects start to form from the neutral gas. The dark ages endure for several hundred million years after recombination - by the time it is a billion years old, the cosmos and its contents will have changed enormously.

The first stars

During these dark ages, the very first generation of stars will condense out of the hydrogen gas created soon after the Big Bang. This means that these stars will have a primordial composition of hydrogen and helium, lacking any heavy elements - or ‘metals’ (as astronomers refer to them). We think that stars forming from this environment will have very different characteristics to those we observe forming in the interstellar medium of galaxies today. It’s not just that the gas present in the early Universe has a primordial composition, but it would also have been warmer than in the disc of today’s spiral galaxies. In particular, current models of star formation suggest it would have beeneasier to form very massive stars, with masses several hundreds of times that of the Sun. Whether or not there are heavy elements within a gas will affect the gravitational pull it generates, and so it seems that larger masses could accumulate before a star ‘switched on’ to start shining. But once you have such a massive star it will only have an incredibly short lifetime, lasting only a few million years or so, due to the fact it has to generate energy more rapidly to counteract the stronger inwards pull of gravity, and thus it will run through its available fuel very rapidly. But in doing so each star will start the conversion of the light elements created in the Big Bang into rest of the heavier elements of the periodic table - up to iron through nucleosynthesis, and beyond iron in a very dramatic supernova event marking the demise of the star. This death throe also disperses these new elements into the surrounding gas, ready to be incorporated into next generations of stars.

Thus it is only this first flush of star formation that produces such enormously massive stars. Later stars will be less massive, longer-lived, and much better resemble those we see around us today. Even though we safely infer their existence from a combination of our understanding of cosmology, along with theoretical and computational models of stellar structure and evolution, the massive first generation stars are likely to be almost impossible to observe in practice. Their very existence is so transitory, and they are so remote; several dedicated searches have as yet failed to identify any such objects.

The epoch of reionisation

Though we might not be able to observe the first stars themselves, we can observe the impact they have on the early Universe. The most massive stars are not only the hottest, but the most luminous, and their intense ultra-violet radiation has enough energy to break apart the atoms in the gas around them. Electrons can be stripped from the atoms so that they become completely ionised, and the neutral atomic gas rapidly changes into an electrically charged plasma. This is the epoch of *reionisation.* Thevery first luminous objects – probably those enormously massive stars, and then later ‘baby’ galaxies – produce increasing levels of radiation that destroy most of the neutral hydrogen around them. First they might ionise only their immediate surroundings, but these isolated bubbles will grow, expand outwards and eventually overlap to form an intergalactic medium that is almost completely reionised. The properties of the gas in the early Universe thus provides one of the few ways in which we can start to date the emergence of the first stars and the first galaxies, even if we can’t observe them directly – the point when the Universe eventually moves out from the dark ages.

Finding early galaxies

Distant galaxies are difficult to find. First of all, they will be smaller than the type of galaxy we are used to observing. The computer simulations of the progress of gravitational collapse suggest that the very first to form will only have masses around a million solar masses. With fewer stars, they will be inherently less luminous, let alone the fact that their extreme distance from us will dilute this luminosity, rendering them very dim. Nonetheless, finding the most distant objects is a very competitive business! Even with the faintest and most distant galaxies detected, there is the problem of finding enough of them at any epoch to properly assess their typical properties.

cosmological redshift and look-back time

A further complication is that the Universe has been expanding during all the time that it has taken for this light to travel across space towards us. This doesn’t only stretch space, but also stretches any light waves travelling through it so that by the time they get to us they appear at much longer, redder wavelengths than they were emitted at. This is the cosmic redshift, and it moves the features in a galaxy’s spectrum that we are most familiar with out of the visible range and into the infrared, while also shifting the part of the spectrum emitted in the ultraviolet (and as a consequence, traditionally less well observed and studied in nearby objects) into the visible. The further away a galaxy from us, the more of intervening space it has had to cross, and the more redshifted its light.

Astronomers use redshift as a proxy for the distance to an object, but for the purposes of this talk, it’s more useful to use redshift as a proxy for how old the object was when the light we’re observing left it. Astronomers talk about a *look-back time*. The light we collect from an object 6 billion light-years away has taken 6 billion years to reach us and so we are seeing that object as it appeared 6 billion light-years ago: it has a look-back time of 6 billion years. Redshift (*z*) is thus also a measure of how old the Universe is at the time that we're seeing a certain object, and thus what period of cosmological history it represents. It's not a strictly linear relationship: recombination (380,000 years after the Big Bang) occurred at *z*~1100; followed by reionisation sometime between redshifts 6 to 12 (roughly about 400 million years-1 billion years after the Big Bang); while an object at redshift *z*~1-2 represents a time when the Universe was about 40% of its current age.

It's not just a case of detectinggalaxies at the highest redshift, but astronomers need to obtain samples of galaxies over a range of redshift, in order to track how their properties develop with time. Changes in their appearance – such as their colour, brightness and morphology – should reveal various stages of their evolution.

pencil beam surveys

One simple method of gathering the light from a range of galaxies at different epochs is simply to stare at a region of sky for a very *very* long time. This is a 'pencil beam' or a 'keyhole' survey, much like a geological drilling sample, where you do not attempt to be comprehensive in getting the light from all galaxies at any epoch, but instead aim to obtain a snapshot of different layers of galaxies back at different times.

hubble deep fields

The most celebrated of these are the *Hubble deep fields.* The original Hubble deep field was produced from an observation in 1995, where the Hubble Space Telescope was directed to stare at a tiny region of sky for ten days; a region so small that it covers only one 24-millionth of the whole sky. It was chosen to have a clear view out into deep space, contaminated by only a handful of foreground stars belonging to the Milky Way. Almost every single object in the image – at least 1,500 of them – is a distant galaxy. A companion field in the southern sky followed three years later, which doesn't look that different from the original field. But this is good news, as it means that we are safe in assuming that the scientific conclusions resulting from the original observation can be taken as representative of the rest of the sky. (This supports the 'cosmological principle', which assumes that the Universe looks more or less the same in all directions, when averaged on the largest scales). These fields were later superseded by the Hubble *ultra-deep field* taken in 2004, the deepest image of the visible universe, which also incorporated images taken in the near-infrared. The data were collected during a million seconds (11 days) of observation of a different (but still tiny) patch of the northern sky, with an angular area equivalent to that subtended by a single 1mm-wide grain of sand held at arm's length. Yet this field still contains 10,000 galaxies! – with look-back times ranging up to about 13 billion years.

The central region of this field has been refined through further accumulation of images, adding up to a total exposure time of 2 million seconds, to be known on its completion in 2014 as the *Hubble Extreme deep field.* Even though it's a smaller region, it still contains 5,500 galaxies, and the faintest is a ten-billionth the brightness of what can be seen by the unaided eye, with a look-back time of 13.2 billion years (ie half a billion years after the Big Bang). This last field has been observed in a wider range of wavebands than the others: from ultraviolet – important for tracing the blue light given off in star formation; to the near-infrared light – to pick up the most redshifted galaxies. It is noticeable that even in these very deep images, there is still plenty of back sky in between them – there is not an observable galaxy in every direction we look.

An example of a galaxy in the Hubble ultra-deep field data estimated to lie at a look-back time of 13.1 billion years, (700,000 years after the Big Bang) is UDFy-38135539. It is so far away that the light it emitted in the ultraviolet we now observe in the infrared. It is a candidate for a galaxy to lie in the reionisation epoch. Despite dating from such an early era, its luminosity is still equivalent to that from a billion stars, with a luminous size is about a tenth the diameter of the Milky Way. Despite being so small, it is actively forming stars as the same rate as our Milky Way.

photometric redshifts

UDFy-38135539 only has an *estimated* redshift however. To get an accurate determination of a galaxy's redshift, and thus pinpoint its distance/cosmological era, you require a good quality spectrum of its light in order to identify characteristic features within it. However this is problematic with very distant (and hence faint and small) targets, where to obtain sufficient photons for a good enough spectrum of a source is prohibitively expensive in terms of telescope time, and challenges even the state-of-the-art ground-based or space-based telescopes. Imaging is much more efficient, and thus a more practical approach for surveying large quantities of objects, as each image collects the fluxes of many sources at once.

To obtain a first approximation to the distance of objects we use a method of *photometric redshift fitting.* A patch of sky (such as one of these deep fields) is observed through a wide range of filters, each sampling the light of any object in the field at a number of different colours. This provides a broad brush estimate of the shape of its spectrum which can then be compared to simulations of how the spectrum of a galaxy might appear if it were observed through this filter and was redshifted by different amounts. The best match between model and data gives an estimated *photometric redshift.* The best we can do is to compare these colours to those expected from a present day galaxy; but this requires an assumption (perhaps from its morphology) about the kinds of galaxy involved, as different types of galaxies have different colours that will affect what is seen at large distance.

Specifically, spiral galaxies have active massive star formation which generates a lot of ultraviolet/blue light, which gets shifted into the visible with distance; in contrast, the stars in elliptical galaxies emit mostly red light which will be gradually lost from the visible, so that they dim much more rapidly than the spirals with increasing redshift. Further complications are that today's galaxies may not be a good template by which to assess the distance of early galaxies, as the properties of any one galaxy are expected to change with time – there will be epochs when it undergoes intense star formation which will change its size/mass/colour/brightness/spectrum from that we observe in galaxies now.

Despite these imperfections, the photometric redshift technique is used extensively in observational cosmology, as it allows immediate comparison of many objects at once. Even though the resulting redshifts have large error bars, and are not unambiguous, it is still a powerful way of sifting the data to pick out which objects should be prioritised as potentially the most interesting. These then become the prime targets for more detailed spectroscopic follow-up and confirmation of the redshift. For example, the furthest known galaxy with a confirmed redshift (Z8-GND-5296 at 7.51) was originally identified through multiband imaging and use of the photometric redshift technique. It is so distant that the galaxy appears as it was 13.1 billion years ago. Surprisingly, its spectrum shows that it is already enriched with heavy elements. It is small, with a mass only about 1-2% that of the Milky Way, but its colour indicates it hosts star formation occurring at a rate of over three hundred solar masses a year – in these circumstances a galaxy will grow very quickly!

'drop-out' selection techniques

This knowledge of how the colours of a galaxy change as it is redshifted can be used in a more directed way to search for distant objects. In this case instead of creating a broad-brush spectrum, we use filters that can isolate specific features in the spectrum. For example, strong line emission that is redshifted into a narrow filter band if the object that emits it is at one particular redshift, or sharp drops in the continuum of starlight that occur (for a certain redshifts) between two filters.

Lyman-αblobs

We know that any region of active star formation is surrounded by hydrogen gas clouds, and the atoms in these clouds can be excited by the ultraviolet light from the massive stars to give off strong line emission. In the nearby universe these 'nebulae' are seen most obviously radiating in a characteristic pink colour, resulting from Balmer Hαemission occuring at 656.3 nm. But because it is such a red colour, this particular line is not much use to us, as it is rapidly redshifted out of the visible when we observe more distant galaxies. Instead we use another dominant emission line from the hydrogen atom as a tracer of active star formation. The Lyman-αline is emitted at 121.6 nm, which occurs in the ultraviolet in current epoch galaxies, but then is shifted into the visible at redshifts above 2. Imagine a very distant galaxy: it may be small, it may not have many stars yet and so it without much starlight it only has a weak continuum, and will remain faint and difficult to pick up even in deep broad band imaging. However, if it is undergoing strong star formation activity it should produce a strong Lyman-αemission line. Thus we use a targeted selection of filters to look for objects which show barely any signal in the neighbouring broad-band filters, but suddenly pop into view in a narrow filter covering the expected position of the Lyman- αline at a particular redshift.

So far the systems found by this technique typically only have a mass between 10 to 100 million solar masses. Interpretation of the results are not straightforward, as the Lyman-αline is also easily absorbed, so we don't know how much of the light from any one galaxy actually escapes out into space. If the galaxy is dusty, much of the light given off might be obscured and the star formation rate wrongly estimated. However, the width of the lines observed do suggest that the ionisation does result from star formation. This method has also serendipitously discovered structures that can't simply just be galaxies. At a few hundred thousand light-years wide they are too large for any individual object expected at their look-back time. For example the largest known (LAB-1, for 'Lyman-αblob 1') lies at a look-back time of 11.5 billion years, yet has a diameter 3 times wider than that of the Milky Way. Such a huge and luminous Lyman-αcloud is very rare. Observations of this particular object in polarised light suggests that instead of a signal of gas excited by star formation in one individual galaxy, it is being lit by the scattered light of many smaller galaxies embedded in, and illuminating a wider gas cloud.

Lyman break galaxies

But not all galaxies – even if they are undergoing periods of active star formation – necessarily show strong line emission. A galaxy with young (ie blue) stars will have a fairly flat continuum spectrum, but below (ie shortward) of 91.2 nm there is a sharp drop in the level of the continuum, caused by the fact that all photons emitted at higher energies than that corresponding to this wavelength (the *Lyman limit*) will be almost completely absorbed by neutral gas around star-forming regions in the galaxy. This produces a step change in the continuum level known as the *Lyman break,* where lots of flux emitted above 91.2 nm drops to barely anything below.

Again, a strategic chose of filters can sample the light of galaxies to either side of where we would expect to observe the continuum break at a certain redshift. We would detect the object in the redder, but not in the bluer, band, so objects at that redshift appear to suddenly pop into view as we move between images taken between the two filters. Given that the Lyman break moves to the visible waveband (ie above 360nm) only for z>3, this is again a method to efficiently scan large tracts of the sky for distant galaxies, preselecting the best candidates for detailed follow-up observation.

However there is always the concern that the objects discovered by these techniques are those that are observable precisely because they are exceptional for some reason, and not representative of other objects around them. There are selection effects inherent in our methods where perhaps we preferentially pick up the most luminous systems that are most vigorously forming stars in an era where most galaxies might be so faint as to otherwise escape detection.

Gravitational lensing

There is one trick we can use to detect a much more random selection of distant galaxies, which employs 'nature's telescope', gravitational lensing. The curvature of space around a large mass – such as that of an entire cluster of galaxies, for example – can bend the light from background objects to smear it into mirages of the background galaxy's light, that appear as arcs and rings. The main advantage of gravitational lensing is that it also magnifies the light of the background galaxy, as light rays that would have ended up travelling to other parts of space have been 'pulled around' so that more of its light is directed towards us. All wavelengths are lensed in the same way, so the spectrum of the object is unchanged by the process. Very dim distant galaxies are thus brought into observability, including many which would have been too faint to detect if it were not for this quirk of cosmic geometry.

One of the furthest galaxies discovered through this method lies in the background of, and is gravitationally lensed by, the large galaxy cluster Abell 2744. The distant object appears in three mirages that appear between the cluster galaxies; without the magnification of gravitational lensing, it would be appear ten times fainter and smaller. The galaxy is estimated to date from when the Universe was only about 500 million years old; it is only 850 light-years across (500 times smaller than the Milky Way) and seems to have a mass of only 40 million Solar masses. From its colours it looks like it has a star formation rate 1/3rd that of the Milky Way, ie about one star every three years. Another distant object revealed by gravitational lensing is MACS0647-JD, which has a photometrically-estimated redshift of 10.7, which if confirmed, would make it the furthest known galaxy (dating from 430 million years after the Big Bang), and less than 600 light-years wide.

generic properties of the distant galaxies found so far

Although the numbers of truly distant galaxies found so far are small, we can start to say something about their general properties. Not surprisingly, we find differences from the present day systems. Most galaxies in the local Universe have either a spiral or an elliptical morphology, with fewer than 10% showing an irregular, or peculiar shape. At higher redshifts many more (over 25%) show a much more disturbed or 'blobby' morphology for example, galaxies in the Hubble deep fields which form elongated, blue 'chains' of structures. This suggests that mergers/interaction activity was more frequent in the early universe, and confirms its importance in the evolution of some types of galaxies. Thus sometimes we may be detecting small proto-galactic fragments rather than actual galaxies, consistent with the idea of structures assembling through mergers of smaller systems; it certainly doesn't seem as if all galaxies were formed at one single point in the history of the universe. The other observable properties of the distant galaxies also interpret this inference: not only areearly galaxies of comparable intrinsic luminosity are progressively smaller in size, but the more distant galaxies are significantly less bright.

Quasar absorption lines

One manifestation of distant objects are of course quasars, which represent an early but probably transient phase in the development of galaxies. This is when the intense light produced by accretion of matter onto the supermassive black hole at the heart of a galaxy can outshine its host, to be seen far across the Universe. Quasars are located at such huge distances that we can make use of their incredibly luminous radiation to probe the contents of the vast tracts of the intergalactic space it has to travel through on its way to us. Any material that happens to lie along the line of sight will absorb some of the quasar's light to leave the imprint of absorption features in the spectrum of the quasar. Analysis of the pattern of absorption lines can reveal some of the physical properties of the absorber, such as its density and chemical composition. The redshift of the absorption also tells us how far the absorbing material is away from us, and so which epoch of the Universe's history it belongs to. Studies of the absorption lines in quasar spectra can inform us how the intergalactic gas has changed during the history of the universe; how well it is clumped together at different distances (and thus times); when it was enriched with heavy elements; and the nature of the gas itself. This method again selects random objects in the universe that just happen to lie along a line of sight rather because of any intrinsic selection effect, and it's very effective for examining the less luminous parts of the Universe that wouldn't be easily observable otherwise, such as very tenuous intergalactic gas.

Lyman-alphaabsorption

Given the ubiquity of hydrogen in the Universe, it is again the Lyman-αline which proves particularly useful for high redshift objects. We have already talked about it as an emission line that traces star formation regions, due to electrons in the hydrogen atom getting excited by the light of the young stars. The spectrum of the quasar itself always has a broad emission line which is emitted in the ultraviolet part of the spectrum, but moves the visible for high redshift objects. This line marks the redshift of the quasar, and any intervening matter can only ever be at lower redshift than the quasar. If foreground material causes an absorption line, it will always appear in the spectrum blueward of quasar's Lyman-αemission. Every cloud of neutral hydrogen (of sufficient density) that lies across our line of sight to a background quasar will leave an imprint in the form of a narrow spike of absorption, and as each cloud is at a slightly different distant/redshift from us, the spikes they create are all spread out to form a 'forest' of these features. The closer to the quasar emission line, the further away from us they are.

The Lyman alpha forest

These features combine to create the as the *Lyman-αforest,* with the number of absorption features increasing dramatically with redshift. This implies that while the clouds responsible for this absorption are abundant in the early Universe, they gradually disappear with time. The absorption cannot simply be explained as due to intervening galaxies, as the spatial distribution of the Lyman alpha clouds track, but don't exactly match, that of the galaxies. As they are less clumped than the distribution of luminous matter, maybe they represent clumps of intergalactic material that have yet to condense properly into a galaxy. We assume that they are either clouds that are the direct precursors of galaxies seen before their gravitational collapse, or clouds that will be accreted by forming galaxies.

TheLyman-αclouds populating the forest typically have a very low density, and the width of the lines compared to the amount of gas required to produce the absorption measuredshows that there has to be more gas present than we detect for its gravity to collect it together. As we are only looking at chance intersections of matter against a point source of light in the sky it is difficult to get true estimate of the size of the absorbers. However there are rare situations when two quasars (or two different gravitationally lensed images of quasars) happen to be located close in the sky to one another and their spectra show absorption features at exactly the same redshift, presumably due a single structure overlapping both lines of sight. Where seen, it suggests that the objects creating the Lyman-αabsorption are spatially extended, but there's no guarantee that we are truly sampling one single coherent object. Instead it may be more than one object contained within the same large scale structure that lies along the line of sight.

A the Lyman-αabsorption is only produced by neutral hydrogen gas, the quasar absorption lines will only be sensitive to a fraction of the mass present – for example it is not sensitive to either dark matter or ionised gas that accompanies the cloud. However, we can use the Lyman-αforest to track the onset of the epoch of reionisation. The distribution of the absorption lines with redshift/distance might be able to tell us something about the radiation responsible for turning the neutral gas to ionised matter. If the neutral hydrogen gas clouds are very evenly distributed it might suggest that many small galaxies are the source of the light; a less uniform, clumpy pattern might suggest different sources creating more of a patchwork pattern of volumes occupied by alternating charged and neutral hydrogen gas regions. The very highest redshift quasars show a rapidly drop in the flux of the Lyman-αforest at redshifts above 6, holding the exciting prospect of marking the very transition to where the ionised bubbles surrounding some of the early galaxies start to join up.

Lyman limit absorption

In the same way that very energetic photons (emitted at a wavelength below 91.2 nm) from a star can be completely absorbed by their neutral surroundings to produce the Lyman break, any energetic light from a distant quasar is also able to ionise any atoms along the line of sight. Even if it isn't a dense absorber, the intervening matter will create a Lyman break feature in the quasar's continuum, with the flux notably suppressed blueward of (redshifted 91.2nm). The clouds responsible for this absorption are denser than typical Lyman forest absorbers; they are thick enough that radiation doesn't penetrate to their core, so the outer regions shield volumes of neutral hydrogen.

damped Lyman- alpha clouds

A much rarer population of absorbers are due to clouds that have a density a million times greater than their immediate intergalactic medium. These are so dense that they are completely absorb all the quasar photons at the right energy to very deep lines, which are almost opaque. These *damped Lyman alpha* systems have a density equivalent to that in clouds to the absorption features produced by the gas discs of present day spiral galaxies. Thus by comparison it seems that these systems are due to the quasar light being intercepted by the disc of an intervening spiral galaxy, but if so, they'd be pretty large structures, about twice the size of present day galaxies. It is the densest regions of the interstellar medium which host star formation, so it is possible that there could be line emission due to star formation within the dense regions in these intervening galaxies; if so it should appear at the same redshift as the absorber. But searches for H-α(redshifted to the infrared) or Lyman-α(at the centre of the damped line) have failed to detect any substantial line emission. This suggests that instead the clouds may be precursors to today's spiral galaxies, which are building up, but not yet shining with stars.

metal absorption lines

Surprisingly, some of the damped Lyman-αsystems also show evidence for absorption lines from heavier elements than hydrogen, such as those from magnesium, zinc and chromium, carbon and silicon. The line strength indicates the mean enrichment is about ten times lower than Solar abundance. So while these may be comparatively rare elements, they can only have been created in massive stars and scattered out into the gas through supernova explosions, and the fact that these elements are present indicate early star formation phase in these dense systems.

The evolution of galaxies

It seems that the detection of the very earliest galaxies will continue to evade us for a while longer. But we can still compare the properties of matched galaxies at different distances/redshifts/times to map out the stages in their evolution in order to understand how they grow and evolve. The average properties of galaxies at a redshift of 3 (when the Universe was around 15% of its current age) are very different from those we see today. Some are red in colour, with an elliptical galaxy morphology, albeit more compact. These will presumably continue to grow in size while maintaining that shape, passively evolving into today's ellipticals. Other distant galaxies are much bluer, actively forming stars at rates of about ~10 solar masses a year. Where they show a spiral morphology they have thicker discs and are not rotating as fast as in the present day, suggesting that there is still a lot of turbulent motion, and the disc has yet to dynamically settle down. There is also debate about how many of the blue-coloured high-redshift galaxies may yet evolve to the redder systems of today.

accretion of gas...

There are various competing physical mechanisms that will dominate the growth of an individual galaxy and the balance between them will regulate that growth. In particular, we must remember that the story of any one galaxy is not just the history of a single cloud of gas existing and evolving in splendid isolation. A galaxy can continue to grow by accumulating gas from external sources. The hierarchical nature of structure formation continues to the present day, meaning that larger galaxies accrete their smaller neighbours in acts of galactic cannibalism, and certainly the blobby shape of high redshift galaxies confirms that this can be an important process. A galaxy can also continue to directly accrete gas from the surrounding tenuous intergalactic medium, simply through gravitational attraction.

...and feedback

There are also mechanisms that have the potential to stifle rather than fuel star formation and galaxy building, by producing energy that heats the cold gas reservoir, or even expels it from the galaxy altogether. The energy released from the vicinity of the supermassive black hole at the core of a massive galaxy, and/or the energy of many supernova events such as might result from an intense starburst, can both heat the galaxy's interstellar medium and thus turn off star formation (the propensity of a gas cloud to collapse under gravity depends on its temperature). The role of both these potential feedback mechanisms can strongly affect the star formation process, but they are complicated to model theoretically and remain one of the biggest problems in our understanding of galaxy evolution. Although it is a field still in its infancy, it is possible that studying abundance gradients of distant galaxies is beginning to reveal the relative importance of these mechanisms in different types of galaxies. Gas accumulated from the intergalactic medium will be primordial, whereas that donated from mergers of other galaxies will be enriched with heavy metals from star formation. These will both be external influences, but any energetic outflow of hot gas from the heart of the galaxy will act to scramble any gradients.

star formation history of the universe

We can also use the amount of ultraviolet light emitted to estimate how the (volume-averaged) star formation rate within a galaxy evolves with time; and as heavy elements are synthesized at the cores of massive stars, this will also track the history of metal enrichment of the Universe. We observe a steep rise in star formation between z~3 to z~1-2 which then drops sharply to the present day rates, suggesting that star formation reached its peak some 8-10 billion years ago (redshifts between 1 and 3), when it was about 10 times higher than it is now. Admittedly the data are far more uncertain beyond redshift 3 – this is not just due to the lack of high redshift objects, but also the difficulty of knowing the level of dust obscuration along the line of sight and how that affects our estimates about the massive star formation rates.

How the Milky Way has changed and evolved through its history

What does all of this mean for the history of our own galaxy, the Milky Way? Clearly it has changed and evolved through its existence: today it might be dominated by old, mainly white/yellow stars in the bulge, with regions of active star formation confined to the spiral arms in the disc, but it would have looked very different in the past. Surveying other, superficially similar galaxies at different look-back times can give an impression of what it might have been like. Although we know it has cannibalised other smaller galaxies, its fairly regular shape, particularly in the outer, and more fragile parts of the disc, shows that it hasn't undergone a major disruptive merger in its recent history. In line with the star formation rate of the Universe, we can guess that most of its stars were formed in between 10 and 8 billion years ago, when the Milky Way would have been brighter, bluer and scattered with many more emission-line nebulae. Before that starburst era would have been largely made of gas - smaller, dimmer and darker, and apparent to a remote observer only as a spike of absorption along the line of sight to a distant quasar.

prospects for the future and conclusions

We have to wait a new generation of telescopes for the hope of truly detecting the first stars and galaxies in all their glory. New facilities such as the ALMA telescope (already partially in operation) which will provide fantastic spatial resolution at mm wavelengths, and thus be sensitive to the atomic and molecular gas content of early galaxies, and help us disentangle the role of dust obscuration. Further down the line, we have to await both NASA's James Webb Space Telescope (due for launch in 2018) and the European Extremely Large Telescope (due to be operational in another decade) before we can seriously start accumulating data about galaxies existing at less than 300 million years after the Big Bang. We may seem stymied at the present, but the future of the history of the Universe will not always be dark.

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