

THE FIRST STARS: CLUES FROM QUASAR ABSORPTION SYSTEMS

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Abstract. Astronomers have now at their disposal telescopes and instruments which allow them to look back in time over most of the history of the Universe, from the present epoch to less than a billion years after the Big Bang, when the Universe was still in its infancy. Using quasars (the bright nuclei of distant galaxies) as background sources of light, we can follow the evolution of galaxies and of the matter between them from the First Stars to the rich diversity of the universe today. In this review, I focus on recent developments in the study of the most metal-poor gas seen in the spectra of quasars, whose properties can be used to infer the nature of the First Stars and, in some cases, even determine the universal fraction of baryons.

1. SETTING THE SCENE

From the perspective of astronomers, the first decade of the new millennium has been termed the era of precision cosmology, when the parameters that describe our Universe have – for the first time in the history of mankind – been determined empirically with an accuracy of 10% or better. Thanks to technological advances in our ability to record faint light signals over many wavelengths of the electromagnetic spectrum, from gamma rays to radio frequencies, it has become possible to piece together the past history of the Universe and make an educated guess as to its future destiny.

This ‘standard model’ of cosmology is illustrated in Figure 1. Our Universe began 13.7 billion years ago, in an event whose popular name – the Big Bang – reflects our ignorance of its nature and cause. As the Universe expanded (and cooled) from this initial infinitesimally small size which encompassed all of space, energy, matter and radiation, it remained opaque and inscrutable for the first 380 000 years, when photons and electrons were so strongly coupled together that light could not travel very far within this primordial fluid. Only once the Universe had cooled sufficiently for electrons and protons to recombine and form hydrogen atoms, were photons free to stream over large volumes. Some of them are reaching our radio telescopes only now, having literally arrived from the edge of the observable Universe. This is the Cosmic Microwave Background, first discovered by Penzias and Wilson in 1965 and studied almost continuously since then with instruments of increasing sensitivity and angular resolution, including the COBE, WMAP and now Planck satellites.

Our cosmic timeline (see Figure 1) then jumps forward by about half a billion years. The wavelength of light emitted at this time has been stretched by the cosmological redshift by a factor of 10 by the time we receive it, but this faint emission is still detectable with the biggest telescopes and most sensitive infrared detectors on Earth (e.g. Robertson et al. 2010; Bouwens et al. 2011 and references therein). There are now many reported cases of galaxies and even individual stellar explosions at redshifts $7 < z < 10$ — we can see directly to these early times in our deepest images of the sky. From then on, over the last 13 billion years of cosmic history, we can follow the evolution of galaxies and of the gas between them in increasing, and at times exquisite, detail.

2. THE COSMIC DARK AGES AND THE FIRST STARS

The half-billion year gap in our knowledge of cosmic history, from the time when the Cosmic Microwave Background was emitted at time $t \sim 380\,000$ years (starting to count time from the Big Bang onwards) to the most distant galaxies currently known, whose light left them at time $t \sim 600$ million years and is only reaching us now, is often referred to as the cosmic ‘Dark Ages’. This period is currently regarded as the last frontier of observational cosmology because, empirically, we have very little concrete information

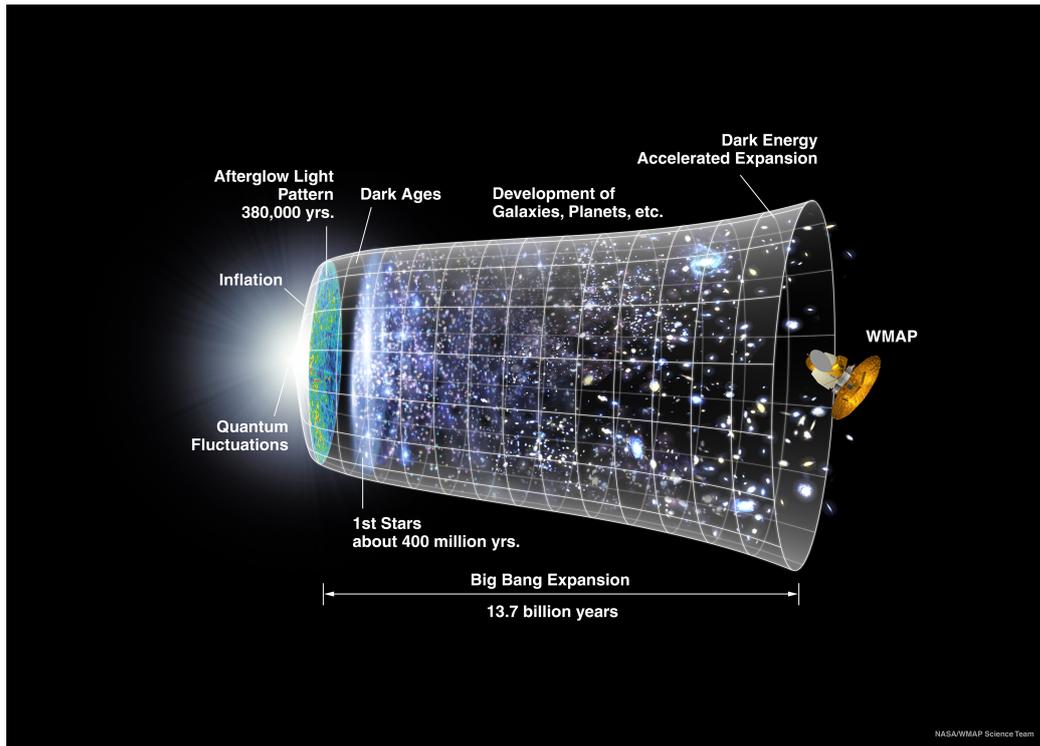


Figure 1. The current ‘standard’ model of the history of our Universe, from the Big Bang at the left to the present epoch of accelerated cosmic expansion, as determined by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite shown at the right of the picture (Credit: NASA/WMAP Science Team).

about it. We know that at that time the Universe consisted only of hydrogen and helium, with very small amounts of their isotopes ^2H and ^3He , as well as minute amounts (less than 1 atom in a billion) of ^7Li —these were the only elements synthesised in the Big Bang itself (we’ll return to this point later). All other elements of the Periodic Table, which make our world such an interesting place, were ‘cooked’ later in the interiors of stars or in the supernova explosions which in some cases mark the end of the life of a star. These familiar forms of matter, which astronomers often refer to as baryons, make up only about 1/6 of the total matter content of the Universe. The other 5/6 is presumed to be some as yet unidentified form of matter which does not interact with light — hence the term ‘dark matter’, but whose presence is revealed by the pull of gravity it exerts on ordinary matter in its vicinity. Thus, during the Dark Ages, the Universe must have been a very bland and uneventful place, consisting only H and He, dark matter, and no light from the stars to illuminate its progress.

All this changed when the First Stars formed. The favoured theoretical picture posits that even at its very beginning our Universe was not perfectly smooth, but had an inherent degree of ‘lumpiness’, with some regions infinitesimally denser than the mean (and others less dense than the mean). As time progressed and the Universe expanded, these primordial inhomogeneities grew under the action of gravity which pulls all forms of matter together, so that the denser regions became even denser and the emptier ones emptier. By time $t \sim 380\,000$ years, these fluctuations in the matter distribution had grown to a few parts in 100 000, still tiny but large enough to be detectable in our maps of the Cosmic Microwave Background. The current thinking is that in the following half billion years these seed fluctuations continued to grow until the gas in the most pronounced of these density peaks was dense enough to cool, lose energy and collapse to centre of its dark matter halo. In the cores of these halos, the gas reached values of density and temperature sufficiently high to ignite nuclear fusion and burn brightly as one of the First Stars. The interested reader may refer to Bromm et al. (2009) and Karlsson et al. (2011) for recent reviews of theoretical ideas on the formation of the First Stars.

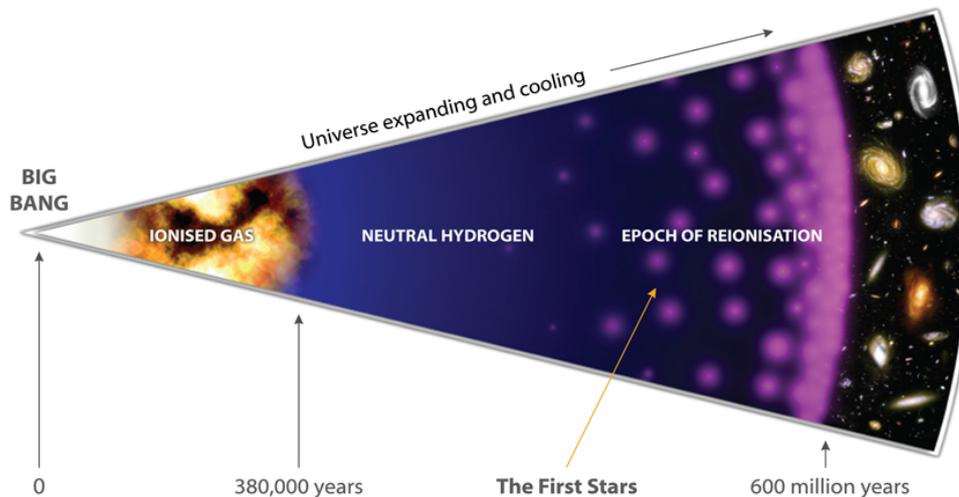


Figure 2. Schematic representation of the ‘Epoch of Reionisation’. Time progresses from left to right.

Our knowledge of the process by which gas turns into stars is still sketchy. One thing we do know is that stars are not all of the same mass – when a cloud of gas cools and condenses to form a cluster of stars, some stars will be as heavy as our Sun, while others will be less massive and yet others can be as massive as 100 Suns. For reasons that are not yet fully understood, the distribution of stellar masses seems to be remarkably constant, at least to a first approximation. That is, the ratio of massive stars to less massive ones seems to be roughly the same in our Galaxy, in neighbouring galaxies and even in very distant ones. Nevertheless, there are good reasons to suppose that if the prestellar cloud of gas collapsing to form stars contained no elements of the Periodic Table other than H and He, as must have been the case for the First Stars, the fragmentation process would have been different from the norm and the distribution of stellar masses would have been highly skewed in favour of the most massive stars, 10 to 100 times the mass of our Sun.

A population of massive First Stars has three important consequences, all three resulting from the fact that, in order to balance the enormous force of gravity, such stars have to burn their nuclear fuel at very high temperatures. The first consequence is that a star with a mass 10–100 times the mass of the Sun shines most brightly in ultraviolet light. Such radiation is powerful enough to ionise the hydrogen in its vicinity. When many such stars had formed, each surrounded by a bubble of ionised hydrogen, a stage was reached when the bubbles merged, and essentially all of intergalactic gas was ionised once again. This was the epoch of ‘reionisation’ (see Figure 2). However by this time ($t \sim 600$ million years), the average density of matter in the Universe was sufficiently low that photons could travel much more freely through this re-ionised intergalactic medium than was the case shortly after the Big Bang. Thus, the epoch of reionisation is actually the time when the window on our Universe is thrown wide open, and we can follow the evolution of gas, stars and galaxies from these early stages all the way to the present time using optical and infrared telescopes on Earth.

The second consequence of the high masses of the First Stars is that they lived a very short time (by astronomical standards). While a star with the mass of our Sun will burn its fuel at a rate sufficient to make it last for approximately 10 billion years, a star with the mass of one hundred Suns will consume its supply of gas much more rapidly, running out of fuel and exploding as a supernova only one or two million years after its birth. This may explain why not a single one of the First Stars, that is a star consisting only of H and He, has been discovered yet. Quite possibly, none are left today.

The third consequence is that, when these stars exploded as supernovae, they distributed over their surroundings the nuclear fusion products which had built up in their interiors during the stellar lifetime. These products include the elements C, N, O, Si, S, and Fe which are the building blocks of life. The gas

in the surroundings of these stellar explosions, now chemically enriched in elements heavier than hydrogen and helium, will later undergo further cycles of star formation. The presence of carbon, oxygen and other heavy elements in the gas allows the formation of more normal stars, including some low mass ones whose lifetimes are longer than the age of the Universe. Some of these stars are still around us today and can be found in the halos of the Milky Way and nearby galaxies. These second-generation stars only have a small fraction, 1/1000 or less, of heavy elements compared to stars that formed more recently, such as our Sun. Furthermore, the relative proportions of two such elements, such as C and Fe for example, could be very different compared with their ratio in the Sun and in other stars that formed later, after many cycles of star formation. (The Sun, being our closest star, is normally used as the standard yardstick in these chemical comparisons).

3. QUASAR ABSORPTION LINE SPECTROSCOPY

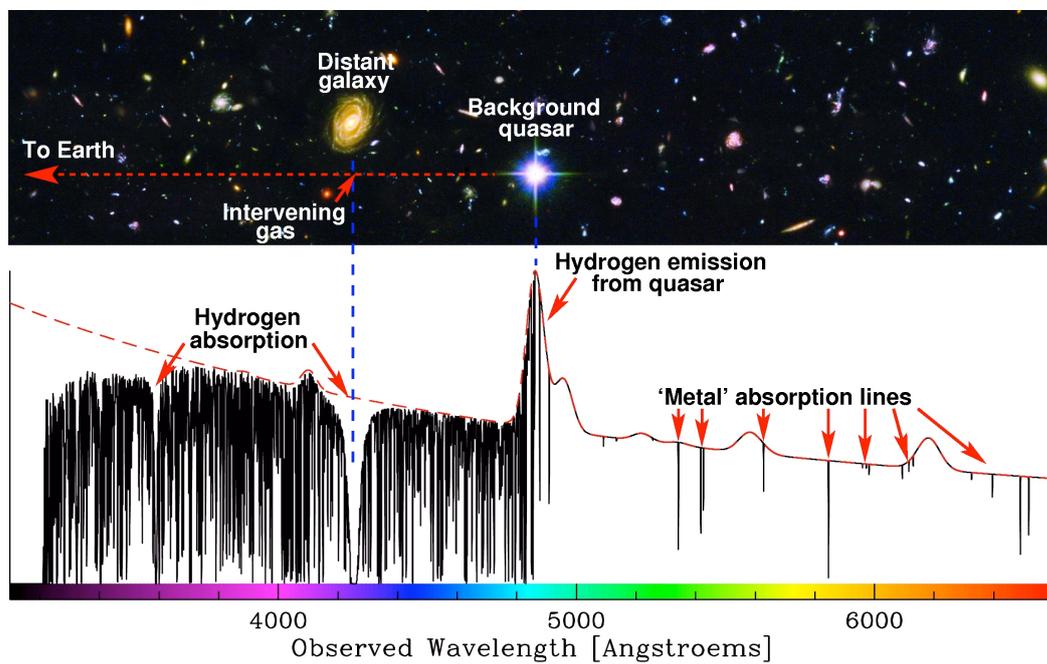


Figure 3. An illustration of the quasar absorption line technique used to probe the distant universe. Encoded in the absorption spectrum of a distant quasar is information on the physical properties of gas and galaxies fortuitously located in the path of the light rays from the quasar to us on Earth. Image courtesy of J. Webb (University of New South Wales) and M. Murphy (Swinburne University of Technology).

The chemical composition of the most metal-poor stars in our Galaxy[†] provides tantalising clues to what might have been the nucleosynthesis by the First Stars, but it is not without its problems. For one thing, stars are complex physical systems so that deducing their chemical composition from the analysis of their spectra is not straightforward. In recent years, astronomers have become acutely aware of the sensitivity of abundance measures to the physical details of the stellar atmospheres, largely through the work of Martin Asplund (at the Max Planck Institute for Astrophysics in Garching near Munich) and his collaborators. For another, almost by definition, the oldest stars in our Galaxy have the highest chance

[†] For simplicity, astronomers refer to all elements heavier than helium as ‘metals’. This is quite a different use of the term from that commonly understood by physicists and chemists. By ‘metal-poor stars’ astronomers mean stars with the least amounts of the heavy elements manufactured by stellar nuclear burning and thus closest in their chemical composition to the pristine gas that existed before the First Stars were born.

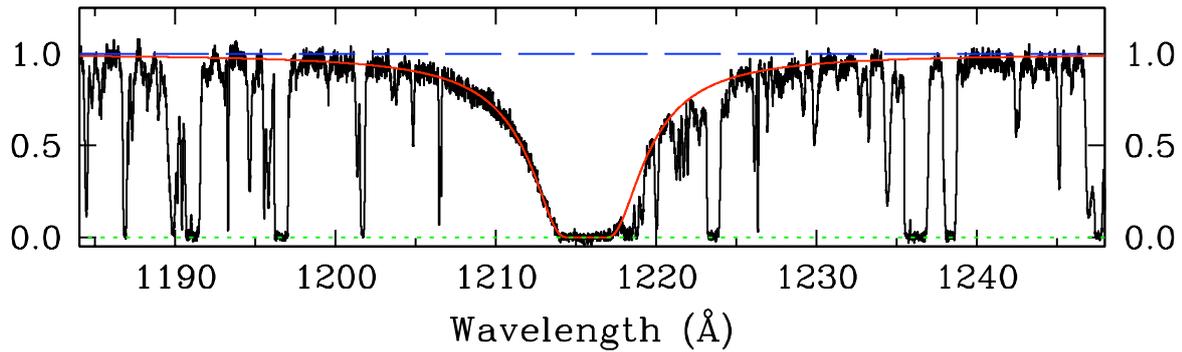


Figure 4. Example of a damped Lyman alpha ($\text{Ly}\alpha$) line. A portion of the quasar spectrum is shown in black. Many narrow absorption lines can be recognised; most of these are $\text{Ly}\alpha$ lines produced by low density gas in the intergalactic medium. The stronger damped $\text{Ly}\alpha$ line, highlighted in red, is easy to recognise, even in spectra of poorer quality than the one shown here. Such strong absorption is indicative of high surface densities of *neutral* gas, normally associated with the interstellar media of galaxies.

of having been contaminated by processed gas accreted from a companion (most stars are born in pairs) or surfacing from their interiors.

Motivated partly by the need to circumvent such difficulties, my colleagues and I have been developing an alternative method to investigate the composition of the gas ejected by the explosions of the First Stars. If the oldest stars in the halo of our Galaxy really formed from such gas, should it not be possible – by looking at very distant galaxies – to detect the gas *before* it was incorporated into a second generation of stars? Such gas, very metal-poor and perhaps with distinctive element ratios, would provide the veritable ‘missing link’ between the now defunct First Stars and the oldest stars still around us today.

To realise this goal, we have exploited the technique of ‘Quasar Absorption Line Spectroscopy’ (see Figure 3), pioneered in the mid-1970s by, among others, Alec Boksenberg, formerly at University College London and now at the Institute of Astronomy, Cambridge and Wal Sargent at the California Institute of Technology in Pasadena. The technique relies on the fact that the energetic nuclei of some galaxies, called quasars, can be intrinsically very bright and can be seen to very large distances; their spectra thus provide a backdrop against which the absorption lines produced by intervening gas, in galaxies and the intergalactic medium, can be studied in much more detail than would otherwise be possible. In Figure 3 different classes of absorption lines are indicated. Most of the ‘hydrogen absorption’ is produced by diffuse intergalactic gas, while the ‘metal absorption lines’ and the strongest hydrogen lines are thought to be associated with galaxies. In the spectrum of a given quasar there are normally many sets of absorption lines, or ‘absorption systems’. Each absorption system is at a different distance along the path travelled by the quasar light on its way to our telescopes on Earth, and therefore appears at a different redshift in the quasar spectrum (as a consequence of the universal expansion).

Among the different types of gas clouds that can produce absorption lines in quasar spectra, we have learnt to recognise those most likely to be associated with galaxies still at an early stage of evolution—the so-called ‘damped Lyman alpha systems’, or DLAs for short. These systems were first highlighted as being of particular interest for studies of galaxy evolution 25 years ago by Art Wolfe (now at the University of California, San Diego) and have been the focus of much research since then. They are very obvious in quasar spectra from the strong absorption line produced by neutral hydrogen at a rest wavelength of 1216 Å (an example is reproduced in Figure 4). More than a thousand DLAs are now known thanks to large spectroscopic surveys of the sky which have been completed in the last few years, such as the Sloan Digital Sky Survey†.

There are still diverging opinions as to what type of galaxy produces a DLA, because very few have

† <http://www.sdss.org/>

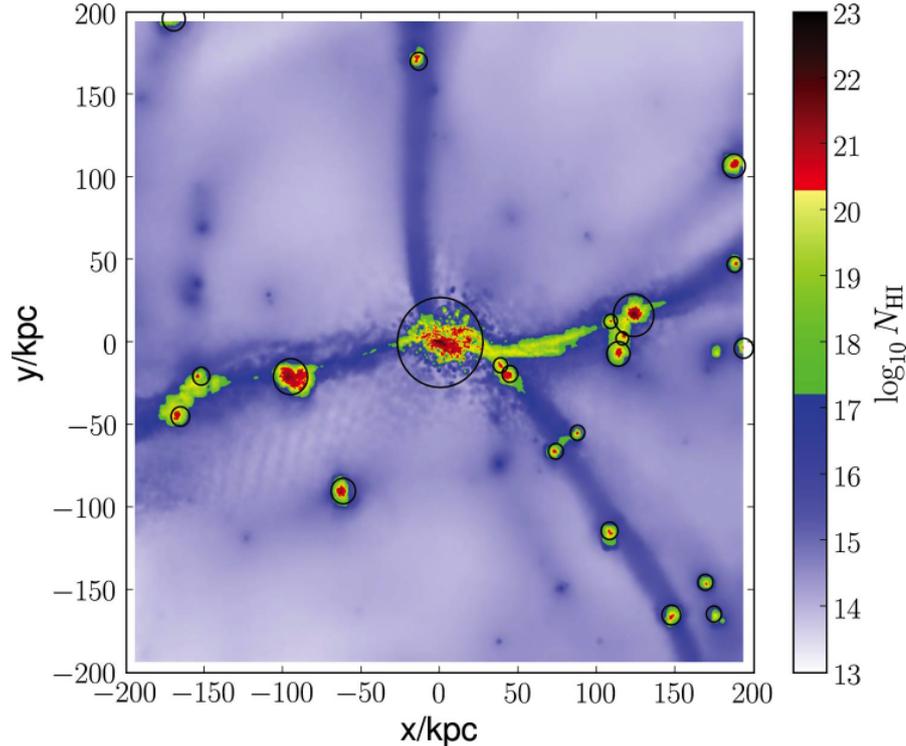


Figure 5. The Milky Way as a DLA. Computer simulations of how galaxies may have formed and evolved through the cosmic ages suggest that at redshift $z = 3$ (approximately 2 billion years after the Big Bang) the progenitor of our Milky Way Galaxy would have been a damped Ly α system. This figure, reproduced from Pontzen et al. (2008), shows a two-dimensional view of the volume around a galaxy like the Milky Way at $z = 3$. The gas in this volume is colour-coded according to its surface density of neutral hydrogen (N_{HI} , shown on the right); gas with $\log N_{\text{HI}} \geq 20.3$ (shown in red) would appear as a DLA in the spectrum of a background quasar.

actually been seen directly (as opposed to being spotted by the strong absorption lines they produce in the spectra of background quasars). In trying to associate DLAs with galaxies we are guided by the results of computer simulations which are now able to produce model universes with ever-increasing detail. An example is reproduced in Figure 5 from the work by an international team led by Andrew Pontzen at the Institute of Astronomy, Cambridge (Pontzen et al. 2008). If these simulations are a faithful representation of the real Universe, it would appear that a galaxy like our Milky Way was indeed a damped Ly α system in the distant past, in that if by a chance alignment a quasar were located behind the inner 10-20 kpc of the Milky Way (as seen by an observer outside the Galaxy), the quasar spectrum would show a strong absorption feature similar to that in Figure 4 at the same redshift as the Milky Way.

There are several advantages to using DLAs instead of stars to probe the earliest stages of cosmic chemical enrichment. Diffuse, cool gas seen in absorption is a far easier physical system to model than stellar atmospheres, so that generally there are fewer ambiguities in interpreting quasar absorption spectra compared to stellar spectra. This is especially true of the absorption spectra produced by metal-poor DLAs where ‘what you see is what you get’. In more complex environments, such as the ionised intergalactic medium or even the neutral interstellar medium of more chemically evolved galaxies, corrections often have to be made for unseen ions, or for some fraction of the gas which may have condensed into solid grains (which do not produce absorption lines), before an accurate abundance analysis can be carried out. Such corrections can be uncertain but, fortunately, they are relatively unimportant in the most metal-poor DLAs.

There are two main difficulties with the approach that my collaborators and I have taken. First, it is necessary to identify the few DLAs (literally one in a hundred or so) which have undergone the least

pollution by star formation from redshift $z \gtrsim 7$, when the First Stars are thought to have formed, to redshifts $z = 2\text{--}3$ (a period of 2–3 billion years) when DLAs are most easily studied. Second, and related to the first point, such rare examples of near-pristine gas are statistically more likely to be found in front of faint, rather than bright, quasars, simply because there are more faint quasars than bright ones. Furthermore, the spectra of these faint quasars must be recorded with great precision in order to detect and measure the weak absorption lines produced by gas with only trace amounts of chemical elements.

Thus, such work has only become possible in the last 10–15 years, with the advent of large aperture optical telescopes equipped with state-of-the-art spectrographs and detectors. Observing time on such premier facilities, such as the 10-m twin Keck telescopes on Mauna Kea in Hawaii and the four 8-m telescopes which make up the Very Large Telescope facility of the European Southern Observatory in Chile, is in great demand, requiring some patience on the part of eager astronomers! Over the last five years or so, my collaborators and I have been pursuing with determination the study of the most metal-poor DLAs, from the initial identification of the most likely candidates in preliminary low-resolution spectra through to dedicated observations of a handful of the best cases, each requiring the equivalent of one night's worth of data from the Keck and VLT telescopes. Fortunately, the scientific rewards have proved such investment highly worthwhile, as I now describe.

4. NUCLEOSYNTHESIS OF CARBON AND OXYGEN

The idea that underlies most of the following discussion is that different chemical elements are produced in different proportions by stars of different masses. For example, massive stars that explode as Type II supernovae are thought to be the main sources of oxygen. Such stars also produce some carbon. But carbon has an additional source in less massive stars, which end their lives as planetary nebulae—a less energetic but still efficient way to spread the products of stellar nucleosynthesis into interstellar space. Massive stars burn their fuel supply in only a few million years after which they end their lives as supernovae; on the other hand, lower mass stars may take a billion years before reaching the planetary nebula stage. Given these different timescales, we would expect the ratio of two elements, such as C and O, to evolve as star formation progresses in a galaxy. At first, it would reflect the relative proportions of C and O synthesised by massive stars only; later C/O would increase by the inclusion of the additional contribution from planetary nebulae.

Predicting the evolution of the ratio of two elements such as C and O in a galaxy as time progresses is a complex and uncertain business. For one thing, the exact proportions of C and O manufactured and released by stars of different masses are not measured from observations, but are calculated from nuclear reaction rates and computer models of stellar interiors. A serious complication is that the details of the stellar interiors and of stellar evolution can themselves depend on the chemical composition of the star. Furthermore, we do not have at our disposal a reliable chronometer of galactic chemical evolution; rather, we tend to use the overall metallicity (i.e. the fraction of *all* elements heavier than helium) of gas and stars as a rough clock with which to measure the progress of chemical enrichment. Our hope is that by comparing the C/O ratio (or more generally the ratios of many such pairs of elements) as a function of metallicity with the predictions of different models of galactic chemical evolution we may be able to disentangle the various physical effects at play. In this way, it may be possible not only to reconstruct the past history of a galaxy, but also to perform empirical checks on theoretical calculations of stellar yields.

The process of galaxy formation can now be modelled with increasing sophistication using computer simulations of structure formation in a cosmological context (e.g. Robertson et al. 2005; Bullock & Johnston 2005; Governato et al. 2009). Nevertheless, simplified analytical models are often convenient for understanding the chemical evolution of gas and stars in a galaxy and have been widely applied in the interpretation of stellar abundance data in the Milky Way. In the model developed by Chiappini et al. (2001), an initial rapid collapse phase lasting about one billion years led to the formation of the halo and bulge stellar populations of our Galaxy. This phase was followed by a protracted period of slow infall

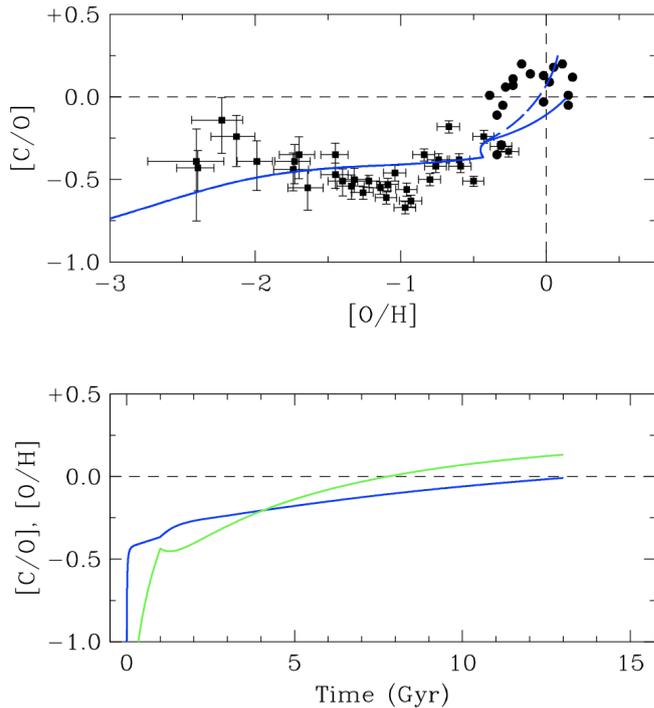


Figure 6. Values of the C/O and O/H ratios measured in stars in the disk (filled dots) and halo (filled squares) of the Milky Way Galaxy. The continuous lines show the behaviour of these element ratios expected on the basis of a widely accepted model for the chemical evolution of our Galaxy, adopting stellar yields appropriate to stars of non-zero metallicity. (Figure reproduced from Akerman et al. 2004).

which, over the course of the following 12 billion years, slowly built the spiral disk. The lower panel in Figure 6 shows how the abundance of O (green or grey line) and the relative abundances of C and O (blue or black line) are expected to grow over the lifetime of the Milky Way in such a Galactic chemical evolution model, using published C and O yields by ‘normal’ stars, that is stars similar to those we still see today in the halo and disk of the Galaxy.

According to this class of models, the oxygen abundance (green line) grew very rapidly, reaching approximately one third of the solar value after only 1 Gyr.[†] Subsequently, O/H grew much more slowly, from one third solar to just above solar over the 12 billion year period during which the disk of the Galaxy grew by slow infall of gas. In the plots in Figure 6, the transition between halo and disk has purposefully been left as a discontinuity, so as to be easily recognised in both panels. By comparing the lower and upper panels in the Figure, it can be appreciated that, while the oxygen abundance grew continuously over the lifetime of the Milky Way, it did so at a very uneven rate. Thus, while the metallicity, as measured by the O/H ratio, can in principle be used as a ‘clock’ to measure the progress of Galactic chemical evolution, in practice it is a very difficult clock to read!

Turning now to the relative abundances of C and O (blue line in both lower and upper panels of Figure 6), the model entertains an even faster rise of C/O than O/H at the very beginning. After 1 Gyr, there is a slow increase during the disk phase of not only the overall oxygen abundance O/H, but also the C/O ratio, reflecting the delayed production of C by low mass stars and other subtle effects. When Akerman et al. (2004) compared these model expectations with the abundances of C and O in a sample of Galactic halo and disk stars, they found a reasonably good agreement between theory and observations (top panel

[†] For convenience, element abundances in different astrophysical environments are normally measured on a logarithmic scale relative to the solar composition. In the notation commonly used, $[O/H] = -1$ denotes a star, or a gas cloud, with an oxygen abundance of 1/10 that of the Sun, while $[O/H] = 0$ denotes a star or gas cloud with the same relative proportions of O and H as the Sun.

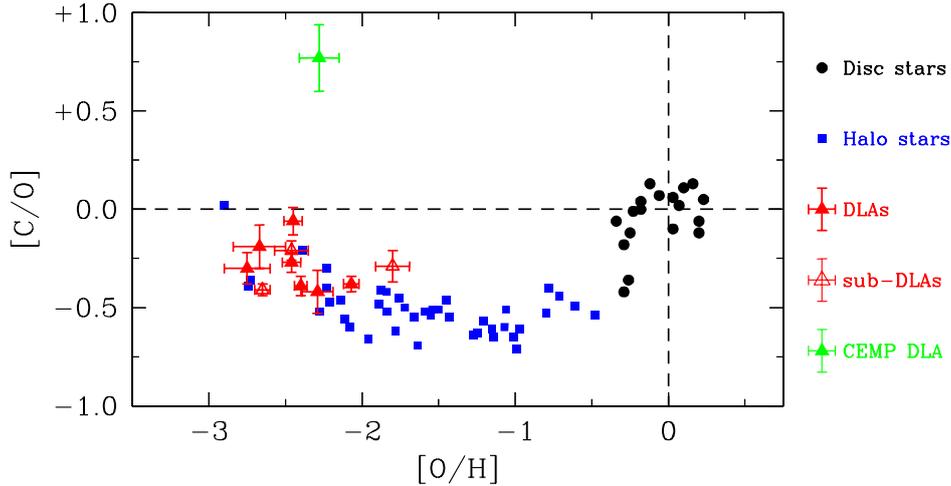


Figure 7. Carbon and oxygen abundances in Galactic stars and damped Lyman alpha systems (reproduced from Cooke et al. 2011). The DLA data confirm the stellar trend of a rise in the C/O ratio as the metallicity (as measured by O/H) decreases from 1/10 solar ($[O/H] = -1$) to 1/1000 solar ($[O/H] = -3$). At the lowest metallicities probed, the C/O ratio appears to be close to solar, contrary to expectations from models which do *not* include nucleosynthesis by the First Stars.

of Figure 6). However, they also noticed that at the lowest values of O/H probed, the C/O ratio did not appear to dive to very low values, as expected, but rather there was a possible hint that, contrary to all model calculations, C/O may actually *increase* again as O/H decreases to values less than 1/10 solar (i.e. for $[O/H] < -1$).

Intriguingly, Akerman et al. found that model and observations could be brought into good agreement with each other if one more ingredient was added to the standard model of Galactic chemical evolution: nucleosynthesis by the First Stars. Some theoretical calculations of nucleosynthesis by metal-free stars do entertain a greatly increased production of C relative to O compared to ‘normal’ stars; inclusion of these yields together with an initial mass function for the First Stars favouring high masses can indeed reproduce the stellar data and predicts that the ratio C/O was at near-solar values when the oxygen abundance was only 1/1000 of the solar value (i.e. $[C/O] \simeq 0.0$ when $[O/H] \simeq -3$).

Nagging doubts remained, however. For one thing, the number of halo stars with low values of O/H where the ratio C/O had been measured were very few, as can be appreciated from inspection of Figure 6. The sample has recently been expanded by Fabbian et al. (2009) who confirmed the trend first suspected by Akerman et al. (2004). More worryingly, Akerman et al. (2004) raised the possibility that the trend may not be real, but a result of the difficulties inherent to the interpretation of stellar spectra, particularly when the stars are very metal-poor.

Such doubts have now been dispelled by measurements of the C/O ratio in the most metal-poor DLAs (Pettini et al. 2008a; Cooke et al. 2011 and references therein; see Figure 7) which appear to confirm the stellar trend reported by Akerman et al. (2004) and Fabbian et al. (2009). The value of the DLA data is that they refer to highly redshifted galaxies, observed as they were in the distant past. Furthermore, the interpretation of the gaseous spectral features of DLAs is more straightforward than the analysis of stellar atmospheres, as explained earlier. The fact that both sets of measurements agree, in distant galaxies and in old stars of our own Galaxy, points to a universal origin for the (relatively) high values of the C/O ratio at the lowest metallicities.

The hypothesis that such high values of C/O reflect the enhanced production of C (relative to O) by a first population of metal-free stars has been strengthened by the recent discovery (Cooke et al. 2010) of a DLA with a pattern of element abundances which is acutely different from that seen in any other so

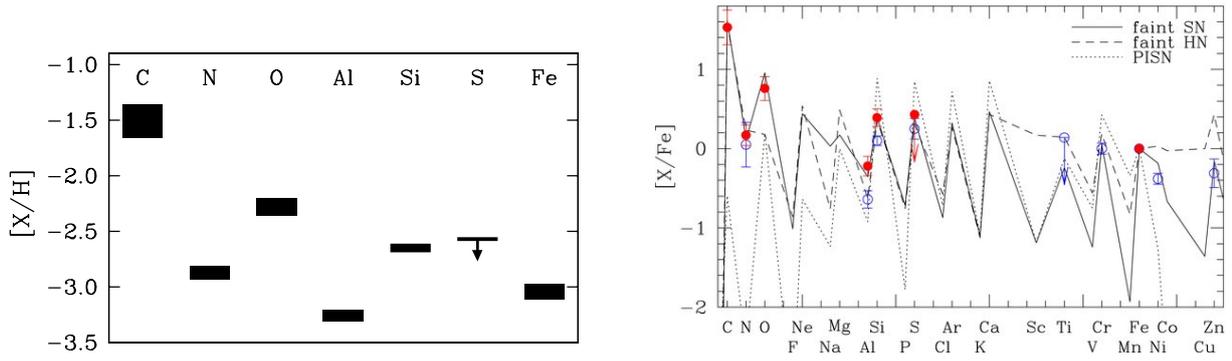


Figure 8. *Left:* Chemical composition of the CEMP DLA at redshift $z = 2.3400$ discovered by Cooke et al. (2010) from Keck HIRES observations of the SDSS quasar J0035–0918 (quasars are given names which denote their celestial coordinates). The abundances of the elements C, N, O, Al, Si, S, and Fe relative to H are shown on a logarithmic scale compared to their relative abundances in the Sun. Thus, in this DLA, Fe is less abundant than in the Sun by a factor of 1000 ($[Fe/H] \simeq -3$), while C is less abundant than in the Sun by a factor of about 30 ($[C/H] \simeq -1.5$). Such marked departures from the solar relative composition are rarely encountered; in most DLAs all the elements shown here would exhibit approximately the same level of underabundance relative to the Sun (that is, all the black squares would be at approximately the same value on the plot). The peculiar composition of this DLA points to an unusual nucleosynthesis by the stars that created these elements before they were dispersed into the gas which we see as a DLA. *Right:* Computer models of nucleosynthesis by a 25 solar mass star of primordial composition exploding as a faint supernova are able to reproduce the chemical pattern of this DLA (red dots), according to the work recently published by Kobayashi et al. (2011), from which this plot is reproduced.

far (shown by the green triangle in Figure 7). As can be seen from the left-hand panel of Figure 8, the C/O ratio in this DLA is nearly one order of magnitude greater than in the Sun, while the C/Fe ratio is 35 times solar! Such extreme departures from the solar scale of relative element abundances are rarely encountered, and are indicative of very unusual nucleosynthesis. So far, they have only been reported in some of the most metal-poor stars of the Milky Way, the so-called Carbon-Enhanced Metal Poor (CEMP) stars. The discovery of a CEMP DLA is a crucial step forward for the interpretation of these abundance anomalies. It adds considerable weight to the idea that such abundances reflect the composition of the gas from which these stars formed (presumably analogous to the gas seen in the CEMP DLA), rather than resulting from subsequent pollution of the stellar atmospheres. Also shown in Figure 8 (right panel) are the results of computer calculations of stellar nucleosynthesis by Kobayashi et al. (2011) for a 25 solar mass star of pristine composition (only hydrogen, helium and the light elements created in Big Bang nucleosynthesis) exploding as a faint supernova in the so-called mixing and fallback scenario. These calculations are able to reproduce the relative proportions of C, N, O, Al, Si, S and Fe in the high redshift CEMP-DLA remarkably well. Such good agreement lends further support to the speculation by Cooke et al. (2010) that such DLAs may be the ‘missing link’ between the First Stars to have formed in the Universe and the most ancient and most metal-poor stars in the halo of the Milky Way and neighbouring galaxies.

Encouraging as these initial results are, it would clearly be foolish to reach sweeping conclusions based on observations of a single case. However, now that we have learnt how to recognise the most pristine DLAs, it should be possible, with perseverance, to increase the sample in coming years and thereby obtain a much more rounded picture of the physical properties of the First Stars, particularly their initial mass function and the type of supernovae they gave rise to. And – who knows? – we may even be fortunate enough to stumble upon a DLA which is truly metal-free, a vestige from the time before the First Stars were born.

5. PRIMORDIAL NUCLEOSYNTHESIS

In my view, one of the most exciting opportunities afforded by observations of the most metal-poor DLAs is the possibility to go even further back in time than the epoch reionisation, to the very first few minutes after the Big-Bang, when the whole Universe resembled a star, and was hot enough to create light elements, such as deuterium and helium, out of pure hydrogen. While we cannot observe this epoch directly, as explained in Section 1, we can infer some of the most fundamental properties of the Universe by measuring the relative proportions of the light elements created by Big Bang nucleosynthesis (BBNS) in gas which has not been significantly polluted by subsequent star formation, such as metal-poor DLAs. It turns out that the relative proportions of hydrogen and its heavier isotope deuterium depend sensitively on the total baryonic content of the universe, Ω_b (see Figure 9). We can literally ‘weigh the universe’, at least in its baryons, by measuring the D/H ratio in DLAs.

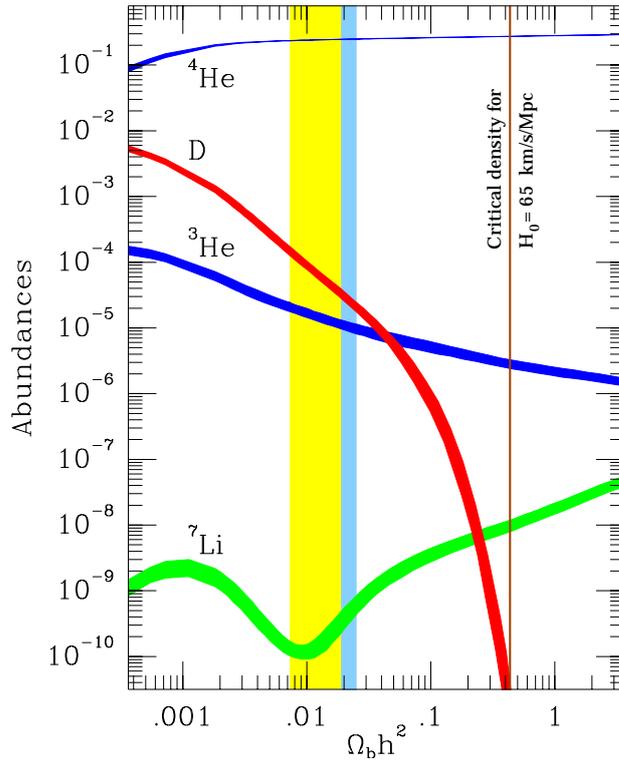


Figure 9. Relative abundances of the light elements produced by Big Bang nucleosynthesis plotted vs. the quantity Ω_b , which denotes the fraction of the critical density contributed by baryons (the ${}^4\text{He}$ abundance is mass fraction, others are by number relative to hydrogen). The widths of the curves indicate the estimated 2σ theoretical uncertainties. (Figure reproduced from Schramm & Turner 1998, *Rev. Mod. Phys.*, 70, 303).

For reasons that go beyond the scope of this review, the measurement of the D/H ratio is a very delicate one, requiring several favourable conditions to be satisfied simultaneously. While its possibility was appreciated 35 years ago (Adams 1976), it could only be realised with the current generation of large telescopes (see Pettini 2006 for a review). Even today, there’s only a handful (less than 10) of reliable measurements of the D/H ratio in DLAs and other high redshift quasar absorption systems. A recent example is reproduced in Figure 10, where the deuterium absorption can be easily recognised in five transitions of the Lyman series, from Ly δ to Ly10, blueshifted by 82 km s $^{-1}$ from the stronger absorption of atomic hydrogen. In metal-poor DLAs measurements of the column densities of H and D can be significantly easier than in other astrophysical environments, giving us some of the most reliable estimates of the D/H ratio in gas that is close to its primordial composition.

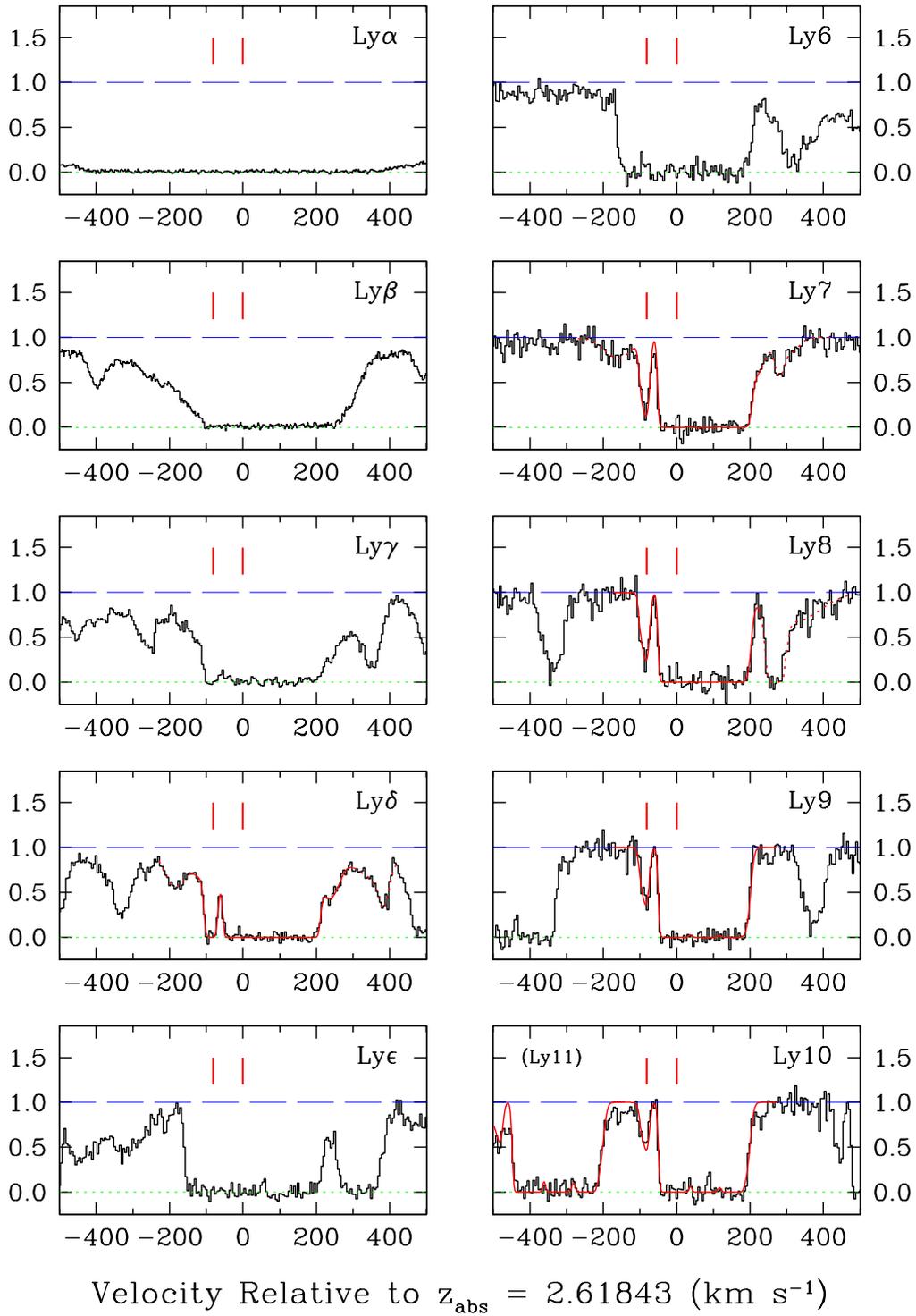


Figure 10. Absorption lines in the Lyman series of the $z = 2.61843$ DLA in the spectrum of the quasar Q0913+072 (reproduced from Pettini et al. 2008b). For each H Lyman line, there is a corresponding D Lyman line, at a slightly shorter wavelength, corresponding to a velocity shift of -82 km s^{-1} . The central locations of the two lines are indicated by the red vertical tick marks in each panel. D absorption is clearly resolved from H in five lines of the Lyman series. This is deuterium which was created in the first three minutes of the history of our Universe, and has remained intact over the next two and a half billion years to redshift $z = 2.61843$.

Despite the paucity of data, the determination of the primordial abundance of deuterium is definitely one of the ‘success stories’ of modern cosmology. The value of Ω_b implied by the mean $\langle \log(D/H)_p \rangle = -4.55 \pm 0.03$, $\Omega_b(\text{BBNS}) = 0.0426 \pm 0.0020$ (Pettini et al. 2008b), is in good agreement with that deduced from the analysis of the temperature anisotropies of the cosmic microwave background, $\Omega_b(\text{CMB}) = 0.0455 \pm 0.0012$.

As scientists, sometimes we take our achievements for granted. The fact that we can measure the cosmological density of ordinary matter in two totally independent ways—one based on a set of nuclear reactions which took place in the first few minutes in the existence of our Universe, the other on the acoustic oscillations in the mix of photons, dark matter and baryons which became imprinted on the microwave sky some 380 000 years later—and get the same answer is a remarkable success of observational cosmology and gives us confidence in the validity of the entire framework. As discussed by Pettini (2006), independent knowledge of the universal density of ordinary matter allows us to improve the precision of other cosmological quantities determined from the analysis of the cosmic microwave background. Furthermore, since deuterium is easily destroyed in stars, the comparison between the primordial and present-day values of the abundance of deuterium gives a measure of the degree to which gas has been processed through stars throughout the history of the Milky Way, which in turn depends on the initial mass function and the stellar yields.

Thus, observations of metal-poor DLAs have contributed in their own way to what is often referred to as ‘today’s consensus cosmology’. Most scientists now agree on the values of the most important cosmological parameters. As far as we can tell, the components of our Universe are in the following proportions: 4% baryons, 22% dark matter, and 74% dark energy. But to me the term ‘consensus cosmology’ also has an ironic connotation, because we remain profoundly ignorant of the nature of dark matter and dark energy, which make up 96% of the mass-energy budget, and most fundamentally, we have no idea as to the underlying physics which determines these fractions. Sometimes I wonder what past fellows of the Royal Society would make of such ‘progress’.

The research described in this review is a joint effort by many scientists with whom I have been very fortunate to collaborate over the years. I am grateful to the various telescopes time allocation committees who have consistently supported our work. Finally, I should like to express my gratitude to Prof. Alec Boksenberg, FRS and Prof. Bernard Pagel, FRS who have been continuing sources of inspiration and guidance throughout my career.

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