Mem. S.A.It. Vol. 85, 192

Memorie della

Precision measures of the primordial deuterium abundance

R. J. Cooke[1]*, M. Pettini[2,3], R. A. Jorgenson[4], M. T. Murphy[5], and C. C. Steidel[6]

[1] Department of Astronomy and Astrophysics, UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA, e-mail: `rcooke@ucolick.org`
[2] Institute of Astronomy, Madingley Road, Cambridge, UK, CB3 0HA
[3] Kavli Institute for Cosmology, Madingley Road, Cambridge, UK, CB3 0HA
[4] Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA
[5] Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia
[6] California Institute of Technology, MS 249-17, Pasadena, CA 91125, USA

Abstract. Near-pristine damped Lyman-α systems (DLAs) are the ideal environments to measure the primordial abundance of deuterium. In this conference report, I summarise our ongoing research programme to obtain the most precise determination of the primordial deuterium abundance from five high redshift DLAs. From this sample, we derive $(\mathrm{D/H})_\mathrm{p} = (2.53 \pm 0.04) \times 10^5$, corresponding to a baryon density $100\,\Omega_{\mathrm{b},0}\,h^2 = 2.202 \pm 0.046$ assuming the standard model of Big Bang Nucleosynthesis. This value is in striking agreement with that measured from the temperature fluctuations imprinted on the cosmic microwave background. Although we find no strong evidence for new physics beyond the standard model, this line of research shows great promise in the near-future, when the next generation 30+ m telescopes equipped with echelle spectrographs come online.

Key words. Galaxies: abundances – quasars: absorption lines – Cosmology: observations – Cosmology: primordial nucleosynthesis

1. Introduction

For almost four decades, it has been recognised that a measurement of deuterium absorption in Lyman-α clouds at cosmological distances would have terrific implications for cosmology and Big Bang Nucleosynthesis (Adams 1976). However, it took almost 20 years to obtain the first secure detection of deuterium in high-redshift Lyman limit systems (Tytler, Fan, & Burles 1996), providing an estimate of the primordial abundance of deuterium, $(\mathrm{D/H})_\mathrm{p}$, to a precision of $\sim$ 10 per cent (Burles & Tytler 1998a,b). Shortly after these first discoveries, it was realised that metal-poor damped Lyman-α systems (DLAs), with neutral H column densities in excess of $\sim 10^{20}$ cm^{-2}, had the potential to revolutionise the study of $(\mathrm{D/H})_\mathrm{p}$, potentially delivering very precise measurements of the primordial D/H ratio (Pettini & Bowen 2001; D'Odorico, Dessauges-Zavadsky, & Molaro 2001).

* Morrison Fellow

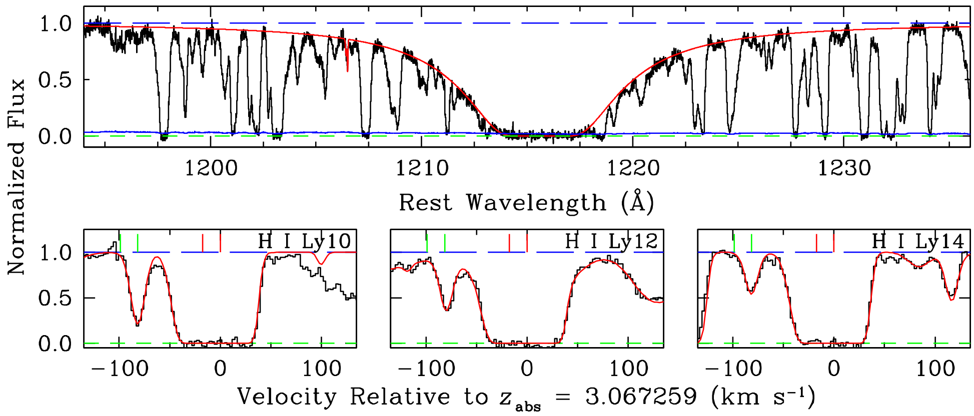

Fig. 1. *Top Panel:* H I Lyα absorption line from the DLA (black histogram) together with the best-fitting model absorption profile (red line). *Bottom Panel:* High order Lyman series H I and D I absorption lines are respectively marked by the red and green tick marks above the spectrum. For all panels, the data and absorption model have been divided by the underlying QSO continuum model.

As part of our dedicated survey to discover and characterise the most metal-poor DLAs (Pettini et al. 2008a; Cooke et al. 2011a,b; Cooke, Pettini, & Murphy 2012), we have uncovered a handful of systems with remarkably clean Lyman series lines (Pettini et al. 2008b; Pettini & Cooke 2012; Cooke et al. 2014), including one system where the red wing of the DLA's Lyα absorption line is almost entirely uncontaminated. In principle, such systems offer an ideal setup to *precisely* measure the primordial deuterium abundance; the damping wings of the DLA's Lyα absorption line (which uniquely determines the total column density of H I atoms along the line-of-sight) in combination with the large number of D I Lyman series lines of varying strength (which pins down the column density of D I atoms along the line-of-sight), ensures that a measurement of $(D/H)_p$ can be obtained at a precision of ~ 3 per cent for an individual system.

This realisation encouraged us to identify and self-consistently reanalyse all literature systems where precise measures of $(D/H)_p$ are possible. In this conference report, we describe the main results of our analysis of this precision sample of primordial deuterium abundances.

2. Data

Our data were acquired with the echelle spectrographs UVES and HIRES, operating on the European Southern Observatory (ESO) Very Large Telescope (VLT) and on the Keck I telescope respectively. A sample of the data from our latest discovery (Cooke et al. 2014) is reproduced in Fig. 1. In addition to this new discovery, the literature systems used in our reanalysis include: the $z_{abs} = 2.53651$ sub DLA towards the quasar HS0105+1619 (O'Meara et al. 2001), the $z_{abs} = 2.61829$ DLA along the line-of-sight to Q0913+072 (Pettini et al. 2008b), the DLA at $z_{abs} = 3.04973$ towards J1419+0829 (Pettini & Cooke 2012), and the $z_{abs} = 2.70242$ DLA towards J1558−0031 (O'Meara et al. 2006).

3. Analysis and results

3.1. A novel technique

In order to accurately measure the level of D I and H I absorption, the emission from the quasar must be modelled to a high-level of accuracy. To overcome the uncertainty (and potential bias) in the placement of the QSO continuum, we have developed a new suite of software routines that successfully models the

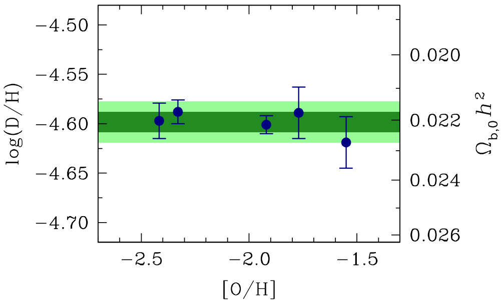

Fig. 2. The five best measures of the primordial deuterium abundance to date (symbols with error bars). The standard model of BBN offers a conversion between the D/H ratio and the baryon density of the Universe, $\Omega_{b,0}\,h^2$. This conversion is shown on the right axis. The green horizontal bands show the 1σ and 2σ bounds for $\Omega_{b,0}\,h^2$ derived from the cosmic microwave background radiation recorded with the Planck satellite (Planck Collaboration 2013). *Modified from Cooke et al. (2014).*

quasar emission spectrum *simultaneously* with the DLA absorption. The uncertainty for the derived D/H ratio from our Absorption LIne Software (ALIS) therefore includes the uncertainty in the QSO continuum placement.

To alleviate human bias (as much as possible), we adopted a 'blind' analysis strategy, whereby the best-fitting D/H value was hidden entirely from view until we deemed the best-fit had been achieved. Once we were satisfied with the best-fitting results, the D/H ratio was revealed, and this is the value we report – no further changes were made to the cloud modelling.

3.2. Cosmological Implications

We consider the five D/H measurements obtained from our study to be independent determinations of the primordial abundance of deuterium. These results are shown in Fig. 2 as the symbols with error bars. A weighted mean of these values corresponds to a primordial deuterium abundance, expressed as a logarithmic and linear quantity:

$$\log\,(\mathrm{D/H})_{\mathrm{p}} = -4.597 \pm 0.006 \quad (1)$$

$$10^5\,(\mathrm{D/H})_{\mathrm{p}} = 2.53 \pm 0.04 \quad (2)$$

For the standard model of BBN, the $(\mathrm{D/H})_{\mathrm{p}}$ ratio can be converted into an estimate of the baryon-to-photon ratio, which in turn can be expressed as the density of baryons in the Universe (see e.g. Steigman 2012), from which we derive:

$$100\,\Omega_{b,0}\,h^2 = 2.202 \pm 0.046 \quad (3)$$

which is in remarkable agreement with that deduced by the *Planck* team from the cosmic microwave background radiation (Planck Collaboration 2013):

$$100\,\Omega_{b,0}\,h^2 = 2.205 \pm 0.028 \quad (4)$$

The fact that these two measurements of the same cosmological quantity agree, based on completely independent techniques from two epochs separated by some 370 000 years, gives strong support to the standard model of cosmology and particle physics.

3.3. The search for new physics

Nevertheless, we can still explore the exciting possibility of deviations from the standard model. One possibility is that there is an excess radiation density beyond that predicted by the standard ΛCDM+BBN cosmology (e.g. dark radiation, sterile neutrinos etc.), often parameterised as an effective number of neutrino species (N_{eff}, which for the standard model $\simeq 3.046$). This signature can be teased out by combining measures of the primordial nuclides. For example, by combining the ^{4}He mass fraction and the primordial deuterium abundance we are able to place a strong, simultaneous bound on both N_{eff} and $\Omega_{b,0}\,h^2$, as shown in Fig. 3. The joint analysis provides the following BBN-only bounds on these quantities: $N_{\mathrm{eff}} = 3.50 \pm 0.20$ and $100\,\Omega_{b,0}\,h^2 = 2.28 \pm 0.05$. We thus conclude that there is still no strong evidence for new physics beyond the standard model, given the current data.

4. Conclusions

We have discovered a handful of near-pristine DLAs where precision estimates of the primordial abundance of deuterium can be obtained. In light of these discoveries, we have

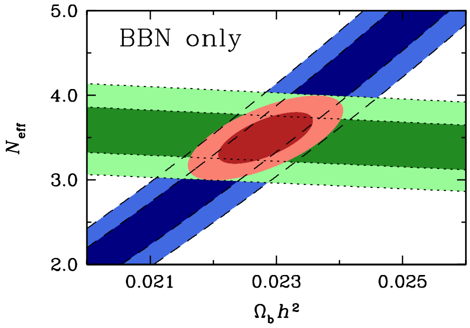

Fig. 3. The 1σ and 2σ confidence contours (dark and light shades respectively) for the current best estimates of the primordial deuterium abundance (blue; Cooke et al. 2014) and the primordial ^{4}He mass fraction (green; Izotov et al. 2013). The red contours are the combined confidence limits. *Reproduced from Cooke et al. (2014).*

conducted a self-consistent reanalysis of the best available literature systems and estimate the primordial abundance of deuterium to be $(2.53 \pm 0.04) \times 10^5$. Our study has also alleviated the 'deuterium dispersion' problem – that the quoted (D/H) values exhibit a larger scatter than the quoted uncertainties.

For the standard model of BBN, this corresponds to a baryon density $100\,\Omega_{b,0}\,h^2 = 2.202 \pm 0.046$, in excellent agreement with the recent determination from the cosmic microwave background recorded with the *Planck* satellite. At present, we find no strong evidence for new physics beyond the standard model, with a BBN-only bound on the effective number of neutrino species $N_{\rm eff} = 3.50 \pm 0.20$.

The outlook for this line of research is highly promising. We have already identified dozens of excellent metal-poor DLAs that are along the line-of-sight to faint quasars. Unfortunately, a reliable chemical abundance analysis for these DLAs will have to wait for the next generation of ground-based optical telescopes with 30+ m aperture, which will be able to feasibly observe these faint quasars. Such studies will bring us ever-closer to understanding the properties of the elusive first stars, and open a new era of high precision cosmology by measuring the primordial chemistry of our Universe.

Acknowledgements. Our dedicated observational programme required the combined efforts of the ESO VLT facility and the W. M. Keck observatory. We are most grateful to the time allocation panels for access to these facilities, and for their ongoing support of this demanding observational programme. Finally, I wish to thank the organisers of *Metal Production and Distribution in a Hierarchical Universe*, for arranging a highly successful and thoroughly enjoyable meeting.

References

Adams, T. F. 1976, A&A, 50, 461
Burles, S., Tytler, D. 1998a, ApJ, 499, 699
Burles, S., Tytler, D. 1998b, ApJ, 507, 732
Cooke, R., Pettini, M., Steidel, C. C., Rudie, G. C., Jorgenson, R. A. 2011a, MNRAS, 412, 1047
Cooke, R., Pettini, M., Steidel, C. C., Rudie, G. C., Nissen, P. E. 2011b, MNRAS, 417, 1534
Cooke, R., Pettini, M., Murphy, M. T. 2012, MNRAS, 425, 347
Cooke, R. J., Pettini, M., Jorgenson, R. A., Murphy, M. T., & Steidel, C. C. 2014, ApJ, 781, 31
D'Odorico, S., Dessauges-Zavadsky, M., Molaro, P. 2001, A&A, 368, L21
Izotov, Y. I., Stasińska, G., & Guseva, N. G. 2013, A&A, 558, A57
O'Meara, J. M., Tytler, D., Kirkman, D., Suzuki, N., Prochaska, J. X., Lubin, D., Wolfe, A. M. 2001, ApJ, 552, 718
O'Meara, J. M., Burles, S., Prochaska, J. X., Prochter, G. E., Bernstein, R. A., Burgess, K. M. 2006, ApJ, 649, L61
Pettini, M., & Bowen, D. V. 2001, ApJ, 560, 41
Pettini, M., & Cooke, R. 2012, MNRAS, 425, 2477
Pettini, M., Zych, B. J., Steidel, C. C., Chaffee, F. H. 2008a, MNRAS, 385, 2011
Pettini M., Zych B. J., Murphy M. T., Lewis A., Steidel C. C., 2008b, MNRAS, 391, 1499
Planck Collaboration 2013, arXiv:1303.5076
Steigman, G. 2012, arXiv:1208.0032
Tytler, D., Fan, X.-M., Burles, S. 1996, Nature, 381, 207