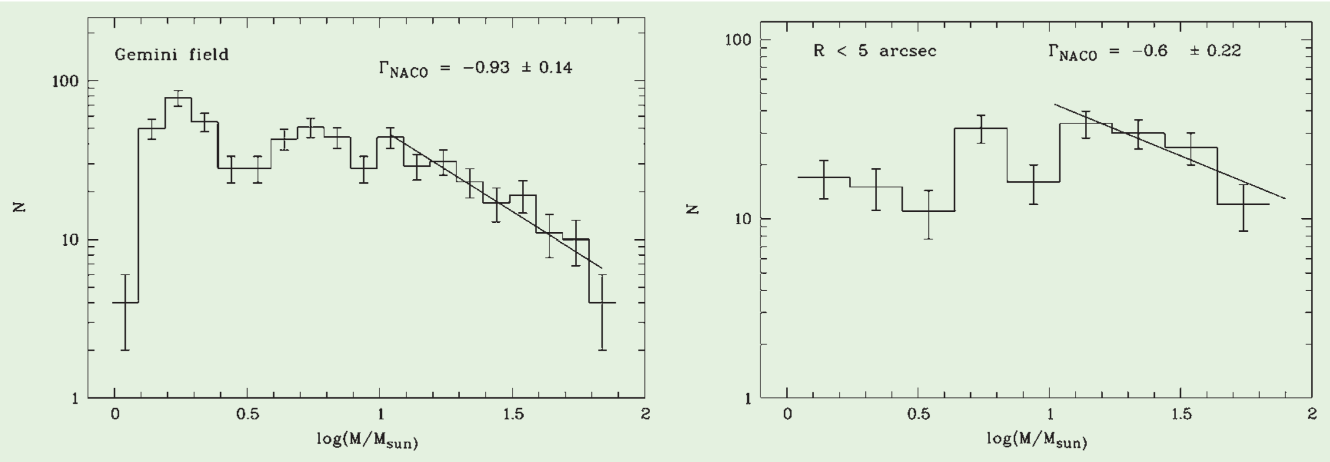

Figure 5: Mass Function of the Arches cluster. Left panel: The area within the Gemini FOV has been selected, such that the MF corresponds to the CMD displayed in Figure 3. A linear change in extinction over the field has been corrected, and a colour cut of 1.35 < H-K < 1.77 mag has been applied to the corrected CMD to select Arches main-sequence stars. The Arches main sequence can clearly be identified down to 18.3 mag in K-band, or 2.5 $M_\odot$ ($\log M/M_\odot = 0.4$), beyond which the bulge population dominates the CMD. Right panel: The mass function of Arches cluster centre stars observed with NACO. Stars within $R < 5''$ are included. A weighted least-squares fit has been performed on data points above 10 $M_\odot$. The MF in the cluster centre appears flatter than the integrated MF, indicating mass segregation.

mer cluster membership of ejected stars. High-resolution NIR spectrographs such as CRIRES expected to go into operation in the next years have the capability to overcome the huge line of sight obscuration towards the Galactic Centre. The determination of spectral types with SINFONI/SPIFFI allows one to disentangle the cluster members from the dense background population, thereby yielding accurate estimates on the field star contamination when deriving mass functions. With these prospects in mind, spectroscopic observations may shed light on the unsolved questions of massive star formation in a dense environment.

8. Conclusions

NAOS-CONICA data of the dense stellar field in the Arches cluster centre yield significantly better spatial resolution than NICMOS on HST. About 50% more stars are resolved in the cluster centre down to the same magnitude limit. The luminosity functions reveal that each magnitude interval up to the brightest stars was affected by crowding losses before. The NACO observations of the densest cluster region within $R < 5''$ are 75% complete down to H = 19.4 mag and K = 17.7 mag or ~ 3 $M_\odot$, while HST/NICMOS and Gemini/Hokupa'a observations were limited to ~10–20 $M_\odot$ in the immediate cluster centre. While a lower Strehl ratio is responsible for the lower performance in the Hokupa'a data, the NICMOS resolution is limited by the smaller HST mirror and correspondingly larger diffraction limit. As we have shown, even moderate AO performance using faint visual reference sources (V = 16 mag) now achieves higher spatial resolution from the ground while at the same time exploiting the light collecting power and sensitivity of 8-m-class telescopes. Thus, a much more complete census of stellar populations in dense fields in our own Galaxy as well as in nearby resolved galactic systems is possible with ground-based AO instruments such as NAOS-CONICA.

References

Blum, R. D., Schaerer, D., Pasquali, A., et al. 2001, *AJ*, **122**, 1875.

Brandner, W., Grebel, E. K., Barbá, R. H., et al. 2001, *AJ*, **122**, 858.

Brandner, W., Rousset, G., Lenzen, R., Hubin, N. et al. 2002, *The Messenger* No. **107**, 1.

Cotera, A.S., Erickson, E.F., Colgan, S.W.J., Simpson. J.P., Allen, D.A., & Burton, M.G., 1996, *ApJ*, **461**, 750.

Devillard, N. 1997, *The Messenger* No **87**, 19.

Eisenhauer, F., Quirrenbach, A., Zinnecker, H., Genzel, R. 1998, *ApJ*, **498**, 278.

Figer, D.F., Najarro, F., Gilmore, D., et al. 2002, *ApJ*, **581**, 258.

Figer, D.F., Kim, S.S., Morris, M., et al. 1999, *ApJ*, **525,** 750.

Lejeune, T., & Schaerer, D. 2001, *A&A*, **366**, 538.

Lenzen, R., Hoffmann, R. et al. 1998, *SPIE* **3354**, 606.

Massey, P., Johnson, K.E., Degioia-Eastwood, K. 1995, *ApJ*, **454**, 151.

Rieke, G.H., & Lebofsky, M.J. 1985, *ApJ*, **288**, 618.

Rousset, G., Lacombe, F. et al. 2002, *SPIE* **4007**, 72.

Salpeter, E.E. 1955, *ApJ*, **121**, 161.

Scalo, J.M. 1998, in *ASP Conf. Ser.*, Vol. **142**, The stellar initial mass function, 201.

Schoedel, R., Ott, T., Genzel, R. et al. 2002, *Nature* **419**, 694.

Stetson, P.B. 1987, *PASP*, **99**, 191.

Stolte, A., Grebel, E.K., Brandner, W., Figer, D.F., 2002, *A&A*, **394**, 462.

Tessier, E., Bouvier, J., Beuzit, J.-L., Brandner, W. 1994, *The Messenger* No. **78**, 35.

Early Galactic Chemical Evolution with UVES

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The UVES instrument on the ESO VLT2 telescope has now been providing high-resolution spectra of faint stars and galaxies for nearly three years. European astronomers have taken advantage of this new facility to conduct extensive and accurate studies of the first stellar generations of our Galaxy, and to probe the chemical composition of gas in the high-redshift universe. In November of last year, a workshop on the theme "Early Galactic Chemical Evolution with UVES" was held at the ESO headquarters in Garching. Attended by more than 50 stellar and extragalactic astronomers, the workshop served as a focus to bring together scientists interested in the general theme of how the chemical enrichment of galaxies progressed over the cosmic ages, from the Big Bang to the present time. The meeting proved to be a valuable opportunity to exchange ideas, assess progress to date, and to chart fu-

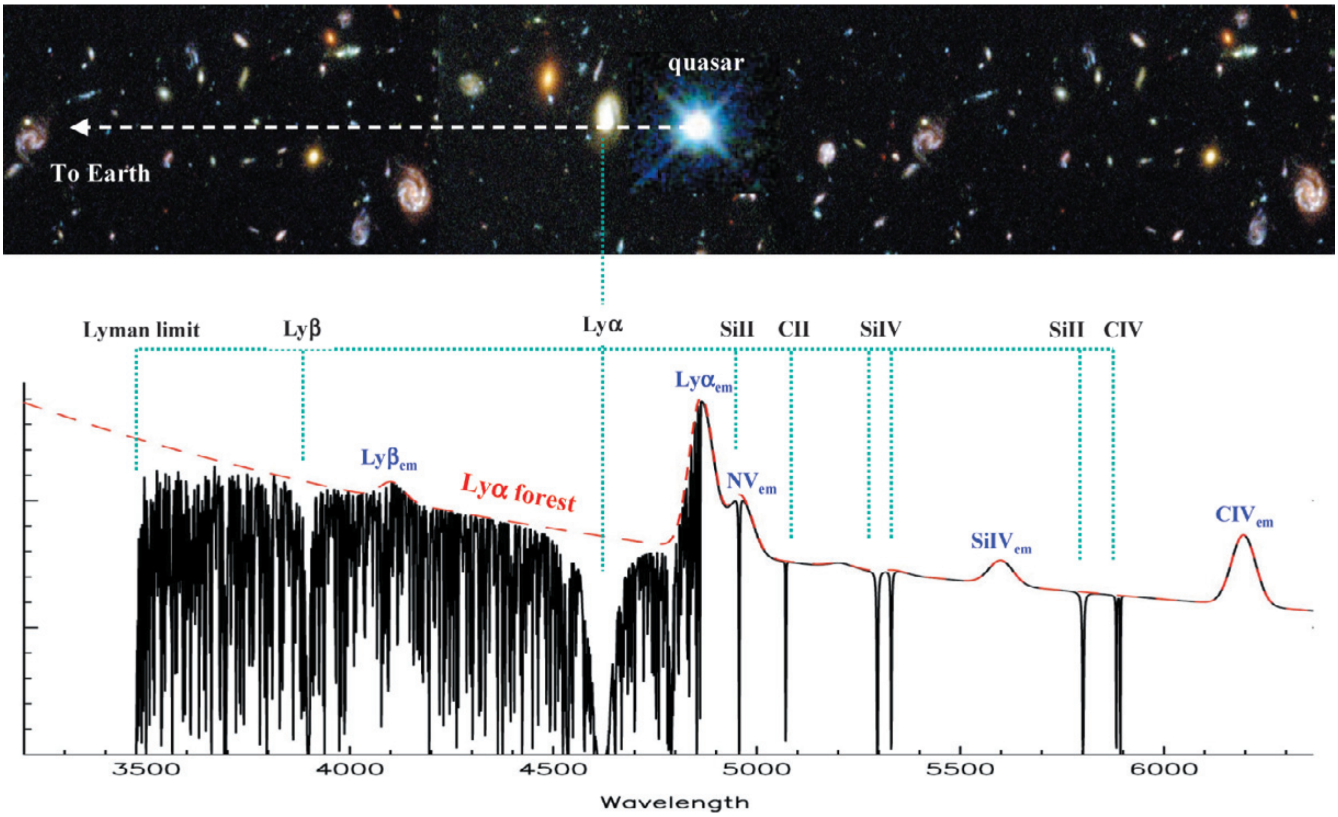

Figure 1: The technique of QSO absorption line spectroscopy is illustrated in this montage (courtesy of John Webb). QSOs are among the brightest and most distant objects known. On the long journey from its source to our telescopes on Earth, the light from a background QSO intercepts galaxies and intergalactic matter which happen to lie along the line of sight (and are therefore at lower absorption redshifts than the QSO emission redshift). Gas in these structures leaves a clear imprint in the spectrum of the QSO in the form of narrow absorption lines which carry a wealth of information on the physical properties and chemical composition of the gas producing the absorption. The strong absorption feature near 4600 Å is a damped Lyman alpha line.

ture directions of research in this field of study. In this article, I highlight some of the extragalactic aspects of the workshop, concentrating in particular on recent developments in the study of element abundances at high redshifts.

To set the scene for the non-specialists, let me just clarify a couple of points. First, to astronomers the words 'high redshift' are synonymous with 'a long time ago'. With UVES on the VLT we can observe galaxies – and measure their chemical composition – at a time when the universe was only 10–20% of its present age. Second, the technique which is most widely used for detailed measurements of element abundances in these distant (both in space and time) reaches of the universe is QSO absorption-line spectroscopy, illustrated in Figure 1. The galaxies are generally not seen directly, but through the absorption they cast in the spectra of background bright sources, such as quasars (or QSOs for short).

The Primordial Abundance of Deuterium

Among the light elements created in the Big Bang, Deuterium is the one whose abundance is most sensitive to the density of baryons in the universe. Astronomers have been aware since the 1970s of the potential of QSO absorption line spectroscopy for the determination of the ratio of deuterium to hydrogen (D/H). If D could be found in distant galaxies which have experienced little star formation, the D/H ratio measured in their interstellar media should be very close to the primordial value. However, this technique has had to wait for more than twenty years to be implemented, since it requires recording the light of relatively faint sources at high spectral resolution and signal-to-noise ratio – a combination which only echelle spectrographs on 8–10-m-class telescopes can deliver. Even with current technology these are still difficult observations, and this is why the total sum of available data today consists of only five measurements (plus one upper limit), obtained with UVES on VLT2, HIRES on the Keck I telescope, and the *Hubble Space Telescope*.

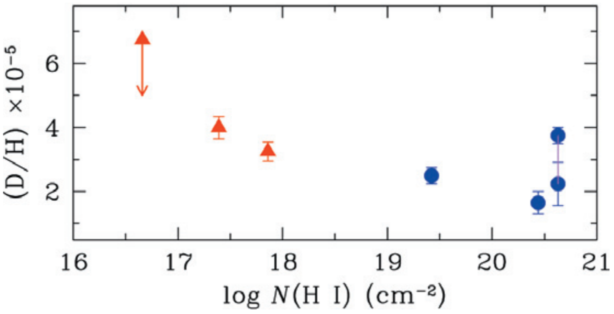

Figure 2: Available measurements of the abundance of deuterium at high redshift (plotted against the neutral hydrogen column density) obtained via QSO absorption line spectroscopy of either Lyman limit (red triangles) or damped Lyman alpha (blue circles) systems. (Adapted from Pettini & Bowen 2001).

These data are reproduced in Figure 2. The mean value from the five detections is $\langle D/H \rangle = (2.6 \pm 0.2) \times 10^{-5}$ which in turn corresponds to a density of baryons $\Omega_B = 0.05$ (for a value of the Hubble constant of 65 km s^{-1} Mpc^{-1}). That is, the baryons of our familiar physical world only make up 5% of the critical density of the universe. Furthermore, since the currently favoured value of the density of matter, in all its forms, is $\Omega_M = 0.3$, the primordial abundances of deuterium and other light elements are one of the strongest pieces of evidence we have for the existence of non-baryonic dark matter, which outnumbers the baryons by 5 to 1.

The value $\Omega_B = 0.05$ now seems secure since an entirely different method for its determination, which uses the power spectrum of the cosmic microwave background, has recently been shown to give results in excellent agreement with those from primordial nucleosynthesis. Thus the problem can be considered ‘solved’... or can it? There are some remaining nagging doubts as to the origin of the dispersion of the different measurements which, as can be seen from Figure 2, deviate from the mean by several times their estimated (random) errors. Is this scatter real, or just evidence for unrecognised systematic errors? Experience would tell us that the second possibility is the more likely, except that when we measure the D/H ratio in the solar neighbourhood we also find an unexplained dispersion in the data. Figure 3 is the most recent compilation of the best relevant data, all obtained with space missions. While all the measurements in the interstellar medium within 100 parsecs of the Sun are in agreement at D/H = 1.6 × 10^{-5}, interstellar sightlines to more distant stars span a range of almost a factor of three. There is a general agreement that this dispersion is both real and unexplained. The puzzle arises because the ISM is well mixed over these distances and shows a high degree of uniformity in other chemical elements such as nitrogen and oxygen, so why should D be different? We know of no way of either producing deuterium nor of destroying it selectively. The scatter we see beyond 100 pc of the Sun is comparable to the total amount of astration of deuterium (its destruction through star formation) over the lifetime of the Milky Way. It therefore seems really important to establish whether such a scatter also exists in other galaxies, particularly those at high redshifts which we see as QSO absorption line systems and which give us our estimate of the primordial D/H ratio. There is thus a strong incentive to improve the statistics in Figure 2 with more measurements with UVES, once suitable background QSOs have been identified. This should be easier now than it has been in the past, thanks to the large numbers of new quasars discovered by on-going large-scale surveys of the sky.

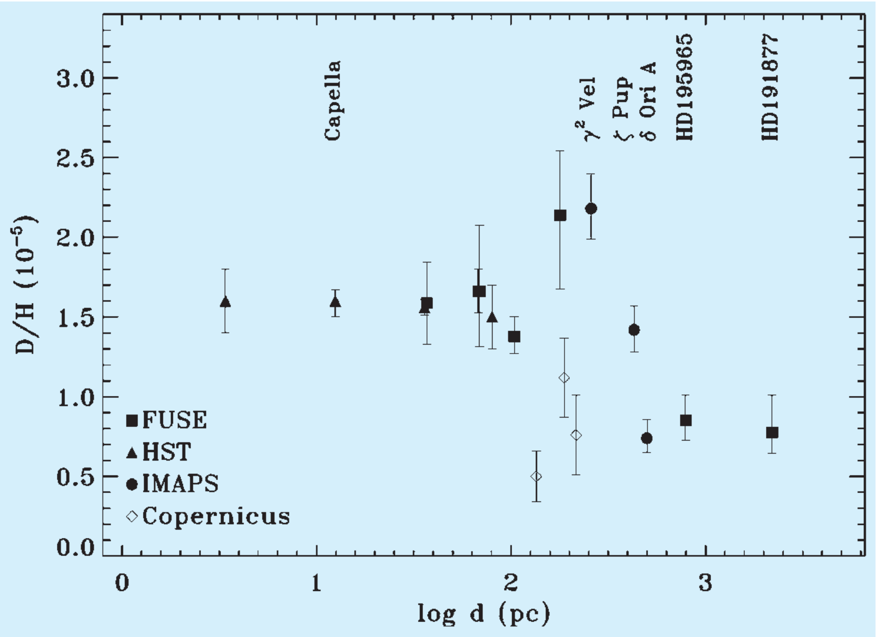

Figure 3: Compilation of available measurements of the abundance of deuterium in the Milky Way interstellar medium, all obtained with space missions as indicated in the legend, as a function of distance from the sun. (Reproduced from Hoopes et al 2003.)

Element Abundances in Damped Lyman Alpha Systems

This class of QSO absorbers, known as DLAs for short, are characterised by large column densities of neutral hydrogen, in excess of 2 × 10^{20} H atoms per square cm. The general view is that they probably represent some early stage in the evolution of the galaxies we see around us today, perhaps at a time shortly after they had condensed out of the intergalactic medium, but before they had had time to form many stars, so that most of their mass still resided in the interstellar medium. While astronomers still debate how DLAs are related to other populations of galaxies seen at high redshift, one thing is clear: they are our best laboratory – by far – for measuring the abundances of a wide variety of elements in the young universe. The bright background light of the quasars in which they are seen allows studies of unprecedented detail with instruments such as UVES.

If we look back to the scientific cases written in the 1980s to seek funds for the construction of large telescopes, we see that the study of element abundances in QSO absorbers such as DLAs figured very prominently. And indeed, right from its commissioning days on the telescope, European astronomers have put UVES through its paces with observations of DLAs, capitalizing in particular on the instrument’s world-beating efficiency throughout the optical spectrum, from ultraviolet to far-red wavelengths. Some European highlights in this field include: the discovery and study of some of the highest redshift DLAs, up to $z_{\rm abs}$ = 4.466 which in today’s favoured cosmology corresponds to only 1.5 billion years after the Big Bang; much improved statistics on the metallicities of DLAs at redshifts greater than 3, based on the abundance of Zn; and the first comprehensive search for molecular hydrogen at

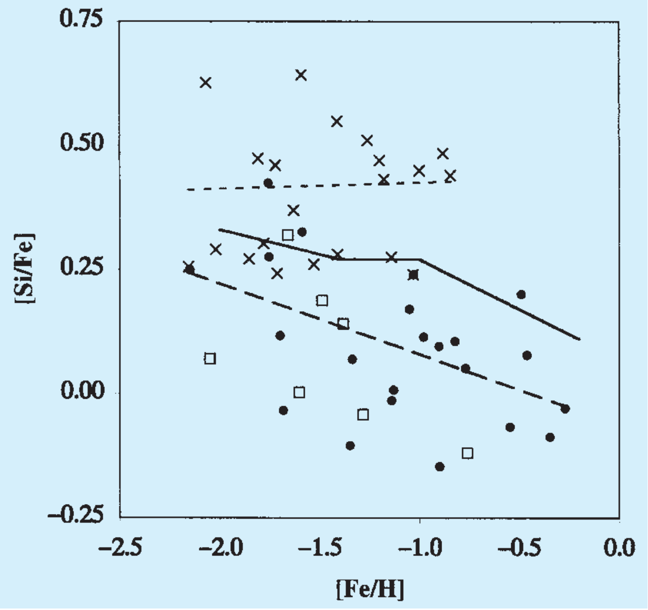

Figure 4: Relative abundances of Si and Fe in damped Lyman alpha systems. Abundances are expressed on a logarithmic scale relative to the solar composition, so that [Fe/H] = –1 denotes an abundance of iron relative to hydrogen equal to one tenth of the solar value. The meanings of the different symbols are given in the legend. Short- and long-dashed lines show the average trends of [Si/Fe] vs [Fe/H] before and after correction for the fractions of Si and Fe locked up in dust grains. The continuous line shows the mean trend for Galactic stars. (Adapted from Vladilo 2002.)

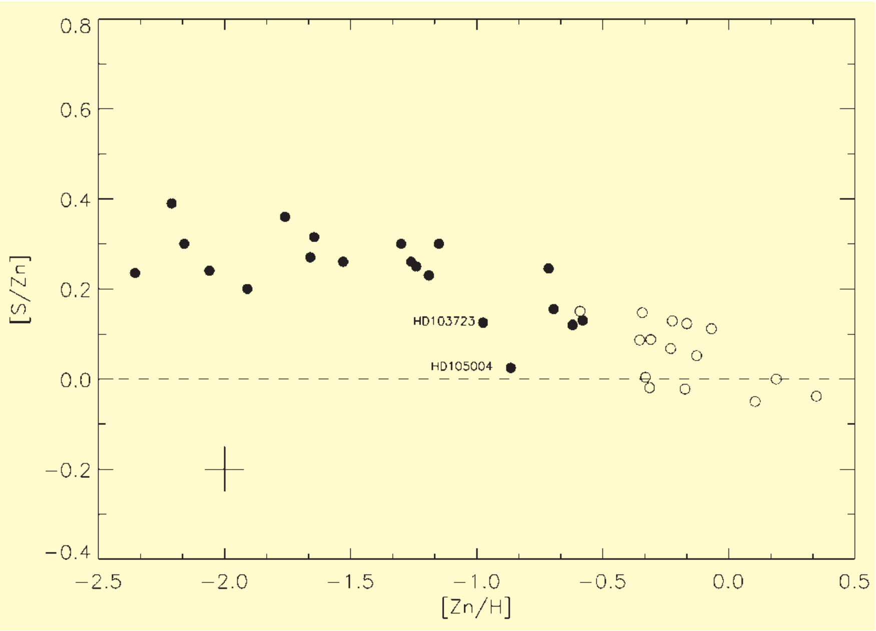

Figure 5: [S/Zn] vs. [Zn/H] for a sample of nearby main-sequence stars. Filled circles refer to stars with halo kinematics and open circles to disk stars. Data for the halo stars were derived from the S I λλ8694.6, 9212.9, 9237.5 and the Zn I λλ4722.2, 4810.5 lines recorded with UVES (Nissen et al. in preparation); those for the disk stars are reproduced from Chen et al. (2002). The two stars, HD103723 and HD105004, belong to a group of low [alpha/Fe] halo stars discovered by Nissen & Schuster 1997. (Figure courtesy of Poul Nissen.)

high redshift. This, the most common of astrophysical molecules, provides a wealth of data on the physical conditions in DLAs, particularly on the temperature and density of both particles and photons in the interstellar media of these early galaxies.

Ultimately, all of this work on DLAs complements local studies, which have focussed on old stars in the Milky Way Galaxy and on regions of ionized gas near hot stars in nearby galaxies, to address some of the same basic questions, such as the star formation histories of galaxies (How did star formation proceed in the early Galaxy and in DLAs?), and the nucleosynthetic origin of different elements (Which stars were responsible for 'cooking' different elements in their interiors and releasing them into the interstellar medium, making them available for subsequent generations of stars?). I shall illustrate these points with a few examples chosen from work carried out by European astronomers with UVES.

Are Oxygen and Other Alpha-Capture Elements Overabundant Relative to Iron in DLAs?

Hidden behind this mouthful of jargon lies one of the cornerstones of chemical evolution studies. Oxygen and other elements which are synthesised by the addition to oxygen of one or more alpha particles (examples are Mg, Si, S, and Ca) are thought to be produced mostly in the interiors of massive stars which explode as Type II supernovae some 10 million years after an episode of star formation. On an astronomical time scale this is quick work. On the other hand, the major producers of Fe are thought to be Type Ia supernovae whose progenitors are stars of relatively low mass which can take up to 1 billion years (100 times longer than the oxygen producers) to explode and release the Fe into the interstellar medium. In Milky Way stars with an iron abundance of less than 1/10 solar (or [Fe/H] < –1 in the usual notation), oxygen and other alpha-elements are indeed relatively more abundant than iron by factors of between two and three. The usual interpretation of this well established fact is that, during its early stages of evolution, our Galaxy reached a metallicity of 1/10 of solar relatively quickly, presumably in less than one billion years, so that Fe had not yet had time to catch up with O in the interstellar medium.

Do we see the same pattern in DLAs? The answer to this question is complicated by the fact that most of the elements concerned can be partly hidden from view in DLAs as they condense to form interstellar dust (this problem does not affect stellar abundance measurements, since the dust all melts away when a star is formed). After some initial debate as to whether dust is present in DLAs, most astronomers working in this field now agree that dust depletions have to be taken into account when analysing the pattern of element abundances in DLAs. When this is done, as in Figure 4, a mixed picture emerges. While some DLAs exhibit an overabundance of Si relative to Fe comparable to that seen in Milky Way stars, others – perhaps most – don't. The conclusion seems to be that DLAs trace galaxies with different pasts; some may have formed stars on timescales similar to that of the early Milky Way, while others apparently did so more slowly, or intermittently, so that Fe could catch up with Si. It makes sense (at least to the author of this article) that DLAs should sample a wide range of galaxy types, and consequently a variety of star formation activity. Even locally, we have recently begun to learn that almost no two galaxies have similar histories in the assembly of their stellar populations, and this is reflected in their varying [alpha/Fe] ratios, as evidenced by the work presented by Kim Venn at the meeting.

Of relevance to this question are also some new stellar abundance measurements reported at the workshop by Poul Nissen and collaborators, and reproduced in Figure 5. Recently obtained UVES data show that the [S/Zn] ratio does show an enhancement (relative to solar) in Galactic stars of low metallicities. This result had been expected, since S is an alpha-capture element and the abundance of Zn generally follows that of Fe to within about 0.1 dex, but it is nevertheless reassuring to see it confirmed empirically. The significance of this particular pair of elements

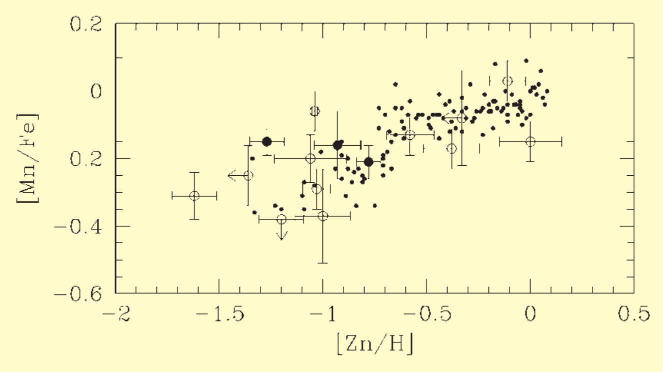

Figure 6: Relative abundances of Mn and Fe in DLAs, plotted vs the abundance of Zn (taken as a proxy for Fe). In the Galactic interstellar medium, Mn and Fe are generally depleted by similar amounts so that the ratio of these two elements in DLAs is expected to be relatively insensitive to the degree of dust depletion. Small dots are data for stars in the Milky Way; open and filled circles are measurements in DLAs. (Reproduced from Dessauges-Zavadsky et al. 2002, where references to the original measurements are given.)

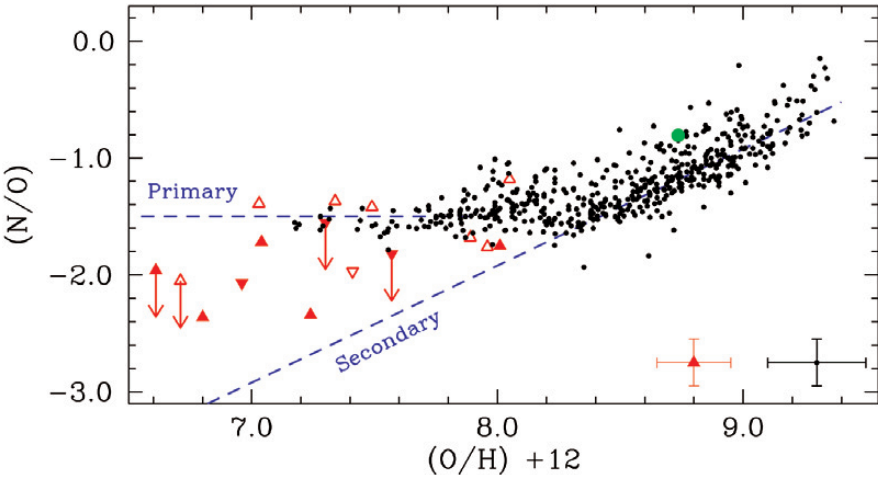

Figure 7: Logarithmic abundances of N and O in nearby H II regions (small dots) and in DLAs (open and filled triangles). Typical errors are shown in the bottom right-hand corner. Adapted from Pettini et al. (2002), where full references to the data and a more extensive discussion of this diagram can be found.

is that neither shows much affinity for dust, thereby circumventing the depletion corrections necessary for Si and Fe. The few available data on S and Zn in DLAs (shown with open squares in Figure 4) conform to the broad picture outlined above; without doubt many more measurements of this diagnostic pair will be attempted in the near future, now that their relative abundances in Galactic stars have been clarified.

The Case of Manganese

Mn shows an opposite trend with metallicity from that of the alpha-capture elements: its abundance relative to Fe decreases, rather than increases, with decreasing metallicity. Could this also be a reflection of the pace of past star formation? Its abundance in damped Lyman alpha systems suggests that this is *not* the case. As can be seen from Figure 6, the DLA measurements match the pattern seen in Milky Way stars even though, as we have seen, the QSO absorbers are likely to sample a variety of galaxies which formed stars at different rates. The agreement between Galactic and extragalactic data suggests that perhaps there is a metallicity dependence in the yield of Mn; in any case, the DLA measurements for manganese are providing us with clues to the chemical yields, rather than to the past history of star formation.

Low- and Intermediate-Mass Stars as the Source of Primary Nitrogen

The details of the nucleosynthesis of nitrogen have been the subject of considerable debate in recent years and this element provides perhaps the best example of how observations at high redshifts are driving models of its production in stars. Available measurements of the abundances of N and O are collected in Figure 7. Without going into too much detail, two points are noteworthy. First, DLAs occupy a region of the diagram which is sparsely sampled by local H II regions. It is much easier to find metal-poor gas at high redshift than in the present-day universe. Thus, the relative abundances of N and O in DLAs offer a clearer window on the early nucleosynthesis of these two elements than was available before the commissioning of UVES. Second, note the relatively large spread of values of the (N/O) ratio, from about –1.2 to –2.4 (on a logarithmic scale). Qualitatively, this is what was expected if the main source of N at low metallicities are intermediate-mass stars, between seven and four solar masses, which release their newly synthesised N into the interstellar medium well after the injection of O by Type II supernovae. The DLA data have provided the first empirical evidence in support of this idea of a delayed production of primary N by intermediate mass stars, an idea which had previously been based on entirely theoretical yield calculations.

Quantitatively, however, the proportion of DLAs with values of (N/O) below the level labelled ‘Primary’ in Figure 7 is surprisingly high, if the time delay is of the order of only 300 million years, as current models predict. Perhaps future observations with UVES will show this to be an artefact of the still limited statistics (and indeed there is by no means universal agreement between different groups as to the pattern of DLA measurements in Figure 7). However, these and similar data have already provided the impetus to theorists to examine more closely the details of the nucleosynthesis of N at low metallicities and mechanisms have been uncovered which have the potential of extending the time delay. One of the most realistic of these seems the inclusion of stellar rotation (hitherto largely ignored) into the calculations of the stellar yields. As shown by Georges Meynet and André Maeder in Geneva, rotation may allow metal-poor stars of masses lower than four solar masses to synthesize N, with the consequence that its release into the interstellar medium may be a more protracted affair, coming to completion on timescales perhaps as long as those of Type Ia supernovae. We can expect significant advances on these questions in the years ahead, both observationally and theoretically.

Concluding Remarks

I hope that this brief review has managed to convey some of the flavour of that exciting two-day meeting in Garching last November. The workshop served to highlight the major impact which UVES has had, and continues to have, on European astronomy, not only in the depth and breadth of new results and projects which the instrument has made possible, but also in the increasing dialogue between stellar and extragalactic astronomers, and between observers and theorists, which UVES has helped to foster.

The meeting concluded with a brief outline by Sandro D’Odorico of current plans for future upgrades of UVES and, looking further ahead, for complementary instruments which will allow high-resolution spectroscopy at wavelengths from the ultraviolet to the near-infrared. This was followed by a brief user feedback session. The session was brief because generally there is a high level of satisfaction among UVES users! The merits of the data archive were highlighted, although the point was also made that the usefulness of the archive will be significantly increased when UVES pipeline reduced data are included in it. Hopefully this important development will be implemented in the near, rather than medium-term, future.

Finally, all participants expressed their sincere thanks to Francesca Primas, whose enthusiasm, generosity, and impeccable organization – always accompanied by her trademark smile – made this meeting such a resounding success.

References

Chen, Y.Q., Nissen, P.E., Zhao, G., & Asplund, M. 2002, *A&A*, **390**, 225.

Dessauges-Zavadsky, M., Prochaska, J.X., & D’Odorico, S., 2002, *A&A*, **391**, 801.

Hoopes, C.G., Sembach, K.R., Hebrard, G., Moos, H.W., & Knauth, D.C. 2003, *ApJ*, in press (astro-ph/0212303).

Nissen, P.E., & Schuster, W.J. 1997, *A&A*, **326**, 751.

Pettini, M., & Bowen, D.V. 2001, *ApJ*, **560**, 41.

Pettini, M., Ellison, S.L., Bergeron, J., & Petitjean, P. 2002, *A&A*, **391**, 21.

Vladilo, G. 2002, *A&A*, **391**, 407.