Scientific Requirements for Extremely Large Telescopes
Proceedings IAU Symposium No. 232, 2005
P. Whitelock, M. Dennefeld & B. Leibundgut, eds.

doi:10.1017/S1743921306000810

Metals in the intergalactic medium

Joop Schaye

Leiden Observatory, P.O. Box 9513, NL-2300 RA Leiden, The Netherlands
email: schaye@strw.leidenuniv.nl

Abstract. The enrichment of the intergalactic medium (IGM) with heavy elements provides us with a record of past star formation and with an opportunity to study the interactions between galaxies and their environments. We discuss what future observations with extremely large telescopes could do for this field. We conclude that a further increase in the quality of the spectra of bright, $z \sim 3$ quasars will be useful, but may not lead to dramatic progress. In contrast, the ability to obtain high-quality spectra of $z > 5$ quasars will be extremely exciting because they will allow us to extend studies of the distribution of metals to early times and to lower density contrasts, and because they may enable us to study the end of reionization. Spectacular progress in our understanding of the interactions between galaxies and the IGM can be made at $z \sim 3$, by obtaining accurate redshifts for large numbers of faint galaxies in the fields of bright quasars, and by obtaining low and intermediate resolution absorption spectra of some of the brighter galaxies.

Keywords. telescopes, galaxies: formation, intergalactic medium, quasars: absorption lines

1. Introduction

The enrichment of the tenuous gas in between galaxies with elements heavier than helium, which are formed in stars, provides us with an archaeological record of past star formation and with a laboratory to study the interactions between galaxies and their environments.

The advent of 8m-class telescopes revolutionized our understanding of the intergalactic medium (IGM). It enabled us to obtain exquisite absorption spectra of a number of quasars, which can fully resolve the H I (though not quite the metal) lines. High signal-to-noise spectra ($\sim 10^2$ per resolution element) of $z \sim 3$ quasars clearly showed that the majority of the Lyman forest lines with column densities $N_{\rm HI} > 10^{15}\,{\rm cm}^{-2}$ have associated absorption by C IV (Cowie *et al.* 1995) and O VI (Carswell *et al.* 2002; Bergeron *et al.* 2002), which prove that although their metallicity is low ($Z \lesssim 10^{-2}\,Z_\odot$), they are not chemically pristine. Subsequent analyses showed, among other things, that carbon (Cowie & Songaila 1998; Ellison *et al.* 2000) and oxygen (Schaye *et al.* 2000) are also present at even lower column densities, that metallicity is an increasing function of the gas density (Schaye *et al.* 2003; Simcoe *et al.* 2004), that the metallicity of the low-density IGM is relatively constant from $z = 4$ to $z = 2$ (Schaye *et al.* 2003), that the IGM contained a significant amount of metals by $z = 5$ (Songaila 2001), that silicon (Aguirre *et al.* 2004) and oxygen (e.g., Telfer *et al.* 2002) are overabundant relative to carbon, and that the metals are clustered on scales of up to $\sim 10^3\,{\rm km\,s}^{-1}$ (measured in redshift space, e.g., Pichon *et al.* 2003).

Redshift surveys of starburst galaxies in the fields of bright background quasars allowed us to study the connection between galaxies and their environments. The abundances of carbon and oxygen appear to be enhanced in the surroundings of $z \sim 3$ Lyman-break galaxies (Adelberger *et al.* 2003, 2005; Pieri *et al.* 2006). Studies of this kind have the potential to give us unique insight into the physics of galactic winds. However, currently the interpretation of the observations is complicated by the fact that accurate coordinates (angular plus redshifts) are only available for a fraction of the brightest ($L > L_*$) galaxies. Because we are only seeing the tip of the iceberg of the galaxy population, the association of observed absorption features with galaxies is ambiguous at best. Fortunately, this ambiguity does not prevent us from mapping the typical environments of the bright galaxies.

Given the tremendous amount of progress that was triggered by the ability to observe bright quasars with echelle spectrographs on 8m-class telescopes, it would not come as a surprise if the advent of Extremely Large Telescopes (ELTs) would again lead to dramatic new insights into the physics of the IGM and its enrichment with metals.

Here, we give a brief overview of the goals and methods of the field (see Schaye & Aguirre 2005 for a more in depth discussion) and speculate where ELTs could contribute the most. We conclude that, contrary to what one may naively expect, a further increase in signal-to-noise and/or resolution of spectra of bright, $z \sim 3$ quasars may, though interesting, not be among the most exciting contributions by ELTs. On the other hand, the ability to obtain high-quality spectra of the brightest $z > 4.5$ quasars will undoubtedly lead to many discoveries. We must, however, not forget that the redshift range for which the mean H I Lyα optical depth is around one, i.e., $z \sim 3$, will always be unique in terms of the information content of the Lyman forest. We therefore anticipate that our understanding of the interactions between galaxies and their environment will be revolutionized by the ability to obtain accurate redshifts, as well as high-quality low to intermediate resolution absorption spectra, of large numbers of galaxies in the fields of bright, $z \sim 3$ quasars.

2. What do we want to measure?

Depending on the enrichment mechanism, the abundances of intergalactic metals could depend on various environmental factors, such as the gas density, temperature, and the distance to particular types of galaxies. The gas density and temperature can be constrained using the absorption lines themselves. This can be done more easily if more ions are observed and if the intrinsic line widths can be measured. To study the environments of galaxies, it is desirable to find and localize many galaxies near sight lines to background sources (which can be both quasars and galaxies).

The abundances are expected to be stochastic, so we need to measure the probability distribution function (pdf), not just the mean. Thus, we would like to know, for each element, the pdf of its abundance as a function of both time and environment.

We would also like to know the fraction of the volume (i.e., the volume filling factor) and of the mass that has an abundance higher than some minimum value. Assuming we know the pdf of the density field, e.g. from theory, the filling factors can be obtained from the pdf of the abundance as a function of density, which makes the density a particularly interesting parameter.

3. How do we do it?

There are two fundamental problems that we need to overcome in order to measure abundances in the diffuse IGM: the intergalactic gas has a very low density, $n_{\rm H} \sim 10^{-6} - 10^{-3}$ cm^{-3} for $z \lesssim 6$, and the abundances of heavy elements are typically very low, $Z \lesssim 10^{-2}\ Z_\odot$. The low density of heavy elements has two important consequences. First, it is very difficult to detect intergalactic heavy elements, particularly in the space-filling low-density IGM. Second, the IGM is highly ionized by the background radiation from

https://doi.org/10.1017/S1743921306000810 Published online by Cambridge University Press

galaxies and quasars, which means that we need to know the ionization balance in order to convert ion abundances into heavy element abundances.

Because detection is such a challenge, any increase in telescope size and/or sensitivity is guaranteed to lead to significant progress. Besides using the largest available telescopes, we can improve our prospects by using absorption rather than emission (because the optical depth is proportional to the ion density whereas the emissivity is proportional to the density squared), by observing in the rest-frame ultraviolet (which is where many of the strongest transitions lie), by focusing on the few metal transitions that can be detected most easily [C IV (1548, 1551), Si IV (1394, 1403), O VI (1032, 1038), C III (977), and Si III (1207)], by aiming for statistical rather than direct detections, and by using synthetic absorption spectra drawn from large-scale hydrodynamical simulations to test methods and to help guide the interpretation.

Ionization corrections depend in general on the intensity and spectral shape of the radiation field, on the gas density and temperature, and, unless the gas is in ionization equilibrium, also on its history. Ionization equilibrium is generally assumed to hold and should be an excellent approximation for hydrogen, though not always for the heavy elements. The gas density, temperature and the intensity of the mean UV background radiation can all be measured from the absorption lines themselves. The major uncertainties are therefore the spectral shape of the UV radiation field and, for systems rarer than Lyman limit systems, the ionizing radiation from local sources (Schaye 2006).

Fig. 1 shows the median carbon abundance as a function of overdensity (*left*) and redshift (*right*), measured from a large sample of high-quality spectra using a statistical technique calibrated by hydrodynamical simulations, for several assumed spectral shapes of the UV background radiation. The abundance of carbon is an increasing function of density, but there is no evidence for evolution. This figure shows clearly that for low densities the uncertainty due to the spectral shape of the UV background is considerable. What matters here is actually not the density contrast, but the ionization parameter. The ionization correction will therefore become highly uncertain below roughly the same optical depth (or column density), rather than below some fixed density contrast. Assuming that the intensity of the UV radiation does not increase towards higher redshifts, a fixed volume density corresponds to a smaller density contrast at higher redshifts. Thus, we can detect C IV and accurately correct for ionization down to lower density contrasts at higher redshifts, and other ions behave similarly.

This means that if we want to estimate metallicities at low overdensities (which correspond to large volume filling factors), then it is better to move to higher redshifts than to push for higher signal-to-noise. However, this is only true as long as we can estimate the density which corresponds to the metal line absorbers. Since the density can generally only be estimated from the strength of the hydrogen absorption, the entire method breaks down for $z \gtrsim 6$ where the mean Lyα absorption becomes saturated (e.g., Fan *et al.* 2002).

To relate the absorption to galaxies we have to overcome yet another challenge: we need to obtain precise redshifts and positions for as many galaxies as possible near the line of sight to the background quasar. If it were possible to do this for a large fraction of the galaxies, then we could measure the properties of the galaxies as a function of distance to certain classes of absorbers. However, in practice most galaxies are too faint to detect, let alone to measure precise redshifts. In that case we can, however, still use absorption spectra to investigate the environment as a function of galaxy properties (for those classes of galaxies for which precise redshifts can be measured).

Note that even if we knew the exact locations of all galaxies near the line of sight, it would still not be possible to unambiguously decide what types of galaxies (e.g., big or

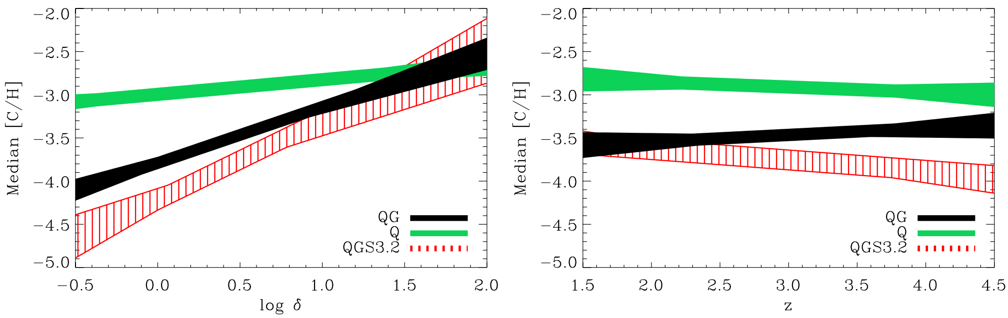

Figure 1. Shaded regions enclose the 1σ confidence contours for fits to the carbon abundance as a function of overdensity $\delta \equiv \rho/\langle\rho\rangle - 1$ and redshift for $z = 3$ (*left*) and $\log\delta = 0.5$ (*right*). Results are shown for the fiducial UV background model (QG) for galaxies and quasars, as well as for a pure quasar background (Q) and for a model in which the flux was reduced by a factor 10 above 4 Ryd to mimic incomplete He II reionization (QGS3.2). Figure taken from Schaye *et al.* (2003).

small) are responsible for enriching the IGM with metals. The reason is that we cannot tell from a single snapshot in the evolution of the galaxy whether the metals surrounding it were ejected by the galaxy as we see it or by its smaller progenitors. Thus, to decide on the enrichment mechanism, it is probably necessary to obtain detailed information on the evolution of the abundances.

4. What do we want from the next generation of ground-based telescopes?

In order of importance:

(*a*) Much more collecting area and the ability to obtain unresolved spectra of faint, extended sources with minimal photon losses. This will allow us to:

- Obtain spectra of a large sample of bright, $z \gtrsim 5$ quasars of a quality similar to those that can be obtained with 8m-class telescopes at $z \sim 2.5$. The redshift range $4.5 < z < 5.5$ is ideal for measuring accurate abundances at low density contrasts and hence for estimating the volume filling factor of enriched gas. Extending the redshift range will also allow us to test for evolution which may be the best way of distinguishing between different enrichment mechanisms. Finally, going to higher redshift will give us insight into the process of reionization. Naturally, *it will only be possible to obtain high-quality absorption spectra of $z > 4$ quasars if we have a means to suppress sky lines.*
- Obtain precise redshifts for relatively faint galaxies near the sight lines to bright $z \sim 3$ quasars. This redshift is ideal for absorption studies of the environments of galaxies because the dynamic range in the forest is close to maximum (which maximizes the information content in the absorption signal) and because it allows us to study the rest-frame UV, where the dominant transitions lie, in the optical. Currently it is only possible to measure accurate redshifts for a small fraction of $L > L_*$ galaxies (e.g., Adelberger *et al.* 2005). Increasing this fraction will dramatically improve our ability to study the interactions between galaxies and the IGM.
- Obtain low and intermediate resolution absorption spectra of bright $z \sim 3$ galaxies. This would give us the ability to drastically increase the number of sight lines that pass close to foreground galaxies and would thus improve the statistics on the galaxy-IGM connection correspondingly.

https://doi.org/10.1017/S1743921306000810 Published online by Cambridge University Press

A much larger collecting area will also allow us to obtain very high ($\gg$100) signal-to-noise ratio spectra of bright, $z \sim 3$ quasars. Although this would be very interesting, we argued that in order to study the enrichment of the low-density IGM (where the metal lines are weakest), we would gain more by going to higher redshift at fixed signal-to-noise.

(*b*) A very large spectral range. This is essential because the rest-frame wavelengths of interest span a large range: from the Lyman limit (λ912) to C IV ($\lambda\lambda$1548, 1551). It is particularly important not to neglect the blue part of the spectrum because we need higher order Lyman lines ($\lambda 912 - \lambda 1026$) to measure the H I content if Lyα (λ1216) is saturated and because O VI ($\lambda\lambda$1032, 1038) is our best hope for measuring the abundance of the dominant heavy element (oxygen) and for probing the hot ($T \gtrsim 10^5$ K), shock-heated gas that may harbor a large fraction of the heavy elements at high redshift (e.g., Theuns *et al.* 2002). Note that a minimum observed wavelength of 3000 Å would make the Lyman limit observable down to $z = 2.3$, while a maximum observed wavelength of 9000 Å would make C IV observable up to $z = 4.8$.

(*c*) A high spectral resolution. A resolution $\Delta v < 10$ km s^{-1} (for bright point sources) is crucial because it allows us to fully resolve the H I Lyα forest. A resolution of $\Delta v <$ 2 km s^{-1} would probably enable us to resolve most of the metal lines. Provided that we can do this at a high signal-to-noise ratio ($S/N \gtrsim 50$), this would certainly be interesting. It would, for example, make it possible to rule out collisional ionization for a larger fraction of metal absorbers. However, over all, we feel that more is to be gained by obtaining $\Delta v < 10$ km s^{-1} spectra of fainter sources.

Acknowledgements

I am grateful to the organizers for inviting me to a great conference. This work was supported by a Marie Curie Excellence Grant from the European Union (MEXT-CT-2004-014112) and by a grant from the IAU.

References

Adelberger, K.L., Steidel, C.C., Shapley, A.E. & Pettini, M. 2003, *ApJ* 584, 45
Adelberger, K.L., Shapley, A.E., Steidel, C.C., Pettini, M., Erb, D.K. & Reddy, N.A. 2005, *ApJ* in press (astro-ph/0505122)
Aguirre, A., Schaye, J., Kim, T., Theuns, T., Rauch, M. & Sargent, W.L.W. 2004, *ApJ* 602, 38
Bergeron, J., Aracil, B., Petitjean, P. & Pichon, C. 2002, *A&A* 396, L11
Carswell, B., Schaye, J. & Kim, T. 2002, *ApJ* 578, 43
Cowie, L.L. & Songaila, A. 1998, *Nature* 394, 44
Cowie, L.L., Songaila, A., Kim, T. & Hu, E.M. 1995, *AJ* 109, 1522
Ellison, S.L., Songaila, A., Schaye, J. & Pettini, M. 2000, *AJ* 120, 1175
Fan, X., Narayanan, V.K., Strauss, M.A., White, R.L., Becker, R.H., Pentericci, L. & Rix, H.-W. 2002, *AJ* 123, 1247
Pichon, C., Scannapieco, E., Aracil, B., Petitjean, P., Aubert, D., Bergeron, J. & Colombi, S. 2003, *ApJ* 597, L97
Pieri, M.M., Schaye, J. & Aguirre, A. 2006, *ApJ* 638, 45
Schaye, J., Rauch, M., Sargent, W.L.W. & Kim, T. 2000, *ApJ* 541, L1
Schaye, J., Aguirre, A., Kim, T., Theuns, T., Rauch, M. & Sargent, W.L.W. 2003, *ApJ* 596, 768
Schaye, J. & Aguirre, A. 2005, in: V. Hill *et al.* (eds.), *From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution*, IAUS, 228, 557
Schaye, J. 2006, *ApJ* in press (astro-ph/0409137)
Simcoe, R.A., Sargent, W.L.W. & Rauch, M. 2004, *ApJ* 606, 92
Songaila, A. 2001, *ApJ* 561, L153
Telfer, R.C., Kriss, G.A., Zheng, W., Davidsen, A.F. & Tytler, D. 2002, *ApJ* 579, 500
Theuns, T., Viel, M., Kay, S., Schaye, J., Carswell, R.F. & Tzanavaris, P. 2002, *ApJ* 578, L5