The CORALS Survey: A Review and Progress Report on The Search for Dust Obscured Quasar Absorption Line Systems.

Sara L. Ellison\textsuperscript{1,2}, Max Pettini\textsuperscript{3}, Chris W. Churchill\textsuperscript{4}, Isobel M. Hook\textsuperscript{5}, Sebastian Lopez\textsuperscript{6}, Samantha A. Rix\textsuperscript{3}, Peter Shaver\textsuperscript{1}, Jasper V. Wall\textsuperscript{7}, Lin Yan\textsuperscript{8}

\textsuperscript{1}European Southern Observatory
\textsuperscript{2}P. Universidad Catolica de Chile, Santiago, Chile
\textsuperscript{3}Institute of Astronomy, Cambridge, UK
\textsuperscript{4}Penn. State University, State College, USA
\textsuperscript{5}Gemini Observatory, Oxford, UK
\textsuperscript{6}Universidad de Chile, Santiago, Chile
\textsuperscript{7}Dept. of Astrophysics, University of Oxford, UK
\textsuperscript{8}SIRTF Science Center, Pasadena, California, USA

1 Ashes to Ashes, Dust to Dust

The presence of dust represents a perennial problem in many fields of astrophysics, ranging from its role in the supernova-determined distance scale to its depletion of refractory elements in the interstellar medium (ISM). However, dust is very much a necessary evil since it regulates the temperature of the ISM and provides a shield against UV radiation, as well as nucleation sites for the formation of H\textsubscript{2}. Despite its ubiquitous astrophysical impacts, the formation of dust, and even its composition, remain poorly understood. Although it is thought that the majority of dust is formed in the outer regions of cool AGB stars, it is also possible that supernovae and AGN may contribute significantly to the dust budget at high redshifts. Given the widespread evidence for significant amounts of dust even at early times, it is hard to escape the possible consequences of depletion and extinction effects on astronomical observations.

The study of QSO absorption line systems is a field in which dust continually plagues our interpretation of the data. This technique uses relatively bright, yet distant, quasars as background sources to study intervening gas clouds, which imprint their signatures on the quasar spectrum allowing detailed study of their composition and structure. Echelle spectrographs such as UVES on the VLT are now, almost routinely, providing exquisite data that permit accurate measurements of gas phase abundances in galaxies and the intergalactic medium out to very high redshifts. However, the interpretation of these measurements and their application to galaxy evolution scenarios is hindered by depletion from the gas phase of refractory elements, effectively ‘hiding’ some of the chemical elements from view. Although techniques are being developed to circumvent the effect of depletion, this is a challenging prospect when little is known about dust composition outside the Local Group.

A perhaps more fundamental concern is that the surveys that search for absorption line systems may themselves be incomplete due to dust in intervening absorbers. If the internal extinction of absorption systems is sufficiently large, then quasars behind such systems may be missed by magnitude limited optical surveys. Junkkarinen et al (2003) have recently underlined this concern with the detection of strong interstellar dust features in a z \sim 0.5 damped Lyman \alpha system. Indeed, Fall & Pei (1993) have used models of dust obscuration to estimate that between 30 and 70\% of QSOs could be missed in present surveys due to this very effect.

2 Towards a Complete View of Absorption Line Galaxies

The Complete Optical Radio Absorption Line System (CORALS) survey was designed to provide a quantitative answer to concerns about absorption line survey dust bias. The aim, simply put, was to compile a sample of QSOs selected at radio wavelengths with \textit{no optical magnitude limit} from which absorption line statistics could be determined. The parent sample for this survey is the Parkes
quarter-Jansky (PQJ) sample (Jackson et al. 2002) which contains 878 flat spectrum radio sources observed at 2.7 and 5.0 GHz. An important feature of the PQJ sample is the extensive follow-up imaging campaigns that have resulted in optical identifications and classifications for all but 9 of the sources. Selected at wavelengths that are immune to dust extinction, but with essentially complete optical identifications\(^1\), the PQJ sample provides us with an excellent opportunity to address the possibility of dust bias in previous magnitude limited absorption system surveys. Although a large spectroscopic campaign was undertaken for many of PQJ sample, these were obtained at low resolution for the purpose of object classification and redshift determination and are not suitable for absorption system studies. Therefore, over the last 5 years, we have been pursuing an active observing campaign that has so far logged some 30 nights on telescopes over 4 continents to address issues associated with obscuration bias.

3 The First CORALS Survey

The initial goal of the CORALS survey was to assess the possible bias in samples of high redshift damped Lyman $\alpha$ systems (DLAs), the highest column density absorbers associated with galaxy scale systems. The sample for this survey consisted of the 66 $z_{\text{em}} > 2.2$ QSOs from the PQJ survey which had magnitudes as faint as $B = 23.5$; complete results from this survey have been published in Ellison et al (2001). Moderate resolution spectra were obtained for this sample using a combination of the AAT and ESO facilities, with the VLT playing the vital role of observing the faintest targets. Although the aim of CORALS I was to provide a complete survey, the faintest targets were the linchpin of the project, since these are the QSOs which will have been previously excluded by magnitude limited optical samples. The total path length covered by CORALS I is $\Delta z \sim 55$, over which a total of 22 DLAs were identified.

In order to compare CORALS I with previous magnitude limited surveys, we assess two main statistics. The first, $n(z)$ is the number density; this is a simple tally of the number of absorption systems per unit redshift. The second statistic, $\Omega_{\text{DLA}}$, is a measure of the total neutral gas content of the DLA population, expressed as a fraction of the closure density of the universe (for a more detailed explanation of these quantities, see Ellison et al. 2001). We determine $n(z)=0.31$ at a mean redshift of $z=2.37$ in CORALS I, in good agreement (within 1$\sigma$) with previous surveys. Similar reasonable agreement is determined for $\Omega_{\text{DLA}}$ (see Figure 1), although the error bars permit an underestimate of up to a factor of $\sim 2$ by previous surveys, which typically include QSOs down to magnitudes of $V \sim 19–20$. However, there is evidence that statistics may depend on survey magnitude for surveys that are only complete to significantly brighter magnitudes. In Figure 2 we plot the cumulative statistics of the CORALS I survey as a function of $B$ band magnitude, and include the Large Bright Quasar Survey (LBQS) to improve the statistics of the brightest QSOs where CORALS has poor coverage. As first pointed out by Ellison et al. (2000) in a previous Messenger article, fewer DLAs are found towards brighter QSOs (e.g. the LBQS, $B < 19$) than fainter subsets (e.g. CORALS $B > 20$), and the total gas content is also somewhat lower, although the error bars remain large. Such a trend is supported by the DLA survey conducted using the Hamburg-ESO (HE) sample of bright QSOs, in which $\Omega_{\text{DLA}}$ is an order of magnitude lower than for CORALS (Smette et al., in preparation). The precise dependence of DLA statistics on survey magnitude limit not only has an important application in the design of future surveys, but also has implications for large datasets being reaped from surveys such as 2dF and SDSS. These surveys are sufficiently large (with $\Delta z$ reaching several thousand) that error bars will be much less dominated by redshift coverage, so that observational biases, even subtle ones, will be important.

4 CORALS II: Extension to Lower Redshift

The preliminary results from CORALS I indicate that at $2 < z < 3$, dust does not seem to play a significant role in ‘hiding’ DLAs from previous surveys, at least when QSOs with magnitudes $V \sim 20$ can be reached. However, it might be expected that biasing becomes more severe towards lower redshifts, since the bulk of star formation has already taken place by $z \sim 1$ (Steidel et al.\(^2\)).

\(^1\)The 9 unidentified sources were due to mis-identifications in earlier samples, not due to excessively faint optical magnitudes. Moreover, only one of these falls within our declination range and above its survey flux-density limit. The unidentified objects in Jackson et al (2002) therefore have negligible effect on the results of the CORALS survey.
With most of the star formation completed, we may expect the ISM of galaxies to exhibit pronounced chemical (and therefore, plausibly, dust) evolution at low $z$. Dust obscuration could thus be invoked to posit a population of ‘missing’, dust obscured DLAs, at low redshift, which could explain the lack of metallicity evolution at $z < 1$ seen by Pettini et al. (1999).

Observationally, it is much more challenging to extend CORALS to $z < 1.5$, due to the onset of the atmospheric cut-off which renders detection of low redshift Ly$\alpha$ impossible from the ground. Although large DLA surveys have been conducted with HST and other space telescopes, these are very expensive in terms of telescope resources. Moreover, current HST instrumentation restricts surveys to bright magnitudes, and we have seen that absorption statistics may depend to some extent on magnitude cut-off. Therefore, we have designed CORALS II to select absorption galaxies via Mg II and Fe II lines – strong metal lines associated with galaxy halos that have transitions observable in the optical regime down to $z \sim 0.3$ (Bergeron & Boisse 1991). By selecting systems with strong Mg II and Fe II absorption, we can efficiently pre-select likely DLAs (Rao & Turnshek 2000).

CORALS II, a complete survey for Mg II absorbers with $0.5 < z < 1.5$ is currently nearing completion; out of 75 QSOs, we have so far observed some 60 targets, the rest pending observation (mostly with FORS on the VLT) in Period 71. The QSO sample is again based on the PQJ flat spectrum quasar sample, although we have now preferentially selected $z_{em} < 2.5$ targets so that Mg II will fall redwards of the Ly$\alpha$ forest. In the majority of cases, we also cover Fe II $\lambda$2600 and usually also Mg I $\lambda$2853. Our aim is to be complete down to an observed $3\sigma$ equivalent width threshold of 0.5 Å for Mg II, although in most cases we achieve limits significantly beyond this. Figure 3 shows the number of QSOs in which we can achieve various sensitivity limits as a function of redshift, based on the data obtained so far. Up to this point, we have a redshift path coverage $\Delta z \sim 50$ for an equivalent width limit of 0.5 Å, which will increase to approximately 60 by the end of the survey. We have so far detected 28 Mg II absorbers with $EW(Mg\ II\lambda 2796) \geq 0.5$ Å and a further 10 with $EW(Mg\ II\lambda 2796) \geq 0.3$ Å. We can compare these statistics with the landmark survey of Steidel & Sargent (1992, hereafter SS92) performed with the Palomar 5-m telescope on a sample of QSOs with $15 < V < 18$. We determine a number density of absorbers that is, considering the error bars, marginally lower than SS92; for an equivalent width threshold of $EW > 0.6$ Å (the limit used by SS92) we determine $n(z) = 0.46 \pm 0.10$ (at $\langle z \rangle = 1.08$) compared with $0.65 \pm 0.07$ at a similar mean redshift for SS92. This is the opposite to what we would expect if a dust bias is at work. In Figure 4 we show the distribution of optical magnitudes for the SS92 survey compared with CORALS II as it currently stands, as well as the complete sample which is still pending completion. Although these magnitudes have error bars which may exceed 0.3 mags (and the CORALS radio-loud QSOs are expected to be highly variable), the basic picture is that the Steidel & Sargent (1992) sample occupy a locus of brighter magnitudes than CORALS. In fact, the SS92 magnitude range is similar to that of the HE QSO survey. Whereas there seems to be a significant deficit of high redshift DLAs in the HE bright QSO sample compared with our complete sample (Smette et al., in preparation), we find tentative evidence of an excess of absorbers towards bright QSO samples at intermediate redshift. This is suggestive of a lensing bias, whereby intrinsically fainter QSOs are boosted by intervening galaxies and are included in brighter flux limited samples (e.g. Smette et al 1997). If we split the sample in half by emission redshift, the number density for $z_{em} > 2.1$ is $n(z) = 0.52 \pm 0.17$ and $0.41 \pm 0.13$ for lower redshifts (for $\langle z \rangle \sim 1.1$ in both cases). Although these values are consistent within the large error bars, the marginally higher $n(z)$ towards higher redshift QSOs is again suggestive of lensing. This is because the lensing efficiency (by intermediate redshift galaxies) is higher for more distant QSOs (e.g. Bartelmann & Loeb 1996). Larger samples, such as the SDSS and 2dF surveys will be able to confirm this trend of $n(z)$ versus emission redshift, even though they are confined to brighter samples. We note that this is probably not an issue for high redshift ($z_{abs} > 2$) DLA surveys because of the low lensing probability in this configuration. Confirming the N(HI) of our complete Mg II sample, and thereby determining $\Omega_{DLA}$, will be an important test of whether a bright magnitude cut-off induces a bias in the determination of the neutral gas density in DLAs at low $z$. Such a bias is predicted to overestimate $\Omega_{DLA}$ (Smette et al. 1997) because the line of sight preferentially passes through the inner part of the lensing galaxy.
5 Along the Way...

Sizeable surveys of any kind often produce spin-off projects which either focus on a few unusual objects, or can exploit large datasets to study the properties of subsets of the data. We briefly review two such spin-offs from the CORALS survey.

Traditional DLA surveys have excluded DLAs within $\sim 3000$ km/s of the QSO due to proximity effects and the possibility that the absorber may be associated with the QSO itself. However, Møller, Warren & Fynbo (1998) have argued that, at least in some cases, proximate DLAs (PDLAs) are likely to be the same beast as intervening absorbers, based on their typical metallicities and lack of high ionization lines. If correct, we can use PDLAs as a probe of galaxies that are clustered around QSOs at high redshift. By comparing the $n(z)$ in the radio-loud quasar CORALS sample, Ellison et al. (2002) found 4 times the number of PDLAs in CORALS I than towards the radio-quiet sample of Peroux et al (2001). Although this result is only significant at the 2$\sigma$ level, it supports the suggestion that galaxies cluster preferentially near radio-loud QSOs.

A second spin-off to have been born of CORALS is the study of multiple DLAs (MDLAs). Lopez & Ellison (2003) define an MDLA as two or more absorbers with $\log N(\text{HI}) > 20.0$ with velocity separations $500 < \Delta v < 10000$ km/s. One of the DLAs discovered during the CORALS I campaign, Q2314$-$409, conforms to this definition and was the first to be studied at high resolution (Ellison & Lopez 2001). The abundances determined from a UVES spectrum show a propensity towards low $\alpha$/Fe (where $\alpha$ elements include such metals as Ca, Si, S and O) for MDLAs compared with single absorbers, a result more recently backed up by Lopez & Ellison (2003), see Figure 5. Having ruled out systematic effects such as ionisation or atypically low dust depletion, we have suggested that this abundance pattern could be due to low star formation efficiencies, possibly linked with environment (assuming that MDLAs are not just chance alignments, as indicated by the low statistical probability of such an event). To confirm this hypothesis will require a larger abundance study of MDLAs, as well as imaging campaigns to determine whether galaxy excesses exist in these fields.

6 Future Work

Compiling the spectroscopic samples to search for absorption systems has represented a significant investment of telescope time over the last 5 years and has yielded the first quantitative estimate of dust bias in magnitude limited surveys. Building on this investment, several follow-up projects are already underway that capitalise on the groundwork we have so far completed. One of the most important of these is to conduct an unbiased census of metallicity amongst the high redshift DLA sample. Although $\Omega_{\text{DLA}}$ appears not to have been seriously biased by selection effects, we currently have no measurement of the metal content of the absorber sample. Using UVES on the VLT, and with supplementary observations with MIKE on Magellan and ESI on Keck, we have almost completed the observations that will eventually yield the first unbiased metallicity measurement of DLAs at high redshift. Results from this will be published next year.

We have also initiated a program to study the optical-IR colours of CORALS QSOs, using a combination of CTIO and ESO facilities. Our aim is to obtain almost simultaneous optical and IR photometry (a high level of simultaneity is required due to the rapid variation associated with radio loud QSOs) in order to investigate whether a significant amount of reddening of the background source can be induced by intervening absorption galaxies. A small effect on the optical colours of the 2dF sample has been seen by Outram et al (2001), but adding an IR band will greatly increase the baseline over which reddening can be detected.

Further in the future will come HST confirmation of the H I column density of Mg II selected absorbers from CORALS II. Although conclusions on survey completeness can already be drawn from the ground-based spectroscopic campaign described here, measuring the N(H I) is essential for determining whether or not these are bona fide DLAs. Moreover, it is only with these measurements that we can determine $\Omega_{\text{DLA}}$ in a complete sample, and compare the gas content with the brighter QSO samples that currently dominate the low redshift measurements (e.g. Rao & Turnshek 2000, see Figure 4). The efficiency of STIS is such that obtaining spectra for all our Mg II absorbers is not feasible (all our ground-based spectroscopy has been done with at least 4-m telescopes). However, the installation of the Cosmic Origins Spectrograph (COS) on HST, currently scheduled for the start of 2005, will provide a facility capable of obtaining moderate resolution spectra sufficient to determine N(H I) for the bulk of our sample.
7 Acknowledgements

We are extremely grateful to the continued support of the various time allocation committees who have granted time for CORALS related projects over the last 5 years and to the various observatory staff who have facilitated work on site.

References

Bartelmann, M., & Loeb, A., 1996, ApJ, 457, 529
Bergeron, J., & Boisse, P., 1991, A&A, 243, 344
Ellison, S. L., & Lopez, S., 2001, A&A, 380, 117
Ellison, S. L., Yan, L., Hook, I., Pettini, M., Shaver, P., Wall, J., 2000, ESO Messenger, 102, 23
Ellison, S. L., Yan, L., Hook, I., Pettini, M., Wall, J., Shaver, P., 2001, A&A, 379, 393
Ellison, S. L., Yan, L., Hook, I., Pettini, M., Wall, J., Shaver, P., 2002, A&A, 383, 91
Fall, S. M., Pei, Y. C., 1993, ApJ, 402, 479
Jackson, C. A., Wall, J. V., Shaver, P. A., Kellermann, K. I., Hook, I. M., Hawkins, M. R. S., et al., 2002, A&A, 386, 97
Junkkarinen et al. 2003, ApJ, submitted
Lopez, S., & Ellison, S., 2003, A&A, accepted, astro-ph/0303441
Møller, P., Warren, S. J., Fynbo, J. U., 1998, A&A 330, 19
Outram, P. J., Smith, R. J., Shanks, T., Boyle, B. J., Croom, S. M., Loaring, N. S., Miller, L, 2001, MNRAS, 328, 805
Pettini, M., Ellison, S., Steidel, C., Bowen, D., 1999, ApJ, 510, 576
Peroux, C., Storrie-Lombardi, L. J., McMahon, R. G., Irwin, M., Hook, I. M., 2001, AJ, 121, 1799
Rao, S., Turnshek, D., 2000, ApJS, 130, 1
Smette, A., Claeskens, J.-F., Surdej, J., 1997, New Astronomy 2, 53
Steidel, C.C., Adelberger, K.L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1
Steidel, C. C., & Sargent, W. L. W., 1992, ApJS, 80, 1
Figure 1: The mass density of neutral gas, $\Omega_{DLA}$, in DLAs. Open circles and squares are measurements from the latest compilations by Péroux et al. (2001) and Rao & Turnshek (2000) respectively. The solid red circle is the value from the CORALS I survey presented here for the redshift interval $1.8 < z_{abs} < 3.5$. These results show that for $z > 2$ the effect of dust bias has caused the under-estimate of $\Omega_{DLA}$ by at most a factor of two.
Figure 2: Cumulative DLA statistics for CORALS I as a function of $B$ band magnitude show a possible trend with QSO magnitude with a lack of DLAs in bright optically-selected samples like the LBQS. Open stars represent values from CORALS I, whereas the solid squares include absorbers from the LBQS (included to reduce the error bars of the bright QSO bin).
Figure 3: Total number of quasars in the CORALS II survey which reach a given rest frame equivalent width detection limit as a function of redshift. Solid line is 0.3 Å and the dashed line is 0.6 Å. For a total of 60 QSOs observed so far, we achieve a limit of 0.6 Å for essentially all QSOs between $0.7 < z < 1.4$ (the small dip at $z \sim 1.2$ is due to incomplete wavelength coverage in some of the spectra).
Figure 4: Comparison of the QSO magnitudes for the Steidel & Sargent (1992) Mg II survey and CORALS II. The bottom panel shows the final targets that are still pending observation. The SS92 survey is effectively a ‘bright’ QSO sample, whereas CORALS II is optically complete and includes QSOs up to 250 times fainter than the SS92 limit.
Figure 5: $\alpha$/Fe ratios for MDLAs (solid red circles), DLAs in fields with known galaxy neighbours (solid red triangles) and single DLAs taken from the literature (open blue stars). DLAs with nearby galaxies both in the field, and seen in absorption (MDLAs) have systematically lower $\alpha$/Fe, a trend particularly obvious in the [S/Fe] ratio. See Lopez & Ellison (2003) for further discussion.