The CORALS Survey

A Review and Progress Report on The Search for Dust Obscured Quasar Absorption Line Systems

Distant, luminous quasars can be used to study intervening gas-rich galaxies - a potentially powerful tool for tracing galaxy evolution over most of the age of the universe. Here we describe the CORALS quasar survey which aims to quantify whether dust in such galaxies could hide a significant fraction of background quasars from view and bias our view of early galaxy formation.

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The existence of microscopic dust grains in interstellar space represents a perennial problem in many fields of astrophysics. Solid grains of dust in a galaxy's interstellar medium (ISM) can mop up certain chemical elements from the gas phase, complicating attempts to measure ISM abundances. In addition, the presence of dust acts as an obsuring veil that dims and reddens background objects, hiding them from the view of optical telescopes. However, dust is very much a necessary evil since it regulates the temperature of the ISM, as well as acting as a shield against harsh UV radiation and providing nucleation sites for the formation of molecular hydrogen. Despite its ubiquitous astrophysical impacts, the formation of dust, and even its composition, remain poorly understood. Nonetheless, the widespread evidence for significant amounts of dust, even in the very early universe, means that it is hard to escape the possible consequences of depletion and extinction effects on astronomical observations.

The study of quasar (or 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 (like galaxies), which imprint their signatures on the quasar spectrum. 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. Identifying galaxies at high redshifts through their absorption signatures has provided astronomers with a powerful probe of galaxy evolution by tracing objects that are generally too faint to study with more direct methods. Despite the high quality data, however, there has been concern for many years that surveys for absorption line galaxies may be affected by dust. That is, if the internal extinction of absorption galaxies is sufficiently large, then optical searches will miss quasars located behind them; this would seriously bias our surveys and skew our view of how galaxies evolve. Indeed, theoretical calculations have estimated that between 30 and 70% of QSOs (and, consequently, the absorption galaxies aligned in front of them) could be missed in present surveys due to this very effect.

Seeing Beyond the Smoke Screen

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 (where dust does not have an effect) with *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 essentially all of the sources. Although a large spectroscopic campaign was undertaken for much of the PQJ sample, these data were obtained at low spectral resolution for the purpose of object classification and redshift determination and are not suitable for absorption system studies. Therefore, over the last five years, we have been pursuing an active observing campaign that has so far logged some 30 nights on telescopes over four continents to address issues associated with obscuration bias.

The First CORALS Survey

The initial goal of the CORALS survey was to assess the possible bias in samples of high redshift damped Lyman α systems

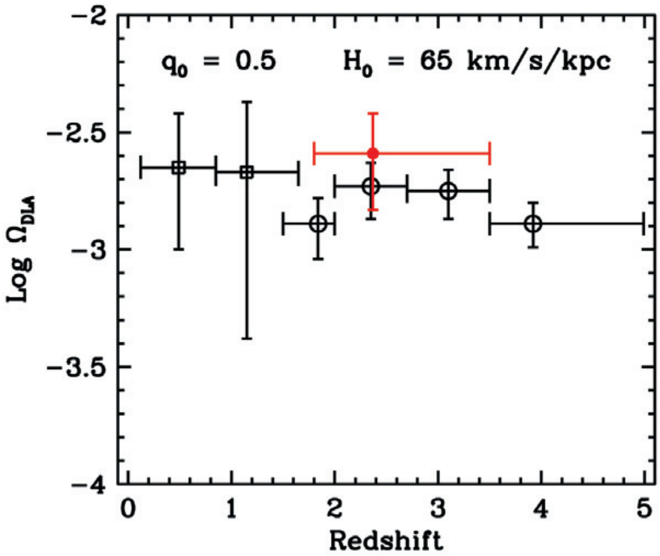

Figure 1: The mass density of neutral gas, Ω_{DLA}, in DLAs. Open circles and squares are measurements from the latest compilations by Péroux et al. (2001) and Rao & Turnshek (2000) respectively. The solid red circle is the value from the CORALS I survey presented here for the redshift interval 1.8 < z_{abs} < 3.5. These results show that, for z > 2, dust bias can only cause an under-estimate of Ω_{DLA} by at most a factor of two.

(DLAs), the highest column density absorbers associated with galaxy scale systems. The sample for this survey consisted of the 66 z_{em} > 2.2 QSOs from the PQJ survey which had magnitudes as faint as B=23.5. In order to determine whether dust had played a significant role in previous DLA surveys, we quantified both the number of absorption systems ($n(z)$), and the amount of neutral gas (Ω_{DLA}), that they contained. The main result of the first CORALS survey (whose results have been published in full by Ellison et al. 2001) is that these quantities ($n(z)$ and Ω_{DLA}) have only been slightly under-estimated in the past, i.e. that dust obscuration does not play a major role in hiding absorption galaxies. For example, in Figure 1 it can be seen that the amount of gas measured in the CORALS survey is at most a factor of about two more than previous magnitude limited samples. Nonetheless, fewer DLAs are found towards brighter QSOs than fainter subsets, 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 Ω_{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 the large datasets being reaped from surveys such as 2dF and the Sloan Digital Sky Survey (SDSS). These surveys are sufficiently large that error bars will be much less dominated by redshift coverage, so that observational biases, even subtle ones, will be important.

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~20 can be reached. However, it might be expected that biasing becomes more severe towards lower redshifts, since the bulk of star formation takes place by z ~1. 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.

Observationally, it is challenging to extend CORALS to z < 1.5, due to the onset of the atmospheric cut-off which renders detection of low redshift Lyα at λ=1216 Å impossible from the ground. Although large DLA surveys have been conducted with the Hubble Space Telescope (HST), these are very expensive in terms of resources. Moreover, current HST instrumentation restricts surveys to bright magnitudes, but it is the faintest QSOs that may be most affected by dust. Therefore, we have designed CORALS II to select absorption galaxies via Mg II and Fe II lines – strong metal features associated with galaxy halos that have transitions observable in the optical regime down to z ~ 0.3. By selecting systems with strong Mg II and Fe II absorption, we can efficiently pre-select likely DLAs.

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 Lyα forest. In the majority of cases, we also cover Fe II λ2600 and usually also Mg I λ2853. Our aim is to be complete down to an observed 3σ equivalent width threshold of 0.5 Å for Mg II, although in most cases we achieve limits significantly beyond this. Up to this point, we have a redshift path coverage Δz ~50 for a rest frame 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 λ2796) ≥0.5 Å and a further 10 with EW(Mg II λ2796) ≥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 equivalant width threshold of EW>0.6 Å (the limit used by SS92) we determine $n(z)$=0.46±0.10 (at $\langle z_{abs}\rangle$ = 1.08) compared with 0.65±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!* Therefore, the preliminary results of this lower redshift survey paint the same picture as at high redshift: dust is not responsible for hiding a large number of absorption systems.

In Figure 2 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 the context of dust bias, the possible surfeit of absorbers towards bright QSO samples at intermediate redshift seems puzzling. One way to explain this is with 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 CORALS sample in half by emission redshift, the number density for z_{em}> 2.1 is $n(z)$=0.52±0.17 and 0.41±0.13 for lower

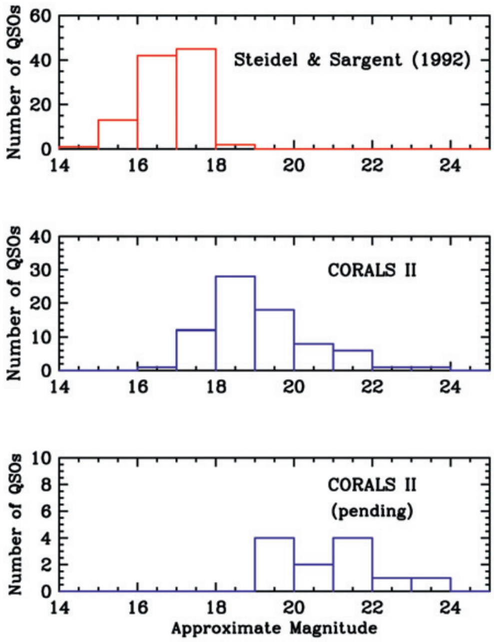

Figure 2: Comparison of the QSO magnitudes for the Steidel & Sargent (1992) Mg II survey and CORALS II. The bottom panel shows the final targets that are still pending observation. The SS92 survey is effectively a 'bright' QSO sample, whereas CORALS II is optically complete and includes QSOs up to 250 times fainter than the SS92 limit.

redshifts (for $\langle z_{abs} \rangle \sim 1.1$ 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. 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. Indeed, Smette et al. (in preparation) find less neutral gas in DLAs towards the bright HE quasars, compared to CORALS.

Confirming the N(HI) of our complete Mg II sample, and thereby determining Ω_{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 Ω_{DLA} (Smette et al. 1997) because the line of sight preferentially passes through the inner part of the lensing galaxy.

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 ~3000 km/s of the QSO due to proximity effects and the possibility that the absorber may be associated with the QSO itself. However, it has been 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 calculating the $n(z)$ for PDLAs in the radio-loud quasar CORALS sample, Ellison et al. (2002) found four times as many systems in CORALS I than in the radio-quiet sample of Peroux et al (2001). Although this result is only significant at the 2σ 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(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 α/Fe (where α 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 3. 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.

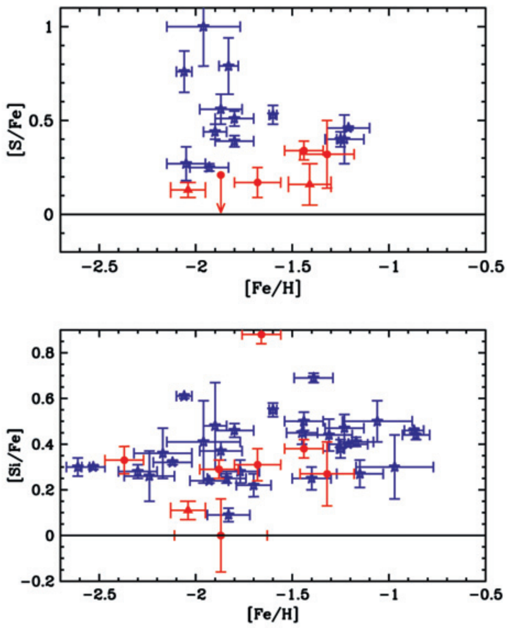

Figure 3: α/Fe ratios for MDLAs (solid red circles), DLAs in fields with known galaxy neighbours (solid red triangles) and single DLAs taken from the literature (open blue stars). DLAs with nearby galaxies both in the field, and seen in absorption (MDLAs) have systematically lower α/Fe, a trend particularly obvious in the [S/Fe] ratio. See Lopez & Ellison (2003) for further discussion.

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