Environment or Outflows? New insight into the origin of narrow associated QSO absorbers

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INTRODUCTION

AGN feedback is widely proposed as the solution to a number of otherwise difficult-to-explain problems in extra-galactic astrophysics. From an observational perspective, it is worth first dissecting the forms of “feedback” that are under discussion, before embarking on any project to observe this potentially universal process. Figure 1 gives a short summary of the topic of feedback, which can broadly be split into two parts (column 2): heating of gas in-situ, and outflows which remove matter from the host galaxy. Both processes may, or may not be associated with jets, so jets have been placed separately. While outflows are assumed to predominantly affect the nuclear region and possibly the ISM of the host galaxy, in-situ heating of the gas must occur on very large scales within the IGM (column 3). The final column presents a selection of observed or yet-to-be-observed consequences of the physical mechanisms: the list is not meant to be exhaustive, but simply present the range of the observations with which we must deal. While there is little argument that some aspects of AGN feedback have been directly detected, conclusive evidence for routine quenching of star formation and removal of the interstellar medium of QSO host galaxy remains elusive.

Of particular relevance to this contribution, are the Narrow Absorption Line systems (NALs) which appear in every box on the right hand side of Figure 1, and are arguably one of the best candidates for directly detecting “ubiquitous” QSO feedback. These absorption lines, generally detected in the rest-frame ultra-violet due to the convenient gathering of several strong transitions, are caused by clouds of ionised and/or neutral gas which intervene between a strong light source and the observer. This material need not be dense to cause significant absorption of the traversing light: the detection of MgII absorption generally implies Hydrogen column densities of a few \(10^{17}\) atoms/cm\(^2\), for CIV this number is two orders of magnitude smaller at \(10^{15}\) atoms/cm\(^2\). In contrast to the well studied Broad Absorption Line systems (BALs), NALs are thought in general to arise from the interstellar medium and surrounding halo gas of ordinary galaxies. Together with the convenient placing of their resonance transition lines in the observed-frame optical at redshifts of interest for QSO feedback, metal NALs can be a very powerful tool for probing the physical state and position/velocity of gas both within and external to the host galaxies.

In these proceedings I will review some of the studies using NALs to look for direct evidence of QSO feedback, from detailed studies of a few objects through to statistical
studies using the largest databases of absorbers available to us today. I will present new results on the distribution of line-of-sight velocity offsets between MgII absorbers and their background QSOs, which reveal a high-velocity population similar to that observed recently for CIV.

**USING ULTRA-VIOLET NALs TO REVEAL QSO FEEDBACK**

Although there is an abundance of data on NALs, covering most of the age of the Universe, and they evidently have the potential to trace the very gas clouds we hope to see being expelled from galaxies, as with many aspects of QSO absorption line studies real scientific progress has been relatively slow. This can be ascribed to two main problems. Firstly, the degeneracy between cosmological distance and velocity makes it difficult to uniquely identify an individual absorber with gas that is intrinsic to the host and outflowing, when an intervening galaxy could produce the same absorption signal at the same redshift offset. The very ubiquity of the absorbing clouds provides a large “contaminant” population of intervening systems, entirely unrelated to the problem at hand. Then there is the puzzling absence of absorption line systems at the redshift of the QSO [17]. This could either be due to the QSO host being gas poor, perhaps
QSOs are only observed after the expulsion of their gas, perhaps the gas is heated to such an extent that the lines are no longer visible, or perhaps the QSO redshifts in the small samples studied have not been measured accurately enough to locate $z_{\text{ABS}} \sim z_{\text{QSO}}$ systems reliably.

Detailed studies of a small number of systems have successfully shown that some NALs are indeed intrinsic to the QSO-host system. Both time-variability and the presence of lines which are not “black” can indicate that NALs originate from within the nuclear region. For example, Misawa et al. [9] studied a sample of 37 high resolution QSO spectra with $2 < z < 4$ to conclude that at least 50% of quasars host high ionisation NALs (CIV, NV, SiIV) which are diluted by unocculted light, and thus lie close to the central engine. Detailed observations of multiple transitions have resulted in mass loss rates and precise distances for a handful of objects at both high and low redshift (e.g. [4, 14]). However, with such small samples, and especially at high redshift where imaging is difficult in front of a bright background QSO, the question always remains as to whether an absorption system at a few kpc is simply the sign of an intervening galaxy.

Detailed analyses of NALs in QSO sightlines that pass close to foreground QSOs also allow us to probe the effect of the QSO on gas which does not lie directly within “firing range” of the QSO (the “transverse proximity effect”). Recent results remain inconclusive: Bowen et al. [3] find no evidence for a reduction in strong MgII systems, whereas Gonçalves et al. [6] find a significant change in ionisation state of gas on scales of 1 Mpc. Hennawi & Prochaska [7] detect an isotropy in the distribution of 17 Lyman-limit systems around QSOs, suggesting that the line-of-sight systems may be photoevaporated.

Such detailed analyses of small numbers of systems have been complemented by the statistical analyses of large samples of NALs. Until recently the question primarily revolved around the presence, or absence, of an excess of absorbers close to QSOs (so called “associated” systems, with velocities below a few hundred, to a few thousand km/s depending on the study). With large samples, an excess of absorbers at $z_{\text{ABS}} \sim z_{\text{QSO}}$ has now been clearly detected (e.g. [12, 18]). Vanden Berk et al. [2] compared the properties of associated absorbers to those at larger redshift separations, finding that they are dustier and have higher ionisation states. But the ambiguity remains as to whether the population arises from neighbouring galaxies or from gas associated with the QSO, its host galaxy and its halo.

THE LINE-OF-SIGHT DISTRIBUTION OF NALS IN FRONT OF QSOS

The Sloan Digital Sky Survey (SDSS) has led to an enormous increase in the quantity of data available on QSO absorption line systems. While the spectra are not of particularly high resolution or signal-to-noise ratio (SNR), preventing detailed analyses of individual systems, the shear numbers of objects allow statistical studies which were previously impossible. Here we present the topic of the statistical analysis of associated NALs, through a new analysis of MgII absorption line systems based on a catalog of nearly 20,000 systems culled from the sixth data release (DR6) of the SDSS survey. The catalog
was constructed using a matched-filter detection algorithm as described in Wild et al. [19]. For reasons of catalog completeness, the NALs are restricted to have rest-frame equivalent width $W_{\lambda 2796} > 0.5$ and the QSO spectra searched are required to have per-pixel-SNR > 8. For the analysis of $z_{\text{ABS}} \sim z_{\text{QSO}}$ absorption systems, accurate redshifts for the QSOs are crucial [11], a difficult problem due to the substantial broadening of the emission lines in QSOs. The results presented here rely upon new QSO redshifts using a combination of available narrow emission lines and new cross-correlation templates (Hewett & Wild in preparation).

In Figure 2 we present the distribution of velocity offsets between the MgII absorption line systems and their background QSOs:

$$\beta = \frac{R^2 - 1}{R^2 + 1} \quad \text{where} \quad R = \frac{1 + z_{\text{QSO}}}{1 + z_{\text{ABS}}}$$

(1)

For the first time for MgII, we can clearly identify three populations:

- At large velocities, $\beta > 0.02$, the constant number density is consistent with an intervening population of absorbers caused by galaxies and gas clouds that are not physically associated with the QSO.
- A clear spike in the numbers is seen at $\beta = 0$, consistent with a Gaussian distribution with mean of approximately zero and width of a few hundred km/s. Whether these NALs primarily originate in galaxies clustered around the QSO or in the QSO host galaxy is the question we must address.
Finally, there is a very clear extended excess of absorbers out to velocities $\beta < 0.02$ or $v < 6000 \text{km/s}$, a feature previously seen clearly in CIV [13, 11, 20], but only hinted at before for MgII [20]. The distribution is well described by a low-velocity component (delta function) centered approximately on zero, an exponentially distributed high-velocity component of width $w$ at $\beta > 0$ (upper dotted line), both superposed on a constant background intervening population ($B$, lower dotted line), and convolved with a Gaussian kernel to account for redshift errors and/or peculiar velocities:

$$N_{\text{ABS}} = \left( A_1 \delta(\beta - \mu) + [A_2 \exp(w_\beta) + B]_{\beta > 0} \right) * G(\sigma)$$

where we find $\sigma = 413 \pm 30 \text{km/s}$ and $w = 125 \pm 23$. The full fit is shown as a dashed line in Figure 2.

Unfortunately the detection of an excess of NALs at the redshift of the QSO is not unambiguous evidence for NALs in the host galaxies of the QSOs. As we show in the next section, galaxy clustering can lead to a signal which is difficult to distinguish with current data.

THE 3D DISTRIBUTION OF NALS AROUND QSOS

With the size of catalogs now available from the SDSS, it is possible to measure directly the 3D clustering of absorbers around QSOs using a cross-correlation style analysis.
With the clustering amplitude in hand, we will then estimate the excess number of absorbers expected along the line-of-sight to the QSOs. The method used to measure the 3D clustering is presented in detail in [20]. To summarise, we count the number of observed QSO-MgII pairs \( N_{\text{obs}} \) as a function of comoving separation \( r \) and compare this to the number of pairs that would expect \( N_{\text{exp}} \) for a constant background distribution of absorbers without clustering. To avoid contamination from NALs that might be associated with outflowing gas from a QSO host, we restrict the NAL sample to those with \( z_{\text{ABS}} < z_{\text{QSO}} - 0.1 \). In Figure 3 we present the new results using the DR6 MgII catalog with improved QSO redshifts. The dash-dot line is a powerlaw fit of the form:

\[
\xi(r) = \frac{N_{\text{obs}}}{N_{\text{exp}}} - 1 = \left( \frac{r}{r_0} \right)^{-\gamma} \tag{3}
\]

where \( r_0 \) is the correlation scale length which we measure to be \( 5.67 \pm 0.4 h^{-1}\text{Mpc} \), with a power law index of \( \gamma = 1.74 \pm 0.09 \), or \( 5.73 \pm 0.3 h^{-1}\text{Mpc} \) at fixed \( \gamma = 1.8 \). This correlation length is similar to that measured for bright galaxies at similar redshifts. There is evidence, at the level of around \( 3\sigma \), for a flattening in the MgII-QSO clustering on small scales (\(< 5h^{-1}\text{Mpc}\)). This may be caused by QSO redshift errors or absorber peculiar velocities which can have a significant effect at small absorber-QSO separations. It may also indicate the presence of a transverse “proximity effect”, where the QSO ionises the gas in its surrounding halo (but see [3]). Clearly there is scope for further investigation of this feature in the future. Discarding the central bin from our power law fit increases the measured correlation length and power law index both by about \( 3\sigma \), leading to a larger predicted clustering signal that only enhances the qualitative conclusions drawn from this study.

**THE CLUSTERING CONTRIBUTION TO THE LINE-OF-SIGHT EXCESS**

In Figure 4 we convert the distribution of line-of-sight QSO-absorber redshift separations into comoving distance units, to allow direct comparison with the 3D-clustering results of the previous section. One free parameter is then required for our toy-model: the distance below which physical processes internal to the host-galaxy dominate the distribution of absorbers, rather than the clustering of galaxies in the QSO neighbourhood. As we shall see, the precise distribution of MgII absorbers around the host galaxy of the QSOs is irrelevant to our results, due to the significant deficit of absorbers detected along the line-of-sight. We therefore define a simple “ionisation radius” \( R_{\text{ion}} \) internal to which the number of absorbers is zero. Finally, the model is convolved with a Gaussian of width equivalent to \( \sigma = 413\text{km/s} \) at the median redshift of absorbers which lie within \( \pm 10h^{-1}\text{Mpc} \) of their background QSO \( (z = 1.3) \), i.e. to match the measured width of the distribution in velocity space (Figure 2). The dashed line in Figure 4 shows the predicted line-of-sight distribution of absorbers in front of QSOs, from galaxy clustering alone and with a ionisation radius \( \sim 420h^{-1}\text{kpc} \) (comoving units), or \( 180h^{-1}\text{kpc} \) (proper units at the median redshift of the sample). We note that this value for the ionisation radius is
FIGURE 4. Distribution of line-of-sight QSO-absorber separation as a function of comoving distance (where line-of-sight redshift separation has been converted into comoving distance in the usual way). The dashed line shows the predicted distribution of MgII absorbers from clustering, assuming the QSO ionises (i.e. removes) all absorbers to a proper distance of $130h^{-1}$kpc.

slightly lower than that given in [20], likely resulting from the completely independent method used to select the absorbers.

Typical MgII halos around galaxies can extend to $\sim 40h^{-1}$kpc (proper) with almost unity covering fractions [15]. Beyond this distance MgII halos are thought to be patchy, and can extend to distances of $70h^{-1}$kpc [8, 21]. Our result shows that the MgII ion, with an ionisation potential of 15.03eV, is destroyed in clouds which lie at even greater distances from QSOs and thus far into the IGM. The spike of absorbers below $\beta < 0.002$, $v < 600$km/s, or $R < 10h^{-1}$Mpc, is entirely consistent with galaxy clustering from galaxies that lie beyond the ionisation zone of the QSO. However, we cannot rule out that $R_{ion}$ is indeed even larger and the low-velocity absorbers are caused by denser, self-shielded, clouds remaining within the ionisation zone, perhaps even intrinsic to the QSO host itself.

Clearly the high velocity tail is, however, caused by a process internal to the QSO itself, and with velocities as high as $0.02c$ ($\sim 6000$km/s) these outflows must be driven by the central AGN engine, rather than any accompanying starburst [16]. The very existence of these absorbers is puzzling, given the clear ability of the QSO radiation to destroy all normal MgII clouds out to very large distances. Their existence also leads us to question the conclusion that the low-velocity absorbers are primarily due to galaxy clustering. Are they the remnants of the densest ISM clouds yet to be destroyed? Are they unrelated to ordinary MgII ISM clouds, and instead created in the turbulence of outflowing gas? Their distance from the nuclear source remains to be determined. If they are external to the nuclear region, then they are surely evidence for the expulsion of (cold) gas from the galaxy ISM. If they are internal to the nuclear region, such low
FIGURE 5. The distribution of line-of-sight velocity offsets between MgII NALs and the background QSOs, separated by the radio luminosity at $10^{25}$ W/Hz of the QSOs. The RQQSO sample has been selected to match the RLQSO sample in optical luminosity.

ionisation gas with narrow velocity widths can constrain models for the inner regions of QSOs [5].

RADIO LOUD VS. RADIO QUIET

One further statistical investigation may lead to significant insight into the origin of the MgII absorbers within 6000 km/s from the QSO. It has been known for some time that QSOs with different radio properties (loud/quiet, flat/steep spectrum) have different fractions of absorption line systems, strongly suggesting a non-intervening origin at least for a subset [1, 12]. More recently, detailed studies of nearby radio galaxies have revealed outflowing neutral Hydrogen in 21cm absorption against the background radio source [10].

In Figure 5 we present the velocity separation of radio loud QSOs (RLQSOs, $L_{\text{FIRST}} > 10^{25}$ W/Hz) compared to a sample of radio quiet QSOs (RQQSOs) matched in optical luminosity to the RLQSOs. We can clearly see that RLQSOs show a larger excess of low-velocity MgII absorbers than RQQSOs with high significance. Within $-0.002 < \beta < 0.002$, RLQSOs have an excess of 6.2 absorbers over the background level, compared to 3.6 for RQQSOs. At high velocities, RLQSOs also seem to show a small increase in MgII NALs: for $0.002 < \beta < 0.02$, RLQSOs have an excess of 2.1 compared to 1.6 for RQQSOs.

The question remains as to whether RLQSOs are more strongly clustered than RQQSOs. If so, then the excess low-velocity MgII absorbers seen in RLQSOs may result solely from them living in higher density neighbourhoods. Unfortunately, the SDSS
DR6 catalog is still not quite large enough to answer this question using the method presented above.

CONCLUSIONS

A number of recent studies have found that NALs intrinsic to the QSO host can be found in at least 50% of QSO spectra, and in most cases they are found to be outflowing. Simply due to observational limitations the position of these confirmed cases is, however, close to the central nucleus. In the few cases where larger distances can be determined from detailed line analyses, it is usually impossible to rule out the presence of an intervening galaxy.

Through the enormous statistical power of the SDSS, we can now determine precisely the contribution of galaxy clustering to QSO-absorber line-of-sight distributions. This leads to the following conclusions:

• QSOs heat the gas to considerable distances along their line-of-sight, with relatively low ionisation MgII ions ionised to several hundred kpc (comoving) into the IGM.
• Within 600km/s there is an excess of NALs, however, this excess is most simply explained by ordinary absorption clouds in and around galaxies which lie outside of the ionising influence of the QSO.
• A subset of absorbers out to velocities of 6000km/s (MgII) or 12000km/s (CIV) can not be explained by intervening galaxies. Their velocity distribution is well fit by a declining exponential (but see [11]), and their high maximum velocities indicate an origin close to the central engine.
• There is a significant excess of low-velocity NALs in RLQSOs, compared to RQQSOs. This excess may also extend into the high-velocity systems. Unfortunately, the statistics are not quite good enough to rule out the possibility that RLQSOs simply live in denser environments.

The heating effect of a QSO on its host galaxy, and likewise on all nearby galaxies, is unmistakable. However, the existence of the high-velocity systems, which we would naively expect not to exist in the intense radiation field of the QSO, leaves a narrow window of doubt as to the true origin of the low-velocity systems. Allowing the ionisation radius to increase, thus removing more intervening clouds, would allow some, if not all, low-velocity systems to arise from gas associated with the QSO, its host galaxy and its halo. There is certainly more work to be done before we can definitively claim the origin of low-velocity NALs to be intervening galaxies.

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