Towards understanding the mass–metallicity relation of quasar absorbers: evidence for bimodality and consequences

Nicolas Bouché

Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse, Garching D-85748, Germany

Accepted 2008 June 7. Received 2008 May 29; in original form 2008 April 7

ABSTRACT

One way to characterize and understand H I-selected galaxies is to study their metallicity properties. In particular, we show that the metallicity of absorbers is a bivariate function of the H I column density (N_{HI}) and the Mg II equivalent width (W_{\lambda 2796}). Thus, a selection upon W_{\lambda 2796} is not equivalent to a H I selection for intervening absorbers. A direct consequence for damped absorbers with log N_{HI} > 20.3 that falls from the bivariate metallicity distribution is that any correlation between the metallicity [X/H] and velocity width (using W_{\lambda 2796} as a proxy) cannot be interpreted as a signature of the mass–metallicity relation akin to normal field galaxies. In other words, damped Lyα absorber (DLA) samples are intrinsically heterogeneous and the [X/H]–W_{\lambda 2796} or [X/H]–Δύ correlation reported in the literature arises from the H I cut. On the other hand, a sample of Mg II-selected absorbers, which are statistically dominated by lowest N_{HI} systems (sub-DLAs) at each W_{\lambda 2796}, is found to have a more uniform metallicity distribution. We postulate that the bivariate distribution [\[X/H]\](N_{HI}, W_{\lambda 2796}) can be explained by two different physical origins of absorbers, namely sight lines through the interstellar medium of small galaxies and sight lines through the out-flowing material. Several published results follow from the bivariate [X/H] distribution, namely (i) the properties of the two classes of DLAs, reported by Wolfe et al. and (ii) the constant dust-to-gas ratio for Mg II absorbers.

Key words: galaxies: evolution – galaxies: haloes – quasars: absorption lines – cosmology: observations.

1 INTRODUCTION

Among quasar [quasi-stellar object (QSO)] absorption-line systems, damped Lyα absorbers (DLAs) with column densities N_{HI} ≥ 2 × 10^{20} cm^{-2} are the most puzzling. Their high column density range indicates that they ought to trace cold neutral gas, hence discs (e.g. Wolfe et al. 1986; Wolfe & Prochaska 1998). This is further supported as in the local universe, most of the H I gas with these column densities are in galaxies (e.g. Rosenberg & Schneider 2003; Zwaan et al. 2005). In addition, Prochaska & Wolfe (1998) (and others) argued that the kinematics of DLAs (traced by low ions) are best explained by models of rapidly rotating discs.

Despite decades of studies, it is not clear whether this cold neutral gas is a part of the interstellar medium (ISM) of large spirals (Wolfe et al. 1986), a part of the haloes of galaxies (Bahcall & Spitzer 1969) or a part of dwarf galaxies (York, Burks & Gibney 1986) akin to the Magellanic Clouds. An alternative scenario for absorption-selected galaxies is that the gas seen in absorption is a part of cold gas clumps in the host-galaxy haloes entrained in outflows produced by supernovae (SNe) (Nulsen, Barcons & Fabian 1998; Schaye 2001).

Among the many different approaches that have been used to make further progress on this issue, one is to use the metallicity of the gas. Since the metallicity of the absorbing gas, and of DLAs in particular, is typically 1/30th solar (e.g. Pettini et al. 1999; Prochaska & Wolfe 1999; Péroux et al. 2003b; Prochaska et al. 2003b), and z > 1 star-forming galaxies have metallicities closer to solar, i.e. more metal-rich by a factor of 10 (e.g. Erb et al. 2006), one is often forced to invoke metallicity gradients in galaxies to 30 kpc and beyond to reconcile the two observations. If indeed absorption and emission metallicities are related to one another solely by a metallicity gradient, one would expect a similar mass–metallicity correlation in DLAs as observed in normal star-forming galaxies (Tremonti et al. 2004; Erb et al. 2006).

While the metallicity of absorbers is usually straightforward to determine (e.g. Prochaska, Wolfe & Gawiser 2000; Péroux et al. 2003b; Prochaska et al. 2003b; Péroux et al. 2006; Prochaska et al. 2006; Kulkarni et al. 2007), the mass (dynamical or baryonic) of absorption-selected galaxies cannot be usually measured directly because the host galaxy is usually elusive. Progress is underway from (i) direct dynamical mass estimates of 14 Mg II-selected...
galaxies by Bouché et al. (2007b) (and Bouché et al., in preparation), and (ii) direct comparison between the host-emission metallicity and the absorption metallicity (Bouché et al., in preparation).

Indirect, and statistical, mass measurements have been made from clustering analysis (Bouché et al. 2006) for strong \( z \gtrsim 0.5 \) Mg ii absorbers with rest-frame equivalent widths \( W_r^{2796} \geq 1 \AA \), which are intimately related to low-\( z \) DLAs (Churchill et al. 2000; Rao & Turnshek 2000; Rao, Turnshek & Nestor 2006). Bouché et al. (2006) found that the host halo-mass \( (M_H) \) and \( W_r^{2796} \) are anticorrelated. For virialized clouds, the host mass and the line-of-sight velocity dispersion ought to be correlated, i.e. a \( M_H-W_r^{2796} \) correlation is expected because \( W_r^{2796} \) is a measure of the line-of-sight velocity width \( (\Delta v) \) as individual Mg ii absorptions are saturated (Ellison 2006). Thus, the results of Bouché et al. (2006) imply that Mg ii clouds are not virialized in the host haloes, and supernovae-driven outflows provide a natural mechanism. While the mass–\( W_r^{2796} \) results have been confirmed by an independent team (Allen, Hewett & Ryan-Webber, in preparation), ad hoc models have been proposed to explain the anticorrelation in a cosmological context (e.g. Tinker & Chen 2008).

Since one would expect a mass–metallicity correlation for all galaxies, the mass–\( W_r^{2796} \) anticorrelation of Bouché et al. (2006) implies a metallicity–\( W_r^{2796} \) anticorrelation, or equivalently a metallicity–velocity width anticorrelation. However, several groups have reported just the opposite: the metallicity in DLAs correlates either with the velocity width \( \Delta v \) (Wolfe & Prochaska 1998; Péroux et al. 2003b; Ledoux et al. 2006; Prochaska et al. 2008) or with the \( W_r^{2796} \) (Meiring et al. 2007; Murphy et al. 2007). It is tempting to assume that \( \Delta v \) is a measure of the line-of-sight velocity dispersion, i.e. it correlates with the mass of the host galaxy, since when combined with the above results, one would naturally imply a normal mass–metallicity relation.

Thus, there appears to be a conflict between the \( M_H-W_r^{2796} \) anticorrelation of Bouché et al. (2006) and the \( W_r^{2796} \) (velocity)–\([X/H]\) correlations reported in the literature. In this letter, we show that the conflict is apparent and reflects the various selections at play (\( \lambda H_I \) versus Mg ii) using Mg ii systems from the literature. In Section 2, we describe our sample where we collected neutral column density \( N_{\lambda H_I} \), Mg ii equivalent widths and metallicities \([X/H]\), Section 3 shows our results.

2 DATA

We combined various samples of Mg ii absorbers and DLAs from the literature, namely we used the samples of Rao et al. (2006), Ellison (2006), Kulkarni et al. (2005), Curran et al. (2007), Murphy et al. (2007) and Ledoux et al. (2006), augmented by the catalogue of Ryabinkov, Kaminker & Varshalovich (2003). The \( \lambda H_I \) column densities come mostly from the STIS survey of Rao & Turnshek (2000), Rao et al. (2006) for the low-redshift absorbers. The entire catalogue contains about 1200 absorbers, of which 377 have both \( W_r^{2796} \) and \( N_{\lambda H_I} \) measured. We then match the literature samples with published metallicity measurements from Péroux et al. (2003a, 2004, 2006), Möller, Fynbo & Fall (2004), Prochaska et al. (2006), Kulkarni et al. (2005), Ledoux et al. (2006), Ellison (2006), Prochaska et al. (2006), Meiring et al. (2007, 2008) and Murphy et al. (2007). The final sample is made of 89 absorbers with known \( N_{\lambda H_I}, W_r^{2796} \) and \([X/H]\).

We show the redshift distribution of the subsamples in Fig. 1. The solid histogram shows the literature sample of 1200 absorbers. The thick histogram shows the 377 absorbers with \( W_r^{2796} \) and \( N_{\lambda H_I} \), and the grey histogram shows the 89 absorbers with \( W_r^{2796}, N_{\lambda H_I} \), and \([Zn/H]\). In order to have homogeneous metallicity measurements, we impose that all metallicity measurements are from Zn. In order to probe for any redshift evolution, we will split the sample into low \( z < 1.6 \) and high \( z > 1.6 \).

3 RESULTS

3.1 Metallicity gradient in \( N_{\lambda H_I}-W_r^{2796} \)

Fig. 2(a) shows the distribution of absorbers in the \( N_{\lambda H_I}-W_r^{2796} \) plane as in Rao et al. (2006). Note that strong Mg ii absorbers have indeed larger \( N_{\lambda H_I} \), and can be regarded as DLAs dominated, however the opposite is not true. A DLA sample covers the entire range of \( W_r^{2796} \). The large connected squares show the logarithmic mean (\( \log N_{\lambda H_I} \)). The logarithmic mean is a better statistic to quantify the distribution of the points. Rao et al. (2006) elected to use the mean \( \langle N_{\lambda H_I} \rangle \) statistics since they were interested in the mean \( \lambda H_I \) column density in order to constrain \( \Omega_{\lambda H_I} \). The solid squares show that (\( \log N_{\lambda H_I} \)) increases with equivalent width, reflecting an increasing fraction of DLAs as a function of \( W_r^{2796} \).

In Fig. 2(a), as noted many times (e.g. Rao et al. 2006; Chelouche et al. 2007), there are no absorbers to the bottom right-hand panel of the figure, i.e. with large \( W_r^{2796} \) and low-\( \lambda H_I \) column densities. The lack of objects in that part of the diagram is due to selection effects; strong Mg ii absorbers are easy to identify there.

The solid squares in Fig. 2(b) show the absorbers whose \([X/H]\) measurement exist in the literature, and color-coded according to \([Zn/H]\) from −2 to 0. This figure clearly shows that the more metal-poor (lighter grey points) are located in a different location as the metal-rich (darker grey points). In other words, there is a strong metallicity gradient across the \( N_{\lambda H_I}-W_r^{2796} \) plane, represented schematically in Fig. 3(a). The metallicity gradient is noted by the vector. For low-\( \lambda H_I \) column densities (\( \log N_{\lambda H_I} < 19.5 \)), there is a lack of metallicity data due to difficulties in measuring \([X/H]\) due to an increasing ionization correction (Péroux et al. 2006; Prochaska et al. 2006).
Figure 2. (a) The distribution of absorbers in the $N_{\text{HI}}-W^2_{2796}$ plane. Strong Mg II absorbers have indeed larger $N_{\text{HI}}$, and can be regarded as DLA-dominated, however the opposite is not true. A DLA sample covers the entire range of $W^2_{2796}$. The large connected squares show that the logarithmic mean $\langle \log N_{\text{HI}} \rangle$.
(b) For those with [Zn/H] measurements, the points are color-coded according to increasing metallicity from [Zn/H] = $-2$ to 0. There is a clear metallicity gradient. Furthermore, the gradient is inclined with respect to the y-axis. In both the panels, the dashed line shows the classical DLA threshold of 20.3.

Figure 3. (a) Schematic representation of the metallicity gradient shown in Fig. 2(b). The ‘metal-poor’ extends over the high-log $N_{\text{HI}}$ region, while the ‘metal-rich’ region extends over the low-log $N_{\text{HI}}$ region (assumed to have uniform metallicity). (b) Mean metallicity $\langle [X/H] \rangle$ for DLAs with log $N_{\text{HI}} > 20.3$ (top panel) and sub-DLAs (bottom panel). The solid lines show the average $\langle [X/H] \rangle$ in bins of $W^2_{2796}$ as in Fig. 2(a). The increase in the mean metallicity for DLAs is $\sim 0.8–1$ dex which is the increase reported by Ledoux et al. (2006). On the other hand, sub-DLAs have roughly a similar metallicity. The $P$-values for the Spearman’s rank correlation test are shown. This figure shows that the $[X/H]–\Delta v$ and $[X/H]–W^2_{2796}$ correlations reported by Ledoux et al. (2006) for DLAs and Murphy et al. (2007) are both a ‘selection effect’: the correlation with metallicity originates from the increased overlap of the metal-poor and metal-rich systems in the $N_{\text{HI}}–W^2_{2796}$ plane (Fig. 2b).

3.2 Biased metallicities

Fig. 2(b) shows that sub-DLAs are generally more metal-rich than DLAs, a result noted already by many (e.g. Khare et al. 2007). However, since the metallicity changes in a subtle way in the $N_{\text{HI}}–W^2_{2796}$ plane (Fig. 3a), one would expect to have different mean metallicity $\langle [X/H] \rangle$ for different $N_{\text{HI}}$-selected samples. This is illustrated in Fig. 3(b), where we plot $\langle [X/H] \rangle$ for DLAs with log $N_{\text{HI}} > 20.3$ (top panel) and sub-DLAs with log $N_{\text{HI}} < 20.3$ (bottom panel). The metallicity $[X/H]$ increases as a function of $W^2_{2796}$ (a proxy for the velocity width $\Delta v$) for DLAs. The $P$-value of the Spearman’s correlation test is $2 \times 10^{-7}$, i.e. the correlation is significant at $>4\sigma$.

Moreover, the increase in the mean metallicity $[X/H]$ is $\sim 0.8–1$ dex, which is the increase reported by Ledoux et al. (2006) for their DLA-sample. On the other hand, for absorbers with log $N_{\text{HI}}$ less than 20.3, the mean metallicity appears constant (Fig. 3b, bottom panel). The Spearman’s correlation test gives a $P$-value much higher (0.10) and shows that the correlation is significant at best at 1.5$\sigma$. Without the one data point at $W^2_{2796} = 0.5$ Å, the $P$-value is still higher: 0.43 and the $W^2_{2796}$ is not correlated with $[X/H]$. We note that the $[X/H]–W^2_{2796}$ relation reported by Murphy et al. (2007) is explained by the fact that their sample is dominated by systems with H I column densities mostly above the DLA threshold $N_{\text{HI}} > 20.3$ (Fig. 2a). Thus, the $[X/H]–\Delta v$ and $[X/H]–W^2_{2796}$ correlations...
reported by Ledoux et al. (2006) for DLAs and Murphy et al. (2007) are both a ‘selection effect’: it originates from the increased overlap of the metal-poor and metal-rich systems in the $N_{\text{HI}}-W_{\lambda 2796}$ plane.

While the fraction of DLAs increases with $W_{\lambda 2796}$, this exercise shows that the selection upon $W_{\lambda 2796}$ is not equivalent to a H I selection, as the two sample will have very different properties: the Mg II-selected sample will be biased towards more metal-rich absorbers, while the H I-selected sample will be more metal-poor, with a strong metallicity dependence on $W_{\lambda 2796}$.

Note that there seems to be no redshift bias in our results: Fig. 2(b) looks similar for the $z_{\text{abs}} < 1.6$ and $z_{\text{abs}} > 1.6$ subsamples, with perhaps an overall shift in metallicities which has been before for DLAs and sub-DLAs (Prochaska et al. 2003a; Kulkarni et al. 2007). Based on these results, we turn towards a physical interpretation.

3.3 Interpretation

As we already noted, the $N_{\text{HI}}$ distribution is bimodal in the $N_{\text{HI}}$–$W_{\lambda 2796}$ plane (Fig. 2a). This is particularly true for systems with $W_{\lambda 2796} < 1.5$ Å. This indicates there might be two classes of intervening absorbers, probing different physical conditions. While observational bias may play a role here, the survey of Rao et al. (2006) is unbiased in regards to H I column density, and the bimodality is already present in their sample.

Given the metallicity gradient shown in the previous section and the absorber distribution in the $N_{\text{HI}}$–$W_{\lambda 2796}$ plane, we make the following assumption to guide our understanding: absorbers in the red metal-rich shaded region in Fig. 3 originate in one physical environment with a more homogeneous metallicity distribution, while the blue metal-poor absorber in the blue region with low $W_{\lambda 2796}$ and high $N_{\text{HI}}$ may be the ‘classical’ DLAs where the sight line is probing the ISM of small galaxies. These two hypotheses are illustrated with Fig. 4.

Since our recent results (Bouché et al. 2006, 2007b) favour the outflow scenario for Mg II-selected absorbers, we postulate that the homogeneous metallicity distribution originates from the metal-rich material being driven out of sub-$L^*$ galaxies. Indeed, several studies (Bouché et al. 2007a; Oppenheimer & Davé 2008) have shown that galaxies with $L < 1/3L^*$ dominate the metal budget in the intergalactic medium, i.e. the metals outside the ISM of galaxies. This material is either directly entrained by ram pressure from the hot outflow, or traces cooling material (where the metallicity is higher and the cooling time is shorter) (Maller & Bullock 2004). Either way it may very well return to the ISM of the galaxy as recent wind models suggest (Oppenheimer & Davé 2008).

This picture outlined in Fig. 4, which may still be somewhat over simplified, naturally explains many other observables of intervening absorbers. For instance, as pointed out in the previous section, a sample of DLAs will be made of a mix of the two types of absorbers. Interestingly, Wolfe et al. (2008) reported evidence for a bimodality in DLAs using [C II] 158 μm cooling rates, $\dot{\epsilon}$. The ‘low-cool’ DLAs have lower velocity widths, lower metallicity and lower dust-to-gas ratios than the ‘high-cool’ DLAs which have larger velocity widths and higher metallicities. Fig. 3 naturally shows that DLAs with large velocity dispersions (as measured by $W_{\lambda 2796}$) would be more metal-rich, than those with low-velocity widths. Furthermore, the Hubble Ultra Deep Field (HUDF) results of Wolfe & Chen (2006) imply that in situ star formation can be the dominant heating mechanism for the ‘low-cool’ population only, consistent with our interpretation shown in Fig. 4. We have shown that the DLA bimodality originates from the biased selection at constant $N_{\text{HI}}$.

The picture outlined in Fig. 4 predicts an increasing reddening $E(B-V)$ (owing to the [X/H] increase) with equivalent width $W_{\lambda 2796}$ as reported by York et al. (2006) (see also Ménard et al. 2008) assuming a constant dust-to-gas ratio for Mg II absorbers since globally $W_{\lambda 2796}$ and $N_{\text{HI}}$ are correlated. This assumption may be the case under the common physical nature (out-flowing material) of strong Mg II samples. After this work was being completed, Ménard & Chelouche (2008) showed that Mg II absorbers on the $N_{\text{HI}}$–$W_{\lambda 2796}$ sequence shown in Fig. 2(a) have indeed a constant dust-to-gas ratio. Interestingly, they concluded that the dust-to-gas ratio was not consistent with that of dwarf galaxies (Small Magellanic Cloud), therefore rejecting the alternative hypothesis often invoked for absorbers, namely that the sight lines go through dwarfs near more normal galaxies. We note that the dust-to-gas ratio for the data points in the upper left-hand panel of Fig. 2(a) (i.e. not on $N_{\text{HI}}$–$W_{\lambda 2796}$ sequence) must be smaller (Ménard & Chelouche 2008), as concluded by Wolfe et al. (2008) for DLAs with low-velocity widths.

3.4 Caveats and possible systematics

Both Prochaska et al. (2008) and Ledoux et al. (2006) used a sample of DLAs at higher redshifts (with $1.7 < z_{\text{abs}} < 4.3$) than the Rao et al. sample of low-$z$ absorbers dominating our study. However, Fig. 2(b) does not change qualitatively for absorbers with $z_{\text{abs}} > 1.6$ in our sample. The overall metallicity is lower, reflecting the redshift evolution of metallicity in DLAs and sub-DLAs (Prochaska et al. 2003a; Kulkarni et al. 2007; Péroux et al. 2007).

Another difference between our analysis and Ledoux et al. (2006) and Prochaska et al. (2008), is that we used $W_{\lambda 2796}$ as a proxy for velocity width $\Delta v$ (Ellison 2006) whereas they used the measured velocity width from high-resolution spectra of the low-ions Si II and Zn II. However, for the dozen of absorbers with both $W_{\lambda 2796}$ and $\Delta v$(Si II or Zn II), we find that the $\Delta v/W_{\lambda 2796}$ correlates with $\Delta v$/Zn II at 99 per cent confidence level. Thus, the selection effect shown in Fig. 3 exists against $W_{\lambda 2796}$ (as in Murphy et al. 2007) and against $\Delta v$/Zn II (as in Ledoux et al. 2006; Prochaska et al. 2008).

![Figure 4](https://academic.oup.com/mnrasl/article-abstract/389/1/L18/995856/figure-4)
One might invoke dust obscuration to account for the results shown in Fig. 3. However, such a dust-bias would have to selectively remove metal-rich DLAs with low $W_r^{2796}$. The results of York et al. (2006) and Ménard et al. (2008) showed that dust obscuration in Mg $\text{II}$-selected samples with the lowest $W_r^{2796}$ is low, i.e. $E(B-V) < 0.02$ below $W_r^{2796} < 2 \, \text{Å}$, which implies a very low fraction of missed absorbers below $W_r^{2796} < 2 \, \text{Å}$ irrespective of $N_{\text{HI}}$. Similarly, such a dust-bias would have to selectively remove metal-poor DLAs with high $W_r^{2796}$. This is unlikely since dust and metal-poor ([$X/H] < -1.0$) DLAs would have to have unphysically high dust-to-metal ratios ($D \geq 10 D_{\text{MW}}$), which is rather difficult to produce (Inoue 2003). On the other hand, metal-rich DLAs with high $W_r^{2796}$ would have larger $E(B-V)$ (Ménard & Chelouche 2008) and therefore would be easier to obscure, but are in fact present in our sample. Finally, we looked at the distribution of the QSO magnitudes in the $N_{\text{HI}}-W_r^{2796}$ plane, and found no evidence for a selective dust-bias.

4 CONCLUSIONS

Our results show the presence of a metallicity gradient in the $N_{\text{HI}}-W_r^{2796}$ plane of intervening absorbers (Fig. 2). In other words, the metallicity of absorbers is a bimodal function of $N_{\text{HI}}$ and $W_r^{2796}$. As a direct consequence, a population of DLAs, selected with log $N_{\text{HI}} > 20.3$, will be heterogeneous. At low $W_r^{2796}$, the $\text{HI}$-selected sample is metal-poor, whereas at high $W_r^{2796}$, it is found to be more metal-rich. Therefore, the correlation between the metallicity [X/H] and the line-of-sight velocity width $\Delta v$ reported by Ledoux et al. (2006) and Murphy et al. (2007) arises from the $\text{HI}$ selection and cannot be interpreted as a signature of the mass–metallicity relation akin to normal field galaxies.

We argue that the bivariate distribution [[$X/H] N_{\text{HI}}, W_r^{2796}$)] can be explained by two different physical origins of absorbers, which are the ISM of small galaxies and out-flowing material, with distinct physical properties (such as metallicities and dust-to-gas ratios). This is supported by the distribution of the absorbers in the $N_{\text{HI}}-W_r^{2796}$ plane. If there are two distinct populations of absorbers, as shown in Fig. 4, this naturally explains the two classes of DLAs (‘low-cool’ and ‘high-cool’), reported by Wolfe et al. (2008) using [C $\text{II}$] 158 $\mu$m cooling rates. DLAs with large velocity dispersions (as measured by $W_r^{2796}$) are more metal-rich than those with low-velocity widths and will have different dust-to-gas ratio for a given dust-to-metal ratio.

Therefore, the correlation between metallicity [X/H] and $W_r^{2796}$ (or $\Delta v$) for DLAs (which we showed to be apparent), the two classes of DLAs of Wolfe et al. (2008), the dust-to-gas results of Ménard & Chelouche (2008) and the results of Bouč et al. (2006) indicating that Mg $\text{II}$-selected absorbers are tracing out-flowing material can all be put into one coherent context.

ACKNOWLEDGMENTS

We thank S. Ellison for providing $W_r^{2796}$ for her sample. We acknowledge enlighting scientific discussions with M. T. Murphy and C. Péroux. We gratefully acknowledge M. T. Murphy and S. Genel for their thorough reading of the manuscript. We also thank the anonymous referee for his/her constructive report.

REFERENCES

Bahcall J. N., Spitzer L. J., 1969, ApJ, 156, L63
Bouč N. et al., 2006, MNRAS, 371, 495
Bouč N. et al., 2007a, MNRAS, 378, 525
Bouč N. et al., 2007b, ApJ, 669, L5
Chelouche D. et al., 2007, ApJ, submitted (arXiv:0706.4336)
Churchill C. W. et al., 2000, ApJ, 543, 577
Curran S. J. et al., 2007, MNRAS, 382, 1331
Ellison S. L., 2006, MNRAS, 368, 335
Erb D. K. et al., 2006, ApJ, 644, 813
Inoue A. K., 2003, PASJ, 55, 901
Khare P. et al., 2007, A&A, 464, 487
Kulkarni V. P. et al., 2005, ApJ, 618, 68
Kulkarni V. P. et al., 2007, ApJ, 661, 88
Ledoux C. et al., 2006, A&A, 457, 71
Meiring J. D. et al., 2008, MNRAS, 384, 1015
Maller A. H., Bullock J. S., 2004, MNRAS, 355, 694
Meiring J. D. et al., 2007, MNRAS, 376, 557
Ménard B., Chelouche D., 2008, MNRAS, submitted (arXiv:0803.0745)
Ménard B. et al., 2008, MNRAS, 385, 1053
Möller P., Fynbo J. P. U., Fall S. M., 2004, A&A, 422, L33
Murphy M. T. et al., 2007, MNRAS, 376, 673
Nuslen P. E. J., Barcons X., Fabian A. C., 1998, MNRAS, 301, 168
Oppenheimer B. D., Davé R., 2008, MNRAS, 387, 577
Péroux C. et al., 2003a, MNRAS, 346, 1103
Péroux C. et al., 2003b, MNRAS, 345, 480
Péroux C. et al., 2004, MNRAS, 352, 1291
Péroux C. et al., 2006, A&A, 450, 53
Péroux C. et al., 2007, MNRAS, 382, 177
Petitini M. et al., 1999, ApJ, 510, 576
Prochaska J. X., Wolfe A. M., 1998, ApJ, 507, 113
Prochaska J. X., Wolfe A. M., 1999, ApJS, 121, 369
Prochaska J. X., Wolfe A. M., Gawiser E. J., 2000, BAAS, 32, 3.09
Prochaska J. X. et al., 2003a, ApJ, 595, L9
Prochaska J. X. et al., 2003b, ApJS, 147, 227
Prochaska J. X. et al., 2006, ApJ, 648, L97
Prochaska J. X. et al., 2008, ApJ, 672, 59
Rao S. M., Turnshek D. A., 2000, ApJS, 130, 1
Rao S. M., Turnshek D. A., Nestor D. B., 2006, ApJ, 636, 610
Rosenberg J. L., Schneider S. E., 2003, ApJ, 585, 256
Ryabinkov A. I. et al., 2003, A&A, 412, 707
Schaye J., 2001, ApJ, 559, L1
Tinker J. L., Chen H.-W., 2008, ApJ, 679, 1218
Tremonti C. A. et al., 2004, ApJ, 613, 898
Wolfe A. M., Prochaska J. X., 1998, ApJ, 494, L15
Wolfe A. M., Chen H.-W., 2006, ApJ, 652, 981
Wolfe A. M. et al., 1986, ApJS, 61, 249
Wolfe A. M. et al., 2008, in press (arXiv:0802.3914)
York D. G., Burks G. S., Gibney T. B., 1986, AJ, 91, 354
York D. G. et al., 2006, MNRAS, 367, 945
Zwaan M. A. et al., 2005, MNRAS, 364, 1467

© 2008 The Author. Journal compilation © 2008 RAS, MNRAS 389, L18–L22