Spotting high-z molecular absorbers using neutral carbon

Results from a complete spectroscopic survey with the VLT*

P. Noterdaeme¹, C. Ledoux², S. Zou¹, P. Petitjean¹, R. Srianand³, S. Balashev⁴, and S. López⁵

1 Institut d’Astrophysique de Paris, CNRS-UPMC, UMR7095, 98bis boulevard Arago, 75014 Paris, France
e-mail: noterdaeme@iap.fr
2 European Southern Observatory, Alonso de Córdova 3107, Vitacura, Casilla 19001, Santiago 19, Chile
3 Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, 411007 Pune, India
4 Ioffe Institute, Polytekhnicheskaya 26, 194021 Saint-Petersburg, Russia
5 Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile

Received 9 November 2017 / Accepted 22 January 2018

ABSTRACT

While molecular quasar absorption systems provide unique probes of the physical and chemical properties of the gas as well as original constraints on fundamental physics and cosmology, their detection remains challenging. Here we present the results from a complete survey for molecular gas in thirty-nine absorption systems selected solely upon the detection of neutral carbon lines in Sloan Digital Sky Survey (SDSS) spectra, without any prior knowledge of the atomic or molecular gas content. H₂ is found in all twelve systems (including seven new detections) where the corresponding lines are covered by the instrument setups and measured to have log N(H₂) ≥ 18, indicating a self-shielded regime. We also report seven CO detections (7/39) down to log N(CO) ~ 13.5, including a new one, and put stringent constraints on N(CO) for the remaining 32 systems. N(CO) and N(C1) are found to be strongly correlated with N(CO)/N(C1) ~ 1/10. This suggests that the C1-selected absorber population is probing gas deeper than the H1–H2 transition in which a substantial fraction of the total hydrogen in the cloud is in the form of H₂. We conclude that targeting C1-bearing absorbers is a very efficient way to find high-metallicity molecular absorbers. However, probing the molecular content in lower-metallicity regimes as well as high-column-density neutral gas remains to be undertaken to unravel the processes of gas conversion in normal high-z galaxies.

Key words. ISM: molecules – quasars: absorption lines

1. Introduction

The detection and analysis of molecular absorption lines along the lines of sight to background light sources has proven to be an extremely useful tool to investigate the physical and chemical state of the interstellar medium (ISM) thanks to the sensitive formation, destruction, and excitation processes of molecules. Such a technique applies from the solar neighbourhood towards nearby stars (e.g. Savage et al. 1977; Boissé et al. 2013) to the gas in and around high-redshift galaxies revealed by damped Lyman-α systems (DLAs; e.g. Levshakov et al. 1998; Ge et al. 1997; Petitjean et al. 2000; Cui et al. 2005; Srianand et al. 2005; Noterdaeme et al. 2008; Jorgenson et al. 2010; Carswell et al. 2011; Balashev et al. 2017). In addition, the detection of molecular species at high-redshift provides original and sensitive probes of fundamental physics and cosmology. Tiny shifts in the relative wavelengths of H₂ Lyman and Werner lines can be used to constrain the possible space-time variation of the proton-to-electron mass ratio down to a few parts-per-million over a timescale of Gyrs (see Ubachs et al. 2016, and references therein). The excitation of CO rotational levels, in turn, provides one of the best thermometers for measuring the temperature of the cosmic microwave background (CMB) radiation at high redshift (Srianand et al. 2008; Noterdaeme et al. 2011). Last but not least, the molecular phase of the ISM makes the link between the gas accreted onto a galaxy and its gravitational collapse that gives birth to stars. However, the small number of known molecular absorbers contrasts with the huge number of DLAs detected so far (e.g. Prochaska et al. 2005; Noterdaeme et al. 2012): only about 25 confirmed high-redshift H₂-bearing DLAs have been reported to date (see Balashev et al. 2017 and references therein), highlighting the small covering factor of the molecular gas and the need for efficient selection techniques.

In the local ISM, early works using Copernicus showed that H₂ and neutral carbon (C1) were frequently observed in the same absorption systems (e.g. Liszt 1981). Despite the high abundance of carbon, it is usually found in ionised forms in high-redshift DLAs and the neutral carbon is seen only in a small fraction of DLAs that also show H₂ absorption (e.g. Ge et al. 2001; Srianand et al. 2005). This is likely due to the first ionisation potential of carbon (11.26 eV) being close to the energy of Lyman-Werner photons that lead to H₂ dissociation (through Solomon process, see e.g. Stecher & Williams 1967). C1 also conveniently produces absorption lines out of the Lyman-α forest that can be identified even at low spectral resolution. We have therefore performed the first blind survey for neutral carbon lines in quasar spectra from the Sloan Digital Sky Survey (SDSS; Ledoux et al. 2015), without any prior knowledge of the associated atomic and molecular content. The 66 C1 candidates constitute our parent sample. We report here on the complete follow up of this sample...
with the Ultraviolet and Visual Echelle Spectrograph (UVES) at a
resolving power \( R \approx 50 000 \) and the X-shooter spectrograph
\((R \sim 5000)\) at the Very Large Telescope (VLT).

2. Observations and results

We obtained spectra for almost all systems that are observable
from Paranal Observatory, that is, a sample of thirty nine con-
firmed C I absorbers. Details about the observing procedures,
data reduction, and metal line measurements are presented in
Ledoux et al. (in prep.). A near-infrared study of the Na I and
Ca II lines as well as the dust extinction properties are presented in
Zou et al. (2018). Here, we focus on the detection of \( \text{H}_2 \) and
CO. Wavelengths and oscillator strengths for \( \text{H}_2 \) and CO lines
are from the compilations of Malec et al. (2010) and Daprá et al.
(2016), respectively.

2.1. Molecular hydrogen

We detect \( \text{H}_2 \) absorption lines whenever covered by our spec-
tra (twelve systems). Five of these are already reported in
the literature (Notaerdaeme et al. 2007, 2010; Srianand et al. 2008;
Jorgenson et al. 2010; Klimenko et al. 2016), from which we
have taken the \( \text{H}_2 \) column densities, and seven are new detections.
We estimated the total \( \text{H}_2 \) column densities for the new
detections through Voigt-profile fitting, focusing on the low rota-
tional levels that contain most of the \( \text{H}_2 \). We note that while the
velocity profile of singly ionised metals is wide with a large num-
ber of components, we detect \( \text{H}_2 \) only at velocities where C I is
also detected. Below we comment on each system, in order of
increasing right ascension of the background quasar.

\( \text{J}091721+015448 \), \( z_{\text{abs}} = 2.107 \); this system was observed
with X-shooter at a spectral resolution of \( \sim 60 \text{ km s}^{-1} \). We obtain
an accurate measurement of the total \( \text{H}_2 \) column density thanks
to the damping wings that are seen for the low rotational levels
in the four bands covered by our spectrum (see Fig. 1) and obtain
\[
\log N(\text{H}_2) = 20.11 \pm 0.06.
\]

\( \text{J}111756+143716 \), \( z_{\text{abs}} = 2.001 \); this system is characterised by
two narrow \( \text{H}_2 \) components seen in the UVES spectrum (Fig. 2)
in different rotational levels. These components also correspond to
those seen in the neutral carbon bands. While our best-fit value
is found to be around \( \log N(\text{H}_2) \sim 18 \), we note that the data
quality is poor and that only one band is covered, making it
impossible to assess the presence of blends. In addition, at such
a column density, the absorption is in the logarithmic part of the
curve of growth. We are therefore unable to associate an uncer-
tainty to this measurement that we display with a large arbitrary
(although quite conservative) 1 dex error bar in Fig. 9.

\( \text{J}131129+222552 \), \( z_{\text{abs}} = 3.092 \); thanks to the high absorption
redshift, no less than twenty Lyman and Werner \( \text{H}_2 \) bands are
covered by our UVES spectrum, shown in Fig. 3. Four compo-
nents can be distinguished in the high rotational levels but lines
from the \( J = 0 \) and \( J = 1 \) rotational levels are strongly damped
and therefore modelled using a single component. The damping
wings together with the large number of detected transitions and
the achieved high signal-to-noise ratio (S/N) values allow for a
very precise measurement of the total \( \text{H}_2 \) column density which
we found to be \( \log N(\text{H}_2) = 19.69 \pm 0.01 \).

\( \text{J}164610+232922 \), \( z_{\text{abs}} = 1.998 \); while the S/N of our UVES
spectrum in the region of \( \text{H}_2 \) lines (see Fig. 4) is quite low\(^1\), two

\(^1\) Although SDSS J164610+232922 is a relatively bright quasar \((g = 18.5)\), only a single 4000 s exposure could be obtained at a high airmass (1.7).

\( \text{J}225719−080104 \), \( z_{\text{abs}} = 1.836 \); this system is more complex
with no less than eight \( \text{H}_2 \) components, strongly blended with
each other. Unfortunately, only three Lyman \( \text{H}_2 \) bands are cov-
ered by the UVES data (Fig. 5), the bluest of which in a region
with low S/N. To remove strong degeneracy between parameters,
we had to fix the excitation temperature \( T_\text{ex} \) to 100 K. While this
is a strong assumption, we note that varying \( T_\text{ex} \) within a factor
of two has little effect on the total column \( \text{H}_2 \) density (changes
\( \sim 0.1 \text{ dex} \)). Still, we caution that this error may be underestimated
and covering blue transitions is required to confirm our column
density measurement (\( \log N(\text{H}_2) = 19.5 \pm 0.1 \)).

\( \text{J}233156−090104 \), \( z_{\text{abs}} = 2.142 \); in spite of the low S/N
achieved for this system, shown in Fig. 6, the data is clearly con-
sistent with strongly damped \( \text{H}_2 \) lines at the same redshift as
that of CO lines (see following section). We fitted the \( J = 0, 1, 2 \)
lines from which we obtain realistic excitation temperatures,
\( T_\text{ex} \approx 140 \text{ K} \) and \( T_\text{ex} \approx 180 \text{ K} \). The total \( \text{H}_2 \) column density is
found to be \( \log N(\text{H}_2) = 20.57 \pm 0.05 \).

\( \text{J}233633−105841 \), \( z_{\text{abs}} = 1.829 \); the \( \text{H}_2 \) profile in this system
is well modelled by two components, that are partially blended
at the X-shooter spectral resolution. The bluest component, how-
ever, dominates the total column density, and the measurement
is facilitated by the presence of damping wings and the high S/N
achieved. We note that the \( 00-0 \) band is partially blended with
unrelated absorption lines, which we modelled when fitting H$_2$ (see Fig. 7). We obtain log N(H$_2$) = 19.0 ± 0.12.

2.2. Carbon monoxide

CO is detected in seven systems in our sample, six of them already reported by our group and one being a new detection presented here for the first time. This brings the number of known high-$z$ CO-bearing quasar absorbers to nine. We measured upper limits on N(CO) for all systems assuming the Doppler parameter to be 1 km s$^{-1}$, similar to what has been measured in all high-$z$ CO absorbers to date. We also assume the CMB radiation to be the main excitation source in diffuse gas at high-$z$ (as observed by Srianand et al. 2008; Noterdaeme et al. 2011).

We calculated the local (i.e. for each band individually) and global $\chi^2$ values for a range of total column densities. CO is detected when the $\chi^2$ curves are consistent with each other and present a clear inflexion point, defining the best-fit value. For non-detections, $\chi^2$(N(CO)) is generally monotonic with a minimum consistent with that of N(CO) = 0 within uncertainty.

The detections towards J1211+0833 (Ma et al. 2015) and J0000+0015 (Noterdaeme et al. 2017) are not formally part of the statistical sample although selected upon their C$_1$ content.

Our 3$\sigma$ upper limit corresponds to the column density where the $\chi^2$ is 9 above this minimum. With this method, not only do we recover all the known CO absorbers but we also identify the new CO system, at $z$ = 2.143 towards SDSS J2331−0908 (Fig. 8), observed by Nestor and collaborators (Prog. ID 080.A-0795). This is only the fourth high-$z$ system with direct and simultaneous measurements of N(CO) and N(H$_2$).

Before discussing our findings, it is worth mentioning that, in the local ISM, the excitation temperature of CO is found to be a few degrees above the CMB temperature (e.g. Burgh et al. 2007), owing to additional excitation processes such as collisions, far-infrared dust emission, and possibly cosmic rays. Relaxing our assumptions we find that the derived CO column density limits (as well as the CO column density for the new detection at $z_{\text{abs}} = 2.143$ towards SDSS J2331−0908) are not changed significantly as the total band equivalent width is almost conserved. For example, allowing an excitation temperature 5 K above the CMB temperature only increases the derived values by less than 0.04 dex.
3. Discussion

Table 1 summarises the H$_2$ and CO detections and column density measurements. Figure 9 presents the H$_2$ and CO column densities as well as the overall molecular fraction $\langle f_{\text{mol}} \rangle = 2N(\text{H}_2)/(2N(\text{H}_2) + N(\text{H} I))$ as a function of N(C I) for our complete sample. Known systems from the literature are also added for comparison but not considered for statistical analysis.

We find that H$_2$ is detected with $N(\text{H}_2) > 10^{19}$ cm$^{-2}$ in all systems with log N(C I) $> 13.5$. In this regime, H$_2$ is likely to be self-shielded and the molecular fraction substantial in the H$_2$-bearing gas. We also observe a possible trend for increasing $N(\text{H}_2)$ with increasing N(C I) (Spearman rank correlation coefficient $r = 0.4$, 1.2 $\sigma$ significance) in our statistical sample, albeit with a large dispersion. We note that systems that were not C I-selected (from literature) seem not to follow this trend. Four of them indeed have $N(\text{H}_2) > 5 \times 10^{19}$ cm$^{-2}$ in spite of relatively low C I column density ($\log N(\text{C I}) \leq 14$). This difference is likely due to the different chemical enrichments: C I-selected systems probe mostly high-metallicity gas (Zou et al. 2018; Ledoux et al., in prep.) while the four mentioned literature systems all have low metallicities.

Since the column density at which H I is converted into H$_2$ strongly depends on the chemical properties of the gas, in particular the abundance of dust grains (e.g. Bialy & Sternberg 2016), we can expect less H I in the molecular cloud envelope for high-metallicity systems compared to low-metallicity ones. In addition, contrary to DLAs, C I systems were selected without any prior knowledge of the H I content (Ledoux et al. 2015) and should have less contribution from unrelated atomic gas that does not belong to the envelope of the H$_2$ cloud. This is seen in the bottom panel of Fig. 9, where the correlation between $\langle f \rangle$ and N(C I) is seen with $r = 0.6$ at 2.1 $\sigma$: the average overall H$_2$ molecular fraction is about 15% in our sample (and about 30% when CO is detected) but $<3\%$ at log N(C I) $< 14$.

The correlation between N(CO) and N(C I) for CO detections is strong with $r = 0.88$ (2.6 $\sigma$). From the column density distributions, we can see that the probability to detect CO becomes much larger above N(C I) $> 5 \times 10^{14}$ cm$^{-2}$ (6/12) than below this value (1/27). In addition, there is no CO detection among the 18 systems with log N(C I) < 14.4. Since the CO detection limits are significantly below ($\sim 1$ dex) the typical N(CO) in the case of detection, this result is robust. Considering also lower and upper limits on both N(CO) and N(C I), we still find the N(CO)--N(C I) correlation to have $\sim 92\%$ probability.

This strong correlation is likely due to the strong dependence of CO abundance on the metallicity (through the abundance of carbon, the abundance of dust grains as molecule-formation catalyst, and an effective shielding of UV photons). In Ledoux et al. (2015), we showed that strong C I systems produce more reddening than other classes of quasar absorbers. We further note that the dust reddening is systematically higher in CO-bearing systems than other H$_2$ systems without CO. The relative behaviours of CO, H$_2$, and C I agree qualitatively with models of ISM clouds immersed in a UV radiation field: these clouds are expected to

---

Fig. 6. As in Fig. 1 but for the UVES spectrum of J2331--0908. The data have been rebinned by 7 pixels for visual purposes only.

Fig. 7. As in Fig. 1 but for the X-shooter spectrum of J2336-1058. The green and purple dotted lines in the bottom panel show the contribution from unrelated Ly$\alpha$ (from a sub-DLA at $z_{\text{abs}} = 1.585$) and O VI ($z_{\text{abs}} = 2.039$) absorption, respectively. The contribution from H$_2$ alone is shown in red and the total absorption-line profile is depicted in orange.

Fig. 8. CO AX bands at $z_{\text{abs}} = 2.1422$ towards J2331--0908 (top four panels, AX(3–0) is not covered by the instrument setup). The bottom-right panel shows a co-addition of the CO bands, using $f/\sigma^2$-weighting, where $f$ is the oscillator strength and $\sigma$ the uncertainty on the normalised flux, for easy visualisation of the detection. The bottom-left panel shows the $\Delta \chi^2 = \chi^2 - \chi^2_{\min}$ curves (grey for individual band, black for total).
References. The references listed in the last column are for molecular measurements. When two references are listed, they correspond to CO then H$_2$ in this order. (1) This work; (2) Noterdaeme et al. (2011); (3) Noterdaeme et al. (2010); (4) Srianand et al. (2008); (5) Noterdaeme et al. (2009); (6) Klimenko et al. (2016); (7) Jorgenson et al. (2010); (8) Noterdaeme et al. (2007). Unless already available from the literature, C1 column densities were obtained through the apparent optical depth method.

Table 1. CO and H$_2$ content of strong C1 absorbers.

| Quasar  | $z_{\text{abs}}$ | $\log N$ (cm$^{-2}$) | Ref. |
|---------|-----------------|----------------------|------|
| J0216−0021 | 1.737 | 14.25 ± 0.02 | <12.97 | – | 1 |
| J0300−0721 | 1.536 | >14.77 | ≤13.79 | – | 1 |
| J0811+0838 | 1.906 | 13.68 ± 0.13 | <13.24 | – | 1 |
| J0815+2640 | 1.681 | >14.73 | ≤13.68 | – | 1 |
| J0820+1559 | 1.547 | >14.71 | ≤14.01 | – | 1 |
| J0852+1935 | 1.788 | 15.01 ± 0.12 | <13.33 | – | 1 |
| J0854+0317 | 1.567 | 14.23 ± 0.01 | ≤13.11 | – | 1 |
| J0857+1855 | 1.730 | 14.57 ± 0.13 | 13.54 ± 0.05 | – | 2 |
| J0917+0154 | 2.107 | 14.32 ± 0.06 | <14.07 | 20.11±0.06 | 1 |
| J0927+1543 | 1.731 | >14.61 | ≤13.32 | – | 1 |
| J1047+2057 | 1.775 | >14.90 | 14.40 ± 0.07 | – | 2 |
| J1117+1437 | 2.001 | 14.40 ± 0.03 | <13.13 | – | 18 |
| J1122+1437 | 1.554 | 13.83 ± 0.03 | <12.99 | – | 1 |
| J1129–0237 | 1.623 | >14.96 | ≤13.31 | – | 1 |
| J1133–0057 | 1.706 | 15.12 ± 0.06 | ≤14.07 | – | 1 |
| J1237+0647 | 2.691 | 15.01 ± 0.02 | 14.17 ± 0.09 | 19.21±0.13 | 3 |
| J1248+2848 | 1.513 | 14.25 ± 0.10 | <13.25 | – | 5 |
| J1302+2111 | 1.656 | 14.30 ± 0.02 | <13.48 | – | 1 |
| J1306+2815 | 2.012 | 14.47 ± 0.04 | ≤13.26 | – | 1 |
| J1311+2225 | 3.092 | 14.30 ± 0.02 | <13.43 | 19.69±0.01 | 1 |
| J1314+0543 | 1.583 | 14.40 ± 0.02 | ≤13.77 | – | 1 |
| J1341+1852 | 1.544 | 13.51 ± 0.03 | ≤13.00 | – | 1 |
| J1346+0644 | 1.512 | 14.51 ± 0.02 | ≤13.60 | – | 1 |
| J1439+1117 | 2.418 | 14.81 ± 0.02 | 13.89 ± 0.02 | 19.38±0.10 | 4 |
| J1459+0129 | 1.623 | 14.32 ± 0.09 | <13.57 | – | 1 |
| J1522+0830 | 1.627 | >14.47 | <13.50 | – | 1 |
| J1603+1701 | 1.890 | 13.80 ± 0.10 | <12.88 | – | 1 |
| J1604+2203 | 1.641 | >15.14 | 14.59 ± 0.11 | – | 5 |
| J1615+2648 | 2.118 | 14.49 ± 0.06 | ≤13.16 | – | 1 |
| J1623+1355 | 1.751 | 14.41 ± 0.07 | ≤13.30 | – | 1 |
| J1646+2329 | 1.998 | 14.32 ± 0.06 | <13.40 | 18.02±0.11 | 1 |
| J1705+3543 | 2.038 | >15.01 | 14.14 ± 0.03 | – | 2 |
| J2123–0050 | 2.060 | 14.11 ± 0.02 | <13.07 | 17.94±0.01 | 1.6 |
| J2229+1414 | 1.586 | 13.96 ± 0.05 | <13.55 | – | 1 |
| J2257–1001 | 1.836 | 14.65 ± 0.01 | <13.09 | 19.5 ± 0.1 | 1 |
| J2331–0908 | 2.143 | >14.70 | 13.65 ± 0.03 | 20.57±0.05 | 1 |
| J2336–1058 | 1.829 | 14.07 ± 0.02 | <12.93 | 19.00±0.12 | 1.2 |
| J2340–0053 | 2.054 | 14.09 ± 0.04 | <12.58 | 18.47±0.04 | 1.7 |
| J2350–0052 | 2.426 | 14.36 ± 0.01 | <12.94 | 18.52±0.49 | 1.8 |

Fig. 9. Column densities of CO (top), H$_2$ (middle) and overall molecular fractions (bottom) vs N(C1). CO detections are represented by red colours. The N(C1)-distributions and median log N(CO) values (horizontal lines) are shown for the statistical sample only (circles). Squares correspond to high-z H$_2$ DLA systems from the literature (Balashev et al. 2010, 2011, 2017; Carswell et al. 2011; Guimaraes et al. 2012; Noterdaeme et al. 2015, 2017; Petitjean et al. 2002).

line of sight. This means that the measured ⟨f⟩ is a lower limit to the actual H$_2$ molecular fraction in the C1-bearing cloud. Since CO and C1 are only found in shielded gas, their observed abundance ratio should be less affected by the presence of unrelated gas. Indeed, we find CO/C1 ≈ 0.1 for all detections (green dotted line in Fig. 9), a value which is also consistent with the non-detections at lower N(C1). This indicates a regime deeper than the layer where the H1–H$_2$ transition occurs.

The CO/H$_2$ ratio is found to be low (~[3–9] × 10$^{-6}$) for three out of four cases where both these molecules are detected and can be more than an order of magnitude lower in other strong H$_2$ systems, including the new CO detection. Even in these cases, the high N(H$_2$) likely indicates well-molecularized regions. Several factors such as the grain size distribution or the intensity of the cosmic-ray field likely play important roles in determining whether CO will be present or not in H$_2$-dominated regions (e.g. Shaw et al. 2016; Noterdaeme et al. 2017; Bisbas et al. 2017). Multiple clouds can also easily explain large H$_2$ column densities without significant CO, in a similar way to how multiple H1–H$_2$ transition layers explain higher N(H1) than predicted by single cloud models (Bialy et al. 2017).

We conclude that C1 is a very good proxy to spot high-redshift molecular absorbers that can be used for a variety of studies including fundamental physics and cosmology. It is
however crucial not only to constrain the physical parameters in individual systems (and hopefully for individual velocity components separately) but also to explore different metallicity regimes (Balashev et al. 2017) using different selections (e.g. Balashev et al. 2014) to understand better the molecular structure of ISM clouds at high redshifts.

Acknowledgements. We thank T. Krühler for help with the X-shooter data reduction. P.N. thanks the European Southern Observatory for hospitality and support during part of this work was done. P.N., P.P.J. and R.S. acknowledge support from the Indo-French Centre for the Promotion of Advanced Research (Project 5504-B). We acknowledge support from the PNCG funded by CNRS/INSU-IN2P3-INP, CEA and CNES, France. This research is part of the project HIH2 funded by the Agence Nationale de la Recherche, under grant ANR-17-CE31-0011-01 (JCJC). S.B. thanks the Institut d' Astrophysique de Paris for hospitality and the Institut Lagrange de Paris for financial support. S.L. has been supported by FONDECYT grant 1140838 and by PFB-06 CATA.

References

Balashev, S. A., Ivanchik, A. V., & Varshalovich, D. A. 2010, Astron. Lett., 36, 761
Balashev, S. A., Petitjean, P., Ivanchik, A. V., et al. 2011, MNRAS, 418, 357
Balashev, S. A., Klimenko, V. V., Ivanchik, A. V., et al. 2014, MNRAS, 440, 225
Balashev, S. A., Noterdaeme, P., Rahmani, H., et al. 2017, MNRAS, 470, 2890
Bialy, S., & Sternberg, A. 2016, ApJ, 822, 83
Bialy, S., Bühr, S., Beuther, H., Henning, T., & Sternberg, A. 2017, ApJ, 835, 126
Bisbas, T. G., van Dishoeck, E. F., Papadopoulos, P. P., et al. 2017, ApJ, 839, 90
Boissé, P., Federman, S. R., Pineau des Forêts, G., & Ritchey, A. M. 2013, A&A, 559, A131
Bolatto, A. D., Wolfire, M., & Leroy, A. K. 2013, ARA&A, 51, 207
Burgh, E. B., France, K., & McCandliss, S. R. 2007, ApJ, 658, 446
Carswell, R. F., Jorgenson, R. A., Wolfe, A. M., & Murphy, M. T. 2011, MNRAS, 411, 2389
Cui, J., Bechtold, J., Ge, J., & Meyer, D. M. 2005, ApJ, 633, 649
Dapré, M., Niu, M. L., Salumbides, E. J., Murphy, M. T., & Ubachs, W. 2016, ApJ, 826, 192
Ge, J., Bechtold, J., & Black, J. H. 1997, ApJ, 474, 67
Ge, J., Bechtold, J., & Kulkarni, V. P. 2001, ApJ, 547, L1
Guimarães, R., Noterdaeme, P., Petitjean, P., et al. 2012, AJ, 143, 147
Jorgenson, R. A., Wolfe, A. M., & Prochaska, J. X. 2010, ApJ, 722, 460
Klimenko, V. V., Balashev, S. A., Ivanchik, A. V., & Varshalovich, D. A. 2016, Astron. Lett., 42, 137
Ledoux, C., Noterdaeme, P., Petitjean, P., & Srianand, R. 2015, A&A, 580, A8
Levkovskov, S. A., Foltz, C. B., Chaffee, F. H., & Black, J. H. 1989, AJ, 98, 2052
Liszt, H. S. 1981, ApJ, 246, L147
Ma, J., Causal, P., Noterdaeme, P., et al. 2015, MNRAS, 454, 1751
Málek, A. L., Buning, R., Murphy, M. T., et al. 2010, MNRAS, 403, 1541
Noterdaeme, P., Petitjean, P., Srianand, R., Ledoux, C., & Le Petit, F. 2007, A&A, 469, 425
Noterdaeme, P., Petitjean, P., Ledoux, C., Srianand, R., & Ivanchik, A. 2008, A&A, 491, 397
Noterdaeme, P., Petitjean, P., Ledoux, C., & Srianand, R. 2009, A&A, 505, 1087
Noterdaeme, P., Petitjean, P., Ledoux, C., et al. 2010, A&A, 523, A80
Noterdaeme, P., Petitjean, P., Srianand, R., Ledoux, C., & López, S. 2011, A&A, 526, L7
Noterdaeme, P., López, S., Dumont, V., et al. 2012, A&A, 542, L33
Noterdaeme, P., Srianand, R., Rahmani, H., et al. 2015, A&A, 577, A24
Noterdaeme, P., Krogager, J.-K., Balashev, S., et al. 2017, A&A, 597, A82
Petitjean, P., Srianand, R., & Ledoux, C. 2000, A&A, 364, L26
Petitjean, P., Srianand, R., & Ledoux, C. 2002, MNRAS, 332, 383
Prochaska, J. X., Tripp, T. M., & Howk, J. C. 2005, ApJ, 620, L39
Savage, B. D., Bohlin, R. C., Drake, J. F., & Budich, W. 1977, ApJ, 216, 291
Shaw, G., Rawlins, K., & Srianand, R. 2016, MNRAS, 459, 3234
Srianand, R., Petitjean, P., Ledoux, C., Ferland, G., & Shaw, G. 2005, MNRAS, 362, 549
Srianand, R., Noterdaeme, P., Ledoux, C., et al. 2009, A&A, 491, L39
Stecher, T. P., & Williams, D. A. 1967, ApJ, 149, L29
Ubachs, W., Bagdonaite, J., Salumbides, E. J., Murphy, M. T., & Kaper, L. 2016, Rev. Mod. Phys., 88, 021003
Zou, S., Petitjean, P., Noterdaeme, P., et al. 2018, A&A, in press, DOI: 10.1051/0004-6361/201732033