Neutral chlorine and molecular hydrogen at high redshift

S. A. Balashev1,2, P. Noterdaeme3, V. V. Klimenko1,2, P. Petitjean3, R. Srianand5, C. Ledoux4, A. V. Ivanchik1,2, and D. A. Varshalovich1,2

Astronomy & Astrophysics

LETTER TO THE EDITOR

Neutral chlorine and molecular hydrogen at high redshift

1. Introduction

It has been shown that the global star-formation rate in the Universe gradually increases from \( z \sim 10 \) to \( z \sim 2 \)–3 and then steeply decreases until the present epoch, \( z = 0 \) (see e.g. Dunlop 2011, and references therein). Because metals are produced by stars, the determination of metal abundance in the gas provides complementary information about star-formation history (Rafelski et al. 2012). This can be done using damped Lyman-\( \alpha \) systems (DLAs) that represent the main reservoir of neutral gas at high redshift (Prochaska & Wolfe 2009; Noterdaeme et al. 2009) and are likely to be located in galaxies or in their close environment (e.g. Krogager et al. 2012). These systems arise mostly in the warm neutral medium (e.g. Petitjean et al. 2000; Kanekar et al. 2014) and have a multi-component velocity structure, with metal absorption lines spread typically over 100–500 km s\(^{-1}\) (Ledoux et al. 1998). In a small fraction of DLAs, the line of sight intercepts cold gas, as traced by molecular hydrogen (e.g. Noterdaeme et al. 2008, 2011; Balashev et al. 2014) and/or 21 cm absorption (e.g. Srianand et al. 2012). Important progress has been made towards understanding the properties of the gas, for example through deriving physical conditions (Srianand et al. 2005; Noterdaeme et al. 2007a; Jorgenson et al. 2009) and physical extent (Balashev et al. 2011), and the incidence of cold gas in DLAs has been related to other properties such as the metallicity (Petitjean et al. 2006) or the dust content (Ledoux et al. 2003; Noterdaeme et al. 2008). However, owing to the strong saturation of H\( \text{I} \) Lyman series lines, it remains impossible to directly determine the H\( \text{I} \) column density associated with the individual cold gas components traced by H\( \text{2} \) absorption. Even for metals, whose absorption lines are not saturated, it is very difficult to determine what fraction originates from the cold phase. Difficulties arise as well with the 21 cm absorption that does not always exactly coincide with H\( \text{2} \) absorption (Srianand et al. 2013) although it could be due to the different structures of the optical and radio emitting regions of the background quasars. Out of all the metals, chlorine shows a unique behaviour in the presence of H\( \text{2} \). Because the ionization potential of chlorine (12.97 eV) is less than that of atomic hydrogen, chlorine is easily ionized in the diffuse neutral medium. However, this species reacts exothermically with H\( \text{2} \) at a very high rate rapidly converting Cl\(^+\) into HCl\(^-\), which subsequently releases neutral chlorine through several channels (Jura 1974; Neufeld & Wolfire 2009). This process is so efficient that chlorine is completely neutral in the presence of a small amount of H\( \text{2} \). In our Galaxy the fact that chlorine abundance anti-correlates with the average number density along the line of sight (Harris & Bromage 1984; Jenkins et al. 1986) has been interpreted as chlorine depletion. However, models predict and observations indicate that gas with moderate dust content presents negligible depletion of chlorine (e.g. Neufeld & Wolfire 2009; Savage & Sembach 1996; Jenkins 2009). Observationally, a tight relation is indeed found between Cl\(^+\) and H\( \text{2} \) in the local ISM (Jura 1974; Sonnentrucker et al. 2006; Mooney et al. 2012). In this Letter, we present the first study of this relation at high redshift and over a wide range of column densities.

ABSTRACT

Chlorine and molecular hydrogen are known to be tightly linked together in the cold phase of the local interstellar medium through rapid chemical reactions. We present here the first systematic study of this relation at high redshifts using H\( \text{2} \)-bearing damped Ly\( \alpha \) systems (DLAs) detected along quasar lines of sight. Using high-resolution spectroscopic data from VLT/UVES and Keck/HIRES, we report the detection of Cl\(^+\) in 9 DLAs (including five new detections) out of 18 high-z DLAs with N(H\( \text{2} \)) \( \geq 10^{17.3} \) cm\(^{-2}\) (including a new H\( \text{2} \) detection at \( z = 3.09145 \) towards J\( 2100–0641 \)) and present upper limits for the remaining 9 systems. We find a \( \sim 5\sigma \) correlation between N(Cl\(^+\)) and N(H\( \text{2} \)) with only \( \sim 0.2 \) dex dispersion over the range 18.1 < log N(H\( \text{2} \)) < 20.1, thus probing column densities 10 times lower than those seen towards nearby stars, roughly following the relation N(Cl\(^+\))/N(H\( \text{2} \)) \( \sim 1.5 \times 10^{-6} \times N(\text{H}_2) \). This relation between column densities is surprisingly the same at low and high redshift suggesting that the physical and chemical conditions are similar for a given H\( \text{2} \) or Cl\(^+\) column density. In turn, the N(Cl\(^+\))/N(H\( \text{2} \)) ratio is found to be uncorrelated with the overall metallicity in the DLA. Our results confirm that neutral chlorine is an excellent tracer of molecule-rich gas and show that the molecular fraction and/or metallicity in the H\( \text{2} \)-bearing component of DLA could possibly be much higher than the line-of-sight average values usually measured in DLAs.

Key words. cosmology: observations – ISM: clouds – quasars: absorption lines

Received 2 December 2014 / Accepted 28 January 2015

1 Ioffe Physical-Technical Institute of RAS, Polytekhnicheskaya 26, 194021 Saint-Petersburg, Russia
e-mail: s.balashev@gmail.com
2 St.-Petersburg Polytechnic University, Polytekhnicheskaya 29, 195251 Saint-Petersburg, Russia
3 Institut d’Astrophysique de Paris, CNRS-UPMC, UMR7095, 98bis Bd Arago, 75014 Paris, France
4 European Southern Observatory, Alonso de Córdova 3107, Vitacura, Casilla 19001, Santiago 19, Chile
5 Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, 411 007 Pune, India
2. Data sample and measurements

Since the first detection by Levshakov & Varshalovich (1985), about two dozen H₂ absorption systems have been detected at high redshifts in quasar spectra. The detection limit of the strongest Cl₁ absorption line (1347 Å, \( f = 0.0153 \), Schectman et al. 1993) in a high quality spectrum (S/N ~ 50, R ~ 50000) corresponds to \( N(\text{Cl}₁) \sim 10^{17} \text{ cm}^{-2} \). The solar abundance of chlorine is \( 10^{-6.5} \) that of hydrogen (Asplund et al. 2009) and given previous measurements of \( N(\text{Cl}₁)/2N(\text{H₂}) \) (e.g. Mooney et al. 2012) we conservatively limit our study to systems with \( N(\text{H₂}) \geq 10^{17} \text{ cm}^{-2} \).

Redshifts, H₁ and H₂ column densities, and metallicities were mainly taken from the literature and are based on VLT/UVES, Keck/HIRES, or HST/STIS data. We refitted H₂ absorption systems towards Q 2123−0050 and Q J2340−0053 to take into account the positions of the detected Cl₁ components. We also detect a new H₂ absorption system in the \( z = 3.09 \) DLAs towards J 2100−0641 in which Jorgenson et al. (2010) have reported the presence of neutral carbon. Indeed, Cl₁ is known to be an excellent indicator of the presence of molecules (e.g. Srianand et al. 2005). We used the MAKEE package (Burles) to archival data from this quasar obtained in 2005, 2006, and 2007 under programs U17H (PI: Prochaska), G400H (PI: Ellison), and U149Hr (PI: Wolfe). We have found strong H₂ absorption lines from rotational levels up to \( J = 5 \) (see Fig. 1) at \( z = 3.091485 \) with a total column density of \( \log N(\text{H}_2) = 18.76 \pm 0.03 \).

For all systems we retrieved data from the VLT/UVES or the Keck/HIRES archives. We reduced the data and fitted the lines using profile fitting. Neutral chlorine is detected in nine literature: Q 1232+082 (Balashev et al. 2011), Q 0812−3208 (Prochaska et al. 2003), Q 1237+0647 (Noterdaeme et al. 2010), and Q 2140−0321 (Noterdaeme et al. 2015). The remaining five are new detections. We measured upper-limits of \( N(\text{Cl}₁) \) for the remaining nine systems. We used mainly the 1347 Å Cl₁ line. Whenever possible, we also used Cl₁ lines at 1088 Å, 1188 Å, 1084 Å, 1094 Å, and 1085 Å, with oscillator strength from Schectman et al. (1993), Morton (2003), Sonnentrucker et al. (2006), and Oliveira & Hébrard (2006), respectively.

Table 1 summarizes the results of Cl₁ measurements. We have kept all components with \( \log N(\text{H}_2) > 17 \). We did not use two known H₂ absorption systems towards Q 0013−0029 and J091826.16+163609.0 since H₂ column densities in these systems are not well defined.

3. Results

Figure 3 shows the Cl₁ column density, \( N(\text{Cl}₁) \), versus \( N(\text{H}_2) \) and compares our high-z measurements to those obtained in the local ISM using the Copernicus satellite (Mooney et al. 2012). As can be seen, our high-z measurements extend the relation to \( \log N(\text{H}_2) \) column densities ten times smaller than those measured in the local ISM. A very close correlation (\( r = 0.95 \)) between Cl₁ and H₂ has been found over the entire \( \log N(\text{H}_2) \) range. It is striking that measurements at high and low redshifts are indistinguishable in the overlapping regime (\( \log N(\text{H}_2) \sim 19−20 \)). The correlation is seen over about three orders of magnitude in column density with a dispersion of only about 0.2 dex. A least-squares bisector linear fit provides a slope of 0.83 and 0.87 for the high-z and \( z = 0 \) data, respectively, with an almost equal normalization (\( \log N(\text{Cl}₁) \sim 13.7 \) at \( \log N(\text{H}_2) = 20 \)). We note that the upper limits on \( N(\text{Cl}₁) \) lie mostly at the low \( \log N(\text{H}_2) \) end and are least constraining since they are compatible with the values expected from the above relation. For this reason, we will not consider them further in the discussion but still include them in the figures for completeness. The slopes are less than one, meaning that the Cl₁/H₂ ratio slightly decreases with increasing \( N(\text{H}_2) \). This is unlikely to be due to conversion of Cl into H₂Cl⁻ and/or HCl, since chlorine chemistry models (Neufeld & Wolfire 2009) and measurements (e.g. towards Sgr B2(S), Lis et al. 2010) show that in diffuse molecular clouds only \( \sim 1% \) of chlorine is in the molecular form. A < 1 slope could in principle be due to dust depletion. However, there is no trend for increasing Cl depletion with increasing \( N(\text{H}_2) \) or Cl₁ column densities in Galactic clouds (see Mooney et al. 2012). In addition, for high redshift measurements, elemental abundance patterns (Noterdaeme et al. 2008) as well as direct measurements (e.g. Noterdaeme et al. 2010) indicate \( A_v < 0.2 \) when modelling of chlorine chemistry (Neufeld & Wolfire 2009) shows that for such low extinction \( A_v < 1 \) all chlorine is in the gas phase.

A possibility is thus that the molecular fraction in the gas probed by Cl₁ is slightly increasing with increasing \( N(\text{H}_2) \). It can be expected since H₂ self-shielding increases while Cl₁ is already completely in the neutral form. Finally, the similarity between our Galaxy and high-z measurements at \( \log N(\text{H}_2) \geq 19 \) might indicate that the chemical and physical conditions in the
Table 1. Measurements of CI I in strong H₂ absorption systems at high redshift.

| Quasar | z_{obs} | z_{DLA} | log N(H I) | [X/H] | X | Ref. | z_{HII} | log N(H₂) | log N(Cl I) | b (km s⁻¹) | [Cl I/H II] |
|--------|---------|---------|------------|--------|---|------|---------|-----------|-------------|------------|------------|
| Q 0027–1836 | 2.56 | 2.40 | 21.75 ± 0.10 | −1.63 ± 0.10 | Zn | 1 | 2.40183 | 17.90 ± 0.07 | <12.71 | – | <1.61 |
| Q 0405–4418 | 3.02 | 2.59 | 21.75 ± 0.10 | −1.12 ± 0.10 | Zn | 2 | 2.59475 | 18.14 ± 0.07 | <12.71 | – | <0.77 |
| Q 0528–2505 | 2.77 | 2.81 | 21.35 ± 0.07 | −0.91 ± 0.07 | Zn | 3 | 2.81098 | 18.11 ± 0.02 | 11.92 ± 0.08 | 4.1 ± 1.5 | 0.01 ± 0.08 |
| Q 0551–3637 | 2.32 | 1.96 | 20.70 ± 0.05 | −0.35 ± 0.08 | Zn | 4 | 2.81112 | 17.85 ± 0.02 | 11.73 ± 0.11 | 4.2 ± 2.0 | 0.08 ± 0.11 |
| Q J0643–5041 | 3.09 | 2.66 | 21.03 ± 0.08 | −0.91 ± 0.09 | Zn | 5 | 2.65860 | 18.54 ± 0.01 | 12.51 ± 0.05 | 5.8 ± 1.4 | 0.17 ± 0.05 |
| J0812+3208 | 2.7 | 2.63 | 21.35 ± 0.10 | −0.81 ± 0.10 | Zn | 6 | 2.62628 | 18.84 ± 0.06 | 12.79 ± 0.05 | 2.0 ± 0.6 | 0.15 ± 0.08 |
| Q 0816+1446 | 3.84 | 3.29 | 22.00 ± 0.10 | −1.10 ± 0.10 | Zn | 7 | 3.28744 | 18.62 ± 0.18 | <13.65 | – | <1.23 |
| Q 1232+0815 | 2.57 | 2.34 | 20.90 ± 0.08 | −1.35 ± 0.12 | S | 8 | 2.33772 | 19.57 ± 0.10 | 13.49 ± 0.08 | 0.8 ± 0.2 | 0.12 ± 0.13 |
| J1237+0647 | 2.78 | 2.69 | 20.00 ± 0.15 | +0.34 ± 0.12 | Zn | 9 | 2.68959 | 19.20 ± 0.13 | 13.01 ± 0.02 | 4.5 ± 0.4 | 0.01 ± 0.13 |
| J1331+170 | 2.08 | 1.78 | 21.18 ± 0.04 | −1.22 ± 0.10 | Zn | 10,11 | 1.77636 | 19.71 ± 0.10 | 12.87 ± 0.02 | 5.7 ± 0.5 | −0.64 ± 0.10 |
| J1439+1118 | 2.58 | 2.42 | 20.10 ± 0.10 | +0.16 ± 0.11 | Zn | 12 | 2.4184 | 19.38 ± 0.04 | <13.25 | – | <0.07 |
| J1441+2737 | 4.42 | 4.22 | 20.95 ± 0.08 | −0.63 ± 0.10 | S | 13 | 4.22401 | 18.05 ± 0.05 | <12.86 | – | <1.01 |
| J1444+0126 | 2.21 | 2.09 | 20.25 ± 0.07 | −0.80 ± 0.09 | Zn | 14 | 2.08696 | 18.16 ± 0.11 | <12.42 | – | <0.46 |
| J2100–0641 | 3.14 | 3.09 | 21.05 ± 0.15 | −0.73 ± 0.15 | Si | 15 | 3.09149 | 18.76 ± 0.03 | <12.86 | – | <0.3 |
| J2123–0050 | 2.26 | 2.06 | 19.18 ± 0.15 | −0.19 ± 0.10 | S | 16 | 2.05933 | 18.09 ± 0.02 | 12.27 ± 0.06 | 2.6 ± 0.5 | 0.38 ± 0.06 |
| J2140–0321 | 2.48 | 2.34 | 22.40 ± 0.10 | −1.05 ± 0.13 | P | 17 | 2.33995 | 20.13 ± 0.07 | 13.67 ± 0.15 | 5–10 | −0.26 ± 0.18 |
| J2340–0053 | 2.09 | 2.05 | 20.35 ± 0.10 | −0.92 ± 0.03 | Zn | 15 | 2.05456 | 18.07 ± 0.06 | 12.25 ± 0.15 | 0.8 ± 0.6 | 0.38 ± 0.16 |
| Q 2348–0108 | 3.01 | 2.43 | 20.50 ± 0.10 | −0.62 ± 0.10 | S | 18, 19 | 2.42688 | 18.12 ± 0.37 | <13.86 | – | <1.94 |
| S. A. Balashev et al.: Cl I and H₂ at high-ζ |

References. (1) Noterdaeme et al. (2007a); (2) Ledoux et al. (2003); (3) Noterdaeme et al. (2008); (4) Ledoux et al. (2002); (5) Albornoz Vásquez et al. (2014); (6) Jorgenson et al. (2009); (7) Guimarães et al. (2012); (8) Balashev et al. (2011); (9) Noterdaeme et al. (2010); (10) Carswell et al. (2011); (11) Balashev et al. (2010); (12) Srianand et al. (2008); (13) Ledoux et al. (2006); (14) Ledoux et al. (2003); (15) Jorgenson et al. (2010); (16) Malec et al. (2010); (17) Noterdaeme et al. (2015); (18) Pettitjean et al. (2006); (19) Noterdaeme et al. (2007b).

cold gas can be similar, otherwise fine tuning would be required between the different factors that affect the N(Cl II)/N(H₂) ratio (e.g. number density, metallicity, dust content, and UV flux).

Before continuing further, we note that in H₂-bearing gas, chlorine is found exclusively in the neutral form (i.e. N(Cl I) = N(Cl II)) (e.g. Jura 1974). Since we expect that all chlorine is in gas-phase, the abundance of chlorine, [Cl/H], in H₂-bearing gas can be expressed as

\[
[\text{Cl/H}] = [\text{Cl}/\text{H II}] + \log f,
\]

where

\[
[\text{Cl}/\text{H II}] = \log \left( \frac{N(\text{Cl})}{2N(\text{H II})} \right) - \log \left( \frac{\text{Cl}}{\text{H}} \right) - \log \left( \frac{\text{H}}{\text{H II}} \right)
\]

and \( f = 2N(\text{H II})/(2N(\text{H II}) + N(\text{H})) \) is the molecular fraction. Therefore, the ratio [Cl/H II] gives a direct constraint on the chlorine-based metallicity of H₂-bearing gas provided the molecular fraction of H₂-bearing gas is known. Conversely, if a constraint can be put on the actual chlorine abundance, [Cl/H II] can provide an estimate of the amount of H I present in H₂-bearing gas. If Cl I is depleted onto dust grains then the mentioned estimates of metallicity and molecular fraction will have to be corrected from the Cl depletion factor.

Figure 4 shows [Cl/H II] as a function of the overall metallicity for DLAs (given in Table 1) at high redshift or as a function of [Cl/H] for clouds in our Galaxy. Since \( f \leq 1 \), [Cl/H II] gives an upper limit on the metallicity in H₂-bearing gas, which is found to be roughly equal to or less than solar metallicity. For 13 out of 21 Cl I bearing clouds in our Galaxy, associated Cl II was measured (Mooney et al. 2012). Therefore, we have estimated the overall chlorine abundance [Cl/H] of these clouds as \( (N(\text{Cl I}) + N(\text{Cl II}))/N(\text{H II}) + 2N(\text{H II})) \) (see Fig. 4). Unfortunately, for high redshift DLAs, not only is Cl II not detected, but DLAs also contain several H I clouds so that chlorine abundance of...
that the molecular fraction and/or the metallicity in the H$_2$- and Cl-bearing components could be much higher than the mean value measured over the whole DLA system. This implies that a large fraction of H1 is unrelated to the cold phase traced by H$_2$. Finally, our understanding of the formation of H$_2$ onto dust grains, self-shielding, and lifetime of cold diffuse gas would certainly benefit from further observations of chlorine and molecular hydrogen in different environments and over a wide range of column densities.

Acknowledgements. S.B. and V.K. thank RF President Program (grant MK-4861.2013.2) and “Leading Scientific Schools of Russian Federation” (grant NSH-294.2014.2). R.S. and P.P. gratefully acknowledge support from the Indo-French Centre for the Promotion of Advanced Research (Centre Franco-Indien pour la Promotion de la Recherche Avancée) under contract No. 4304-2.

References

Alborsone Vásquez, D., Rahmani, H., Noterdaeme, P., et al. 2014, A&A, 562, A88
Asplund, M., Grevesse, N., Sauval, A., & Scott, P. 2009,ARA&A, 47, 481
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
Carswell, R. F., Jorgenson, R. A., Wolfe, A. M., & Murphy, M. T. 2011, MNRAS, 411, 2319
Dunlop, J. S. 2011, Science, 333, 178
Guimaraes, R., Noterdaeme, P., Petitjean, P., et al. 2012, AJ, 143, 147
Harris, A. W., & Bromage, G. E. 1984, MNRAS, 208, 941
Jenkins, E. B. 2009, ApJ, 700, 1299
Jenkins, E. B., Savage, B. D., & Spitzer, Jr., L. 1986, ApJ, 301, 355
Jorgenson, R. A., Wolfe, A. M., Prochaska, J. X., & Carswell, R. F. 2009, ApJ, 704, 247
Jorgenson, R. A., Wolfe, A. M., & Prochaska, J. X. 2010, ApJ, 722, 460
Jura, M. 1974, ApJ, 190, L33
Krogager, J.-K., Fynbo, J. P. U., Møller, P., et al. 2012, MNRAS, 424, L1
Ledoux, C., Petitjean, P., Bergeron, J., Wampler, E. J., & Srianand, R. 1998, A&A, 337, 51
Ledoux, C., Srianand, R., & Petitjean, P. 2002, A&A, 392, 781
Ledoux, C., Petitjean, P., & Srianand, R. 2003, MNRAS, 346, 209
Ledoux, C., Petitjean, P., & Srianand, R. 2006, ApJ, 640, L25
Levshakov, S. A., & Varshalovich, D. A. 1985, MNRAS, 212, 517
Lis, D. C., Pearson, J. C., Neufeld, D. A., et al. 2010, A&A, 521, L9
Malec, A. L., Buning, R., Murphy, M. T., et al. 2010, MNRAS, 403, 1541
Mooney, D., Federman, S. R., & Shearer, Y. 2012, ApJ, 744, 174
Morton, D. C. 2003, ApJS, 149, 205
Neufeld, D. A., & Wolfire, M. G. 2009, ApJ, 706, 1594
Noterdaeme, P., Ledoux, C., Petitjean, P., et al. 2007a, A&A, 474, 393
Noterdaeme, P., Petitjean, P., Srianand, R., & Le Petit, F. 2007b, A&A, 469, 425
Noterdaeme, P., Ledoux, C., Petitjean, P., & Srianand, R. 2008, A&A, 481, 327
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., Srianand, R., Rahmani, H., et al. 2015, A&A, accepted [arXiv:1502.03921]
Oliveira, C. M., & Hébrard, G. 2006, ApJ, 653, 345
Petitjean, P., Srianand, R., & Ledoux, C. 2000, A&A, 364, L26
Petitjean, P., Ledoux, C., Noterdaeme, P., & Srianand, R. 2006, A&A, 456, L9
Prochaska, J. X., & Wolfe, A. M. 2009, ApJ, 696, 1543
Prochaska, J. X., Howk, J. C., & Wolfe, A. M. 2003, Nature, 423, 57
Rafelski, M., Wolfe, A. M., Prochaska, J. X., Neelamman, M., & Mendez, A. J. 2012, ApJ, 755, 89
Savage, B. D., & Sembach, K. R. 1996, ARA&A, 34, 279
Schechter, R. M., Federman, S. R., Beidick, D. J., & Ellis, D. J. 1993, ApJ, 406, 735
Sommerer, P., & York, D. G. 2006, ApJ, 650, L115
Srianand, R., Petitjean, P., Ledoux, C., Ferland, G., & Shaw, G. 2005, MNRAS, 362, 549
Srianand, R., Noterdaeme, P., Ledoux, C., & Petitjean, P. 2008, A&A, 482, L39
Srianand, R., Gupta, N., Petitjean, P., et al. 2012, MNRAS, 421, 651
Srianand, R., Gupta, N., Rahmani, H., et al. 2013, MNRAS, 428, 2198

Fig. 4. ([Cl/H$_2$] as a function of the overall metallicity for high-$z$ DLAs (red points) and the chlorine-based metallicity for Milky Way clouds (blue points). The dashed line represents the one-to-one relation.

the very cloud of interest cannot be measured. Therefore, we consider the overall metallicity (averaged over velocity components) measured using another non-depleted element (usually Zn or S, see Table 1). In Fig. 4 it can be seen that the $[Cl/H_2]$ ratio is likely not correlated with the overall metallicity of the DLA (Pearson correlation coefficient 0.3 at 0.3 significance level). For Milky Way clouds it can be seen that $[Cl/H]$ is typically one third solar, which can be interpreted as evidence for chlorine depletion (Mooney et al. 2012).

The large difference between $[Cl/H_2]$ and $[X/H]_{DLA}$ for the high redshift clouds can be explained by a molecular fraction $f < 1$ in H$_2$-bearing clouds, by a higher metallicity in the H$_2$-bearing gas compared to the overall DLA metallicity, or by both effects. If we assume that the metallicity in the H$_2$-bearing gas is equal to the overall DLA metallicity we find (using Eq. (1)) that the molecular fraction in the H$_2$-bearing gas is typically an order of magnitude higher than the overall inferred DLA molecular fraction. Interestingly, two systems sitting close to the one-to-one relation are those where CO molecules have been detected (Q1439+1118 and Q1237+0647). In such systems, the H$_2$ component is probably fully molecularized and its metallicity is close to the overall metallicity of the DLA.

4. Conclusion

We have studied the neutral chlorine abundance in high redshift ($z \sim 2$–4) strong H$_2$-bearing DLAs with log $N$(H$_2$) $> 17.3$. These systems arise in the cold neutral medium of galaxies in the early Universe. We have used 17 systems from the literature and also present a new H$_2$ detection at $z = 3.09145$ in the spectrum of J2100–0641. We have detected Cl I absorption lines in half of these systems, including five new detections. The derived upper limits for N(Cl I) for the remaining systems are shown to be consistent with the behaviour of the overall population. Our measurements extend the Cl I-H$_2$ relation to lower column densities than measurements towards nearby stars. We show that there is a 5σ correlation between the column densities of both species over the range 18.1 < log $N$(H$_2$) < 20.1 with indistinguishable behaviour between high and zero redshift systems. This suggests that at a given $N$(H$_2$) the physical conditions are likely similar in our Galaxy and high-$z$ gas, in spite of possible differences in the dust depletion levels. As we expect the Cl to be depleted less in the high-$z$ absorbers studied here, we use the abundance of chlorine with respect to H$_2$ to constrain the molecular fraction and the metallicity in H$_2$-bearing gas. Our results suggest...