

No C⁺ emission from the $z = 3.137$ damped Lyman- α absorber towards PC 1643+4631A

R.J. Ivison,¹ A.P. Harrison², and I.M. Coulson³

¹ Institute for Astronomy, University Of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK

² MRAO, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK

³ Joint Astronomy Centre, 660 North A'ohōkū Place, University Park, Hilo, HI 96720, USA

Received 21 July 1997 / Accepted 24 September 1997

Abstract. We describe a search for redshifted [C II] in a $z = 3.137$ damped Ly α absorption system that has a large neutral hydrogen column density and which was controversially reported to be a source of CO emission, indicative of rapid star formation (Frayer, Brown & Vanden Bout 1994; Braine, Downes & Guilleloteau 1996). There is no sign of [C II] emission in our spectrum, which was obtained during excellent observing conditions at the James Clerk Maxwell Telescope (JCMT) and covers 1890 km s^{-1} . The upper limit we have placed on the integrated line intensity ($3\sigma(T_{\text{MB}}) < 5.9 \text{ K km s}^{-1}$ for a profile akin to that of the CO lines) constrains the [C II]/CO(1–0) line-intensity ratio to $3\sigma < 8300$, based on the line intensity reported by Frayer et al. (1994), or to $3\sigma < 58700$ based on the data obtained by Braine et al. (1996). These limits are consistent with values measured in the Galactic plane and for nearby starburst nuclei; the former, however, is significantly lower than the ratio found in low-metallicity systems such as the Large Magellanic Cloud (which might be expected to have much in common with a damped Ly α absorption system at high redshift). This can be taken as evidence against the reality of the CO line detections, with the proviso that a system significantly larger than present-day disk galaxies would *not* have been fully covered by our small beam whereas it *would* have been properly sampled by the Frayer et al. observations. Finally, we demonstrate (as did Ivison et al. 1996) that knitting together overlapping bands can generate erroneous results — specifically, an emission feature that has a width, profile and central velocity consistent with the controversial CO emission lines and which could have drawn us to entirely the wrong conclusions.

Key words: galaxies: quasars: absorption lines; individual: PC 1643+4631A – galaxies: formation; ISM – infrared: galaxies – radio lines: galaxies

1. Introduction

It has been suggested that damped Lyman α absorption systems (DLAAS) — massive clouds of gas which produce saturated Ly-

man α absorption features in the spectra of background quasars — are the high-redshift progenitors of current disk galaxies (Wolfe 1993). The properties of DLAAS are therefore interesting in terms of the formation process of galaxies such as our own (Lanzetta et al. 1991).

There is some evidence that the number or size of DLAAS evolves over the redshift range $3.0 < z < 3.5$ (White, Kinney & Becker 1993), which implies the conversion of gas into stars at $z \sim 3$; indeed, some DLAAS at $z \sim 2$ have metallicities of 10–20 per cent Solar (Pettini et al. 1994), and some contain sufficient dust to slightly redden their background quasars (Pei et al. 1991). Although their interstellar medium has clearly been enriched, direct evidence of star formation has yet to be demonstrated (Hu et al. 1993).

If $z \sim 3$ DLAAS are protogalactic systems then they should have reservoirs of low-metallicity gas and high star-formation rates. In support of this, Frayer et al. (1994) reported CO(1–0) and (more tentatively) CO(3–2) emission from a $z = 3.137$ DLAAS towards the quasar PC 1643+4631A (Schneider, Schmidt & Gunn 1991); their data were consistent with the gas being clumped, with dimensions similar to those of a galactic disk and a mass of around $10^{12} M_{\odot}$ (we assume $q_0 = 0.5$, $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ throughout this paper). The CO luminosity was estimated to be several orders of magnitude greater than that of the Milky Way.

Braine et al. (1996) attempted to confirm the Frayer et al. result using the IRAM interferometer, but concluded that the earlier CO detections were spurious. They pointed out that an interferometer is less prone to distorted baselines than the conventional single-dish approach, and noted that its ideal application is the detection of broad, weak lines from sources smaller than the primary beam (in this case, $50''$ at 3 mm). It is worth mentioning, however, that weak sources spread over $\geq 20''$ ($\geq 35 \text{ kpc}$) would be heavily resolved by the IRAM interferometer and hence very difficult to detect. The NRAO 140-ft and 12-m dishes used by Frayer et al. have HPBW of $63''$ and $75''$ (115 – 135 kpc), so the CO detections of Frayer et al. can be understood (in the context of the Braine et al. data) only if the

molecular gas proves to be extended on scales an order of magnitude larger than the Milky Way. (CO has also been reported towards PKS 0528–250 in a DLAAS at $z = 2.14$ — Brown & Vanden Bout 1992 — and, again, the validity of the detection was disputed — Wiklind & Combes 1994).

In a galactic environment, skins of atomic gas are thought to cover each clump of molecular gas, with the thickness of the skin determined by the abundance of dust, which provides protection from the global UV field for the CO molecules within. In the atomic skin, incident UV photons left over from dissociating and ionizing are absorbed by dust grains, which cool via far-IR continuum emission; photoelectrons, ejected as a consequence of UV absorption by the grains, heat the atomic and molecular hydrogen. The C⁺ ions are then collisionally excited and emit the [C II] ($^2P_{3/2} \rightarrow ^2P_{1/2}$) fine-structure line (Hollenbach, Takahashi & Tielens 1991; Mochizuki et al. 1994). The [C II] emission is an important cooling process in galaxies, accounting for up to 1 per cent of the far-IR luminosity (Stacey et al. 1991).

Our objective here was to search for [C II] — an unmistakable signature of star-formation activity — in a DLAAS with a large column density of neutral hydrogen, $N(\text{HI}) = 5 \times 10^{20} \text{ cm}^{-2}$ (White et al. 1993), and where CO had apparently been detected, and to thereby independently confirm that star formation is ongoing in that system and that enriched gas is present. Demonstrating the potential of [C II] as a probe of metallicity, of DLAAS star-formation history, and of the evolution of galaxies at these redshifts, would represent a major advance in our studies of the early Universe.

For nearby galaxies, the rest frequency of the [C II] transition (1.900537 THz) means that the line is inaccessible from the ground and, to date, all detections in the near Universe have been made by the balloon-borne experiments (Mochizuchi et al. 1994), the Kuiper Airborne Observatory (Stacey et al. 1991) or the Cosmic Background Explorer (Bennett et al. 1994). However, at high redshifts the [C II] line is shifted into windows observable from Mauna Kea with the 15-m JCMT; specifically, for $4.14 < z < 5.33$ the line appears in the B window, and for $2.76 < z < 3.22$ it appears in the C window. To date, there have been no detections of highly redshifted [C II] (e.g. Isaak et al. 1994).

2. Observations and data reduction

The data reported here were obtained during excellent observing conditions in 1994 Dec and 1995 Jan, mostly as part of an experiment in flexibly scheduled service observing at the JCMT. We used the single-channel SIS receiver, C2, with a broad-band digital autocorrelation spectrometer (DAS) as the backend. The beam ($11''$ FWHM, or around 20 kpc at $z = 3.137$) was nutated by $60''$ in azimuth, at a rate of 1 Hz, with the telescope position-switching by the same distance every 30 s to alternate the signal and reference beams. The maximum pointing offset during the observations was less than $4''$. T_{sys} ranged from 1050 to 2300 K, and the sky transparency was excellent. A total of 105 min was

Table 1. Log of observations towards PC 1643+4631A.

Mean UT date	T_{sys} /K	Central v_{lsr} for $z = 3.137$ /km s ⁻¹	Integration time /s
1994 Dec 23.78	1148	+0	3600
1995 Jan 20.73	2305	-430	1800
1995 Jan 20.78	1706	+430	1800
1995 Jan 21.70	1396	-860	3600
1995 Jan 21.78	1716	-430	1800

spent on source, with a 175 per cent overhead for sky subtraction, position switching, calibration and pointing checks.

The maximum bandwidth of the DAS (920 MHz, or 600 km s^{-1} at 459.399807 GHz) is barely sufficient when searching for high-frequency lines, particularly when the target line is broad as was expected to be the case here. For this reason, four slightly overlapping spectra were obtained (with band centres at 458.74362, 459.39987, 460.05612 and 460.71237 GHz — see Table 1), giving a full velocity coverage of 1890 km s^{-1} . These were reduced, using SPECX V6.7 (Padman 1993), baseline-subtracted (zero order baselines) and binned to give a velocity resolution of 40 km s^{-1} . The overlap regions were averaged.

Our conversion from atmosphere-corrected antenna temperatures, T_A^* , to the T_R^* scale assumes a forward spillover efficiency, η_{fss} , of 70 per cent, and is accurate to ± 10 per cent. The conversion factor between the T_R^* scale and flux density is $S_\nu = 26 \times (T_R^*/\text{K}) \text{ Jy}$, which assumes an aperture efficiency of 42 per cent. The beam efficiency at 460 GHz, measured on Mars, was 53 ± 5 per cent, so $T_{\text{MB}} = 1.89 \times T_R^*$, with an overall uncertainty of around 20 per cent.

3. Results

In Fig. 1 we present our JCMT spectrum, together with the CO data from Frayer et al. (1994). The overall rms is $\sigma(T_{\text{MB}}) = 15 \text{ mK}$, or 12 mK if we limit ourselves to the central portion of the spectrum. The resulting upper limit on the integrated line intensity, calculated using the formulae derived by Seaquist, Ivison & Hall (1995), assuming a rectangular profile with FWHM 680 km s^{-1} (similar that of the CO(1–0) line reported by Frayer et al. 1994), is $3\sigma(T_{\text{MB}}) < 5.9 \text{ K km s}^{-1}$. Frayer et al. (1994) give $T_{\text{MB}}(\text{CO}(1-0)) = 3.2 \pm 1.2 \text{ K km s}^{-1}$, or $10.0 \text{ Jy km s}^{-1}$, or $9.3 \times 10^{-21} \text{ W m}^{-2}$, hence the measured [C II]/CO(1–0) intensity ratio is $3\sigma < 8300$.

Braine et al. (1996) reported an rms of 1.25 mJy in channels of width 224 km s^{-1} for their observations of CO(3–2). This translates into a limit on the integrated line intensity of $3\sigma < 1.6 \text{ Jy km s}^{-1}$ or $3\sigma < 4.4 \times 10^{-21} \text{ W m}^{-2}$ (assuming a rectangular profile with FWHM 800 km s^{-1} , as reported by Frayer et al. 1994) — a factor of 7.1 lower than the integrated CO(3–2) line intensity ($11.4 \pm 3.5 \text{ Jy km s}^{-1}$) reported by Frayer et al. (1994). Assuming that the CO(1–0) has been similarly overestimated, this yields a [C II]/CO(1–0) intensity ratio of $3\sigma < 58700$.

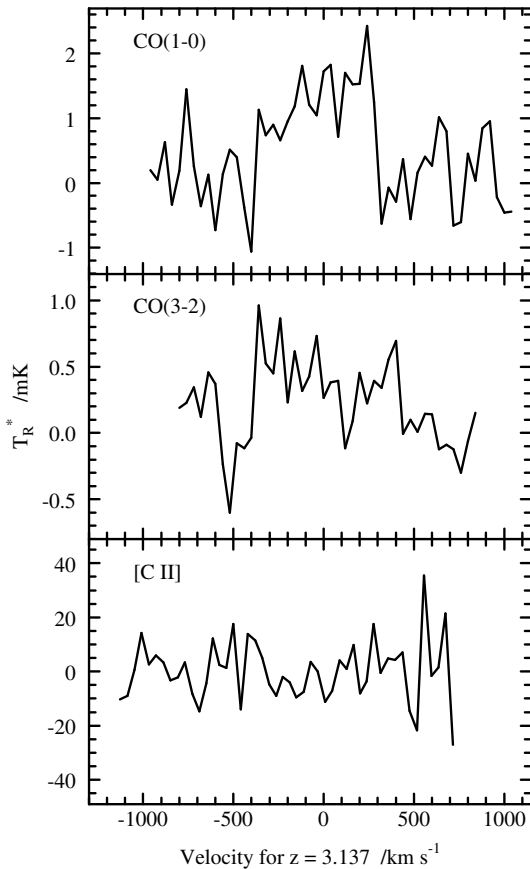


Fig. 1. Spectra of the $z = 3.137$ DLAAS towards PC1643+4631A (this paper; Frayer et al. 1994). The zero point of the velocity scale represents the expected position of the plotted lines for $z = 3.137$. Top: NRAO 140-ft CO(1–0); middle: NRAO 12-m CO(3–2); bottom: JCMT 15-m [C II], with $v_{\text{lsr}} = 0 \text{ km s}^{-1}$ corresponding to 459.399807 GHz. The spectra have been binned to 40 km s^{-1} in all cases. Zero-order baseline corrections have been applied.

Fig. 2 shows a graphic demonstration of the dangers of coadding overlapping spectra to improve velocity coverage. In this case, baselines were not subtracted from the individual segments. The effect of combining the poor baselines is to generate a very convincing emission feature (still more so if we subtract a linear baseline at this stage — see the lower panel of Fig. 2). The apparent emission line is centred at $v_{\text{lsr}} = 0 \text{ km s}^{-1}$ for $z = 3.137$ and has a full width similar to that of the controversial CO lines, though more Gaussian in profile.

The integrated intensity of the apparent line is $45 \pm 10 \text{ K km s}^{-1}$ on the T_{MB} scale, which would have indicated a [C II]/CO(1–0) intensity ratio of 63000. This would have led us to completely the wrong conclusion since this value is consistent with those of low-metallicity systems (see the discussion that follows). Moreover, this would have been regarded as strong support for the validity of the CO detections and as indicative of rapid ongoing star formation in the DLAAS towards PC 1643+4631A.

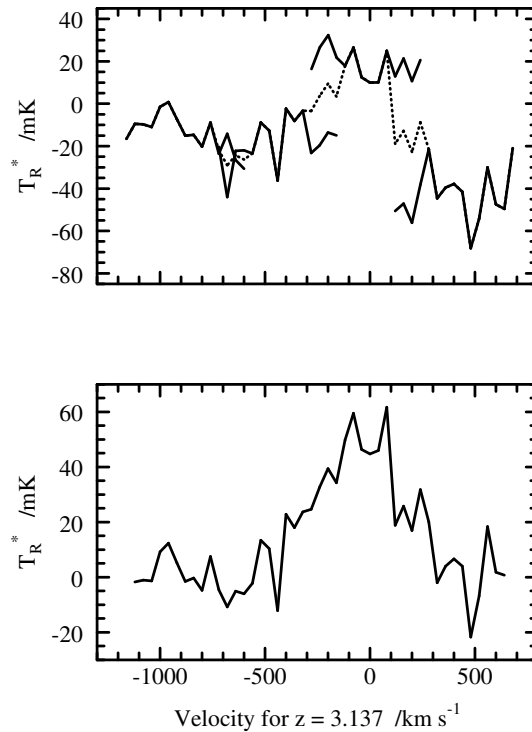


Fig. 2. Top: Spectrum (*dashed line*) of the DLAAS towards PC1643+4631A, with $v_{\text{lsr}} = 0 \text{ km s}^{-1}$ corresponding to 459.399807 GHz ([C II] for $z = 3.137$), constructed from individual 600-km s^{-1} segments (*solid lines*) without correcting their baselines (following the method of Frayer et al. 1994). Bottom: The combined spectrum after subtracting a linear baseline.

Offsets such as those seen in the upper panel of Fig. 2 are usually the result of incomplete sky subtraction, or poor instrumental stability. We suspect the former in this case, even though the spectra were obtained during excellent and seemingly quite stable conditions. It is possible that more frequent nodding between the signal and reference beams would have reduced the offsets, but such anomalies are a fact of life in the submillimetre regime and we can be grateful to some extent that the baselines produced Rx2 and DAS are such good approximations of zeroth order. There are no fool-proof methods of achieving perfect sky subtraction and if there is a lesson to be learned, it is that high-bandwidth receivers and spectrometers are extremely desirable in this field.

4. Discussion

In nearby starbursts, the photodissociated gas represents a substantial fraction (40 per cent) of the total gas mass in the nuclei, and the line-intensity ratio of [C II] to CO(1–0) is 4100, with a very small scatter (Stacey et al. 1991). In the Galactic plane, the ratio is around 1300 (Nakagawa et al. 1993), whilst in low-metallicity regions such as 30 Dor, or the Large Magellanic Cloud (LMC) in general, the ratio is high (77000 and 23000 for 30 Dor and the LMC, respectively) because there are few dust grains to shield the molecular gas. The UV therefore penetrates

deep inside each clump, dissociating CO and creating a thick skin of C⁺ ions (Mochizuki et al. 1994). Note that although the metallicity is thought to have the dominant influence on the [C II]/CO(1–0) line intensity ratio, the global UV field strength is also expected to have some effect.

Given that DLAAS at $z > 3$ are expected to be low-metallicity systems, perhaps similar in many respects to the LMC, the data we have presented (in particular the low limit on the [C II]/CO(1–0) intensity ratio, based on the claimed CO(1–0) detection) support the view that the CO detections of Frayer et al. (1994) were spurious. There is, however, one proviso concerning the beams used to sample the emission region: the area of our beam (11'' FWHM) was ~ 40 times smaller than those used by Frayer et al., and if the emission region proves to be an order of magnitude larger than the Milky Way then we would not only have missed the majority of the emitting gas, but we may well have been chopping onto some of it.

5. Concluding remarks

We have searched for redshifted [C II] towards a $z = 3.137$ damped Ly α absorption system that has a large neutral hydrogen column density and which was controversially reported to be a source of CO emission, indicative of rapid star formation. We find no sign of [C II] emission and have placed an upper limit of $3\sigma(T_{\text{MB}}) < 5.9 \text{ K km s}^{-1}$ on the integrated line intensity.

This places a useful constraint on the [C II]/CO(1–0) line-intensity ratio ($3\sigma < 8300$, based on the line intensity reported by Frayer et al. 1994) which is consistent with ratios measured in normal-metallicity systems in the present-day Universe, but is significantly lower than the ratio found in systems with low metallicities such as we might expect to find in high-redshift damped Lyman α absorption systems. We interpret this as evidence against the reality of the CO line detections towards this system, as long as the system is not significantly larger than present-day disk galaxies such as the Milky Way (which would compromise our measured ratios on the basis of disparate beam sizes).

We have also demonstrated the dangers inherent in knitting together overlapping bands to increase velocity coverage. Clearly, wide-band receivers and backends are urgently required if we are to generate a trustworthy database of CO, [C II], etc., spectra of high-redshift systems.

Acknowledgements. The JCMT is operated by the Observatories on behalf of the UK Particle Physics and Astronomy Research Council (PPARC), the Netherlands Organization for Scientific Research and the Canadian National Research Council. RJI is supported by a PPARC Advanced Fellowship.

References

Bennett C.L. et al., 1994, ApJ, 434, 587
 Braine J., Downes D., Guilloteau S., 1996, A&A, 309, L43
 Brown R.L., Vanden Bout P.A., 1992, ApJ, 397, L11
 Brown R.L., Vanden Bout P.A., 1993, ApJ, 412, L21
 Frayer D.T., Brown R.L., Vanden Bout P.A., 1994, ApJ, 433, L5

Hollenbach D.J., Takahashi T., Tielens A.G.G.M., 1991, ApJ, 377, 192
 Hu E.M., Songaila A., Cowie L.L., Hodapp K.-W., 1993, ApJ, 419, L13
 Isaak K.G., McMahon R.G., Hills R.E., Withington S., 1994, MNRAS, 269, L28
 Ivison R.J., Papadopoulos P., Seaquist E.R., Eales S.A., 1996, MNRAS, 278, 669
 Lanzetta K.M. et al., 1991, ApJS, 77, 1
 Mochizuki K. et al., 1994, ApJ, 430, L37
 Nakagawa T., Doi Y., Mochizuki K., Yui Y.Y., Okuda H., Yui M., Shibai H., 1993, in Holt S.S., Verter F., eds, AIP Conf. Proc., Back to the Galaxy. AIP, NY, p. 303
 Padman R., 1993, 'SPECX Users' Manual', Cavendish Laboratory, Cambridge
 Pei Y.C., Fall S.M., Bechtold J., 1991, ApJ, 378, 6
 Pettini M., Smith L.J., Hunstead R.W., King D.L., 1994, ApJ, 426, 79
 Schneider D.P., Schmidt M., Gunn J.E., 1991, AJ, 101, 2004
 Seaquist E.R., Ivison R.J., Hall P.J., 1995, MNRAS, 276, 867
 Stacey G.J., Geis N., Genzel R., Lutgen J.B., Poglitsch A., Sternberg A., Townes C.H., 1991, ApJ, 373, 423
 White R.L., Kinney A.L., Becker R.H., 1993, ApJ, 407, 456
 Wiklind T., Combes F., 1994, A&A, 288, L41
 Wolfe A.M., 1993, in Rocca-Volmerange B. et al., eds, First Light in the Universe: Stars or QSOs? p. 77