

Spectroscopy of the QSO pair Q1228 + 076/ Q1228 + 077

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Summary. We report a further case of a pair of quasars in which the higher redshift member of the pair shows absorption lines at a redshift very close to the emission redshift of the other QSO, which is situated nearby on the plane of the sky. In this case Q1228 + 077 ($z_{\text{em}} = 2.391$) has a definite absorption system at $z_a = 1.8971$, which differs by $2000 \pm 100 \text{ km s}^{-1}$ from the emission redshift of Q1228 + 076 (1.878) which lies 3.4 arcmin away on the plane of the sky. This is direct evidence that the absorption system in question is due to intervening matter unrelated to the background quasar. The spatial and velocity separations above are consistent with absorption in the halo of a galaxy in a cluster which also contains the foreground quasar.

1 Introduction

The origin of the narrow absorption lines found in the spectra of many quasars is a subject of continuing debate. The two chief theories are that the lines are due to absorption in large haloes of galaxies along the sight line to the QSO and unassociated with it (e.g. Bregman 1981; Young, Sargent & Boksenberg 1982) or that they are due to material expelled from the QSO (at speeds up to $0.6c$) (Kippenhahn 1977). There are several quasars known in which absorption is seen at the same redshift as a galaxy nearby to the QSO on the sky [but with $z(\text{gal}) \ll z_{\text{em}}(\text{QSO})$], thereby demonstrating that the absorption is due to intervening rather than expelled matter (Boksenberg & Sargent 1978; Boksenberg *et al.* 1980; Blades, Hunstead & Murdoch 1981; Burbidge *et al.* 1977). However, these are all relatively low-redshift absorption systems, based on low ionization species, primarily Ca II or Mg II. We have extended such studies to high redshifts by observing QSO pairs and searching for absorption in the higher redshift member at a redshift close to that of the lower redshift member. Positive results were obtained for the pair Q0028 + 003/Q0029 + 003 (Shaver, Boksenberg & Robertson 1982) in which the absorption at $z_a = 1.7334$ in Q0029 + 003 is only 190 km s^{-1} from the emission redshift of the other QSO (62 arcsec away on the sky, or 390 kpc for $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega = 0$, as used throughout this paper). This absorption system contains the important high ionization species C IV. We adopt the terms

'associated absorption' to describe such absorption at the emission redshift of another QSO nearby on the sky, and 'common absorption' for absorption seen in both quasars of a pair at essentially the same redshift (Shaver & Robertson 1983a). A second positive result was found for the pair Q0307 – 195A, B (Shaver & Robertson 1983b) in which both common and associated absorptions are observed in the one pair: absorption occurs in both members of the pair (i.e. common) at $z = 2.122$ ($\Delta V = 77 \text{ km s}^{-1}$ between the systems in the two QSOs) and this is also associated absorption because it is equal to the emission redshift of QSO B.

The present paper reports a further example of associated absorption, in the QSO pair Q1228 + 076/Q1228 + 077. The existence of three such cases virtually rules out the possibility that the agreement of absorption and emission redshifts could be due to chance coincidences in expelled absorption systems.

2 Observations

The QSOs Q1228 + 076 (= KP 1228.5 + 07.6) and Q1228 + 077 (= KP 1228.7 + 07.7) were discovered in the Kitt Peak grism survey (Sramek & Weedman 1978). This reference gives magnitudes of about 17.5 and 17.0 respectively, emission redshifts of 1.88 and 2.39, and a separation of 3.39 arcmin. A low-dispersion spectrum of Q1228 + 077 (the higher redshift member) was given by Fairall (1978). We observed these two objects on 1982 April 26 using the 3.9-m Anglo-Australian telescope with the Royal Greenwich Observatory spectrograph and the Image Photon Counting System (Boksenberg & Burgess 1973).

Q1228 + 077 was observed at a dispersion of 33 Å mm^{-1} , with a slit width of 1.5 arcsec in seeing of ~ 3 arcsec. The wavelength range covered was 3718–4685 Å at one grating angle (73 min exposure) and 4340–5190 Å at a second grating angle (33 min exposure). The spectral resolution varies with wavelength, but is close to 1.4 Å (FWHM) over most of the range, degrading to 1.6 Å at 4000 Å and 2.4 Å at 3750 Å. Standard procedures were used for correction of pixel-to-pixel gain variations in the detector, linearization of the wavelength scale, correction for atmospheric extinction, and normalization using observations of a

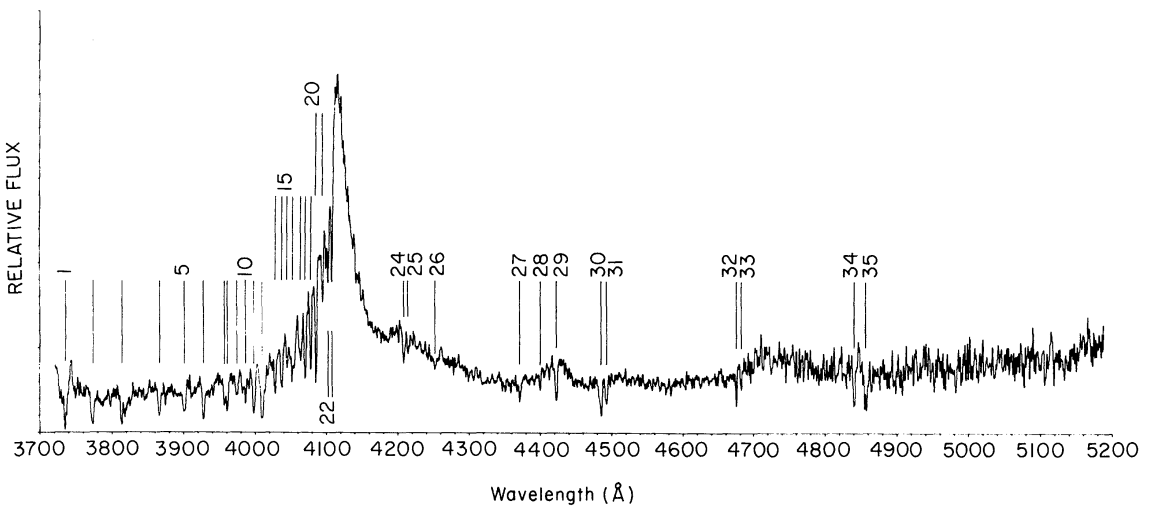


Figure 1. Intermediate dispersion spectrum of Q1228 + 077. The data as shown have been smoothed with a three-point Gaussian filter, resulting in a resolution of 1.6 Å (FWHM) over the bulk of the wavelength range, degrading to 1.8 Å at 4000 Å and 2.5 Å at 3750 Å. The absorption lines listed in Table 1 are indicated. The noisy data from just beyond line No. 33 are from a second observed wavelength range (see text). The ordinate for both this spectrum and Fig. 2 is a relative scale of λF_{λ} .

standard star to remove variations in instrumental sensitivity with wavelength. The resulting spectrum is shown in Fig. 1. Vacuum heliocentric wavelengths are used throughout. The signal-to-noise ratio drops markedly beyond $\lambda 4685$ because the observation at the second wavelength setting was shorter and of poorer quality. (This observation was not used at $4340 < \lambda < 4685$ because of the variation of resolution with wavelength.) The following broad emission lines can be seen: Lyman α at $\lambda 4117$, N v at $\lambda 4204$, O I at $\lambda 4427$ and Si IV/O IV at $\lambda 4750$. From these lines we derive a value of 2.391 ± 0.002 for the emission redshift of Q1228 + 077. The usual 'Ly α forest' of absorption lines occurs blueward of the Ly α emission. A number of absorption lines longward of Ly α are also seen. Before discussing this spectrum in detail, we consider the observation of the other QSO in the pair.

Q1228 + 076 was observed at low dispersion (156 \AA mm^{-1}), covering the wavelength range 3230–7070 \AA , and again using a slit width of 1.5 arcsec. The exposure was 12 min. This was sufficient to show the strong broad Ly α and C IV emission lines with adequate signal-to-noise ratio, but not sufficient to give useful sensitivity for detection of absorption lines or any other weak features. The spectrum is shown in Fig. 2. The emission redshift is 1.878 ± 0.002 , determined from the peak of the C IV line after smoothing with a Gaussian of FWHM 10 \AA , as for Q0028 + 003 (Shaver, Bokserberg & Robertson 1982). This is consistent with the redshift derived from Ly α if allowance is made for a probable absorption line just blueward of the Ly α peak.

3 Absorption spectrum of Q1228 + 077

In Table 1 the absorption lines in the spectrum of Q1228 + 077 are listed. There are three high redshift systems, at $z_a = 1.8971 \pm 0.0001$, 2.0192 ± 0.0002 and 2.1367 ± 0.0002 for

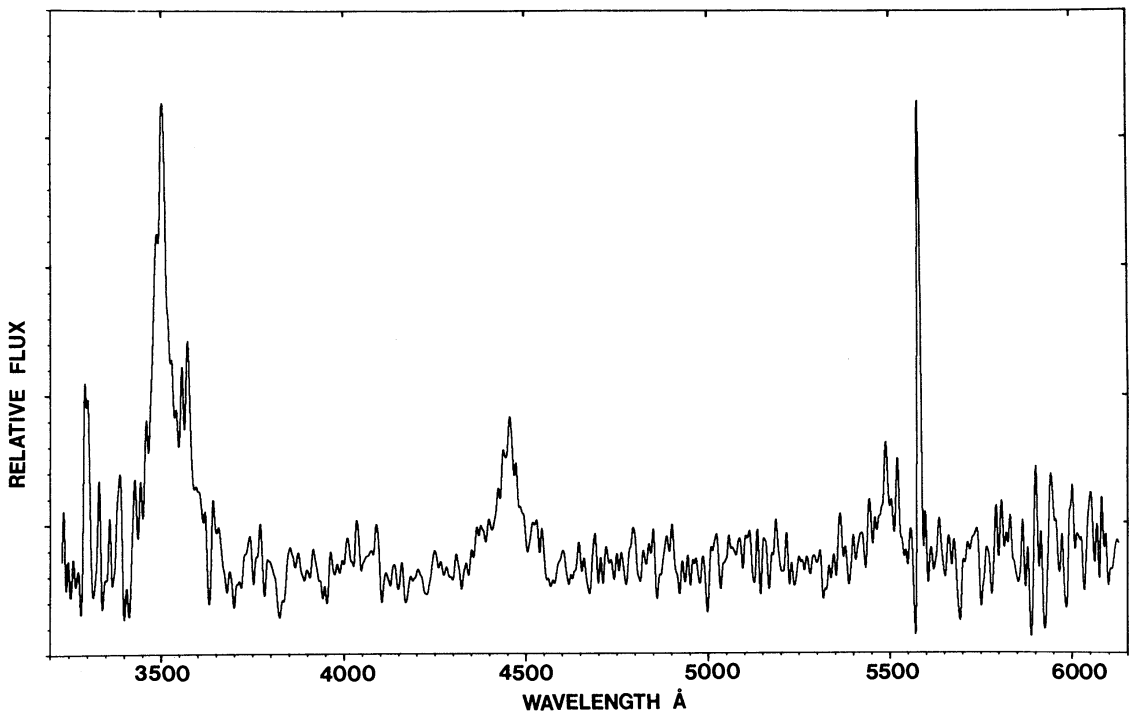


Figure 2. Low-dispersion spectrum of Q1228 + 076. In this figure the data have been smoothed with a Gaussian of FWHM 7 \AA , resulting in a resolution of 10 \AA over most of the wavelength range. The broad emission lines visible are Ly α at 3500 \AA , C IV at 4458 and C III at 5493. The feature at 5577 \AA is a night sky residual.

Table 1. Absorption lines in the spectrum of Q1228 + 077.

No.	λ_{obs} (Å)	σ_{λ} (Å)	W_{obs} (Å)	σ_w (Å)	Identification	z_{abs}	Absorption system
1	3735.6	0.6	3.8	0.7			
2	3772.9	0.4	3.8	0.4			
3	3813.5	0.4	2.6	0.4	HI 1215.67	2.1370	C
4	3865.9	0.4	2.2	0.2	CII 1334.53	1.8968	A
5	3900.9	0.4	1.9	0.2			
6	3927.8	0.3	2.1	0.2			
7	3957.1	0.3	1.6	0.3			
8	3960.9	0.2	1.6	0.2			
9	3974.0	0.2	1.1	0.2			
10	3986.3	0.2	0.5	0.1			
11	3998.3	0.2	2.4	0.2			
12	4010.4	0.2	4.8	0.3			
13	4028.5	0.2	1.2	0.1	CII 1334.53	2.0187	B
14	4037.7	0.2	1.4	0.1	Si IV 1393.76	1.8970	A
15	4045.4	0.2	0.7	0.1			
16	4052.9	0.2	2.7	0.2			
17	4064.0	0.2	1.5	0.1	Si IV 1402.77	1.8971	A
18	4070.6	0.15	1.7	0.1			
19	4078.3	0.15	1.4	0.1			
20	4085.8	0.15	1.8	0.07			
21	4095.4	0.15	0.70	0.06			
22	4103.1	0.15	0.66	0.06			
23	4108.5	0.2	1.1	0.1			
24	4208.8	0.2	1.0	0.1	Si IV 1393.76	2.0197	B
25	4214.9	0.3	0.46	0.1	Ca II 3934.81	0.0712	D
26	4252.8	0.4	0.27	0.1	Ca II 3969.63	0.0713	D
27	4371.6	0.3	0.9	0.17	Si IV 1393.76	2.1366	C
28	4400.2	0.3	0.56	0.14	Si IV 1402.77	2.1368	C
29	4422.9	0.2	1.67	0.15	Si II 1526.71	1.8970	A
30	4485.4	0.2	2.6	0.2	C IV 1548.19	1.8972	A
31	4492.9	0.2	1.6	0.2	C IV 1550.76	1.8972	A
32	4674.7	0.6	1.0	0.13	C IV 1548.19	2.0195	B
33	4681.7	0.6	0.62	0.15	C IV 1550.76	2.0190	B
34	4840.8	0.4	1.9	0.4	Al II 1670.79	1.8973	A
35	4857.0	0.5	2.2	0.5	{ C IV 1548.19* Fe II 1608.46	{ 2.1372 2.0197	{ C B

* Weaker member of doublet not detected.

systems A, B and C respectively. System A is certain, but systems B and C should be regarded as probable at this stage. There is also a possible low redshift system, D, at $z_a = 0.0712 \pm 0.0002$ and containing only Ca II *H* and *K* lines. It is further discussed below. All reliable lines longward of the Ly α emission have identifications within one of these four systems, as do five lines shortward of Ly α . The few lines seen in systems B and C are of moderate ionization, while system A is of mixed ionization since it includes Si II, C II and Al II as well as Si IV and C IV.

System A is of greatest interest because of its close correspondence in redshift with the emission redshift of Q1228 + 076. It is clearly the strongest of the three systems. The C IV doublet ratio of 1.65 ± 0.2 for this system indicates that the absorption is between the linear and saturated regimes (assuming that the lines are not damped), and curve of growth analysis indicates a column density $N(\text{cm}^{-2})$ of $\log N(\text{C IV}) \approx 14.5$, typical of QSO absorption systems. The indicated Doppler broadening velocity is $b \sim 100 \text{ km s}^{-1}$. This cannot be thermally produced since it corresponds to the unreasonable temperature of $7 \times 10^6 \text{ K}$ ($3/2 kT = 0.9 \text{ keV}$). Instead, the usual presence of subcomponents is indicated. This is supported by the observed asymmetry of the C IV lines – both components are resolved and are steeper on the red side than the blue side.

The absorption redshift of system A ($z = 1.8971$) differs from the emission redshift of Q1228 + 076 by $2000 \pm 100 \text{ km s}^{-1}$ (in the rest frame of the latter). If Q1228 + 076 and the cloud which produces absorption system A in Q1228 + 077 are moving independently in a cluster of galaxies, this corresponds to a line-of-sight velocity dispersion of $\sim 1400 \text{ km s}^{-1}$, consistent with that for a typical rich cluster. This would be reduced to $\sim 1000 \text{ km s}^{-1}$ if allowance is made for the systematic blueshift of broad high ionization emission lines discussed by Gaskell (1982), but it is not clear that such a correction is appropriate for our determination of the emission redshift of Q1228 + 076. The separation of 3.39 arcmin between Q1228 + 076 and 1228 + 077 corresponds to 1.3 Mpc at $z = 1.897$, consistent with typical cluster dimensions. The hypothesis that the $z = 1.8971$ absorption is due to the halo of a galaxy in a cluster containing the nearer QSO is also broadly consistent with current estimates of absorption cross-sections: taking a halo diameter of 100 kpc around each galaxy and a cluster radius of 1.5 Mpc, an absorption system can be expected in ~ 10 per cent of cases if the cluster contains ~ 100 galaxies (i.e. Abell richness class ~ 2). The expected success rate in detecting this type of absorption in a background QSO at the redshift of a second QSO nearby on the sky will clearly be dependent on the fraction of QSOs which occur in clusters of galaxies. This may be quite close to unity, at least at appreciable redshifts (Stockton 1980, 1982; Stocke & Perrenod 1981). While absorption in the halo of a cluster galaxy is the preferred interpretation of system A in Q1228 + 077, absorption in a halo surrounding the lower redshift QSO itself is an alternative for Q0029 + 003 (Shaver *et al.* 1982) and is the more likely explanation for Q0307 – 195A, B (Shaver & Robertson 1983b).

If the $z_a = 1.8971$ absorption in Q1228 + 077 is indeed due to a galaxy in a cluster associated with Q1228 + 076 as proposed here, then this constitutes evidence (albeit indirect) for the existence of an extremely distant cluster of galaxies. (The lookback time to this redshift is 65 per cent of the age of the Universe for $\Omega = 0$ and 80 per cent for $\Omega = 1$.) It will be possible to refine this argument when a larger sample of QSO pairs has been observed.

To conclude the discussion of this associated absorption system, we note that it represents direct evidence that the absorption in system A is due to an intervening object unrelated to the background QSO in which the absorption appears. On the question of whether QSO redshifts are cosmological or not, the observations of associated absorption in all three pairs (Q1228 + 076/7, 0028 + 03/0029 + 003, 0307 – 195A, B) give strong support to the hypothesis that the redshifts are cosmological. If they were not, an absorption process with an identical non-cosmological redshift to that of the emission line region would be needed, in spite of the very different physical conditions of these two regions.

We turn now to absorption system D in Q1228 + 077. Line number 25, identified as Ca II *K* at $z_a = 0.0712$, has a signal-to-noise ratio adequate to warrant independent tabulation, whereas the corresponding *H* line (No. 26) can only be tabulated because of its good agreement in redshift with No. 25. Taken together, these lines constitute a possible absorption system. If it is real, we would expect to observe a galaxy with this redshift nearby on the sky. Indeed there are two galaxies nearby (on the Palomar Sky Survey): a ~ 16 mag elliptical 50 arcsec north-east of Q1228 + 077 and a ~ 17 mag elliptical 48 arcsec south-east. Their redshifts are unknown, but their magnitudes are consistent with typical galaxies at $z = 0.0712$ ($M = -21$ and -20). There are presently only three known cases of absorption in a QSO at the (low) redshift of a galaxy nearby on the sky (see Section 1), and all of these are at smaller projected separations than the case of Q1228 + 077, in which the line-of-sight to the QSO probes the galaxy haloes at radii of 46 and 44 kpc (if they are in fact at $z = 0.0712$). These radii are, however, about equal to the halo sizes required to explain the observed frequency of QSO absorption lines (Young *et al.* 1982). It will therefore be of

interest to obtain redshifts for the galaxies and further data for the possible $z_a = 0.0712$ system in Q1228 + 077.

Finally, we note that the survey in which Q1228 + 076 and 1228 + 077 were discovered also located a third bright QSO Q1228 + 078 (KP 1228.0 + 07.8) 13.7 arcmin north-west of Q1228 + 076. Young *et al.* (1982) give an emission redshift of 1.813 for this QSO and present a high-dispersion spectrum which shows absorption at $z_a = 1.809$ and 1.633. Thus it exhibits no associated or common absorption with respect to the Q1228 + 076/7 pair, as may be expected since it is separated by a projected distance of more than 5 Mpc from the other two QSOs.

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Note added in proof

AAT spectroscopic observations in 1983 May have shown that neither of the two galaxies near Q1228 + 077 has a redshift near 0.0712. The NE galaxy has an absorption spectrum with redshift 0.086 and the SE galaxy shows omission lines with a redshift of 0.066. The possible absorption system D in Q1228 + 077 is therefore not supported.