Studies of broad emission line profiles in QSOs - II. Properties of a large, predominantly radio selected sample

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Studies of broad emission line profiles in QSOs – II.
Properties of a large, predominantly radio selected sample

Belinda J. Wilkes* Steward Observatory, University of Arizona, Tucson, AZ 85721, USA

Accepted 1985 August 13. Received 1985 June 17; in original form 1984 April 5

Summary. Emission line parameters for 214 QSOs are reported. The majority were originally selected according to the flatness of their radio spectra from the Parkes 2700, 5000 MHz surveys. The optical spectra of these objects were presented graphically in an earlier paper (WWJP, see text). Preliminary studies of the properties of this sample, including line velocity width and equivalent width distributions, have been made. Specific emission lines have been investigated in more detail to confirm or refute earlier results.

1 Introduction

The basic physical conditions of the radiating gas in the broad emission line region (BELR) of QSOs are well established (see e.g. Davidson & Netzer 1979; Kwan & Krolik 1981); only the finer details remain to be debated. This is not the case, however, for the spatial distribution or dynamics of the gas, for which there remain a large number of competing models (Blumenthal & Mathews 1975, 1979; Mathews 1974; Kwan & Carroll 1982; Krolik & London 1983). The common denominator of these models is generally a large number of small, optically thick clouds or filaments providing a low covering factor and moving at high velocities; the sense of this motion has not been determined. The main reason for the lack of a more specific model is the shortage of observational constraints. The stellar nature of QSOs prohibits any direct observation of the gas motion and, although a composite picture is provided by the shapes of the emission line profiles, their study is difficult for the following reasons. First, QSOs are faint and it is both time-consuming and laborious to obtain the necessary high-quality data; secondly, the properties of QSO spectra are diverse and there can be no certainty that the few bright ones that are studied in detail are representative of QSOs as a whole. It is therefore necessary to approach the problem in two different ways: first to study the line profiles of a small number of QSOs in detail (Wilkes 1984; Paper I hereafter); secondly to investigate the distribution of first-order properties over a larger sample both for their own sake, to shed some light on the class as a whole, and also to facilitate comparison with the smaller sample to determine how typical the latter objects are.

In a recent publication (Wilkes et al. 1983, WWJP hereafter) the optical spectra of 295 QSO

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candidates are presented; the majority of these were originally selected from the Parkes 2700 and 5000 MHz radio surveys by their flat spectral index ($\alpha<0.5$). In this paper emission line measurements are presented for those active galactic nuclei (AGNs) in the sample which possess measurable lines. A very important attribute of this sample is the fact of radio selection which results in its being relatively unbiased in terms of optical properties, in particular, the strengths and widths of the emission lines, upon which objective prism surveys (for example) are heavily dependent. Consequently, although it is not a well-defined sample in the sense of being complete to a specific flux level, it is randomly selected in terms of its optical emission line properties. It is therefore a good starting point for a study of the range of these properties present in AGNs. Similar studies for steep spectrum radio sources have been made (e.g. Baldwin et al. 1973; Smith et al. 1977, and references therein). The quality of the spectral data in both resolution and signal-to-noise (S/N) properties varies widely from object to object and thus the sample is incomplete at low equivalent widths. It should be noted that a number of the AGNs in the WWJP compilation are optically selected and are included in this paper for completeness. They are not free from bias in terms of optical properties and were not included in full sample analysis unless otherwise noted.

Throughout this paper each object is referred to by PKS coordinate designation. A number of the objects have been studied by other authors on the basis of different data and are also known by other names. Such information can be found by referring to one of the QSO catalogues (Hewitt & Burbidge 1980; Véron-Cetty & Véron 1984) and will not be repeated here except in a small number of cases. All measurements reported here are based on these data alone; confirmatory or conflicting results from the literature are noted where relevant. No attempt has been made to distinguish between SyI galaxies and QSOs on the basis of these data.

2 Observations

The optical spectra for this sample were obtained using the 4-m Anglo–Australian Telescope (AAT), the RGO spectrograph and associated Image Dissector Scanner (IDS) and/or Image Photon Counting System (IPCS) detectors by a number of observers during the period 1975–80 (WWJP, Jauncey et al. 1984, and references therein). References are given in Table 1 to the original papers discussing the present data, and observational details for individual QSOs may be found there. As described in WWJP, many of the objects were observed several times during this period and the data summed to improve the S/N provided no variability was detected. No strong constraints on variability exist, however, due to the low S/N of the spectral data and lack of photometry. The measurements presented here represent a mean over a time-scale of a few years between 1975 and 1980. Graphical presentation of the optical spectra, details of observed wavelength range, photometric quality, resolution, etc. may be found in WWJP. In this paper spectral line positions, identifications, widths, equivalent widths and intensity ratios are reported. The distribution of these properties for each line was studied; general results, along with a more detailed discussion of several of the broad lines, are given below.

3 Measurement

Measurement of emission line parameters, such as full-width-half-maximum (FWHM) and flux, are subjective, particularly for low-quality data. It is advantageous when studying a large number of objects for all measurements to be made in a consistent manner; consequently, all the spectra were measured, including those that have been studied previously (see references in Table 1). Measurement errors are present due to weak, blended emission and absorption features as well as noise; these are best judged by inspecting the individual profiles in WWJP.
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| 0637-752   | 0.656    | 16   | MgII λ2798   | 4636              | 4730      | 64    | 100           |       |
| [NII] λ2369 |         |      | MgII λ2798   | 6398              | 1030      | 6     | 5             |       |
| H I λ4102  |         |      | MgII λ2798   | 7588              | ---       | ---   | ---           |       |
| H I λ4340  |         |      | MgII λ2798   | 7192              | 4800      | 27    | 21            |       |
| 0642-349   | 2.162    | 2    | H I λ1216    | 3839              | 3240      | 152   | 260           |       |
|            |          |      | N V λ1240    | 3934              | 3560      | 22    | 36            |       |
| O I λ1304  |         |      | CIV λ1549    | 4137              | 1460      | 3     | ---           |       |
|            |          |      | HeII λ1640   | 5183              | 2370      | 11    | 18            |       |
| CIII] λ1909 |         |      | MgII λ2798   | 6047              | 6740      | 38    | 54            |       |
| 0723-008   | 0.129    | 2    | [OII] λ3727  | 4200              | 5670      | 30    | 107           | N galaxy
|            |          |      | H I λ4861    | 5494              | ---       | ---   | ---           |       |
| [OIII] λ4959 |         |      | HeII λ1640   | 5598              | 1180      | 6     | 28            |       |
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| 0748-126   | 0.884    | 4    | MgII λ2798   | 5273              | 2750      | 41    | ---           |       |
| 0812-02    | 0.404    |      | MgII λ2798   | 3929              | 4350      | 68    | 100           |       |
| [Nv] λ3969  |         |      | MgII λ2798   | 4808              | 690       | 3     | 3             |       |
| [OII] λ3727 |         |      | MgII λ2798   | 5231              | 920       | 6     | 3             |       |
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| H I λ4102  |         |      | MgII λ2798   | 5767              | 2660      | 11    | 4             | Noisy
| H I λ4340  |         |      | MgII λ2798   | 6101              | 4060      | 40    | 12            |       |
| H I λ4861  |         |      | MgII λ2798   | 6830              | 5000      | 100   | 28            | Noisy
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| 0819-032   | 2.355    | 2    | H I λ1216    | 4084              | 4780      | 237   | 330           |       |
|            |          |      | N V λ1240    | 4412              | 26        | 36    | ---           |       |
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| OIV)/SiIV λ1400 | 4709    | 7060  | CIV λ1549    | 5199              | 2900      | 101   | 100           |       |
| HeII λ1640 |         |      | CIII] λ1909  | 5501              | 4250      | 22    | 2             |       |
| 0845-051   | 1.238    | 5    | CIV λ1549    | 3475              | 7140      | 43    | 100           |       |
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| 0859-14 | 1.333 | CIV λ1549 | 3609 | 4730 | 73 | 100 |
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| 0902-256 | 1.640 | OI λ1304 | 3474 | --- | --- | --- |
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| CIV λ1549 | 4095 | 5450 | 85 | 100 |
| CIII | λ1909 | 5030 | 6630 | 33 | 32 |

| 0906-01 | 1.029 | CIII | λ1909 | 3800 | 6160 | 27 | 130 |
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| 0915-213 | 0.849 | CIII | λ1909 | 3523 | 4220 | 52 | 120 |
| MgII λ2798 | 5175 | 2490 | 59 | 100 |
| [NeV] λ3426 | 6337 | --- | --- | --- | Noisy |

| 0919-260 | 2.297 | OVI | λ1034 | 3406 | 1940 | 15 | 35 |
| HI λ1216 | 4016 | 3370 | 130 | 230 | SB, BW |
| NV λ1240 | 4082 | 3960 | 43 | 76 |
| CIV/SiIV λ1400 | 4611 | 5910 | 23 | 34 |
| OIV/SiIV λ1400 | 5110 | 2470 | 51 | 100 |
| MgII λ1640 | 5428 | 1170 | 6 | 9 |

| 0925-203 | 0.347 | MgII λ2798 | 3769 | 3500 | 47 | 100 |
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| HI λ4340 | 5857 | 3580 | 29 | 20 |
| HI λ4681 | 6549 | 2770 | 58 | 39 |
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| [OIII] λ5007 | 6746 | 890 | 25 | 15 |

| 0959-443 | 0.837 | CIII | λ1909 | 3498 | 7270 | 39 | 85 |
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| 1004-217 | 0.331 | MgII λ2798 | 3723 | 2340 | 19 | 100 |
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| 1004-141 | 2.707 | HI λ1216 | 4508 | --- | --- | --- |
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| 1009-321 | 1.757 | CIV λ1549 | 4269 | 5200 | 149 | 100 |
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<p>| 1032-199 | 2.189 | HI λ1216 | 3879 | 4640 | 200 | 370 | EC |
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References:
1. Peterson et al. (1976).
2. Wright et al. (1977).
5. Wright et al. (1979c).
12. Wright et al. (1979a).
The redshift was estimated from the peak wavelengths of those lines which were positively identified; the low-ionization lines O\textsc{i}$\lambda$1304 and C\textsc{ii}$\lambda$1335 were excluded from this determination since they are believed to be redshifted relative to the high-ionization lines (Gaskell 1982, Paper I). The O\textsc{iv}/Si\textsc{iv}$\lambda$1400 feature was also excluded since the two emission lines are heavily blended, so that their relative strengths and hence their expected rest frame wavelength are undetermined.

The FWHM is commonly used as an indicator of the velocity dispersion of an emission line. Many factors affect the accurate measurement of this parameter, in particular the amount of depression of the peak height due to the combined effects of low-resolution, poor S/N and uncertainty in the adopted continuum level. The likely measurement error, estimated by measuring the FWHM for the highest and lowest plausible continuum levels, was generally 5–30 per cent for strong lines. The error can be much greater than this for weak, noisy and/or absorption-contaminated lines. The reliability of each measurement can best be judged by inspecting the observed line profile in WWJP.

In order to obtain parameters for Ly$\alpha$ and the doublet N\textsc{v}$\lambda$1240 blended into its red wing, it was necessary to deblend the lines in some way. The degree of blending of the two features varies according to their relative strengths and FWHM. One or more of the following procedures was used for deblending, depending upon the nature of the data. The method used is indicated in Table 1.

(i) When the peaks were well resolved and it was possible to trace the shape of the red wing of Ly$\alpha$, a continuum was fitted through this wing. The N\textsc{v} and, if present, Si\textsc{ii}$\lambda$1264 features were then isolated and measured following the regular procedure. This method was used only when the lines were relatively narrow (FWHM $\leq$4000 km s$^{-1}$) and N\textsc{v} strong [$I$(N\textsc{v}) $\geq$30 per cent $I$(Ly$\alpha$)] and thus is not expected to lead to any measurement errors additional to those for unblended lines.

(ii) When the degree of blending was too great for (i), two alternative methods were used, in conjunction where possible, their relative success being dependent upon the quality and nature of the data. In a number of objects no deblending was possible due to poor data or unusual line profiles in which case measurements for the combined profile are given in Table 1.

(a) A synthetic blend was generated using an unblended line profile from the same spectrum (usually C\textsc{iv}$\lambda$1549) as a prototype (see Paper I, Wilkes & Carswell 1982). The presence of absorption in the blue wing of Ly$\alpha$ was allowed for as far as possible. An individual component could then be isolated by subtracting the synthesis of the other components from the observed feature. When there was a velocity difference between the peak positions of Ly$\alpha$ and the prototype, a compensating shift was applied when generating the synthesis; it is the shape of the profile not its absolute position which is important for this procedure. This method relies upon the profiles of all the composite lines being similar to that of the prototype. This is generally true to within $\sim$10 per cent in high-resolution data, i.e. frequently not detectable in low-resolution data. For a few unusual objects where the profiles were clearly different the method was not used. Thus errors at $<$10 per cent level are expected in combination with those due to continuum uncertainty and the possible presence of weak emission and absorption features that plague all profile measurements (see discussion in Wilkes & Carswell 1982).

(b) The blue wing of Ly$\alpha$, with any obvious narrow absorption lines removed, was reflected about the peak forming a symmetric profile which was then subtracted to isolate N\textsc{v} and Si\textsc{ii}. Additional sources of error for this method are the depression of the Ly$\alpha$ blue wing by blended narrow absorption lines which can amount to $\sim$10 per cent of the total line flux in low-resolution data, the uncertainty in the peak position of Ly$\alpha$, particularly when the N\textsc{v} flux
is relatively high, and the use of a symmetric Lyα profile (generally true to within the margin of errors, Wilkes & Carswell 1982). The position about which the Lyα profile was reflected was adjusted to fit the core and extreme wings of the profile where N v contributes less flux. The method was not employed where the line profiles were clearly asymmetric or the N v flux too strong to allow a reasonable fit.

The results are displayed in Table 1 as follows: Column 1: coordinate designation of QSO (/2 indicates a radio-quiet object near the radio source found during the search for the optical identification of that source); column 2: mean redshift as determined from the peak positions of the unblended emission lines; column 3: references to the original papers reporting these data (additional references are given by WWJP and will not be repeated here); column 4: name and rest wavelength (Å) of emission line; column 5: observed peak wavelength (Å); column 6: Rest-frame FWHM in km s⁻¹; column 7: observed equivalent width (Å); column 8: relative flux; column 9: notes. The following coding has been utilized in the notes: OS = optically selected; SB = use of a synthetic blend to debend Lyα, N v (see above); BW = reflection of blue wing of Lyα; RC = fitting of continuum through the red wing. The flux (column 8) was measured relative to a reference line fixed arbitrarily at a flux of 100; C iv λ1549, Mg ii λ2798 or H β λ4861 were used where possible. Any notable peculiarities or measurement problems are given below for objects indicated by * in Table 1. It should be noted that, since the spectral resolution is generally 300–900 km s⁻¹ (see WWJP), any features having FWHM ≤ 1200 km s⁻¹ are at best marginally resolved.

4 Notes on individual objects

0022−422. N v peak appears redshifted due to absorption on the shortward side.
0008−264. The C iii] equivalent width is unusually high. An alternative redshift is 1.572 with C iv at 3984 Å.
0029−414. Mg ii is redshifted ~1800 km s⁻¹ relative to C iii].
0036−392. Hump at blue end is due to poor flux calibration.
0046−315. N v flux uncertain due to absorption.
0048−071. Lyα, N v, Si ii fluxes are inaccurate due to uncertain continuum shortward of this feature.
0049−393. This QSO is unusual in several respects. First, there is a strong broad absorption line shortward of C iv by ~300 Å and no corresponding absorption for the other emission lines. Secondly, He ii appears very strong and broad, probably due to blending with Fe ii emission (Gaskell 1981). Thirdly, the emission line peaks do not line up, the simplest interpretation being that strong N v [0.5′/L(Lyα)] has shifted the apparent peak of Lyα and that the O vi line is predominantly Lyβ. The spectrum also shows an absorption system at z = 2.792 containing N v, Si ii, C iv but no apparent Lyα lines. A spectrum was also presented by Whelan, Smith & Carswell (1979) who determine a redshift of 2.85 from Lyα, C iv.
0054−006. N v, Si ii fluxes uncertain due to absorption.
0150−334. This object has two possible redshifts: 0.610, in which case [Ne v] and [O ii] appear broader than normal; or 1.907, the features being C iv, C iii] and a third which is unidentified at 2060 Å rest wavelength.
0234−301. C iv is significantly blueshifted with respect to Lyα and is broader, suggesting that Lyα is more severely affected by absorption than it appears at this low resolution.
0254−334/R. C iv appears broader than Lyα and has a red asymmetry (unusual, see Young, Sargent & Boksenberg 1982, and Paper I), it may be due to Fe ii emission. N v is weak, <10 percent Lyα flux.
B. J. Wilkes

0254−334/2. This QSO, ∼1.2 arcmin from the radio source, has been classified as a broad absorption line object. The emission lines are difficult to measure at low resolution, values here are quoted for the emission longward of the absorption trough.

0329−255. N v is unusually strong, the peak position of Lyα was estimated by deblending the feature.

0414−189. Redshift revised since earlier reference, see WWJP.

0448−187. Only one clear line, identified as C iv because of suggestion of Lyα emission ∼3710 Å.

0537−441. BL Lac? See reference.

0537−286. A strong Lyman limit jump is present at a redshift of 2.984.

0723−008. The Hβλ4861 profile is broad and severely blended with [O iii]λ4959; no measurement was possible. There is also a strong, unidentified narrow peak ∼5000 km s⁻¹ shortward of Hβ; this may be a displaced narrow component as observed, e.g. in 3C227 (Osterbrock, Koski & Phillips 1976).

0748+126. Four lines are reported by Wills & Wills (1976) confirming this redshift.

0858−77. Lines are weak and hard to measure. [O iii] doublet is blended together and at end of scan.

1111+149. Wills & Wills (1976) report the same redshift based upon two lines.

1117−248. Mg ii, Hβ features possess a narrow component which is included in the profile measurements.

1146−037. Hβ is broad and blended with the [O iii] doublet, making profile measurements very uncertain.

1148−171: 1216 blend is on the end of the scan making measurements inaccurate.

1151−34. Hβ is too broad to measure.

1157+014. C iv is contaminated by two strong absorption features, flux and equivalent width estimates were not possible.

1158+007. Mg ii is redshifted ∼3000 km s⁻¹ relative to C iii], an unusually large shift.

1200−051. No [O iii]λ4959 is apparent.

1215+013. Lines very weak, may be galaxy.

1311−270. C iv line peak is blueshifted ∼800 km s⁻¹ relative to that of Lyα, this may be due to absorption in the red wing of C iv.

1327−214. With the exception of Mg ii, the lines are weak and noisy.

1336−000. Wills & Lynds (1978) report z=0.558 based upon one line only.

1355−41. Hβ and [O iii]λλ4959, 5007 are severely blended.

1427+109. Alternatively lines may be identified as Mg ii and [Ne v]λλ3426, yielding a redshift of 0.495.

1430−178. The continuum shortward of Lyα is highly uncertain. N v is weak or negligible. Night sky emission is present at 5577 Å.

1454−076. [Ne v]λλ3426 may be present at 5800 Å.

1502+106. This QSO has two possible redshifts, the second being 1.833 with the 4383 Å line identified as C iv (Smith et al. 1977). The Mg ii and Ne v identifications fit the measured wavelengths in this spectrum better than C iv and C iii]. However the higher redshift would identify the feature ∼3450 Å as Lyα rather than poor continuum calibration. (See also discussion by Wright et al. 1979c).

1542−042. N v is weak or negligible.

1614+051. N v is too weak to measure.

1618+177. Although only one line is reported here, this object has been heavily studied and the redshift is well known (e.g. Lynds, Stockton & Livingstone 1965).
1655 + 077. Also observed by Kuhr, Liebert & Strittmatter (1985, in preparation), who found no C\textsc{iv} line.

1743 + 173. Night sky emission is present at 5577 Å.

1942 - 571. Hβ emission is at the end of the scan, measurements are uncertain.

2044 - 168. The C\textsc{iv} profile is narrow and red asymmetric suggesting absorption in its blue wing. This is confirmed in high-resolution data (Paper I).

2112 - 407. Both C\textsc{iv} and Lyα have strong, possibly broad absorption in their blue wings. N\textsc{v}, Si\textsc{ii} fluxes are inaccurate.

2126 - 158. The peculiar shape of C\textsc{iv}, used as the prototype profile, and absorption in the blue wing of Ly\textalpha{} render measurements of N\textsc{v}, Si\textsc{ii} inaccurate. O\textsc{vi} is substantially blueshifted, suggesting a strong Ly\beta{} component, although the presence of absorption in the red wing may contribute to the shift. O\textsc{i}\λ{}1304 flux was not measured due to strong absorption.

2149 - 306. The irregular profile of C\textsc{iv} and absorption in the blue wing of Ly\textalpha{} cause uncertainty in N\textsc{v}, Si\textsc{ii} measurements. C\textsc{iv} appears to be blueshifted \(\sim\) 1400 km s\(^{-1}\) with respect to Ly\textalpha{}.

2153 - 209. Alternatively, the line at 4400 may be Mg\textsc{ii}, giving a redshift of 0.571.

2154 - 325. Alternatively, the line at 4355 may be Mg\textsc{ii}, giving a redshift of 0.556.

2158 - 214. The proximity of the 1216 blend to the short-wavelength end of the scan renders measurements of its components inaccurate.

2211 - 192. This redshift is highly uncertain due to weak, noisy lines.

2212 - 299. The sharp blue wing of Lyα suggests absorption, this is confirmed in high-resolution data (Paper I).

2245 - 328/R. C\textsc{iv} and 1400 Å are unusually strong and blueshifted with respect to the 1216 blend. Deblending was performed by assuming the peak was due to Ly\textalpha{}. However, an alternative interpretation is that the blend is predominantly N\textsc{v} emission.

2329 - 384. C\textsc{iv} is apparently redshifted. Since it was observed at a different date from the remainder of the spectrum, it is possible that the wavelength scales are not relatively correct.

5 Results

The full sample of 295 QSO candidates, presented in WWJP, includes 81 objects with no measurable emission lines. The majority of these have low-quality spectra, only 22 being strong BL Lac candidates. Active galaxies with weak or no emission lines may represent a large fraction of the class, but no quantitative statement concerning the fraction of BL Lac objects in an unbiased sample can be made until the objects in question are positively identified. It should be noted that, due to the non-uniformity of the spectral data across the sample, it is not complete down to any specific equivalent width or line flux limit.

Emission line strengths are of great importance both in comparing different samples of QSOs and in modelling the physical conditions of the emitting gas. In Table 2 the distribution of equivalent widths for the broad and narrow lines is detailed as follows: Column 1: name and rest wavelength (Å) of emission line; columns 2, 3, 4: mean equivalent width, standard deviation (Å) and the total number of objects used in the distribution; column 5: number of objects in which the line fell in the observed wavelength range but was undetected. This last number gives an indication of the effect on the distribution due to the ill-defined lower limit on detectable equivalent width of an emission line. In Table 3 the distributions of various line intensity ratios are listed: Column 1: line ratio; columns 2, 3, 4: total number of objects, mean and standard deviation for each intensity ratio; column 5: notes. The mean ratios are in general agreement with those of Baldwin (1975, 1979). No significant difference was found between the distributions of
Table 2. Distribution of rest-frame equivalent widths for prominent broad and narrow lines.

<table>
<thead>
<tr>
<th>Line</th>
<th>Parameters of Distribution</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$W_e/\AA$</td>
<td>$\sigma/\AA$</td>
</tr>
<tr>
<td>OVI $\lambda$1034</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>Ly$\alpha$ 1216</td>
<td>65</td>
<td>34</td>
</tr>
<tr>
<td>NV $\lambda$1240</td>
<td>19</td>
<td>9</td>
</tr>
<tr>
<td>SIII $\lambda$1264</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>OI $\lambda$1304</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>OIV$\lambda$/SiIV $\lambda$1400</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>CIV $\lambda$1549</td>
<td>32</td>
<td>20</td>
</tr>
<tr>
<td>HeII $\lambda$1640</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>CIII$\lambda$1909</td>
<td>17</td>
<td>12</td>
</tr>
<tr>
<td>CII $\lambda$2326</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>MgII $\lambda$2798</td>
<td>27</td>
<td>15</td>
</tr>
<tr>
<td>[NeV] $\lambda$3426</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>[OII] $\lambda$3727</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>[NeIII] $\lambda$3869</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>H$\beta$ $\lambda$4861</td>
<td>47</td>
<td>25</td>
</tr>
<tr>
<td>[OIII] $\lambda$5007</td>
<td>32</td>
<td>28</td>
</tr>
</tbody>
</table>

Table 3. Parameters for intensity ratio distributions of the prominent broad lines.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>n</th>
<th>$\bar{X}$</th>
<th>$\sigma$</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>I(OVI)/I(Ly$\alpha$)</td>
<td>11</td>
<td>0.18</td>
<td>0.11</td>
<td>Contaminated by absorption</td>
</tr>
<tr>
<td>I(NV)/I(Ly$\alpha$)</td>
<td>33</td>
<td>0.32</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>I(SIII)/I(Ly$\alpha$)</td>
<td>20</td>
<td>0.10</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>I(OI)/(CIV)</td>
<td>15</td>
<td>0.23</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>I(CII)/I(CIV)</td>
<td>5</td>
<td>0.07</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>I($\lambda$1400)/I(CIV)</td>
<td>41</td>
<td>0.25</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>I(CIV)/I(Ly$\alpha$)</td>
<td>39</td>
<td>0.36</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>I(CIII$\lambda$)/I(CIV)</td>
<td>62</td>
<td>0.40</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>I(MgII)/I(CIII)</td>
<td>42</td>
<td>0.89</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>I(H$\beta$)/I(MgII)</td>
<td>14</td>
<td>0.87</td>
<td>0.50</td>
<td>Problems due to blended [OIII] Lines</td>
</tr>
</tbody>
</table>

equivalent width or line intensity ratios of optically and radio-selected objects in this sample. The numbers quoted refer to all the available objects.

The number versus redshift distribution for the sample is displayed in Fig. 1. The strong peak at $z \sim 2$ found in objective prism surveys (Osmer & Smith 1980) is notably absent. There is a bias towards low-redshift, only three objects having $z > 3$, which is typical of radio-selected samples.
Figure 1. Number–redshift distribution of the sample [optically selected (OS) objects are unshaded].

(Smith 1982). The lack of high-redshift objects in radio-selected samples of QSOs was originally thought to be due to the additional UVX criterion often used to distinguish between multiple candidates for optical identification (e.g. Baldwin et al. 1973). However, subsequent analysis with this bias removed failed to increase the number of radio-selected high-redshift QSOs substantially (Smith et al. 1977; Baldwin, Wampler & Burbidge 1976). Studies of extragalactic radio sources based upon very accurate positions also show a lack of high-redshift objects implying a real turn-over in the comoving space density of radio-loud QSOs (Peacock & Wall 1981). There is not expected to be a significant bias due to UVX selection in the present sample. Colour was used initially to supplement the 10 arcsec accuracy of the Parkes radio positions but follow up NRAO radio observations with 2-arcsec accuracy were also made (Peterson et al. 1976; Savage & Wright 1981).

An important property of any QSO sample in terms of modelling the BELR is the observed distribution of linewidths (Osterbrock 1977). Potentially, this could serve to distinguish between disc-like and spherical geometries for the emitting gas. The FWHM distribution of C IV, believed to be the only uncontaminated broad line in this sample, is shown in Fig. 2. Its nature appears similar to that presented by Baldwin (1979), the mean is 4500 km s\(^{-1}\) but a tail extends to large widths. It should be noted that the selection effect against finding weak, broad lines may affect this distribution, but not substantially, since C IV is a prominent emission line.

Figure 2. Distribution of full-width-at-half-maximum for the C IV emission line (OS unshaded).
6 Line positions

6.1 Redshift of low-ionization lines

Gaskell (1982) first noted a mean apparent redshift of the O i λ 1304 emission lines in high-redshift QSOs of 560±120 km s⁻¹ with respect to C iv (the errors quoted here indicate the 1σ dispersion of the sample not the measurement error). This effect has been confirmed in high-resolution spectra of seven QSOs in Paper I, where a mean shift of 760±130 km s⁻¹, with respect to the mean laboratory wavelength of O i, 1303.5 Å, was reported. If the same rest wavelength were used as in Gaskell’s (1982) paper, i.e. 1304.36 Å, appropriate for optically thick gas, the shift reported in Paper I becomes 560 km s⁻¹, in excellent agreement with Gaskell’s result. In Table 4 the distribution of the mean shift in peak position of O i λ 1304 and C ii λ 1335 with respect to that of C iv are tabulated for this sample. Column 2: reference line; columns 3, 4, 5: the mean shift standard deviation and number of objects for the distribution; column 6: significance of mean shift in terms of σ/√n. These measurements were again made relative to the mean laboratory wavelength of O i and so should be compared to the higher value quoted above. The mean shift for O i is 1290±180 km s⁻¹, a factor of 1.7 higher than the earlier results. The two most discrepant O i profiles, those of 0819−032 and 1542+042, were omitted from this distribution to guard against misidentification. Their inclusion increases the mean shift to 1480±220 km s⁻¹. Taking into account the widths of the two distributions, the more conservative estimate of 1290±180 km s⁻¹ is 2.5σ higher than the earlier results. The small number of C ii lines detected in this sample yield a shift in good agreement with that of O i, where highly discrepant line positions were again omitted from the distribution. Thus, the present data provide further confirmation that a shift of the low-ionization lines with respect to C iv is present and indicates that there is a large dispersion in the magnitude of this shift.

One possible interpretation for shifts of this nature is incorrect identification of the features, the measured mean line positions indicating intrinsic wavelengths of 1309.8 Å and 1343.2 Å respectively. As discussed by Gaskell (1982), the most likely contender for such a misidentification of the O i feature is a Si ii doublet of mean wavelength 1307.66 Å. However, the weakness or absence of other associated Si ii lines such as λλ 1196, 1264, 1531, 1817 Å argue against such an identification (Gaskell 1982; Dumont & Mathez 1981; Jordan 1969). The data presented here support this conclusion, in particular, the mean ratio of O i λ 1304 to that of Si ii λ 1264 in the sample is 0.55±0.41, a factor of 2 higher than predicted if the 1304 feature were due purely to Si ii.

It has also been shown (Gaskell 1982) that Mg ii is redshifted by 565±100 km s⁻¹ relative to C iv. Its position relative to C iii] in this sample indicates a similar shift (600±90 km s⁻¹, see Table

<table>
<thead>
<tr>
<th>Line</th>
<th>Reference Line</th>
<th>Δν/kms⁻¹</th>
<th>σ/kms⁻¹</th>
<th>n</th>
<th>Signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>O i λ 1304</td>
<td>C iv</td>
<td>1290</td>
<td>800</td>
<td>19</td>
<td>7</td>
</tr>
<tr>
<td>C ii λ 1335</td>
<td>C iv</td>
<td>1320</td>
<td>1046</td>
<td>7</td>
<td>3.3</td>
</tr>
<tr>
<td>C iv λ 1549</td>
<td>C ii λ 1909</td>
<td>120</td>
<td>1200</td>
<td>65</td>
<td>0.5</td>
</tr>
<tr>
<td>Mg ii λ 2798</td>
<td>C ii λ</td>
<td>600</td>
<td>600</td>
<td>44</td>
<td>6.7</td>
</tr>
<tr>
<td>Mg ii λ 2798</td>
<td>[O ii]</td>
<td>-200</td>
<td>810</td>
<td>22</td>
<td>1</td>
</tr>
<tr>
<td>[O ii] λ 3727</td>
<td>[O ii] λ 5007</td>
<td>100</td>
<td>310</td>
<td>6</td>
<td>1.3</td>
</tr>
<tr>
<td>H i λ 4861</td>
<td>[O ii] λ 5007</td>
<td>220</td>
<td>730</td>
<td>23</td>
<td>1.5</td>
</tr>
</tbody>
</table>
4. The C\textsc{iii}] line was used as a reference line in this sample, since this increased the number of objects for which the position of Mg\textsc{ii} could be compared with that of the higher ionization lines. The presence of a small but insignificant shift between the C\textsc{iv} and C\textsc{iii}] lines suggests that the relative positions of C\textsc{iv} and Mg\textsc{ii} in this sample are \(~100\) km s\(^{-1}\) closer than Mg\textsc{ii} and C\textsc{iii}]. In either case the shifts are in excellent agreement with Gaskell's initial value. In the case of Mg\textsc{ii}, the identity of the feature is not seriously in question, and the only alternative interpretation to a real velocity shift is that the apparent line peak is shifted due to blending with Fe\textsc{ii} emission in the wings. Since Fe\textsc{ii} emission is present in both wings and is substantially weaker than Mg\textsc{ii}, this is unlikely (Gaskell 1982).

Assuming that the velocity shifts are real, we are immediately led to the question of which (if any) of the emission lines indicate the true redshift of the QSO (assuming the redshift is mainly cosmological). The relative positions, of Mg\textsc{ii}, [O\textsc{ii}]\(\lambda 3727\), [O\textsc{iii}]\(\lambda 5007\) and H\(\beta\) were investigated for this sample. These results are also given in Table 4 and show that within the margin of errors, all these lines are at rest with respect to one another. In Seyferts and a few low-redshift QSOs it has occasionally been possible to measure the redshift of the underlying galaxy (Heckman et al. 1981); results so far indicate that the narrow lines are within \(~100\) km s\(^{-1}\) of the system velocity although systematically blueshifted by a small amount. Assuming that low- and high-redshift QSOs behave alike in this respect, the lack of significant shifts between Mg\textsc{ii} and the forbidden lines implies that Mg\textsc{ii} also indicates the 'true' redshift of the system. This in turn leads to the conclusion that the high-ionization lines are blueshifted by \(~600\) km s\(^{-1}\) with respect to the systemic velocity of the QSO (as discussed by Gaskell 1982). The larger velocity shift of O\textsc{i}\(\lambda 1304\) and C\textsc{ii}\(\lambda 1335\) for the present sample implies that these lines may be redshifted with respect to the systemic velocity by a comparable amount.

The assumption that QSOs are alike at low and high redshift is drastic but necessary, particularly since there are no narrow lines in the visible region for high-redshift QSOs to use for confirmation of the relative line positions. To the best of my knowledge, there are no accurate measurements of the relative positions of O\textsc{i}, C\textsc{iv}, Mg\textsc{ii} in the same QSO to confirm or negate the assumption. The large data bank of \textit{IUE} observations is not useful in this case due to uncertainty in the zero-point of the wavelength scale which is generally 'overcome' by assuming the UV lines are at the same redshift as the optical.

Study of the relative profiles of emission lines from atoms in very different ionization states leads to information of the ionization equilibrium of the emitting gas as a function of velocity in the BELR. Subsequent modelling of gas velocity as a function of radius leads to spatial resolution which can be obtained in no other way. It is clear that shifts such as those reported above provide invaluable constraints on models. Possible interpretation in terms of radial motion and some form of obscuration has been discussed (Gaskell 1982; Wilkes & Carswell 1982, Paper I); extending these ideas to explain shifts in both directions, if the above results are confirmed, will complicate the situation considerably.

6.2 Ly\(\alpha\)

Observers have often remarked on the slightly higher redshift of the Ly\(\alpha\) over C\textsc{iv} emission lines. This effect has generally been attributed to a combination of blending with N\textsc{v} in the red wing and absorption in the blue wing. Gaskell (1982) investigated the shifts for a sample of published measurements and found a mean of \(400\pm100\) km s\(^{-1}\). In the sample presented here a similar mean shift is present, \(350\pm120\) km s\(^{-1}\), giving an effective rest wavelength for Ly\(\alpha\) of 1217.1 Å, assuming C\textsc{iv} to be at 1549.1 Å.

The velocity separation of Ly\(\alpha\) and N\textsc{v} is \(\sim6000\) km s\(^{-1}\), comparable with the velocity widths of the emission lines (mean \(\sim4500\) km s\(^{-1}\)). One would expect that the apparent peak wavelengths
Figure 3. Predicted shift of the \( \text{Ly}\alpha \) peak as a function of FWHM of the component lines for different strengths of \( \text{N}\,\lambda \) relative to \( \text{Ly}\alpha \).

of the two lines would be shifted once the lines become severely blended, i.e. for broader lines and stronger \( \text{N}\,\lambda \) flux. It is possible to make some prediction of the expected shift, as a function of \( \text{N}\,\lambda \) strength and the FWHM of both lines, by synthesizing such a blend. In this procedure the \( \text{Ly}\alpha \) and \( \text{N}\,\lambda \) profiles were assumed to be identical and a ‘typical’, observed, high-resolution (1.5 Å) \( \text{C}\,\lambda \) profile was used as a prototype for both. A synthetic blend was generated by summing two prototype profiles with a specified FWHM and relative strength, positioned at the rest wavelengths of \( \text{Ly}\alpha \) and \( \text{N}\,\lambda \) respectively (see Wilkes & Carswell 1982). The position of the \( \text{Ly}\alpha \) peak in the synthetic blend was then studied as a function of the FWHM and the relative strengths of the two lines. The results are displayed in Fig. 3 where the \( \text{Ly}\alpha \) peak shift (in velocity units) is plotted as a function of FWHM for specified \( \text{N}\,\lambda \) to \( \text{Ly}\alpha \) flux ratio as labelled. Clearly, no shift is predicted for FWHM <4000 km s\(^{-1}\) while for FWHM >6000 km s\(^{-1}\) a shift is expected for any blend having an \( \text{N}\,\lambda \) strength above the mean (30 per cent x \( \text{Ly}\alpha \), Table 3).

Table 5. Parameters describing the distribution of velocity shift of the \( \text{Ly}\alpha \) emission line peak relative to \( \text{C}\,\lambda \) for FWHM \( \geq 5000 \text{ km s}^{-1} \) and for \( I(\text{N}\,\lambda)/I(\text{Ly}\alpha ) \geq 0.3 \).

<table>
<thead>
<tr>
<th>Subset</th>
<th>( \Delta v ) ( \text{Ly}\alpha ) / km s(^{-1})</th>
<th>( \Delta v ) ( \text{C},\lambda ) / km s(^{-1})</th>
<th>( \sigma ) / km s(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>195</td>
<td>26</td>
<td>109</td>
</tr>
<tr>
<td>B</td>
<td>572</td>
<td>18</td>
<td>250</td>
</tr>
<tr>
<td>W</td>
<td>145</td>
<td>12</td>
<td>101</td>
</tr>
<tr>
<td>S</td>
<td>532</td>
<td>22</td>
<td>185</td>
</tr>
<tr>
<td>N+W</td>
<td>70</td>
<td>8</td>
<td>117</td>
</tr>
<tr>
<td>N+S/B+W</td>
<td>357</td>
<td>16</td>
<td>139</td>
</tr>
<tr>
<td>B+S</td>
<td>717</td>
<td>10</td>
<td>350</td>
</tr>
</tbody>
</table>

key: \( N = \Delta v \leq 5000 \text{ km s}^{-1} \)
\( B = \Delta v > 5000 \text{ km s}^{-1} \)
\( W = NV/Ly\alpha < 0.3 \)
\( S = NV/Ly\alpha \geq 0.3 \)
To determine whether such an effect is occurring in the present dataset, the velocity of the Lyα profile with respect to that of C iv was studied as a function of FWHM and the relative strengths of N v and Lyα as follows: First, the sample was divided into two subsets according to FWHM (C iv) \( \leq 5000 \text{ km s}^{-1} \). Secondly, it was divided according to \( I(N v)/I(Ly\alpha) \geq 0.3 \). The parameters for the relative velocity distributions are given in Table 5 for all subsets. Clearly, a larger shift is observed, on average, for broader lines and strong N v, as expected from the above discussion. A highly significant difference is not expected: first, since the subsets describe two halves of a continuous distribution; and secondly, two effects are involved and they do not necessarily reinforce one another. The sample was divided further to distinguish those objects where both effects are reinforcing one another. The results are again shown in Table 5 and show the velocity shift increasing from 70 km s\(^{-1}\), where the profiles are narrow and N v is weak, to 717 km s\(^{-1}\), where they are broad and N v strong.

The large scatter inherent in the data precludes quantitative confirmation that N v blending is the dominant cause of the velocity shifts observed between the Lyα and C iv line peaks. However, the similarity between the predicted trends and those observed on the average in this dataset implies that the shifts can be explained in this way, i.e. there is no intrinsic difference in the velocities of the two lines.

6.3 C\( \text{\textsc{iii}} \)\( \lambda \)1909

This profile is believed to be blended in its blue wing with some combination of Si\( \text{\textsc{iii}} \)\( \lambda \)1892, Al\( \text{\textsc{iii}} \)\( \lambda \)1858 and Fe\( \text{\textsc{ii}} \)\( \lambda \)1860 (Paper I, Gaskell, Shields & Wampler 1981; Wills, Netzer & Wills 1980). The S/N and resolution of the spectra in the sample are not high enough to detect this feature in individual cases (as in Paper I); however, cumulative evidence may be obtained from studying the distribution of FWHM and peak wavelength for the C\( \text{\textsc{iii}} \) profile. The FWHM distribution is shown in Fig. 4. It is broader than those of other unblended lines and has a mean of \( \sim 5800 \text{ km s}^{-1} \), significantly larger than that of C iv (Fig. 2) at 99.4 per cent significance. Since both C iv and C\( \text{\textsc{iii}} \) emission originate in similar areas of the BELR (Kwan & Krolik 1981) it is unlikely that their velocity dispersion (and hence their line profiles) should be intrinsically so discrepant. This implies contamination of the C\( \text{\textsc{iii}} \) profile in one or both of its wings, confirming earlier results, but at a level insufficient to cause a shift in the peak wavelength, whose mean with respect to C iv in this sample is 1908.7 Å, in exact agreement with the laboratory wavelength.

The position of C\( \text{\textsc{iii}} \) has been reported to vary from object to object. Wills (1980) presented evidence from a large sample of 189 QSOs for a correlation between the peak wavelength of C\( \text{\textsc{iii}} \) measured with respect to C iv and the mean redshift of the QSO. In particular he found that

![Figure 4. Distribution in FWHM of C\( \text{\textsc{iii}} \) across the sample (OS unshaded).](image-url)
objects with \( z > 1.8 \) have a higher effective wavelength than those with \( z < 1.8 \) by 2.5 Å, a difference significant at the 4\( \sigma \) level. The mean effective wavelength for the objects in Wills’ sample is 1908.25 ± 0.28 Å, 2\( \sigma \) shortward of the laboratory mean. In contrast that of the present sample (60 objects) has a mean in exact agreement with the laboratory wavelength (see above).

To test for the Wills effect in this sample, the effective wavelength of C\( \text{m} \) with respect to C\( \text{iv} \) is plotted as a function of mean redshift (Fig. 5). No correlation is apparent, the linear correlation coefficient for the data is 0.13 (30 percent chance of random occurrence). Division of the sample into two subsets for \( z \gtrsim 1.8 \), following Wills’ method, yields no significant difference in their mean effective wavelength. This data sample does not display the same dependence between effective wavelength and redshift as that of Wills (1980). This is particularly surprising, since there is probably some overlap between the AAT data in Wills’ sample, which gave a 2.4\( \sigma \) result, and those used here.

![Figure 5](image.png)

**Figure 5.** The effective wavelength of C\( \text{m} \) (in Å) measured with respect to C\( \text{iv} \) as a function of mean redshift.

6.4 1400Å BLEND

This feature was originally identified with the doublet Si\( \text{iv}\lambda 1397 \). However, since the mean wavelength of the quintet O\( \text{iv}\lambda 1402 \) was revised from 1407 Å based on laboratory measurements by Bromander (1969), both features have been believed to contribute and their relative strengths have been the subject of some discussion. The distribution of published wavelengths was studied by Wills & Netzer (1979), who quote a mean wavelength of 1401.2 ± 0.6 Å, implying that O\( \text{iv} \) is the main contributor to the blend, while Young et al. (1982) find 1399.68 ± 0.43 Å and Gaskell et al. (1981) 1399.8 ± 0.5 Å, both implying roughly equal contributions from the two lines.

In this sample, the distribution of effective wavelength for the feature with respect to the mean redshift (computed without including the position of this blend) yields a mean wavelength of 1400.6 ± 7 Å, in good agreement with the values mentioned above. This result indicates a mean intensity ratio of \( I(\text{O}\text{iv}) : I(\text{Si}\text{iv}) \sim 2:1 \).
6.5 \textit{O \textsc{vi}} \lambda 1034/Ly\beta \lambda 1025

This feature is buried in the Ly\alpha forest of absorption lines and, even at high-resolution, the shape of the emission line is often unclear. Its identity was originally believed to be O \textit{vi} on theoretical grounds (Netzer 1976), although photoionization models had trouble reproducing its strength \([0.2 \times I(\text{Ly}\alpha)]\). However, more recent photoionization models predict the presence of Ly\beta (Kwan & Krolik 1981) and, in addition, observational evidence for its presence in a number of spectra has been reported. The high-resolution studies in Paper I implied the presence of Ly\beta in two of the three profiles studied. These results are based upon debending the observed profile using that of C \textit{iv} in the same object as a prototype. In addition, Green \textit{et al.} (1980) make the same suggestion based upon the observed wavelength of the feature in five \textit{IUE} spectra of low-redshift QSOs.

In this sample, the effective wavelength varies considerably from object to object (e.g. 1022.5 Å for 2126–158; 1035.3 Å for 0002–422). The mean for the 12 lines in the sample is 1031.5 ± 1.2 Å, 3σ shortward of the laboratory mean wavelength of the doublet (1034.8 Å). If the highly discrepant position in 2126–158 is omitted, this mean increases to 1032.5 ± 0.9 Å, still 2.6σ shortward. Although the result is not highly significant for this data set alone, it contributes to the mounting evidence that Ly\beta contaminates the O \textit{vi} emission line profile in a number of QSOs.

7 Conclusions

Emission line parameters for 214 radio-selected QSOs, covering a wide redshift range, have been presented. Preliminary studies of the sample, including FWHM and relative intensity distributions for the broad lines and equivalent width distributions for both broad and narrow lines, have been made.

The broad emission lines were studied in more detail and the following results obtained:

(i) Mg \textit{ii} \lambda 2798 is redshifted \(~600 \text{ km s}^{-1}\) relative to the high-ionization lines in intermediate-redshift QSOs while it is at rest with respect to (wrt) the forbidden lines in low-redshift QSOs; this confirms earlier results (Gaskell 1982; Wilkes & Carswell 1982, Paper I).

(ii) O \textit{i} \lambda 1304, C \textit{iii} \lambda 1335 are redshifted 1290, 1320 km s\(^{-1}\) respectively wrt the high-ionization lines and Ly\alpha in high-redshift QSOs, larger than shifts reported previously.

(iii) The mean redshift of Ly\gamma wrt C \textit{iv} by \(~350 \text{ km s}^{-1}\) in this sample is believed to be due to the combined effect of blending with N \textit{v} in the red wing and Ly\alpha forest absorption lines in the blue.

(iv) The dependence of the C \textit{iii}] line position upon redshift (Wills 1980) was not confirmed in this much smaller sample.

(v) The FWHM distribution of C \textit{iii}] has a larger mean and standard deviation than those of uncontaminated emission lines; this is consistent with the presence of blended features.

(vi) The mean effective wavelength for the 1400 Å feature is consistent with previous results and implies a ratio \(I(\text{O iv})/I(\text{Si iv})\) of 2.

(vii) The mean position of the O \textit{vi} \lambda 1034 feature implies contamination by Ly\beta \lambda 1025 in a number of objects, confirming earlier reports (Paper I, Green \textit{et al.} 1980).

Acknowledgments

I thank my collaborators in Australia: Drs A. E. Wright, D. L. Jauncey and B. A. Peterson for allowing me to further analyse the data presented in WWJP. I am greatly indebted to my thesis adviser, Dr R. F. Carswell for his continual help and guidance during the course of this research, to Drs R. J. Rudy and D. M. Whittle for enlightening discussion and the referee for his attention to detail. I also thank Linda Forbes and Helen Bluestein for their typing expertise. It is a pleasure
to thank the Director and staff of Steward Observatory for their hospitality during my stay there and to acknowledge the UK Science and Engineering Research Council for financial support on a NATO postdoctoral research fellowship.

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