THE ASTROPHYSICAL JOURNAL, Vol. 153, August 1968

A SYSTEMATIC METHOD FOR IDENTIFYING ABSORPTION LINES AS APPLIED TO PKS 0237−23*

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Received May 20, 1968

ABSTRACT

A systematic method for identifying the absorption lines in quasi-stellar sources with rich absorption spectra is described, and the lines that are expected on theoretical grounds to have the highest probability of appearing in absorption in quasi-stellar sources are listed. The computational scheme that was developed for recognizing and analyzing candidate redshifts is then described; this computational scheme is supplemented by a set of rules used to determine if a candidate redshift is acceptable The computational scheme and formal rules were applied to a set of nonsense spectra, i.e , random-number spectra, with the same main characteristics as the absorption spectrum of PKS 0237−23 determined by Greenstein and Sargent The average number of acceptable redshifts per nonsense spectrum was 0.7. Five acceptable redshifts were found in the real spectrum: z = 2 2015, 1.671, 1 656, 1.513, and 1.364 No acceptable redshift was found at z = 1 95. A list of additional lines that should be detectable if the identifications proposed here are correct is given for slightly longer and shorter wavelengths than covered in the observations of Greenstein and Sargent Some characteristics of the identifications are also described.

I. INTRODUCTION

We describe a systematic method for identifying the absorption lines in quasi-stellar sources with rich absorption spectra. An essential and novel feature of our method is that a quasi-statistical test of the significance of the identifications is provided. The method was developed primarily in connection with the reinvestigation of the absorption spectrum of PKS 0237−23 by Greenstein and Sargent (Bahcall, Greenstein, and Sargent 1968; earlier observational work on this object which has an emission redshift of 2.223 is described by Arp, Bolton, and Kinman 1967; Burbidge 1967; and Greenstein and Schmidt 1967).

We have attempted to determine if the absorption spectrum of PKS 0237−23 can be understood as the superposition of absorption lines at several different redshifts. We required of our solution that the identified lines correspond to transitions that are theoretically expected to be strongest, in absorption, in a low-density plasma with element abundances not too different from typical galactic abundances. We have also estimated the likelihood that our identifications could arise by chance.

A crucial element in our analysis is the choice of standard lines which are considered most likely to appear in absorption. The chosen standard lines and the criteria used in determining them are given in § II. The number of redshifts required to explain the observed spectrum, the numerical values of the individual redshifts, and the standard lines that would actually appear in the observed spectrum were all unknowns. No significant progress could be made until an efficient computational scheme was developed for recognizing and analyzing candidate redshifts; this scheme is described in § III. Many chance coincidences occur between the standard and the observed lines in the physical spectrum when the theoretical absorption redshift is allowed to vary over large ranges. It was therefore necessary to obtain a quantitative estimate of the likelihood that an acceptable set of identifications could arise by chance. We first formalized the rules for

* Supported in part by the National Science Foundation (GP-7976, formerly GP-5391) and the Office of Naval Research [Nonr-220(47)].

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an acceptable absorption redshift in the real spectrum; these rules are given in § IV. We then applied our computational procedures and formal rules to the analysis of random-number spectra that had some of the main characteristics of the observed spectral lines, i.e., the same number of lines, relative strengths, and minimum spacing. Our results for the analysis of nonsense (i.e., random-number) spectra are given in § V. The average number of acceptable redshifts per nonsense spectrum was 0.7.

The investigation of the observed spectrum, described in § VI, yielded five acceptable redshifts, $z = 2.2015$, 1.671, 1.656, 1.513, and 1.364, which explain almost all of the observed strong lines. The total number of identified lines is twenty-eight. No acceptable redshift was found at 1.95. We include in § VI a prediction of further lines which should be detectable with additional observations if the identifications proposed here are correct. The characteristic properties of the identifications are also described in this section.

In the accompanying paper (Bahcall, Greenstein, and Sargent 1968), the observations of Greenstein and Sargent on the absorption spectrum of PKS 0237−23 are described and various possibilities are discussed for the physical location of the absorbing material.

II. THE STANDARD LINES

We have compiled a list of standard lines that might be expected to appear in absorption in the spectra of quasi-stellar sources. The criteria used in compiling these lines are (cf. Bahcall and Salpeter 1966): (1) only allowed, one-electron electric dipole transitions with wavelengths between 940 and 3300 Å are included; (2) only transitions from states that can be expected to be appreciably populated at densities less than or of the order of 10^7 cm^{-3} are considered (in practice this means only ground states, their associated excited fine-structure states, and the metastable $1s2s\ ^3S_1$ state of He I); and (3) only the elements with relatively high galactic abundances are included. We have included relatively few of the many lines that arise from ions with ionization potentials less than hydrogen, since no consistent evidence for these many candidate lines has appeared in previously studied absorption spectra of quasi-stellar sources (nor in our preliminary analysis of PKS 0237−23). Moreover, the previously analyzed absorption spectra of quasi-stellar sources usually contain lines arising from such highly ionized atoms as Si III, Si IV, and C IV.

In Table 1 we present a list of thirty-eight lines that satisfy the above criteria and are expected, on the basis of galactic abundances, f-values, and previous analyses of spectra in quasi-stellar sources, to have the highest a priori probability of appearing in the spectra of quasi-stellar sources. The correlation between the observed spectrum and the standard lines used in the search for redshifts will, of course, be highest when the standard list contains only lines that appear in the observed spectrum. For most of the cases in which two or more lines in Table 1 arise from the same ion, the expected relative strengths of the transitions have been estimated and are given in parentheses adjacent to the relevant wavelengths. This method of indicating relative strengths will be followed throughout the present paper. Most of the strengths were calculated using LS coupling or were taken from the compilations of Wiese, Smith, and Glennon (1966). Unfortunately, no reliable theoretical or experimental strengths are available for the Fe II lines. The relative strengths of the important Si II multiplets are also not well known (Wiese 1968)), although fairly accurate estimates of the relative strengths within a given multiplet of Si II can be made theoretically.

In Table 2 we present a more extensive list of allowed absorption lines that, because they were expected to be less strong, were considered as possible candidates for identifications but were not included in our primary search list of standard lines. A majority of the ions whose lines are listed in Table 2 are represented by more than one line. However, for most of these cases, the relative strengths of the various lines are not well known.

III. METHOD OF ANALYSIS

The observed and the random-number spectra were both analyzed in the following way. A matrix was constructed, with the aid of a computer, which had the following elements:

$$z_{ij} = [\lambda_{\rm obs}(i)/\lambda_{\rm std}(j)] - 1 , \qquad (1)$$

where the observed wavelengths are denoted by $\lambda_{\rm obs}(i)$, $i = 1, \ldots, N_{\rm observed}$ and the standard wavelengths by $\lambda_{\rm std}(j)$, $j = 1, \ldots, N_{\rm standard}$. Two distinct and complete investigations were carried out. In the first investigation, $N_{\rm obs}$ was equal to 45; in the second, the four lines λλ3789.3, 3924.5, 4077.6, and 4082.4 were added by Greenstein and Sargent to the list of observed lines, making $N_{\rm obs}$ equal to 49. The list of standard lines included,

TABLE 1

LINES MOST LIKELY TO SUCCEED

Ion	$\lambda_{\rm laboratory}$ (Å)	Ion	$\lambda_{\rm laboratory}$ (Å)
H I (0 1)	949 74	C II (1 uv)	1335 3
H I (0 2) .	972.54	Si IV (2)	1393 76
C III . . .	977 03	Si IV (1)	1402 77
Si II (0.15) .	989 87	Si II (0.15)	1526 72
Si II* (0 3)	992 68	Si II* (0 3)	1533 45
H I (0 5)	1025 72	C IV (2)	1548 20
O VI (2)	1031 95	C IV (1)	1550 77
O VI (1)	1037 63	Al II .	1670 81
N II (1 uv)	1085 10	Al III (2)	1854 72
Fe III	1122 53	Al III (1)	1862 78
Fe II .	1144 95	Fe II	2344 2
Si II (0.6).	1193 28	Fe II	2374 5
Si II* (1 4)	1194 50	Fe II	2382 8
Si III. .	1206 51	Fe II	2586 7
H I (3.3)	1215 67	Fe II .	2600 2
N V (2)	1238 81	Mg II (2)	2795 50
N V (1)	1242 80	Mg II (1)	2802 70
Si II (1).	1260 42	He I (0 7)	3187 74
Si II* (2)	1264 76	He I (2 5)	3888 65

NOTE —The expected relative strengths of the lines are indicated in parentheses; they were computed neglecting saturation and assuming that the populations of the various fine-structure states are the same as the populations at infinite density An asterisk is placed next to the ion label for lines arising from excited fine-structure states The multiplet number (uv) is given for lines which represent the weighted average wavelengths for transitions arising on both ground and excited fine-structure states

in the first study, all the lines in Table 1 plus the oxygen, sulfur, and chlorine lines in Table 2 and the Si II lines λλ1817, 1807, 1309, and 1304 Å. These four Si II lines have theoretical absorption strengths that are less than the strength of Si II lines listed in Table 1 (Wiese 1968). In the second investigation, only the lines appearing in Table 1 were used in the standard spectrum. The computer printed out the entire observed-standard matrix. In addition, it also tabulated the number of z_{ij}'s (i.e., identifications) that lay within $\pm\epsilon$ of each z; the tabulation was carried out in steps of δ from a maximum z, $z_{\rm max}$, to a minimum z, $z_{\rm min}$. The following parameters were used, respectively, for the two investigations: tolerance $\epsilon = 1 \times 10^{-2}$, 1.15×10^{-2}; step size $\delta = 1 \times 10^{-3}$, 5×10^{-4}; $z_{\rm max} = 4.0$, 2.5, and $z_{\rm min} = 1 \times 10^{-3}$, 1×10^{-3}. The computer also printed a distinguishing mark, a star, next to each z for which the number of identifications was greater than or equal to some minimum value. This minimum value was six for the first investigation and five for the second investigation.

TABLE 2

SOME OTHER ALLOWED ABSORPTION LINES

The notation is the same as in Table 1.

Ion	$\lambda_{laboratory}$ (A°)	Ion	$\lambda_{laboratory}$ (A°)
Si II (1)	989.9	Ge II*	1261.9
Si II* (2)	992.7	As II	1263.8
S III (1)	1012.5	Ti III	1291.6
S III* (3)	1015.6	Ti III	1298.7
Si II (1)	1020.7	O I (5)	1302.2
S III* (5)	1021.3	Si II (1)	1304.4
Si II* (2)	1023.7	O I* (3)	1304.9
C II (2 uv)	1036.8	O I* (1)	1306.0
A I (4)	1048.2	Si II* (2)	1309.3
S IV (1)	1062.7	Ni II	1317.4
Cl II (1)	1063.8	C I (4 uv)	1329.3
A I (1)	1066.7	C II (1)	1334.5
Cl II (3)	1071.0	C II* (2)	1335.7
S IV* (2)	1073.0	As II	1356.0
N II (1)	1084.0	Cu II	1358.8
N II* (3)	1084.6	Ni II	1370.2
N II* (5)	1085.7	S I	1388.4
Ge III	1088.5	S I	1425.1
V III	1123.6	Ni II	1455.0
Fe III*	1124.9	S I	1474.0
V III*	1125.7	Ge II	1538.1
Fe III*	1128.7	C I (3 uv)	1561.0
N I (2 uv)	1134.6	Ge II*	1576.9
Fe II*	1148.3	Sc III	1598.1
Fe II*	1151.2	Ge II	1602.5
V III	1153.2	Sc III*	1603.1
V III*	1159.8	Sc III	1610.3
Mn II (4 uv)	1163.0	Ge II*	1649.2
V III	1169.3	Ca II (2)	1650.0
S III (1)	1190.2	Ca II (1)	1652.0
S III* (3)	1194.1	C I (2 uv)	1657.2
N I (1 uv)	1199.9	S I	1807.3
S III* (5)	1201.1	Si II (1)	1808.0
As III	1209.3	Si II* (2)	1817.4
Ge II	1237.1	He I (0.2)	2829.1
S II (1)	1250.5	He I (0.3)	2945.1
S II (2)	1253.8	Ca II (2)	3933.7
S II (3)	1259.5	Ca II (1)	3968.5

The starred redshifts were then analyzed with the aid of a second computer program. This second program printed out in a convenient form the observed wavelengths and their strengths, the observed wavelengths divided by $1 + z$, the identifications based on the line lists of Tables 1 and 2, and the predicted wavelengths, assuming a redshift z, for each of the standard lines. Each starred redshift was then analyzed to see if it satisfied a list of six formal rules (see § IV) that were formulated in advance and were considered necessary for acceptance as a physical redshift.

In order to investigate the possibility that the identifications found in this manner were due to accidental coincidences, we constructed and analyzed a series of nonsense spectra that had the same characteristic features as the lines in the observed spectrum. In particular, each of the nonsense spectra contained N_{obs} lines between 3300 and 4700 Å, with the same number of lines having strengths 5, 4, 3, etc., as in the observed spectrum. The strengths were distributed randomly among the various nonsense lines. In the first investigations, five nonsense spectra were constructed by choosing random numbers for each $\lambda_{\text{nonsense}}(i)$, $i = 1, \ldots, 45$, except for the values of i for which, in the sequentially ordered observed spectrum, $\lambda_{\text{obs}}(i + 1) - \lambda_{\text{obs}}(i) \leq 10$ Å. In order to simulate the series of closely spaced lines that exist in the observed spectrum, the first member of a closely spaced series ($\Delta\lambda \leq 10$ Å) was chosen from a random-number table; the $\lambda_{\text{nonsense}}(i)$'s for the longer-wavelength members of the series were then calculated by requiring that $\lambda_{\text{nonsense}}(i + 1) - \lambda_{\text{nonsense}}(i) = \lambda_{\text{obs}}(i + 1) - \lambda_{\text{obs}}(i)$. Twenty-five lines, comprising nine closely spaced series, were coupled by this procedure.

In the second investigation, the process of generating closely spaced series was dropped. Instead, the minimum spacing between two successive nonsense wavelengths was required to be greater than or equal to 3 Å, the average resolution (Greenstein and Sargent 1968) in the observed spectrum.

IV. DEFINITION OF AN ACCEPTABLE REDSHIFT

A redshift z was considered a candidate for acceptance if it appeared starred in the observed-standard matrix, i.e., if the number of identifications was at least six or five, respectively, in the two investigations. The rules for accepting or rejecting candidate redshifts were codified in order that they could be rapidly and uniformly applied to the analysis of both the observed and nonsense spectra. The choice of rules was guided by a priori astrophysical expectations and an investigation of the accuracy with which wavelengths of the absorption lines could be measured (Greenstein and Sargent 1968).

The first problem was to define an acceptable identification of an individual spectral line or a group of related spectral lines. We required, in fixing the permissible wavelength discrepancy, that

$$|\lambda_{\text{obs}}(i) - (1 + z)\lambda_{\text{std}}(j)| \leq 2.0 \text{ Å}$$

in order that $\lambda_{\text{obs}}(i)$ be identified with $\lambda_{\text{std}}(j)$ at a redshift z. We also required that a consistent pattern exist for the relative intensities of transitions originating on ground and on excited fine-structure states. Thus it was not acceptable to have Si II(2) λ1193.3 and Si II*(2) λ1264.8 present and Si II*(5) λ1194.5 and Si II(1) λ1260.4 absent. We also rejected identifications in which the weaker component of a doublet was assigned a strength much greater than the strong member of the doublet. In particular, we rejected identifications in which at least one of the lines was of strength 3 or greater and the observed ratio of strengths differed by a factor of 4 or more from the predicted ratio. If both lines were of strength 1 or 2, their relative strengths were considered unreliable and no relative-intensity requirement was imposed. Our wide latitude in the intensity requirement was necessary because only visual estimates of the relative strengths were available when the theoretical analysis was carried out. An example of an identification that would be rejected on the basis of relative intensities is C IV(2) λ1548.2, corresponding to a strength-2 line, and C IV(1) λ1550.8, corresponding to a strength-4 line.

Two further definitions are required. A standard line, $\lambda_{std}(j)$, was considered to be in the "accessible" part of the spectrum for a given redshift z if $(1 + z)\ \lambda_{std}(j)$ lay between 3300 and 4700 Å, the observed part of the spectrum. A "strong line" was considered to be one with a visual strength greater than or equal to 3.

The following six criteria, or rules, were required to be satisfied in order that a candidate redshift be accepted: (1) Ly-α must be present if accessible; (2) there must be at least two identified strong lines; (3) if Si III is accessible but not identified, then Ly-α must be a strong line. Moreover, either Si II $\lambda\lambda$1193.3 and 1260.4 or C II λ1335.3 or Si IV $\lambda\lambda$1393.8 and 1402.8 and N V $\lambda\lambda$1238.8 and 1242.8 must be present. If either Si II or C II is present, then Si IV and N V cannot be considered present, and vice versa. (4) At least 50 per cent of the standard lines that originate on ground fine-structure states and are accessible at the candidate redshift must be identified; (5) if the Mg II doublet $\lambda\lambda$2795.5 and 2802.7 is accessible, then at least the stronger component, 2795.5, must be an identified strong line; and (6) the total number of identifications must be at least four.

The above-stated rules were designed to be sufficiently restrictive that identifications based on chance coincidences would not lead to accepted, but unphysical, redshifts. They are, in fact, sufficiently severe that they may exclude some physical redshifts. Our main purpose, however, was to try to make identifications in a way in which one could be confident that they were not accidental, instead of trying to identify every line. The rules purposely discriminate against redshifts containing primarily weak lines, since the existence, wavelength determinations, and strengths of weak lines are less reliable than for strong lines. Hence an identification procedure in which the weaker lines are not discriminated against would be expected to contain a higher percentage of accidental coincidences than an identification procedure which emphasizes the stronger lines.

V. RESULTS FOR THE NONSENSE SPECTRA

In the first set of investigations, five nonsense spectra were analyzed in the manner described in §§ III and IV. Two acceptable redshifts were found, one in each of two spectra. The total number of identified lines was equal to ten lines out of the 225 examined in the five spectra, for an average of two identified lines per spectrum.

In the second set of investigations, ten nonsense spectra were analyzed. In the ten spectra examined, four had no acceptable redshifts, five had one acceptable redshift, and one had two acceptable redshifts. This amounts to 0.7 acceptable redshifts per nonsense spectrum. The total number of identified lines was equal to thirty-four lines out of the 490 lines examined, for an average of 3.4 identified lines per spectrum. The acceptable redshifts obtained in this investigation were, with the number of identified lines in parentheses, 1.701(6), 1.458(5); 1.704(5), 1.322(4), 1.288(5), 0.884(4), and 0.586(5). The lines identified in the successful candidate redshifts are shown in Table 3.

VI. RESULTS FOR THE OBSERVED SPECTRUM

a) *The Acceptable Redshifts*

In the first investigation of the real spectrum, four redshifts were found which satisfied the criteria of § IV. They are $z = 2.2015$, 1.6706, 1.6560, and 1.3642. In the second investigation, one additional acceptable redshift, $z = 1.5132$, was found. No absorption redshifts greater than the emission redshift of 2.22 were found. The five acceptable redshifts for the observed spectrum are shown in Table 4. The relative velocities between absorbers and the emission-line region of PKS 0237−23 can be calculated from the redshifts using a formula given by Bahcall, Sargent, and Schmidt (1967); the relative velocities are $0.007c$, $0.186c$, $0.193c$, $0.244c$, and $0.301c$.

The five acceptable redshifts were found in the observed spectrum and, on the average, only 0.7 acceptable redshifts were found per nonsense spectrum. Moreover, the

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TABLE 3

THE SEVEN ACCEPTABLE REDSHIFTS AMONG THE TEN NONSENSE SPECTRA

The numbers in parentheses beside the "observed" lines represent their randomly-assigned visual strengths. The numbers to the right of the standard lines, also in parentheses, represent wavelength discrepancies (predicted minus observed wavelength) in the observed frame. Labels such as nonsense 1 or nonsense 2 specify different random number spectra.

$\lambda_{observed}$	Identifications	Identifications	$\lambda_{observed}$	Identifications	$\lambda_{observed}$	Identifications	$\lambda_{observed}$	Identifications
Nonsense 1	z = 1.7010	z = 1.4585	Nonsense 2	z = 1.2875	Nonsense 5	z = 0.8835	Nonsense 10	z = 1.7040
3403.6 (3)	Si II (1) 1260.4 (0.8)	. . . . . .	3508.0 (3)	Si II* (2) 1533.5 (-0.2)	3495.1 (2)	Al III (2) 1854.7 (-1.7)	3350.4 (3)	N V (2) 1238.8
3416.0 (3)	Si II*(2) 1264.8 (0.2)	. . . . . .	3546.5 (1)	C IV (1) 1550.8 (0.9)	3509.6 (2)	Al III (1) 1862.8 (-1.0)	3360.5 (1.5)	N V (1) 1242.8
3426.6 (3)	. . . . . .	Si IV (2) 1393.8 (0.0)	3823.0 (3)	Al II 1670.8 (-1.0)	4470.9 (3)	Fe II 2374.5 (1.5)	3409.7 (4)	Si II (1) 1260.4
3450.4 (2)	. . . . . .	Si IV (1) 1402.8 (-1.7)	4244.6 (5)	Al III (2) 1854.7 (0.1)	4487.7 (3)	Fe II 2382.8 (0.3)	4129.0 (2.5)	Si II (1) 1526.7
3605.6 (2)	C II (1 uv) 1335.3 (0.1)	. . . . . .	4262.0 (2)	Al III (1) 1862.8 (-0.9)	. . . . .	. . . . . .	4186.0 (2)	C IV (2) 1548.2
3805.3 (5)	. . . . . .	C IV (2) 1548.2 (1.0)	Nonsense 4	z = 0.5855	Nonsense 9	z = 1.3215	. . . . . .	. . . . . .
3813.7 (2.5)	. . . . . .	C IV (1) 1550.8 (-1.1)	3716.1 (1)	Fe II 2344.2 (0.7)	3544.4 (1)	Si II (1) 1526.7 (-0.1)	. . . . . .	. . . . . .
4109.7 (3)	. . . . . .	Al II 1670.8 (-2.0)	3764.0 (3)	Fe II 2374.5 (0.8)	3558.8 (3)	Si II*(2) 1533.5 (-1.1)	. . . . . .	. . . . . .
4124.1 (1.5)	Si II (1) 1526.7 (-0.4)	. . . . . .	4122.5 (2)	Fe II 2600.2 (0.1)	3594.6 (5)	C IV (2) 1548.2 (-0.4)	. . . . . .	. . . . . .
4180.1 (3)	C IV (2) 1548.2 (1.6)	. . . . . .	4433.7 (3)	Mg II (2) 2795.5 (-1.4)	3600.2 (3)	C IV (1) 1550.8 (0.1)	. . . . . .	. . . . . .
4188.4 (3)	C IV (1) 1550.8 (0.2)	. . . . . .	4444.3 (4)	Mg II (1) 2802.7 (-2.0)	. . . . .	. . . . . .	. . . . . .	. . . . . .

TABLE 4

PROPOSED IDENTIFICATIONS FOR PKS 0237-23

The numbers in brackets to the right of the standard lines represent wavelength discrepancies (predicted minus observed wavelength) in the observed frame.

Observed Wave Lengths*	Visual Strengths	z_{abs} = 2.2015	z_{abs} = 1.6706	z_{abs} = 1.6560	z_{abs} = 1.5132	z_{abs} = 1.3642
3346.9	4	. . . .	. . . .	Si II(1) 1260.4[+0.8]	. . . .	. . . .
3355.3	3	. . . .	. . . .	. . . .	C II(1 uv) 1335.3[+0.6]	. . . .
3364.7	2	. . . .	Si II 1260.4[+1.4]	. . . .	. . . .	. . . .
3445.1	3	. . . .	. . . .	. . . .	. . . .	. . . .
3473.8	3	N II (1 uv) 1085.1[+0.2]	. . . .	. . . .	. . . .	. . . .
3501.0	4.5	. . . .	. . . .	. . . .	Si IV(2) 1393.8[+1.8]	. . . .
3525.2	5	. . . .	. . . .	. . . .	Si IV(1) 1402.8[+0.2]	. . . .
3554.8	2	. . . .	. . . .	. . . .	. . . .	. . . .
3568.0	4	. . . .	C II(1 uv) 1335.3[-1.9]	. . . .	. . . .	. . . .
3592.3	3	Fe III 1122.5[+1.5]	. . . .	. . . .	. . . .	
3609.2	3	. . . .	. . . .	. . . .	. . . .	Si II(1) 1526.7[+0.3]
3660.0	3	. . . .	. . . .	. . . .	. . . .	C IV(2) 1548.2[+0.3]
3667.3	3	Fe II 1144.95[-1.7]	. . . .	. . . .	. . . .	C IV(1) 1550.8[-1.0]
3685.1	1	??Fe II* 1151.2[+0.5]??	. . . .	. . . .	. . . .	. . . .
3695.3	3	. . . .	. . . .	. . . .	. . . .	. . . .
3703.3	2	. . . .	. . . .	Si IV(2) 1393.8[-1.5]	. . . .	. . . .
3717.2	2	. . . .	. . . .	. . . .	. . . .	. . . .
3724.0	4	. . . .	Si IV(2) 1393.8[-1.8]	Si IV(1) 1402.8[+1.8]	. . . .	. . . .
3748.2	1	. . . .	Si IV(1) 1402.8[-1.9]	. . . .	. . . .	. . . .
3760.0	1.5	. . . .	. . . .	. . . .	. . . .	. . . .
3766.0	1	. . . .	. . . .	. . . .	. . . .	. . . .
3776.3	2.5	. . . .	. . . .	. . . .	. . . .	. . . .
3789.3	2	. . . .	. . . .	. . . .	. . . .	. . . .
3838.4	2	. . . .	. . . .	. . . .	Si II(1) 1526.7[-1.4]	. . . .
3861.7	3	Si III 1206.5[+0.9]	. . . .	. . . .	. . . .	. . . .
3874.3	1	. . . .	. . . .	. . . .	. . . .	. . . .
3880.0	1	. . . .	. . . .	. . . .	. . . .	. . . .
3886.1	2.5	. . . .	. . . .	. . . .	. . . .	. . . .
3891.7	5	Ly-α 1215.7[+0.3]	. . . .	. . . .	. . . .	. . . .
3899.7	1	. . . .	. . . .	. . . .	. . . .	. . . .
3905.1	2	. . . .	. . . .	. . . .	. . . .	. . . .
3910.3	1	. . . .	. . . .	. . . .	. . . .	. . . .
3924.5	1	. . . .	. . . .	. . . .	. . . .	. . . .
3932.8	2.5	. . . .	. . . .	. . . .	. . . .	. . . .
3950.3	2.5	. . . .	. . . .	. . . .	. . . .	Al II 1670.8[-0.2]
4018.3	3	. . . .	. . . .	. . . .	. . . .	. . . .
4024.9	3	. . . .	. . . .	. . . .	. . . .	. . . .
4077.6	1	. . . .	Si II(1) 1526.7[-0.3]	. . . .	. . . .	. . . .
4112.1	3	. . . .	. . . .	C IV(2) 1548.2[-0.1]	. . . .	. . . .
4118.8	3	. . . .	. . . .	C IV(1) 1550.8[0.0]	. . . .	. . . .
4134.9	4	. . . .	C IV(2) 1548.2[-0.3]	. . . .	. . . .	. . . .
4141.1	4	. . . .	C IV(1) 1550.8[+0.4]	. . . .	. . . .	. . . .
4147.2	1	. . . .	. . . .	. . . .	. . . .	. . . .
4386.0	1.5	. . . .	. . . .	. . . .	. . . .	Al III 1854.7[-1.1]
4404.7	2	. . . .	. . . .	. . . .	. . . .	Al III 1862.8[-0.7]
4439.1	1	. . . .	. . . .	Al II 1670.8[-1.4]	. . . .	. . . .
4463.5	3	Si IV(2) 1393.8 [-1.4]	Al II 1670.8[-1.4]	. . . .	. . . .	. . . .
4482.4	1	. . . .	. . . .	. . . .	. . . .	. . . .
4492.8	1	Si IV(1) 1402.8 [-1.8]	. . . .	. . . .	. . . .	. . . .

*Greenstein and Sargent (1968)

identified lines are made up of a small set of standard lines, the accessible members of which are at least partially represented in each of the five redshifts. These results suggest that there is a significant correlation between the observed spectrum of PKS 0237−23 and the standard lines given in Table 1. In what follows we shall therefore assume that the five acceptable redshifts found in the observed spectrum correspond to physical absorption and not to accidental coincidences. It is, of course, not unlikely that at least one of the five redshifts corresponds to chance coincidences.

The five acceptable redshifts explain all eight of the strength-4 and -5 lines and ten out of fourteen of the strength-3 lines. Only ten out of the twenty-seven strength-1 and -2 lines are explained. This discrimination in the identifications against the weaker lines is primarily a result of our criteria for an acceptable redshift and cannot be used as an independent argument in favor of the correctness of the identifications.

The $z = 2.20$ redshift was originally found by Arp *et al.* (1967), although only three (Ly-α, Si III, Fe II) of their twenty-seven identifications appear in our Table 4.

The absorption redshift at $z = 1.95$ proposed by Burbidge (1967) and by Greenstein and Schmidt (1967) failed to satisfy rule 4 of § IV. Our over-all results are inconsistent with the rule, claimed by Burbidge and Burbidge (1967), that either $z_{\text{absorption}}$ equals z_{emission} or $z_{\text{absorption}}$ equals 1.95.

b) Predicted Lines

A number of additional absorption lines can be predicted which lie outside the previously observed region but which might be detectable with further observations. These lines can be predicted from the redshifts given in Table 4 and from the fact that the pattern of lines appears largely to repeat itself among at least the four smaller redshifts. For the $z = 2.20$ system, we expect Ly-β at 3283.4 Å and the C IV doublet at $\lambda\lambda$4956.6 and 4964.8 Å. The $z = 1.6706$ system implies that Ly-α should be at 3246.6 Å and Si III at 3222.1 Å. For the 1.656 system, we expect Ly-α at 3228.8 and Si III at 3204.5. The $z = 1.364$ redshift should be represented by the Si IV doublet at 3295.1 Å and 3316.4 Å. In addition to the above-predicted strong lines, the possibly weaker Si II 1526.7 line of $z = 1.656$ might be discoverable at 4055.0 Å and the Al III doublet of $z = 1.513$ might be discoverable at 4661.3 and 4681.5 Å. The possible presence of the C IV doublet in the 1.513 system at 3890.4 and 3897.4 Å, near the Ly-α line in the 2.202 system, might be detectable with a higher-dispersion plate.

c) Further Properties of the Identifications

The following additional points concerning the identifications proposed in Table 4 should be noted. First, there is a more or less common pattern in all of the redshifts which includes the C IV and Si IV doublets, the Si II lines $\lambda\lambda$1260.4 and 1526.7, and the Al II line λ1670.8. The C II line λ1335.3 appears in two redshifts. All of the lines in this common pattern have also been identified in the spectrum of 3C 191 (Burbidge, Lynds, and Burbidge 1966; Stockton and Lynds 1966; Bahcall, Sargent, and Schmidt 1967) with the exception of Al II 1670.8. If the pattern also applies to 3C 191, then the Al II line should be present at 4922.5 Å in this object. Second, the following probable identifications listed in Table 4 have not previously been identified in the spectra of quasi-stellar sources: N II λ1085.1, Fe III λ1222.5, Al II λ1670.8, and Al III $\lambda\lambda$1854.7 and 1862.8. They constitute five of the fifteen standard lines that appear, as probable, in Table 4. Third, all but one of the identified lines in Table 4 were predicted to be likely absorption lines by Bahcall and Salpeter (1966) before any quasi-stellar sources with rich absorption spectra were discovered. The one exception is N II λ1085, which was not included in their Table 1 because Bahcall and Salpeter listed only lines with rest wavelengths greater than 1100 Å. Fourth, no lines from the excited fine-structure states of Si II appear; this implies a limit on the electron density or the ambient flux near the absorbing material (Bahcall 1967; Bahcall and Wolf 1968). There is an inconclusive indication that the excited fine-structure states of N II are occupied in the 2.20 system from the fact that the observed line with which N II λ1085 is identified, $\lambda_{obs} = 3473.8$ Å, is listed as wide by Greenstein and Sargent (1968). The C II λ1335 in the $z = 1.67$ system can be considered an identification only if the excited fine-structure states of C II are occupied. The uncertain identification of the Fe II line λ1151.2 in the 2.20 system cannot be regarded as significant evidence for absorption from excited fine-structure states of Fe II, since the other lines that originate on the excited fine-structure states of Fe II are not identified. Fifth, no lines from neutral atoms are definitely identified. In particular, the O I λ1302.2, which appears in the interstellar spectrum of π and δ Scorpii (Morton and Spitzer 1966), is absent, as are also the resonance lines of C I, N I, and S I. Sixth, the absence of the weaker ground-state Si II lines, $\lambda\lambda$1304 and 1807, indicates that at least the stronger Si II lines $\lambda\lambda$1260 and 1527 are not heavily saturated. A similar conclusion applies to the spectrum of 3C 191 in which also $\lambda\lambda$1260 and 1526 are present but λ1304 is absent.

One further, more general remark is also of interest. The rest wavelengths of all the observed lines in each of the five redshift systems were inspected for coincidences between the rest wavelengths and the a priori less likely lines listed in Table 2. No consistent and convincing evidence for any of the less likely lines was found, although some (possibly accidental) coincidences were noted. For example, the observed lines $\lambda\lambda$3355.3 and 3724.0 correspond to A I λ1048.2 and Mn II λ1163.0 in the 2.20 system, and the observed lines $\lambda\lambda$3799.3 and 3899.7 coincide with the Ge II $\lambda\lambda$1602.5 and 1649.2 pair in the 1.36 system.

I am grateful to J. L. Greenstein and W. L. W. Sargent for their careful measurements of the absorption lines in PKS 0237−23, without which this investigation would not have been possible. It is a pleasure to thank M. Schmidt for stimulating conversations and generous assistance. I am indebted to J. Mathews for an important suggestion regarding the computational procedure and to J. Butkus for checking the analysis, as part of his freshman honors work, of some of the nonsense spectra. B. A. Zimmerman provided valuable help and advice with the computing.

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