THE ASTROPHYSICAL JOURNAL, **184**: 57–63, 1973 August 15

A SEARCH FOR HIGH-IONIZATION REDSHIFT SYSTEMS IN THE ABSORPTION SPECTRA OF FIVE QUASARS

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Received 1973 January 22; revised 1973 March 26

ABSTRACT

We have searched the absorption spectra of five quasars for the presence of redshift systems dominated by the highly ionized doublets C IV, N V, and O VI, which could be the strongest lines produced by absorbing clouds with collisional ionization temperatures between 10^5 ° and 10^6 ° K. There is at most marginal evidence for one such system apiece in the spectra of PHL 957 and 4C 05.34, which are the two quasars with the largest known emission redshifts. Highly ionized redshift systems of this type are not widespread among the five quasars we investigated; the number of redshifts found in the observed spectra is not significantly larger than the number found in similar random-number spectra. Less than 5 percent of the observed absorption lines are identified in a statistically significant way by redshift systems of this type.
Subject headings: quasi-stellar sources or objects — redshifts

I. INTRODUCTION

Systematic searches for redshift systems in the rich absorption spectra of quasars (see Bahcall 1968; also Bahcall and Joss 1973, and references therein) have been carried out under the assumption that low-ionization lines (especially Lα) will be present if they are in the accessible part of the spectrum; this is equivalent to assuming that the absorbing cloud is not extremely highly ionized. Cohen (1973) has recently pointed out, on the basis of a collisional ionization model for an absorbing cloud, that the low-ionization lines may not be among the strongest absorption lines if $T \gtrsim 10^5$ ° K, where T is the ionization temperature. In fact, for a plausible abundance of heavy elements within the cloud, the strongest lines for 10^5 ° $\lesssim T \lesssim 10^6$ ° K will be due to C IV, N V, and O VI (similar results have been obtained by McKee, Tarter, and Weisheit 1973). If redshift systems due to such clouds are actually present in the spectra of quasars, they may well have been overlooked in previous analyses by Bahcall and his collaborators.

In the present paper, we present the results of an investigation of the rich absorption spectra of five quasars (PKS 0237−23, TON 1530, PHL 938, 4C 05.34, and PHL 957) to determine whether high-ionization redshift systems may be present. In § II we outline our method of analysis, in § III we present our results for the above five quasars, and in § IV we estimate, with the aid of random-number spectra, the probabilities for apparent high-ionization systems to arise by chance in the spectra of the quasars we investigated. In the Appendix, we discuss in more detail the method of construction of the random-number spectra.

II. METHOD

We used the method of analysis of rich absorption-line spectra developed by Bahcall (1968). We included 16 lines in our list of standard lines: O VI $\lambda\lambda$1031.95, 1037.63;

N V λλ1238.81, 1242.80; C IV λλ1548.20, 1550.77; C IV (av) λ1549.50; Si IV λλ1393.76, 1402.77; C III λ977.03; Fe III λ1122.53; Si III λ1206.51; Al III λλ1854.72, 1862.78; Lα; and Lβ. We required that the absolute wavelength discrepancy between an observed line and a redshifted standard line be less than or equal to 2 Å for an acceptable identification.

In order to search for high-ionization redshift systems, we established a set of formal rules to determine whether a candidate system would be accepted. The rules were:

1. At least two complete doublets among the three doublets (C IV, N V, O VI) must be present.

2. The ratio of line strengths for each accepted doublet must be consistent with atomic physics and spectroscopic limitations.

3. The two accepted doublets must contain at least two lines of strength greater than or equal to 2.

By trial and error, we found that less stringent rules resulted in an undesirably large number of acceptable systems within random-number spectra having the same essential characteristics as the observed spectra (see § IV and the Appendix). The same difficulty was encountered when we attempted to include in our analysis the absorption lines in PHL 957 observed by Lowrance *et al.* (1972) with a high-resolution integrating television system. In other respects, our method of search was identical to that of previous analyses (see Bahcall and Joss 1973, and references therein).

The observational data were taken from Bahcall, Greenstein, and Sargent (1968) (for PKS 0237−23), Bahcall, Osmer, and Schmidt (1969) (for TON 1530), Burbidge, Lynds, and Stockton (1968) (for PHL 938), Lynds (1971) (for 4C 05.34), and Lowrance *et al.* (1972) (for PHL 957).

III. RESULTS FOR FIVE QUASARS

We have searched the observed spectra of five quasars for acceptable high-ionization redshift systems between $z = 4.0$ and a minimum redshift $z_{\rm min}$, the value of which

TABLE 1

HIGH-IONIZATION ABSORPTION REDSHIFT SYSTEMS IN TWO QUASARS*

Observed Wavelength (Å)	Strength	Identification†	Wavelength Discrepancy (Å)	Identifications in Low-Ionization Systems
4C 05.34: emission redshift $z_{\rm em} = 2.877$; absorption redshift $z_{\rm abs} = 2.5711$				
3683.54......	3	O VI (2) 1031.95	+1.7	Lβ 1025.72 ($z = 2.5925$)
3706.10......	3D	O VI (1) 1037.63	−0.6	{Lγ 972.54 ($z = 2.8106$); O VI 1031.95 ($z = 2.5925$); C II 1334.53 ($z = 1.7758$)}
[4010.48.....	1	Fe III 1122.53	−1.8	{Si II 1260.42 ($z = 2.1819$); Si IV 1402.77 ($z = 1.8593$)}]
4422.83......	4B	N V (2) 1238.81	+1.1	None
4436.74......	3	N V (1) 1242.80	+1.4	Si IV 1393.76 ($z = 2.1819$)
PHL 957: $z_{\rm em} = 2.69$; $z_{\rm abs} = 2.6181$				
3735.0.......	2W	O VI (2) 1031.95	−1.3	None
3753.9.......	2W	O VI (1) 1037.63	+0.4	Lβ 1025.72 ($z = 2.6613$)
4482.5.......	1	N V (2) 1238.81	−0.4	None
4495.0.......	1	N V (1) 1242.80	+1.6	Si IV 1393.76 ($z = 2.2250$)

* Letters following the line strengths stand for diffuse (D), broad (B), and wide (W), as denoted by the observers. The identification in brackets is questionable and was not considered as evidence supporting the other identifications.

† Relative intrinsic strengths between the members of each doublet are given in parentheses.

was set equal to the minimum redshift for which two of the three doublets C IV, N V, and O VI fall within the observationally accessible portion of the spectrum. The value of $z_{\min}$ varies from ~ 1.5 for TON 1530 to ~ 1.8 for 4C 05.34. We found one acceptable system apiece in the spectra of PHL 957 and 4C 05.34 at redshifts of $z = 2.6181$ and $z = 2.5711$, respectively; the properties of these systems are summarized in table 1. The acceptability of both systems relies upon the identification of the doublets of N V and O VI. Another system ($z = 2.2055$) in the spectrum of PHL 957 obeys all of our formal rules, but we rejected it because of an unacceptably large wavelength discrepancy (3.6 Å) between the two lines of the closely spaced doublet of O VI. (If this doublet is discounted, the system is unacceptable.) This system is virtually identical to the system $z = 2.2056$ in table 5 of Lowrance *et al.* (1972). We found *no* acceptable systems in the spectra of three other quasars (PKS 0237−23, TON 1530, and PHL 938).

We also note that, among the eight identified lines in the two acceptable systems, five have already been identified in previous searches for low-ionization systems. Moreover, among these five previously identified lines, four were essential to the acceptability of low-ionization systems in which they were identified.

IV. RANDOM-NUMBER SPECTRA

In order to estimate the probability that an acceptable high-ionization redshift system will occur by chance, we have generated and analyzed 20 random-number spectra corresponding to each quasar. These spectra were required to have the same essential characteristics as the observed spectra, e.g., the minimum separations between lines were the same as those imposed on the observed spectra by the spectroscopic techniques and observational conditions. Further details concerning the characteristics of the random-number spectra are given by Bahcall (1968) (for PKS 0237−23), Bahcall *et al.* (1969) (for TON 1530), Bahcall and Feldman (1970) (for PHL 938), Bahcall and Goldsmith (1971) (for 4C 05.34), and Bahcall and Joss (1973) (for PHL 957). (See also the Appendix to the present paper.) In all cases, we checked to ensure that acceptable redshift systems in these spectra would not have been accepted in previous searches for low-ionization systems.

The results of our analysis of the random-number spectra are summarized in table 2. On the basis of the number of acceptable systems in the random-number spectra, we estimate that the probability of the two acceptable systems having occurred by chance in the observed spectra of PHL 957 and 4C 05.34 is ~ 10 percent, and that the probability of two acceptable systems having occurred by chance among all five quasars is ~ 25 percent. We note that five out of the 14 acceptable systems in the random-number spectra have redshifts appreciably larger than the emission redshifts of the respective quasars, while no acceptable absorption redshift much in excess of the emission redshift has yet been found in any observed quasar spectrum. However, this consideration is of limited value in the context of the present probability estimates, because high-ionization redshift systems have also not yet been reported in the absorption spectra of quasars.

The total number of lines in the quasar absorption spectra we have studied is 267. Since the two candidates for high-ionization absorption redshift systems explain at most nine lines, we conclude that the percentage of absorption lines which can be explained with statistical validity as having been formed under the conditions of high collisional ionization considered by Cohen (1973) and McKee *et al.* (1973) is less than 5 percent. Another way of summarizing this conclusion is to note that a total of 23 redshifts have been previously identified in these quasars using the same techniques employed in the present paper. Thus, at most 2/25 of the redshifts identified in this statistically significant way are likely to have been produced under conditions of high collisional ionization.

TABLE 2

ACCEPTABLE REDSHIFTS AMONG THE RANDOM-NUMBER SPECTRA

Object	Acceptable Redshifts in 20 Random-Number Spectra*	Number of Acceptable Redshifts per Random-Number Spectrum†
PHL 957...........	2.55	0.20 ± 0.51
	2.49	
	2.31‡	
	1.96‡	
4C 05.34...........	*3.48*	0.15 ± 0.36
	2.91	
	2.28	
PHL 938...........	*2.69*	0.20 ± 0.40
	2.55	
	1.79	
	1.72	
TON 1530.........	None	0
PKS 0237−23......	*2.76*	0.15 ± 0.36
	1.79	
	1.70	

* Italicized redshifts are larger than the observed emission redshift of the quasar.

† The quoted errors are one standard deviation per random-number spectrum.

‡ These two redshifts were in the same random-number spectrum. This is the only case where more than one acceptable redshift was found in a single spectrum.

This work was initiated while one of us (J. N. B.) was a visiting professor in the astronomy department of the University of California at Berkeley; J. N. B. wishes to express his gratitude for the hospitality and stimulation provided by the members of the Berkeley astronomy department. This work was supported in part by NSF grant 16147 A#1 and the Miller Institute for Basic Research.

APPENDIX

In this Appendix, we discuss the method by which the random-number spectra are generated.

The purpose of the random-number spectra is to determine the statistical validity of the candidate redshifts that are found in the observed spectra. Hence, the random-number spectra are generated in a way that simulates the limitations imposed on the observed spectra by the spectroscopic techniques and observational conditions; the random-number spectra are thus superficially indistinguishable from the real spectra. In particular, the minimum and maximum wavelengths (λ_{min} and λ_{max}, respectively) allowed for the lines in a random-number spectrum are set equal to the minimum and maximum wavelengths accessible to the observed spectrum; the minimum separation $\Delta\lambda_{min}$ between each pair of lines in a random-number spectrum is set equal to the spectral resolution of the observed spectrum; the total number n of lines in each random-number spectrum is set equal to the total number of observed lines; and the distribution of line strengths and other line characteristics is set equal to the observed distribution (e.g., if there are two wide lines of strength 3 in the observed spectrum, then two randomly chosen lines in each random-number spectrum are considered to be wide and of strength 3). (See Bahcall 1968 and Bahcall and Joss 1973 for additional details concerning the generation of the random-number spectra.)

TABLE A-1

A comparison of the observed absorption-line spectrum of 4C 05.34 with two typical random-number spectra ($\lambda_{min} = 3500Å$, $\lambda_{max} = 6000Å$, $\Delta\lambda_{min} = 6Å$, n = 93).

Observed Spectrum		Random-number Spectrum # 1		Random-number Spectrum # 2	
Wavelength(Å)	Strength*	Wavelength(Å)	Strength*	Wavelength(Å)	Strength*
3497.85	2	3523.30	0	3561.24	2
3514.81	2	3591.19	1	3572.72	0
3535.98	2	3602.92	0D	3599.68	4B
3565.61	3D	3705.78	1	3611.45	4
3582.46	3	3763.98	3	3627.59	1
3592.18	0	3792.08	1	3643.24	1
3603.32	3	3798.91	0D	3659.23	2
3630.26	0	3835.99	3	3692.97	2
3641.86	3	3869.55	0	3709.26	4B
3668.39	2	3914.35	3	3747.34	2
3683.54	3	3924.81	1	3782.47	1
3706.10	3D	3937.94	1D	3793.04	1
3727.17	4B	3956.61	1	3823.24	3
3744.74	1	3988.19	3	3861.85	1
3766.27	3	4023.70	3D	3901.81	2
3779.43	2	4076.32	1D	3939.39	0
3816.09	2D	4111.23	0	3958.61	3D
3843.96	1	4152.67	3	4018.55	2
3867.06	3D	4184.18	3	4037.78	0
3874.82	0	4201.07	3	4047.19	1
3882.94	1	4243.88	1	4056.02	3
3894.82	2	4256.00	1	4070.67	1
3908.29	1D	4266.18	1	4133.38	1D
3965.40	1	4324.60	2	4166.56	1
3974.34	1	4338.26	2	4213.48	3D
3985.83	2	4352.18	0	4249.75	4
3997.07	5	4358.24	2	4259.82	2
4010.48	1	4365.21	1D	4284.93	3
4019.67	3	4418.41	2	4297.61	1
4042.23	1	4432.13	0	4313.47	2
4053.04	3	4446.15	5	4328.88	3
4061.50	1	4452.67	1	4338.91	1
4069.19	3	4519.05	3	4348.87	0D
4084.42	1D	4532.05	5	4375.27	3
4142.34	0	4621.73	1	4388.52	1
4154.96	0	4656.89	3	4418.08	3
4163.15	1	4662.96	1	4454.23	1
4171.36	1	4684.57	4	4461.34	0
4185.46	2D	4733.20	1	4503.57	2
4197.38	2	4806.53	4	4519.52	0
4215.43	2	4852.62	2	4528.46	3
4223.59	4	4861.75	3	4573.64	5
4233.72	0	4880.21	3	4595.82	5
4246.98	3	4900.10	3	4613.70	0
4256.62	2	4909.73	2D	4620.88	2
4296.49	3	4924.22	0	4635.74	3
4304.62	1	4934.06	0	4642.92	4

* Letters following line strength indicate "broad" (B) and "diffuse" (D), as denoted by Lynds (1971).

TABLE A-1—Continued

Observed Spectrum		Random-number Spectrum # 1		Random-number Spectrum # 2	
Wavelength(Å)	Strength*	Wavelength(Å)	Strength*	Wavelength(Å)	Strength*
4317.20	0D	4940.95	3D	4659.06	1
4329.81	0D	4985.14	1	4696.95	1
4366.50	5B	5053.17	1	4713.98	1
4380.43	2	5075.71	5	4739.39	1
4391.09	1D	5096.67	3D	4790.58	0D
4422.83	4B	5111.49	0D	4805.96	2
4436.74	3	5164.38	1	4874.45	2
4451.95	0	5229.52	2	4902.36	2
4465.08	4D	5259.22	5B	4913.46	1D
4479.62	2	5265.24	2	4923.13	2
4502.44	1	5272.59	4D	4942.07	3D
4507.97	3	5278.71	1	5000.06	1
4519.12	1	5306.40	1D	5042.83	2D
4529.91	5	5315.46	2	5163.50	1
4549.09	2	5375.76	1	5171.03	3
4557.29	1	5388.08	1	5195.68	1
4582.94	5	5419.25	1	5214.36	1
4624.25	1	5431.81	2	5250.01	0
4631.03	4	5447.91	0	5302.86	5
4639.10	1	5475.07	1	5312.43	1
4653.94	2	5485.46	0	5325.81	0
4665.62	1	5501.72	1	5348.65	3
4676.18	1	5510.89	4B	5374.12	1
4688.01	2	5537.20	1	5394.61	0
4710.81	4	5550.57	2	5419.63	0
4728.07	1	5585.54	2	5438.21	2D
4734.45	1	5591.97	1	5447.22	3
4759.55	1	5618.99	1	5464.87	0D
4800.96	2	5628.92	0	5490.48	1
4816.94	2	5635.19	0	5509.81	2
4842.29	1	5643.07	1	5523.15	1
4972.03	1	5692.85	2	5544.10	0
5008.10	1	5708.55	2	5563.62	1
5032.97	0	5729.07	2	5593.76	1
5045.89	1	5751.70	1D	5667.79	2
5189.21	0	5777.93	3	5690.33	0
5196.77	0	5793.22	0	5762.73	3
5377.37	3	5824.18	1	5791.96	3
5386.67	3	5831.38	2	5815.52	2
5402.04	0	5854.38	2	5825.69	1
5444.95	1	5860.73	2D	5835.54	4D
5455.57	1	5869.98	4B	5871.09	1D
5478.41	0	5885.25	3	5909.62	1D
5839.00	0D	5925.57	3	5942.45	1D
5903.80	1D	5975.23	4	5969.66	3
6005.61	1D	5986.46	1	5985.83	5B

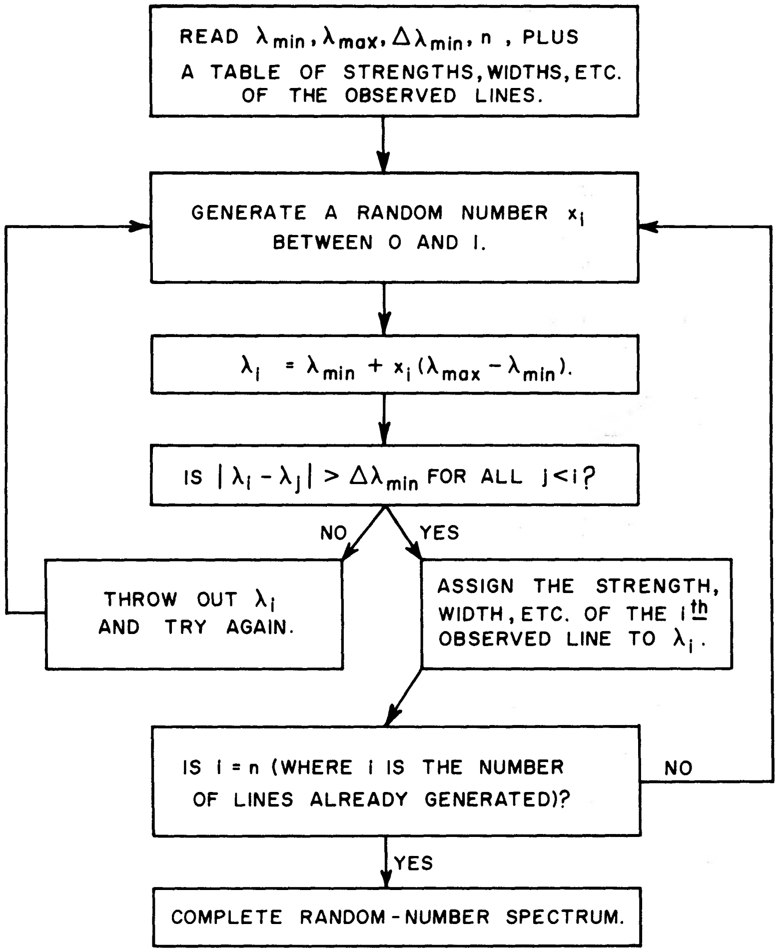

FIG. 1.—Flow chart for the computer program that generates the random-number spectra

The random-number spectra are generated by a computer program whose operation is described in figure 1. Once generated, each spectrum is analyzed by exactly the same method that is used to determine acceptable redshift systems in the corresponding observed spectrum. Thus, the average number of acceptable systems in 10–20 random-number spectra is a statistically meaningful measure of the number of acceptable systems that arise by chance in each observed spectrum.

In table A1, the observed spectrum of 4C 05.34 (Lynds 1971) is compared with two typical random-number spectra that were generated by the above method.

REFERENCES

Bahcall, J. N. 1968, *Ap. J.*, **153**, 679.
Bahcall, J. N., and Feldman, U. 1970, *Ap. J.*, **161**, 389.
Bahcall, J. N., and Goldsmith, S. 1971, *Ap. J.*, **170**, 17.
Bahcall, J. N., Greenstein, J. L., and Sargent, W. L. W. 1968, *Ap. J.*, **153**, 689.
Bahcall, J. N., and Joss, P. C. 1973, *Ap. J.*, **179**, 381.
Bahcall, J. N., Osmer, P. S., and Schmidt, M. 1969, *Ap. J.* (*Letters*), **156**, L1.
Burbidge, E. M., Lynds, E. R., and Stockton, A. N. 1968, *Ap. J.*, **152**, 1077.
Cohen, J. G. 1973, *Ap. J.* (in press).
Lowrance, J. L., Morton, D. C., Zucchino, P., Oke, J. B., and Schmidt, M. 1972, *Ap. J.*, **171**, 233.
Lynds, R. 1971, *Ap. J.* (*Letters*), **164**, L73.
McKee, C. F., Tarter, C. B., and Weisheit, J. C. 1973, *Ap. J.* (in press).