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AN ANALYSIS OF THE SPECTRUM OF THE LARGE-REDSHIFT QUASI-STELLAR OBJECT OQ 172*

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ABSTRACT

The quasi-stellar object OQ 172, with $z = 3.53$, has been observed in detail with the image-dissector spectrum scanner on the Lick 120-inch (3-m) telescope. A list is given of 175 absorption lines; considerable line blending is still present. Analysis of the absorption lines shows that multiple redshift systems are present. The best-determined system, at $z = 3.066$, has lines from excited fine-structure levels in the ground states of Si II and C II. Other possible systems have $z = 2.564$, and close pairs at $z = 3.094$, 3.089 and 2.698, 2.691. Lyman lines at a very large number of discrete redshifts may be present. There is no detectable absorption at the Lyman limit at the emission-line redshift, and Lβ if present is quite weak. The absorption-line systems also show little Lyman continuum absorption. Some limits are derived on the thickness, density, and distance from the central source of the absorbing clouds.

Subject headings: line identifications — quasi-stellar sources or objects — redshifts

I. INTRODUCTION

The study of bright quasi-stellar objects with large redshifts is particularly interesting because they represent extreme examples of the quasar phenomenon. The object 1442+101 ≡ OQ 172 has the largest emission-line redshift so far discovered (Wampler *et al.* 1973) and it shows a rich absorption-line spectrum in the spectral region that lies on the short-wavelength side of Lα. It has become apparent from the study of this and other large-redshift QSOs that, although there are many similarities in the emission-line spectra, the absorption-line spectra of the objects with high redshifts are profoundly different from object to object. This is particularly evident when the redshifts are sufficiently large to allow the observations to be extended below the wavelength corresponding to the redshifted Lyman limit. The spectrum of 0642+44 ≡ OH 471 is cut off below the Lyman limit (Carswell and Strittmatter 1973), PHL 957 and 4C 5.34 show a sharp drop in the continuum level near the Lyman edge (Oke 1970; Oke, Neugebauer, and Becklin 1970), but there is substantial flux in the spectrum of OQ 172 at wavelengths well below the position of the redshifted Lyman limit. There also appear to be differences in the emission-line spectra of these sources. The lines O VI $\lambda\lambda$1025, 1031 and Lβ are strong emission lines in OH 471, O VI is probably present in 4C 5.34 (Lynds 1971), and Lβ has been reported to be present in the spectrum of PHL 957 (Oke *et al.* 1970). However, we have found no clear evidence that these emission lines are present in OQ 172.

These spectral differences clearly suggest differences in the nature of the gas clouds that lie between us and the energy source, and also in some cases in the clouds producing the emission lines. It is not yet clear whether these differences are caused by differences in the sources themselves (for instance, differences in absolute luminosities), or whether they are due to "accidental" differences such as alignment, total mass of intervening gas, etc. In this paper we give an analysis of the spectrum of OQ 172 (§§ II and III) and discuss the implications of the fact that the Lyman continuum of OQ 172 is optically thin (§ IV).

II. THE OBSERVATIONS

The source OQ 172 was observed in the spring of 1973 with the Lick Observatory Cassegrain image-tube scanner (Robinson and Wampler 1972). The apparent magnitude V of the continuum is 17.9 (Wampler *et al.* 1973). Table 1 gives a log of the observations. The spectra of OQ 172 were calibrated using secondary standards that in turn have been calibrated against the Hayes (1970) primary standard-star system obtained using the Crossley telescope. We have a comparatively large number of scans of OQ 172 taken on different nights with various gratings, grating settings, and spectral resolution. These spectra have been digitally added together to form an average spectrum that has a

TABLE 1
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Date (U.T.)	Dispersions (Å mm^{-1})	λ (beg.)	λ (end)
1973 May 5	100	4740	7148
1973 May 6	100	6548	8838
1973 May 6	50	4970	6018
1973 April 8	100	3178	5506
1973 March 3	100	3058	5494
1973 May 27	100	2734	5187
1973 May 31	50	4035	5143
1973 June 2	50	5671	6675

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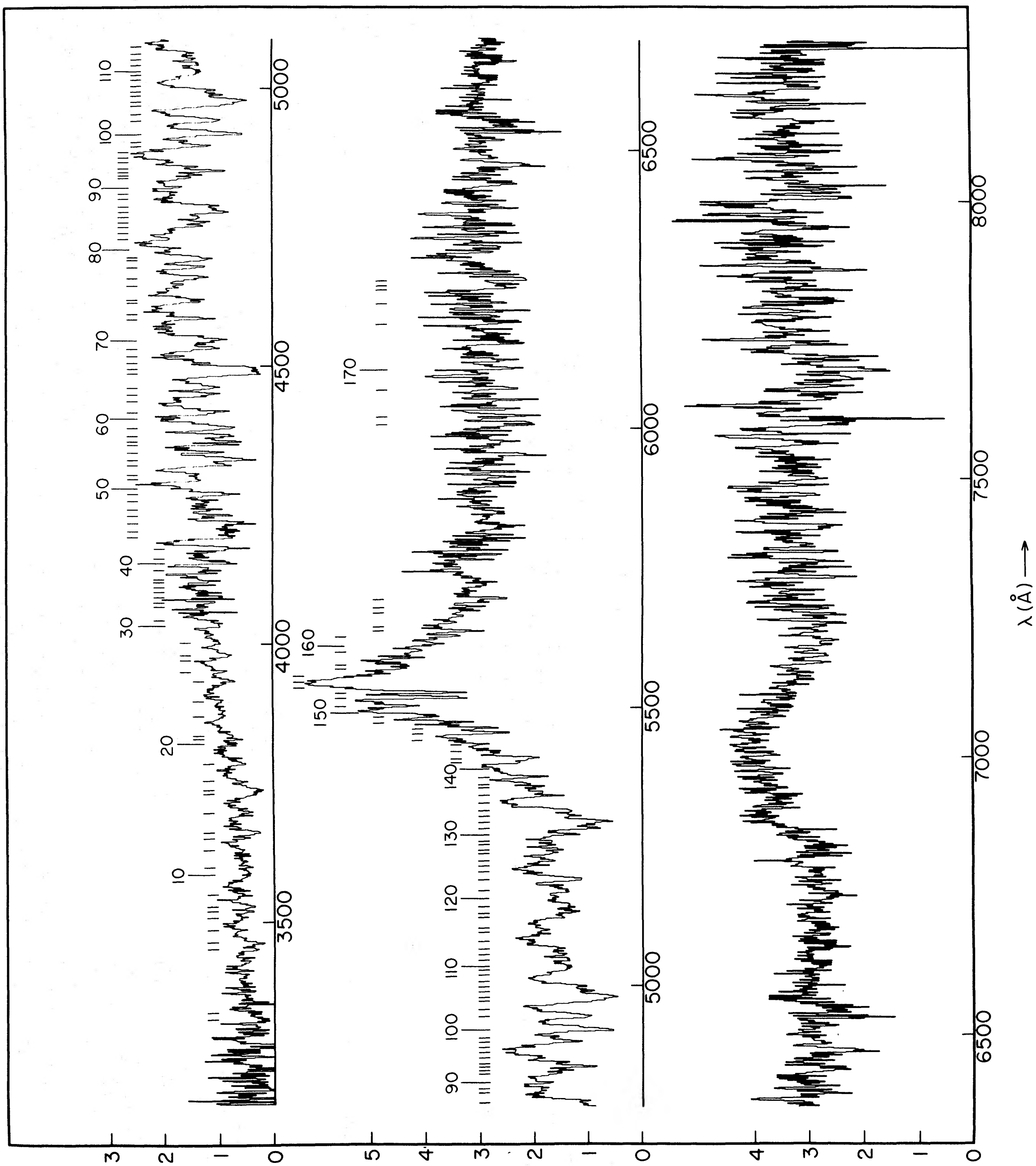

FIG. 1.—Composite spectrum incorporating all scans of OQ 172. The absorption lines listed in table 2 are indicated.

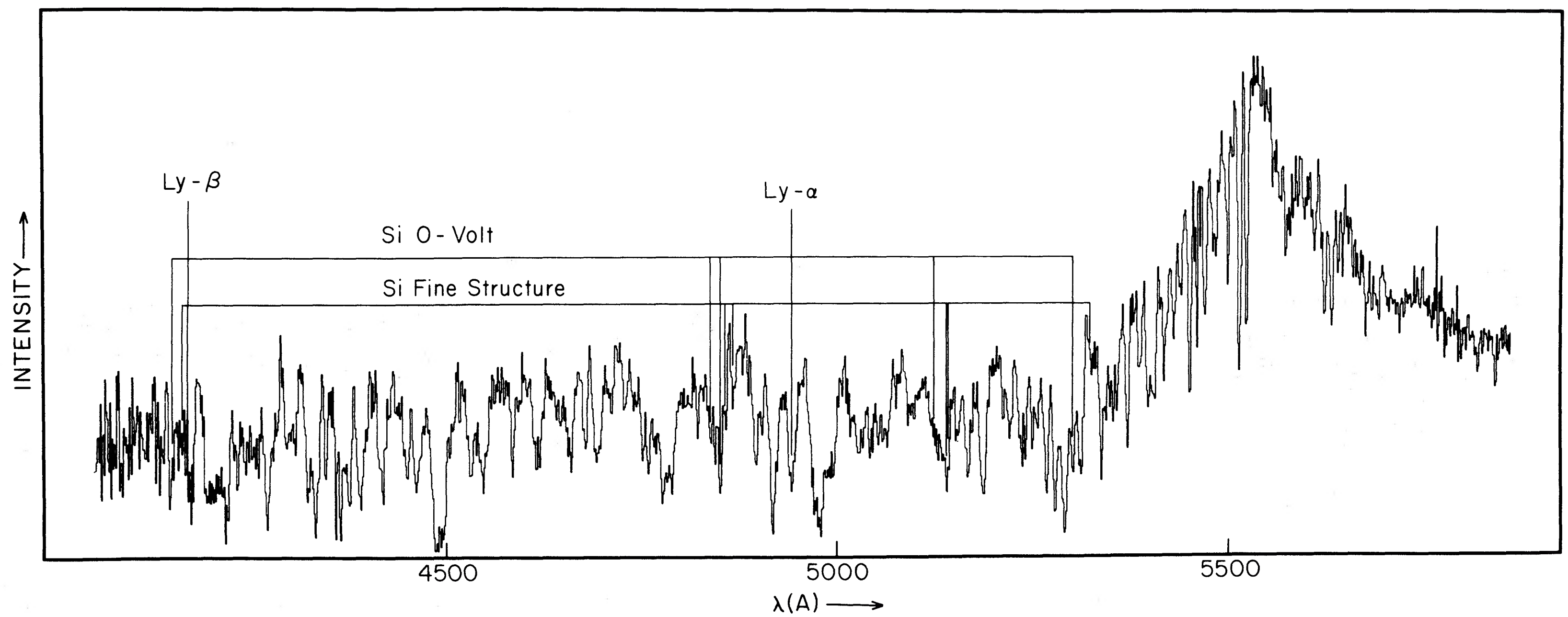

FIG. 2.—Composite spectrum incorporating only the scans made in second order. Some features in the $z = 3.066$ system are indicated.

high signal-to-noise ratio. This spectrum is shown in figure 1. The internal agreement of the calibrated spectra is good for those nights that were judged to be of photometric quality. Consequently, the intensity scale shown in figure 1 is believed to be accurate to approximately ± 10 percent. Spectra taken on nights of lower photometric quality were scaled to fit the high-quality spectra before being added to the composite spectrum.

Our normal practice is to obtain spectra with about 7 Å resolution using our gratings in first order. However, for OQ 172 we also obtained three spectra in second order (3.5 Å resolution) covering the wavelength interval 4043–6600 Å. These spectra resolved a number of the blends seen in the first-order spectra, and several of the stronger lines nearly reached zero central intensity. Figure 2 shows a portion of a composite of these three second-order spectra. We believe that even with 3.5 Å resolution the line profiles were instrumentally limited and considerable blending is present. It is probable that with higher resolution a number of apparently blended features would be resolved and many of the stronger features could be shown to be saturated.

By carefully examining our data we have compiled a wavelength list of 175 absorption features that we have found in the spectrum of OQ 172. These wavelengths, corrected to the Sun but not converted to vacuum wavelengths, are listed in table 2. The internal accuracy of the listed wavelengths is about ± 0.5 Å but systematic errors as large as 1.5 Å may be present. We have attempted to check the wavelength calibration using the nightsky emission lines, and in all cases the measured wavelength was within 0.5 Å of the tabulated wavelength. Of course, this only indicates that the wavelength calibration is good near the nightsky lines. Since we used a mixture of He, Ar, Ne, and Hg in our comparison spectrum, there are a number of gaps, several hundred angstroms in extent, over which the wavelength calibration is only a smooth interpolation to the fit obtained from the comparison lines. It is in these regions that the greatest errors in the calibration may exist. In addition to possible errors arising from the wavelength calibration, many if not most of the measured features are blends of two or more lines. Consequently, the tabulated wavelengths are only mean values for the "center of gravity" of the blend. This propensity for the absorption features in OQ 172 to be blended at 3.5 Å resolution has caused severe difficulty in interpreting the spectrum. In figure 1 we have noted the location of the wavelengths listed in table 2. The reader is cautioned to examine figures 1 and 2 carefully to assess the likelihood that a feature he may be interested in is blended. Because of the problem with blending we have not tabulated the equivalent widths of the lines. Again, reference may be made to the figures to estimate the strength of a particular line.

The emission lines, used to obtain the redshift of OQ 172 (Wampler *et al.* 1973), are also listed in table 2. There appears to be a weak emission line, not noticed previously, which, if it has the same redshift as the other emission lines, is at a rest wavelength of 1267 ± 4 Å. This line could be due to Si II $\lambda\lambda 1261$–1265, although this feature has not been reported in emission in the spectra of other quasi-stellar sources. A similar feature which could be Si II $\lambda\lambda 1527$–1533 is possibly present in the wing of C IV $\lambda 1549$, at a wavelength corresponding to 1521 Å; this is, however, rather far from the expected wavelength of the Si II feature. It is also possible that these lines are artifacts produced by absorption in the wings of Lα and C IV which have depressed the continuum level. The intensity ratio Lα/C IV is 2.7 ± 0.4, a value close to the value 4 found for other quasi-stellar sources. We have attempted to decide if Lβ is in emission and have found little evidence for a feature at $\lambda 4650$, the wavelength corresponding to redshifted $\lambda 1026$. Because there is substantial radiation well below the Lyman continuum limit, this is somewhat surprising, particularly since Lβ has been found in the spectra of other quasi-stellar sources (Oke *et al.* 1970; Carswell and Strittmatter 1973). Although there is undoubtedly heavy absorption in this spectral region, the highest points of the spectrum do not rise above a continuum level extrapolated from longer wavelengths. It can be seen from figure 1 that there are some very strong absorption lines some distance on either side of the expected position of Lβ which could produce a spurious effect like a line at the expected Lβ position on data taken with very low resolution.

III. ANALYSIS OF THE ABSORPTION LINES

We have attempted to interpret the absorption lines listed in table 2 as lines produced by cosmically abundant elements in gas clouds of various redshifts. This is a difficult task, since the spectrum of OQ 172 is so rich in absorption features. We found, by comparing spectra taken on different nights, that we were able to reproduce the measured wavelength of a given absorption line to an accuracy of about ± 0.5 Å. With this uncertainty, and taking into account that many of the measured features are probably blends of several lines, the probability of finding a line by chance within an acceptable error of a predicted feature was about 1/5.

Absorption-line spectra of this type can be analyzed by two methods: (*a*) a search for strong features and doublets and trial fits with various characteristic resonance lines, e.g., by computing wavelength ratios (cf. Burbidge, Lynds, and Stockton 1968), and (*b*) "automatic" methods such as a search by computer for a specified number of line fits with an expected list of characteristic lines (cf. Bahcall 1968). We have tried both methods. In method (*b*) we cross-correlated the observed wavelengths with a list of "standard" lines expected in QSO spectra, and also autocorrelated them. There is such a large number of lines in OQ 172, however, that the correlation functions showed too much noise to enable any believable identifications to be picked out.

Method (*a*) yielded some half-dozen possible redshift systems. However, not only is there a very large number of lines, many blended, but we do not know

TABLE 2

WAVELENGTHS OF ABSORPTION LINES IN OQ 172

No.	λ	No.	λ	No.	λ	No.	λ
1	3325.2	45	4217.3	89	4809.8	133	5301.2
2	3337.4	46	4230.9	90	4821.4	134	5311.3
3	3451.7	47	4241.7	91	4839.3	135	5325.7
4	3462.0	48	4257.0	92	4845.2	136	5338.7
5	3486.4	49	4269.7	93	4849.5	137	5352.1
6	3508.6	50	4280.2	94	4856.4	138	5357.9
7	3520.2	51	4295.2	95	4867.5	139	5371.0
8	3528.9	52	4304.4	96	4876.9	140	5387.0
9	3549.2	53	4321.9	97	4885.9	141	5398.5
10	3586.4	54	4331.9	98	4895.2	142	5404.9
11	3599.5	55	4345.5	99	4903.0	143	5418.5
12	3629.9	56	4358.2	100	4917.2	144	5430.4
13	3651.7	57	4363.9	101	4941.1	145	5439.3
14	3661.1	58	4374.5	102	4953.4	146	5450.4
15	3697.7	59	4388.0	103	4969.8	147	5459.9
16	3731.4	60	4405.2	104	4976.1	148	5470.3
17	3738.0	61	4416.2	105	4986.4	149	5481.3
18	3754.9	62	4436.7	106	4995.0	150	5486.3
19	3786.4	63	4448.3	107	5004.8	151	5497.9
20	3821.4	64	4460.6	108	5016.1	152	5514.2
21	3830.5	65	4486.1	109	5025.6	153	5524.0
22	3836.1	66	4494.7	110	5031.4	154	5534.5
23	3871.1	67	4505.6	111	5042.9	155	5543.4
24	3897.7	68	4517.3	112	5053.0	156	5557.4
25	3934.2	69	4530.6	113	5062.8	157	5566.3
26	3949.9	70	4546.6	114	5076.5	158	5575.6
27	3971.4	71	4584.4	115	5093.1	159	5598.5
28	3979.5	72	4593.3	116	5100.6	160	5609.9
29	4002.0	73	4614.7	117	5119.7	161	5622.8
30	4033.3	74	4620.0	118	5126.0	162	5632.8
31	4039.9	75	4644.5	119	5139.8	163	5648.4
32	4067.2	76	4658.7	120	5154.2	164	5667.0
33	4074.1	77	4677.7	121	5167.0	165	5677.3
34	4085.0	78	4691.2	122	5186.5	166	5692.3
35	4093.5	79	4696.2	123	5201.0	167	6003.6
36	4102.2	80	4710.5	124	5212.6	168	6019.5
37	4111.6	81	4729.2	125	5221.0	169	6067.5
38	4116.9	82	4740.2	126	5234.3	170	6105.3
39	4134.4	83	4750.8	127	5238.7	171	6187.2
40	4147.1	84	4758.3	128	5247.8	172	6224.8
41	4156.7	85	4768.0	129	5254.3	173	6249.2
42	4171.9	86	4777.7	130	5267.1	174	6256.6
43	4193.1	87	4787.0	131	5279.0	175	6266.3
44	4202.5	88	4801.7	132	5290.4		

NOTE.—Emission lines: Lα λ1216, λ5539; Si II λ1263, λ5739; C IV λ1549, λ7015.

a priori which ions will produce strong lines in a suspected redshift system. For these reasons the usual practice of accepting a system if it contains four to five lines which can be matched to observed lines would produce many accidental identifications. It is therefore necessary to use additional information, particularly line intensities and profiles. We list in tables 3 and 4 four of the redshift systems found, although it may turn out that when higher dispersion spectra are available and blended lines are resolved, that additional systems will be found to be acceptable. The spectroscopic data in tables 3 and 4 are taken from Wiese, Smith, and Glennon (1966) and Wiese, Smith, and Miles (1969).

The most interesting system is listed in table 3. Of the 22 lines identified in this system, eight have been identified as lines due to Si II. In addition to the zero-volt Si II lines, fine-structure lines also appear to be present (see fig. 2; also fig. 1 and table 2), and are present in C II in addition. Although fine-structure lines have been seen previously in 3C 191 (Stockton and Lynds 1966; Bahcall, Sargent, and Schmidt 1967) and may be present in 1331+170 (Strittmatter *et al.* 1973), they have not been seen in an absorption-line system that has such a low redshift compared with the emission-line redshift. The population of the fine-structure levels implies that the absorbing cloud producing these lines is located physically near the object and is not a chance intergalactic cloud or a cloud associated with a foreground galaxy (cf. Bahcall and Wolf 1968).

There are two second-order scans which together cover the wavelength region in which fine-structure lines appear; they overlap for 150 Å at 5000 Å. In no case are any of the tabulated fine-structure lines absent when they fall within the observed region. In view of

TABLE 3

REDSHIFT SYSTEM AT z = 3.0663 IN OQ 172

Line	Identification	log gf	λ (tab) (Å, vacuum)	λ (obs) (Å, vacuum)	z
164	Si IV	+0.03	1393.76	5668.6	3.0671
144	C II	−0.02	1335.71 fs	5431.9	3.0667
144 wing	C II	−0.28	1334.53	...	...
142	C I	−0.47	1329.3 bl	5406.4	3.0671
135	Si II	−0.44	1309.27 fs	5322.9	3.0656
133	Si II	−0.74	1304.37	5307.2	3.0688*
130	S I	−0.22	1295.66	5268.6	3.0660
119	Si II	+0.63	1264.75 fs	5141.2	3.0650
118	Si II	+0.38	1260.42	5127.4	3.0680
117	S II	−1.32	1259.53	5121.1	3.0659
115	S II	−1.40	1253.79	5094.5	3.0633†
101	Lα	−0.08	1215.67	4942.5	3.0657
99	Si III	+0.23	1206.51	4904.4	3.0650
97	S III	+0.40	1200.97	4887.3	3.0694‡
96	N I	+0.15	1199.9 bl	4878.3	3.0654
95	Si II	−0.22	1197.39 fs	4868.9	3.0663
94	Si II	+0.48	1194.50 fs	4857.8	3.0668
93	Si II	+0.09	1193.28	4850.9	3.0652
91	Si II	−0.22	1190.42	4839.3	3.0652
73	N I	−0.27	1134.6 bl	4616.0	3.0682
45	C II	−0.63	1037.02 fs	4218.5	3.0679
45 wing	C II	−0.93	1036.34	...	...
42	Lβ	−0.80	1025.72	4173.1	3.0685§
27	C III	−0.09	977.03	3972.5	3.0659

* Blend with O I?

† Blend of two lines. Red wing of blend agrees.

‡ Doubtful.

§ O I λ1026.6 may be blended.

the importance of this result, in order to check against the appearance of spurious features, we divided the second-order scans into two halves, and reduced the data obtained during the first and second half of the observation separately. Each half clearly shows the fine-structure lines. Further, an additional scan of the wavelength region 3700–4750 Å was obtained very recently with an 830-line grating. The only fine-structure line falling in this region and listed in tables 2 and 3 is C II λ1037, No. 45. It is clearly present.

The absorption-line system z = 3.066 has moderately low ionization, since some neutral elements appear to be present. In addition to the lines identified in table 3, the following lines are probably present: Si IV λ1402.77, Fe II λ1144.95, Fe III λ1122.53, Lγ, and Lδ.

The first system listed in table 4 was the first one picked out, because there is a very obvious strong doublet in the short-wavelength wing of the Lα emission line, and the relative intensities and wavelength ratio are consistent with its being C IV $\lambda\lambda$1550.77, 1548.20, rather strongly saturated, a doublet very commonly seen in absorption. However, although the wavelengths listed and the intensities support the identification of this as a real system, it does not contain many lines.

The other two possible systems in table 4 fall into a different category, in that they show only Lyman lines. It has been suggested by Lynds (1971) that many of the absorption lines seen in the spectrum of 4C 5.34 are caused by Lα in clouds of sufficiently low surface density so that lines from other elements are not seen. Particularly because the Lyman continuum is optically thin, the same situation may also exist for OQ 172. To test for this possibility a second "automatic" method was used: we put the data from the scanner on a logarithmic wavelength scale and autocorrelated them. In this way line intensities and profiles are properly taken into account. Peaks in the autocorrelation function would be expected to appear at shifts corresponding to ratios of prominent lines or rich absorption-line systems. Figure 3 shows the results of this analysis using all the data. It is evident that there are peaks in the function corresponding to various combinations of the Lyman lines, and combinations of Lα with Si II and other features. This plot suggests that many of the absorptions are probably Lyman lines at a large number of redshifts. In order to determine the number of different redshift systems that may be present we also autocorrelated the logarithms of the wavelengths of the lines given in table 2. At a shift corresponding to the Lβ/Lα ratio we find an excess of about 20 coincidences over the chance coincidence rate. However, the fluctuations in the background rate are large and the actual number of different redshift systems is very uncertain. Data with higher spectral resolution will be required for the different redshift systems to be sorted out with confidence. In figure 4 we plot two spectra of OQ 172 with one spectrum shifted by the amount corresponding to the ratio of Lβ/Lα. It is evident that many of the strong lines can be identified as Lβ/Lα pairs.

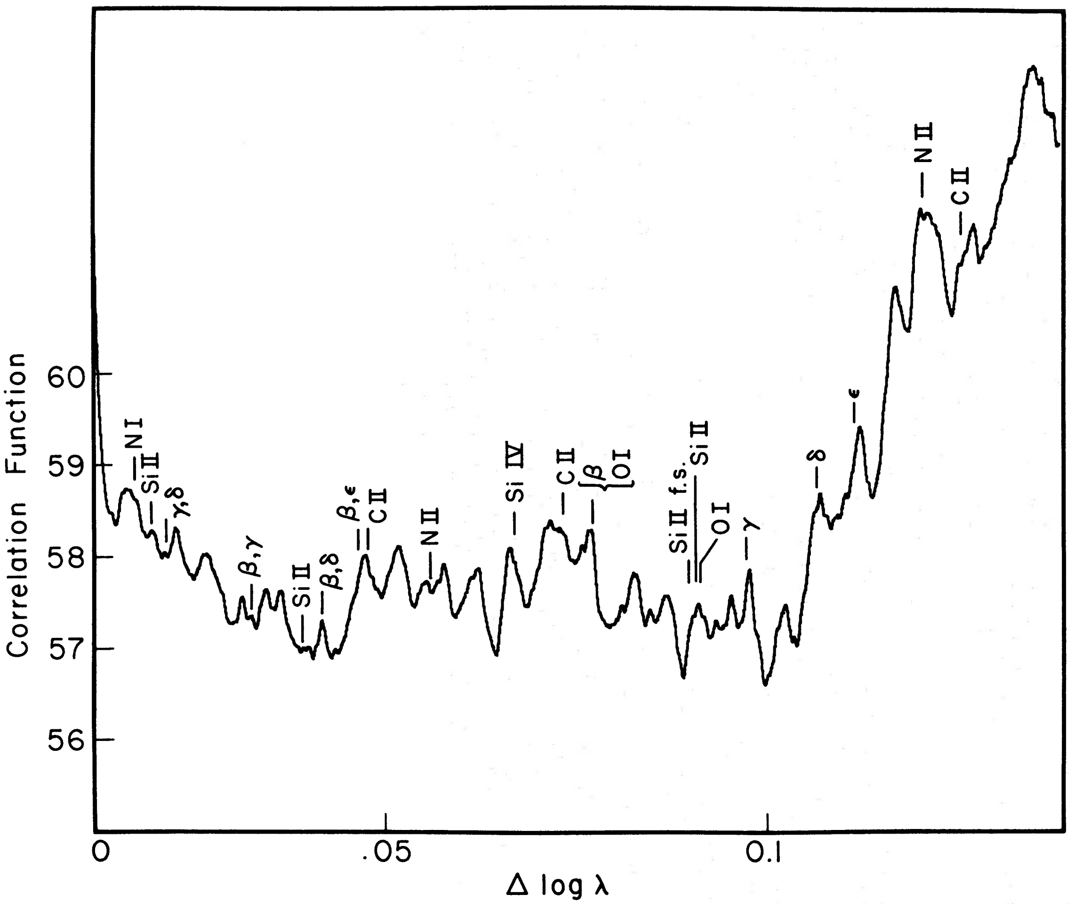

FIG. 3.—Autocorrelation function computed by successively shifting spectrum by Δ log λ and multiplying by unshifted spectrum. Identifications of peaks denote correspondence between Lα and lines of various ions. Symbols β, γ, etc., denote correspondence between Lβ and Lγ, etc. Si II fs refers to Si II lines from excited fine-structure states.

TABLE 4

FURTHER POSSIBLE REDSHIFT SYSTEMS IN OQ 172

Line	Identification	log *gf*	λ (tab) (Å, vacuum)	λ (obs) (Å, vacuum)	*z*
z = 2.5639:					
153	C IV	−0.72	1550.77	5525.6	2.5631
152	C IV	−0.42	1548.20	5515.7	2.5627
84	C II	−0.02	1335.71 fs	4759.6	2.5633
84 wing	C II	−0.28	1334.53	...	...
54	Lα	−0.08	1215.67	4333.1	2.5644
15	O VI	−0.89	1037.63	3698.8	2.5647
8	N III	+0.03	990.98 bl, wfs	3529.9	2.5621
z = 3.094–3.089:					
104	Lα	−0.08	1215.67	4977.5	3.0945 }
103	Lα	−0.08	1215.67	4971.2	3.0893 }
43	Lβ	−0.80	1025.72	4194.3	3.0891
28	Lγ	−1.24	972.54	3980.6	3.0930
16	Ly cont.	...	912	3732.5	3.0926
z = 2.698–2.691:					
66	Lα	−0.08	1215.67	4496.0	2.6984 }
65	Lα	−0.08	1215.67	4487.4	2.6913 }
19	Lβ	−0.80	1025.72	3787.5	2.6925
10	Lγ	−1.24	972.54	3587.4	2.6887

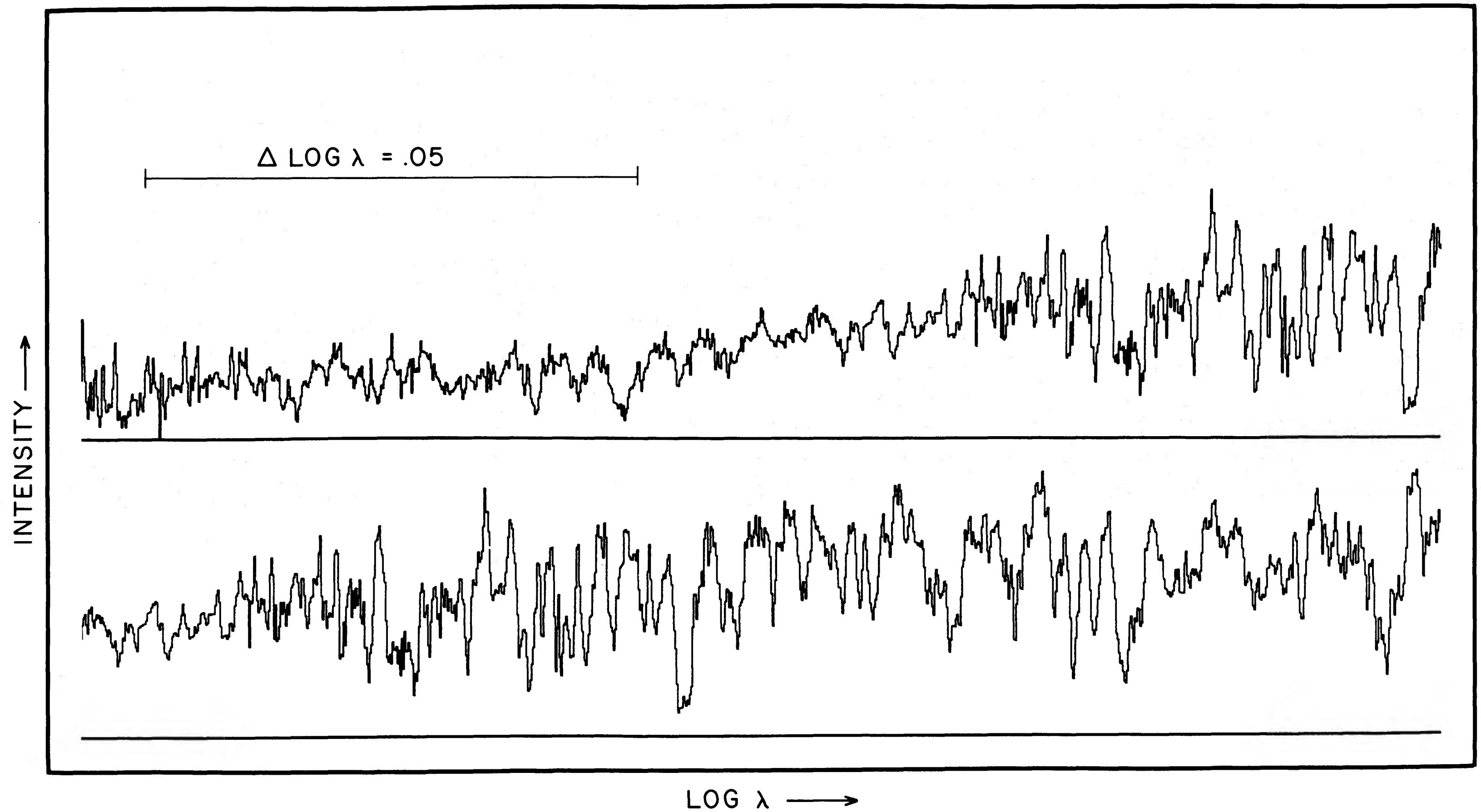

FIG. 4.—Two tracings of the blue portion of the spectrum of OQ 172, offset by log [$\lambda(L\alpha)/\lambda(L\beta)$]. There are many coincidences between absorption lines in the bottom tracing, which might be $L\alpha$, and lines in the top tracing, which might be $L\beta$.

The result of this analysis is that many of the absorption features seen in the spectrum of OQ 172 are probably due to hydrogen absorption. Lines from metallic ions may also be present, and the most likely candidates are ions of Si and C. There is substantial radiation even at wavelengths below the redshifted Lyman limit of several of the absorption-line systems. The gradual falloff of the continuum level in the violet may be due to overlapping Lyman continuum absorption in various redshift systems. In fact, the drop by about a factor of 2 in the continuum level near $\lambda 3740$ may be due to continuum absorption with an optical depth $\tau \simeq 0.5$ from the absorption-line redshift system, $z = 3.066$.

Both the possible redshift systems 3 and 4 have strong double Lα. In the system at $z = 3.094$–3.089 the longer-wavelength component of Lα is the stronger, but the longer-wavelength component of Lβ is blended with other lines and could not be measured, and the feature measured for Lγ is a blend of both components.

In the system at $z = 2.698$–2.691, the two components of Lα are of equal intensity, the features measured for both Lβ and Lγ are broad blended features, and Lδ may be present.

IV. DISCUSSION

A striking difference was noted in §§ I and II between the behavior of the continuum at the positions of the Lyman limit at the emission-line redshift in the two QSOs of highest redshift, OQ 172 and OH 471. One might expect that this behavior, which obviously depends on the optical thickness of the emitting gas in the Lyman continuum, would be correlated with the ratio of intensities of Lα and Lβ emission. Bahcall (1966) made a detailed study of this problem—the escape of Lyman radiation from an ionized gas cloud; see also Osterbrock (1962). Bahcall showed that for an optically thin nebula, Lα/Lβ is near 5 and is rather insensitive to the temperature T_e. For an optically thick nebula, the detailed analysis of the diffusion outward of all lines but Lα is a complicated problem; considerable but not complete attenuation of the higher lines occurs so that their escaping quanta are created in a shell of optical depth of not more than unity. In OQ 172, for a model with the usual assumption that the ionization is caused by a flux of ultraviolet radiation, the Lβ/Lα intensity ratio is probably $\lesssim 0.1$, and this is hard to reconcile with the lack of appreciable optical depth shortward of the Lyman limit. It appears to require a highly nonhomogeneous model for the region producing the emission lines, in which they arise in optically thick blobs very near to, but covering only a small fraction of, a central strong continuum source. If the inner edges of these blobs are photoionized by radiation from the central source, then we should still see unattenuated Lβ emission from any blobs located on the far side of the central source. This suggests that each blob may instead contain a source of its own self-ionizing radiation.

Further difficulties arise when we try to extend the discussion to the absorption lines, which are presumably produced in outward-moving gas considerably further out than the emitting blobs but not a very large distance from the central source because the fine-structure levels in Si II and C II are populated. Many of the absorption lines are probably essentially black in the center, so that the absorbing gas must totally cover this source.

Radio data for OQ 172 are available from the catalogs of Kraus and Andrew (1970); Witzel, Véron, and Véron (1971); Jauncey, Niell, and Condon (1970); Hoskins *et al.* (1972); Murdoch (1974); and most recently by Gearhart *et al.* (1974). The radio flux shows a maximum and turnover at about 1 GHz. It then falls rather steeply to about 20 GHz, and then rises again (Gearhart *et al.* 1974). This suggests that more than one radio component is present. The scales of typical compact radio components are such that it is likely that at least one compact component lies behind, and is entirely covered by, the gas clouds producing the absorption lines. However, the shape of the spectrum at the cutoff indicates that the mechanism at work is probably synchrotron self-absorption rather than free-free absorption.

We now turn to a consideration of constraints on the physical conditions set by our observations of the absorption lines. First, we wish to point out that, using the cosmological interpretation for redshifts, the intrinsic luminosity of OQ 172 is very high. Using the well-known formula relating observed flux and emitted luminosity (cf. Oke *et al.* 1970), for a Hubble constant of 50 km s^{-1} Mpc^{-1}, the bolometric luminosity of OQ 172 is about 4×10^{46} and 4×10^{47} ergs s^{-1} for $q_0 = 1$ and 0, respectively.

In order to examine the constraints placed on various quantities by the observations, we first note that, as well as there being no detectable break at the Lyman limit in the emission-line redshift, there is substantial radiation below the Lyman limit in those absorption-line systems where it is observable. We must therefore consider the case in which gas clouds covering the source are optically thin in the Lyman continuum. These gas clouds are probably in ionization equilibrium and we can equate the number of ionizations to the number of recombinations. Let r be the distance of the absorbing gas from the ionizing source, L the luminosity of the source in ergs s^{-1}, n the number of electrons cm^{-3}, and f the fraction of the hydrogen that is neutral, i.e., $f = N_{\rm H}/N_{\rm H^+}$. We use 5×10^{-13} as the recombination coefficient (Allen 1964), 10^{-17} cm^2 as the cross-section for absorption of a quantum in the Lyman continuum in which 1 erg $\simeq 5 \times 10^{10}$ quanta, and $10^{-1}L/4\pi r^2$ as a reasonable approximation to the radiative flux in the Lyman continuum. The condition for ionization equilibrium then gives

$$n \simeq 10^4(fL/r^2)\,. \tag{1}$$

If we take the column density of neutral hydrogen atoms to be 10^{15} cm^{-2}, a value required to produce Lα absorption with close to saturation conditions (cf.

Chan and Burbidge 1971), so that $n\Delta r \simeq 10^{15} f^{-1}$, we have

$$\frac{\Delta r}{r} = \frac{10^{11} r}{f^2 L}\,. \tag{2}$$

If the redshifts are cosmological and the difference between the emission- and absorption-line redshifts is a velocity shift, the speeds required must be of the order of c in those cases where $z_{\rm em} - z_{\rm abs} \simeq 1$. If the outward velocity is derived from radiation pressure (Mushotzky, Solomon, and Strittmatter 1972; Scargle 1973) we need

$$\frac{\Delta\lambda}{\lambda}\frac{L}{4\pi r^2}\frac{1}{c}\frac{r}{c} \simeq n\Delta r m_{\rm H} c\,; \tag{3}$$

the right-hand side gives the outward momentum for all atoms in a unit column. This momentum is produced by absorbing radiation from a line of width $\Delta\lambda$, wavelength λ, for a time $\simeq r/c$. Setting $\Delta\lambda/\lambda \simeq 10^{-3}$ and simplifying equation (3) using the estimate for $n\Delta r$, we have

$$L = (5 \times 10^{26} r)/f. \tag{4}$$

Substituting equation (4) into equation (2) we obtain

$$\Delta r/r = (2 \times 10^{-16})/f. \tag{5}$$

Clearly, very small values of Δr can be avoided only if f is very small. The identification of lines with a wide range of ionization potentials, however, as in system 1, table 3, indicates that there is a wide mixture of ionization states. It is therefore possible that f is relatively high, perhaps on the order of 10^{-3}. If this is true, equation (2) can be used to set severe constraints on the density and thickness of the absorbing shell. For $r \simeq 10^{23}$ cm and $L \simeq 10^{47}$ ergs s^{-1} we find $n \simeq 10^2$ cm^{-3} and $\Delta r \simeq 10^{16}$ cm. For $r \simeq 3 \times 10^{17}$ cm and $L \simeq 10^{42}$ ergs s^{-1} we find $\Delta r \simeq 10^{10}$ cm and $n \simeq 10^8$ cm^{-3}; the same values as the latter are obtained for $r \simeq 3 \times 10^{19}$ cm and $L \simeq 10^{46}$ ergs s^{-1}.

The radio spectrum of OQ 172 is complex (Gearhart *et al.* 1974), suggesting that several components are involved. If they are highly compact and the absorbing clouds lie between us and the radio source, then we can use the fact that radio flux is observed to place a further restriction on the absorbing cloud. That the radio spectrum is not cut off at low frequencies by free-free absorption sets an upper limit to the emission measure coming from that fraction of the gas that is ionized, x, where $x/(1 - x) = 1/f$. We have (Allen 1964)

$$x^2 n^2 \Delta r \lesssim 10^{25} T_4^{3/2}\ \text{cm}^{-5}. \tag{6}$$

For $f \lesssim 10^{-3}$, $x \simeq 1$; T_4 is the temperature in 10^4 ° K and is probably less than 1.5. Squaring equation (3) and dividing this by inequality (6), we find that

$$f^2 \Delta r \gtrsim 5 \times 10^4, \tag{7}$$

and if we use $f = 10^{-3}$ as before, we obtain $\Delta r \gtrsim 5 \times 10^{10}$ cm, which is consistent with results obtained from equation (5).

Finally, it is worth noting that if the turnover in the radio spectrum at about 1000 MHz is due to synchrotron self-absorption, the maximum brightness temperature yields a minimum size for the angular diameter of the source. Discussions of compact radio sources (Jones, O'Dell, and Stein 1974) indicate, from consideration of the flux in Compton scattered photons, that the magnetic field should be of the order of a few milligauss. The observed radio maximum then gives a lower limit to the angular diameter of the source of about 6×10^{-3} arc seconds. At a cosmological distance this is at least 10 pc, or larger with $H = 50$ km s^{-1} Mpc^{-1} and $q_0 < 1$. This is consistent with the first of the possible set of dimensions obtained from equation (4), except that the density n obtained from this set of values, $n \simeq 10^2$ cm^{-3}, is rather low in view of the fact that the fine-structure levels of Si II and C II are populated in the redshift system $z = 3.066$ in table 3.

V. CONCLUSIONS

The large emission-line redshift of OQ 172, $z = 3.53$, brings Lα to a wavelength of 5539 Å and makes visible a long stretch of ultraviolet spectrum. In particular, the redshifted positions of Lβ and the Lyman series limit fall at the easily observable positions 4647 and 4131 Å, respectively. As we have discussed, there is no detectable absorption drop (or onset of continuous emission) at the Lyman limit, nor is there a measurable emission line at the position of Lβ. The physical conditions must therefore be different in OQ 172 and OH 471. We have suggested that the emission regions in OQ 172 are complex, and that the main continuum source is a source of synchrotron radiation, extending from radio to ultraviolet wavelengths, which does not undergo absorption from the gas producing the emission lines but only from the large number of gas clouds or filaments with multiple redshifts, $z < 3.53$. These gas clouds must be optically thin in the Lyman continuum. The emission lines, meanwhile, arise in gas which appears to be optically thick, since Lα/Lβ > 5, and in which the usual broadening mechanisms (perhaps electron scattering or random cloud motions) are at work.

In the very rich absorption-line spectrum in OQ 172, the system at $z = 3.066$ with 22 lines is the most interesting. Its redshift is well established. The ionization level is not very high; the elements C, N, Si, S appear in several ionization stages. The appearance in this system of absorptions from the fine-structure states of the ground levels of C II and Si II strengthens the arguments for the case that the absorption lines arise in gas associated with the QSO, not only in OQ 172, but in other objects with absorptions at many different redshifts.

Sulfur lines are not often identified in QSOs, so their presence in OQ 172 is worth noting. Burbidge *et al.* (1968) identified S lines in PKS 0237-23; a check on these identifications should be made. It would be interesting also to investigate whether the line strengths in OQ 172 imply a high abundance of S.

Further observations at higher resolution are required in order to make further progress in analyzing the absorption spectrum of OQ 172. The region between the emission lines of Lα and C IV λ1549 should also be studied in greater detail.

An absorption system listed in table 4 has $z = 2.564$; the strongest features besides Lα are C IV $\lambda\lambda$1548, 1551 which appear in the blue wing of Lα emission. This phenomenon may be due to "line-locking," if the absorbing gas is driven outward from the central source by radiation pressure.

The autocorrelation study carried out on OQ 172 has indicated that many of the unidentified absorptions are Lα/Lβ pairs (perhaps 20 sets), some of which have in addition higher Lyman lines at the appropriate redshifts. If this is so, there will undoubtedly be many more lines which are due to Lα alone, with insufficient optical depth to produce measurable Lβ.

Consideration of the ionization equilibrium and column density in the gas producing the absorption lines, together with the assumption that radiation pressure drives the gas outward from the energy source, leads to equations setting limits to the shell (or filament) thickness and density as a function of the distance of the absorbing gas from the source and the luminosity of the source. Luminosities that are consistent with a cosmological or a local distance for OQ 172 both yield feasible filament (shell) thicknesses and distances from the source, e.g., $\Delta r \simeq 10^{16}$–10^{10} cm, $r \simeq 10^{23}$–3×10^{17} cm, and densities e.g., 10^2–10^8 cm^{-3}. A further restriction set by the radio spectrum is that $\Delta r \geqslant 5 \times 10^{10}$ cm. We conclude that these data do not provide a criterion for distinguishing between cosmological or local distances.

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REFERENCES

Allen, C. W. 1964, *Astrophysical Quantities* (London: Athlone Press).
Bahcall, J. N. 1966, *Ap. J.*, **145**, 684.
———. 1968, *ibid.*, **153**, 679.
Bahcall, J. N., Sargent, W. L. W., and Schmidt, M. 1967, *Ap. J.* (*Letters*), **149**, L11.
Bahcall, J. N., and Wolf, R. A. 1968, *Ap. J.*, **152**, 701.
Burbidge, E. M., Lynds, C. R., and Stockton, A. N. 1968, *Ap. J.*, **152**, 1077.
Carswell, R. F., and Strittmatter, P. A. 1973, *Nature*, **242**, 394.
Chan, Y.-W. T., and Burbidge, E. M. 1971, *Ap. J.*, **167**, 213.
Gearhart, M. R., *et al.* 1974, preprint.
Hayes, D. S. 1970, *Ap. J.*, **159**, 165.
Hoskins, D. G., Murdoch, H. S., Hazard, C., and Jauncey, D. L. 1972, *Australian J. Phys.*, **25**, 559.
Jauncey, D. L., Niell, A. E., and Condon, J. J. 1970, *Ap. J.* (*Letters*), **162**, L31.
Jones, T. W., O'Dell, S. L., and Stein, W. A. 1974, *Ap. J.*, in press.
Kraus, J. D., and Andrew, B. H. 1970, *Ap. J.* (*Letters*), **159**, L41.
Lynds, R. 1971, *Ap. J.* (*Letters*), **164**, L73.
Murdoch, H. S. 1974, *Nature*, **247**, 443.
Mushotzky, R. F., Solomon, P. M., and Strittmatter, P. A. 1972, *Ap. J.*, **174**, 7.
Oke, J. B. 1970, *Ap. J.* (*Letters*), **161**, L17.
Oke, J. B., Neugebauer, G., and Becklin, E. E. 1970, *Ap. J.*, **159**, 341.
Osterbrock, D. E. 1962, *Ap. J.*, **135**, 195.
Robinson, L. B., and Wampler, E. J. 1972, *Pub. A.S.P.*, **84**, 161.
Scargle, J. D. 1973, *Ap. J.*, **179**, 705.
Stockton, A. N., and Lynds, C. R. 1966, *Ap. J.*, **144**, 451.
Strittmatter, P. A., Carswell, R. F., Burbidge, E. M., Hazard, C., Baldwin, J. A., Robinson, L. B., and Wampler, E. J. 1973, *Ap. J.*, **183**, 767.
Wampler, E. J., Robinson, L. B., Baldwin, J. A., and Burbidge, E. M. 1973, *Nature*, **243**, 336.
Wiese, W. L., Smith, M. W., and Glennon, B. M. 1966, *Atomic Transition Probabilities*, Vol. **1** (NSRDS-NBS 4).
Wiese, W. L., Smith, M. W., and Miles, B. M. 1969, *Atomic Transition Probabilities*, Vol. **2** (NSRDS-NBS 22).
Witzel, A., Véron, P., and Véron, M. P. 1971, *Astr. and Ap.*, **11**, 171.

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