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SPLITTING OF ABSORPTION LINES IN 3C 191

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ABSTRACT

Spectroscopic observations of the quasar 3C 191 have been made at a higher dispersion than previous studies in an attempt to detect absorption from the excited fine-structure level of the ground state of C II. It was found that the previously studied absorption system is split into two systems ($z_A = 1.945$, $z_B = 1.949$), which show apparent line-locking on the C IV λ1550 doublet. Both systems show a similar and wide range of ionization. The results are interpreted in terms of a multiple cloud model which is photoionized by a central source, and the possible implications for the ionization structure in QSOs generally are discussed.

Subject headings: quasi-stellar sources or objects — redshifts

I. INTRODUCTION

The quasar 3C 191 ($z_{\rm em} = 1.953$) is of special interest in that it was the first QSO found to have a rich absorption line spectrum ($z_{\rm abs} = 1.947$) (Burbidge *et al.* 1966), and it remains the best example of a quasar in which there is significant absorption from excited fine-structure levels of the ground state. As was shown by Bahcall and Wolf (1968), the relative population of excited fine-structure levels provides a powerful probe of the physical conditions in the absorbing material. In the case of 3C 191, Stockton and Lynds (1966) found absorption features corresponding to the Si II λ1264 and λ1533 transitions from the $J = 3/2$ excited fine-structure level of the ground state. It is for this reason, and the fact that $z_{\rm abs} \approx z_{\rm em}$, that 3C 191 is widely regarded as the prototype of objects having an intrinsic absorption-line spectrum. The object was further analyzed by Bahcall *et al.* (1967), who deduced from the relative Si II line strengths that (*a*) the absorption arose in a region of density $n \leqslant 10^3$ cm^{-3}, with equality holding if electron collisions provide the excitation mechanism, and (*b*) the distance R of the absorbing material from the 3C 191 continuum source satisfies $R \geqslant 10^{2\pm1}$ pc, with equality holding if the fine-structure excitation is due to ultraviolet fluorescence. In either case, it follows from the computed atomic cross sections (cf. Bahcall and Wolf 1968, Fig. 1) that the C II $J = 3/2$ level is more readily populated than the corresponding Si II level—which leads one to expect a strong C II λ1335.7 absorption line in 3C 191. This feature is not resolved from the λ1334.5 ground-state line in the existing spectrograms of 3C 191. Its relative intensity, however, does provide an important check on the excitation mechanism (Grewing and Strittmatter 1973), and in particular might allow limits to be placed on the infrared luminosity of QSOs.

For this reason, we decided to undertake higher resolution studies of 3C 191. Our attempts to resolve the C II fine structure, however, have been unsuccessful due to the discovery that the absorption system in 3C 191 is in fact double, with apparent line-locking occurring in the C IV resonance doublet. A doubling of the absorption spectrum had previously been inferred from the earlier data by Scargle (1973) on the basis of a radiation pressure driven outflow model for the absorbing material.

II. THE OBSERVATIONS

Five spectrograms of 3C 191 have been obtained with the Cassegrain spectrograph and RCA 33063 image tube at the Steward Observatory 2.3-m telescope. The reciprocal dispersion is approximately 45 Å mm^{-1}, giving a useful spectral coverage per plate of ~800 Å. The observational material is summarized in Table 1; and two spectrograms, SI 1232 and SI 1237, are reproduced in Figure 1 (Plate 1). The spectrograms were microdensitometered on the PDS machine at Kitt Peak National Observatory using a 16 × 16 μ aperture, and the digital data so obtained were then reduced on the University of Arizona CDC 6400 computer. Our reduction process involved removal of ion events and conversion to intensity via a step wedge calibration. The final intensity plot is shown in Figure 2. In Table 2 we list the wavelengths

TABLE 1

SUMMARY OF OBSERVATIONAL MATERIAL

Plate (SI)	Widening (mm)	Exposure (min)	Spectral Range (Å)
1167a......	0.2	68	3400–4600
1167b......	0.2	79	3400–4600
1181.......	0.2	68	3300–4300
1232.......	0.6	220	3300–4300
1237.......	0.4	143	3800–4800

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TABLE 2

DEFINITE ABSORPTION LINES

λ (Å)	Identification	1 + z	Comments
3411...........	Unknown	...	...
3514...........	Si II λλ1190.4, 1193.3 1194.5, 1197.4	...	Very broad, considerable structure
3556.6.........	Si III λ1206.5	2.9478	Wide
3569.5.........	Unknown	...	
3680.6.........	Lα	2.9453	
3586.6.........	Lα	2.9494	
3648.5.........	N V λ1238.8	2.9452	
3653.9.........	N V λ1238.8	2.9495	
3660.0.........	N V λ1242.8	2.9450	
3664.1.........	N V λ1242.8	2.9483	Weak
3712.5.........	Si II λ1260.4	2.9455	
3715.9.........	Si II λ1260.4	2.9482	
3725.0.........	Si II λ1264.4	2.9461	
3729.0.........	Si II λ1264.4	2.9492	Weak
3933.1.........	C II (λ1335.3)	(2.9455)	Blend of 1334.5 and 1335.7
3936.2.........	C II λ1334.5	2.9496	
4104.9.........	Si IV λ1393.8	2.9451	
4111.5.........	Si IV λ1393.8	2.9498	
4131.7.........	Si IV λ1402.8	2.9453	
4137.9.........	Si IV λ1402.8	2.9497	
4496.1.........	Si II λ1526.7	2.9450	
4517.4.........	Si II λ1533.5	2.9458	
4559.9.........	C IV λ1548.2	2.9453	
4567.2.........	C IV $\left\{\begin{matrix}1550.8\\1548.2\end{matrix}\right\}$	$\left\{\begin{matrix}2.9451\\2.9500\end{matrix}\right\}$	
4573.4.........	C IV λ1550.8	2.9491	

of definite absorption features in the spectrum of 3C 191. Also listed, where possible, are line identifications and the corresponding redshift factors $1 + z$. Certain other possible features are present in our spectra which are either weak and/or variable in character from plate to plate; these have not been listed in Table 2. In comparing our data with those of Stockton and Lynds (1966), we are able to confirm most of their absorption features, and to show that many of them are double. We do not, however, confirm absorption at 3629 or 3972 Å. All features measured by Bahcall *et al.* (1967) are present on our spectra.

III. DISCUSSION

It is clear from Figures 1 and 2 that most of the strong absorption features in the spectrum of 3C 191 are double, with the redward component generally being rather weaker. The features are clearly resolved at wavelengths longward of ~4000 Å but appear only as redward wings at the lower wavelengths. This is due to the decrease in effective resolution in velocity space at lower wavelengths using a conventional grating spectrograph. The structure in the C IV λ1550 feature is particularly striking in that this doublet appears triple. In this respect it is similar to the Mg II doublet in the QSO 1331+170 (Strittmatter *et al.* 1973). The suggestion of two absorption systems is amply confirmed by the redshift factors in Table 2—system A with $z = 1.9453$, and system B with $z = 1.9494$. The velocity difference $\Delta v \approx 630\ \mathrm{km\ s^{-1}}$ is slightly in excess of the C IV λ1550 doublet splitting. Although an apparent locking of this type could well occur by chance, especially in an object with similar absorption and emission line redshifts, we feel that it is quite likely a systematic effect. The circumstantial evidence which supports this belief is the fact that (i) the QSO 1331+170 shows similar locking in Mg II at an absorption redshift which is much less than that of the emission lines, (ii) this type of locking is expected to occur during radiation-pressure–driven mass loss, and (iii) Scargle (1973) had inferred from line widths derived from earlier observations, and from a resonance-line scattering radiation pressure outflow model, that locking in C IV and/or N V was taking place in 3C 191. The apparent line-locking in 3C 191 is of special significance because it occurs in conjunction with appreciable excited fine-structure level population. Thus, line-locking occurs in absorption systems for which there is independent evidence that they are intrinsic to the QSO.

With the exception of the Si II λ1526 and λ1533 features, all lines seen in system A appear to be present in system B, although generally at a reduced strength. In particular, the Si II λ1264 fine-structure transition appears to be present in system B. The situation for C II λ1335 is uncertain because this feature remains unresolved. It appears from the asymmetry in the profile that the line is considerably weaker in system B than in system A. The measured wavelength, after allowance for the asymmetry caused by system B, is in good agreement with that predicted for an equilibrium population blend of C II λλ1334.5, 1335.7 in system A.[1]

[1] The position and strength of this feature may be less certain than those of the other lines because the observed wavelength is very close to the Ca II K line in the night sky.

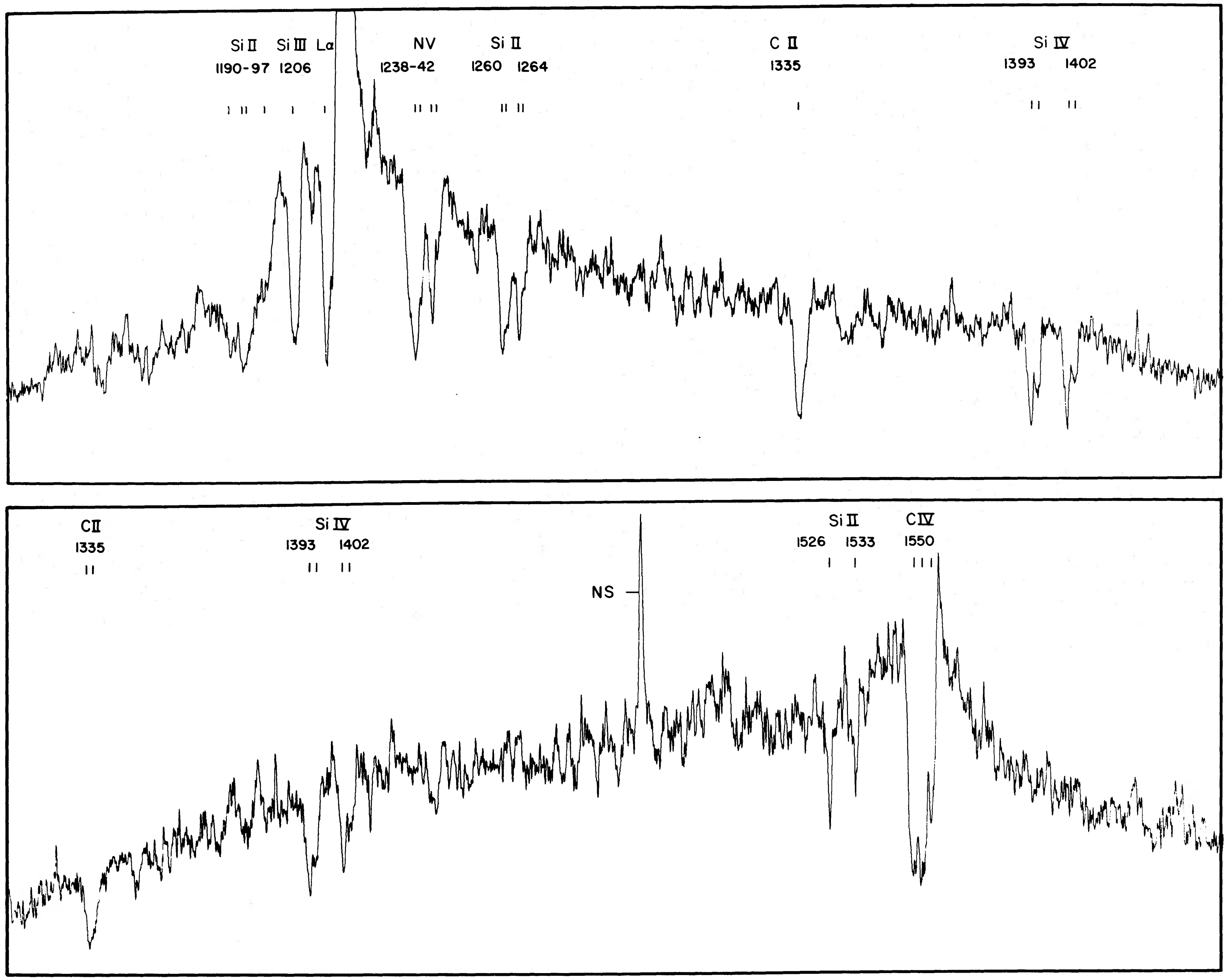

FIG. 2.—Intensity tracings of spectrograms SI 1232 (*top*) and 1237 (*bottom*). Prominent spectral features are labeled.

TABLE 3

LINE EQUIVALENT WIDTHS (in Å)

Ion	Line	Observed	W_A/W_B	QSO Rest Frame	Computed	Computed Column Density (cm^{-2})
			ABSORPTION			
Si III...........	1206	4.2	...	1.4	1.9	8.5×10^{14}
Lα.............	1216	⩾12		⩾4	3.7	2.7×10^{19}
N V...........	1238	5.7	3:2:	1.9	0.51	2.9×10^{14}
	1242	2.6	2:1:	0.88	0.27	
Si II............	1260	3.7	1.2:1	1.25	1.5	3.8×10^{14}
	1264	2.4	2:1	0.81	...	...
C II............	1334	5.6	...	1.9	1.9	5.9×10^{15}
Si IV...........	1393	4.6	1.4:1	1.5	1.8	1.5×10^{15}
	1402	3.7	1.4:1	1.26	1.6	
Si II............	1526	1.4	1:0	0.47	0.68	3.8×10^{14}
	1533	1.0	1:0	0.34	—	...
C IV...........	1550	12	1.4:1.4:1	4.1	4.3	2.0×10^{16}
			EMISSION			
Lα.............	1216	224		76	1120	
C IV...........	1550	150		50	185	
He II...........	1640	38		13	91	
C III...........	1909	...		...	131	
Mg II..........	2800	...		...	34	
Ne V...........	3426	...		...	39	

The observations are thus consistent with population by collisions or radiation. Higher resolution studies will be attempted in the hope of clearly resolving the C II feature in both systems, but the question of possible infrared excitation must be deferred until then. It appears that the N V λλ1238, 1242 doublet is also present in both systems, although the weaker, system B contributions are only barely resolved. In Table 3 we have listed the equivalent widths, W, of clearly resolved absorption lines. In virtually all cases this is due to the combined effect of system A and system B. An estimated ratio of equivalent widths W_A/W_B is given where possible. The accuracy of the present data is determined largely by systematic calibration effects. In particular, the zero intensity level is uncertain both because of image tube (signal dependent) and sky background, and because the step wedge calibration is unreliable near plate saturation. For this reason, profiles of strong emission lines (Lα and C IV) cannot be determined from these data. Equivalent widths of certain emission lines, however, have been determined with the UCSD Digicon, and these are also listed in Table 3. The absorption-line equivalent widths listed in Table 3 are systematically smaller than those of Bahcall *et al.* (1967), but we have been unable to account for this difference.

The ionization in both systems is similar, but the C IV and Si IV features may be stronger relative to C II and Si II in system B. The weakness of Si II λ1304[2] in both systems and the virtual absence of Si II λ1526 in system B indicate that the Si II λ1260 lines are not highly saturated. The central depth of Si II λ1260, on the other hand, then suggests that the Si II lines must be virtually resolved at the present dispersion. This would imply a velocity dispersion of $v \approx 10^2$ km s^{-1}. It is unfortunate that uncertainties in the Si II oscillator strengths preclude a fuller study of the curve of growth for this species. The situation for Si IV and C IV is unclear, since each component of these doublets has (or in the case of C IV, may have) the same equivalent width. In system B neither the Si IV λλ1393, 1402 lines nor the C IV λ1550 feature appears as deep as in system A, and therefore cannot reach zero intensity at line center. Whether this is due to unresolved, multiple components in system B, or only partial obscuration of the continuum source by the cloud giving rise to this system, cannot be determined from the present data. The N V doublet, however, appears from the relative line strengths to be unsaturated.

The degree of saturation in the Si II lines is of crucial importance to an analysis of the fine structure. Little can be deduced about relative level populations from equality of line strengths if both ground-state and excited lines are saturated. Also, if the ground-state transitions were highly saturated, no ultraviolet radiation fine-structure level excitation would occur beyond optical depth unity. The meaning of a line ratio in these circumstances is unclear. In the case of 3C 191, however, it is clear that at least some of the Si II ground-state lines are unsaturated and that the line ratios may be used to determine limits on the particle density and distance of the absorbing gas from the central source, in the manner of Bahcall *et al.* (1967). Since our relative line strengths are similar to

[2] It should be noted that the Si II λλ1304, 1309 transitions are barely detectable in either system. According to published oscillator strengths (Wiese *et al.* 1969; Morton and Smith 1973), this transition is intermediate in strength between the λ1260 and λ1526 lines. If the current identifications are correct, the oscillator strengths must be wrong—and vice versa.

those found in Bahcall *et al.* (1967), the limits we deduce are the same as theirs: $n \lesssim 10^3$ cm^{-3}, and $R \gtrsim 3 \times 10^{20}$ cm.

IV. A PHOTOIONIZATION MODEL

In order to interpret the observational data, we will consider a photoionization model for the absorbing clouds. We shall make the following assumptions:

i) The ionization of the *absorbing* clouds is due to photoionization by a central continuum source which is surrounded by a system of clouds, two of which lie along the line of sight. The fraction of sky subtended by the clouds as seen from the ionizing source is $\Omega/4\pi$.

ii) The ultraviolet continuum of the central source is given by

$$L_\nu = 2 \times 10^{30}(\nu/\nu_1)^{-\alpha} \text{ ergs s}^{-1}\text{ Hz}^{-1} ,$$

where ν_1 is the Lyman limit frequency. This relationship is typical of QSOs (Oke *et al.* 1970), as are the luminosity and colors of 3C 191.

iii) Element abundances are solar (Withbroe 1971).

iv) The clouds giving rise to each system are physically distinct.

The calculations were carried out using a computer code that has previously been used to study photoionization in H II regions, planetary nebulae, and Seyfert galaxies (Williams 1967, 1973). Solutions for the ionization and thermal equilibria were obtained and used to compute absorption-line equivalent widths for comparison with observation. A Voigt absorption profile was assumed for each of the lines with the velocity dispersion deduced from the observations of the line widths (see discussion below). Oscillator strengths were taken from Morton and Smith (1974).

Certain constraints can be placed upon the calculations from general considerations. It appears from the observed lines in each system that a wide range of ionization (N^{+4}, $C^{+3} \rightarrow Si^+$, C^+) is present in each of the clouds. This can be accounted for in either of two ways: (i) the cloud could be optically thin to ionizing radiation, in which case the ionization must be fairly uniform throughout the gas, and the flat ionizing spectrum results in the simultaneous coexistence of many consecutive stages of ionization; or (ii) the cloud is optically thick in the Lyman continuum, and absorption of the ultraviolet continuum causes the ionization to change (decrease) with distance in the gas. For a given level of ionization in a cloud, the column density of gas will be greater in the optically thick situation. *A priori*, the existence of two distinct systems along the line of sight to 3C 191, each with a wide range in the ionization, would appear to argue against an optically thick region for at least the inner cloud, since it would then shield the outer region from ionizing radiation.

A number of models have been computed for the line-formation region of 3C 191 using different parameters for the spectral index of the ionizing radiation α, gas density n, distance R of the gas from the continuum source, and cloud thickness. For reasonable values of the spectral index, $0 < \alpha < 2$, the ionization of a cloud is much too high to account for the observed spectrum of 3C 191 at densities $n \lesssim 10^3$ cm^{-3}, unless the clouds are more distant than $\sim$1 kpc from the central continuum source. At this distance, excitation of the fine-structure levels cannot occur by ultraviolet radiation. It is, in principle, possible that the excitation is due to infrared radiation, but the observed ionization would then imply a still greater distance from the central source and an infrared energy flux (at 34 μ in the QSO frame) more than 10^4 times that in the observed part of the spectrum. We have therefore assumed in our calculations that the fine-structure excitation is due to collisions, and hence that $n = 10^3$ cm^{-3}. A level of ionization similar to that found in 3C 191 occurs for clouds of this density at distances $R \approx 10$ kpc.

The question then arises as to whether a detailed fit can be made to the observed absorption equivalent widths. Within the present assumptions, there appears to be no way in which the equivalent widths can be reproduced in a cloud which is optically thin to the H I continuum. The reason for this lies in the fact that the observed equivalent widths of the Si II absorption lines require a Si II column density of at least 10^{14} cm^{-2} (greater if the velocity dispersion is less than the 100 km s^{-1} suggested in § III). Since the relative abundances of H^0/H and Si^+/Si are similar for a wide range of input conditions (they have similar ionization potentials), the assumed solar Si/H abundance ratio then leads to an H^0 column density of $\gtrsim 10^{19}$ cm^{-2} for a cloud—an amount which results in an appreciable optical depth ($\tau_{912} \approx 10^2$) in the H^0 continuum. With a power-law spectrum, this in turn implies that the He^+ continuum is also optically thick ($\tau_{228} \approx 10$). This may cause problems for a two-cloud model because of the shielding of one cloud by the other; therefore we will consider first the simpler question of whether a photoionization model of the present type can adequately account for a single cloud spectrum.

In Table 3 we have listed the calculated equivalent widths for a model with $\alpha = 1$, $v_D = 10^2$ km s^{-1}, $n = 10^3$ cm^{-3}, and a cloud thickness $\Delta r = 10^{17}$ cm. The fit appears to be very satisfactory. The ratio $\Delta r/R \approx 10^{-5}$ is certainly low, but we note that Morton (1975) derives a value $\Delta r/R \approx 2 \times 10^{-3}$ for the absorbing clouds near ζ Oph, and a value of 10^{-4} has been deduced for the filaments in the Cygnus Loop (Cox 1972).

The only significant discrepancy between the observed and computed absorption line strengths in system A arises in the case of N V $\lambda\lambda$1238, 1242, where the computed values are too small. Part of this discrepancy may be due to the greater widths the N V lines have in comparison with the other lines, which may indicate blending with some unidentified line. Alternatively, the system B contribution to the N V lines may be greater than that for the other lines. If not, then the predicted column density of N^{+4} in our model is roughly a factor of 4 times too small. Other discrepancies are small, and can be ascribed to the use of a single value of the line width v_D, rather than the measured width for each line. The overall agreement between the model and observations, at least for a single cloud, is quite good.

The model, nonetheless, runs into difficulties when both clouds are considered. As indicated previously, the calculations all show that substantial column densities of Si II (and C II) do not build up until the optical depth at the Lyman H^0 and He^+ limits is large [$\tau(\lambda 912) \approx 100$]. That is, in order to produce the observed absorption-line strengths for C II $\lambda 1334$ and Si II $\lambda 1260$, essentially all of the ionizing radiation along the line of sight must be absorbed in the inner cloud, leaving no radiation to produce the N V which is observed in the other cloud. This is, as far as we are aware, the only real objection to an otherwise very satisfactory photoionization model. It is, however, an important objection.

The photoionization model may conceivably be reconciled with the observations if any of the following are true:

i) The observations of the N V lines in system B are near the limit of our resolution, and may possibly be due to noise. There is no difficulty in accounting for the strengths of the remaining lines in the outer cloud, according to the photoionization model, if there is no N V. The existence of N V requires radiation below 228 Å; however, C IV and Si IV are produced by photons longward of the He II ionization limit, where the optical thickness of the inner cloud is not so large. The calculations show that all lines seen in system B, except N V, can be accounted for by photoionization in the outer cloud, even though shielded by the inner cloud with $\tau(\lambda 912) = 100$.

ii) It is possible that the inner of the two clouds only partially covers the ionizing source, thereby permitting the outer one to receive an adequate flux of ionizing radiation. There is some evidence for this, because the equivalent widths and central depths of the Si IV lines in system B are equal, indicating saturation, yet neither line reaches zero intensity, and both lines appear to be resolved.

iii) The photoionizing spectrum may be radically different from that assumed in the calculations; for example, there may be a large flux in the soft X-ray region of the spectrum.

iv) Metals may be overabundant in 3C 191.

Except for (i), an explanation of the above type tends to detract from the simplicity, and hence credibility, of the model. It is conceivable that the absorption spectrum of 3C 191 is produced by some entirely different mechanism, such as shock fronts and post-shock cooling zones (Cox 1972). In this case, the absorption must arise at still greater distances from the central source. The photoionization model cannot, however, be ruled out until some of the above points have been cleared up. Indeed, the good agreement obtained for the spectrum of a single cloud suggests that such a model continue to be considered seriously.

As a further possible check on the photoionization model, we have studied the emission lines expected to arise from the absorbing region. The emission-line equivalent widths have been computed for the same model considered above, assuming a cloud covering factor, $\Omega/4\pi$, of unity. If the clouds subtend a solid angle $\Omega < 4\pi$ as seen from the central source, the tabulated emission strengths should be multiplied by this factor. Although the predicted emission-line strengths are greater than those observed, especially Lα, approximate agreement with observation is obtained if $\Omega/4\pi \approx 0.25$, a value large enough to permit two QSO associated clouds along the line of sight with a reasonable probability. The emission-line widths in such a model should be similar to the velocity differences ($\sim 10^3$ km s^{-1}) between clouds. The observations are consistent with this expectation. In any event, unless $\Omega/4\pi \ll 0.1$, a significant contribution to the emission lines should come from a volume having a radius ~ 10 kpc,[3] a size at which it might be resolved using speckle interferometry techniques. Such a model has some similarities to the quasar line-emission models proposed by Scargle *et al.* (1974). It thus appears that because of the constraints imposed upon the density ($n \leqslant 10^3$ cm^{-3}) and distance ($R \geqslant 10$ kpc) of the absorbing matter by the fine-structure level population and ionization, the line-emitting region of 3C 191 (or at least part of it) may be different from that which has often been assumed to hold for quasars. Similar conclusions were arrived at by McKee *et al.* (1973) for the absorbing gas in some QSOs. Many previous studies of QSOs (Bahcall and Kozlovsky 1969*a*, *b*; Davidson 1972; MacAlpine 1972) have assumed the gas density to be around 10^{7-8} cm^{-3} in order to collisionally quench forbidden-line radiation, which is observed to be very weak in the bright, well-studied object 3C 273. In order to produce the required ionization at these high densities, the gas must reside close to the central ionizing source, typically 10 pc or less. Clearly a near-infrared spectroscopic search for forbidden-line emission, for example, from [Ne V] $\lambda 3426$, the predicted strength of which is listed in Table 3, would help settle this question. It may turn out that QSOs have both core and "shell" emission-line regions, with the forbidden lines providing an index of their relative strength. In this connection, it is interesting to note that a halo region with strong forbidden-line emission has recently been found by Wampler *et al.* (1975) around the QSO 3C 48. The extent of this emission line region is ~ 10 kpc.

V. SUMMARY

Our principal results and conclusions may be summarized as follows:

i) The absorption spectrum of 3C 191 contains two redshift systems, apparently line-locked on the C IV doublet. The redshifts are $z_A = 1.945$ and $z_B = 1.949$.

ii) The range of ionization observed in the two systems is very similar. The system B lines are generally weaker, and some question exists as to the strength of

[3] Provided the clouds are intrinsic to 3C 191, the absorbing region must be at least 10 kpc from the source. For constant ionization and absorption column densities, the emission-line strengths are given by $S \propto n_e^2 R^2 \Delta R \approx (n_e \Delta r)(n_e R^2) \approx$ const. Thus, for intrinsic clouds, the emission-line strength would be approximately the same even if infrared emission were responsible for the excitation of the fine-structure levels.

N V $\lambda 1240$, because the two systems are only barely resolved.

iii) Absorption lines from excited fine-structure levels of Si II are definitely present in system A, and probably are present in system B.

iv) The absorption spectrum of a single system can be accounted for very satisfactorily in terms of photoionization of a cloud of density 10^3 cm^{-3}, thickness $\sim 10^{17}$ cm, and distance from the central source of ~ 10 kpc.

v) If our tentative identification of the N V doublet and Si II $\lambda 1264$ in system B is correct, there may be some difficulty in interpreting the results for *both* clouds in terms of a simple central source ionization model. Our results would be reconciled with an ionization model if, for example, the inner cloud does not completely cover the photon source. There is independent support for this from the Si IV line strengths.

vi) If the cloud covering factor $(\Omega/4\pi) \geqslant 0.1$, the absorbing clouds should contribute substantially to the observed emission-line strengths. The emitting "halo" may be resolvable using speckle interferometry techniques.

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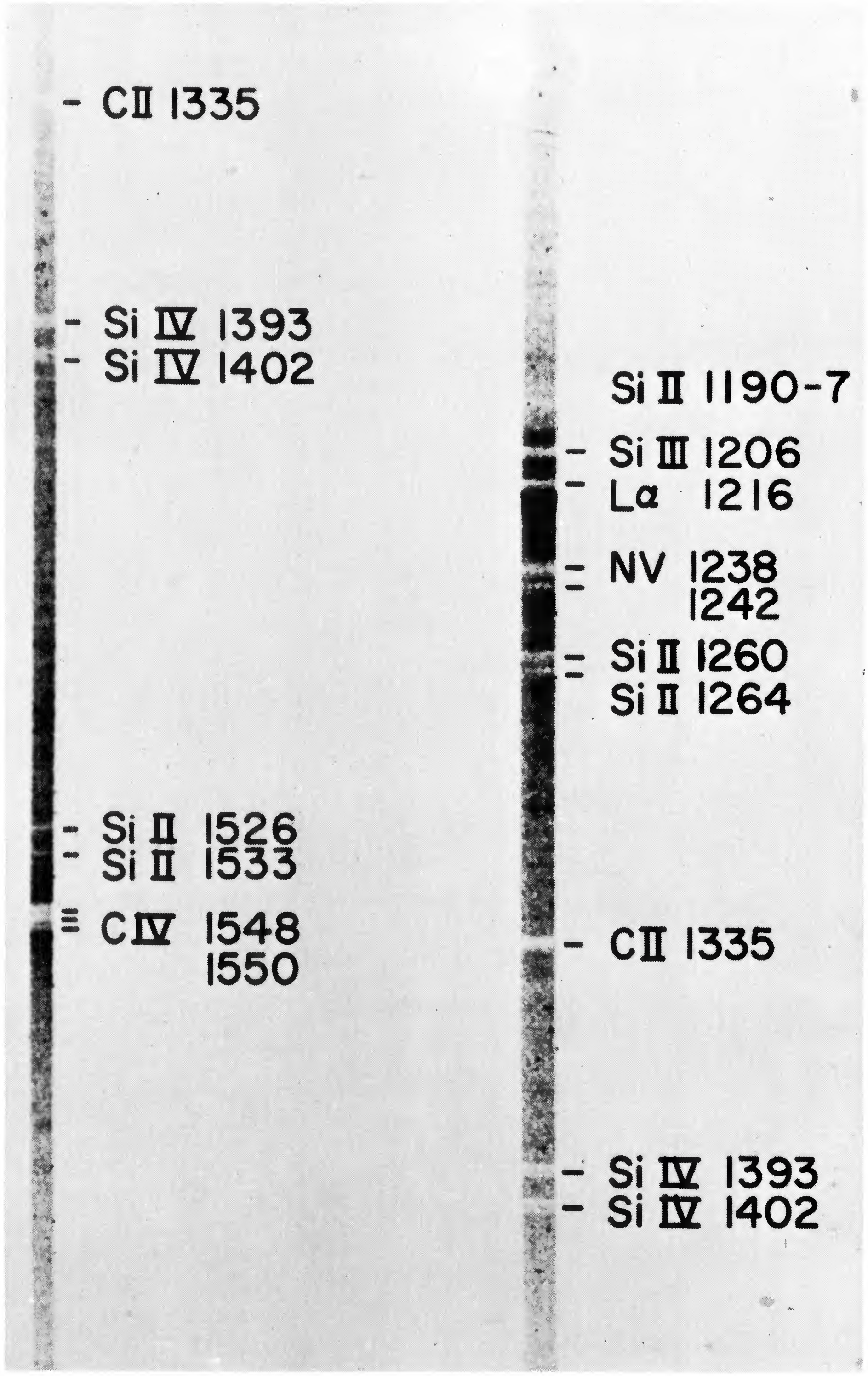

FIG. 1.—Reproductions of spectrograms SI 1232 and 1237 of 3C 191 are shown. They cover the wavelength range 3300–4800 Å at a reciprocal dispersion of 48 Å mm^{-1}.

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