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ROCKET SPECTROSCOPY OF ZETA ORIONIS

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ABSTRACT

A spectrum of ζ Ori extending from 922 to 1453 Å with approximately 0.8 Å resolution has been recorded at rocket altitudes. All lines used in existing models of stellar atmospheres appear in the recorded spectrum with the exception of those masked by telluric N_2 or strong P Cygni–type profiles and by an O V line at 1371.29 Å. Fifteen multiplets of subordinate lines have been reliably identified, indicating an approximate range of excitation from 0 to 50 eV. Transitions in C III (1176 Å), N III (991 Å), N V (1239, 1243 Å), O VI (1032, 1038 Å), Si IV (1394, 1403 Å), S IV (1063, 1074 Å), and S VI (933, 944 Å) have been observed as P Cygni–type profiles presumably arising in a circumstellar envelope. The degree of ionization, transitions present, and mean radial velocities are all consistent with viewing the envelope as a hot ($\sim 10^5$ ° K), rarefied plasma in which collisional ionization is important. Interstellar lines in C I (1277, 1280 Å), C II (1036, 1334 Å), N I (1134–1135 Å), N I (1200–1201 Å), N II (1084–1086 Å), O I (1302, 1305 Å), Si II (1190, 1193 Å), Si II (1260 Å), and Si II (1304 Å) have been definitely identified. Other transitions in Ar II, S I, C I, and Fe II are tentatively identified. The equivalent width of the Lα line is found to be 10.4 ± 1.6 Å corresponding to a columnar density of $2.0 \pm 0.7 \times 10^{20}$ cm^{-2}.

I. INTRODUCTION

In 1969 October an effort was made to obtain moderate-resolution (0.8 Å) spectrograms of several Orion Sword and Belt stars in the vacuum-ultraviolet with a view to studying qualitatively the degree of ionization, excitation, and line blanketing in the stellar atmospheres, P Cygni–type lines arising in the circumstellar envelopes of the supergiants, and if possible making quantitative measurements of interstellar lines. Two identical objective-grating spectrographs mounted aboard an Aerobee 150 rocket were used for this purpose, one intended to obtain the spectra of ζ and ϵ Ori, the other the spectra of θ^1, θ^2, and ι Ori. In spite of the absolutely perfect functioning of the attitude control system, the instrument was not sensitive enough to record usable spectra of the Sword stars; and of the Belt stars only the spectrum of ζ Ori was of sufficiently good quality for analysis. Thus, presented in this report are the results from the observation of ζ Ori exclusively, the data consisting of a single spectrogram with wavelength coverage extending from 922 to 1453 Å. The star is a visual binary; according to the Yale Bright Star Catalog the brightest component is classified O9.5 Ib with $m_v = 2.05$ and its companion is classified B3 with $m_v = 4.21$. On the basis of the instrumental sensitivity the companion star is thought to be sufficiently cool and faint to have negligible effect on the spectrum of the bright component.

Tentative identifications of most spectral features have been made. Each feature may be related to several ionic or atomic transitions. The mean radial velocities associated with seven P Cygni–type lines originating in the circumstellar envelope have been determined, including that of O VI ions as revealed by strong doublet lines at 1031.91 and 1037.61 Å. A large number of interstellar lines have been tentatively identified, but with the exception of the atomic hydrogen Lα line none can be analyzed quantitatively. This is due to the limited instrumental resolution and the confused blending of interstellar lines with stellar or other interstellar lines—a problem, incidentally, which better resolution might not solve.

II. THE EXPERIMENT

The spectrographs were launched on 1969 October 16 aboard an Aerobee 150 rocket at 10:30 MST from the White Sands Missile Range in New Mexico. At a mean altitude of 182 km the ζ Ori spectrogram was acquired during an exposure interval of 230 s. The optical axis of the spectrograph used for the Belt stars was parallel to the rocket axis and was pointed by the guidance system at ζ Ori with a peak-to-peak fluctuation of $\pm 12''$. The spectrograph used for the Sword stars was oriented $3°45'.5$ with respect to the rocket axis, and the proper azimuth attitude was achieved to locate the Sword stars accurately in the field of view. The spectrographs themselves and the film-handling procedures were identical in every way to those reported earlier (Smith 1969, 1970).

The resulting spectrogram of ζ Ori possessed a nearly linear dispersion of 33.7 Å mm^{-1} and a resolution of about 0.8 Å. It was widened by only the residual rocket motion about the pointing direction which gave a spectrum width normal to the plane of dispersion of 0.1 mm. A typical calibration curve determined by placing the entire instrument in a collimated beam of Lα light is shown in Figure 1. The film used throughout the experiment was Kodak Pathé SC5, and the instrumental dynamic range of about a factor of 3 is typical of this film type. The illustrated calibration curve corresponds to scanning the spectrum with densitometer slit dimensions of 0.088 Å in width and 0.039 mm in height. Because the maximum and minimum densities of the recorded spectrogram extend far beyond the range over which the instrument may be thought to be calibrated, much of the spectrogram cannot be reduced to a relative flux distribution with any accuracy. Therefore, the whole spectrum is presented in Figure 2 in the form of film density versus wavelength. For this purpose the densitometer slit height was increased to 0.072 mm to improve the grain statistics.

The calibration curve of Figure 1 was used to derive a flux distribution in the neighborhood of the observed Lα line in order to determine the interstellar columnar density of hydrogen atoms. The justification of this procedure lies in the observation that a portion of the contour lies within the calibrated range of flux values. If a computed contour is fitted to the measured contour within this calibrated range, an estimate of the columnar density of hydrogen atoms may be made in which the principal source of error lies in the establishment of the continuum level.

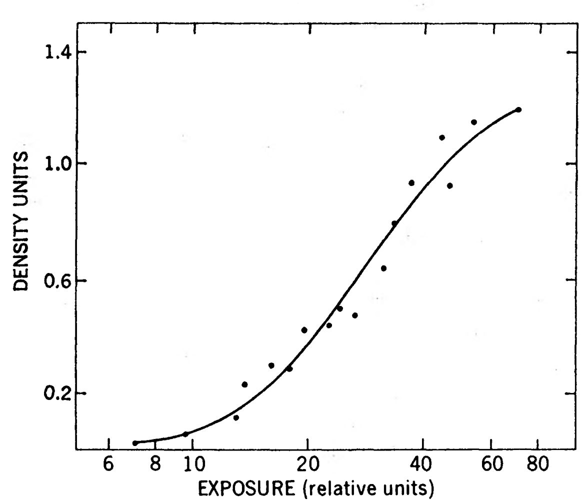

FIG. 1.—Calibration function of the rocket spectrograph. *Abscissa*, log of the exposure to Lα light in relative units; *ordinate*, density units averaged over the densitometer slit height.

The densities and fluxes plotted in Figures 2 and 3, respectively, are derived by smoothing the densitometer measurements using a triangular weighting function 0.63 Å full width at half-maximum. The wavelength scale is based on a quadratic fit of identified features in the smoothed densitometer trace to telluric N_2 (~960 Å) bands, the interstellar and telluric N I (1134.6 Å) line, and the interstellar Si II line (1304.4 Å). As in previous flights, the resulting wavelength scale is accurate to within 0.3 Å.

III. RESULTS

An enlarged reproduction of the ζ Ori spectrogram appears in Figure 4 (Plate 2) with the strongest features identified. It is evident that for this particular piece of exposed SC5 film the background fog is indistinguishable from clear plate noise. Figure 2 contains in two sections a smoothed microdensitometer trace of the spectrogram in which film density is plotted as a function of wavelength. A background fog level of 0.075 density units is indicated on the ordinate axes by a dashed horizontal line. The multiplets shown in Figure 2 include at least one transition which correlated with an observed spectral feature. Horizontal lines connect members of the same multiplet; occasionally not all such members are shown due to space limitations.

The identified spectral lines are listed in Table 1. Column (1) contains the ion identification together with a multiplet or line reference. Regarding the latter, a number refers to the compilations of Moore (1950, 1965, 1970), a letter k refers to the emission line tables of Kelly (n.d., 1968), P to an article of Palenius (1967), and HA indicates that a paper of Hallin (1966) was used. Notes indicating the character and reliability of the identification are also referred to in this column. Laboratory-measured wavelengths of the identified transitions and the observed wavelengths of the corresponding spectral features are listed in columns (2) and (3), respectively, and the excitation potentials in column (4). For those transitions exhibiting P Cygni–type profiles the wavelength at the center of the shortward-shifted absorption component is listed in column (3). The N V (1238.8, 1242.8 Å) and O VI (1031.9, 1037.6 Å) doublet lines are resolved, producing two minima whose wavelengths both appear in column (3). The doublet lines in S IV (1062.7, 1073.5 Å) and S VI (933.4, 944.5 Å), which should be resolved, exhibit clearly only one absorption component whose position is noted in column (3). Listed in column (5) are *gf*-values taken from Varsovsky (1961), Allen (1963), Wiese, Smith, and Glennon (1966), and Garstang and Shamey (1967). No blends have been indicated as such because most of the observed features in the spectrum, which is cluttered with absorption lines, can be plausibly correlated with two or more transitions.

As observed in the results of the previous two flights, absorption features appear in the spectrum due to the effects of telluric N_2, N I, O_2, and H_2O. The strongest of these are bands of N_2 at wavelengths less than 1000 Å, principally those at 960, 966, and 972 Å. At low altitudes an O_2 band should be seen at 1244 Å. In the present case this band produces little or no effect on the spectrum, probably because of the relatively high altitude at which the exposure was made. The O I triplet at 1302–1306 Å apparently affects the spectrum at these wavelengths; however, it is difficult to say to what degree the effect is telluric in origin. It is probable that there is some interstellar O I between the Earth and ζ Ori. Finally, the features at 1017, 1056, 1114, and 1222 Å are thought to be due at least in part to water vapor evaporated from the payload and rocket surfaces. In the following paragraphs specific comments concerning most of the observed atomic or ionic lines are made.

a) H I

The Lα absorption line with an equivalent width of 10.4 Å (see below) must be predominantly due to interstellar hydrogen. The remaining Lyman lines of wavelengths included in the spectrogram are to a large extent masked by stronger lines.

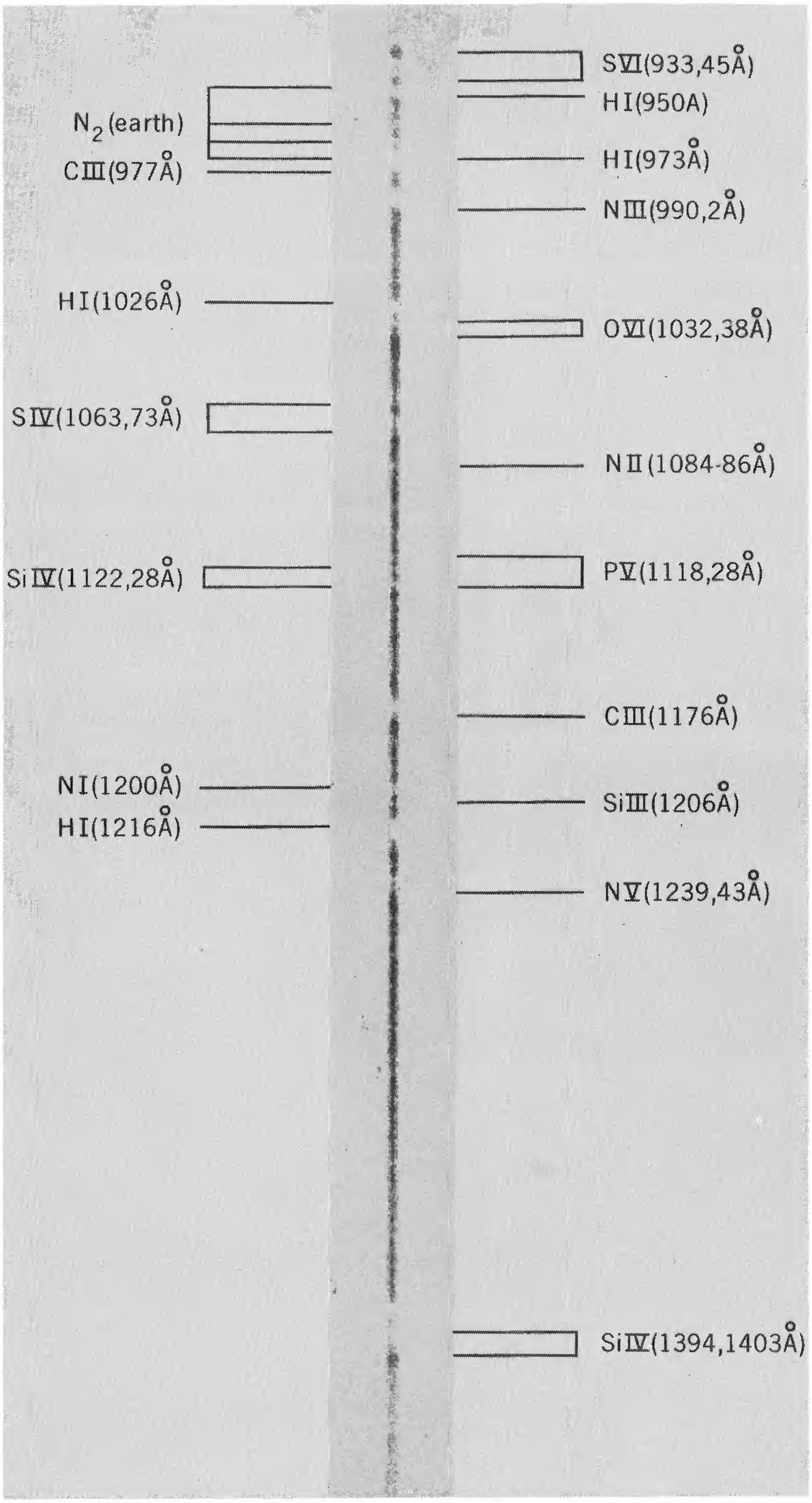

FIG. 4.—Spectrum of ζ Ori from 922 to 1453 Å. The dispersion of the original spectrogram is 33.7 Å mm^{-1}; the resolution, 0.8 Å. Some of the strongest and most reliably identified features are indicated.

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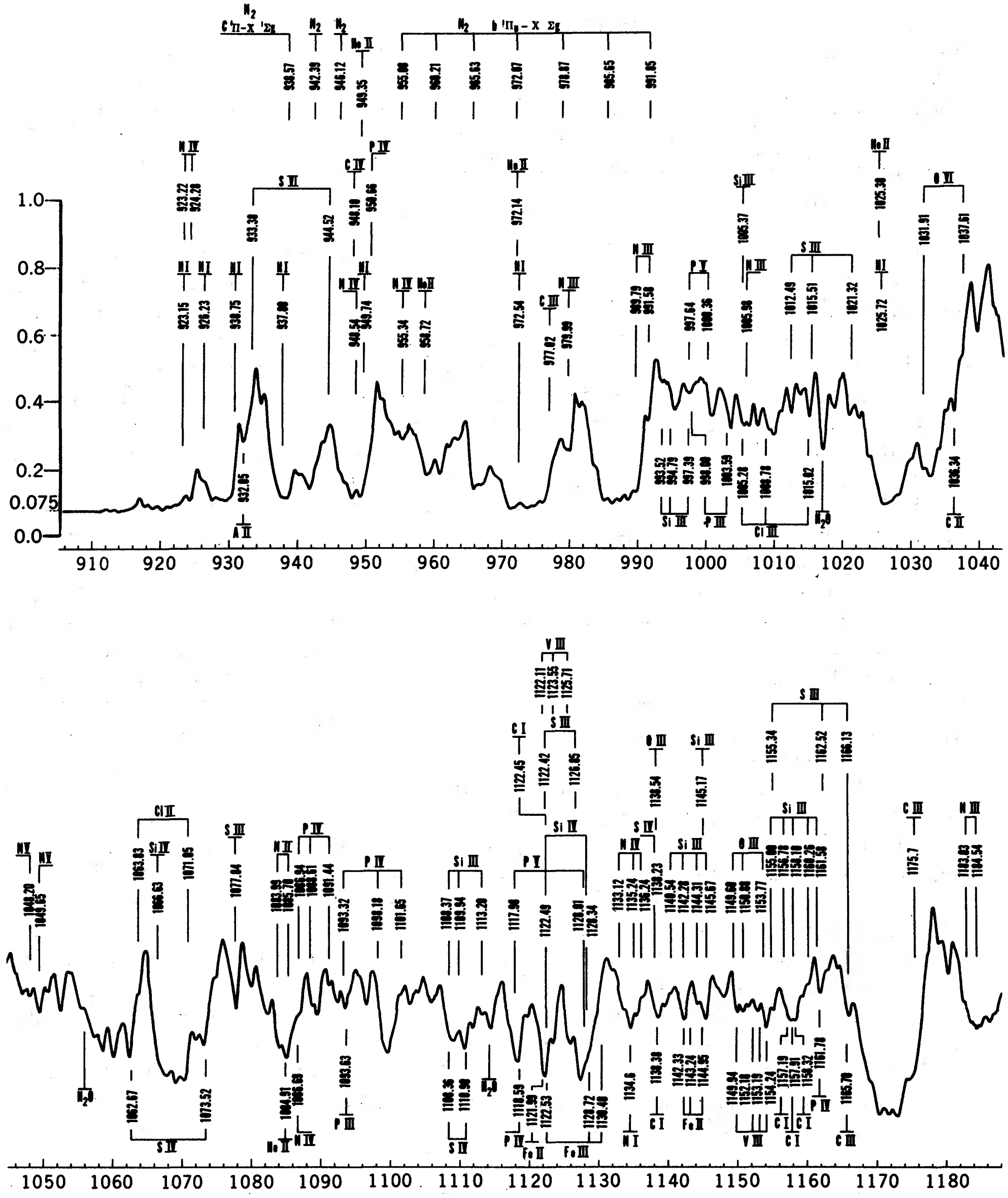

FIG. 2.—Smoothed microdensitometer traces in four sections of the ζ Ori spectrogram. Plotted on the ordinate axes are film densities averaged over the densitometer slit height. The background fog level is indicated on the ordinate axes by a dashed horizontal line (directly under 0.075).

b) He II

Most of the transitions in He II which might be seen are masked by stronger lines. An exception is a feature near 1085 Å which must be due in part to this ion.

c) C I, C II, C III, C IV

The presence of interstellar C I is probably established by the features listed in Table 1; the most convincing of these appear at 1277.5 and 1280.0 Å. The resonance

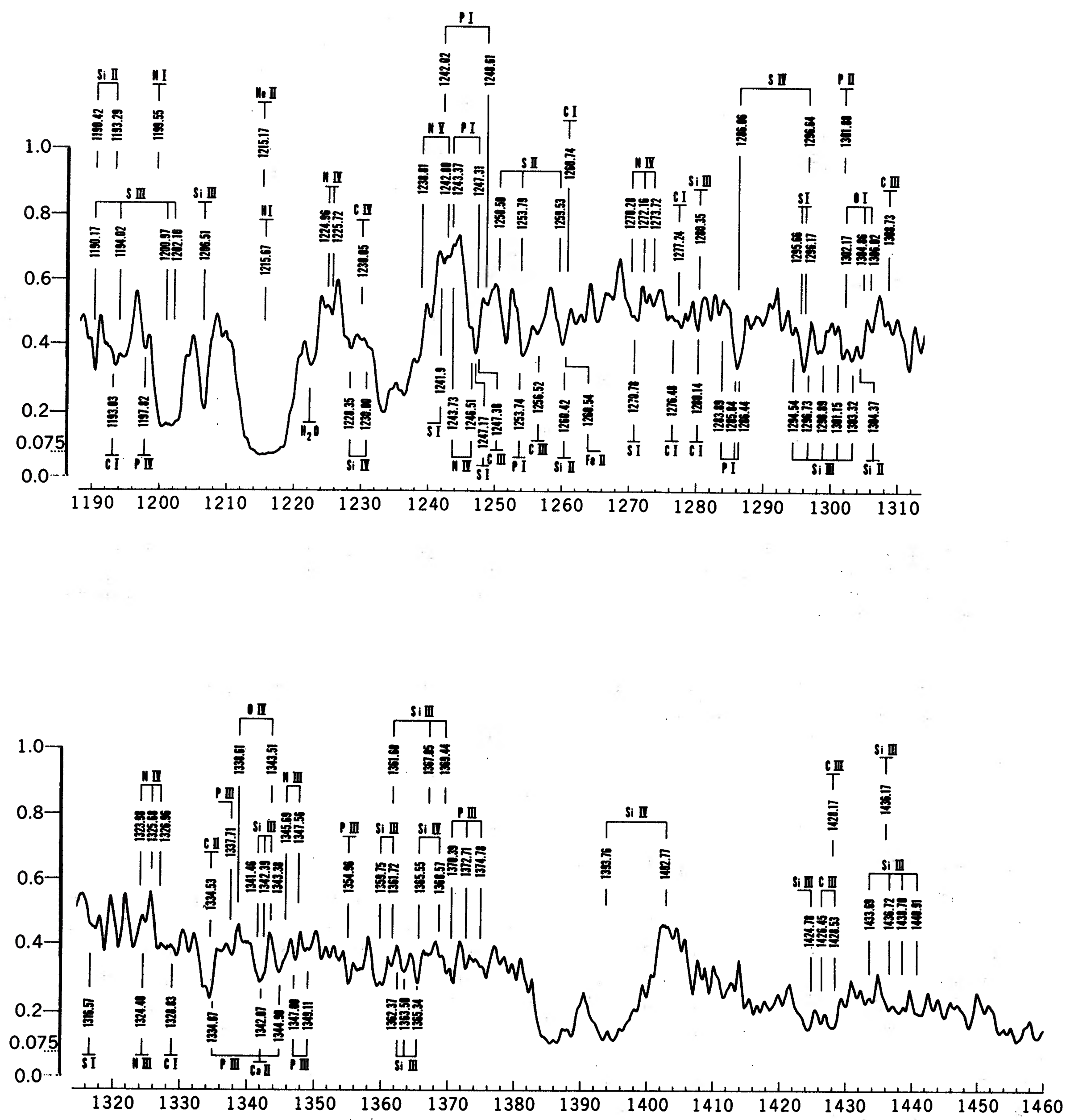

FIG. 2—*Continued*

transitions in C II at 1036.4 and 1334.5 Å are definitely revealed by features close to these wavelengths, and must be principally interstellar in origin.

The transition in C III originating in the metastable $^3P^o$ state with $\lambda = 1175.7$ Å appears as a very strong P Cygni–type profile with some indication that the stellar line may be seen through the circumstellar envelope. One would expect, on the basis of this result, that a circumstellar line corresponding to the resonance transition in C III at 977.03 Å should be observable as well. The spectrum contour from 971 to 982 Å is certainly consistent with this expectation, but the spectrum at these wavelengths is in-

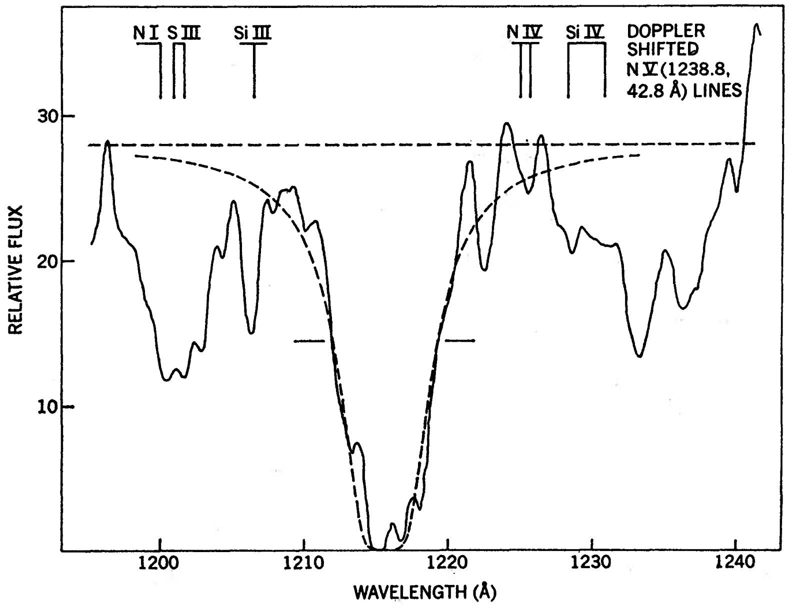

FIG. 3.—Lα line in the spectrum of ζ Ori. *Solid contour*, measured relative flux distribution; *dashed contour*, a smoothed computed profile fitted to the observations in the core of the line. *Dashed horizontal line*, assumed position of the continuum. Solid horizontal lines indicate the flux level below which the instrument calibration is unreliable.

fluenced strongly by N_2 bands at 972.1 and 978.9 Å, and an unambiguous identification of a P Cygni profile is impossible.

There is weak evidence for C IV near 1230 Å where there is a wide (4 Å) depression in the spectrum. Transitions in Si IV may also help explain this feature.

d) N I, N II, N III, N IV, N V

Features at 1134.6 and 1201.3 Å reveal the important effect of N I atoms on the observed spectrum. Under the assumption that the 1134.6 Å feature is due exclusively to interstellar N I, a preliminary calculation of the N I columnar density gives a value of $\sim 4 \times 10^{18}$ cm^{-2}. Combined with the columnar density of atomic hydrogen as revealed by the Lα line, the ratio of the interstellar abundances of N I to H I is $\sim 2 \times 10^{-2}$. This value is approximately a factor of 10^2 greater than what one would expect on the basis of assumed solar abundances, and one must conclude that apart from uncertainty in the equivalent width of the 1134.6 Å line, telluric nitrogen makes a significant contribution to the N I absorption spectrum.

A feature at 1084.8 Å is due at least in part to N II which must occur predominantly in the H II region surrounding ζ Ori; a transition in He II (1085.0 Å) also produces an observable effect.

Ground-state transitions in N III (989.8–991.6 Å) probably produce a P Cygni–type profile near 990 Å. The emission associated with this profile is barely observable, however. Subordinate lines in N IV have been tentatively identified and are listed in Table 1; the maximum excitation is 62.0 eV. Tentative identifications of lines in N V near 1049 Å have also been made which indicate an excitation of 76.6 eV. The resonance transitions in N V (1238.8, 1242.8 Å) produce a strong P Cygni–type profile near 1240 Å which of course arises in the circumstellar envelope.

TABLE 1

IDENTIFICATION OF LINES IN THE UV SPECTRUM OF ZETA ORIONIS

Ion Multiplet	λ (Å) Laboratory	λ (Å) Measured	Level cm^{-1}	gf
HI	949.74	948.0	0.00	0.02778
(4) s,l*				
HI	972.54	973.5	0.00	0.0579
(3) s				
HI	1025.72	1026.0	0.00	0.1582
(2) s				
HI	1215.67	1215.7	0.00	0.8324
(1) s				
HeII	949.30	948.0	329179.1	0.03081
(19) s	949.35			
HeII	958.67	958.8	329179.1	0.04343
(18) m	958.72			
HeII	972.08	973.5	329179.1	0.06429
(17) s	972.14			
HeII	1025.24	1026.0	329179.1	0.1767
(15) s	1025.30			
HeII	1084.91	1085.1	329179.1	0.3574
(14) m,l	1084.98		329184.9	
HeII	1215.09		329179.1	
(13) s	1215.17	1215.7	---	0.9544
	1215.18		---	
CI	1128.00	1122.3	16.40	---
(27) i,m,p	1122.34		43.40	---
CI	1138.38		0.00	---
(23) i,w,p	1138.60		16.40	---
	1138.74	1138.6	16.40	---
	1138.95		43.40	---
	1139.09		43.40	---
CI	1157.19		0.00	---
(17) i,w,p	1157.41	1158.0	16.40	---
	1157.71		43.40	---
CI	1157.77		16.40	---
(16) i,w,p	1157.91		0.00	---
	1158.02	1158.0	43.40	---
	1158.13		16.40	---
	1158.13		43.40	---
	1158.49		43.40	---
CI	1158.03		16.40	---
(15.01)i,w,p	1158.32		0.00	---
	1158.40	1158.0	43.40	---
	1158.54		16.40	---
	1158.67		16.40	---
	1158.91		43.40	---
CI	1193.01		16.40	---
(11) i,m,p	1193.03		0.00	---
	1193.24	1193.3	43.40	---
	1193.26		16.40	---
	1193.39		43.40	---
	1193.65		43.40	---
CI	1260.74		0.00	0.029
(9)	1260.93		16.40	0.029
	1261.00	1260.0	16.40	0.022
	1261.12		16.40	0.036
	1261.43		43.40	0.036
	1261.55		43.40	0.11
CI	1276.48		0.00	---
(7.01)i,w,p	1276.75	1276.7	16.40	---
	1277.19		43.40	---
CI	1277.25		0.00	0.064
(7) i,w,l	1277.28		16.40	0.14
	1277.51	1277.5	16.40	0.048
	1277.55		43.40	0.26
	1277.72		43.40	0.048
	1277.95		43.40	0.0031

* The eye estimated strength of the feature is strong, s; moderate, m; weak, w; or very weak, v. The suggested identification is likely, l; or possible, p. The feature appears as a P Cygni type profile, c; or is probably interstellar in origin, i.

TABLE 1 (Cont'd.)

Multiple	λ (Å) Laboratory	λ (Å) Measured	Level cm-1	gf
NIII (k) v,p	1345.69	1345.8	~310000	---
	1346.27	---	309856.7	---
	1347.56	---	309856.7	---
NIV (3) w,l	921.99	---	67199.6	0.27
	922.52	---	67136.4	0.21
	923.06	---	67199.6	0.16
	923.22	---	67343.8	0.80
	923.68	---	67199.6	0.21
	924.28	924.3	67343.8	0.26
NIV (k) s,p	948.16	948.5	405893.2	---
	948.24	948.5	405909.0	---
	948.54	948.5	405944.4	---
NIV (8) m,l	955.34	955.4	130695.0	0.22
NIV (k) w,p	1086.08	1086.7	405893.2	---
	1086.27	1086.7	405909.0	---
	1086.69	1086.7	405944.4	---
NIV (k) m,l	1133.12	1133.5	377206.0	---
	1135.24	1135.4	377206.0	---
	1136.24	1135.4	377206.0	---
NIV (k) w,l	1224.96	1225.5	405893.2	---
	1225.19	1225.5	405909.0	---
	1225.72	1225.5	405944.4	---
NIV (k) v,p	1243.73	1243.7	499851.0	---
	1244.92	---	499851.0	---
	1246.51	1246.2	499851.0	---
NIV (k) w,l	1270.28	1270.5	405944.4	---
	1272.16	1272.5	405909.0	---
	1272.74	1272.5	405944.4	---
	1273.47	1273.6	405893.2	---
	1273.72	1273.6	405909.0	---
NIV (k) v,p	1323.98	1324.8	419979.4	---
	1325.68	---	419971.3	---
	1326.96	1326.6	419967.8	---
NV (k) v,p	1048.20	1048.0	617905.0	---
NV (k) w,p	1049.65	1049.3	---	---

Multiplet	Laboratory	Measured	Level cm-1	gf
NV (k) v,p	1048.20	1048.0	617905.0	---
NV (k) w,p	1049.65	1049.3	---	---
NV (1) c	1238.82	1233.2	0.00	0.31
	1242.80	1236.1	0.00	0.16
OI (2) i,w,l	1302.17	1301.7	0.00	0.16
	1304.86	1304.4	158.5	0.096
	1306.02	1306.6	226.5	0.031
OIII (k) w,p	1138.54	1138.6	210458.5	---
OIII (k) w,p	1149.60	1150.0	197086.7	---
	1150.88	1150.8	197086.7	---
	1153.77	1154.1	197086.7	
OIV (P) v,p	1338.60	1337.7	180481.3	---
	1342.99	1341.9	180724.6	---
	1343.51	1341.9	180724.6	---
OVI (1) c,s	1031.91	1026.9	0.00	0.26
	1037.61	1034.4	0.00	0.13
SiII (5) i,m,l	1190.42	1190.3	0.00	0.92
	1193.29	1193.3	0.00	2.00
SiII (4) i,w,l	1260.42	1260.0	0.00	3.6
SiII (3) i,w,l	1304.37	1304.4	0.00	0.34
SiIII (6) v,p	993.52	993.7	52630.00	---
	994.79	---	52758.00	---
	997.39	997.6	53019.00	---
SiIII (43)	1005.35	1005.5	142847.6	---
	1005.35	1005.5	142847.6	---
	1005.36	1005.5	142847.6	---
	1005.37	1005.5	142849.7	---
	1005.38	1005.5	142849.7	---
	1005.40	1005.5	142851.7	---

TABLE 1 (Cont'd.)

Ion Multiplet	λ (Å) Laboratory	λ (Å) Measured	Level cm^{-1}	gf
CI	1279.89		16.40	0.026
(5) i,w,l	1280.14		0.00	0.020
	1280.33	1280.0	43.40	0.075
	1280.40		16.40	0.015
	1280.60		16.40	0.020
	1280.85		43.40	0.026
CI	1328.83		0.00	0.039
(4) i,w,p	1329.09		16.40	0.039
	1329.10	1329.4	16.40	0.048
	1329.12		16.40	0.030
	1329.58		43.40	0.14
	1329.60		43.40	0.048
CII	1036.34	1036.3	0.00	0.12
(2) i,m,l	1037.02		63.42	0.24
CII	1334.53	1334.4	0.00	0.52
(1) i,m,l	1335.66		63.42	0.11
	1335.71		63.42	0.96
CIII	977.02	~974.0	0.00	0.81
(1) c,l				
CIII	1165.70	---	52338.0	---
(k) w,p	1165.87	1165.9	52394.8	---
CIII	1174.93		52338.0	0.33
(4) s,c	1175.26		52315.0	0.26
	1175.59	1171.7	52338.0	0.20
	1175.71		52394.8	1.00
	1175.99		52338.0	0.26
	1176.37		52394.8	0.32
CIII	1247.38	1247.0	102351.4	0.27
(9) m,l				
CIII	1256.52	1256.3	238160.7	---
(k) v,l				
CIII	1308.73	1309.2	182520.2	---
(k) v,p				

Ion Multiple	λ (Å) Laboratory	λ (Å) Measured	Level cm^{-1}	gf
CIII	1426.45	1426.3	238160.7	---
(k) v,p	1427.85	1428.0	238160.7	---
	1428.53	1428.0	238160.7	---
CIII	1428.17	1428.0	259672.1	---
(k) v,p	1428.66	---	259659.3	---
	1428.95	---	259672.1	---
	1429.08	---	259659.3	---
CIV	1230.05	~ 1230	320048.5	---
(k) m,p	1230.51	~ 1230	320080.0	---
NI	1134.17	1134.6	0.00	0.096
(2) i,m	1134.41	1134.6	0.00	0.19
	1134.98	1134.6	0.00	0.26
NI	1199.55	1201.3	0.00	0.72
(1) i,s	1200.22	1201.3	0.00	0.44
	1200.71	1201.3	0.00	0.24
NII	1083.99	1084.8	0.00	0.17
(1) i,m	1084.56	1084.8	49.1	0.13
	1084.58	1084.8	49.1	0.39
	1085.53	1084.8	131.3	0.0085
	1085.55	1084.8	131.3	0.12
	1085.70	1084.8	131.3	0.70
NIII	979.77		101031.5	0.08
(12) w,l	979.84	979.6	101031.5	0.72
	979.92		101023.8	1.12
	980.01		101023.8	0.08
NIII	989.79	987.2	0.00	0.36
(1) c	991.51		174.5	0.07
	991.58		174.5	0.65
NIII	1005.98	1005.8	131003.5	0.36
(17) w,p	1006.03	1005.8	131003.5	0.18
NIII	1183.03	1184.3	145876.1	0.12
(20) w,p	1183.03	1184.3	145876.1	0.24
	1184.54	1184.3	145986.5	0.12
	1184.54	1184.3	145986.5	0.60
NIII	1324.40	1324.7	267244.4	---
(k) v,p				

TABLE 1 (Cont'd.)

Ion Multiplet	λ (Å) Laboratory	λ (Å) Measured	Level cm^{-1}	gf
SiIII (5) m,p	1108.37	1109.0	52630.00	---
	1109.94	1110.7	52758.00	---
	1109.97	1110.7	52758.00	---
	1113.17	1113.2	53019.00	---
	1113.20	1113.2	53019.00	---
	1113.23	1113.2	53019.00	---
SiIII (32) w,p	1140.54	1140.4	129615.00	---
	1141.58	---	129747.00	---
	1142.28	1142.3	129747.00	---
	1144.31	1144.3	130006.00	---
	1144.96	1145.4	130006.00	---
	1145.67	1145.4	130006.00	---
SiIII (41) w,p	1145.12	1145.4	142847.6	---
	1145.15	1145.4	142847.6	---
	1145.16	1145.4	142847.6	---
	1145.18	1145.4	142849.7	---
	1145.19	1145.4	142849.7	---
	1145.22	1145.4	142851.7	---
SiIII (31) w,p	1155.00	1155.2	129615.00	---
	1155.96	---	129747.00	---
	1156.78	1158.0	129747.00	---
	1158.10	1158.0	129747.00	---
	1160.26	1160.3	130006.00	---
	1161.58	1161.9	130006.00	---
SiIII (2) m	1206.51	1206.5	0.00	1.68
SiIII (63) w,p	1280.35	1280.0	122213.00	---
SiIII (4) v,p	1294.54	---	52758.00	---
	1296.73	---	52630.00	---
	1298.89	---	52758.00	1.80
	1298.96	---	53019.00	---
	1301.15	---	52758.00	0.40
	1303.32	1303.0	53019	0.50
SiIII (39) m,p	1341.46	1342.0	142847.6	---
	1341.50	1342.0	142849.7	---
	1342.35	1342.0	142847.6	---
	1342.39	1342.0	142849.7	---
	1342.43	1342.0	142847.6	---
	1343.38	---	142847.6	---

Ion Multiplet	λ (Å) Laboratory	λ (Å) Measured	Level cm^{-1}	gf
SiIII (68) v,p	1359.75	1359.8	175134.0	---
	1360.36	1359.8	175167.0	---
	1361.72	1361.5	175240.2	---
SiIII (46) v,p	1361.60	1361.5	153281.0	---
	1367.05	1367.0	153281.0	---
	1369.44	1369.8	153281.0	---
SiIII (38) v,p	1362.37	---	142851.7	---
	1363.46	1363.5	142849.7	---
	1363.50	1363.5	142851.7	---
	1365.25	1365.4	142847.6	---
	1365.29	1365.4	142849.7	---
	1365.34	1365.4	142851.7	---
SiIII (62) v,p	1424.78	1424.3	122213.0	---
SiIII (66) v,p	1433.69	1433.6	175240.2	---
	1436.72	1436.5	175167.0	---
	1438.23	1438.1	175240.2	---
	1438.70	1438.1	175134.0	---
	1439.39	1439.3	175167.0	---
	1440.91	1441.2	175240.2	---
SiIII (52) v,p	1436.17	1436.5	159068.4	---
SiIV (11) m,l	1066.63	1067.7	160376.8	---
SiIV (3) m,l	1122.49	1122.3	71289.6	---
	1128.32	1127.4	71749.9	---
	1128.34	1127.4	71749.9	---
SiIV (20) v,l	1228.35	1228.4	218269.5	---
	1230.80	~1231.0	218431.3	---
SiIV (19) v,p	1365.55	1365.4	218269.5	---
	1368.57	1368.8	218431.3	---
	1368.57	1368.8	218431.3	---
SiIV (1) c	1393.76	1386.3	0.00	1.1
	1402.77	1394.7	0.00	0.53
PI (k) i,v,p	1242.02	1242.0	0.00	---
	1248.20	---	0.00	---
	1248.61	1248.8	0.00	---

TABLE 1 (Cont'd.)

Multiplets	λ (Å) Laboratory	λ (Å) Measured	Level cm⁻¹	gf
PI (k) i,w,p	1243.37	---	0.00	---
	1245.19	---	0.00	---
	1247.31	1247.0	0.00	---
PI (k) i,m,p	1253.74	1254.0	0.00	---
PI (k) i,m,p	1283.89	---	0.00	---
	1285.84	1286.00	0.00	---
	1286.00	1286.00	0.00	---
PII (2) i,m,p	1301.87	1301.7	0.00	---
PIII (2) w,l	998.00	997.6	0.00	---
	1003.59	1003.6	559.6	---
PIII (k) w,p	1093.63	1093.4	100201.2	---
PIII (1) m,l	1334.87	1334.4	0.00	---
	1344.34	1334.7	559.6	---
	1344.90	1334.7	559.6	---
PIII (k)	1337.50	1337.7	116873.6	---
	1337.71	1337.7	116884.9	---
PIII (k) w,p	1343.69	---	173813.4	---
	1347.00	1347.2	173988.4	---
	1347.51	1347.2	173988.4	---
	1348.45	1349.0	174106.2	---
	1349.11	1349.0	174106.2	---
PIII (k) v,p	1354.96	1355.0	117834.5	---
PIII (k) w,p	1370.39	1370.9	175260.8	---
	1372.01	---	175314.1	---
	1372.71	1372.7	175376.6	---
	1374.78	~1375.0	175427.2	---
PIV (1) s,l	950.66	948.5	0.00	2.75
PIV (k) w,l	1086.94	~1087.0	189389.0	---
	1088.61	1088.7	189389.0	---
	1091.44	1091.4	189389.0	---

Ion Multiplet	λ (Å) Laboratory	λ (Å) Measured	Level cm⁻¹	gf
PIII (k) w,p	1343.69	---	173813.4	---
	1347.00	1347.2	173988.4	---
	1347.51	1347.2	173988.4	---
	1348.45	1349.0	174106.2	---
	1349.11	1349.0	174106.2	---
PIII (k) v,p	1354.96	1355.0	117834.5	---
PIII (k) w,p	1370.39	1370.9	175260.8	---
	1372.01	---	175314.1	---
	1372.71	1372.7	175376.6	---
	1374.78	~1375.00	175427.2	---
PIV (1) s,l	950.66	948.5	0.00	2.75
PIV (k) w,l	1086.94	~1087.0	189389.0	---
	1088.61	1088.7	189389.0	---
	1091.44	1091.4	189389.0	---
PIV (k) w,p	1093.32	1093.4	226888.6	---
	1098.18	---	226888.6	---
	1101.65	1101.6	226888.6	---
PIV (k) m,p	1118.59	1118.3	105189.9	---
PIV (k) w,l	1161.78	1161.9	233995.0	---
PIV (k) w,l	1197.82	1197.7	257520.2	---
PV (k) w,p	997.64	997.6	204208.3	---
	1000.36	1000.8	204197.1	---
PV (k) m,l	1117.98	1118.3	0.00	1.27
	1128.01	1127.4	0.00	0.63
SI (k) i,v,p	1241.9	1242.0	0.00	---
SI (k) i,m,p	1247.17	1247.0	0.00	---
SI (k) i,w,p	1270.78	1271.2	0.00	---

TABLE 1 (Cont'd.)

Ion Multiplet	Laboratory	Measured	Level cm^{-1}	gf
SI (9) i,m,l	1295.66	1295.9	0.00	---
	1296.17	1295.9	0.00	---
SI (8)	1316.57	1317.0	0.00	---
SII (1) i,m,p	1250.50	---	0.00	0.45
	1253.79	1254.0	0.00	0.89
	1259.53	1260.0	0.00	1.34
SIII (2) w,l	1012.49	1012.5	0.00	0.30
	1015.51	1015.2	297.2	0.52
	1015.76	---	297.2	0.38
	1021.10	1021.2	832.5	0.38
	1021.32	1021.2	832.5	1.12
SIII (8) w,l	1077.84	1077.9	11320.00	---
SIII (k) m,p	1122.42	1122.3	84099.5	---
	1126.48	---	84018.9	---
	1126.85	1127.4	84046,4	---
SIII (k) v,p	1155.34	1155.2	84099.5	---
	1162.52	1163.0	84046.4	---
	1166.13	1166.0	84018.9	---
SIII (1) m,l	1190.17	1190.3	0.00	0.42
	1194.02	1194.0	297.2	0.94
	1194.40	1194.0	297.2	0.32
	1200.97	1201.3	832.5	1.77
	1201.71	1201.3	832.5	0.32
	1202.10	1201.3	832.5	0.021
SIV (1) c,m,p	1062.67	---	0.00	0.94
	1072.99	1073.2	950.2	0.19
	1073.52		950.2	1.69
SIV (k) m,p	1108.36	1109.0	123503.9	---
	1110.90	1110.7	123503.9	---
SIV (k) w,p	1138.23	1138.6	123503.9	---
SIV (k) m,p	1286.06	1286.1	133617.9	---
	1296.64	---	134243.9	---

Ion Multiplet	λ (Å) Laboratory	λ (Å) Measured		
SVI (1) c	933.38	928.8	0.00	0.05
	944.52	---	0.00	1.0
ClII (1) i,m,p	1063.83	1063.5	0.00	0.94
	1071.05	1070.3	0.00	2.82
ClII (1) v,p	1005.28	1005.5	0.00	0.56
	1008.78	1009.2	0.00	0.10
	1015.02	1015.2	0.00	1.66
ArI (1) w,p	919.78	---	0.00	1.72
	932.05	931.9	1432.0	0.86
CaII (2) w,p	1342.07	1342.0	0.00	---
VII (3) w,p	1122.11	1122.3	339.00	---
	1123.00	1123.4	145.00	---
	1123.55	1123.4	0.00	---
	1125.71	1125.9	583.0	---
VIII (2) w,p	1149.94	~1150.0	583.0	---
	1151.04		339.0	---
	1152.18		145.0	---
	1153.19	~1153.0	0.00	---
	1154.24	1154.1	583.0	---
FeII (12) i,m,p	1121.99	1122.3	0.00	---
FeII (10) i,w,p	1142.33	1142.3	0.00	---
	1143.24	---	0.00	---
	1144.95	1145.4	0.00	---
FeII (9) i,w,p	1260.54	1260.0	0.00	---
FeIII (1) m,l	1122.53	1122.3	0.00	4.50
	1124.88	---	436.2	2.32
	1126.72	1127.4	738.9	0.88
	1128.02	1127.4	436.2	1.17
	1128.72	1128.0	738.9	1.46
	1129.19		932.4	1.12
	1130.40	1130.0	1027.3	0.50
	1131.19	---	932.4	0.38
	1131.91	---	738.9	0.17

e) O I, O III, O IV, O VI

The O I multiplet at 1302.2–1306.0 Å, which on the basis of past experience should appear in the spectrum, can be associated with a weak absorption feature near these wavelengths. Another likely source of absorption is interstellar Si II ions with a resonance transition at 1304.4 Å. The weakness of the feature must be due to the combined reasons that the rocket was above most of the terrestrial O I and the interstellar lines are quite narrow.

Tentatively identified subordinate lines in O III are listed in Table 1; the maximum excitation is 26.1 eV.

It is possible that the 1338.6 and 1343.0, 1343.5 Å transitions in O IV appear as P Cygni–type profiles. Both the absorption lines with which the transitions are identified are shifted shortward by about 1 Å. Other transitions may affect the profiles, particularly those in Si III and Ca II ions, and perhaps even to the exclusion of O IV altogether. If the oxygen lines are present, then we can conclude that both the abundance and radial velocity of the excited O IV ions in the expanding envelope are considerably less than in the case of the O5f star ζ Pup (Smith 1970).

The strongest P Cygni profile observed corresponds to the 1031.9, 1037.6 Å resonance lines in O VI; these lines seem to be of comparable strength to those observed in ζ Pup.

f) Si II, Si III, Si IV

Four lines of interstellar Si II have been reliably identified at 1190.3, 1193.3, 1260.0, and 1304.4 Å.

Si III definitely exists in the stellar atmosphere in significant quantities as evidenced by the well-defined resonance line at 1206.5 Å. Fifteen other multiplets of subordinate lines have been listed in Table 2, but all of these identifications are considered only tentative. The highest excitation in Si III represented by the subordinate lines is 21.7 eV.

Four multiplets of Si IV subordinate lines are listed, all of which are considered to be only tentatively identified. On the other hand, the resonance transitions in Si IV at 1393.8, 1402.8 Å appear as a strong P Cygni–type profile.

g) P I, P II, P III, P IV, P V

The evidence for interstellar P I and P II is very weak, yet transitions in these ions may contribute to the contour of the spectrum at the indicated wavelengths. By contrast the ions of P III, P IV, and P V very likely contribute to the stellar or circumstellar spectrum. As expected, the strongest evidence is associated with transitions from the ground-state configurations of these ions, and in the case of P IV it is possible that the resonance transition at 950.7 Å appears as a P Cygni–type profile. All other transitions which could possibly account for the relatively large absorption feature centered on

TABLE 2

UNIDENTIFIED LINES IN THE SPECTRUM OF ZETA ORIONIS

λ(Å) Measured	λ(Å) Measured	λ(Å) Measured	λ(Å) Measured
995.4	1062.4	1286.1m	1323.0
1000.8	1099.5m	1311.6	1334.0m
1052.5	1251.5	1318.6	
1060.0	1265.3	1320.8	

NOTE.—A letter m indicates that the estimated line strength is moderate; all other lines listed are weak.

948.5 Å should appear weakly in the spectrum with the exception of a telluric N_2 band that might produce at least some of the observed absorption. A disturbing consequence of this identification is that if it were true, one might reasonably expect to see circumstellar lines associated with the resonance transitions in P V at 1118.0 and 1128.0 Å, and there is no evidence for this. It is therefore concluded that the identification of the 948.5 Å absorption feature with a Doppler-shifted P IV (950.7 Å) line is not warranted. The maximum excitation indicated by the subordinate lines is 21.7, 31.9, and 25.3 eV in P III, P IV, and P V, respectively.

h) S I, S II, S III, S IV, S VI

Although there is only one multiplet out of those listed for S I and S II which is considered reliably identified, interstellar sulfur very likely affects the recorded spectrum. S III in the ground state assuredly exists in the stellar atmosphere; the maximum excitation from tentatively identified subordinate lines is 10.4 eV. The S IV ground-state transitions are readily apparent near 1070 Å. The absorption feature centered on 1069 Å may be at least in part due to Doppler-shifted transitions in S IV (1073.0, 1073.5 Å) arising in the circumstellar envelope. On the basis of these numbers the mean radial velocity of S IV ground-state ions in the circumstellar envelope would be 1300 km s^{-1}. However, one would expect to see the same effect for the 1062.7 Å line of this multiplet; and the evidence in this respect is poor. Tentatively, identified stellar subordinate lines of S IV indicate a maximum excitation of 16.6 eV.

Observations of ζ Pup suggest that the strong O VI circumstellar lines observed in ζ Ori might be accompanied by circumstellar lines in S VI corresponding to transitions at 933.4 and 944.5 Å. It is believed that the broad absorption feature centered on 928.8 Å is mostly the result of Doppler-shifted 933.4 Å transitions in S VI. The shifted absorption feature to be expected from the 944.52 Å component of this doublet must be strongly modified by a telluric N_2 band near 938.6 Å.

i) Cl II, Cl III

There is only very weak evidence for resonance transitions in Cl II and Cl III. If Cl IV is present in the stellar atmosphere, its spectral effects are masked by the circumstellar N III line and a telluric N_2 band. No subordinate lines are observed.

j) Ar II

A weak feature at 931.9 Å corresponds to a relatively strong transition ($gf = 0.86$) from the ground-state configuration of Ar II at 932.1 Å. The Ar II ions in this case must be principally in the H II region surrounding ζ Ori. Those ions of argon which one would expect in the stellar atmosphere—namely, Ar III and Ar IV—all possess resonance lines at wavelengths less than 912 Å, and are therefore unobservable.

k) Ca II

Of the possible transitions which may contribute to the absorption feature near 1342 Å, the resonance line in interstellar Ca II (1342.1 Å) is one of the most likely; a P Cygni-type profile corresponding to the 1343.0, 1343.5 Å transitions in O IV constitutes another possible explanation for the feature.

l) V III

Listed in Table 1 are two multiplets of V III containing resonance lines for which there is some weak spectral evidence. A weak depression in the spectrum extending from about 1150 to 1154 Å may be due to transitions in both V III and O III.

m) Fe II, Fe III, Fe IV

There is no reliable evidence for interstellar Fe II in the recorded spectrum. Three multiplets with resonance lines corresponding to absorption features are listed in Table 2, but the identification is considered tentative. A multiplet of Fe III containing a resonance line at 1122.5 Å very likely influences the spectrum from 1122 through 1132 Å together with Si IV.

Spectral features which seem to be real, but for which there are either inadequate identifications or none at all, are listed in Table 2. The feature at 1334 Å is likely due at least in part to the C II resonance transition at 1334.5 Å, but the line is broad and centered at 1334.0 Å, implying an unknown source of absorption at this wavelength.

Summarized in Table 3 are the data concerning the P Cygni–type profiles found in the recorded ζ Ori spectrum.

The mean velocities are determined from the wavelength shift corresponding to the center of the shortward-shifted absorption component. All the doublet lines, i.e., those of N V (1238.8, 1242.8 Å), O VI (1031.9, 1037.6 Å), Si IV (1393.7, 1402.8 Å), S IV (1062.7, 1073.5 Å), and S VI (933.4, 944.5 Å) are resolved. In the case of the N V, O VI, Si IV, and S VI doublets the shorter-wavelength components were used because their absorption components should be least affected by emission, and in the case of S VI to avoid the complication arising from a telluric N_2 absorption band at 938.6 Å. For S IV the 1073.5 Å line was used because the contour of the 1062.7 Å transition was so peculiar the center of the absorption component could not be found. The velocities in parentheses are taken from Morton, Jenkins, and Bohlin (1968). These authors also report a circumstellar profile for the Si III resonance transition at 1206.5 Å, an observation which is not substantiated by the data reported here. However, the possibility that Si III ions in the ground state exist in substantial quantities in the circumstellar envelope is not eliminated. The interstellar Lα absorption may reduce the expected longward-shifted emission from excited circumstellar Si III ions, and the optical depth in the circumstellar envelope might be sufficiently small to allow the unshifted Si III (1206.5 Å) absorption line to be clearly seen as it is.

The velocities in the third row correspond to the wavelengths for each multiplet at which the short-wavelength absorption edge meets the continuum. These parameters are determined by a necessarily inaccurate extrapolation, and hence the derived velocities are only rough estimates.

Although the features associated with circumstellar S IV ions are indeed peculiar, it is difficult to imagine any other plausible source of absorption sufficiently strong to account for the observed profile. If the identification is correct, then the shape of the absorption component corresponding to the 1062.7 Å transition must be affected by noise

TABLE 3

RADIAL VELOCITIES OF IONS IN THE CIRCUMSTELLAR ENVELOPE OF ZETA ORIONIS

Ion	C III	N III	N V	O VI	Si IV	S IV	S VI
Laboratory wavelength (Å)	1175.7	991.0	1238.8	1031.9	1393.8	1062.7	933.4
	...	...	1242.8	1037.6	1402.8	1073.5	944.5
Mean velocity (km s^{-1})	1020	1140	1380	1460	1600	1300	1480
	(1050)	...	(1770)	...	(1600)	...	...
Extrapolated maximum velocity (km s^{-1})	2800	3200	2600	3300	3100	2400	...

or some unknown absorber. Also, the opacity in the line at 1073.5 Å would have to be sufficiently small to permit seeing to the unaccelerated atmospheric layers. The absorption component of the 1073.5 Å transition is probably influenced by a strong Si IV subordinate line at 1066.6 Å. This line was observed to be strong in the spectrum of ζ Pup (O5f) (Smith 1970).

The columnar density of atomic hydrogen was determined by fitting a computed profile to the core of the observed Lα line in a manner described previously (Smith 1969). This procedure was followed instead of making a standard equivalent-width measurement in order to facilitate the decision as to what area under an assumed continuum level should be included in the Lα line. As can be readily appreciated, such a decision is at best difficult and often hazardous to make because the spectrum at these short wavelengths is extremely ragged. In the case at hand, the calibration curve presented in Figure 1 was used to obtain the relative flux distribution from 1200 to 1240 Å; the results are given by the solid contour in Figure 3, together with identifications of several features. The measured flux distribution was not corrected for smoothing effects due to the intrinsic instrumental profile, fluctuations in the rocket pointing, and the averaging of densitometer data points. Instead, the computed profile was smoothed by using a trapezoidal weighting function 1.0 Å full width at half-maximum which was intended to approximate the smoothing of the data from all sources. The approximation is crude; however, the differences between the smoothed and unsmoothed computed profiles are negligible except at low flux values where the instrument calibration is in any case poor. Dotted lines in Figure 3 show the smoothed computed profile and the assumed continuum level. The solid horizontal lines indicate the flux level below which the instrument calibration is considered unreliable.

The column density of hydrogen atoms corresponding to the illustrated computed profile is $(2.03 \pm 0.67) \times 20^{20}$ cm^{-2}, and the equivalent width of the Lα line is 10.4 ± 1.6 Å. These values may be compared with those of Jenkins and Morton (1967) who found a column density of 1.6×10^{20} cm^{-2} and an equivalent width of 9.3 ± 1 Å, and with those of Carruthers (1968) who for these same quantities derived 1.1×10^{20} cm^{2} and 7.7 ± 1.5 Å, respectively. Recently, Jenkins (1971) has redetermined the columnar densities to four stars which included ζ Ori by a detailed statistical analysis of the existing Princeton spectrograms. For ζ Ori the column density of hydrogen atoms is $(1.75\ [+0.70, -0.50]) \times 10^{20}$ cm^{-2} which agrees well with the value derived in this paper. Assuming that the distance to ζ Ori is 457 pc, the mean number density of hydrogen atoms becomes 0.14 ± 0.05 cm^{-3}.

IV. DISCUSSION AND SUMMARY

Morton and his associates (Bradley and Morton 1969; Hickok and Morton 1968) have constructed atmosphere models in radiative equilibrium of hot stars with effective temperatures ranging from 28,640° to 37,450° K and with log $g = 3.5$ and 4.0, assuming that LTE and hydrostatic equilibrium are valid throughout the atmospheres. A group of 110 lines has been used in each model to estimate the effect of strong line blanketing in the vacuum-ultraviolet. Most of these lines have been reliably identified in the ζ Ori spectrum presented here. Many, however, appear as circumstellar lines and thus prevent an unqualified assertion that they arise in the unaccelerated layers of the stellar atmosphere; one can only make this assumption. The Cl IV multiplet at 973.2–985.7 Å may be present in the spectrum; but if it is, it is masked by the circumstellar lines of C III (977.0 Å) and N III (989.8–991.6 Å). A transition in O V at 1371.29 Å does not appear strongly enough to rate even a "possible" identification; neither, incidentally, does it appear in the rocket spectrum of ζ Ori secured by the Princeton group (Morton *et al.* 1968). In addition to these multiplets which have been used in the models but not found in the spectrum is one which has been only tentatively identified, namely, that of N III at 1006.0 Å. Finally, all of the hydrogen lines with the exception of Lα and all of the He II lines with the exception of the 1084.9, 1085.0 Å transition are masked by stronger features; there is no doubt in this case, however, that they should be included in the model atmosphere.

Fifteen multiplets containing subordinate lines in the ions of He II, C, III, N III, Si IV, P IV, and S III have been identified on a reliable basis. In the tentatively identified category are found 53 additional multiplets with transitions originating in excited levels of C III, C IV; N III, N IV, N V; O III, O IV; Si III, Si IV; P III, P IV, P V; S III, S IV; and Fe IV. Most of the features in the spectrum with which these transitions have been identified are judged weak or very weak. In those cases where the observed feature is moderate to strong, eight multiplets in all, the identification is confused by the possible presence of equally plausible lines. The highest excitation revealed by the reliably identified lines occurs in the N IV ion with multiplets at 1225.0–1225.7 Å and 1270.3–1274.7 Å; the excitation is 50.11 eV. Tentatively identified lines in N V at 1048.2 and 1049.6 Å originate near 76.3 eV.

A low-dispersion spectrogram of ζ Ori at visible wavelengths has been published by Abt *et al.* (1968) in which some strong lines characteristic of the stellar type (O9.5 Ib) have been identified. Earlier, Wilson (1958) analyzed six spectrograms of ζ Ori obtaining equivalent widths of 35 lines at wavelengths extending from 4144 to 6563 Å. The C III (1256.5 Å) line which has been reliably identified and a multiplet appearing in the visible spectrum of ζ Ori at 4647.4–4651.4 Å are both associated with the same lower level ($3s\ ^3S$) at 29.5 eV. A tentatively identified ultraviolet multiplet in the same ion at 1426.4–1428.5 Å also has the same lower-level identification. Another tentatively identified multiplet in Si III at 1361.6–1369.4 Å and one in the visible at 4552.6–4574.8 Å have a common lower level ($4s\ ^3S$) at 19.0 eV. No other coincidences of lower levels for transitions in the ultraviolet and visible have been noted. The range of excitation observed in the ultraviolet lines includes that apparent in the visible, the maximum observed excitation in each case being nearly the same. (The excitation in He II as observed in the visible is about 50 eV.) At ultraviolet wavelengths one can observe very low excitations; indeed, one can observe the resonance lines in the most abundant ions which, of course, cannot be observed in the visible.

Except for the ions of N III and S IV the mean radial velocities of detected ions in the circumstellar envelope are consistent with those published by Carruthers (1968) and Morton *et al.* (1968). In the case of N V the present value of 1380 km s^{-1} is very nearly the average of theirs, and in the case of the excited (6.5 eV) C III ions the value listed here is very close to that of Morton *et al.* which is about 200 km s^{-1} less than Carruthers's value.

The distribution of ions in the circumstellar envelope will depend not only on the temperature and electron density conditions throughout the envelope, but also on whether or not the ion is at, or one stage lower than, the maximum possible state of ionization. Thus, for the atoms of N, O, Si, and S due to the ionization potentials involved, the maximum possible ionization results in N VI, O VII, Si V, and S VII, respectively. One would expect to find at all elevations above the stellar surface where the electron temperature and pressure were such as to produce these ions recombinations to the next lowest state of ionization, i.e., N V, O VI, Si IV, and S VI. These ions should consequently exhibit a mean radial velocity greater than those which are insensitive to this saturation effect (N III and S IV are examples in the case at hand). This point has been emphasized by Underhill (1970).

It is worthwhile to note the strength of the O VI (1031.9, 1037.6 Å) P Cygni line. The ionization potential of O V is $\sim$114 eV, and for any reasonable set of conditions in the stellar atmosphere of ζ Ori one would not expect a large abundance of O VI. In addition, the circumstellar C III (1175.7 Å) which originates in the metastable ($2p\ ^3P^o$) level is strong and therefore indicates that a dilute radiation field exists where the C III ions are found. As in the case of ζ Pup (O5f) these facts are consistent with viewing the circumstellar envelope, at least where the O VI ion density is largest, as a hot ($\sim 10^5$ ° K) plasma in which collisional ionization is an important process. If true, it will be necessary to compute P Cygni profiles on the basis of a model which includes collisional ionization before the observations can be used to check mass-loss estimates. In this respect the mean radial velocity as determined and listed here is not necessarily a useful parameter for model circumstellar envelopes. For example, if a monotonically increasing function of elevation above the stellar surface is assumed for the plasma velocity, then the point at which the mean radial velocity of a given ion occurs does not in general correspond to the point at which the maximum ion density occurs. Rather, it depends on the details of the velocity and density distributions, and these are obscured by the inaccuracies in the present observations.

Thus, while the problem of determining the mean radial velocities of circumstellar ions with the data at hand is perhaps not of overwhelming importance, it does point out the observational need for moderate-resolution (1 Å) spectrograms with greater relative photometric accuracy, and the theoretical need for suitable models, semiempirical if necessary, with which to extract characteristic parameters of the envelopes from the observations.

Of the 12 interstellar C I resonance lines listed in Table 1, only two are probably present in the spectrum, namely, the transitions at 1277.2 and 1280.1 Å. At higher resolution the former of these seems to be best suited for the determination of interstellar C I abundances. Both of the expected doublet transitions in C II near 1037 and 1335 Å are present and should be easily observed at higher resolution against a suitable background star. In this regard recent rocket experiments have provided spectrograms of ζ Oph and ζ Per with a dispersion of 4.5 Å mm^{-1} and a resolution of 0.5 Å. In both spectrograms the 1334.5 and 1335.7 Å lines of C II appear strongly. In the present case, the evidence for the 1335.7 Å line is weak, consisting of a small depression in the spectrum from 1335.5 to 1336.8 Å. An estimate of the population ratio of the elevated $^2P^o_{3/2}$ level at 0.0078 eV to the $^2P^o_{1/2}$ ground state may be made if one assumes that the upper level is populated by collisions in an interstellar cloud. Use of the cross-sections and radiative-decay rate of Bahcall and Wolf (1968), a cloud density of 10^2 cm^{-3}, a temperature of 10^2 ° K, and a value of 6×10^{-4} for the density ratio of electrons to hydrogen atoms leads to a computed population ratio of 0.064. That one should expect interstellar absorption from C^+ ions can be inferred from the interstellar spectrum of ζ Ori (Adams, 1949) in which the H- and K-lines of Ca II appear as weak, broad features. If the $^2P^o_{3/2}$ level of C^+ is populated through collisions, the fine-structure levels of the ground-state configuration in carbon atoms should be similarly populated. However, the lines in the multiplets at 1277.3 and 1280.1 Å (arising from the ground-state configuration) are too close together to be resolved by the instrument, and thus we have no indication of their relative strength. Because of the weak evidence for the C II (1335.7 Å) line and the possibility that interstellar conditions exist such that, theoretically, we might expect the ground-state fine-structure levels in C and C^+ to be populated, all the lines arising from these levels are included in Table 1. All of these lines except the resonance lines must be considered only possibly present in the spectrum in view of the problematical nature of the evidence.

The strong N I (1134.2–1135.0 Å) and N I (1200.0–1200.7 Å) multiplets are due both to interstellar and telluric absorption whereas the N II (1084.0–1085.7 Å) multiplet must arise mainly in the H II region surrounding the star. It is interesting to note that a resonance line in Ar II (932.0 Å) has been tentatively identified in the spectrum; if real, these ions would also be found mainly in the H II region. All three members of the O I (1302.2–1306.0 Å) triplet appear to be present, and thus as in the case of N I these lines are due both to interstellar and telluric absorption.

Three multiplets of Si II are found at 1190.4–1193.3 Å, 1260.4 Å, and 1304.4 Å, as expected. Because of interference from stellar and other interstellar lines, perhaps the best of these to measure at higher resolution is the resonance line at 1304.4 Å even though it has the lowest *gf*-value of the four lines.

Two resonance lines in S I at 1295.7 and 1296.2 Å are probably present and could be profitably observed at higher resolution. Possibly a Ca II line at 1342.1 Å is also present in the spectrum. At high resolution this line would not be confused with P Cygni profiles arising in circumstellar O IV ions near 1340 Å and would provide a useful link to observations of interstellar lines in the visible spectral regions.

It should be emphasized that even under ideal conditions of high resolution and photometric accuracy the interstellar lines will, except in a few cases, be difficult to isolate from other features both stellar and interstellar. For example, even though the 1260.4 Å resonance line of Si II by virtue of its strength is easy to identify in the ζ Ori spectrum, it will nevertheless be difficult to distinguish the contribution to the profile near this wavelength by C I at 1260.7–1261.6 Å. Indeed, at wavelengths less than 2000 Å all observable interstellar lines of C I occur in multiplets which may exhibit considerable intrinsic blending. In the case of C II the interstellar transitions at 1334.5 and 1335.7 Å will probably be so strong due to the abundance of this ion that the stellar contributions to this line will be difficult to isolate even with a rapidly rotating background star such as ζ Oph. The difficulty in analyzing the N I (1134.6 Å) and O I (1302.2 Å lines appearing in sounding-rocket spectra is clear; it is simply that the contribution to the line widths from these same ions in the Earth's atmosphere is impossible to calculate accurately, and, in the case of O I, estimates of this "contamination" made on the basis of the observed O I (1304.9 Å) line will be very uncertain due to the presence of the Si II (1304.4 Å) line.

The equivalent width of the Lα line in this experiment agrees more closely with the other published results of rocket spectroscopy than with the OAO-II satellite results of Savage and Code (1970). It is to be admitted that the weakest point in the derivation of the equivalent width in this experiment is the determination of the relative flux distribution in the Lα line profile. The film is simply not photometrically accurate. However, one can readily see from the spectrum presented here that an instrumental profile at 15 Å full width at half-maximum response as employed in the Wisconsin experiment will be too broad to reliably exclude the effects of nearby stellar lines, and these latter are strong. The question of which values of the Lα equivalent width for ζ Ori are more nearly correct remains open, awaiting a photometrically accurate instrument of sufficiently good resolution to provide the answer.

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REFERENCES

Abt, H. A., Meinel, A. B., Morgan, W. W., and Tapscott, J. W. 1968, *An Atlas of Low-Dispersion Grating Stellar Spectra*.
Adams, W. S. 1949, *Ap. J.*, **109**, 354.
Allen, C. W. 1963, *Astrophysical Quantities* (2d ed.; London: Athlone Press).
Bahcall, J. N., and Wolf, R. A. 1968, *Ap. J.*, **152**, 701.
Bradley, P. T., and Morton, D. C. 1969, *Ap. J.*, **156**, 687.
Carruthers, G. R. 1968, *Ap. J.*, **151**, 269.
Garstang, R. H., and Shamey, L. J. 1967, in the *Magnetic and Related Stars*, ed. R. C. Cameron (Baltimore: Mono Book Corp.).
Hallin, R. 1966, *Ark. f. Fys.*, **31**, 511.
Hickok, F. R., and Morton, D. C. 1968, *Ap. J.*, **152**, 195.
Jenkins, E. B. 1971, preprint, Princeton, University.
Jenkins, E. B., and Morton, D. C. 1967, *Nature*, **215**, 1257.

Kelly, R. L. n.d., *Table of Emission Lines in the Vacuum Ultraviolet for all Elements*, University of California Radiation Laboratory, publication 5612.
———. 1968, *Atomic Emission Lines Below 2000 Angstroms* (U.S. Naval Research Laboratory Report 6648).
Moore, C. E. 1950, *N.B.S. Circ.*, No. 488, Section 1.
———. 1965, *N.S.R.D.S. N.B.S.*, No. 3, Section 1.
———. 1970, *ibid.*, No. 3, Section 3.
Morton, D. C., Jenkins, E. B., and Bohlin, R. C. 1968, *Ap. J.*, **154**, 661.
Palenius, H. P. 1967, *Ark. f. Fys.*, **34**, 571.
Savage, B. D., and Code, A. D. 1970, *Ultraviolet Stellar Spectra and Related Ground-Based Observations*, IAU Symposium 36, ed. C. Houziaux and H. E. Butler (Dordrecht: D. Reidel Publishing Co.).
Smith, A. M. 1969, *Ap. J.*, **156**, 93.
———. 1970, *ibid.*, **160**, 595.
Underhill, A. B. 1970, private communication.
Varsovsky, C. M. 1961, *Ap. J. Suppl.*, **6**, 75.
Wiese, W. L., Smith, M. W., and Glennon, B. M. 1966, *N.S.R.D.S. N.B.S.*, No. 4.
Wilson, R. 1958, *Pub. Roy. Obs. Edinburgh*, **11**, 61.