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ROCKET-ULTRAVIOLET SPECTRA OF EIGHT STARS IN OPHIUCHUS AND SCORPIUS

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ABSTRACT

Rocket ultraviolet spectra longward of 1100 Å have been obtained for the O and B stars ζ Oph and β^1, δ, ν, π, σ, τ, and ω^1 Sco. Detailed discussions are given for ζ Oph (O9.5 V) and δ Sco (B0 V), for which resolutions of 0.5 and 0.6 Å, respectively, were achieved. Wavelengths, line identifications, and relative intensities are presented in the tables and figures. The strongest photospheric absorption lines are attributed to C II, C III, N III, Si III, Si IV, and S III with He II, N IV, N V, O IV, Al II, and Si II also possible. The interstellar Lα absorption line is the strongest feature in all the spectra except τ Sco which does not extend to 1216 Å. Several other interstellar absorption lines are present in the high-resolution spectra including C II, O I, Si II, and possibly C I and N I in δ Sco, and C II and O I in ζ Oph. The resonance lines of C IV and perhaps also N V in ζ Oph appear to be shifted to shorter wavelengths by -900 and -400 km s^{-1}, respectively, indicating that there may be mass flow from this star. Some lines in ζ Oph which cannot be attributed to interstellar absorption are remarkably narrow, corresponding to turbulent velocities $\lesssim 100$ km s^{-1} or rotational velocities $\lesssim 130$ km s^{-1} compared with values 2 or 3 times larger obtained from visual spectra.

I. INTRODUCTION

The B0 V star δ Sco and similar stars nearby have proven to be interesting targets for several Princeton rocket flights. In the far-ultraviolet spectra of δ and π Sco obtained in 1965 by Morton and Spitzer (1966) the absorption lines were mainly attributed to the stellar atmospheres, but a few lines were tentatively identified with C II, O I, Al II, and Si II in the interstellar medium. Stone and Morton (1967) measured the equivalent widths and derived column densities which seemed rather high. With a later rocket Jenkins, Morton, and Matilsky (1969) found densities of interstellar H I in the directions of β^1, δ, and π Sco slightly above normal in contrast with lower values found in some other directions in the Galaxy (Jenkins 1970). Consequently, it seemed desirable to obtain additional ultraviolet spectra of the Scorpius stars with improved resolution to study both the stellar and interstellar lines.

II. INSTRUMENTATION AND FLIGHT

For the rocket flight discussed in this paper we used a pair of objective spectrographs similar to those described by Morton and Spitzer (1969) and Morton (1967), but with several important modifications. Both Schmidt cameras now used lithium fluoride correctors which passed wavelengths longward of about 1100 Å, though the apertures were still only 50 mm. One camera viewed a grating with 1200 lines mm^{-1} for the lower-resolution spectra with a dispersion around 68 Å mm^{-1}, while the other camera viewed a grating with 3600 lines mm^{-1} to provide spectra at 19 Å mm^{-1}.

The two spectrographs were flown on an Aerobee rocket (NASA 4.271) from the White Sands Missile Range on 1970 June 2 at 4^h47^m UT. The peak altitude of 165 km was reached in 215.7 s. A gyroscopic attitude control system pointed the rocket first at

ζ Oph for an 83-s exposure from 110 up to 162 km and then towards δ Sco for 153 s from 165 down to 62 km. The Princeton passive gyro system used on previous flights for fine stabilization was replaced this time by a pair of rate-integrating gyros which kept the whole rocket steady during the exposures by fine control of the same gas jets that provided the absolute orientation. The rate gyro in pitch limited motions in the dispersion direction to about $\pm 20''$ with the result that the narrowest lines in the high-resolution spectrum of ζ Oph and δ Sco had full widths at half-depth of 0.5 and 0.6 Å, respectively. Perpendicular to the dispersion the yaw gyro had a small programmed drift which widened the spectra to 35 μ for ζ Oph and 80 μ for δ Sco. Unfortunately, fine stabilization was not available about the roll axis, which pointed toward the target stars, and an unusually large drift in this axis of the control system smeared or tilted the spectra of all off-axis stars. Only ζ Oph and δ Sco were close enough to the center of the field to have the highest spectral resolution.

The stars observed and the wavelength ranges covered by each spectrograph are listed in table 1. The spectral types, magnitudes, and colors are from Johnson *et al.* (1966) while the $E(B - V)$ extinctions are based on the intrinsic colors of Johnson (1963). According to Bertiau (1958) all the Scorpius stars in table 1 belong to the Sco-Cen Association with distances ranging between 167 and 179 pc. Blaauw (1961) adopted 170 pc for the distance of ζ Oph and showed that its space motion indicated it is a runaway star from the northern part of the same association. Four of the Scorpius stars β^1, ν, π, and σ are listed as spectroscopic binaries by Batten (1967), and δ Sco and ζ Oph have variable radial velocity according to Hoffleit (1954). The star σ Sco also is a β Canis Majoris variable.

III. DATA REDUCTION

a) *Photography and Densitometry*

The Kodak far-ultraviolet film type 101-01, described by Millikan and Coykendall (1971), was used for all exposures. After the flight, the films were soaked in distilled water for 2 minutes and then developed at 68° F in D-19 for 6 minutes, except for the low-resolution Scorpius exposure which was developed for only 4 minutes. The developing was monitored with a safe light and cut short on this one film which had a higher fog level as a result of either zero-order light from the horizon or zero- and first-order Lα emission from the night sky.

The intensity calibration was made by exposing strips of film for a range of times to a hydrogen lamp in a vacuum spectrograph and assuming reciprocity failure was absent. Separate H and D curves were made for each developing time, and for four

TABLE 1

STARS OBSERVED IN OPHIUCHUS AND SCORPIUS

Star	Spectral Type	V	$B - V$	$U - V$	$E(B - V)$	Wavelength Range: Low Dispersion (Å)	Wavelength Range: High Dispersion (Å)
ζ Oph......	O9.5 V	2.56	+0.02	−0.83	0.32	1110–1800	1192–1505
β^1 Sco.....	B0.5 V	2.59	−0.08	−0.94	0.20	1120–1420	1130–1370
δ Sco......	B0 V	2.32	−0.12	−1.02	0.18	1110–1490	1110–1404
ν Sco AB...	B2 IV–V	4.01	+0.03	−0.61	0.27	1140–1470	...
π Sco......	B1 V + B2	2.91	−0.20	−1.09	0.06	1120–1440	1165–1380
σ Sco......	B1 III	2.88	+0.13	−0.56	0.39	1140–2165	1350–1850
τ Sco......	B0 V	2.81	−0.25	−1.26	0.05	1745–2625	1565–1810
ω^1 Sco.....	B1 V	3.97	−0.05	−0.87	0.21	1130–1415	...

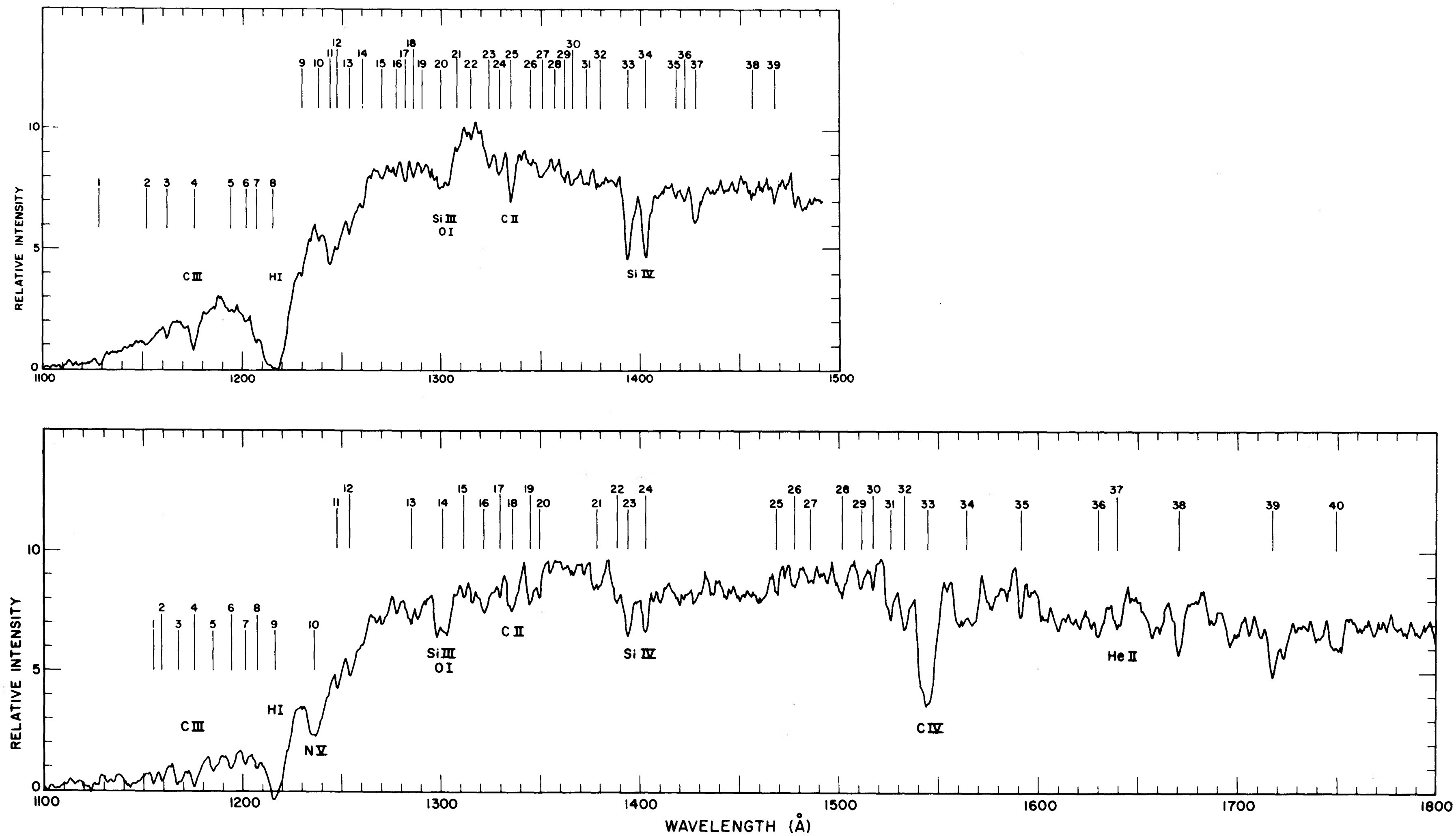

FIG. 1.—Relative intensities in the low-dispersion rocket spectra of the B0 V star δ Sco (*top*) and the O9.5 V star ζ Oph (*bottom*). Wavelengths for the numbered features are given in table 2.

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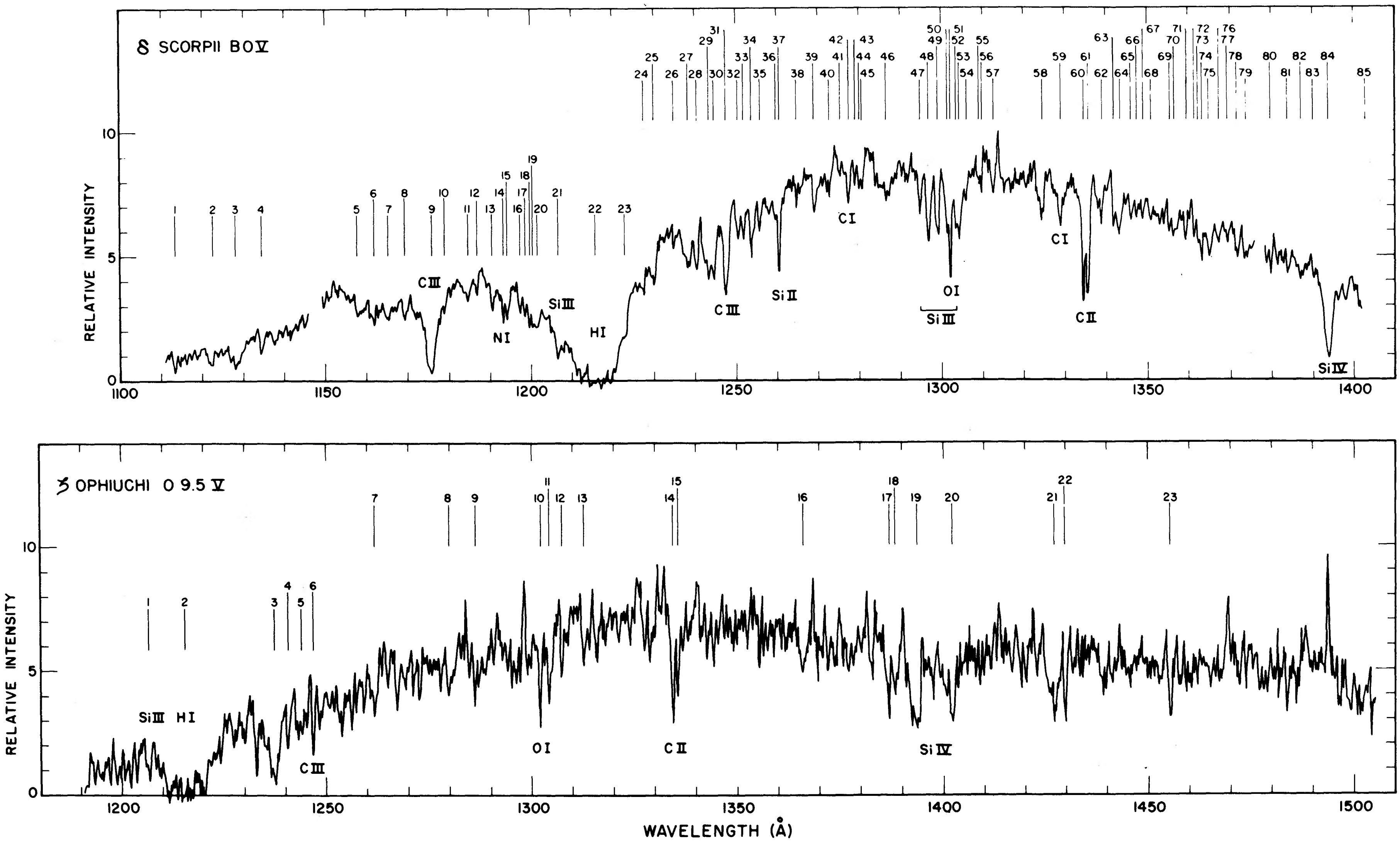

FIG. 2.—Relative intensities in the high-dispersion rocket spectra of the B0 V star δ Sco (*top*) and the O9.5 V star ζ Oph (*bottom*). Wavelengths for the numbered features are given in table 2.

wavelength bands between 1200 and 1750 Å, but the differences were negligible in all cases. We used the digital densitometer of the Sacramento Peak Observatory to scan the spectra in a raster pattern with a spot 10 μ wide in the dispersion direction and 20 μ long in the perpendicular direction. The resulting relative-intensity curves for ζ Oph and δ Sco are shown in figures 1–2. In a discussion of observations of interstellar Lα absorption, Savage and Jenkins (1972) found good agreement between the intensity profiles of the OAO-2 photoelectric spectra and the rocket photographic spectra of ζ Oph and δ and π Sco after they were reduced to the OAO resolution. Thus it is unlikely there are any serious errors in our curves due to the film calibration.

b) *Wavelengths*

The procedure for obtaining absolute wavelengths from photographs taken with an objective spectrograph has been described by Morton, Jenkins, and Bohlin (1968). The film scale for each camera was derived from the measured separations of the zero-order images of a known star field photographed on the ground with all baffles and the rocket skin removed. During flight the baffles and skin vignetted part of the zero-order field in the low-dispersion spectrograph and all zero orders in the high-dispersion instrument. The zero orders recorded on the low-dispersion flight exposures confirmed the scale used for this camera. The adopted grating constants of 8332.5 and 2777.5 Å were taken to be 1 part in 10^4 smaller than the nominal values quoted by Bausch and Lomb since the grooves ruled by their Chicago engine are narrower by this amount. Mercury spectra taken before the flight gave a first approximation for the diffraction angles at the film centers. These angles made it possible to estimate the incidence angles for the low-dispersion spectra from the zero-order stars on the same film. Then an accurate measurement of the relative camera positions before flight gave the incidence angles for the high-dispersion spectra. This procedure resulted in wavelength scales that placed the lines λ1215.7 of H I, λ1302.2 of O I, and $\lambda\lambda$1334.5, 1335.7 of C II within 1 Å of their laboratory values on the high- and low-dispersion spectra of both ζ Oph and δ Sco. Appropriate constants also were derived for the off-axis stars. The parameters for each spectrum were used to transform the densitometer millimeter scale to angstroms and provide a large-scale plot of relative intensities from which the line wavelengths were read. Finally, for the observed wavelengths in tables 2 and 3 we added corrections up to ± 0.3 Å to obtain the best fits for several lines with reliable identifications in each spectrum.

The spectra probably contain many more lines than those in tables 2 and 3, which list only the features that were easily distinguishable from the film noise. If we compare the adopted observed wavelengths in table 2 with the laboratory values for the best established identifications, we find rms errors of ± 0.08 and ± 0.2 Å, respectively, for the high- and low-dispersion spectra of δ Sco and ± 0.5 and ± 1.5 Å respectively for ζ Oph. Larger errors are expected for ζ Oph because the spectra are weaker and narrower than δ Sco.

IV. LINE IDENTIFICATIONS

The right-hand halves of tables 2 and 3 list the probable identifications for the lines measured in the spectra of ζ Oph and δ and σ Sco. Wavelengths λ_{lab} and lower-level statistical weights g_l were taken from Moore (1950, 1965) except for a few lines of N III and O IV listed by Kelly (1968) and noted by a "K" in place of the multiplet number. The excitation potentials (E.P.) for the lower levels were based on the scale adopted by Moore (1965). The f-values f_{lu} were obtained from Weise, Smith, and Glennon (1966) and Weise, Smith, and Miles (1969). Smith (1971) has summarized recent measurements of many resonance lines and has suggested the factors in table 4 by which particular values in tables 2 and 3 should be multiplied. Each factor applies

TABLE 2

IDENTIFICATIONS OF LINES IN δ SCORPII AND ζ OPHIUCHI

δ Sco High Disp. No	δ Sco High Disp. λ^*_{Obs} (Å)	δ Sco Low Disp. No	δ Sco Low Disp. λ^*_{Obs} (Å)	ζ Oph High Disp. No	ζ Oph High Disp. λ^*_{Obs} (Å)	ζ Oph Low Disp. No	ζ Oph Low Disp. λ^*_{Obs} (Å)	Ion	UV Mult. No	λ_{Lab} (Å)	g_1	$f^{\dagger}_{lu}$	E.P. (eV)	O‡
1	1113.37							Si III	5	1113.174	5	0.009	6.58	P
								Si III	5	1113.204	5	0.133	6.58	P
								Si III	5	1113.228	5	0.748	6.58	P
2	1122.46							Si IV	3	1122.486	2	0.84	8.84	P
3	1127.98	1	1127.9					Si II	13.06	1127.442	4	-	6.86	P
								Si II	13.06	1127.907	6	-	6.86	P
								Si IV	3	1128.325	4	0.083	8.90	P
								Si IV	3	1128.340	4	0.75	8.90	P
4	1134.36							N I	2	1134.168	4	0.024	0	I
								N I	2	1134.417	4	0.048	0	I
								N I	2	1134.979	4	0.064	0	I
		2	1151.7											
						1	1155.0							
5	1157.76					2	1159.2							
6	1161.85	3	1161.8											
7	1165.25													
						3	1167.5							
8	1169.14							C IV	11.19	1168.873	4	-	40.28	P
								C IV	11.19	1168.990	6	-	40.28	P
9	1175.75b	4	1175.6b			4	1175.6	C III	4	1175.7(6)	9	0.26	6.50	P
10	1178.81													
11	1184.44b					5	1185.0	N III	20	1183.030	2	0.18	18.09	P
								N III	20	1184.544	4	0.18	18.10	P
12	1186.69													
13	1190.35n							S III	1	1190.17	1	0.61	0	P
								Si II	5	1190.418	2	0.31	0	I
14	1193.11n							Si II	5	1193.284	2	0.61	0	I
15	1194.03n	5	1194.06			6	1194.2	S III	1	1194.02	3	0.46	0.04	P
								S III	1	1194.40	3	0.15	0.04	P
								Si II	5	1194.496	4	0.76	0.04	P
16	1197.31b							Si II	5	1197.389	4	0.15	0.04	P
17	1198.46							C IV	11.18	1198.58	-	-	40.28	P
18	1199.44							N I	1	1199.550	4	0.18	0	I
19	1200.25							N I	1	1200.218	4	0.11	0	I
								N I	1	1200.707	4	0.059	0	I
20	1201.40b	6	1201.7			7	1201.2	S III	1	1200.97	5	0.51	0.10	P
								S III	1	1201.71	5	0.091	0.10	P
								S III	1	1202.10	5	0.006	0.10	P
								O_2		1206				T

TABLE 2 (continued)

δ Sco High Disp. No	δ Sco High Disp. λ^*_{Obs} (Å)	δ Sco Low Disp. No	δ Sco Low Disp. λ^*_{Obs} (Å)	ζ Oph High Disp. No	ζ Oph High Disp. λ^*_{Obs} (Å)	ζ Oph Low Disp. No	ζ Oph Low Disp. λ^*_{Obs} (Å)	Ion	UV Mult. No	λ_{Lab} (Å)	g_1	$f^{\dagger}_{lu}$	E.P. (eV)	O‡
21	1206.50b	7	1206.8	1	1206.5	8	1207.2	Si III	2	1206.510	1	1.70	0	P
								Si III	11	1206.533	3	1.78	10.28	P
								Si III	22	1207.517	5	0.41	15.15	P
22	1215.7b	8	1215.4b	2	1215.4b	9	1216.2b	H I	1	1215.671(2)	2	0.832	0	I
23	1223.61b													
24	1227.49													
25	1229.98	9	1229.6					C IV	11.14	1230.046	2	-	39.68	P
										1230.511	4	-	39.68	P
26	1234.77													
27	1238.386	10	1238.4	3	1237.3	10	1236.0	N V	1	1238.821	2	0.156	0	P
28	1240.43			4	1240.6									
29	1243.32	11	1243.9	5	1243.8b			N V	1	1242.804	2	0.078	0	P
30	1244.57							O_2		1244.5				T
31	1247.42	12	1247.5	6	1246.7n	11	1247.8	C III	9	1247.383	3	0.090	12.69	P
32	1250.49							S II?	1	1250.50	4	0.005	0	I
33	1251.79													
34	1253.70	13	1253.7			12	1254.0	S II?	1	1253.79	4	0.010	0	I
35	1255.85							C III?	11.53	1256.52	3	-	29.53	P
								C III?	11.67	1256.549	3	-	32.10	P
36	1259.65							S II?	1	1259.53	4	0.012	0	I
37	1260.41n	14	1260.4					Si II	4	1260.418	2	1.2	0	I
								Fe II	9	1260.542	10	-	0	I
								C I	9	1260.736	1	0.029	0	I
				7	1261.8									
38	1264.76							Si II	4	1264.730	4	1.1	0.04	P
								Si II	4	1265.023	4	0.12	0.04	P
39	1269.13	15	1269.9											
40	1272.80													
41	1275.36													
42	1277.42	18	1277.2			13	1277.6	C I	7	1277.245	1	0.064	0	I
43	1278.90													
44	1279.99			8	1279.8b			C I	5	1280.135	1	0.020	0	I
45	1280.68	17	1281.7											
46	1286.4b	18	1285.8	9	1286.1b									
		19	1290.2											
47	1294.67							Si III	4	1294.543	3	0.235	6.55	P
48	1296.70							Si III	4	1296.726	1	0.565	6.54	P
49	1298.93							Si III	4	1298.891	3	0.141	6.55	P
								Si III	4	1298.960	5	0.423	6.58	P
50	1301.21	20	1300.6			14	1301 b	Si III	4	1301.146	3	0.188	6.55	P
51	1302.12n			10	1302.1n			O I	2	1302.174	5	0.031	0	I
52	1303.5							Si III	4	1303.320	5	0.140	6.58	P

TABLE 2 (continued)

δ Sco High Disp. No	δ Sco High Disp. λ^{*}_{Obs} (Å)	δ Sco Low Disp. No	δ Sco Low Disp. λ^{*}_{Obs} (Å)	ζ Oph High Disp. No	ζ Oph High Disp. λ^{*}_{Obs} (Å)	ζ Oph Low Disp. No	ζ Oph Low Disp. λ^{*}_{Obs} (Å)	Ion	UV Mult. No	λ_{Lab} (Å)	g_1	$f^{\dagger}_{1u}$	E.P. (eV)	O‡
53	1304.27			11	1304.2			Si II	3	1304.369	2	0.091	0	I
54	1306.01													
		21	1307.9	12	1307.3			C III	11.44	1308.73	1	-	22.63	P
55	1309.07							Si II	3	1309.274	4	0.090	0.04	P
56	1309.73													
57	1312.60			13	1312.7	15	1311.6	Si III	10	1312.590	3	0.048	10.28	P
		22	1314.9											
						16	1321.8							
58	1324.40b	23	1323.9					C II	11	1323.9(4)	10	0.23	9.29	P
								N III	K	1324.40	6	-	33.13	P
59	1328.89	24	1329.2			17	1329.8	Si III	48	1328.806	1	2.1	19.02	P
								C I	4	1328.833	1	0.039	0	I
								C III	11.59	1329.187	1	-	30.64	P
60	1334.59n	25	1335.1	14	1334.40	18	1336.0	C II	1	1334.532	2	0.26	0	IP
61	1335.64n			15	1335.55			C II	1	1335.662	4	0.027	0.01	P
								C II	1	1335.708	4	0.24	0.01	P
62	1338.88							O IV	K	1338.603	2	-	22.38	P
63	1341.90							Si III	39	1342.0(5)	15	0.217	17.72	P
64	1343.34b	26	1344.7			19	1344.8	O IV	K	1342.995	4	-	22.41	P
								Si III	39	1343.388(2)	8	0.101	17.72	P
								O IV	K	1343.507	4	-	22.41	P
65	1346.2							N III	K	1345.69	-	-	38.40	P
								N III	K	1346.27	8	-	38.42	P
66	1347.5							N III	K	1347.56	8	-	38.42	P
								C III	11.66	1347.947	3	-	32.10	P
67	1349.0	27	1350.7			20	1349.2							
68	1350.9													
69	1355.42													
70	1356.38b	28	1356.8											
71	1359.22													
72	1361.24							Si III	46	1361.597	3	-	19.02	P
73	1362.15	29	1361.7					Si III	38	1362.366	3	0.10	17.72	P
74	1363.19							Si III	38	1363.459	5	0.14	17.72	P
								Si III	38	1363.504	3	0.082	17.72	P
75	1364.92	30	1365.6					Si III	38	1365.253	7	0.19	17.72	P
								Si III	38	1365.292	5	0.049	17.72	P
								Si III	38	1365.337	3	0.005	17.72	P
76	1367.20							Si III	46	1367.049	3	-	19.02	P
77	1369.37							Si III	46	1369.437	3	-	19.02	P

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TABLE 2 (continued)

δ Sco High Disp. No	λ^*_{Obs} (Å)	δ Sco Low Disp. No	λ^*_{Obs} (Å)	ζ Oph High Disp. No	λ^*_{Obs} (Å)	ζ Oph Low Disp. No	λ^*_{Obs} (Å)	Ion	UV Mult. No	λ_{Lab} (Å)	g_1	f_{lu} †	E.P. (eV)	O ‡
78	1371.65b													
79	1373.85b	31	1372.7											
80	1379.77	32	1379.5			21	1378.3							
81	1383.79													
82	1387.02			17	1387.0			N III	K	1387.31	-	-	30.46	P
				18	1388.3	22	1388.5							
83	1390.20													
84	1393.74	33	1393.7	19	1393.6b	23	1393.8	Si IV	1	1393.755	2	0.536	0	P
85	1402.9	34	1402.6	20	1402.2	24	1402.8	Si IV	1	1402.769	2	0.266	0	P
		35	1417.7					Si III	9	1417.237	3	0.261	10.28	P
		36	1421.8											
		37	1427.6	21	1427.1b			C III	11.52	1426.45	3	-	29.53	P
								C III	11.52	1427.85	3	-	29.53	P
								C III	11.52	1428.53	3	-	29.53	P
				22	1429.9n									
		38	1456.0	23	1455.3n									
		39	1467.4			25	1468.4							
						26	1477.8	C III	12.04	1478.0(3)	15	-	33.48	P
						27	1485.8							
						28	1501.5	Si III	36	1501.3(6)	15	-	17.72	P
						29	1511.1							
						30	1517.0							
						31	1526.0	Si II?	2	1526.719	2	0.130	0	I
						32	1532.8	C III	11.65	1531.85	3	-	32.10	P
								Si IV	24	1533.220	10	0.176	31.00	P
								Si II?	2	1533.445	4	0.130	0.04	P
						33	1544.4	C IV	1	1548.202	2	0.190	0	C
								C IV	1	1550.774	2	0.095	0	C
						34	1564 b							
						35	1591.2	C III	11.58	1591.48	1	-	30.64	P
						36	1630.0							
						37	1639.8	He II	12	1640.4(3)	8	0.641	40.81	P
						38	1670.4	Al II?	2	1670.81	1	1.84	0	P
						39	1717.4	N IV	7	1718.551	3	0.38	16.20	P
						40	1749.5	N III	19	1747.86	2	0.20	18.09	P
								N III	19	1751.24	4	0.02	18.10	P
								N III	19	1751.75	4	0.18	18.10	P

* b, broad line; n, narrow line

† See Table 4 for recent corrections to some f-values

‡ Probable origin: C, circumstellar; I, interstellar; P, photospheric; T, telluric

TABLE 3

OBSERVED WAVELENGTHS AND IDENTIFICATIONS IN σ SCORPII

High Dispersion		Low Dispersion								
No.	λ_{Obs} (Å)	No.	λ_{Obs}* (Å)	Ion	UV Mult. No.	λ_{Lab} (Å)	g_l	f_{lu}†	E.P. (eV)	O‡
		1	1178	C III?						P
		2	1216 b	H I	1	1215.671	2	0.832	0	I
		3	1299 b	Si III	4	1298.9(6)	9	0.564	6.6	P
		4	1302.6	O I	2	1302.174	5	0.031	0	I
		5	1316.0							
		6	1329.4	Si III	48	1328.806	1	2.1	19.02	P
				C III	11.59	1329.187	1	–	30.64	P
		7	1335.4	C II	1	1335.3(3)	6	0.27	0	PI
		8	1365.4	Si III	38	1365.3(3)	15	0.106	17.72	P
1	1394.2	9	1393.7	Si IV	1	1393.788	2	0.536	0	P
2	1403.0	10	1402.6	Si IV	1	1402.769	2	0.266	0	P
		11	1430.9							
		12	1436.5							
		13	1512.8							
		14	1516.8							
3	1527.8	15	1527.0	Si II?	2	1526.719	2	0.130	0	
4	1532.2	16	1533.4	Si II?	2	1533.445	4	0.130	0.04	
5	1548.5	17	1548.8	C IV	1	1549.1(2)	2	0.286	0	P
		18	1560.5							
		19	1595.3							
		20	1608.0							
		21	1622.2							
		22	1630.9							
		23	1640.0	He II	12	1640.4(3)	8	0.641	40.81	P
		24	1720.2 b	N IV?	7	1718.551	3	0.38	16.20	P

* b, broad line.

† See table 4 for recent corrections to some *f*-values.

‡ Probable origin: I, interstellar; P, photospheric.

to all *f*-values in a multiplet. A dash in tables 2 and 3 indicates unavailable data. In this initial search for identifications we considered only the elements of relatively high cosmic abundance, namely H, He, C, N, O, Na, Mg, Al, Si, S, Cl, Ar, Ca, and Fe. For photospheric lines we have omitted all absorptions from levels with higher excitation than the 40.6 eV of He II Balmer α at 1640.4 Å. Lines were labeled interstellar only if they originate from the ground state of an ion since the low particle density and dilute radiation field between the stars is likely to leave most ions in their ground states, as described by Bahcall and Wolf (1968).

TABLE 4

CORRECTIONS TO N.B.S. *f*-VALUES

Ion	Multiplet Number	λ (Å)	Correction Factor	Ion	Multiplet Number	λ (Å)	Correction Factor
C I.........	7	1278	1.6	O I........	2	1304	1.55
C I.........	9	1261	1.5	Si II.......	4	1263	0.58
C II........	1	1335	0.44	Si III......	2	1207	0.89
N I.........	1	1200	0.74	Si IV......	1	1397	0.89
N I.........	2	1135	0.61	S III.......	1	1198	0.062

a) Telluric Lines

Since the Scorpius exposure had a zenith distance of 59° and the latter part was at altitudes as low as 62 km, we can expect some absorption from telluric O_2 due to the strong peak in its cross-section around 1244.5 Å and also possibly due to the second strongest peak near 1206 Å (Friedman 1960). Any contribution at the shorter wavelength is indistinguishable from the stellar Si III lines, but λ1244.5 very likely is present in the spectra of the Scorpius stars and confuses the longer-wavelength components of the N V doublet.

b) Photospheric Lines

Table 2 shows that a number of the lines in ζ Oph and δ Sco can be identified with C II, C III, N III, Si III, Si IV, and S III, just the ions we should expect in the atmospheres of stars with surface gravities of 10^4 cm s^{-2} and effective temperatures around 30,000° K according to the calculations of Morton (1965) and Hickok and Morton (1968). Lines of He II, O IV, N IV, N V, Al II, and Si II may also be present. The high-resolution spectra show that δ Sco and ζ Oph have C II absorption at 1335.7 Å from the low-lying excited state at 0.0079 eV as well as at 1334.5 Å from the ground state—an indication the ion is present in the photosphere, or at least in a dense shell around each star. However, in both stars the short-wavelength component is stronger, although it has the smaller value for *gf*. We believe interstellar C II contributes to the stronger absorption from the ground state, but not to the longer-wavelength one. Another photospheric line of C II appears to be present in δ Sco at 1324 Å. There also is some evidence for weak Si II absorption from a low-lying excited state at 0.04 eV in the photosphere of δ Sco as well as a strong interstellar contribution. The line at 1670.4 Å in ζ Oph is much wider than expected for a cosmic abundance of Al II in a star or the interstellar medium and therefore must have an additional contribution from another ion.

The equivalent widths and profiles of the stronger photospheric lines in δ Sco and ζ Oph will be presented in a later paper by Matilsky (1972). He has found that most of these lines agree with the predictions of the blanketed LTE model atmospheres of Hickok and Morton (1968), Bradley and Morton (1969), and Van Citters and Morton (1970). The results of similar calculations for the photospheric counterparts of some of the possible interstellar lines gave the values listed in table 5. For Si II and S II the collision damping constants were assumed to be 10 times the classical value, so that the derived widths probably are greater than would be obtained from more exact expressions used for C II. An effective temperature of 25 200° provided the best representation for δ Sco while an interpolated value near 31 000° was the best for ζ Oph. The widths in table 5 confirm that the C II resonance line should have a significant photospheric component in both stars and that photospheric Si II might be detectable in δ Sco.

The smearing of the off-axis spectra left only the strongest features resolved in most of these stars. In β^1 and π Sco we have identified λ1335.3 of C II, λ1175.7 of C III,

TABLE 5

THEORETICAL EQUIVALENT WIDTHS OF STELLAR LINES (in angstroms)

T_{eff} (°K)	log *g*	C II 1334.53	C II 1335.68	Si II 1193.28	Si II 1260.42	S II 1250.50	S II 1253.79	S II 1259.53
25 200........	4.0	0.23	0.30	0.04	0.08	0.03	0.04	0.04
28 640........	4.0	0.17	0.21	0.03	0.03	0.01	0.02	0.02
32 940........	4.0	0.12	0.16	10^{-3}	10^{-3}	10^{-4}	10^{-4}	10^{-4}

$\lambda\lambda$1206.5 and 1299–1303 of Si III, and $\lambda\lambda$1393.8, 1402.8 of Si IV as photospheric absorptions, as well as the interstellar Lα line. In the high-dispersion spectrum of τ Sco we found absorptions at λ1640.4 of He II and λ1718.6 of N IV as well as the feature near 1670 Å which also was seen in ζ Oph. Since σ Sco was closer to the center, a number of lines were found, particularly in the well-exposed low-dispersion spectrum. The derived wavelengths and identifications are listed in table 3. The wavelength uncertainties are such that a broad line at 1720.2 Å could be λ1718.6 of N IV. Underhill, Leckrone, and West (1972) have considered alternative identifications for a similar feature in the OAO-2 spectra of hot supergiants.

Most of the unidentified lines in our spectrum probably result from the many weaker ultraviolet transitions that occur in the ions expected to be abundant in hot stars. However, before we can quote convincing identifications we need higher resolution, more accurate observed wavelengths, and better signal-to-noise ratios to show all the multiplet patterns.

The earlier rocket spectra of δ and π Sco obtained by Morton and Spitzer (1966) extended to longer wavelengths and showed lines of He II and C IV as we have found in ζ Oph. In the short region of overlap of the spectra of δ Sco we have confirmed all the original wavelengths and identifications with the exception of an uncertain line at 1431.7 Å which had been associated with O IV. For the wavelengths in common between our spectra and those of α Vir (B1 V) obtained by Smith (1969), the same principal features are present, though comparisons are difficult because his spectra are plotted on a density scale, have slightly poorer resolution, and show some inconsistencies between the long and short exposures. Nevertheless, we definitely agree on the presence of C II $\lambda\lambda$1334.5, 1335.7; C III $\lambda\lambda$1175.7, 1247.4; Si III $\lambda\lambda$1206.5, 1294.7–1303.5; and probably S III $\lambda\lambda$1190.2–1202.1.

c) *Interstellar Lines*

The interstellar Lα absorption line due to neutral hydrogen is the strongest feature in the spectra of ζ Oph and β^1, δ, π, and σ Sco, and it is the only feature discernible in the weaker spectra of ν and ω^1 Sco. For all these stars this absorption is strong enough to mask any line likely to originate in the photosphere. The column densities N_H and equivalent widths W_λ in table 6 were obtained from the Lα lines observed with this rocket. Column densities could have been derived by measuring the equivalent width of each absorption line, but uncertainties in placing the continuum level would have reduced the accuracy of the result. For this reason we have adopted a more reliable procedure suggested by Jenkins (1971), where we attempted to reconstruct the spectrum's appearance in the absence of hydrogen absorption by multiplying the recorded data by

$$\exp(+\tau) = \exp[(4.26 \times 10^{-20} \text{ atom}^{-1} \text{ cm}^2 \text{ Å}^2) N_H (\lambda - \lambda_0)^{-2}] .$$

TABLE 6

INTERSTELLAR LYMAN-α ABSORPTION LINES

Star	Camera	N_H (10^{20} cm^{-2})	W (Å)
ζ Oph.........	Low dispersion	5.0 ± 2	16
β^1 Sco.........	High and low dispersion	14 ± 6	27
δ Sco.........	Low dispersion	12.5 ± 3	26
σ Sco.........	Low dispersion	20 ± 3	33
π Sco.........	High dispersion	6.3 ± 2	18
ω^1 Sco........	Low dispersion	16 ± 4	29

We then found the particular value of N_H which gave the smoothest behavior on either side of the line center λ_0. The equivalent widths listed in table 4 were calculated from N_H according to the relation

$$W_\lambda = 7.31 \times 10^{-10} (\text{Å atom}^{-1/2} \text{ cm}) N_H^{1/2}$$

(Morton 1967). These values confirm the widths of 29, 26, and 20 Å for β^1, δ, and π Sco, respectively, which Jenkins *et al.* (1969) derived from earlier spectra with very poor resolution. The column densities in table 6 have been used by Savage and Jenkins (1972) to calibrate the low-resolution Lα spectral scans obtained with OAO-2 to survey the distribution of neutral hydrogen in the vicinity of the Sun. A film flaw in the rocket spectrum of ν Sco prevented a reliable measurement of the Lα strength, but it was consistent with $N_H = 1.5 \times 10^{21}$ cm^{-2} quoted by Savage and Jenkins.

The evidence for an interstellar contribution to the λ1334.5 component of the C II multiplet in both ζ Oph and δ Sco has been described already. This is the carbon ion expected to be most abundant in interstellar space, but the high-resolution spectrum of δ Sco also shows there may be interstellar neutral carbon absorptions from the ground state. For the region covered by our spectrum the strongest lines should be $\lambda\lambda$1277.24, 1260.74, 1328.83, and 1280.14 in order of decreasing *f*-value. Lines were observed at 1277.42, 1260.41, 1328.89, and 1279.99, but the 1260.41 line must be mainly Si II, and the 1328.89 line could be photospheric C III or Si III. Confirmation of C I requires a spectrum which includes the important lines at 1656.93 and 1560.31 Å as well as some of the weaker lines lying between 1100 and 1200 Å. The spectra of ζ Oph are too noisy to show C I with the strength we have attributed to δ Sco.

Two relatively weak lines near 1199.55 and 1200.22 Å in the high-resolution spectrum of δ Sco may be due to the strongest members of an N I triplet with the ground state a common lower level. The absence of the third and weakest member at 1200.71 Å is consistent with the strengths of the observed components. However, the feature at 1134.36 Å appears too strong to be the second N I triplet. Again the ζ Oph spectra are too noisy to check the presence of N I.

The λ1302.17 line of O I is clearly visible in the high-resolution spectra of δ Sco and ζ Oph. This is the ground-state absorption in the triplet in which λ1304.87 requires 0.020 eV excitation and λ1306.04 requires 0.028 eV. If the O I originates in the stellar atmosphere, the levels should be populated according to a Boltzmann distribution giving strength ratios for unsaturated lines of 5:3:1 with increasing wavelength. In the vicinity of 1300 Å in the high-resolution spectrum of δ Sco we believe our wavelength scale is accurate within an rms error of ± 0.1 Å because of the good agreement with the laboratory values for the Si III multiplet as well as for λ1302 of O I. Consequently we conclude that λ1304.87 is absent, and therefore the λ1302 line is interstellar O I, although there remains a weak unidentified line at 1306.01 Å. Brunner *et al.* (1970) have noted that all three telluric O I transitions should be optically thick above the rocket, but they found none of the lines was more than 0.05 Å wide and hence should make no noticeable contribution to our spectra.

The sharp line at 1260.41 Å in δ Sco is best identified with the strongest transition from the ground state in Si II, though there could be contributions from C I and Fe II. Singly ionized silicon in the ground state also can explain narrow lines at 1190.35, 1193.11, and 1304.27 whose strengths relative to λ1260 are consistent with the ratios of the *f*-values if the broadening is by radiation damping. Weaker absorptions from the low-lying excited state also seem to be present, but since some of these transitions have larger *gf*-values, we believe interstellar Si II is the main contributor to the ground-state lines. In ζ Oph there is no definite evidence for the strongest line of Si II at 1260.41 so that the features at 1304.2, 1526.0, and 1532.8 Å are unlikely to be Si II. The latter pair of lines also appears clearly in σ Sco without any line at 1260.41. The S II triplet at

1250.50, 1253.79, and 1259.53 Å cannot explain the three lines near these wavelengths in δ Sco, because the observed strengths are inconsistent with the *f*-values.

In earlier spectra of δ and π Sco, which were limited to wavelengths longward of 1260 Å by a calcium fluoride corrector, Morton and Spitzer (1966) noted the possible identifications of interstellar C II, O I, Al III, and Si II. Stone and Morton (1967) assumed that each feature was entirely interstellar and found that the column densities were unexpectedly large. The new spectra confirm the presence of C II, O I, and Si II, but the feature at 1670.4 Å appears to be too strong to be due to only interstellar Al II. Furthermore, the improved resolution shows that the C II line in the earlier spectra must have had a significant stellar component and that the O I line was contaminated by stellar Si III. The existence of Si II is now based on lines at 1190.4, 1193.3, and 1260.4 Å in δ Sco while the spectra of ζ Oph and σ Sco suggest that the line at 1526 Å used by Stone and Morton must be identified with some other ion. Photospheric Si II also may be present, but not with enough strength to affect the interstellar lines. Jenkins (1972) has derived column densities for the interstellar carbon, nitrogen, oxygen, and silicon lines identified in ζ Oph and δ Sco. If most of the absorbers have relatively low Doppler motions, the ratios of nitrogen, oxygen, and silicon are approximately solar, but carbon is some 7 times overabundant.

Smith and Stecher (1971), in their spectrum of ζ Oph, have identified eight features between 1280 and 1510 Å with interstellar CO. Our high-dispersion spectrum of this star has comparable resolution and almost as good a signal-to-noise ratio between 1200 and 1480 Å, but we see no conclusive matches with the laboratory wavelengths of CO. These features are definitely absent in our high-resolution spectrum of δ Sco.

d) *Circumstellar Lines*

Rocket spectra of hot supergiants have shown that the resonance absorption lines of the higher ion states such as C IV, N V, Si III, and Si IV are shifted by 1000–2000 km s^{-1} shortward of their laboratory wavelengths (Morton 1967, 1969). These absorptions apparently occur in shells expanding faster than the escape velocity. In the high-resolution spectrum of δ Sco (B0 V) the difference between the observed and laboratory wavelengths for the stellar Si IV line λ1393.76 is within the 0.1 Å found for the interstellar lines of C II, O I, and Si II. Therefore any velocity shifts for Si IV cannot be significantly larger than 30 km s^{-1}. A similar limit probably is applicable to Si III, although the resonance line at 1206.51 Å may be confused by two excited lines and a telluric feature. The original rocket spectra by Morton and Spitzer (1966) showed that the unresolved C IV resonance doublet in δ Sco cannot be shifted by much more than 200 km s^{-1}, and a similar limit also applies to the Si IV and C IV lines in π Sco (B1 V).

In our spectra of ζ Oph (O9.5 V) the Si IV lines probably lie within 100 km s^{-1} of their rest positions, but there appears to be a significant wavelength shift in the C IV feature amounting to -4.7 Å or -900 km s^{-1} away from the star. The other lines longward of 1500 Å in the low-dispersion spectrum of ζ Oph tend to confirm the adopted wavelength scale, though the N IV line could be shifted by -200 km s^{-1}. This N IV absorption occurs from a 16.2-eV excited level, but Morton, Jenkins, and Brooks (1969) found a velocity of -800 km s^{-1} in ζ Pup (O5f) compared with -1500 to -1800 km s^{-1} for C IV, N V, and Si IV. The N V doublet at 1238.8 and 1247.8 Å is not clearly discernible on either spectrum of ζ Oph; but if lines 3 and 4 on the high-dispersion exposure are N V, they are shifted by about -400 km s^{-1}. Small portions of the spectrum of ζ Oph obtained by Smith and Stecher (1971) show a Si IV line at 1393.8 Å close to the laboratory wavelength, but the unresolved C IV pair is consistent with our suspicion of a velocity shift for this ion. However, additional observations with better signal-to-noise ratios and more accurate wavelengths are needed before we can be sure that mass outflow is occurring in this main-sequence star.

TABLE 7

NARROW ABSORPTION LINES IN ζ OPHIUCHI*

No.	Ion	E.P. (eV)	Obs. (Å)	$\Delta\lambda_{1/2}$ (Å)	$v_{1/2}$ (km s^{-1})	v_t (km s^{-1})	$v \sin i$ (km s^{-1})
6...........	C III	12.69	1246.7	0.80	192	100	130
15...........	C II	0.01	1335.6	0.69	155	75	100
22...........	...	...	1429.9	0.90	189	100	130
23...........	...	...	1455.3	0.89	188	100	130

* No correction has been applied for the instrumental profile of 0.5 Å so that the intrinsic widths could be narrower.

e) *Narrow Lines in ζ Ophiuchi*

One very puzzling discovery in our high-resolution spectrum of ζ Oph is the exceptional narrowness of some of the absorption lines. The four best examples are listed in table 7, where $\Delta\lambda_{1/2}$ is the full width at half-depth and $v_{1/2} = c\Delta\lambda_{1/2}/\lambda$. Since the instrumental profile was about 0.5 Å full width at half-depth, the intrinsic widths of these lines in ζ Oph could be even narrower than indicated by table 7. Line 23 could be due to λ1455.22 of Ti III or λ1455.66 of Fe IV. The visual spectrum of ζ Oph is noteworthy for its broad lines corresponding to axial rotation with $v \sin i = 350$ km s^{-1} or random turbulent motions with a most probable speed $v_t = 290$ km s^{-1} according to Slettebak (1956). Herbig (1968) estimated $v \sin i \sim 250$ km s^{-1}. We have used the profile plots of Slettebak (1949, 1956) and our values of $v_{1/2}$ to obtain $v_t \lesssim 75$–100 or $v \sin i \lesssim 100$–130 km s^{-1} for the narrow ultraviolet lines in ζ Oph. It is conceivable that the C II line from the 0.0079-eV level could originate in a particularly dense region of interstellar space, but none of the other lines fits the wavelength of a likely interstellar absorption. Perhaps the narrow lines are formed predominantly in the slower-rotating polar regions or relatively high in the atmosphere where the turbulent velocity might be smaller, or possibly they originate in a shell which has a lower rotational velocity than the visual photosphere.

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