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# ROCKET OBSERVATIONS OF ORION STARS WITH AN ALL-REFLECTIVE ULTRAVIOLET SPECTROGRAPH

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ABSTRACT

On September 20, 1966, an all-reflective objective spectrograph on an Aerobee rocket photographed the far-ultraviolet spectra of ten O and B stars in the vicinity of $\epsilon$ Orionis. Wavelengths from 1100 to 2750 Å were recorded with about 1 Å resolution. This paper describes the method of determining absolute wavelengths by using the zero-order images and presents the results for 283 lines measured in the spectra of the O and B stars $\gamma$, $\delta$, $\epsilon$, $\zeta$, $\eta$, $\theta^1 + \theta^2$, $\iota$, and $\sigma$ Orionis.

The interstellar Lyman-$\alpha$ absorption line was observed in $\delta$, $\epsilon$, $\zeta$, $\eta$, $\iota$, and $\sigma$ Ori, but the presence of other interstellar lines is less certain. There seem to be C I lines in $\delta$, $\epsilon$, and $\zeta$, and lines of O I, Al II, and Si III also may be present in some of these spectra.

In the bright giant $\delta$ Ori and the supergiants $\epsilon$ and $\zeta$ Ori, the ultraviolet resonance lines of C IV, N V, Si III, and Si IV, as well as a C III multiplet from 6.5 eV excitation, are present in absorption, shifted shortward of their laboratory wavelengths with velocities up to 1800 km sec$^{-1}$, thus showing that these stars are ejecting mass. The C IV and Si IV lines have emission components at their long-wavelength edges in all three stars. The C III, N V, and Si III lines also are found in $\iota$ Ori, and perhaps the N V line in $\gamma$ Ori, again with shifts up to 1600 km sec$^{-1}$. Both of these stars are giants. Little or no shift was found for the Si IV and C IV lines in the main-sequence stars $\eta$ and $\sigma$ Ori.

Many of the remaining lines originate from ions of the more abundant elements in the photospheres, but at least 100 features are still unidentified.

## I. INTRODUCTION

The initial flights of the Princeton rocket program used objective gratings and Schmidt cameras to obtain ultraviolet spectra of stars, as described by Morton and Spitzer (1966) and Morton (1967*a*). At short wavelengths these instruments were limited by the transmission of the Schmidt correctors; even with lithium fluoride the efficiency dropped sharply shortward af 1200 Å. Consequently, we had the Perkin-Elmer Corporation build a spectrograph consisting entirely of reflective elements so that the short-wavelength sensitivity was limited by only the efficiencies of the coatings on the grating and mirrors.

As before, an attitude control system (ACS) was used to orient the Aerobee rocket within $1\frac{1}{2}°$ of target, and the limit cycle in the dispersion direction was then reduced to $\pm 20''$ by a passive gyro system. The spectrograph was free to rotate in this direction, and input torques from the rocket were absorbed by a spinning rotor attached to the spectrograph with freedom to precess in a direction perpendicular to the dispersion. Spectral resolution of about 1 Å was obtained with this system, which was built around a gyro from a war-surplus autopilot for a Lancaster bomber. Some of the results from the Orion spectra have been reported already by Jenkins and Morton (1967*a*, *b*). Figures in these papers show the stabilized part of the payload and a reproduction of the whole field photographed by the spectrograph.

## II. DESCRIPTION OF THE INSTRUMENT

The optical layout of the all-reflective spectrograph is shown in Figure 1. The design of the camera was based on principles described by Schwarzschild (1905) and Burch (1947). Similar systems have been used for reflecting microscopes (Johnson 1953), and recently Bowen (1967) has discussed an application to stellar spectrographs. In our camera the two mirrors and the focal plane are spheres, all with the same center of curvature. Since the system has no preferred axis, coma is absent, and third-order spherical aberration is zero when the ratio of the radii of the mirrors is $\frac{1}{2}(3 + \sqrt{5}) = 2.618$. In practice the ratio was reduced to 2.6065 to give partial correction for fifth- and higher-order spherical aberration. For this camera the limiting aperture was 50 mm, and the effective focal length, which is the radius of the focal surface, was designed to be 100 mm to give a focal ratio of f/2. The field of view was 12°.3 in diameter. The major disadvantages of the system were the relatively large secondary mirror and the concave focal surface. Since the ultraviolet photographic emulsion was not available on concave glass, the film was attached to glass disks of the proper curvature with double-sided sticky tape by applying a brief differential pressurization at 100 lb in$^{-2}$. The plane grating with 1200 lines mm$^{-1}$ (Bausch and Lomb 35-53-27-12) was blazed nominally at 1060 Å for a 90° angle between incident and diffracted beams. A baffle of parallel vanes

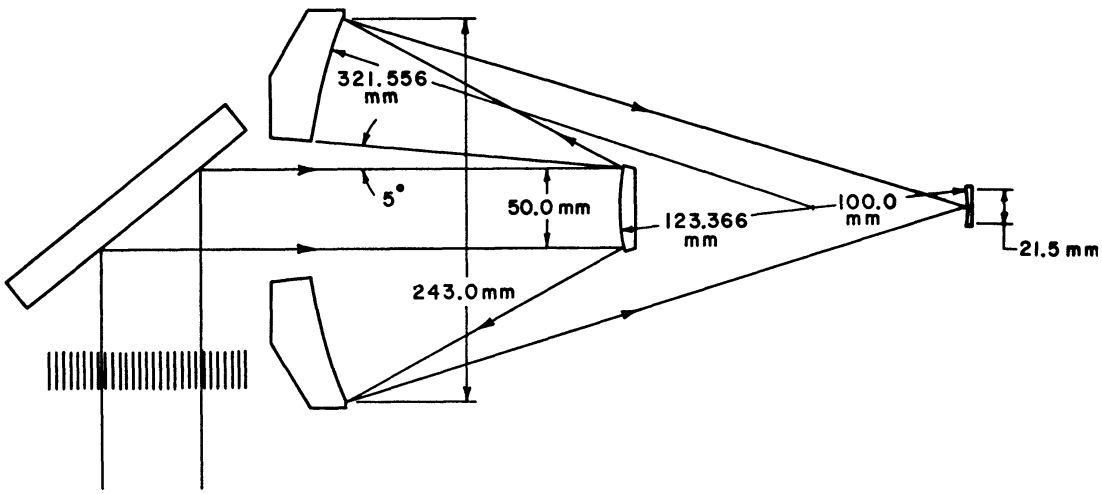


FIG. 1.—Optical layout of f/2 all-reflective spectrograph. The light enters through a door in the side of the rocket toward the plane grating, which diffracts the beam along the roll axis The mirrors and focal surface are concentric spheres. The baffle in front of the grating reduces the intensity of the zero-order images to avoid excessive confusion with the spectra.

with 50 per cent attenuation at $\pm 4^\circ.9$ from the mean incident beam was installed in front of the grating to reduce the number of zero-order images that would overlap the spectra.

For maximum reflectivity in the region 1000–1200 Å the grating and both mirrors were specially coated with a layer of lithium fluoride immediately after aluminization according to the process described by Angel, Hunter, and Tousey (1961). A very thin layer of magnesium fluoride was added on top for protection against humidity.

The camera axis was mounted along the roll axis of the rocket so that the grating viewed the sky in the direction of the yaw axis through a door in the skin which opened while the target was being acquired. The passive gyro system provided stability in the dispersion direction, about the pitch axis, while drift and limit-cycle jitter of the ACS gyros in roll widened the spectra. The mechanical parameters for the fine stabilization of the all-reflective spectrograph were similar to those quoted by Morton and Spitzer (1966, Table 1) for the two Schmidt cameras, except that the mass of the stabilized platform was increased by 50 per cent and its moment of inertia was 4 times larger.

## III. THE ROCKET FLIGHTS

All-reflective spectrographs now have been flown four times on Aerobee 150 rockets from the White Sands Missile Range. The first flight occurred on May 24, 1966, at $5^h07^m$ U.T. on NASA Aerobee 4.51. An electrical failure in the ACS timer pointed the rocket 17°.5 off the target of ζ Oph in the dispersion direction. Moreover, the rocket underperformed, reaching an altitude of only 141 km, with the result that it landed in a remote section of the White Sands National Monument. The recovery was delayed several hours, and the films in the cassette were exposed to the desert heat while we negotiated with the Monument authorities. A spectrum of ζ Oph was obtained, but as a consequence of the pointing error the wavelength coverage was from 2550 to 3670 Å with overlapping second order from 1275 to 1835 Å. No features could be measured with certainty.

This payload was reflown on Aerobee 4.176 on September 20, 1966, at $10^h45^m$ U.T. All systems functioned properly, and the rocket reached a peak altitude of 165.1 km in 221.4 sec. A 181-sec exposure beginning at 125.9 sec and 124.6 km and ending at 306.9 sec and 129.2 km obtained spectra of ten stars in the vicinity of the target ε Orionis. An exposure with a 35-mm Nikon aspect camera showed that the ACS initially oriented the rocket toward the target within 0°.5 in roll and 1°.6 in pitch. During the 181-sec exposure, the drift and limit-cycle motion of the ACS was 0°.1 in roll and 0°.6 in pitch, although one brief excursion extended the roll motion to a total of 0°.2.

The spectra obtained on this second flight are the ones analyzed in the present paper. The entire spectrograph field for the 181-sec exposure has been reproduced by Jenkins and Morton (1967*a*, *b*). The spectra are only 5′.7 wide, the narrowest so far obtained with this type of system. The Kodak Pathé SC5 film was dipped in distilled water for 10 sec for rehydration, and then developed in D19B at 68° F for 3 min, a minute longer than normal, to enhance the weakest features. If the baffling had been perfect, zero orders would have appeared only at one edge of the film beyond the shortest wavelengths of the spectra. However, a gap at the bottom of the grating admitted some light from a more distant section of the sky, so that it became superposed on the spectra toward longer wavelengths. The spectra and the zero orders seem to be a little out of focus in the center of the field and near the short-wavelength edge. The film may have lifted off the focal surface during the flight, since a source of trapped air was found later in the holder behind the film. The resolution was 1 Å in well-focused areas, indicating that our platform must have been stable to $\pm 20''$. The nightsky Lyman-α glow produced no detectable fogging during the 181-sec exposure.

A copy of the first instrument was flown on Aerobee 4.203 on May 5, 1967, at $7^h30^m$ U.T., again for ζ Oph. The rocket reached 177 km, and the ACS acquired the target within 2°.3 in roll and 1° in pitch. However, after recovery, we found an oily film on the large mirror. Development of the photographs revealed zero-order images but no ultraviolet spectra. Infrared spectroscopic analysis showed that the residue on the mirror included organic compounds known to be used as plasticizers in Tygon tubing. We had used such tubing to flush the payload with dry nitrogen just before launch, and therefore we believe that this tubing was the source of the contamination. We have learned since of occasions in the laboratory when some plasticizer has been flushed out of Tygon tubing. Nylon or gum rubber should have less risk.

The original payload was refurbished and flown for a third time on Aerobee 4.226 on November 1, 1967, at $11^h30^m$ U.T. The excellent spectrum of ζ Pup obtained with this rocket is described by Morton and Jenkins (1968).

## IV. REDUCTION OF ORION SPECTRA

The photograph obtained on September 20, 1966, revealed spectra of the ten Orion stars listed in Table 1. The stars $\theta^1$ and $\theta^2$ Ori together formed a very weak image between δ and ι. No features were seen in the faint spectrum of ψ Ori which overlaps ε and extends that spectrum toward shorter wavelengths. The zero orders and the strong spectra show that the camera spent a very short part of this 181-sec exposure in a position displaced by one spectrum width normal to the dispersion from ε toward δ, so that the spectrum of σ could be slightly contaminated by ε Ori.

The spectrograph orientation and the imaging properties of the camera can be deduced from the coordinates of the many zero-order images recorded on the film. The analysis of the position information, however, must incorporate an initial assumption on how the film deforms when transferred from a spherical surface in the camera to a flat plane prior to measurement. The distortion was assumed to be symmetric about the film center with an equal-angle polar projection as the appropriate mapping function, so that the distances from the center and azimuths about that point were invariant. This particular transformation was favored since the spherical coordinates of the spectrograph could be related directly to polar coordinates measured on the film. A scale factor of 34′.383 $mm^{-1}$ along any diameter was derived from a two-dimensional least-squares fit to the coordinates of thirty-seven identified stars whose positions were known from the Boss and $AGK_2$ catalogues. An inspection of the residuals between the actual measurements and the relative positions predicted from the best-fit scale factor indicated that

TABLE 1

STARS OBSERVED IN ORION

| Star | MK | $V$ | $U-V$ | $B-V$ | $E_{B-V}$ | $M_v$ | Notes | Wavelength Range (Å) | Ultraviolet Spectrum |
|---|---|---|---|---|---|---|---|---|---|
| γ Ori | B2 III | 1 64 | −1 10 | −0 22 | 0 02 | −3 3 | . | 1668–2747 | Strong* |
| δ Ori | O9 5 II | 2 24 | 1 28 | − 22 | 08 | 6 3 | SB | 1100–1951 | Strong |
| ε Ori | BO Ia | 1 69 | 1 21 | − 18 | 09 | 6 9 | | 1100–1806 | Strong |
| ζ Ori AB | O9 5 Ib+B3 | 1 77 | 1 27 | − 21 | 09 | 6 6 | . | 1100–1670 | Strong |
| η Ori | BO 5 V | 3 35 | 1 10 | − 17 | .11 | 4 0 | SB | 1178–1800 | Weak |
| θ¹ Ori | O6p+B | 4 58 | 0 81 | + .05 | 37 | 5 5(C) | T | 1232–1356 | Very weak† |
| θ² Ori | O9 5 Vp | 5 08 | 1 05 | − 11 | 19 | 4 6 | SB | 1228–1352 | Very weak† |
| ι Ori | O9 III | 2 77 | 1 32 | − 24 | .07 | 5 2 | SB | 1130–1310 | Weak |
| σ Ori | O9 5 V | 3 80 | 1 25 | − 24 | 06 | 4 9 | | 1138–1634 | Weak |
| ψ Ori | B2 IV | 4 59 | −1 14 | −0 20 | 0 04 | −3 4 | SB | 1281–2379 | Very weak‡ |

NOTE —SB, spectroscopic binary; T, Trapezium. Absolute magnitudes $M_v$ primarily from Borgman and Blaauw (1964)

* γ Ori has an overlapping second-order spectrum from 1100 to 1373 Å

† θ¹ and θ² Ori overlap over the whole range.

‡ Longward of 1673 Å ψ Ori overlaps ε Ori.

the error vectors were distributed more or less randomly, that is, there appeared to be no anomalous film distortions, and consequently the assumed projection was sufficiently accurate. The position errors, which were of the order of 10 $\mu$, probably arose from inconsistencies in measuring corresponding points in asymmetric images of differing densities.

As with previous flights, we also have used the zero-order images to establish an absolute wavelength scale. This time the quality of the spectra warranted an exact deduction of wavelengths with the two-dimensional grating equation to account for the displacement of each spectrum out of the plane normal to the grating rulings. If we represent this plane by the equator $\mathcal{E}$ of a sphere centered on the grating, as shown in Figure 2, then a star $S$ at latitude $\phi$ has its mirror image or zero order $T$ at $-\phi$, and the spectrum is dispersed from this point on a small circle $\mathfrak{F}$ at the same latitude. The positions of all the spectral lines and the zero order of θ Lep were measured parallel to the dispersion direction and converted to relative separations in diffraction longitude $\theta - \theta_0$ along $\mathcal{E}$ in the spherical coordinate system, where $\theta_0$ is the angle from the grating normal $N$ to the film center. Corrections for the deformation of the film were necessary only for the spectra of $\eta$, $\theta^1$, $\theta^2$, and $\iota$, which were far from the center. The incidence angles $i$, along the grating equator, were calculated for the projections of the star positions on this plane.

For constructive interference we impose the condition that rays from corresponding points on adjacent rulings must differ in phase by an integral number of wavelengths $n$. The two auxiliary diagrams in Figure 2 show that we must correct for the latitude $\phi$ of each source by using the grating equation in the form

$$n\lambda = a(\sin i + \sin \theta) \cos \phi \, , \tag{1}$$

where $a$ is the ruling interval. Since the grating used on this flight was ruled on Bausch and Lomb's Chicago engine, the grooves are closer together by 1 part in $10^4$ of the specified space, so that $a = 8332.5$ Å.

Preflight laboratory exposures of mercury spectra showed that the geometric center of the film was displaced to latitude $\phi_c = 21'.1$ from the grating equator. Comparison with measurements of the flight film showed that the spectrum of $\epsilon$ Ori was at latitude

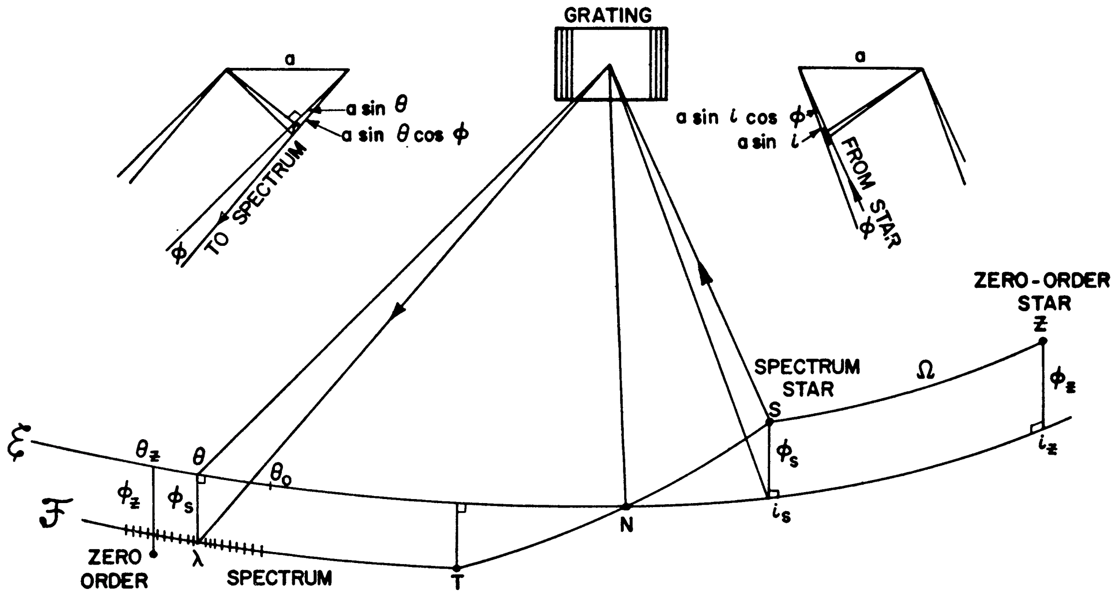


FIG. 2 —Illustration of angles used in reduction of spectra when stars are displaced out of the plane $\mathcal{E}$ which is normal to the grating rulings. A star at latitude $+\phi$ has its spectrum along the small circle $\mathfrak{F}$ at latitude $-\phi$. The incidence and diffraction angles $i$ and $\theta$ are measured along the grating equator $\mathcal{E}$ from the grating normal $N$. The center of the film is $\theta_0$. Two magnified sections at the top show how path differences are calculated for the skew rays. $a$ is the separation of adjacent grating rulings.

$\phi_s = 27'.7$ and the zero-order image of $\theta$ Leporis had $\phi_z = 37'.3$. All these latitudes were on the southwest side of the grating equator when projected on the celestial sphere. Since the separation $\Omega$ of the two stars on the sky is known accurately from their coordinates in the Boss Catalogue, the difference in incidence angles along the grating equator can be obtained from

$$\cos (i_s - i_z) = \frac{\cos \Omega - \sin \phi_s \sin \phi_z}{\cos \phi_s \cos \phi_z} \, . \tag{2}$$

Once we know $\theta_0$, the diffraction angle at the film center, we can use the measured position of the zero-order image $(\phi_z - \theta_0)$ and the relation $i_z = -\theta_z$ to calculate the incidence angle for the spectrum star from

$$i_s = (i_s - i_z) - \theta_z = (i_s - i_z) - (\theta_z - \theta_0) - \theta_0 \, , \tag{3}$$

and hence the wavelength of any feature in the spectrum of $\epsilon$ Ori. For the $\theta_0$ adopted below, $i_s$ ($\epsilon$ Ori) $= -38°45'59''$. From the above data on $\theta$ Lep and $\epsilon$ Ori, we deduced that the 1950 coordinates of the grating normal were $\alpha = 4^h11^m33^s$ and $\delta = +32°19'43''$ and the position angle of the dispersion direction at $N$ was $\psi = 145°13'44''$. With the last three constants we were able to calculate incidence angles for all the other stars in Table 1 without requiring accurate measurements of their separations perpendicular to the dispersion.

The laboratory exposures provided a first approximation for $\theta_0$, but unfortunately in this flight the position of the film in its holder was not reproducible to better than 3'. Consequently, the final value $\theta_0 = 51°20'25''$ was obtained from the best fit of the measured wavelengths of the Lyman-$\alpha$ absorption line in the spectra of $\delta$, $\epsilon$, and $\zeta$ Ori to the laboratory value of 1215.67 Å. We have assumed that this line is entirely interstellar in origin, with no significant velocity shift. The stellar Lyman-$\alpha$ in such hot atmospheres with low surface gravity should be relatively weak. Corrections of the order of 0.1 Å for the Earth's orbital motion and the solar motion relative to the interstellar medium were neglected. In contrast with previous reductions, this time the wavelength scale was not established independently of any spectral features, but good internal agreement was found among the three hydrogen lines, viz., 1215.60 Å for $\delta$, 1215.79 Å for $\epsilon$, and 1215.58 Å for $\zeta$. Furthermore, Table 2 shows that we obtained wavelengths correct within 1 Å for the excited stellar lines of He II at 1640.4 Å, N IV at 1718.5 Å, and Fe III at 1895.5, 1914.1, and 1926.3 Å.

When all the parameters were fixed, application of equation (1) gave the wavelengths of the lines in Tables 2 and 3. The numbers preceding the wavelengths identify the lines in the reproduction of the spectra in Figure 3.

## V. IDENTIFICATIONS OF LINES

For the three well-exposed spectra in Table 2 we have noted possible identifications where the laboratory and measured wavelengths are within about 1 Å, except for a few cases of blends where greater differences are acceptable. In the weak spectra of Table 3 larger errors are possible. The laboratory wavelengths are from Moore (1950, 1965) except for some C III lines which were calculated directly from her *Atomic Energy Levels* (Moore 1949). Succeeding columns list ultraviolet multiplet numbers, excitation potentials (E.P.), total transition probabilities ($gf$) for the contributing lines, and the most likely place of origin for the line. The final column notes any important lines apparently missing and their $gf$ values in parentheses. The $f$-values are primarily from Weise, Smith, and Glennon (1966) or Allen (1963), with a few recent ones from Lawrence and Savage (1966), Savage and Lawrence (1966), and Gaillard and Hesser (1968).

### *a) Interstellar Absorption Lines*

The interstellar Lyman-$\alpha$ line of hydrogen definitely is present in $\delta$, $\epsilon$, $\zeta$, $\eta$, $\iota$, and $\sigma$ Ori. It is doubtful that the stellar H I line is strong enough in any of these stars to contribute to the observed profiles. The large wavelength errors in $\eta$ and $\sigma$ are not unreasonable for such weak spectra. The line was not strong enough to measure in the overlapping orders of $\gamma$ or in the very weak exposure of $\theta^1 + \theta^2$ Ori.

The presence of any other interstellar features is much less certain, but there are several possible identifications with lines from the ground states of neutral and singly ionized atoms of abundant elements. Normally, we do not expect many of these ion states in the photospheres of hot stars. The lines might arise in the shells surrounding the supergiants, but then the velocity shifts should be seen.

In our spectral range the C I resonance lines with the largest $f$-values are at 1656.9 and 1560.3 Å. These lines seem to be present in $\zeta$ Ori, along with a theoretically weaker line at 1260.7 Å. The 1656.9 and 1260.7 lines also may occur in $\delta$ and $\epsilon$ Ori, although the 1560.3 line is absent in these stars. A feature near 1335 Å in $\delta$, $\epsilon$, $\zeta$, and $\sigma$ may be due partly to interstellar C II, particularly in $\zeta$ and $\sigma$ where the measured wavelength is clos-

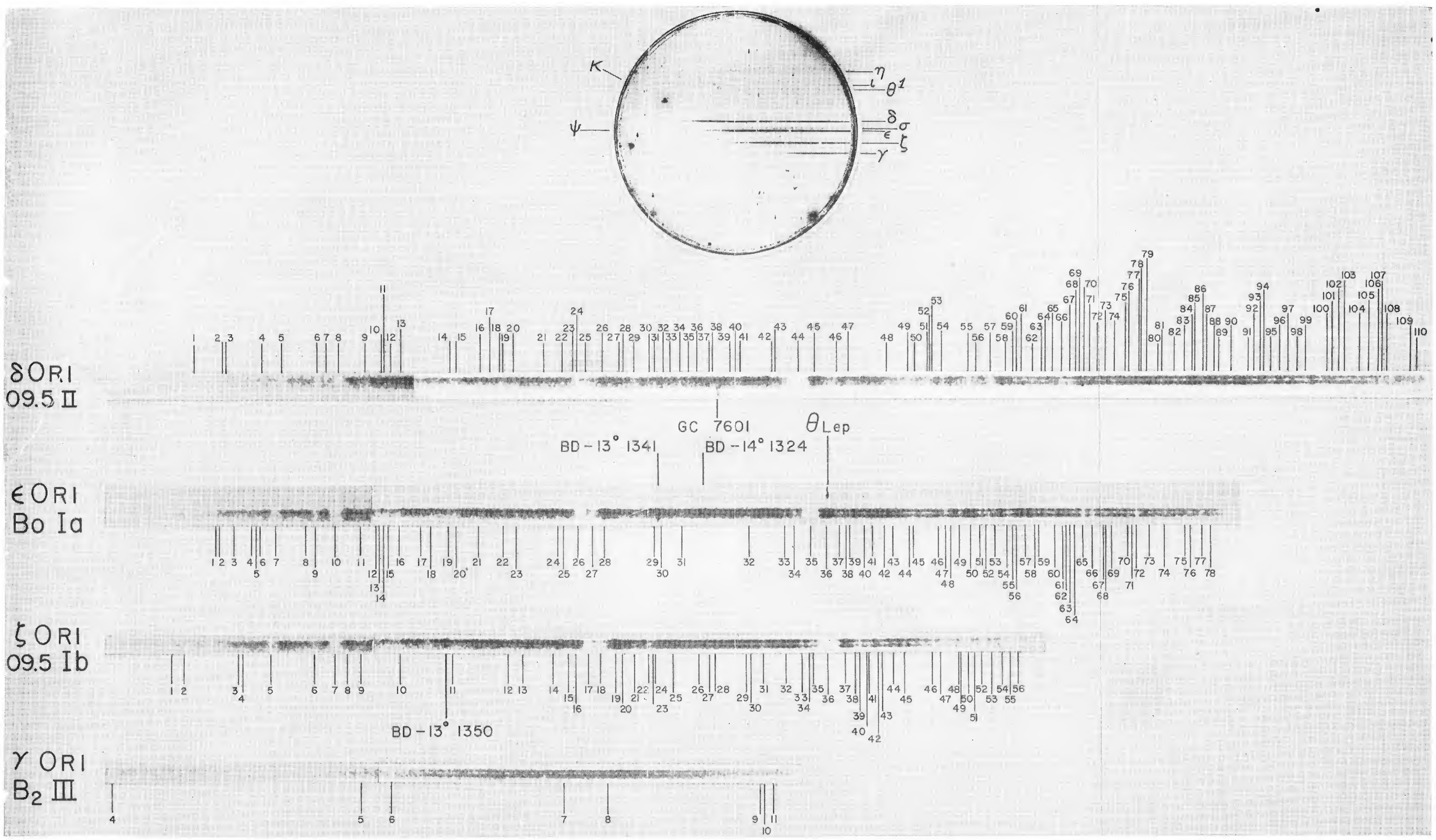


FIG. 3.—Ultraviolet spectra of δ, ε, ζ, and γ Orionis with the lines labeled by the numbers in Tables 2 and 3. Star names or catalogue numbers are given for the zero-order images. Wavelengths increase toward the right. For presentation, the second-order spectrum of γ has been lined up with the first orders of the other stars, with splices at the short-wavelength ends for enhanced reproductions of the weakly exposed portions. The first order of γ is very weak and extends considerably beyond the left edge of the figure. The whole flight film is reproduced at the top to show the original positions of the spectra.

TABLE 2

WAVELENGTHS AND IDENTIFICATIONS OF LINES IN δ , ϵ , AND ζ ORIONIS

| | δ Ori O9.5 II | | ϵ Ori BoIa | | ζ Ori O9.5Ib | | Possible Identifications | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ines | No. | λ* (Å) | No. | λ* (Å) | No. | λ* (Å) | Ion | λ(laboratory) (Å) | Mt. No. † | E.P. (ev) | gf | O ‡ | Missing L |
| | | | | | 1 | 1100.1 | | | | | | | |
| | 1 | 1107.1 | | | 2 | 1109.4 | $H_2$: | 1108.1, 1108.6, 1110.1 | | | | I | |
| | 2 | 1128.6 | 1 | 1128.6 | | | Si IV | 1128.3 (2 lines) | 3 | 8.90 | | P | 1122.5 |
| | 3 | 1131.2 n | 2 | 1131.5 n | | | | | | | | | |
| | | | 3 | 1146.7 n | | | | | | | | | |
| | | | | | 3 | 1149.0 n | | | | | | | |
| | | | | | 4 | 1150.6 n | | | | | | | |
| | | | 4 | 1155.3 | | | | | | | | | |
| | 4 | 1157.5 | 5 | 1158.2 | | | | | | | | | |
| | | | 6 | 1161.3 | | | | | | | | | |
| | 5 | 1173.8 bs | 7 | 1171.9 bs | 5 | 1171.6 bs | C III | 1175.7 (6 lines) | 4 | 6.46 | 2.3 | C | |
| | | | 8 | 1194.3 w | | | | | | | | | |
| | 6 | 1200.1 bs | 9 | 1201.2 s | 6 | 1200.1 | Si III | 1206.5 | 2 | 0 | 1.9 | C | |
| | 7 | 1206.3 | | | | | Si III | 1206.5 | 2 | 0 | 1 9 | PI | |
| | 8 | 1215.6 bs | 10 | 1215.8 bs | 7 | 1215.6 bs | H I | 1215.7 (2 lines) | 1 | 0 | 0.832 | I | |
| | | | | | 8 | 1223.8 w | | | | | | | |
| | 9 | 1234.5 b | 11 | 1234.5 b | 9 | 1232.8 b | N V | 1238.8, 1242.8 | 1 | 0 | 0.468 | C | |
| | 10 | 1247.8 w | 12 | 1246.4 w | | | C III | 1247.4 | 9 | 12.64 | 0.27 | P | |
| | | | 13 | 1248.4 | | | | | | | | | |
| | 11 | 1249.6 w | 14 | 1251.5 nw | | | S II: | 1250 5 | 1 | 0 | 0.019 | I | |
| | 12 | 1253.8 w | 15 | 1254.5 | | | S II: | 1253.8 | 1 | 0 | 0.038 | I | |
| | 13 | 1260.8 | | | 10 | 1260 9 w | {S II: | 1259.5 | 1 | 0 | 0 056 | I | |
| 064) | | | | | | | C I: | 1260.7 | 9 | 0 | 0.029 | I | 1277.2(0. |
| | | | 16 | 1262 2 | | | | | | | | | |
| 091) | | | 17 | 1277.7 n | | | C I: | 1277 2 | 7 | 0 | 0.064 | I | 1560.3(0. |
| | | | 18 | 1285.1 n | | | | | | | | | |
| | 14 | 1297.4 w | 19 | 1297.2 w | 11 | 1296 4 w | Si III: | 1294 5 - 1303.3 (6 lines) | 4 | 6.56 | 3.6 | P | |
| | 15 | 1300.6 w | 20 | 1301.8 w | | | P II: | 1301.9 | 2 | 0 | | I | |
| | | | | | | | O I | 1302.2 | 2 | 0 | 0.25 | I | |
| | 16 | 1319.6 w | 21 | 1318.6 nw | | | | | | | | | |
| | 17 | 1326 0 n | | | | | Ti III: | 1327.6 | 4 | 1.05 | | P | |
| | 18 | 1333.5 | | | 12 | 1334.3 w | {C II | 1334.5 | 1 | 0 | 0.23 | PI | |
| | | | | | | | P III | 1334.9 | 1 | 0 | | P | |
| | 19 | 1336.1 w | 22 | 1336.1 | | | C II | 1335.7 (2 lines) | 1 | 0.01 | 0.45 | P | |
| | 20 | 1344.5 b | 23 | 1344.9 | 13 | 1343.6 | P III | 1344.3, 1344.9 | 1 | 0.07 | | P | |
| | 21 | 1365.7 bw | | | 14 | 1364.3 n | | | | | | | |
| | | | 24 | 1373.2 w | 15 | 1373.9 | Ni II | 1374 1 | 9 | 0.19 | | P | |
| | | | 25 | 1377.2 nw | | | | | | | | | |
| | 22 | 1379.0 w | | | 16 | 1378.9 | | | | | | | |
| | 23 | 1385.7 | | | | | | | | | | | |
| | 24 | 1388.6 bs | 26 | 1388 0 bs | 17 | 1387.2 bs | Si IV | 1393.8 | 1 | 0 | 1 1 | C | |
| | 25 | 1394.5 bs | 27 | 1397.0 bs | 18 | 1395.3 bs | Si IV | 1402.8 | 1 | 0 | 0.5 | C | |
| | 26 | 1406.6 e | 28 | 1405.3 e | 19 | 1406.6 e | Si IV | 1402.8 | 1 | 8.84 | 0.5 | C | |
| | | | | | 20 | 1410.0 nw | | | | | | | |
| | 27 | 1418.7 w | | | 21 | 1418.7 | | | | | | | |
| | 28 | 1421.1 | | | | | | | | | | | |





1968ApJ...154..661M

TABLE 2 - Continued

| δ Ori 09.5 II | | ε Ori B0Ia | | ζ Ori 09.5Ib | | Possible Identifications | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | λ* (Å) | No. | λ* (Å) | No. | λ* (Å) | Ion | λ(laboratory) (Å) | Mt. No. † | E.P. (ev) | gf | O ‡ | Missing Lin |
| | | | | 22 | 1427.8 b | C III: | 1426.4, 27.8, 28.5 | - | 29.40 | | P | |
| 29 | 1429.3 b | | | | | C III: | 1427.9 - 29.1 (6 lines) | - | 32.05 | | P | |
| | | | | 23 | 1430.7 n | | | | | | | |
| | | | | 24 | 1431.9 n | | | | | | | |
| 30 | 1440.2 w | 29 | 1439.6 | | | | | | | | | |
| 31 | 1443.7 w | 30 | 1444.1 | 25 | 1443.5 nw | | | | | | | |
| 32 | 1451.1 nw | | | | | Ti IV: | 1451.8 | 3 | 15.79 | | P | 1469.2 |
| 33 | 1455.2 nw | | | | | Ni II | 1455.0 | 7 | 0 | | P | |
| | | | | | | Ti III: | 1455.2 | 5 | 1 78 | | P | |
| | | 31 | 1457.4 | | | | | | | | | |
| 34 | 1461.5 | | | 26 | 1460.5 | | | | | | | |
| 35 | 1467.4 w | | | 27 | 1467.9 | Ti IV: | 1467.2 | 3 | 15 89 | | P | 1469.2 |
| | | | | | | Ni II | 1467 8 | 6 | 0 | | P | 1510 9 |
| | | | | 28 | 1470.7 e | | | | | | | |
| 36 | 1474.0 n | | | | | | | | | | | |
| 37 | 1482.1 n | | | | | | | | | | | |
| 38 | 1484.1 nw | | | 29 | 1490.6 | | | | | | | |
| | | | | 30 | 1494.0 w | | | | | | | |
| 39 | 1497.1 w | | | | | | | | | | | |
| 40 | 1499.8 | | | | | Ti III: | 1498.6 | 3 | 1 05 | | P | |
| | | | | | | Ni II | 1500.4 | 7 | 0.19 | | P | |
| | | | | | | Si III: | 1500.2 - 01.9 (6 lines) | 36 | 17.72 | | P | |
| 41 | 1502.3 | 32 | 1502.4 | 31 | 1501.9 | P III | 1501.6, 1502.3 | 6 | 9.25 | | P | 1504.7 |
| | | | | | | O II | 1502.9, 03.1, 04.1 | - | 20.49 | | P | |
| | | | | 32 | 1516.8 | | | | | | | |
| 42 | 1525.6 w | 33 | 1526.5 s | 33 | 1526.7 s | Si II | 1526.7 | 2 | 0 | 0 26 | PI | |
| 43 | 1527.9 | | | | | | | | | | | |
| | | | | 34 | 1531.4 | C III: | 1531.8 | - | 31.97 | | P | |
| | | | | | | O IV: | 1531.6 - 32.5 (4 lines) | - | 63.03 | | P | |
| | | | | | | P II | 1532 6 | 1 | 0 | | I | |
| | | 34 | 1532.9 s | 35 | 1533.2 w | Si IV | 1533.2 | 24 | 31.00 | | P | |
| | | | | | | Si II | 1533.4 | 2 | 0 04 | 0.52 | P | |
| 44 | 1542.7 bs | 35 | 1543.4 bs | 36 | 1542.9 bs | C IV | 1548.2, 1550.8 | 1 | 0 | 0.572 | C | |
| 45 | 1553.6 e | 36 | 1554.4 e | 37 | 1554.7 e | C IV | 1548.2, 1550.8 | 1 | 0 | 0.572 | C | |
| | | | | 38 | 1560.6 w | C I | 1560.3 | 3 | 0 | 0.091 | I | |
| | | | | | | Ar II | 1560.2 | 14 | 13.42 | | P | |
| | | 37 | 1563.1 bs | 39 | 1563.1 | Ca III | 1562.5 | 4 | 26.34 | | P | |
| | | 38 | 1567.3 nw | 40 | 1567.9 n | | | | | | | |
| 46 | 1569.2 | 39 | 1569.3 ns | 41 | 1569.1 nw | | | | | | | |
| | | | | 42 | 1575.0 w | Ar II | 1575.0 | 14 | 13.42 | | P | |
| 47 | 1577.6 w | | | 43 | 1577.6 w | C III: | 1576.5 - 78.5 (12 lines) | - | 33 | | P | |
| | | 40 | 1579.0 | | | | | | | | | |
| | | 41 | 1585.0 | 44 | 1584.8 | | | | | | | |
| | | 42 | 1592.1 s | 45 | 1591.3 s | C III: | 1591 5 | - | 30.51 | | P | |
| | | 43 | 1597.7 n | | | | | | | | | |
| 48 | 1603.7 w | | | | | | | | | | | |
| | | 44 | 1608.1 nw | 46 | 1609.2 | Fe II | 1608.4 | 8 | 0 | | P | |
| | | 45 | 1610.6 | | | | | | | | | |

TABLE 2 - Continued

| δ Ori 09.5 II | | ε Ori BoIa | | ζ Ori 09.5Ib | | Possible Identifications | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | λ* (Å) | No | λ* (Å) | No. | λ* (Å) | Ion | λ(laboratory) (Å) | Mt. No. † | E.P. (ev) | gf | O ‡ | Missing Lines |
| | | | | 47 | 1614.3 w | | | | | | | |
| 49 | 1617.8 | | | | | Fe II | 1618.5 | 8 | 0.05 | | P | |
| 50 | 1622.3 w | | | | | Fe II | 1621.7 | 8 | 0 05 | | P | |
| | | | | 48 | 1625.9 nw | Fe II | 1625.9 | 8 | 0.08 | | P | |
| | | 46 | 1627.6 | 49 | 1626.9 n | | | | | | | |
| 51 | 1629.9 | | | | | Fe II | 1629.2 | 8 | 0.08 | | P | |
| 52 | 1631.6 | 47 | 1631.4 s | 50 | 1630.9 ns | Fe II | 1631.1 | 8 | 0.08 | | P | |
| 53 | 1633.7 w | 48 | 1634.8 nw | 51 | 1634.8 nw | {Fe II | 1634.4 | 8 | 0.11 | | P | 1636 3 |
| | | | | | | Si IV | 1634.6 | 28 | 31.51 | | P | |
| 54 | 1640.4 s | 49 | 1640.4 s | 52 | 1639.4 s | {Fe II | 1639.4 | 8 | 0.12 | | P | |
| | | | | | | He II | 1640.4 | 12 | 40.64 | 5 126 | P | |
| | | 50 | 1647.5 | 53 | 1646.2 | | | | | | | |
| | | 51 | 1653.1 s | 54 | 1651.9 b | | | | | | | |
| 55 | 1658.2 b | 52 | 1657 3 s | 55 | 1656.7 | C I | 1656 9 | 2 | 0 | 0.17 | I | |
| | | | | 56 | 1661.4 b | | | | | | | |
| 56 | 1662.9 w | 53 | 1663.6 | | | | | | | | | |
| | | 54 | 1671.2 bs | | | {Ar III | 1669.7 | 6 | 17.89 | | P | |
| | | | | | | Al II | 1670.8 | 2 | 0 | 1.5 | I | |
| 57 | 1672.6 s | 55 | 1673.5 n | | | {Si IV | 1672.6 | 27 | 31.51 | | P | |
| | | | | | | Ar III | 1673.4 | 6 | 17.89 | | P | |
| | | 56 | 1676 6 nw | | | Ar III | 1675.6 | 6 | 17 89 | | P | |
| 58 | 1683.1 | 57 | 1682.1 ns | | | Ne II | 1681.7 | 7 | 26.79 | | P | |
| 59 | 1687.5 nw | 58 | 1688.0 s | | | Ne II | 1688.4 | 7 | 26.79 | | P | |
| 60 | 1688.9 n | | | | | | | | | | | |
| | | 59 | 1690.7 | | | | | | | | | |
| 61 | 1692 0 w | | | | | | | | | | | |
| 62 | 1700.1 | 60 | 1700.1 | | | Cr III: | 1700.3 | 34 | 5.34 | | P | |
| 63 | 1705.8 nw | 61 | 1705.1 | | | | | | | | | |
| 64 | 1707.9 nw | 62 | 1707.7 | | | | | | | | | |
| | | 63 | 1710.4 w | | | {Fe II | 1709.6 | 37 | 0.35 | | P | |
| | | | | | | Ni II | 1709.6 | 4 | 0 | | P | 1754.8 |
| 65 | 1712.8 w | 64 | 1712.3 w | | | Cr III: | 1711 6 | 34 | 5 35 | | P | |
| 66 | 1719.2 s | 65 | 1718.2 s | | | {N IV | 1718 5 | 7 | 16.13 | 1.14 | P | |
| | | | | | | Cr III: | 1720 0 | 34 | 5.35 | | P | |
| 67 | 1725 2 b | 66 | 1724.1 s | | | Fe II | 1725.0 | 37 | 0.30 | | P | |
| 68 | 1728.4 w | | | | | | | | | | | |
| 69 | 1730.6 nw | 67 | 1731.4 w | | | | | | | | | |
| 70 | 1732.9 n | 68 | 1732.7 w | | | | | | | | | |
| 71 | 1736.2 | 69 | 1736.1 nw | | | | | | | | | |
| 72 | 1741.4 w | | | | | | | | | | | |
| 73 | 1747.5 | 70 | 1746.5 nw | | | N III | 1747.9 | 19 | 18.01 | 0 40 | P | |
| | | 71 | 1748.3 nw | | | | | | | | | |
| | | 72 | 1752.0 s | | | {N III | 1751.2, 1751.8 | 19 | 18 02 | 0.80 | P | |
| | | | | | | Ni II | 1751.9 | 4 | 0 | | P | 1754 8 |
| 74 | 1753.3 nw | | | | | | | | | | | |
| 75 | 1761.0 n | 73 | 1759.9 | | | C II | 1760.4, 1760.8 | 10 | 9 25 | 5 9 | P | |
| 76 | 1762.3 nw | | | | | | | | | | | |
| 77 | 1769.5 w | 74 | 1769.2 | | | | | | | | | |

TABLE 2 - Continued

| | δ Ori 09.5 II | | ε Ori BoIa | | | Possible Identifications | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| es | No. | λ* (Å) | No. | λ* (Å) | | Ion | λ(laboratory) (Å) | Mt. No † | E.P. (ev) | gf | O ‡ | Missing Lin |
| | 78 | 1770.4 w | | | | | | | | | | |
| | 79 | 1774.1 w | | | | Ni II | 1774.0 | 3 | 0 | | P | |
| | 80 | 1781.5 w | 75 | 1782 0 w | | | | | | | | |
| | 81 | 1784.0 w | 76 | 1784.9 nw | | | | | | | | |
| | 82 | 1792.0 | 77 | 1791.6 s | | | | | | | | |
| | | | 78 | 1797.2 w | | Si IV | 1796 2 (2 lines), 1797.5 | 23 | 31.00 | | P | |
| | 83 | 1798.8 | | | | | | | | | | |
| | 84 | 1803 8 nw | | | | N III | 1804.3 | 22 | 30.33 | 0.22 | P | 1885 2(8 9) |
| | | | | | | Ni II | 1804.5 | 2 | 0 | | P | 1832 7 |
| | 85 | 1805.5 nw | | | | N III | 1805 5 | 22 | 30.33 | 0.44 | P | 1885.2(8.9) |
| | 86 | 1810.6 | | | | | | | | | | |
| | 87 | 1812.0 nw | | | | | | | | | | |
| ) | 88 | 1817.6 w | | | | Si II: | 1816 9, 1817 4 | 1 | 0 04 | 2.67 | P | 1808.0(1 33 |
| | 89 | 1820 7 | | | | | | | | | | |
| | 90 | 1828.2 | | | | | | | | | | |
| | 91 | 1839.5 n | | | | Cr IV: | 1840.1 | 11 | 12 98 | | P | |
| | 92 | 1842.9 bw | | | | | | | | | | |
| | 93 | 1846.7 nw | | | | | | | | | | |
| | 94 | 1848 6 nw | | | | Fe II | 1848.2 | 7 | 0 05 | | P | |
| | | | | | | {Cr IV: | 1851.8 | 11 | 12 92 | | P | |
| | 95 | 1853.5 b | | | | {Al III | 1854.7 | 1 | 0 | 1.31 | P | |
| | | | | | | {Ca III | 1854.7 | 6 | 27.88 | | P | |
| | 96 | 1858.7 nw | | | | Fe II | 1857.9 | 7 | 0 08 | | P | |
| | 97 | 1863 0 b | | | | {Al III | 1862.8 | 1 | 0 | 0.65 | P | |
| | | | | | | {Cr IV: | 1863.0 | 11 | 12.87 | | P | |
| | 98 | 1869.7 w | | | | Ca III | 1870.3 | 5 | 28.20 | | P | |
| | 99 | 1874.4 b | | | | Cr IV | 1873.9 | 11 | 12.84 | | P | |
| | 100 | 1888.6 n | | | | P IV | 1888.6 | 5 | 12.99 | | P | |
| | 101 | 1891.6 | | | | | | | | | | |
| | 102 | 1895.7 | | | | {Fe III | 1895.5 | 34 | 3 71 | 10.8 | P | |
| | | | | | | {Ni II | 1896.2 | 1 | 0 | | P | |
| | 103 | 1900.0 w | | | | | | | | | | |
| | 104 | 1908.9 nw | | | | N III | 1908.1 | 27 | 41 30 | 8.4 | P | |
| | 105 | 1914.3 | | | | Fe III | 1914.1 | 34 | 3 71 | 8 4 | P | |
| (0.3) | 106 | 1920.5 w | | | | N III | 1919.5 - 21.5 (6 lines) | 29 | 41.51 | 11.1 | P | 1917 7,18 7 |
| | 107 | 1922.9 | | | | | | | | | | |
| | 108 | 1925.9 w | | | | Fe III | 1926.3 | 34 | 3 71 | 6 0 | P | |
| | 109 | 1939 8 w | | | | Ni II | 1939 7 | 1 | 0 | | P | |
| | 110 | 1943.6 bw | | | | Ca III | 1943.1 | 13 | 33.60 | | P | |

* Character of observed line: b, broad; n, narrow; s, strong; w, weak; e, emission

† Ultraviolet multiplet number

‡ Probable origin of line: P, photosphere; C, circumstellar shell; I, interstellar medium

: Identification less certain

TABLE 3

WAVELENGTHS AND IDENTIFICATIONS OF LINES IN $\gamma$, $\eta$, $\theta^1$, $\theta^2$, $\iota$, AND $\sigma$ ORIONIS

| $\gamma$ Ori B2 III | | $\eta$ Ori B0.5 V | | $\iota$ Ori O9 III | | $\sigma$ Ori O9.5 V | | Possible Identifications | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | $\lambda$* (Å) | No | $\lambda$* (Å) | No. | $\lambda$* (Å) | No. | $\lambda$* (Å) | Ion | $\lambda$(laboratory) (Å) | Mt. No. † | E.P. | gf | O ‡ |
| 3 | 1101.1** | | | | | | | | | | | | |
| 4 | 1150.2 b | | | | | | | | | | | | |
| | | | | 1 | 1173.5 b | | | C III | 1175.7 (6 lines) | 4 | 6.46 | 2.3 | C |
| | | | | 2 | 1203.4 | | | Si III | 1206.5 | 2 | 0 | 1.9 | C |
| | | | | 3 | 1206.1 n | | | Si III | 1206.5 | 2 | 0 | 1.9 | PI |
| | | 1 | 1213.7 bs | 4 | 1215.1 bs | 1 | 1218.6 bs | H I | 1215 7 (2 lines) | 1 | 0 | 0.832 | I |
| 5 | 1234.3 bs | | | 5 | 1233.4 b | | | N V | 1238.8, 1242.8 | 1 | 0 | 0.468 | C |
| 6 | 1244.8 | | | | | | | | | | | | |
| | | | | | | 2 | 1248.5 | C III: | 1247.4 | 9 | 12.64 | 0.27 | P |
| | | | | 6 | 1255.7 n | | | | | | | | |
| | | | | | | 3 | 1266.8 | | | | | | |
| | | | | 7 | 1275.9 | | | | | | | | |
| | | | | 8 | 1279.5 | | | | | | | | |
| | | | | 9 | 1286.5 | | | | | | | | |
| | | | | | | 4 | 1289.2 | | | | | | |
| | | 2 | 1295.7 | 10 | 1294.3 | | | Si III | 1294.5 - 1303.3(6) | 4 | 6.56 | 3.6 | P |
| | | 3 | 1299.1b | 11 | 1298.1 | | | | | | | | |
| 7 | 1301.2 n | 4 | 1302.6 n | 12 | 1303.4 | | | O I | 1302.2 | 2 | 0 | 0.25 | I |
| 8 | 1314.7 | | | | | | | | | | | | |
| | | 5 | 1327.6 | | | | | | | | | | |
| | | | | | | 5 | 1334.1 | C II | 1334.5 | 1 | 0 | 0.54 | PI |
| 9 | 1362.6 w | | | | | | | | | | | | |
| 10 | 1363.9 w | | | | | | | | | | | | |
| 11 | 1366.6 w | | | | | | | | | | | | |
| | | 6 | 1391.8 b | | | | | Si IV | 1393.8 | 1 | 0 | 1.1 | P |
| | | 7 | 1400.3 b | | | | | Si IV | 1402.8 | 1 | 0 | 0.5 | |
| | | | | | | 6 | 1409.0 | | | | | | |
| | | 8 | 1476.3 b | | | | | | | | | | |
| | | 9 | 1547.6 b | | | 7 | 1549.1 s | C IV | 1548.2, 1550.8 | 1 | 0 | 0.572 | P |
| 1 | 1791.8 b | | | | | | | | | | | | |
| 2 | 1805.9 | | | | | | | N III | 1804.3, 1805.5 | 22 | 30.33 | 0.66 | P |
| 3 | 2202.1 | | | | | | | | | | | | |
| 4 | 2300.3 b | | | | | | | C III: | 2297.6 | 8 | 12.64 | 1.41 | P |
| | | | | $\theta^1$ Ori O6 p | | $\theta^2$ Ori O9.5 V | | | | | | | |
| | | | | 1 | 1241.7 | 1 | 1237.9 | | | | | | |

* Character of observed line: b, broad; n, narrow; s, strong; w, weak

† Ultraviolet multiplet number

‡ Probable origin of line: P, photosphere; C, circumstellar shell; I, interstellar medium

: Identification less certain

** The first 9 entries for $\gamma$ Ori are second-order wavelengths. The corresponding first-order wavelengths are twice as large.

est to the line with zero excitation potential. In the other two stars the line from the excited level also may contribute and therefore must originate in the photosphere. We cannot make a definite conclusion about N I because the strongest expected lines at 1200 Å would be masked by the shifted Si III line. We see nothing at the 1135 Å location of the next strongest N I line, but here the spectra are rather weak. The O I line at 1302.2 Å may occur in $\delta$ and $\epsilon$ Ori, but these features also could be part of a nearby Si III multiplet.

There could be interstellar Al II absorption at 1670.8 Å in $\epsilon$ Ori, but no line is found near this wavelength in $\delta$ Ori. Interstellar Si II absorption at 1526.7 Å could be responsible for lines in $\epsilon$ and $\zeta$ if we can account for the 1533 Å line by photospheric absorption of excited O IV or Si IV rather than excited Si II. In $\delta$ Ori there is a measured line at 1525.6 Å and none around 1533 Å, but the 1808.0 ground-state line, which should be noticeably stronger, is conspicuously absent. Therefore, the 1526 Å line in $\delta$, and possibly in $\epsilon$ and $\zeta$, is more likely caused by something other than Si II. On the other hand, the unshifted Si III line at 1206.5 Å in $\delta$ and $\iota$ Ori could be interstellar. Each of these stars has a circumstellar component of this line shifted to a shorter wavelength by the expansion velocity of the shell so that it is unlikely the unshifted line also can be formed in the star. A P II line at 1532.6 is possible in $\epsilon$ and $\zeta$, and one at 1301.9 cannot be excluded in $\delta$ and $\epsilon$, although there are several competing identifications in each case from ions that should be more abundant. S II lines from the ground level at 1250.5 and 1253.8 Å may be present in $\delta$ and $\epsilon$, but the strongest line of this triplet at 1259.5 is absent. Conceivably this last line could be blended with a C I line in $\delta$ and $\zeta$ Ori. Among the lines tentatively identified as Fe II and Ni II, there are absorptions from both the ground state and excited levels so that these lines must be primarily photospheric, although there could be interstellar contributions.

### *b) Circumstellar Lines*

In the bright giant $\delta$ and the supergiants $\epsilon$ and $\zeta$ Ori, the strongest absorption lines besides interstellar Lyman-$\alpha$ have been identified as the resonance lines of C IV, N V, Si III, and Si IV displaced shortward of their laboratory wavelengths by 5–8 Å and a multiplet of C III from an excited level at 6.5 eV shifted in the same direction somewhat less. The C IV, N V, and Si IV lines are all doublets, but only the Si IV pair is resolved. The C III feature is a multiplet of six rather close lines. In each of these stars emission lines are visible slightly longward of the laboratory positions for C IV and Si IV. Very weak emission also may be present on the long-wavelength side of the N V absorption. The displacements have been expressed as Doppler velocities in Table 4. These velocities were based on the final wavelength scale adopted in this paper; consequently, they represent a slight revision of those already reported by Morton (1967*b*). The centers of the resonance absorption lines correspond to average velocities of 1430 km sec$^{-1}$ for $\delta$, 1270 for $\epsilon$, and 1530 for $\zeta$ Ori, all directed toward the observer. The velocities of the short-wavelength edges of some of the lines are also included in Table 4 for discussion later. The shifted C IV and Si IV lines were discovered in the previous Princeton Orion spectra (Morton 1967*a*), where they were interpreted as being formed in expanding shells surrounding the stars. In the reduction of the original data it was assumed that the emission lines were unshifted, but the increased accuracy of the wavelength scale from the present flight shows that the emission lines have noticeable positive velocities. This effect probably results from distortion of the short-wavelength edges by the absorption lines. Likewise, the emission may fill in the adjacent edge of each absorption line, thus increasing the apparent shift of its center. In $\zeta$ Ori our velocities for C III and Si III are reasonably consistent with those obtained on a more recent flight by Carruthers (1968), but for N V we have 1770 km sec$^{-1}$ compared with his 1100 km sec$^{-1}$.

In the O9 giant $\iota$ Ori we find the unresolved N V doublet with a shift of 1620 km sec$^{-1}$, Si III with 770 km sec$^{-1}$, and C III with 560 km sec$^{-1}$, while Carruthers reported 1450 km sec$^{-1}$ for N V and no detectable displacements for C III and Si III. The first Princeton

Orion flight had 3000–4000 km $sec^{-1}$ for C IV and Si IV, but the measures were very uncertain, and therefore the N V velocity may be closer to the correct value. The N V doublet apparently is also present in our spectrum of $\gamma$ Ori with a shift of 1400 km $sec^{-1}$. Carruthers, on the other hand, found strong features which he attributed to Si III and Lyman-$\alpha$, but none due to N V, so that there is some doubt about our identification. We cannot eliminate the possibility that our line is in first order at 2468.6 Å. The single line measured in the overlapping spectra of $\theta^1$ and $\theta^2$ Ori has the N V wavelength with little or no shift. Unfortunately, we do not know whether the line is formed in the O6 or the O9.5 V star. Since the hotter star is more reddened, it is not certain which one is brighter in the ultraviolet.

Within the errors of measuring the weak spectrum of $\eta$ Ori (B0.5 V), the Si IV and C IV lines are unshifted, which is consistent with the observations of the main-sequence stars $\delta$ Sco (B0 V) and $\pi$ Sco (B1 V) by Morton and Spitzer. The C IV line in $\sigma$ Ori (O9.5 V) also shows no shift.

TABLE 4

VELOCITIES* OF CENTERS AND SHORT-WAVELENGTH EDGES OF CIRCUMSTELLAR LINES IN ORION SPECTRA

| Star | C III 1175.7 | Si III 1206.5 | N V 1240.1 | Si IV 1393.8 | Si IV 1402.8 | Si IV em 1402.8 | C IV 1549.5 | C IV em 1549.5 |
|---|---|---|---|---|---|---|---|---|
| $\delta$ Ori O9.5 II (center) | −480 | −1600 | −1360 | −1120 | −1770 | +810 | −1320 | +790 |
| $\delta$ Ori O9.5 II (edge) | −1300 | .... | ... | −1550 | ... | ... | −2420 | .. |
| $\epsilon$ Ori B0 Ia (center) | −970 | −1320 | −1360 | −1250 | −1240 | +530 | −1180 | +950 |
| $\epsilon$ Ori B0 Ia (edge) | −1660 | −1810 | ... | −1760 | .... | ... | −2090 | ... |
| $\zeta$ Ori O9.5 Ib (center) | −1050 | −1600 | −1770 | −1420 | −1600 | +810 | −1280 | +1010 |
| $\zeta$ Ori O9.5 Ib (edge) | −1810 | −1860 | ... | −1970 | | | −2280 | |
| $\iota$ Ori O9 III (center) | −560 | −770 | −1620 | | | | | |
| $\gamma$ Ori B2 III (center) | | | −1400 | | | | | |

* In kilometers per second.

### *c) Photospheric Absorption Lines*

It is reasonable to assume that all unshifted lines from either the higher ion states or excited levels of lower ionizations originate in the stellar photospheres rather than in circumstellar shells or the interstellar medium. Considerable help in the identification of the far-ultraviolet photospheric lines has been provided by a detailed study of the spectrum of $\epsilon$ Ori from 3634 to 4157 Å carried out at Utrecht by Lamers (1967). He was able to identify almost all the lines visible at 2.3 Å $mm^{-1}$ without finding any unusual velocity shifts.

The He II Balmer multiplet at 1640 Å is definitely present in $\delta$, $\epsilon$, and $\zeta$ Ori. The next higher member lies at 1215.14 Å, where it would be entirely masked by the highly saturated interstellar H I line.

The observed lines at 1334 and 1336 Å in $\delta$, $\epsilon$, $\zeta$, and $\sigma$ Ori probably are primarily photospheric lines of C II from the lowest levels (0 and 0.01 eV), since an excited C II doublet at 1760.6 Å from 9.25 eV is seen in $\delta$ and $\epsilon$. The ultraviolet C II is consistent with lines originating from higher levels (16 to 29 eV) found by Lamers. The 1247.4 line of C III from 12.6 eV is present in $\delta$, $\epsilon$, and $\sigma$, and some of the multiplets from 30 eV which were found in $\delta$ and $\pi$ Sco are seen in $\delta$, $\epsilon$, and $\zeta$ Ori, but not all multiplets are visible in any one star. Since there are C III lines from 40 eV in the ground-based spectrum of $\epsilon$ Ori, it seems likely that the 30-eV lines are in our spectra, though apparently at the borderline of visibility.

The only ultraviolet N II line in our wavelength range would be at 1886.8 Å, and it seems to be missing, but there are several possible N III lines in δ and ϵ Ori. The N IV line at 1718.5 is rather certain in δ and ϵ, and it was found in the previous spectrum of ζ which extended to longer wavelengths. Lamers found lines of N II and N III, and probably a few lines from N IV. O II and O IV may be present in the ultraviolet spectra of δ, ϵ, and ζ Ori. Lamers had lines of O II from 23 to 33 eV and possibly some O IV from 58 eV. A Ne II doublet at 1681.7 and 1688.4 Å is likely in δ and ϵ Ori; Lamers also found this ion in ϵ Ori.

The ultraviolet Al II resonance line identified as interstellar in ϵ Ori could be partly photospheric, but a doublet from 4.6 eV at 1763.8 and 1767.6 Å is missing. However, the presence of the Al III doublet at 1854.7 and 1862.8 is fairly certain.

As mentioned in the subsection on interstellar lines, the absence of the 1808.0 line of Si II in δ Ori makes the identification of Si II at 1526 and 1533 Å in any of the stars rather unlikely. Lamers failed to find Si II in his spectrum. δ and ι Ori may have an unshifted component of the resonance line of Si III at 1206.5 Å. Lamers found excited lines from 21.6 eV; therefore, our spectra may have a contribution of the Si III multiplets from 1294 to 1303 Å and from 1500 to 1502 Å. Several photospheric lines of Si IV from excited levels may be present in δ, ϵ, and ζ Ori at the laboratory wavelengths, in addition to the shifted resonance lines. Lines of this ion from 24 to 38 eV definitely were found without a shift in the ground-based spectrum of ϵ Ori.

There may be ultraviolet lines of P III in δ, ϵ, and ζ Ori, and a line of P IV seems plausible in δ Ori. Lamers found some possible P II lines in ϵ Ori, but none from higher ion states. There is no convincing evidence for any sulfur ions in our spectra, though Lamers found both S II and S III. The S III multiplet of six lines from 1190 to 1202 Å seems to be absent in all stars, but there could be some confusion with the shifted Si III line.

The remaining identifications in Table 2 are relatively straightforward, so that no special discussion will be given.

### *d) Unidentified Lines*

We still have forty-three lines in δ, thirty-four in ϵ, and twenty-three in ζ Ori, as well as several lines in the weaker spectra, for which we have not yet found any acceptable identifications. The possibility that some of the lines originate in the expanding shells with various velocities complicates the comparison with laboratory wavelengths.

## VI. DISCUSSION AND SUMMARY

This paper has presented wavelength measurements and line identifications of the far-ultraviolet spectra of nine stars in Orion. A resolution of 1 Å was obtained on the stronger exposures, demonstrating the usefulness of an f/2 all-reflective objective spectrograph for rocket observations of stellar line spectra.

The problem of the interstellar Lyman-α absorption line, found in six of the stars, already has been discussed by Jenkins and Morton (1967*b*). The line widths correspond to about one-tenth the hydrogen column density derived from the 21-cm observations. Of course, most of the radio emission could come from beyond Orion, but then 90 per cent of the atomic hydrogen in this direction would be more than 140 pc out of the galactic plane. In the good exposures of δ, ϵ, and ζ Ori our Lyman-α widths indicate an average volume density of only 0.1 $cm^{-3}$ of hydrogen atoms over the 450 pc to Orion.

The ionization of the interstellar medium is controlled by the radiation longward of 911.8 Å which escapes from the H II regions around hot stars so that for each element the dominant ion state should be the highest one with the ionization potential less than 13.595 eV. Therefore, in the ultraviolet spectra of δ and π Scorpii we were not surprised to discover absorption lines of C II, O I, Al II, and Si II which could be attributed to the interstellar gas. These are the only abundant ions having absorptions from the ground state in the wavelength region observed. However, it was puzzling to find from the analysis of

Stone and Morton (1967), as revised by Gaillard and Hesser (1968), that the lines were rather strong, corresponding to 30 times the H I density anticipated from the 21-cm observations if the abundance ratios are the same as in the Sun.

We knew from ground-based spectra (Adams 1949) that in the Orion stars the interstellar Ca II line is somewhat stronger than in the Scorpius stars. Consequently, we had expected to find the same ultraviolet lines in Orion, as well as absorption lines due to N I and S II at somewhat shorter wavelengths. The discussion in the preceding section has shown that some of these ions may be present, although there is evidence that the ionization may be lower than expected, with C I and Si I being more abundant than C II and Si II. Interstellar C I is likely in $\delta$, $\epsilon$, and $\zeta$ Ori, but the C II probably originates primarily in the photospheres. O I is possible in $\delta$ and $\epsilon$, though the observed line could be due to part of a Si III photospheric multiplet. One line in $\epsilon$ could be identified with Al II. In $\delta$ there is a line 1.3 Å away from a resonance line of Si I at 1873 Å (the other spectra do not extend to this wavelength), but Si II seems to be absent. Of all these interstellar lines, only the C I features seem at all convincing, and even there the identifications are not certain. Perhaps the absence of strong ultraviolet interstellar lines in the Orion stars is consistent with the weak Lyman-$\alpha$ line. It would be very interesting to know the strength of Lyman-$\alpha$ in the Scorpius stars.

The shifted resonance absorption lines of C IV and Si IV were found in the far-ultraviolet spectra of $\delta$, $\epsilon$, $\zeta$, and $\iota$ Ori on a previous Princeton flight (Morton 1967*a*). We believe these lines are formed in shells of gas being ejected from the stars at velocities of the order of 1500 km sec$^{-1}$. With the improved resolution and coverage to shorter wavelengths, the September 20, 1966, flight revealed the shifted lines of C III, N V, and Si III for the first time in these stars. The C III absorption is particularly noteworthy since it is from an excited level and has a smaller velocity. Lower in the expanding shell before the material has been accelerated to maximum velocity, the particle density and radiation field must be capable of producing these excited ions. An analysis of the strength of the unsaturated N V and Si IV lines by Morton (1967*b*) has given a rate of mass loss of about $10^{-6}$ $M_\odot$ yr$^{-1}$ from each of $\delta$, $\epsilon$, and $\zeta$ Ori. Lucy and Solomon (1967) have suggested that the outer layers of these stars can be accelerated outward by absorptions in the strong resonance lines which transfer momentum from the photons to the particles, although their theory gives a somewhat lower rate of mass loss. Their model for the expanding shell predicts a maximum velocity which should be represented by the short-wavelength edges of the shifted lines. In Table 4 we have listed the velocities for those edges that are well enough defined to measure. In $\epsilon$ and $\zeta$ Ori, Si III, Si IV, C IV, and even the excited C III line have similar velocities for their short-wavelength edges, averaging 1830 km sec$^{-1}$ for $\epsilon$ and 1980 km sec$^{-1}$ for $\zeta$. There is considerable variation among the values for the three lines in $\delta$ Ori, but in this star the edges are not so well defined.

Many of the lines in our spectra have been classed as photospheric absorptions from the ionized states of the abundant elements, which we should expect in such hot atmospheres. Still, there remain more than one hundred lines in all the spectra without any identification. Presumably most of these are formed in the photosphere. The reproduction of the spectra in Figure 3 shows that the weaker lines in the bright giant and supergiants are somewhat more plentiful longward of the C IV lines at 1550 Å and could contribute significantly to the total opacity in this region. The lower density of lines shortward of 1550 Å may result partly from the poorer focus at these wavelengths.

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## REFERENCES

Adams, W. S. 1949, *Ap J.*, **109**, 354.
Allen, C. W. 1963, *Astrophysical Quantities* (2d ed ; London: Athlone Press).
Angel, D W., Hunter, W. R., and Tousey, R. 1961, *J. Opt. Soc. Am* , **51**, 913.
Borgman, J., and Blaauw, 1964, *B.A N* , **17**, 358.
Bowen, I. S. 1967, *Quart. J.R.A S.*, **8**, 9.
Burch, C. R. 1947, *Proc. Phys Soc London*, **59**, 41
Carruthers, R 1968, *Ap. J.*, **151**, 269.
Gaillard, M., and Hesser, J. E. 1968, *Ap. J.*, **152**, 695.
Jenkins, E. B., and Morton, D. C. 1967*a*, *Sky and Tel.*, **33**, 162.
———. 1967*b*, *Nature*, **215**, 1257.
Johnson, B. K. 1953, *J. Roy. Microscopical Soc* , **73**, 24.
Lamers, H. J. 1967 (private communication).
Lawrence, G. M , and Savage, B. D. 1966, *Phys. Rev.*, **141**, 67.
Lucy, L. B., and Solomon, P. M. 1967, *A.J.*, **72**, 310.
Moore, C. E. 1949, *Atomic Energy Levels* (N B.S. Circ., No 467).
———. 1950, *An Ultraviolet Multiplet Table* (N B.S. Circ., No. 488, §§ 1 and 2).
———. 1965, *National Standard Reference Data Series*, N.B.S. 3 (§§ 1 and 2).
Morton, D. C. 1967*a*, *Ap. J.*, **147**, 1017.
———. 1967*b*, *ibid.*, **150**, 535.
Morton, D. C., and Jenkins, E. B. 1968, *A J* , **73**, S 110.
Morton, D. C., and Spitzer, L. 1966, *Ap J.*, **144**, 1
Savage, B. D., and Lawrence, G. M. 1966, *Ap. J.*, **146**, 940.
Schwarzschild, K. 1905, *Theorie der Spiegeltelescope* (*Mitt. Göttingen Observ* , Part 10).
Stone, M E., and Morton, D C 1967, *Ap. J.*, **149**, 29.
Weise, W. L , Smith, M. W., and Glennon, B. M. 1966, *Atomic Transition Probabilities*, Vol. 1 (*National Standard Reference Data Series*, N.B.S. 4).