FAR-ULTRAVIOLET INTENSITIES OF ORION STARS

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Abstract. Photometric data in the 1050–1180 Å and 1230–1350 Å wavelength ranges, and electronographic spectra in the 1000–1600 Å wavelength range, were obtained in an Aerobee rocket flight on January 30, 1969. The spectral intensities derived from these data for main-sequence stars are in good agreement with the model atmospheres of Morton and co-workers. Giant and supergiant stars, however, appear to be up to one magnitude weaker, at 1115 Å, than main-sequence stars of the same spectral class.

The correction for interstellar reddening appears to be not inconsistent with a $1/\lambda$ extrapolation of earlier determinations of Smith (1967) and Stecher (1965), except in the case of θ Ori, in which the predicted color excess appears to be much too great, confirming the existence of a peculiar reddening law in the Orion Nebula region.

This paper covers some of the results of an Aerobee rocket flight from White Sands Missile Range, New Mexico, on January 30, 1969, in which an electronographic objective spectrograph and ultraviolet photon-counter photometers were used to obtain spectra in the 1000–1600 Å wavelength range, and photometric data in the 1050–1180 Å and 1230–1350 Å wavelength ranges, for early-type stars in Orion. Details of the observations are published elsewhere (Carruthers, 1969b, c, d), as are details of the instrumentation (Carruthers 1969a, d); the present paper will only summarize some of the astrophysically significant results.

The regions of the sky which were covered in the photometer scans are shown in Figure 1. Two photometers for the 1050–1180 Å range (effective wavelength 1115 Å), differing by a factor of 5 in sensitivity, were used, in order to cover a wider range of stellar intensities in this previously little-explored wavelength range. Only one photometer for the 1230–1350 Å range (effective wavelength 1270 Å) was flown; its absolute sensitivity was intermediate between the two 1115 Å photometers. As this photometer saturated on the brightest stars, the number of stars covered in this wavelength range was somewhat less than in the 1050–1180 Å range. However, some stars observed by the 1270 Å photometer were in common with stars observed in an earlier flight in March 1967 (Carruthers, 1968); since we were much more confident of the detector calibrations for this flight than for the earlier one, the earlier results were 'corrected' using the present results. This was also done for the earlier 1115 Å results, which, on the basis of the present data, appear to have been about a factor of 4 too low.

Photometric data of useful quality were obtained for 20 stars or unresolved groupings of stars (see Table I). Tabulated are here the measured photon fluxes, in the ultraviolet and in the visible (the latter was obtained using the visual magnitudes of Iriarte *et al.* (1965) and taking the photon flux at 5560 Å to be 1065 photons cm^{-2} sec^{-1} Å^{-1} (Code, 1960)). Data obtained with the more sensitive of the two 1115 Å photometers are enclosed in brackets. The color excess E(B-V) was determined for

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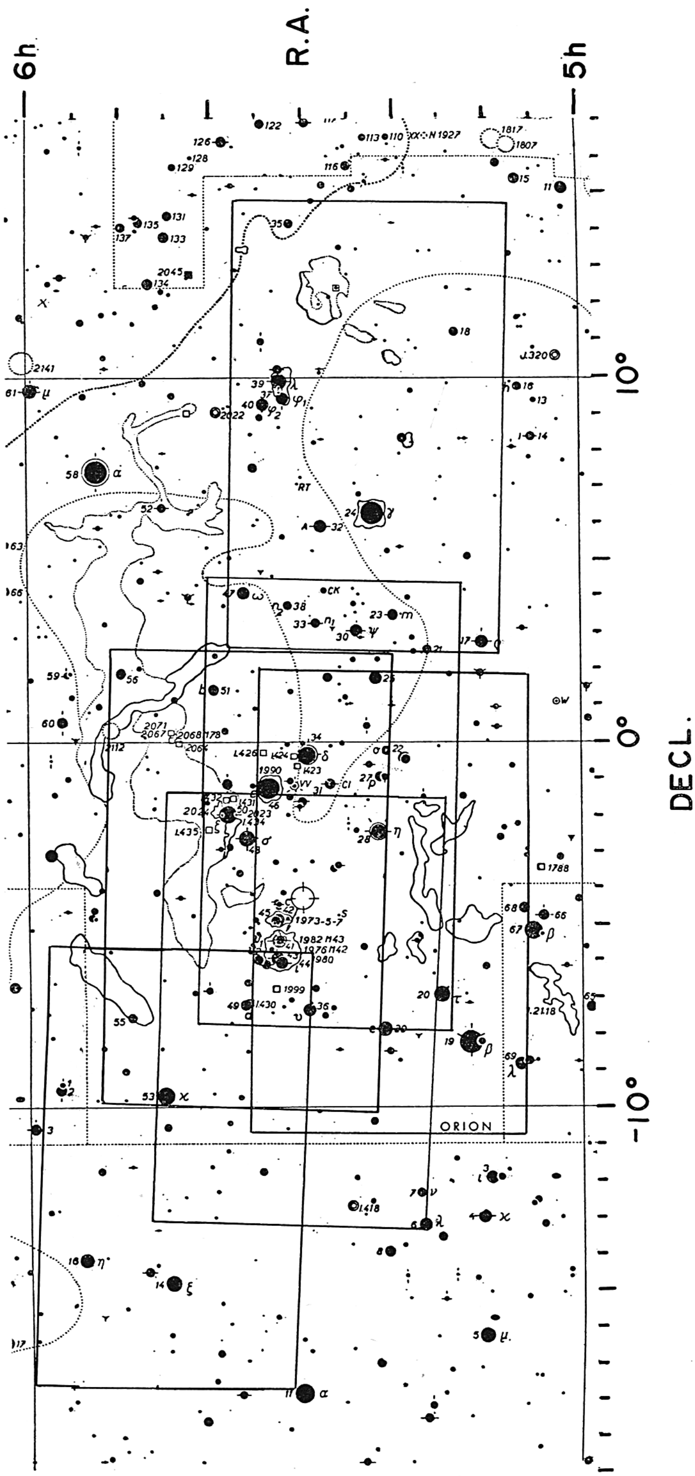

Fig. 1. Regions of the sky covered by the scanning photometers.

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TABLE I

The photometric data

Star	SP.	#Obs.	V	N_{5560}	N_{1115}	N_{1270}	$\frac{N_{1115}}{N_{5560}}$ Obs.	$\frac{N_{1270}}{N_{5560}}$ Obs.	E(B-V)	E(1115-V)	E(1270-V)	$\frac{N_{1115}}{N_{5560}}$ C	$\frac{N_{1270}}{N_{5560}}$ C
κ Ori	B0.5 I_a	5	2.06	160	806	> 734	5.04	> 4.60	0.04	0.37	0.32	7.08	> 6.18
λ Eri	B2 IV	1 (B)	4.27	20.9	(74.3)	–	(3.56)	–	0.05	0.46	0.40	(5.43)	–
β Ori	B8 I_a	1	0.15	928	(92.8)	437.	(0.100)	0.464	0.00	0.00	0.00	(0.100)	0.464
υ Ori	B0 V	7	4.63	15	274(231)	215.	18.23(15.4)	14.4	0.04	0.37	0.32	25.63(21.6)	19.3
ι Ori	O9 III	5	2.76	84 } 96.8	1299	> 758	13.4	> 7.83	0.08	0.74	0.64	26.7	> 14.1
GC 6926(BS 1887)	B0 V		4.77	12.8									
θ^1C Ori	$O6_p$		5.13	9.4					0.31	2.87	2.48		
θ^1D Ori	O9.5 V		6.70	2.22					0.38	3.52	3.05		
θ^1A Ori	B0.5 V	7	6.72	2.17 } 26.6	501	360	18.82	13.52	0.28	2.59	1.84		
θ^2 Ori A	O9.5 V_p		5.07	10.0					0.22	2.04	1.76		
θ^2 Ori B	B0.5 V_p		6.41	2.8					0.22	2.04	1.76		
42 Ori	B2 III	7	4.60	15.4	243(203)	197	15.8(13.2)	12.75	0.05	0.46	0.40	24.12(20.2)	18.4
σ Ori	O9.5 V	6	3.83	31.3	465	412	14.84	13.15	0.06	0.555	0.48	24.75	20.5
η Ori	B0.5 V	6	3.32	50.2	408	420	8.13	8.36	0.10	0.925	0.80	19.07	17.5
ζ Ori	O9.5 Ib	6	1.74	215	1813	> 987	8.43	> 4.6	0.06	0.555	0.48	14.06	> 7.15
ε Ori	B0 Ia	6	1.70	223	1548	> 925	6.94	> 4.15	0.05	0.46	0.40	10.60	> 6.00
δ Ori	O9.5 II	6	2.21	139	1214	> 860	8.73	> 6.20	0.06	0.555	0.48	14.56	> 9.65
25 Ori	BI V_{pe}	1	4.95	11.15 } 16.9	(63.1)	88.5	(3.73)	5.24	0.05	0.46	0.40	(5.76)	7.57
GC 6800	B2 IV		5.67	5.76									
ψ Ori	B2 IV	2	4.61	15.21 } 21.8	232(111)	173	10.6(5.10)	8.06	0.02	0.185	0.16	(6.05)	9.22
33 Ori	B3		5.52	6.57									
23 Ori	B1 V	1	5.00	10.65	(40.9)	67.6	(3.83)	6.34	0.11	1.02	0.88	(9.71)	14.28
ω Ori	B3 III	1	4.59	15.55	(32.8)	41.2	(2.11)	2.65	0.09	0.83	0.72	(4.54)	5.14
32 Ori	B5 IV	1	4.20	22.19	(32.8)	49.2	(1.48)	2.21	0.03	0.28	0.24	(1.90)	2.76
γ Ori	B2 III	2	1.63	238	1548	> 1032	6.50	> 4.34	0.03	0.2	0.24	8.40	> 5.40
ϕ^1 Ori	B0 IV	2	4.42	18.2	165(103)	135	9.12(5.67)	7.45	0.15	1.39	1.20	33.73(21.0)	22.5
λ Ori	O8	2	3.39	47	522	367	11.11	7.8	0.13	1.20	1.04	33.66	20.35

each star using the observed colors of Iriarte *et al.* (1965) and the intrinsic colors of Johnson (1963).

The measured ultraviolet fluxes were then corrected for interstellar extinction in the manner of Smith (1967), using extinction factors at 1270 Å and 1115 Å obtained by a $1/\lambda$ extrapolation of the extinction measurements of Stecher (1965) and Smith (1967) to shorter wavelengths. These extinction factors, combined with the observed E(B-V), yield the tabulated ultraviolet color excesses and corrected photon flux ratios.

It was then found that, for the main-sequence stars σ, υ, and η Ori, there is good agreement between their corrected photon flux ratios and those of the blanketed B0V model atmosphere of Hickok and Morton (see Figure 2), with the differences among the three stars essentially as expected from their different spectral classes (O9.5, B0, B0.5, respectively). Also, the combined flux of ι Ori (O9 III) and BS 1887 (B0V) is in good agreement with the main-sequence model. The later-type stars ω Ori (B3III) and 32 Ori (B5IV) are in good agreement with the blanketed B4V model of Adams and Morton (1968). However, at 1115 Å, the giant and supergiant stars γ, δ, ε, ζ, and κ Ori are significantly less bright, relative to the visible, than main-sequence stars of similar spectral classes. In particular, κ Ori appears to be about one magnitude below the main-sequence brightness, as is confirmed by comparison with ι Ori in both this and the previous flight. This deficiency is in part expected, due to the low surface gravity of these stars, but in addition, there may be continuous absorption in the expanding shells of gas surrounding these luminous stars, which are made evident by P-Cygni-type profiles of the stronger ultraviolet lines (see, e.g., Morton, 1967a, b; Carruthers, 1968; Morton *et al.*, 1969).

Somewhat anomalous results are obtained for λ Ori (O8) and ϕ^1 Ori (B0 IV), in that λ Ori appears deficient at 1270 Å, particularly relative to 1115 Å, whereas ϕ^1 Ori appears too bright at 1270 Å. These stars are separated by only 0.5° in the sky, and are part of the same association, hence the reddening factor is presumably about the same for both. The relative deficiency at 1270 Å in λ Ori could be due to strong absorption in the NV 1239–1243 Å resonance line, which rocket observations have shown to be much stronger than expected in the O stars, such as ζ Pup (Carruthers, 1968; Smith, 1969; Morton *et al.*, 1969). The apparent excess at 1115 Å for λ Ori may be due to over-correcting for interstellar reddening at this wavelength (see discussion of θ Ori, below); this star is somewhat more reddened than most of the others

TABLE II

Corrected photon flux ratios for March 1967 flight (includes reddening factors)

Star	N_{1115}/N_{5560}	N_{1270}/N_{5560}
γ Vel	25.0	16.8
ζ Pup	31.3	18.7
ι CMa	0.07	0.10
κ Ori		8.24
γ Ori		6.63

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that were observed. The excess brightness at 1270 Å for ϕ^1 Ori could be due to additional, fainter stars and/or emission nebulosity in the field of view of the photometer. A similar explanation may also apply to 42 Ori, which appears too bright in both wavelength ranges. Alternately, this latter star may be misclassified, particularly if it is responsible for exciting the emission nebulosity which surrounds it.

Recent ground-based spectroscopic studies of 42 Ori, by N. R. Walborn of Yerkes Observatory (private communication, 1970) indicate that, in fact, the spectral classification should be B1 V, instead of B2 III as originally listed.

As mentioned previously, the results of our March 1967 flight were corrected by comparison with the present results for stars in common. Table II gives corrected fluxes for three stars not observed in the present flight, and 1270 Å fluxes for two stars for which the 1270 Å photometer in this flight was saturated. Although this is a rather crude method for obtaining stellar fluxes, the results seem to indicate that the hot stars ζ Pup (O5f) and γ Vel (WC7+O7) are somewhat less bright than expected from the model atmosphere theory (Morton, 1969), as also indicated by Smith (1969, private communication) from satellite photometry, particularly in comparison with other O stars such as S Mon (O7). Both ζ Pup and γ Vel exhibit P-Cygni-type profiles in their stronger ultraviolet lines, indicating the presence of expanding shells of gas.

Perhaps the most interesting result of all is that for the group of stars θ Ori, which excites the Orion Nebula. If the observed flux is corrected for reddening as for the other stars, the resulting corrected flux would be far off scale in Figure 2, in fact,

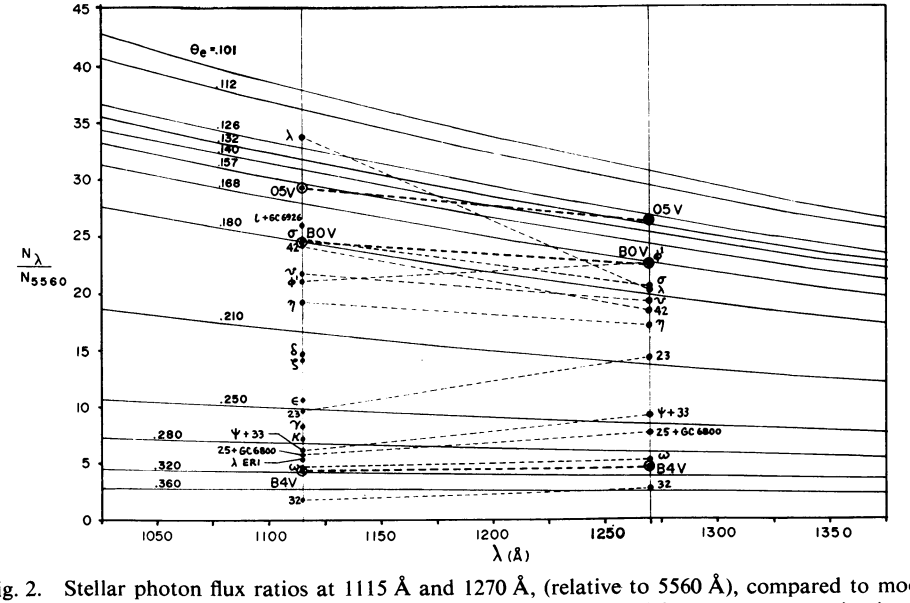

Fig. 2. Stellar photon flux ratios at 1115 Å and 1270 Å, (relative to 5560 Å), compared to model atmosphere predictions. The observed flux ratios have been corrected for interstellar extinction as per Smith (1967). Circled points are averages, over the photometer passbands, of the predicted flux ratios from O5 V and B0 V model atmospheres of Hickok and Morton (1968) and the B4 V model of Adams and Morton (1968). Also shown are curves for unblanketed models of Mihalas (1965).

it would correspond to a flux ratio greater than that of a black body of infinite temperature! Therefore, it is apparent that the reddening correction must be in error. The relative brightnesses of 42, θ, and ι Ori, as measured by the photometers, are confirmed by densitometer traces of the electronographic spectra, as shown in Figure 3. The appearance of the spectrum of θ Orionis does not indicate any substantial contribution of discrete nebular emission lines in the 1000–1350 Å range, and the two subgroups θ^1 and θ^2 Ori appear to contribute comparably (Carruthers, 1969b), though the spatial resolution was not adequate to allow a definitive evaluation of the separate contributions.

Therefore, instead of correcting for the interstellar extinction to obtain intrinsic fluxes, the opposite procedure was used in that intrinsic fluxes were assumed to derive

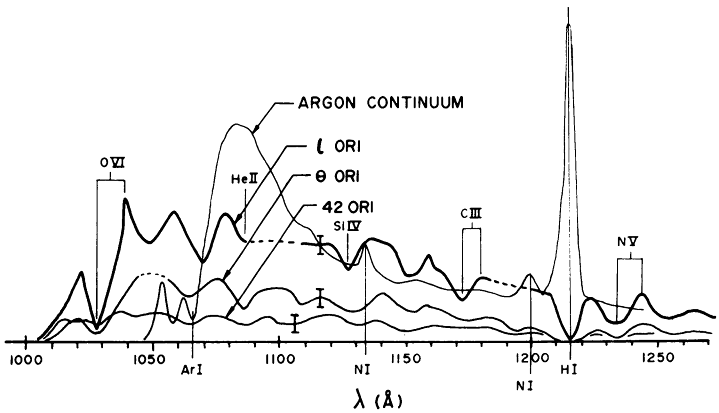

Fig. 3. Microdensitometer tracings of ultraviolet stellar spectra in the Orion Sword region and preflight calibration spectrum. The limits of error due to grain noise and background fluctuations are indicated.

the interstellar extinction (Carruthers, 1969c). The combined spectrum of θ Ori was taken to be equivalent to that of an unblanketed 30000° model atmosphere. The resulting color excesses at 1270 and 1115 Å are E(1270-V) = 0.53 mag, and E(1115-V) = 0.37 mag. For comparison, the averaged E(B-V) = 0.28 mag. Hence, it is apparent that a $1/\lambda$ extinction law does not hold for θ Ori, in fact, it appears that the extinction is *decreasing* toward shorter wavelengths in the 1050–1350 Å range. However, the probable errors of this method of determining the reddening law are probably of the order of $\pm 20\%$, and hence do not exclude the possibility of a flat extinction curve in this wavelength range. In Figure 4 are shown the normalized color excesses, $\Delta E = E(\mathrm{M}_\lambda\text{-V})/E(\text{B-V})$, for comparison with previous extinction measurements for other stars, and extrapolation thereof, and with previous ground-based measurements of the extinction law for θ Ori.

The present ultraviolet measurements confirm the anomalous nature of the reddening law for the Orion Nebula region. Although no results are available for the intermediate wavelength range 1350–3000 Å, the present results seem to imply that the

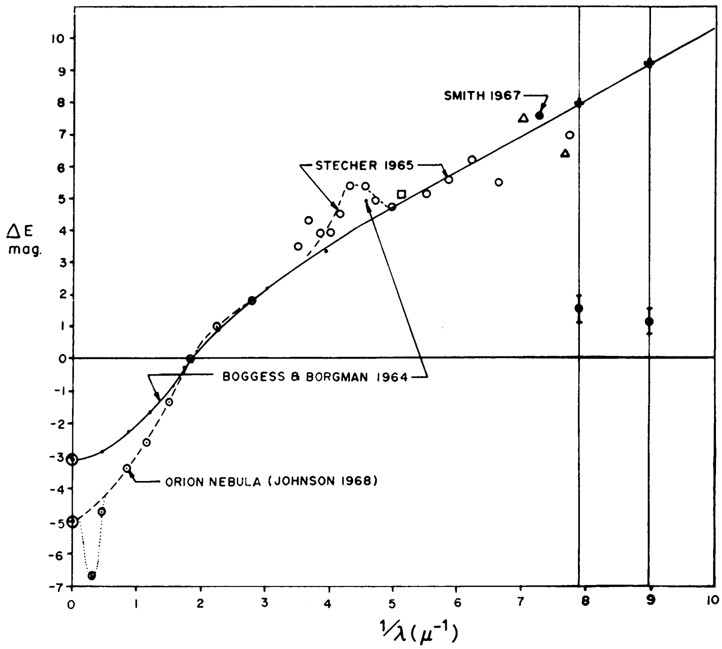

Fig. 4. Comparison of the observed interstellar extinction in the Orion Nebula region with that observed in other regions of the sky by Boggess and Borgman (1964), small dots; Stecher (1965), unfilled symbols; and Smith (1967). Extrapolation of these results to 1270 Å and 1115 Å assuming a $1/\lambda$ law gives values shown by crosses. The dotted portion of the extinction curve for the Orion Nebula indicates the possible effect of circumstellar infrared emission (Johnson, 1967). The present results are indicated by circles with error bars, where the error limits include both measurement errors and uncertainties in the intrinsic stellar fluxes.

absorption is essentially neutral in the far ultraviolet, i.e., that the attenuating particles are large compared to the wavelengths of interest. A relative lack of small particles had already been inferred by the anomalous reddening curve in the wavelength range accessible from the ground, and was attributed to their having been driven out of the nebula by the radiation pressure of the exciting stars (Johnson and Morgan, 1955).

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Discussion

Campbell: What is the accuracy of your absolute photometry in the region 1230–1350 Å?
Do you recover your instruments in a form suitable for re-calibration?

Carruthers: The accuracy of our calibrations, I feel, is about $\pm 10\%$. However, we have much more confidence in the calibrations for this flight than for the March 1967 flight, because this time we were able to recalibrate in the field, up to 2 days before the flight, whereas for the March 1967 flight the last calibration was one month before the flight. In view of the observed tendency of detectors to decrease in efficiency with time, it was not surprising that the previous flight efficiencies were found to have been considerably lower than was thought at the time.

When possible, we recalibrate the detectors after recovery of the payload, but the results are generally not a very good indication of what the detector efficiencies were at the time of the observations. This is because the detector windows are contaminated by the heating effects of atmospheric re-entry, and by dirt and moisture after ground impact.

Greenberg: In connection with your observation that the far ultraviolet extinction for θ Ori appears to have levelled off (or even dropped) relative to the ground based measurements I should like to point out that this is consistent with the extinction curve of θ Ori in the 1–3 μ^{-1} range deviating from the average extinction by being more concave downward. This behavior can be attributed to a larger mean interstellar grain size. The effect of the larger particles would be to bring about extinction saturation at longer wavelengths with a subsequent gradual drop toward shorter wavelengths.

Carruthers: Johnson's curve for the reddening in the visible also hints at a downward curvature of the reddening law even in the ground-accessible ultraviolet above 3000 Å, as indicated on the slide.

Heintze: In the past the shape of the extinction curve is also determined by comparing measured energy distributions with calculated ones. The use of the 1964 adoption of the energy distribution of α Lyr and the adoption of too high effective temperatures of the stars considered causes a steeper slope of the extinction curve towards the UV than by using Hayes' energy distribution of α Lyr and the lower effective temperatures generally adopted now.

Davis: Did your observation of θ Ori include the contribution from the Orion Nebula? Our Celescope measurements of the Orion sword region also show θ Ori and the Orion Nebula to be brighter than would result from stellar models of the appropriate spectral type for θ by itself.

Carruthers: We do not feel that the nebula made an appreciable contribution to the measured fluxes, unless it is from a part of the nebula very close to the exciting stars, because our spectra of θ Ori do not show any emission lines or other indications of the nebula, and the widths of the spectra are no greater than would be expected for the two components, θ^1 and θ^2 Ori, separated by 2 arc min.

Bless: We have obtained spectral scans of θ^1 and θ^2 Ori with the OAO. The field of view of the instrument also includes much of the Orion nebula. The integrated spectral type and color of $\theta^1 + \theta^2$ is 0.1 spectral type earlier than ζ Oph and about $0^m.05$ bluer in (B-V). However, after correction for the relative magnitude, the flux observed from the Orion region is about 10 times greater at 1200 Å than that from ζ Oph, slowly decreasing to 4 times greater at 1800 Å. To the extent that a composite spectrum and color is meaningful, this suggests that either these stars are very strange, that the nebula contributes a large flux, or that the interstellar reddening in the nebula is abnormal, as has been observed in the visual. At the moment the last explanation seems the most plausible, in agreement with Carruthers' interpretation of his observations.

Underhill: Is the ultraviolet brightness of $(\theta^1 + \theta^2)$ Ori (which I take to be chiefly due to θ^1C Ori, O6) the same as that of ζ Pup, O5f?

Carruthers: Even after accounting for reddening, ζ Pup appears to be considerably fainter than expected for an O5 star; it appears more comparable to an O9 star such as ι Ori. In the case of θ Ori, the intrinsic brightness could not be determined directly because of the anomalous reddening; we had to assume the former to derive the latter. However, it appears that θ Ori is considerably brighter in the UV, relative to the visible, than ζ Pup, unless there is even less extinction for θ Ori in the UV than in the visible, which seems unlikely.

Stecher: The ratio of selective to total extinction for θ Ori was found to be 5.6 by Sharpless instead of the normal value of ~ 3. It is reasonable to expect a deviation from the usual curve but quite exciting to find that it is the case.

Haupt: Can you exclude completely some residual atmospheric extinction?

Carruthers: Yes, we feel that residual atmospheric extinction was negligible, except for the last few scans of γ, ϕ^1, and λ Ori at the end of the flight. These, which were observed at the last pointing position showed decreasing intensities related to earlier scans of these stars. In general, in repeated scans of the same stars we got very good agreement except for this one case in which atmospheric attenuation was apparent just before re-entry.