PART II

STELLAR LINE SPECTRA

A. ROCKET AND SATELLITE OBSERVATIONS OF ULTRAVIOLET SPECTRA

OBSERVATIONS OF ULTRAVIOLET STELLAR SPECTRA

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1. Introduction

The dividing line between photometry and spectrometry is not always obvious and for the purpose of this review, I will define ultraviolet stellar spectroscopy as observations with sufficient spectral resolution to allow the detection of individual spectral lines and their measurement in terms of wavelength and strength. From an examination of the existing observations this results in a resolution requirement of $\delta\lambda < 10$ Å. Since the best spectral resolution so far obtained is about 1 Å then this places the results to be discussed within the range 1–10 Å. In terms of $\lambda/\delta\lambda$ this corresponds to a range of about 2000–200 and it is important to bear in mind that these represent low resolution spectra. In fact the limit of 200 that I have imposed would rarely be used for spectroscopic studies in ground based observatories where it corresponds, in the notation of the optical astronomer, to a dispersion of about 1000 Å/mm, the resolution limit being set by the photographic plate, typically taken as 20 μ. Hence, even the faintest objects like quasars are usually studied with a dispersion of a few hundred Å mm^{-1}. The fact that such a resolution can be included here is an indication of the exceptionally strong resonance lines which occur in the ultraviolet and which can be detected with such a resolution. On the other hand, the richness of the ultraviolet spectrum is making and will continue to make, demands on improved resolution in order to separate the many features. The best achieved resolution of about 1 Å goes only part-way to solving this problem.

In such a rapidly advancing field, this review cannot be completely up-to-date. However, I believe it is comprehensive as far as published information is concerned and therefore a reasonable starting point for the subsequent papers of the Conference which will present some of the very recent data.

2. The Observations

The first UV stellar spectra were obtained by Morton and Spitzer [1] of δ and π Scorpii during a rocket flight in 1965 and were made possible by the development of a star-pointing control system for the Aerobee rocket. This pointing control, the *Inertial Attitude Control System* (*IACS*) of Space General Corporation (U.S.A.) is a 3-axis stabilized, cold gas reaction jet system used to orient the entire rocket at any given time during free fall. More than five pre-programmed positions can be acquired during a single flight by changing the inertial attitudes of two free gyro sensors. In each orientation, the control system continuously aligns the rocket with the null positions of

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the sensors. A 3-axis rate gyro is used for system damping. In basic form, the IACS is capable of pointing a payload within 3° of a desired direction and has a limit cycle of ±15 arcmin. The performance of this system has been considerably improved in the *Stellar Tracking Rocket Attitude Positioning* (*STRAP*) system which has been developed at the NASA Goddard Space Flight Center from the basic IACS with the addition of a star sensor and an auxiliary low-thrust jet system. This achieves a limit cycle performance of about ±30 arcsec for 3rd magnitude objects, improving to about ±10 arcsec for brighter objects.

All published UV stellar spectra have been obtained from Aerobee rockets using either the IACS or STRAP pointing systems. After their pioneering flights, the Princeton group have obtained further observations and have been joined by Carruthers of the Naval Research Laboratory and Stecher and Smith, both at Goddard. Although this review is not concerned with techniques as such, it is necessary to consider them to a degree sufficient to appreciate the data. This will be done by briefly describing the instrumental concepts of the four groups involved.

Morton and his colleagues (Princeton) employed a fine stabilisation system in conjunction with the IACS to give an improved pointing stability in the direction of dispersion. This was done passively by pivoting the instrument platform and attaching a large gyro. Instrument stability of better than ± 20 arcsec and a spectral resolution of about 1 Å have been achieved in this way. The components of the system used in the first few flights [1, 2] are indicated in Figure 1. The platform was mounted to the rocket bay with a single degree of freedom. Two spectrographic cameras (only one is shown) were rigidly attached to one side of the platform and the gyro to the other. The dispersion direction was placed perpendicular to the platform axis. The spectro-

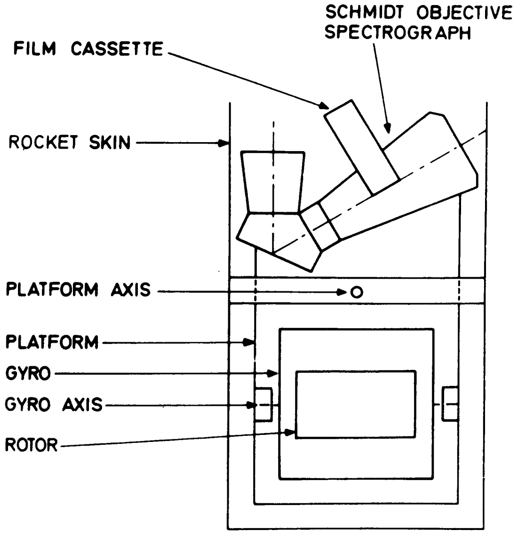

Fig. 1. Schematic of a Princeton objective spectrograph payload. For example of UV data recorded with such an instrument, see Figure 5.

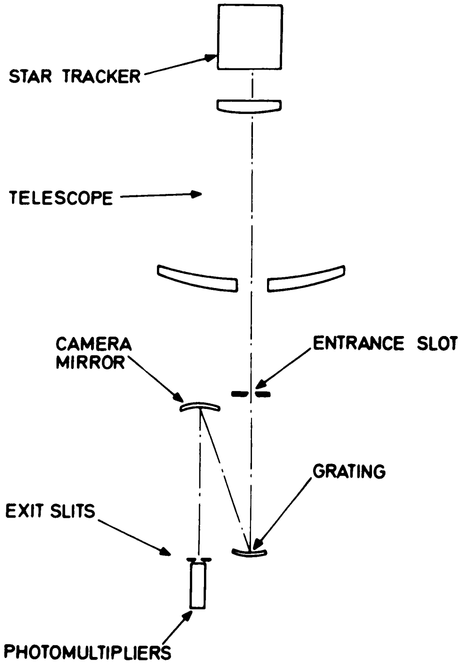

Fig. 2. Schematic of a scanning photoelectric spectrometer system with telescope as flown by Stecher (see text). For example of UV data recorded with such an instrument, see Figure 6.

graphic cameras each consisted of a plane objective grating followed by an *f*/2 Schmidt camera with a 10° diameter field. Correctors of CaF_2, LiF and fused silica were used in various flights. A solenoid actuated magazine gave 6 exposures on Kodak Pathé SC5 film for each camera. On later flights, an all-reflective camera with LiF overcoating on all surfaces was used for improved short wavelength performance [3–5].

Stecher [6, 7] (Goddard) uses the STRAP system with a payload consisting of a 33 cm *f*/10 telescope feeding a scanning photoelectric spectrometer. This instrument is indicated schematically in Figure 2. The spectrometer section contains a concave grating, rotated about an axis in the plane of the diagram, a folding mirror and three exit slits with photomultipliers, here seen side-on. The latter were used simultaneously and a continuous pointing-error signal from the star sensor, telemetered with the spectrum data, allowed subsequent wavelength corrections to be made at each point in the spectrum. A resolution of 10 Å was obtained, the limitation in this case being due to the exit slit widths rather than to pointing instability.

Smith (Goddard) has used the STRAP system with an objective grating camera (a concave grating in Wadsworth mount) to obtain spectra below 1200 Å [8]. Because of the low reflection efficiencies of the coatings available in these spectral regions, such a single element system, although of small aperture, may still be comparable in speed to a large telescope with spectrograph for which at least two additional reflections are required. Furthermore, the system has the advantage of a relaxed stability requirement compared to a telescope with spectrograph as can be seen from the following expression

$$\delta w = (G/T)\, D\, \delta\lambda ,$$

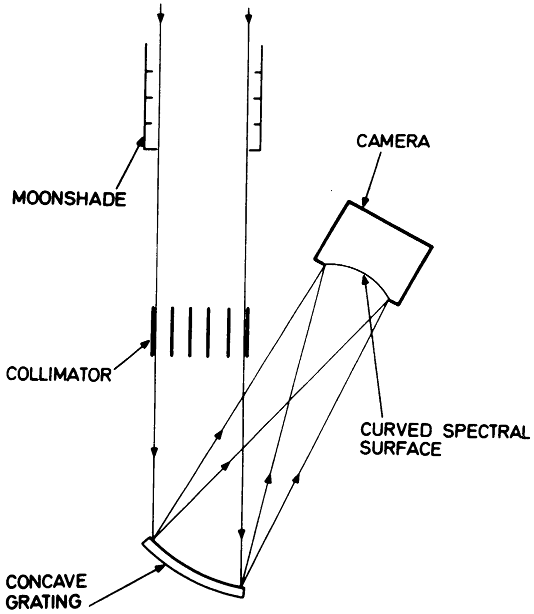

Fig. 3. Schematic of an objective grating camera in a Wadsworth mounting using the same basic principle as the payload launched by Smith [8]. For example of UV data, recorded with such an instrument, see Figure 7.

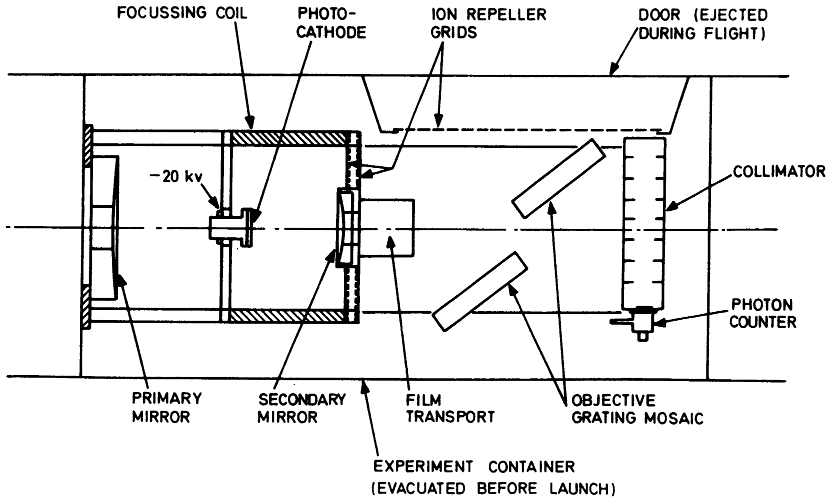

Fig. 4. Diagram of the objective grating camera incorporating an electronographic detector flown by Carruthers [9]. (By permission of the University of Chicago Press.) For example of UV data, recorded with such an instrument, see Figure 8.

which relates the degradation in resolution $\delta\lambda$ produced only by an angular pointing noise δw. G is the aperture of the grating and D its angular dispersion; T is the aperture of the telescope. In this particular configuration, the grating is also the telescope and G/T is unity compared with typical values of ~ 0.1 for telescope/spectrometer systems. With this system Smith has obtained UV spectra with the best spectral resolution (0.8 Å) yet achieved.

A representation of a Wadsworth camera is shown in Figure 3 which includes a baffled hood to reduce instrumentally scattered moonlight, if applicable, and a collimator system, to limit geometrically the background fogging due to Lyman α night glow.

TABLE I

Observations of UV stellar spectra

Star	m_V	MK	Wavelength range	Resolution	Reference source
γ^2 Vel	1.9	WC7 + O7	1127–1193 Å	1.6 Å	[5]
			1050–1250 Å	2–3 Å	[9]
			1100–3000 Å	10 Å	[10]
ζ Pup	2.2	O5f	1100–1965 Å	1.6 Å	[5]
			1050–1250 Å	2–3 Å	[9]
			1100–3000 Å	10 Å	[10]
λ Ori	3.7	O8	1150–1350 Å	2–3 Å	[9]
ι Ori	2.8	O9 III	1130–1310 Å	~ 1 Å	[4]
			1100–1400 Å	2–3 Å	[9]
			1230–2100 Å	~ 3 Å	[2]
ζ Ori	1.8	O9.5 Ib	1100–1670 Å	~ 1 Å	[4]
			1070–1400 Å	2–3 Å	[9]
			1200–1730 Å	~ 3 Å	[2]
δ Ori	2.2	O9.5 II	1100–1951 Å	~ 1 Å	[4]
			1200–1420 Å	~ 3 Å	[2]
σ Ori	3.8	O9.5 V	1138–1634 Å	~ 1 Å	[4]
ε Ori	1.7	B0 Ia	1100–1806 Å	~ 1 Å	[4]
			1230–1590 Å	~ 3 Å	[2]
δ Sco	2.3	B0 V	1260–1720 Å	~ 1 Å	[1]
κ Ori	2.1	B0.5 Ia	1120–1400 Å	2–3 Å	[9]
			1620–2780 Å	~ 3 Å	[2]
η Ori	3.3	B0.5 V	1178–1800 Å	~ 1 Å	[4]
			1230–1440 Å	~ 3 Å	[2]
β CMa	2.0	B1 II–III	1050–1300 Å	2–3 Å	[9]
π Sco	2.9	B1 V	1260–2180 Å	~ 1 Å	[1]
α Vir	1.0	B1 V	928–1350 Å	0.8 Å	[8]
ε CMa	1.5	B2 II–III	1100–3000 Å	10 Å	[10]
γ Ori	1.6	B2 III	1668–2747 Å	~ 1 Å	[4]
			1150–1370 Å	2–3 Å	[9]
α CMa	−1.4	A1 V	1100–3000 Å	10 Å	[10]

Carruthers (N.R.L.) has obtained objective grating spectra using an electronographic detector system [9] which is displayed schematically in Figure 4. The system incorporated a KBr photocathode and Schwarzschild optical system and was preceded by an objective mosaic of 4 plane gratings operated in the second order. LiF overcoated Al was used for all reflecting surfaces. The effective aperture and field of view were 15 cm and 7° respectively and the inherent resolution capability, about 1 Å. Care was taken to reduce the background fog level resulting from positive ions either of ionospheric origin or from ionizing collisions in the residual gas. The IACS was used with an additional feedback system to reduce the jitter rate within its limit cycle to less than 1 arcmin $\sec^{-1}$; the resulting spectral resolution was typically 3 Å for a 10 sec exposure.

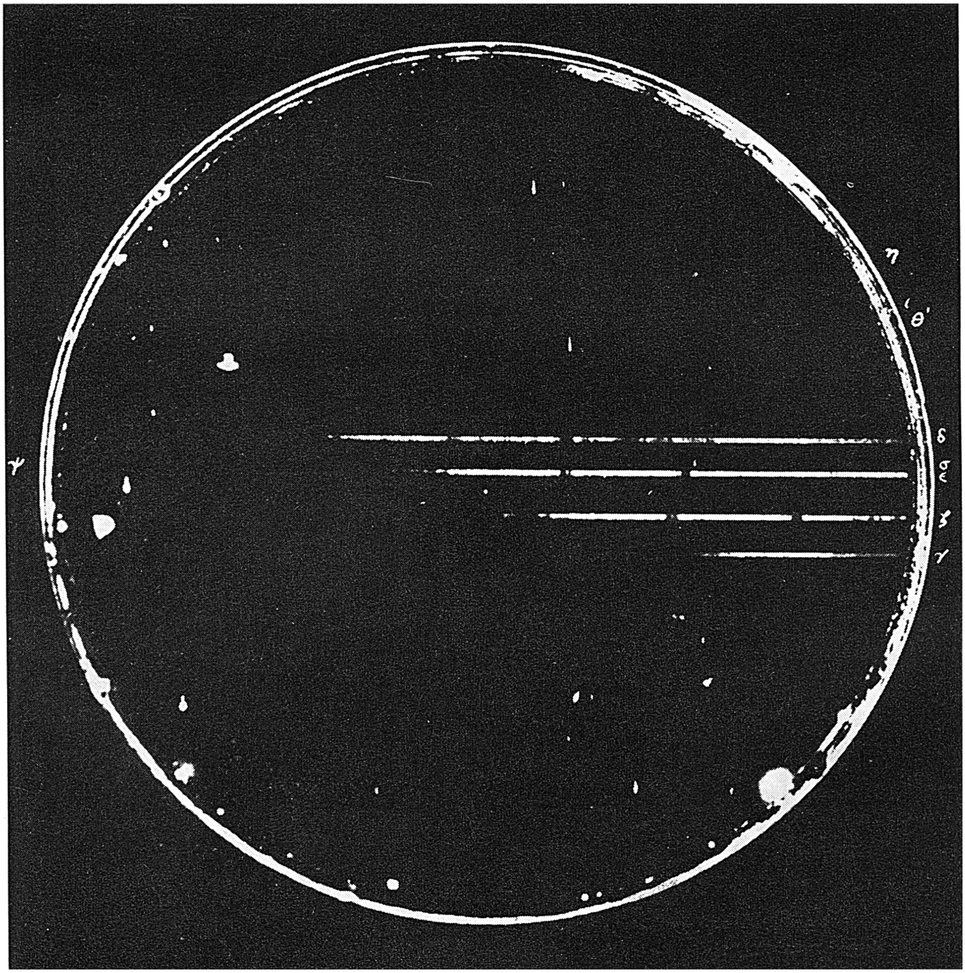

Fig. 5. UV objective spectra of the Orion region obtained by Morton *et al.* [4]. (Reproduced from a print kindly supplied by Morton.)

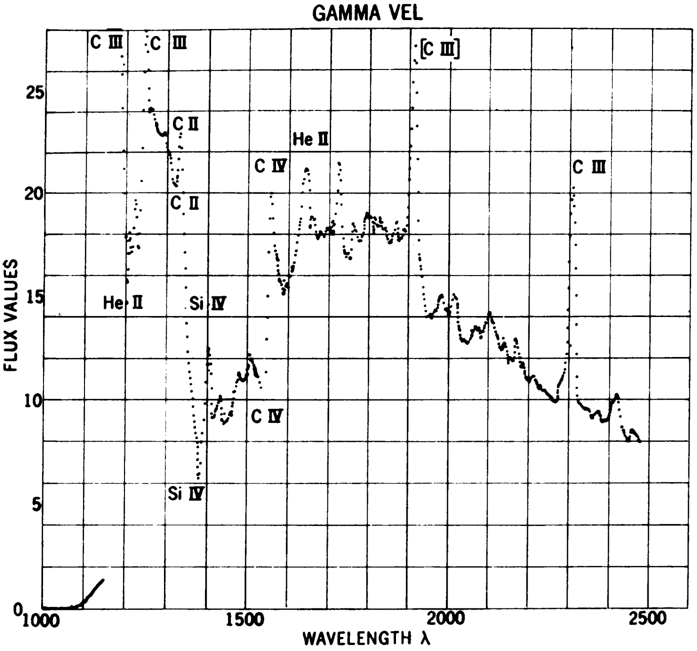

Fig. 6. A spectral scan of γ Vel from 1200–2500 Å obtained by Stecher [10]. The flux is in units of 10^9 erg cm^{-2} sec^{-1} Å^{-1} (from Goddard preprint [10] by courtesy of Stecher).

3. Results

The observed data on UV stellar spectra that are available in the literature at the time of writing are summarized in Table I, which gives for each star the observed wavelength range and spectral resolution, together with the reference source. The table is selective to the extent that observations which are labelled 'very weak' by the authors or which involve superimposed spectra have been excluded. Not surprisingly, the observations are limited to bright early-type stars.

An example of the type of data obtained by each of the four groups who have contributed to Table I is given in Figures 5–8. These correspond to the instrumental concepts given in Figures 1–4. Figure 5 displays an objective spectrogram of the Orion stars obtained by Morton and his colleagues [4]; Figure 6 gives a spectrum scan of γ Vel obtained by Stecher [10]; Figure 7 gives a microdensitometer tracing of the spectrum of α Vir obtained by Smith [8] and Figure 8 gives microdensitometer tracings of a selection of spectra obtained by Carruthers [9].

It is indicative of the rapid expansion of UV astronomical spectroscopy that Table I is already out of date, as will be made clear by subsequent papers. Each of the four groups has carried out further successful rocket flights and the first UV stellar spectra from a satellite have been obtained by Code and his colleagues at Wisconsin using a scanning spectrometer with resolution ~10 Å on the *Orbiting Astronomical Observatory* (OAO-A2). This work is being described by Bless in a number of papers in this conference.

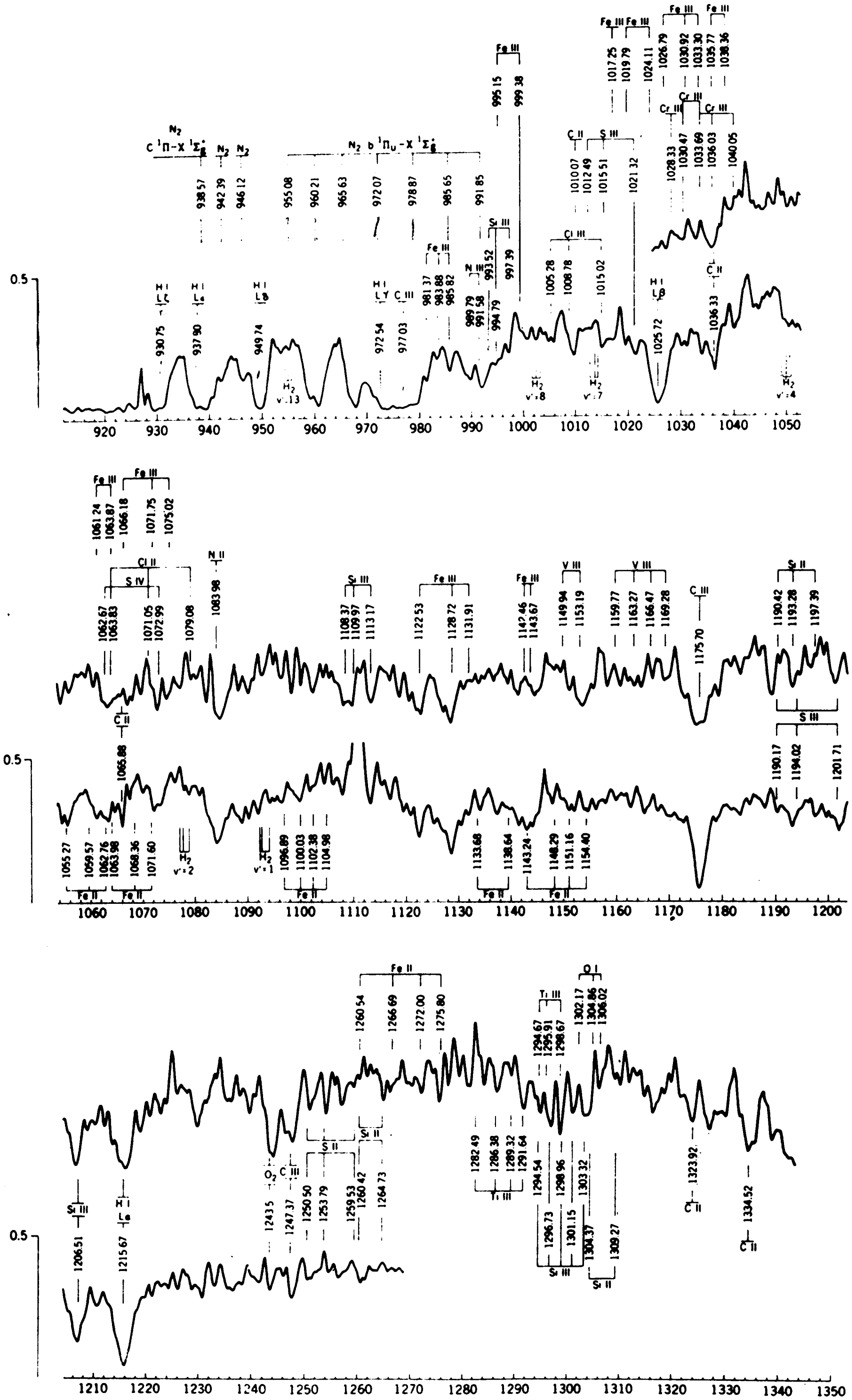

Fig. 7. Microdensitometer traces of the spectrograms of α Vir obtained by Smith [8] over the range 920–1350 Å. The upper and lower tracings correspond to short and long exposures respectively with the ordinate density scale reflecting the lower trace only.
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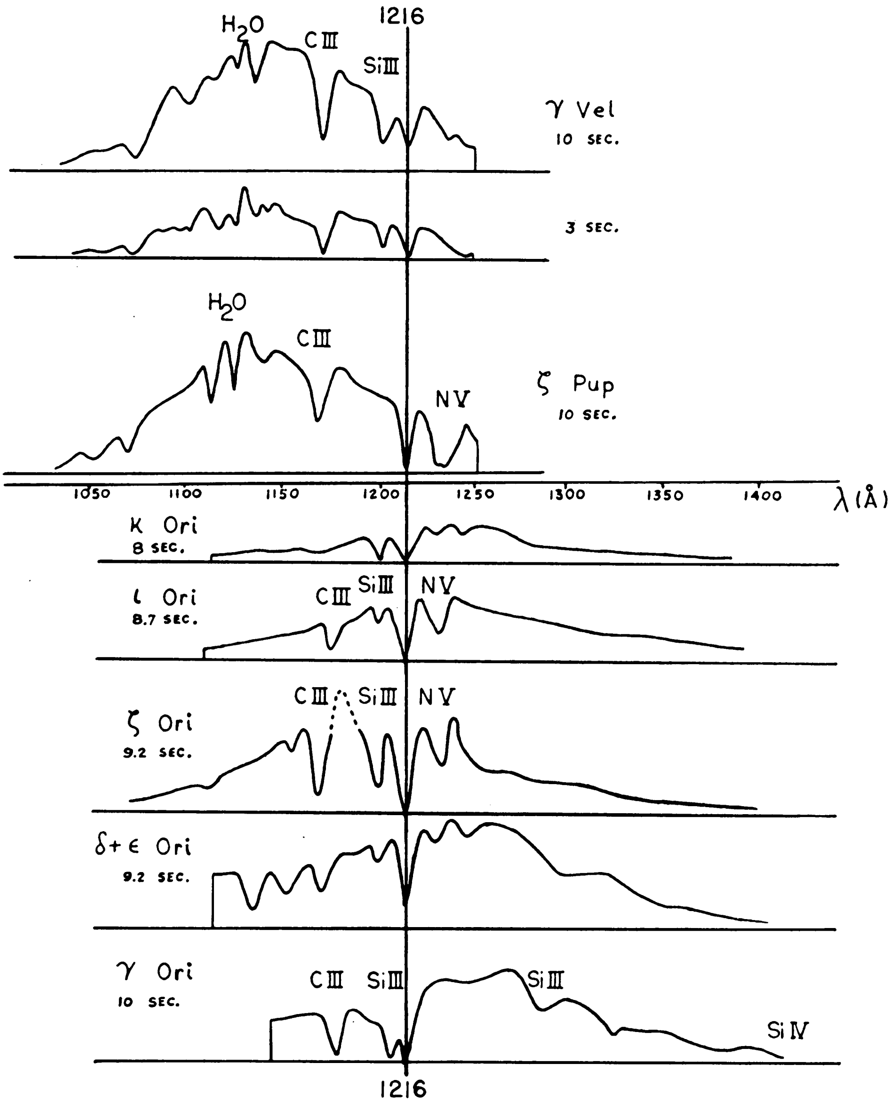

Fig. 8. Microdensitometer tracings for a selection of stellar spectra obtained by Carruthers [9]. (By permission of the University of Chicago Press.)

4. Discussion of Results

A. STELLAR FEATURES

The observed absorption line spectra give general support to the theoretical predictions, in the sense that they show the presence of very strong resonance lines of abundant ions and demonstrate directly the severe line blanketing which affects the photometric data. The analysis of photospheric lines has concentrated on the identification of observed features. This is made necessary by the richness of the ultraviolet spectra and is best illustrated by the observations of Morton *et al.* [4] and Smith [8] which combined the best spectral resolution yet obtained (~ 1 Å) with well exposed spectra. In the spectra of δ, ε and ζ Ori, Morton *et al.* have observed nearly 200 absorption lines in the region 1100–2000 Å of which more than 100 remain unidentified. Smith's observation of α Vir (B1 V) in the range 928–1350 Å gave about 90 lines for which classifications are proposed, leaving many more features unidentified (see Figure 7).

Calculations of emergent flux are now available for a number of theoretical line-blanketed model atmospheres of early-type stars against which the observed UV stellar spectra can be compared. The first estimate of the strengths of ultraviolet spectral lines was made by Gaustad and Spitzer [11] for a B2 star using a curve of growth analysis based on a Schuster-Schwarzschild model. Since then, more refined calculations have been made of the emergent ultraviolet flux from early-type stars by introducing line absorption into model atmospheres of the type developed by Underhill [12, 13]. The models are based on a plane-parallel atmosphere in hydrostatic equilibrium, radiative equilibrium and local thermodynamic equilibrium with a chemical composition of $\mathrm{He/H} = 0.15$ by number plus heavy elements as determined from the solar photosphere. Calculations are available for a number of early-type main-sequence models with surface gravity $= 10^4 \mathrm{cm\ sec}^{-2}$ as follows: O5 V [14], B0 V [14], B1 V [15], B2 V [16, 17, 18], and B4 V [19].

In addition to these, a series of models for B8–F2 is available [20] based on the same assumptions but with line blanketing calculated for the hydrogen Balmer lines only.

The most extensive comparison of model atmosphere calculations has been made in respect of photometric observations by Bless *et al.* [21] who examined the UV data of a number of observers [22–25] which covered the range 1115 Å–2800 Å and included 35 main-sequence stars of spectral types B and A. The models were identified with the observations through the effective temperature scale of Morton and Adams [26]. It was concluded that the existing model atmospheres could adequately represent the UV photometric observations of main sequence stars within their possible errors (± 0.5 mag.) at wavelengths above 1500 Å but that gross discrepancies could occur at shorter wavelengths, particularly 1150 Å.

A more detailed check on model atmospheres is possible with the UV spectroscopic data but an extensive comparison has yet to be made. However, discrepancies are apparent between the theoretical and observed strengths of some spectral lines. Further, Smith's [8] comparison of his observations of α Vir with the B1 V model atmosphere calculations of Mihalas and Morton [15] shows that many more lines are present than are included in the calculations; he concludes that the net effect of these additional lines will be significant in terms of line blanketing. It is therefore apparent that more sophisticated model atmospheres are required, not only to include all significant line absorption, but also to examine departures from the fundamental hypotheses of the 'classical' model atmosphere. Convective energy transport has been considered in model atmospheres by Mihalas who shows that the ultraviolet flux can be appreciably smaller than in radiative models. Also, Guillaume *et al.* have studied the effect of microturbulence on spectral lines and show that lines can be increased substantially in strength by such effects. A review and discussion of the problems of model atmospheres in predicting UV stellar spectra is to be given by Miss Underhill [27].

All the main-sequence stars so far observed have been characterized by an absorption line spectrum. However, many other stars listed in Table I show emission as well as absorption lines, indicating gross departures from the classical model atmospheres and the presence of extended or circumstellar atmospheres. This is not surprising for γ^2 Vel (WC7 + O7) and ζ Pup (O5 f) which are known to be emission line objects from observations in the visible but in addition to these objects all super-giants listed in Table I include some emission features in their spectra. Thus, emission lines have been reported [2, 4, 9] in ε Ori (B0 Ia), κ Ori (B0.5 Ia), ζ Ori (O9.5 Ib), δ Ori (O9.5 II) and ι Ori (O9 III). The lines show a P Cygni type profile with violet shifted absorption components indicating expansion velocities of the order of 1500 km/sec. This effect occurs in the strong resonance lines of Si III (1207 Å), Si IV (1394–1403 Å), C IV (1548–51 Å) and N V (1239–43 Å), together with the low lying transition of C III (1157 Å). The emission component appears in varying degrees of strength and is sometimes totally absent, but the effect is recognized by the large shift in the absorption line produced in the expanding shell. The several other lines observed in the spectra show no shift, indicating their formation in lower photospheric layers. The observed velocities are comparable with those associated with Wolf-Rayet stars and their presence in early type supergiants is somewhat surprising although the ground-based observations of Wilson [28, 29] and Underhill [30] had indicated velocities of this order associated with emission lines of He II, C III and N III.

Since the observed velocities are considerably in excess of the escape velocities, it is clear that the early-type supergiants are losing mass. The loss rate has been calculated by Morton [31, 32] for δ, ε and ζ Ori using the Si IV and N V lines. Other shifted lines were excluded because they were saturated. The broad and shallow nature of the N V line eliminates radiation damping as the broadening mechanism since core saturation would be needed to explain the observed width. The broadening is therefore due to Doppler motions and the observed profile indicated turbulence rather than differential expansion. Assuming microturbulence rather than macroturbulence, Morton calculated column densities of N V and Si IV from the observed strengths of the absorption lines. A simple model was then adopted in which the lines are formed in a shell of constant expansion velocity where the ionization balance is imposed by the dilute radiation from the star. This requires that the electron temperature in the shell be less than 10^5K and the electron density less than 10^{10} cm^{-3}. An electron temperature of 10^4K was adopted and a colour temperature of 26000 K for the star was derived from the analysis. Since this refers to radiation below the Lyman limit, it appears a reasonable value when compared with the effective temperatures of about 32000 K for these objects [26].

Morton's resulting estimates of mass loss lie between $1\text{–}2 \times 10^{-6}$ $M_\odot$ yr^{-1}. This is a factor of 10 higher than Lucy and Solomon [33] deduced from a theoretical model in which the radiation pressure in the strong resonance absorptions produced expansion.

Since the stars have a mass of about 30 $M_\odot$ and spend about 10^6 yrs as hot supergiants, a few percent of their mass will be lost in this time. However, the simplifying assumptions in the model must render this estimate a very approximate one.

Observations of ζ Pup and γ^2 Vel have also shown emission features with shifted absorption lines indicating large expansion velocities. In ζ Pup, Morton *et al.* [5] derived an expansion velocity of about 1800 km $\sec^{-1}$ from the resonance lines of Si III, Si IV, C IV and N V. However, from the lines of He II (1640 Å) and N IV (1718 Å) formed from well excited levels they derived much lower velocities of 350 and 780 km/sec respectively. They deduced that these lines are formed at lower levels, in the region where the acceleration process occurs. The observations of γ^2 Vel which cover the most extensive wavelength range are those of Stecher [10] which are reproduced in Figure 6 and show a number of carbon lines due to C II, C III and C IV. Since then Stecher [34] has also reported N IV 1718 Å in emission (apparent in Figure 6) and N V (1239–43 Å) in absorption. Since γ^2 Vel is a WC star this questions the Beals hypothesis [35, 36] of a chemical separation in Wolf-Rayet objects and supports Miss Underhill's [37] arguments that a physical rather than a chemical interpretation may be possible. However, a proper analysis of the data will be needed to settle the point.

B. INTERSTELLAR LINES

Ultraviolet spectroscopic studies of early-type stars will undoubtedly provide the most powerful techniques for studying the physics and chemistry of the interstellar gas. In reviewing the present position, I should preface my remarks with the opinion that the only unambiguous detection of an interstellar line in the ultraviolet is the Lyman α line of neutral hydrogen. Many of the observations listed in Table I embrace this line which is seen in absorption and attributed to an interstellar origin, measurements of its strength then being used to determine the density of interstellar atomic hydrogen. The observations fall into two regions in Orion and the Gum nebula. For Orion, 6 stars (δ, ε, ζ, η, ι and σ Ori) have been measured by Morton *et al.* [4] and 4 (κ, ζ, ι and γ Ori) by Carruthers [9]. In the Gum nebula, measurements for ζ Pup and γ^2 Vel have been made by Morton *et al.* [5] and Stecher [10]. An intercomparison of this data shows that column densities of atomic hydrogen derived from the measurements of Lyman α by the different observers all lie within a factor of 2.

The broadening of the strong interstellar Lyman α line is due entirely to radiation damping, hence the column density N_{H} is given in terms of equivalent width W_λ by the expression

$$N_{\mathrm{H}} = 1.9 \times 10^{18}\, W_\lambda^2\ \mathrm{cm}^{-2}.$$

Using the Princeton observations [4] for 6 Orion stars, Jenkins and Morton [3] derived column densities N_{H} in the range $1–3 \times 10^{20}$ cm^{-2}. Using a distance of 450 pc to Orion obtained from Blaauw and Borgmann [38] they obtained an average density of 0.1 cm^{-3} for interstellar atomic hydrogen. On the other hand, observations of the 21 cm line [39] suggest a column density $N_{\mathrm{H}} = 1.5 \times 10^{21}$ cm^{-2} in front of Orion, and hence an average density of about 1 cm^{-3}, a factor of 10 higher than that obtained from Lyman α.

The analysis of ζ Pup by Morton *et al.* [5] gives a column density $N_H = 5 \times 10^{19}$ cm^{-2}. They estimate a distance of 450 pc but allowing for the extent of the Gum H II region they deduce a column length for neutral hydrogen of 390 pc, giving an average interstellar density of 0.04 cm^{-3}. This compares with the value of 1.5 cm^{-3} obtained by McGee [40] from 21 cm observations. In this case, the discrepancy is greater than a factor of 10.

The large difference in the estimates of the concentration of interstellar atomic hydrogen from the radio and ultraviolet data seems to be outside the experimental errors and is a considerable puzzle. The estimate from Lyman α assumes that the observed line is entirely interstellar, which seems a reasonable assumption in view of the early spectral type of the objects being studied. Any stellar absorption line would increase the discrepancy and therefore a strong stellar emission line would be needed in order to bring the two sets of data into agreement. However, such an emission line would have to have a profile which matched the observed absorption wings which resemble those expected by radiation damping. This seems highly unlikely, particularly since such an emission line would have to be present in all the observed stars. If we accept the discrepancy as real then a possible explanation is that the 21 cm emission is produced by matter lying beyond the stars in question. This will require the interstellar medium to be locally deficient (by a factor of about 10) since Orion and the Gum nebula are separated by 65°. Failing this, the mechanism for the production of the 21 cm line would have to be re-examined. It will be interesting to see if this discrepancy is repeated in new observations covering a wider range of galactic position.

The analysis of the observed spectra have included a search for interstellar molecular hydrogen by means of the resonance lines of the Lyman band $^1\Sigma_g^+ - {}^1\Sigma_u^+$ which lie between 1040 Å and 1120 Å. The spectra which covered this wavelength range with a reasonable spectral resolution for the purpose are those of Carruthers [9] and Smith [8]. In neither case were the transitions detected and from his observations of ζ Pup Carruthers [41] estimated an upper limit to the density of interstellar molecular hydrogen of 10% of atomic hydrogen. Smith's observations of α Vir were made with a spectral resolution of 0.8 Å and resulted in an upper limit of 3×10^{-4} cm^{-3} for the interstellar density of the molecule. A direct comparison with atomic hydrogen was not made because the Lyman α line was expected to have a strong stellar component, but if the atomic hydrogen densities derived from this line are adopted then an upper limit to the molecular hydrogen density is about 1% of atomic hydrogen.

The observed spectra have also been examined for the presence of interstellar lines of other abundant elements. Although a number of identifications are suggested, no reference claims unambiguously that the observed features are totally interstellar. The only analysis is that of Stone and Morton [42] using the observations of δ and π Sco [1]. Spectral lines of O I, C II, Si III and Al II are assumed to be interstellar and their measured equivalent widths analysed to yield densities of the ions. The results were modified by Gaillard and Hesser [43] using improved oscillator strengths for the O I lines, to give abundance ratios for these elements in reasonable agreement with those in the Sun except for Al, which appears overabundant. A direct comparison with interstellar atomic hydrogen was not possible because the Lyman α line was not covered by the observations, but the density of atomic hydrogen was estimated by assuming solar abundances and gave a value of about 35 cm^{-3}. This is nearly 2 orders of magnitude greater than that derived directly from Lyman α in Orion and Gum nebula stars. The observations used were the first stellar spectra obtained and were stated by the authors [1] to be of poor photometric quality. In addition to this, the spectral types B0 and B1 are such that a stellar contribution to the observed line strengths is a distinct probability. Because of these factors, the conclusions must be suspect and any analysis of the chemistry of the interstellar medium must await new observations, particularly of the hottest stars using improved spectral resolution.

The nearest present approach to this requirement is the observation of ζ Pup by Morton *et al.* [5] in which interstellar lines of C II, N I, Al II and Fe II are suspected but in which O I, Si I, and Si II seem to be absent. The presence of N I and the absence of O I, if real, may be explained by the oxygen being concentrated in the interstellar grains.

5. Conclusion

It is normal to end a review with some kind of 'look ahead'. It is apparent that ultraviolet astronomical spectroscopy is still in its early stages and that the future looks bright and exciting. The published results described above were obtained entirely with pointing rockets and are confined to bright early-type stars. They have already made a considerable impact on the study of these objects and the intervening interstellar medium. The need to extend the observations to other objects is abundantly clear. Deserving of mention are the late-type stars, for studies of stellar chromospheres and coronae as well as their Fraunhofer spectra; a wide variety of variable stars, including magnetic variables, novae, eclipsing binaries and cepheids; galactic nebulae, including planetaries, diffuse nebulae and supernova remnants; and extra-galactic nebulae including both normal and abnormal galaxies. Further the rich character of the ultraviolet spectrum revealed by the pioneering rocket observations has demonstrated the need for improvements in spectral resolution, at least for the brighter objects. It is clear that the full exploitation of such a wide field will need satellite systems with a full pointing capability in addition to stabilised rockets. This is demonstrated by the important new results obtained by OAO-A2 and presented at this conference.

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Discussion

Underhill: That the mass of supergiants of types near B0 is about 30 solar masses is a conclusion not supported by the evidence from radii (interferometric measures), brightness temperatures in the V band, M_V, and g estimated from the spectrum *via* N_e. Model atmospheres quite clearly show that g relates uniquely to N_e with very little dependence on T_{eff} over the range $8000\,K < T_{eff} < 33000\,K$. In the case of ε Ori, B0 Ia, the mass may well lie in the range 3 to 8 $M_\odot$.

Wilson: The estimate that is obtained from the UV data is, of course, the rate of mass loss, the value of 30 $M_\odot$ for the mass of the objects being quoted in the subsequent discussion by the author (Morton) of the particular paper I was referring to. Since he is here, I can let him explain its source. If the masses are the lower values you have deduced, then the mass loss to be expected in the lifetimes of these objects will be a substantial fraction of their total mass.

Solomon: (Regarding the mass loss rate of 10^{-6} $M_\odot$ yr^{-1} which was quoted from Morton's analysis of the observations.) It should be pointed out that there is no self-consistent analysis of the ionization equilibrium which reproduces at a single electron density, in the high velocity flow, the simultaneous existence of C III, C IV, Si III, Si IV and N V. For example, if the N V data are fitted one gets extremely small mass loss rates (since this requires very small electron densities) with $\dot{M} < 10^{-9}\ M_{\odot}\ \mathrm{yr}^{-1}$. This difficulty makes any observational estimate of the mass loss rate highly questionable.

Morton: To estimate the masses of the Ori supergiants I assumed that they have evolved from the main sequence. Reasonable estimates of the absolute visual magnitudes and bolometric corrections correspond to the theoretical luminosity of an evolved 30 solar mass star calculated by Stothers.

Bless: Isn't it dangerous to produce arguments about early-type supergiants on the basis of model atmospheres? Both the models and observations indicate that these objects are not in hydrostatic equilibrium.

Underhill: From the present admittedly inadequate model atmospheres and the line and continuous spectra predicted from them we do have an idea what the electron density is in a supergiant atmosphere (from the break-off of the Balmer and Paschen series and from the Stark wings of high series members), we can estimate the brightness temperature in the V band from the few absolute flux measurements available and compare this with predicted values to confirm that our temperature scale is not seriously in error and we can estimate the radius of the photosphere from the known M_V and the brightness temperature. The radii found for one or two stars by the Narrabri group confirm that these estimates are at least self-consistent.

Hydrostatic equilibrium is assumed in order to obtain a depth-pressure relationship. The known stellar winds are not sufficiently strong to make one suspect that the hydrostatic equilibrium pressure-depth relationship is wrong by a large factor.