THE INTERPRETATION OF SPACE OBSERVATIONS OF STARS AND INTERSTELLAR MATTER

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1. Introduction

This report will review space observations of stars and the interstellar medium and what we can expect to learn from instruments planned for the near future. Older observations are described in more detail by Underhill and Morton (1967), and Houziaux and Butler (1970). The interpretation of these measurements depends heavily on the results of theoretical and experimental atomic physics. Therefore the last section will describe some of the areas where new atomic data are essential for our understanding of space observations.

Rockets or satellites are necessary to detect all wavelengths between 0.1 and 3000 Å except for two bands from 2000 to 2200 Å and from 2700 to 3000 Å accessible at balloon altitudes. However, for most sources outside the solar system the bound–free absorption of atomic hydrogen will obliterate all wavelengths between 100 and 912 Å. For example, unit optical depth at 304 Å occurs at 12 parsecs even if the interstellar hydrogen density is as low as 0.1 atom cm^{-3}.

2. Current Ultraviolet Observations

A. STELLAR ENERGY DISTRIBUTIONS

Stellar fluxes can be obtained from filter photometers or broad-band spectral scans if the calibration is done carefully and corrections are made for interstellar absorption. The most reliable photometer observations are those by Smith (1967), Bless *et al.* (1968), and Carruthers (1969) while photoelectric scans have been reported by Stecher (1969, 1970). The ultraviolet energy distributions permit direct estimates of effective temperatures and bolometric corrections for the hotter stars as well as the continuous absorption by interstellar grains. Comparisons with theoretical model atmospheres help show whether the models can be trusted for abundance determinations and estimates of photon emission at unobserved wavelengths. Discrepancies may indicate omission of some sources of continuum or line opacity in the models or deviations from local thermodynamic equilibrium (LTE).

For the A and F main-sequence stars Davis and Webb (1970a, b) have shown that the models with only hydrogen and helium opacity predict excessive ultraviolet fluxes. Recently they have compared α CMa (A1V) with improved models including bound–free absorption of neutral C and Si and still there are discrepancies between 1200 and 3000 Å even if the heavy elements are overabundant by a factor ten as shown in Figure 1. Non-LTE effects in the continuum seem unlikely for A stars and the addition

De Jager (ed.), Highlights of Astronomy, 466–475. *All Rights Reserved*

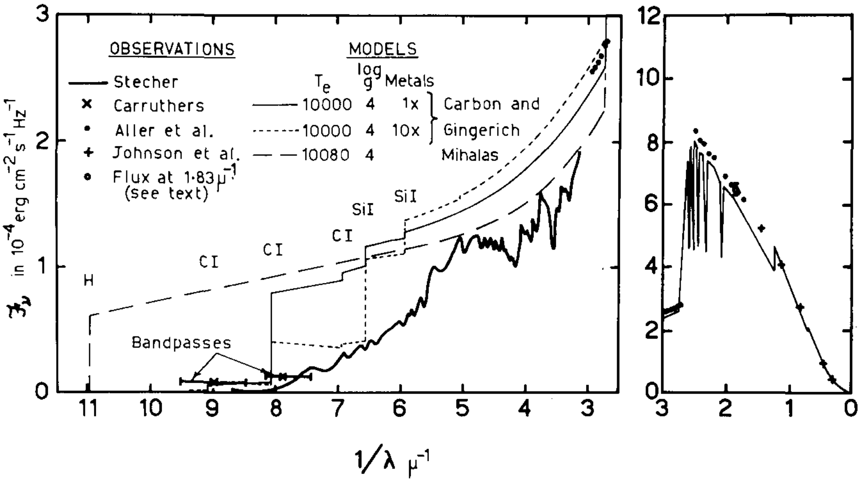

Fig. 1. Comparison of theoretical models with the observed flux distribution of α CMa (A1V) placed on an absolute scale through the measured angular diameter. The models include the bound-free absorptions shown, but no line blanketing except the hydrogen Balmer series (Davis and Webb, 1970b).

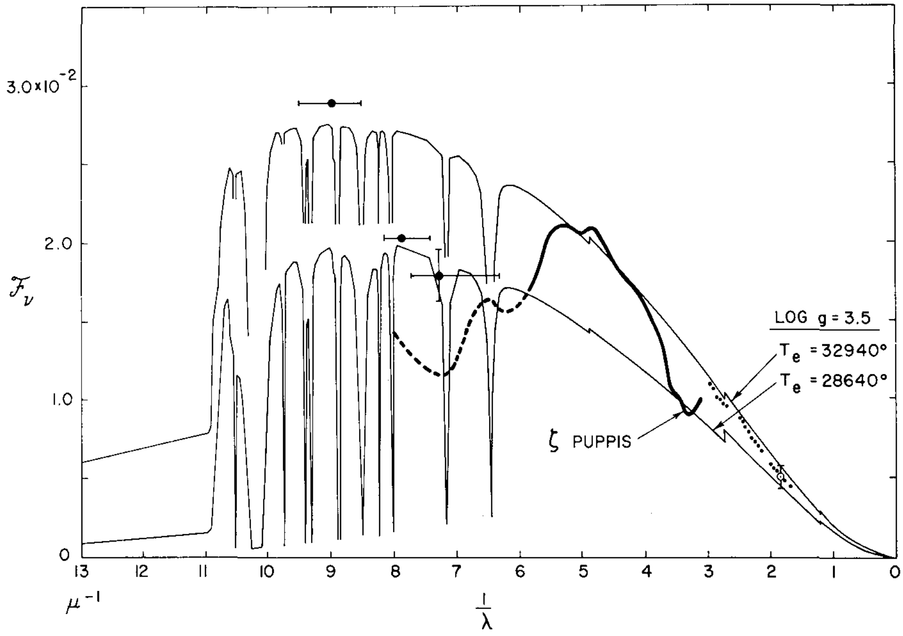

Fig. 2. Comparison of theoretical models with the observed flux distribution of ζ Pup (O5f) placed on an absolute scale through the measured angular diameter. Two blanketed models are represented by the light lines while the measurements are shown by the dots and the heavy line, with dashes where emission and absorption lines have been smoothed.

of the Lyman-α line would only round the edge at 1240 Å so that some other opacity sources may have been omitted such as the combined absorption by many lines, which is often described as line blanketing.

Models for main-sequence B stars which include the blanketing of strong ultraviolet lines between 912 and 1700 Å (Bradley and Morton, 1969; Van Citters and Morton, 1970) show reasonable agreement with the observed fluxes, with the models falling below the measurements by about 0.1 mag. at 1376 Å (Morton, 1969a) and by the same order at longer wavelengths (Bless *et al.*, 1968).

Observations of the O stars are not yet adequate for a thorough comparison with the models. However, Figure 2 from Davis *et al.* (1970) shows that the energy distribution of the 05f star ζ Pup has a peculiar dip between 1250 and 1800 Å. Opacity in addition to the C IV and Si IV resonance lines may be needed, but non-LTE effects are also possible since Auer has shown that they are most important among the O stars.

B. STELLAR LINE SPECTRA

The shapes and strengths of lines provide much more severe tests of the stellar models because these features are usually formed over wide ranges of depth in the atmosphere. The ultraviolet spectra of hot main-sequence stars, as described by Morton and Spitzer (1965), Carruthers (1968), Smith (1969), and Bohlin (1970), have absorption lines superposed on continuous emission, unlike the Sun which has emission lines shortward of 1800 Å. For stars without extended atmospheres it is hard to imagine any non-equilibrium process which would give line emission at wavelengths around the black-body maximum so that we expect a B star at 1000 Å to appear like the Sun at 6000 Å. The spectrum of α Vir (B1V) in Figure 3 shows the extreme crowding of the absorption lines at short wavelengths. Here we have the Lyman series of hydrogen and lines of the lower ionized states of all the abundant elements except oxygen and neon, which do not have strong transitions in this region. The figure represents a densitometer scan of a very narrow photographic image with considerable grain noise so that the labels in many cases indicate positions of expected lines rather than positive identifications. A careful analysis of multiplet patterns in higher resolution spectra will be necessary for the final identifications.

The changing pattern of line strengths with spectral type is shown in Figure 4 which was obtained from low-resolution scans with the Wisconsin Orbiting Astronomical Observatory. A preliminary comparison by Code and Bless (1970) for the strong C IV and Si IV resonance doublets calculated with the best models (Van Citters and Morton, 1970) show significant discrepancies in the total strength of both features and the effective temperature for maximum strength of Si IV. Such errors probably result from uncertainties in the collision damping constants and the failure of the LTE hypothesis in the cores of the lines.

The spectra of hot supergiants (Morton, 1967, 1969b; Carruthers, 1968) as well as the 05f star ζ Puppis and the Wolf-Rayet star γ^2 Velorum (Morton *et al.*, 1969; Stecher, 1970; Smith, 1970) also have the resonance lines of C IV, N V, Si III, and Si IV in absorption, but they are shifted to shorter wavelengths indicating mass ejection at

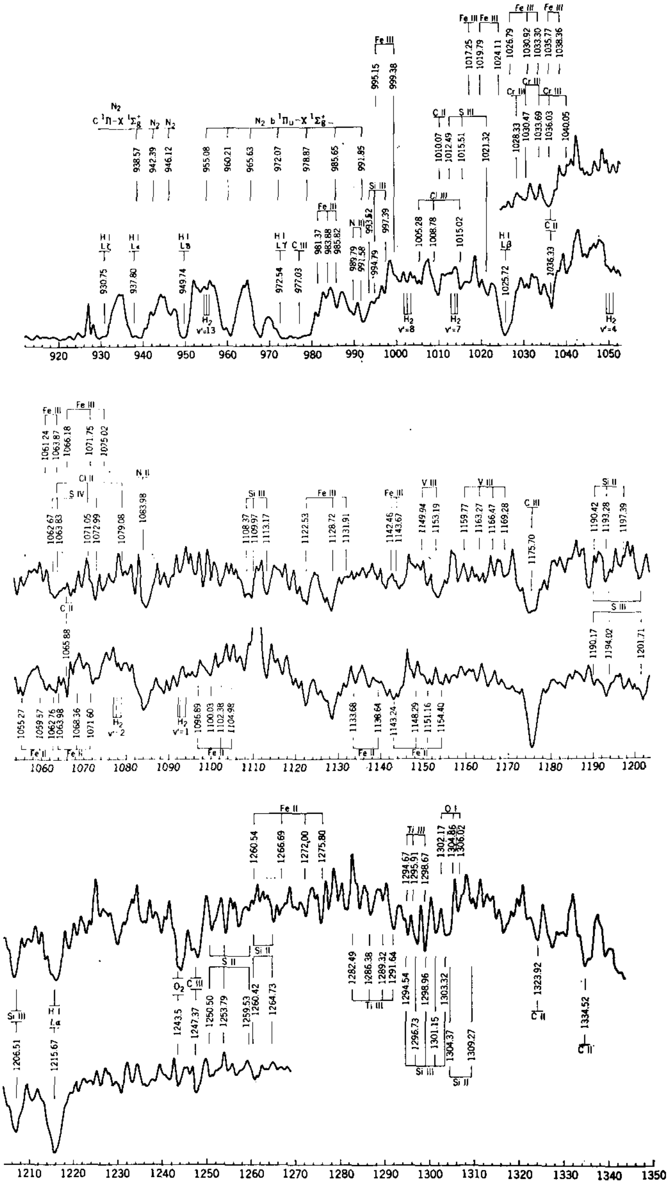

Fig. 3. Microdensitometer traces of spectra of α Vir (B1V) obtained by Smith (1969) between 920 and 1350 Å.

1000 to 2000 km sec^{-1}. Many of the lines also have emission components approximately centered on the rest wavelength. These spectra are very similar to those observed on the ground from some quasi-stellar sources. According to a theory proposed by Lucy and Solomon (1970) the matter is accelerated by photons absorbed from the

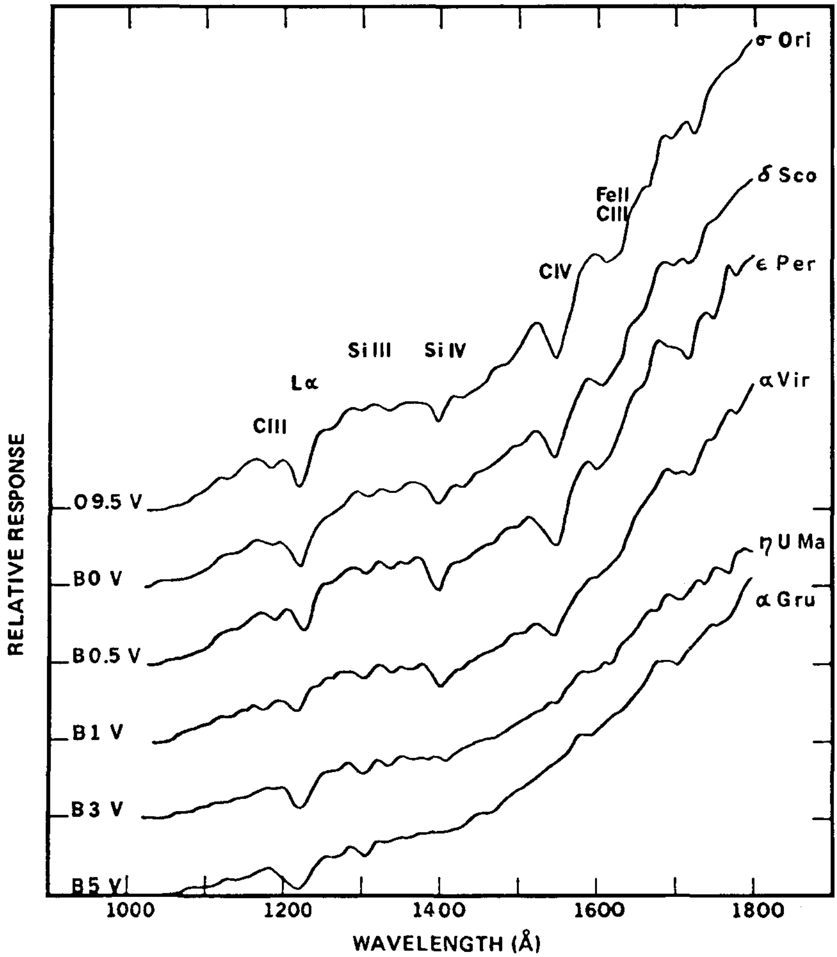

Fig. 4. Ultraviolet spectral scans of main-sequence hot stars obtained with the Wisconsin Orbiting Astronomical Observatory by Code and Bless (1970).

stellar radiation field by the strong resonance lines. The lines seem to be formed in a low density shell so that the broadening is entirely by Doppler motions. However, collisions may be important in transferring momentum from the accelerated carbon, nitrogen, and silicon ions to the much more abundant protons.

The spectrum of α Car (F0Ib–II) from 2400 to 4800 Å obtained by the Gemini astronauts (Kondo *et al.*, 1970) shows that we can expect lines of neutral and ionized magnesium, silicon, and iron in the cooler stars.

C. INTERSTELLAR ABSORPTION LINES

Ultraviolet absorption lines of interstellar atoms, ions, and molecules superposed on stellar spectra can give direct estimates of abundances over definite paths in the Galaxy. The hydrogen Lyman-α line is normally several angstroms wide, and dominates any stellar component for types B1 and hotter so that pure radiation damping can be assumed to cause the broadening. Around much of the galactic plane the hydrogen densities derived from the Lyman-α line seem to be about $\frac{1}{7}$ the average indicated by the 21 cm emission (Jenkins, 1970; Carruthers, 1970a), though Savage and Code (1970) suggest that the strength of the line has been underestimated by other investigators. The simplest interpretation of the discrepancy places the Sun in a typical low density region extending over several hundred parsecs with most of the radio emission originating at greater distances, but there is the alternative possibility that the usual Lorentz profile is not valid out to 10^5 natural widths. A conclusive statement on the applicability of the $1/\Delta\nu^2$ law for large $\Delta\nu$ would be very helpful.

Molecular hydrogen should be dissociated easily by photons which excite the Lyman electronic bands shortward of 1108 Å, leaving few such molecules in most of space. (Stecher and Williams, 1967; Hollenbach *et al.*, 1970). Thus it is not surprising that the Lyman absorption bands are missing in spectra of ζ Pup, γ^2 Vel, α Vir, and γ Cas as reported by Carruthers (1967), Smith (1969, 1970), and Bohlin (1970). However, Carruthers (1970) did find eight members of the series in the spectrum of ξ Per which is in a thick dust cloud where the molecules must be shielded from the destructive ultraviolet radiation.

A recent rocket spectrum of δ Sco and ζ Oph obtained by Morton and Jenkins definitely shows the interstellar resonance line of neutral oxygen at 1302 Å. This line, along with those of C II, Al II and Si II had been identified tentatively in δ and π Sco some years ago (Stone and Morton, 1967; Gaillard and Hesser, 1968).

Since the resonance lines of most of the abundant ions expected in the interstellar medium lie between 912 and 3000 Å, space observations with high spectral resolution are crucial for determining temperatures, electron densities, and abundance ratios (Spitzer and Zabriskie, 1959). The dilute radiation field and low collision frequencies due to low densities between the stars leave almost all particles in their ground states so that no absorption lines are expected from states above $\sim 10^{-3}$ eV which can be excited by the 2.7 K background radiation. We observe resonance lines of Na I, Ca I, Ca II, K I, Ti II and Fe I in visual spectra, but the ionization potentials of all these particles are less than the 13.6 eV carried by some photons in H I regions, so that the dominant ion states are one level higher. Thus the determination of element abundances requires large and uncertain corrections depending on temperatures, electron densities, and the interstellar radiation, all of which can vary widely with location. In contrast, far-ultraviolet lines will permit direct measurement of the most populated ion state of each element e.g. H I, C II, N I, O I, Mg II, Al II, Si II, P II, S II, Ti III, and Fe II to give abundances with only small ionization corrections. Ratios among ion states such as C I:C II:C III:C IV also can be obtained from the ultraviolet lines to give electron temperatures and densities, as well as possible effects of X-ray and cosmic-ray ionization.

D. GALACTIC NEBULAE

No ultraviolet emission lines have been detected so far from nebulae, but Osterbrock (1963) has listed the strongest transitions to be expected. We may anticipate considerable similarity with the red-shifted emission spectra of the quasi-stellar sources with their permitted lines of H I, He II, C IV, Mg II, and Si IV and forbidden lines of C II, C III, N IV, and O IV (Burbidge and Burbidge, 1967).

E. X RAY SOURCES

To date no definite features have been reported in the continuous spectra of the X-ray sources, but certainly some should have strong lines like the Sun. When high spectral resolution becomes possible, absorption edges due to interstellar carbon, nitrogen, and oxygen, also may be detected, as predicted by Bell and Kingston (1967). Such measures would provide alternative abundance determinations of many of the heavier elements, and the only possible way to estimate the proportion of neon, which has no suitable ultraviolet lines. In addition to discrete sources there is an X-ray background which may have important effects on the ionization and heating of the interstellar medium.

3. New Atomic Data Required

A. BOUND–BOUND ATOMIC TRANSITIONS

The data on wavelengths, energy levels, and multiplet classification are reasonably adequate for the important ions of light elements but continued work on the less abundant and heavy elements will be necessary before we can identify all the lines we expect to observe with the orbiting astronomical observatories.

Radiative transition probabilities are necessary for abundance analyses and the calculation of the blanketing effects of the stronger lines. Reliable measurements are now available for the resonance transitions of the more abundant atoms and ions so that the interpretation of the strongest interstellar lines is possible, but *f*-values are still needed for the majority of the weaker absorptions from the ground state and abundance analyses in stellar atmospheres will require data on lines originating from the higher levels as well. Laboratory measurements are usually preferred, but calculated *f*-values are always acceptable when the experimental data are not available.

Collision-excitation cross-sections are necessary in order to interpret the ultraviolet lines of nebular spectra in terms of the ion and electron densities and electron temperatures. Here we need cross-sections for the principal intercombination lines as well as the permitted transitions. Collisions are also important in the non-LTE calculations for stellar atmospheres. We still lack good data for the transitions between levels with $n \geqslant 2$ in hydrogen and helium and all the singlet-triplet transitions in neutral helium. Cross-sections are also needed for transitions between the lowest levels of the most abundant ions in hot stars, (e.g. C IV, N V, and Si IV) to estimate the level populations so that accurate line profiles can be calculated.

Collision damping constants are urgently required, especially for the stronger lines of higher ion states, in order to calculate the ultraviolet line blanketing in B-type atmospheres, to study non-LTE effects on line profiles, and to estimate element abundances from the resonance lines. In visual spectra of hot stars we determine abundances from relatively weak Doppler-broadened absorption lines arising from excited states, so that large corrections are necessary for the populations of lower levels. Alternatively in the ultraviolet we can use the strong resonance lines, and avoid the excitation corrections, if we know how the damping constants vary with temperature and pressure.

B. BOUND–FREE ATOMIC IONIZATION

Radiative ionization cross-sections, including their wavelength dependence, are necessary for calculating stellar continuous opacity and interstellar ionization. Peach (1970) has calculated cross-sections for the principal neutrals and ions to be expected in all but the hottest atmospheres on the assumption the energy levels are populated according to Boltzmann distributions for temperatures from 4000 to 48000K.

For the interstellar medium Hudson and Kieffer (1970) have compiled the available experimental results on the ionization of most neutrals from the ground state. Still needed are data on S I and ions such as N II, Al II, Si II, and S II. Measured cross-sections are always preferred, but they may be difficult to obtain for the ions so that theoretical values such as those of Henry and Williams (1968) are very worthwhile. Recombination coefficients to excited states are also needed if they are not hydrogenic. These atomic data, along with the interstellar radiation field as derived from space observations or theoretical stellar fluxes, then permit the calculation of the ionization equilibrium of each element in both H I and H II regions as functions of electron density and temperature. Comparison with observed ratios such as C I:C II or Mg I:Mg II for H I and N II:N III for H II regions will give n_e and T_e and show whether X-rays and cosmic rays are contributing to the ionization.

Transition probabilities for radiative excitation from the ground state up to any autoionizing levels must be included in the total ionization cross-section since such levels could dominate the ionization equilibrium of some atoms in interstellar space. At present experimental autoionization f-values are available for only Al I and Ca I. Similarly the rate coefficients for dielectronic recombination must be known for these atoms.

Collisional ionization cross-sections are important for non-LTE calculations in stellar atmospheres – especially values for the abundant heavy ions – one application being to estimate the populations of the lowest levels for profile calculations.

X-ray ionization also may be important in determining the total production of electrons in H I regions. The usual ionization processes are easy to calculate, but special effects need investigation, such as whether an inner electron expelled from C II, N I, O I etc. will result in further ionization from an outer shell.

C. MOLECULES

Many simple molecules besides H_2 should show ultraviolet absorption from interstellar space. Radio lines already have been detected from OH, CO, H_2O, and NH_3 while CH_2, CH_3, and C_2H_2 with electronic transitions between 1400 and 1500 Å are likely candidates for discovery in the ultraviolet. The available basic data on all these species are urgently needed for the interpretation of the spectra that soon should be detected with the third orbiting astronomical observatory.

Astronomers have always been totally dependent on the measurements from the spectroscopy laboratory and the calculations of atomic parameters for the interpretation of the visible light from stars and nebulae. If we do not now obtain similar data for the ultraviolet and X-ray wavelengths, we shall waste our investment in expensive space telescopes.

References

Bell, K. L. and Kingston, A. E.: 1967, *Monthly Notices Roy. Astron. Soc.* **136**, 241.
Bless, R. C., Code, A. C., and Houck, T. E.: 1968, *Astrophys. J.* **153**, 561.
Bohlin, R. C.: 1970, *Astrophys. J.* **162**, 571.
Bradley, P. T. and Morton, C. D.: 1969, *Astrophys. J.* **156**, 687.
Burbidge, G. and Burbidge, M.: 1967, *Quasi-Stellar Objects*. Freeman and Co., San Francisco.
Carruthers, G. R.: 1968, *Astrophys. J.* **151**, 269.
Carruthers, G. R.: 1969, *Astrophys. Space Sci.* **5**, 387.
Carruthers, G. R.: 1970a, *Space Sci. Rev.* **10**, 459.
Carruthers, G. R.: 1970b, *Astrophys. J.* **161**, L81.
Code, A. D. and Bless, R. C.: 1970, in *IAU Symposium* **36**, p. 173.
Davis, J. and Webb, R. J.: 1970a, *Astrophys. J.* **159**, 551.
Davis, J. and Webb, R. J.: 1970b, Astronomical Society of Australia, Conference on Stellar Atmospheres, May 1970.
Davis, J., Morton, D. C., Allen, L. R., and Hanbury-Brown, R.: 1970, *Monthly Notices Roy. Astron. Soc.* **150**, 45.
Gaillard, M. and Hesser, J. E.: 1968, *Astrophys. J.* **152**, 695.
Henry, R. J. W. and Williams, R. E.: 1968, *Publ. Astron. Soc. Pacific* **80**, 669.
Hollenbach, D. J., Werner, M. W., and Salpeter, E. E.: 1971 *Astrophys. J.* **163**, 165.
Houziaux, L. and Butler, H. E.: 1970, 'Ultraviolet Stellar Spectra and Related Ground-Based Observations', *IAU Symposium* **36**.
Hudson, R. D. and Kieffer, L. J.: 1970, preprint.
Jenkins, E. B.: 1970, in *IAU Symposium* **36**, p. 281.
Kondo, Y., Henize, K. G., and Kotila, C. L.: 1970, *Astrophys. J.* **159**, 927.
Lucy, L. B. and Solomon, P. M.: 1970, *Astrophys. J.* **159**, 879.
Morton, D. C.: 1967, *Astrophys. J.* **147**, 1017.
Morton, D. C.: 1969a, *Theory and Observation of Normal Stellar Atmospheres, Third Harvard-Smithsonian Conference* (ed. by O. Gingerich), MIT Press Cambridge, p. 253.
Morton, D. C.: 1969b, *Astrophys. Space Sci.* **3**, 117.
Morton, D. C. and Spitzer, L.: 1966, *Astrophys. J.* **144**, 1.
Morton, D. C., Jenkins, E. B., and Brooks, N. H.: 1969, *Astrophys. J.* **155**, 875.
Osterbrock, D. E.: 1963, *Planetary Space Sci.* **11**, 621.
Peach, G.: 1970, *Mem. Roy. Astron. Soc.* **73**, 1.
Savage, B. D. and Code, A. D.: 1970, in *IAU Symposium* **36**, p. 302.
Smith, A. M.: 1967, *Astrophys. J.* **147**, 158.
Smith, A. M.: 1969, *Astrophys. J.* **156**, 93.
Smith, A. M.: 1970, *Astrophys. J.* **160**, 595.
Spitzer, L. and Zabriskie, F. R.: 1959, *Publ. Astron. Soc. Pacific* **71**, 412.
Stecher, T. P.: 1969, *Astron. J.* **74**, 98.
Stecher, T. P.: 1970, *Astrophys. J.* **159**, 543.
Stecher, T. P. and Willams, D.: 1967, *Astrophys. J.* **149**, L29.

Stone, M. E. and Morton, D. C.: 1967, *Astrophys. J.* **149**, 29.
Underhill, A. B. and Morton, D. C.: 1967, *Nature* **158**, 1273.
Van Citters, G. W. and Morton, D. C.: 1970, *Astrophys. J.* **161**, 695.

DISCUSSION

A. Underhill: In the line forming regions of the atmospheres of O, B and A stars, the temperatures and densities appear to be such that LTE is not valid. This means that the number of atoms or ions in the ground level may vary by a factor ranging from 10^4 to 10^{-4} times that given by LTE. Detailed analyses will be required in each case to find the precise factor. This makes interpretation of the wings difficult and the uncertainty in the number of atoms in the ground level is probably a greater source of uncertainty than the present lack of knowledge about damping constants. Some years ago, I suggested that in the UV we would see *deep* into an atmosphere. This point of view was too naive and is mistaken. Consequently, it is essential to reject the hypothesis of LTE when calculating UV spectra, and in particular when studying resonance lines.

D. C. Morton: The wings of the lines are formed in the deeper levels not far above the region where the continuum originates, so that as we move away from the core in wavelength LTE theory should become a better approximation, at least for B and A stars.

R. N. Thomas: I think Morton's and Underhill's comments on LTE versus non-LTE need to be put into context. Morton referred always to the continuum, whereas Underhill's remarks concerned the lines. What we are interested in is the *whole* atmosphere, from optical depth $\tau = 1$ at the most transparent wavelength, to the boundary of the H II region surrounding the star. In the line core, that difficult region to resolve, we cover a range of 10^4 in optical depth, while across the visible continuum we cover a factor of 10 in optical depth and by including the UV continuum we cover another factor of $\lesssim 10$. So the lines cover an enormously greater range of atmosphere than does the continuum, and I must agree with Underhill that non-LTE effects and parameters are paramount. This is especially true when we want to interpret the velocity fields observed by Morton, and any mechanical heating that might be associated with them. It is just a matter of defining clearly the regions to which we are referring.

E. Trefftz: I would like to make the remark that radiation of wavelengths longer than those in the UV can cause ionization from low lying metastable levels, i.e. those levels which do not have optically allowed transitions to lower levels. The metastable levels may be highly populated according to the *colour* temperature of the radiation field.