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THE FAR-ULTRAVIOLET SPECTRAL INTENSITY OF A B3 V STAR

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ABSTRACT

A low-resolution, vacuum-ultraviolet spectrum of η Ursa Majoris has been obtained with a scanning prism spectrometer in a pointed Aerobee rocket. Line blanketing appears to be considerably weaker than has been suggested in recent blanketed models. The absolute intensity is more than $\frac{1}{2}$ mag below model predictions. An additional source of continuous opacity in the far ultraviolet may be needed to explain the discrepancy.

I. INTRODUCTION

The first far-ultraviolet wide-band observations of hot stars (Chubb and Byram 1963; Byram, Chubb, and Werner 1965) indicated substantial discrepancies between the intensities observed and the predictions of then current model atmospheres. Morton (1964) showed that part of the difference might be accounted for by the effects of the strong absorption lines expected in the far ultraviolet. Recent models of hot stars, taking line blanketing into account in some detail (Mihalas and Morton 1965; Adams and Morton 1968; Hickok and Morton 1968), in fact do give somewhat better agreement between observations and theory. Nevertheless, the present data and the recent measurements by Smith (1967) still give absolute intensities $\frac{1}{2}$ mag or more below those predicted by the models.

Comparison of models with wide-band measurements is difficult, because the effects of line blanketing are not directly observed, the effective wavelength of the detector depends on the spectral distribution of the source, and an absolute intensity calibration is necessary. Results obtained with a wavelength scanning system, such as those reported here, can provide information on the blanketing and, potentially, the effective temperature, without an absolute calibration.

II. INSTRUMENTATION

A low-resolution spectrum of the B3 V star η Ursa Majoris (HR 5191) in the 1175–1800 Å region was obtained with equipment designed primarily to acquire planetary spectra from an Aerobee rocket. The optical portion of the instrument was a 35-cm diameter Dall-Kirkham telescope of 2.17-m effective focal length, with a figured 10° lithium fluoride prism mounted 6.5 cm from the focus. Reciprocal dispersion in the focal plane was 175 Å mm^{-1} at 1300 Å. A gear wheel with pinholes (six each of 0.32-, 0.8-, and 1.2-mm diameter) spaced around its edge scanned the dispersed image of the star; a diaphragm limited the scan to the region between 1175 and 1800 Å. The detector was an EMR 541G photomultiplier with photon-counting electronics. The rocket was pointed by a NASA STRAP III attitude-control system, and for finer pointing the secondary

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mirror was servo-controlled by a star-tracker integral to the telescope. The instrument package is described in greater detail elsewhere (Bottema, Fastie, and Moos 1968).

Calibration of the instrument was performed in stages, as vacuum-spectroscopic facilities capable of accepting the assembled payload were not available. A wavelength scale was determined by dead reckoning, using the index of refraction of lithium fluoride tabulated by Hennes and Dunkelman (1966). Uncertainties in target or slit positioning and in the wavelength scale can best be expressed in terms of the equivalent LiF-index difference; thus the probable alignment tolerance, equivalent to an index uncertainty of 0.02, corresponds to a wavelength error of 200 Å at 1700 Å but only of 20 Å at 1200 Å. The reflectivity of the mirrors was measured at 1216 and 1657 Å; at other wavelengths measurements of a glass slide with a similar Al-MgF_2 coating were used. Over most of

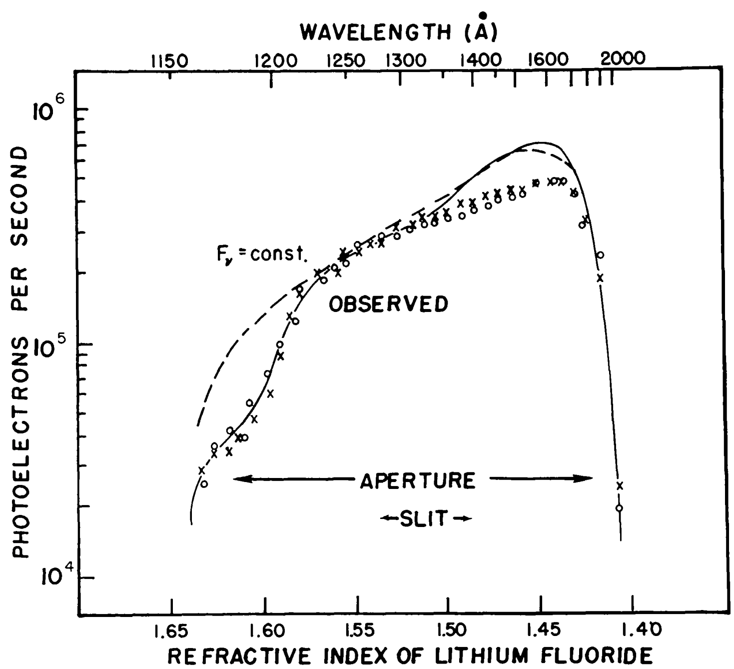

FIG. 1.—Raw stellar-spectrum data plotted against units of constant resolution. Molecular-oxygen absorption near 1400 Å is evident in the spectrum obtained at 127 km (*circles*); consequently, only the 138-km data (*crosses*) were used in this region. Solid line represents a smoothed average of spectra, corrected for dead time in photon-counting circuitry. Also shown is the expected instrument response for a signal of constant energy flux per unit energy band width (F_γ = const.), which is predicted by unblanketed models for stars of this type.

the range, the prism transmission was found to be only a few per cent lower than that dictated by reflection losses. The relative sensitivity of the photomultiplier was determined by comparing its output with the visible fluorescence of a freshly deposited sodium salicylate film (Samson 1967). Errors relative to an absolute calibration at 1216 Å are believed to be no greater than 30 per cent at 1175 or 1700 Å.

The absolute sensitivity of the detector at 1216 Å was determined by comparing it with an aged pair of sealed NO ionization cells. The photomultiplier was recovered after flight and recalibrated; its output relative to the cells was unchanged. All cross-calibrations, performed over a period of six months, were reproducible to 10 per cent or better. The sensitivities of the NO cells were determined by comparing them with continuous-flow ionization chambers at the Laboratory for Atmospheric and Space Physics at Boulder, Colorado, two years before the flight, and at the Naval Research Laboratory seven months after the flight. During this period the sensitivities of the cells declined by almost a factor of 2, evidently because of window contamination; after the window on one cell was repolished, the original Boulder sensitivity was obtained. For the flight calibration, values 20 per cent higher than the NRL measurements were assumed in order to allow for window deterioration. We estimate that the over-all absolute calibration of the instrument could be in error by as much as a factor of 1.75.

III. RESULTS

The rocket was launched from White Sands Missile Range, New Mexico, at 04:30 M.S.T. (11:30 U.T.) on December 5, 1967. Performance of the pointing systems was such that the position of the stellar image varied less than 0.05 mm (equivalent to an uncertainty in the LiF index of 0.005). Telemetry data from the first two small-hole, stellar-spectrum scans are given in Figure 1. The solid line is a smoothed average of the scans, corrected for dead time in the electronics. By comparing data from the medium holes

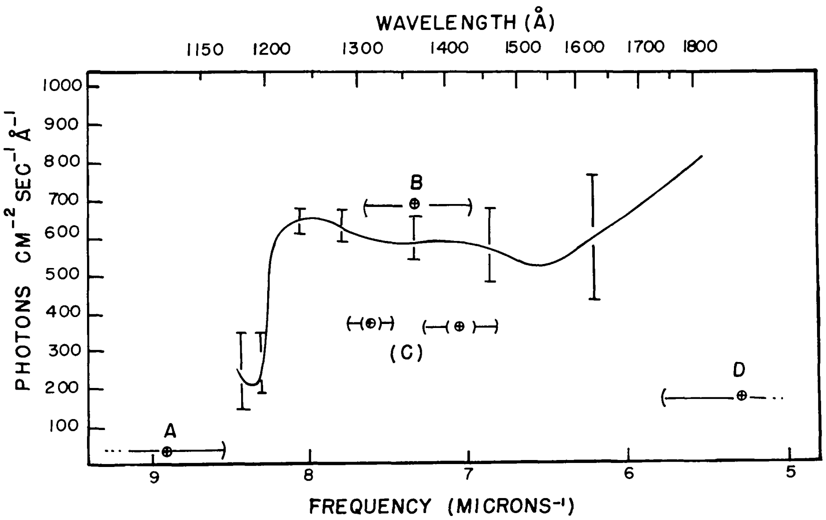

FIG. 2.—Data converted to photon flux for comparison with wide-band photometer measurements made by (*A*) Byram *et al.* (1965); (*B*) Smith (1967); (*C*) Chubb and Byram (1963); and (*D*) Alexander *et al.* (1963). Approximate photometer band passes are shown. Error bars in the photon flux are relative to an absolute calibration at 1216 Å and are spaced to reflect the varying resolution; absolute calibration could be in error up to a factor of 1.75. Structure at longer wavelengths is not statistically significant; although there is some indication of a rise in intensity above 1700 Å, there is large uncertainty in the response of the instrument in that region. The sharp drop below 1200 Å is probably real.

with data from the small holes, it was possible to verify that the entire spectrum had been captured by the small holes and that the dead-time adjustment was correct. Absorption by the Schumann-Runge continuum of molecular oxygen (observed on later stellar spectra as the rocket descended into the atmosphere), in conjunction with the spectra of Jupiter and Venus obtained earlier in the flight (Moos, Fastie, and Bottema 1968), confirmed that the image was well focused and provided a check on the wavelength scale. Over-all error in the wavelength determination is probably about 20 Å at 1200 Å.

The absolute spectral intensity deduced from the counting rate is shown in Figure 2. Error bars were drawn under the assumption that the 1216 Å calibration was correct and reflect the compounding of uncertainties in the wavelength scale, errors in the relative sensitivity calibration, jitter in the pointing systems, and shot noise. An error in the absolute calibration could shift the entire curve by as much as a factor of 1.75. Several wide-band photometer measurements are also plotted. Fluxes measured by Smith (1967) at 1376 Å and by Byram *et al.* (1965) at 1115 Å are presented without modification. A band width of 400 Å at an effective wavelength of 1900 Å was assumed for the photometer flown by Alexander, Bowen, and Heddle (1963). This star was not observed by the 1427 Å photometer of Chubb and Byram (1963), and their 1315 Å photometer went off-scale; values estimated from their measurements of other B3 V stars are plotted.

IV. DISCUSSION

Several blanketed models of main-sequence B stars by Mihalas and Morton and their collaborators were folded through the instrumental sensitivity and resolution and were normalized to the observed spectrum at 1500 Å (Fig. 3). Only a few of the predicted lines have sufficient equivalent width to affect appreciably the simulated spectra. In the B0 model the C III line at 1176 Å causes a sharp drop at the extreme short-wavelength end of the spectrum, while dips from Si IV near 1400 Å and from C IV near 1550 Å are barely noticeable. The feature near 1330 Å in the B1.5 and B4 models is caused by C II while the combination of Lyman-α and several C II, Si III, and S III lines near 1200 Å forms a wide dip in the region between 1175 and 1220 Å.

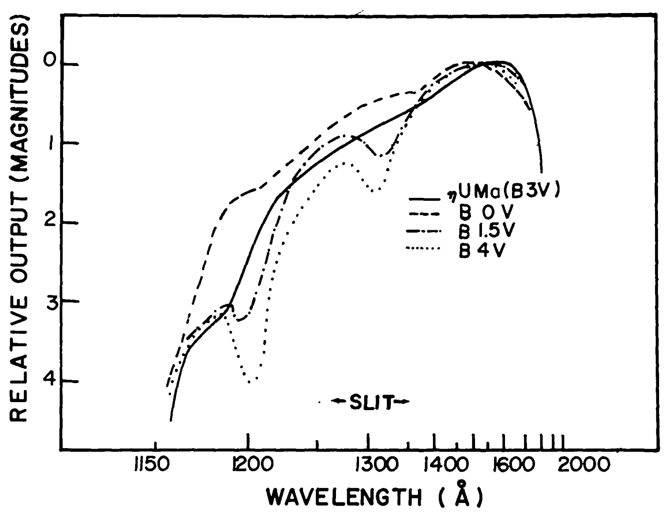

FIG. 3.—Comparison of the observed spectrum with spectra predicted by several blanketed models: B0 V, Hickok and Morton (1968); B1.5 V, Mihalas and Morton (1965); and B4 V, Adams and Morton (1968). Model spectra have been folded through the instrument response and normalized to the observed spectrum at 1500 Å.

The amount of line blanketing depends on the damping constants for the lines, which are unknown. Constants 10 times the classical value were assumed in the model spectra, so it is not surprising that some of the lines in the observed spectrum are not as strong as predicted. In particular, carbon lines appear to be very weak. The only prominent absorption feature in the observed spectrum is the abrupt drop at wavelengths shorter than 1200 Å. We cannot exclude the possibility that the drop is due to an incorrect assumption concerning mirror reflectivity. However, the drop may well be a manifestation of the general flux deficiency below Lyman-α reported by Carruthers (1968) for some giant stars in the Orion region. He suggested interstellar absorption as a possible cause of the deficiency; this does not seem likely for η UMa, which is nearby (70 pc) and at high galactic latitude. Absorption in an extended atmosphere is also unlikely, as the star is main sequence and has a rotation velocity $V \sin i$ of 230 km sec^{-1} (Slettebak 1949), which is not exceptionally large for a star of its type.

In the 1270–1700 Å region the observed spectrum approximates a continuous distribution with constant F_ν (Fig. 1).[1] This is in agreement with Underhill's (1963) unblanketed

[1] Smith (1967) has determined an extinction of less than 0.2 mag for this star at 1376 Å. The extinction curve of Bless (unpublished) then gives a negligible relative extinction of less than 0.02 mag between 1270 and 1700 Å.

model for a B3 V star; however, only small departures from flatness are expected for somewhat hotter and cooler types—ratios of relative fluxes between 1270 and 1500 Å differ less than 20 per cent between her B2 and B6 models. The difference at these wavelengths for blanketed B1.5 and B4 models (Fig. 3) is slightly greater because of line blanketing. Although the B3 star does fall between the B1.5 and B4 models at 1270 Å, as expected, this cannot be regarded as significant, because the difference between models is comparable with the calibration error over this wavelength range.

Except as a measure of line blanketing, relative-intensity measurements in this spectral region therefore do not provide a sensitive test of the models; consequently, it is necessary to compare the observed and predicted absolute intensities. At 1400 Å, for example, Underhill's unblanketed B3 V model predicts a flux of 1250 photons cm^{-2} sec^{-1} $Å^{-1}$, whereas the absolute-intensity measurements summarized in Figure 2 suggest a probable flux of half this value. While it is not out of the question that a combination of interstellar extinction, some blanketing by strong lines, further blanketing by weak lines, and errors in the calibrations could account for the discrepancy, we regard it as unlikely. In this connection we note that the blanketed B4 model of Adams and Morton (1968) gives good agreement with Smith's (1967) measurement because of a very strong C II line predicted in Smith's band pass; this line is not evident in our spectrum.

V. CONCLUSION

All available absolute-intensity measurements of η UMa in the vacuum ultraviolet fall considerably below the predictions of unblanketed stellar models. The low-resolution spectrum presented here suggests that line blanketing is not strong enough to account for the discrepancy. It appears that some additional source of continuous opacity may be needed to account for the low far-ultraviolet intensity of hot stars.

The success of this experiment owes much to the group at the Sounding Rocket Branch of Goddard Space Flight Center who prepared the rocket, telemetry, and attitude-control systems. We would like to thank Dr. George Carruthers for a useful comment, Dr. Carruthers and Mr. Gilbert Fritz for their help with post-flight calibrations, and Miss Andrea Dewey for her help with the data reduction.

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REFERENCES

Adams, T. F., and Morton, D. C. 1968, *Ap. J.*, **152**, 195.
Alexander, J. D. H., Bowen, P. J., and Heddle, D. W. O. 1963, *Space Research, III*, ed. W. Priester (Amsterdam: North-Holland Publishing Co.), p. 1068.
Bottema, M., Fastie, W. G., and Moos, H. W. 1968, report to the Spring Meeting of the Optical Society of America, Washington, D.C. (to be published).
Byram, E. T., Chubb, T. A., and Werner, M. W. 1965, *Ann. d'ap.*, **28**, 594.
Carruthers, G. R. 1968, *Ap. J.*, **151**, 269.
Chubb, T. A., and Byram, E. T. 1963, *Ap. J.*, **138**, 617.
Hennes, J., and Dunkelman, L. 1966, *The Middle Ultraviolet: Its Science and Technology*, ed. A. E. S. Green (New York: John Wiley & Sons, Inc.), p. 356.
Hickok, F. R., and Morton, D. C. 1968, *Ap. J.*, **152**, 203.
Mihalas, D. M., and Morton, D. C. 1965, *Ap. J.*, **142**, 253.
Moos, H. W., Fastie, W. G., and Bottema, M. 1968 (to be published).
Morton, D. C. 1964, *Ap. J.*, **139**, 1383.
Samson, J. A. R. 1967, *Techniques of Vacuum Ultraviolet Spectroscopy* (New York: John Wiley & Sons, Inc.), p. 212.
Slettebak, A. 1949, *Ap. J.*, **110**, 498.
Smith, A. M. 1967, *Ap. J.*, **147**, 158.
Underhill, A. B. 1963, *Space Research, III*, ed. W. Priester (Amsterdam: North-Holland Publishing Co.), p. 1080.