A SENSITIVE OBSERVATION OF THE FAR-ULTRAVIOLET (1160–1700 Å) SPECTRUM OF ARCTURUS AND IMPLICATIONS FOR ITS OUTER ATMOSPHERE

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ABSTRACT

A low-resolution far-ultraviolet (1160–1700 Å) spectrum of Arcturus (α Boo, K2 IIIp) has been obtained by using a new very sensitive rocket-borne spectrograph with a multielement microchannel plate detector. H I λ1216, O I λ1304, and a broad unresolved emission near 1510 Å were detected. A 2 σ feature is probably O I λ1356. The ratio of O I λ1304 to O I λ1356 is similar to the solar ratio. This spectrum is very different from that of the Sun, with few emission features. The absence of certain emission lines in the spectrum of Arcturus implies either coronal temperatures outside the 20,000 to 350,000 K range (except for possibly 180,000 ± 20,000 K) or a lower coronal base pressure than previously assumed. A model of the chromosphere-corona transition region predicts fluxes too low to be detected at present. The observation was coordinated with a simultaneous determination of the Arcturus Lα flux by the U2 detector on the Princeton Experimental Package aboard OAO-Copernicus. The two measurements agree within 10% of each other.

Subject headings: stars: chromospheres — stars: coronae — stars: individual — stars: late-type — ultraviolet: spectra

I. INTRODUCTION

Arcturus (α Boo) is the brightest K giant in the sky and a prototype for Population II K giants. It has been extensively studied in the visible (Griffin 1968) and near-infrared portions of the spectrum (e.g., Geballe, Wollman, and Rank 1972; Montgomery et al. 1969), and theoretical models now exist for its photosphere (Carbon and Gingerich 1969; Johnson, Collins, and Krupp 1977) and chromosphere (Ayres and Linsky 1975). Computed radiative equilibrium photospheric models of Arcturus predict extremely weak continuum emission in the spectral range 1160–1700 Å due to the cool temperatures in the upper photosphere. Observations of emission lines or continua are therefore indicative of nonradiative heating in and above the photosphere of Arcturus.

Previous rocket observations of Arcturus have detected H I λ1216 and O I λ1304 emissions (Moos and Rottman 1972; McKinney, Moos, and Giles 1976) as well as an unidentified feature near 1510 Å. The present rocket observations were made with a new high-transmission spectrograph with a multispectral element microchannel plate-detection system (Weiser et al. 1976). This system is much more sensitive than those used by this laboratory in three previous rocket observations of Arcturus. The results confirm the previous observations of Lα and the O I λ1304 triplet, and also show, with the low spectral resolution of the instrument, a broad feature centered around 1510 Å. One other feature, probably O I λ1356, was observed. In addition, it was possible to determine very low line flux upper limits. These low limits have been used to determine upper limits to the coronal base pressure that indicate that this pressure is lower than the value Ayres and Linsky (1975) obtained by assuming it to be equal to the pressure at the top of the chromosphere.

In this paper we present details of the instrument (§ II); a discussion of the data reduction, detected emissions, and upper limits to emissions observed on the Sun but absent on Arcturus (§ III); analyses and predictions of coronal emissions, and chromosphere-corona transition-region emissions, are discussed in § IV, along with the relation of our observations of presumed chromospheric lines with previous observations.

II. EXPERIMENTAL DETAILS

The experimental package was launched aboard a NASA Aerobee rocket (26.039) from White Sands Missile Range, New Mexico. Arcturus was observed for 33.3 s at 7h06m UT on 1975 March 15 on the flight downleg above 148 km. The instrumental package included a 35.5 cm Cassegrain telescope with 1° pointing (Giles et al. 1975) which fed a two-channel Czerny-Turner LiF prism spectrograph. The spectrograph and detector were specially constructed for this flight; they are described in detail by Weiser et al. (1976) and will be described only briefly here. One channel of the spectrograph, the target channel,
received the stellar image, which is a few arcsec wide, positioned at the center of a 26” diameter entrance slit. The other channel monitored the terrestrial airglow from an area of the sky which was 1’ in diameter and situated 400” from the target. The detector system consists of two microchannel plates, one behind the other in a chevron configuration, with a solar blind CsI photocathode deposited onto the face of the input plate. The wavelength of the incoming far-ultraviolet photons was detected by an individual resistive strip anode for each channel placed behind the microchannel plates (Lawrence and Stone 1975); this permitted simultaneous determinations to be made of photons from all wavelengths rather than from a single spectral element at a time (as had been the case on previous observations). This and the high quantum efficiency of the windowless cathode produced a substantial increase in the effective sensitivity. The spectrograph was evacuated to a pressure of less than $2 \times 10^{-6}$ torr by an ion pump until observing altitude was reached, at which time a sealed door was opened to admit the ultraviolet light. During descent, the door was resealed, maintaining the vacuum.

The telescope–spectrograph system was calibrated at the Johns Hopkins University against NBS standard diodes (Canfield, Johnston, and Madden 1973), by using the techniques and facilities described by Fastie and Kerr (1975). A more detailed discussion of the calibration and flight performance of the experimental package may be found in Weiser et al. (1976). Recovery of the instrument in excellent condition permitted postflight calibration checks. The dark count level measured in the laboratory was 1 count per second for each entire spectrum. In flight, the dark count was less than 2.5 counts per second per spectrum of 300 bins (a bin corresponds roughly to 75 µm along the resistive strip anode) measured with the door closed. Scattered light and cross-talk between the two channels were negligible. Laboratory tests show that the detector preserved Poisson statistics, so the standard deviation of $N$ total counts is simply $\sqrt{N}$. The spectral resolution of the instrument, when pointed at a star in flight, varied across the wavelength range with a full width at half-maximum (FWHM) of $7\,\AA$ at 1200 Å, $12\,\AA$ at 1400 Å, and $25\,\AA$ at 1600 Å. The instrument effective area, defined as the product of the optically active area of the telescope primary (646 cm$^2$), the telescope transmission, the spectrograph transmission, and the detector quantum efficiency, varied from approximately 26 cm$^2$ at 1216 Å, to 35 cm$^2$ at 1300 Å, and to 12 cm$^2$ at 1600 Å. Uncertainties in the absolute calibration (1 σ) are approximately 20%, at 1216 Å, 22% at 1300 Å, and 25%, at 1600 Å.

High-resolution line intensity profiles of H I λ1216 on Arcturus (Moos et al. 1974) indicate that terrestrial absorption of this emission is not significant. Such profiles do not exist for O I λ1304, and the terrestrial absorption of the O I triplet had to be considered. The present observation occurred over a relatively small altitude range (180 to 148 km). The O I λ1304 signal was subdivided into 16 groups of 2 s observing time each. Since the signal did not significantly change over the total observing time, terrestrial absorption of O I λ1304 was judged to be insignificant.

The calculated absorption by molecular oxygen (Watanabe 1958) is negligible. However, water-vapor outgassing can affect rocket observations (Fastie, Crosswhite, and Heath 1964). Terrestrial Lyα measurements of the early portion of this flight made with the airglow monitor show a slight H$_2$O absorption with an exponential decrease with a time constant of approximately 30 s. Thus absorption due to water-vapor outgassing was negligible at the time of the Arcturus observation, which occurred approximately 200 s after the spectrograph door opened (Weinstein 1976).

III. DATA REDUCTION AND RESULTS

a) Data Reduction

The reduction of the data from the flight tapes is discussed in detail by Weinstein (1976). Figure 1a shows the Arcturus spectrum accumulated during the 33.3 s observation. The data were distributed over 300 bins, corresponding to approximately equal (75 µm) lengths across the resistive strip of the detector. In the spectrum of Figure 1a, a sliding sum was made over seven adjacent bins so that only every seventh bin contains completely independent data. The FWHM for in-flight raw stellar lines is also about seven bins. The sliding sum process has slightly degraded the resolution to a FWHM of 10 Å at 1200 Å and 40 Å at 1600 Å. The spectrum of Figure 1a contains contributions from terrestrial airglow as well as from α Boo, but airglow is negligible across the target spectrum (less than 0.03 counts per second per bin as measured from target transition spectra and confirmed by the airglow channel spectra). The exception is Lyα, where it contributes about 25% of the total signal.

b) Spectral Features

Three readily apparent features of the Arcturus spectrum are the H I λ1216 Lyα emission lines, the O I λ1304 $^5$S$^o$–$^3$P triplet, and a broad feature centered at 1510 Å.

Centered around λ1356 (marked by the arrow in Fig. 1a) is another feature which is statistically significant ($>2\,\sigma$) with respect to the background. To determine whether this feature was real, the spectrum of Arcturus was divided into 16 spectra of 2 s observation time each. Fifteen of the 16 subspectra were recombined, eliminating a different subspectrum in each of the resulting 16 groups. In each group, after a sliding sum over seven bins was applied, the feature was observed with the same statistical significance ($>2\,\sigma$) with respect to background. This implied that the feature was not due to a spurious event.

Burton and Ridgeley (1970) list two possibilities in the solar spectrum around 1356 Å with intensities significantly higher than the adjacent background, O I λ1358.51 and a feature at λ1355.55 attributed to a blend of O I λ1355.60 and C I λ1355.84. We identify...
Fig. 1.—(a) The Arcturus spectrum accumulated during the 33.3 s observation. Terrestrial airglow is included, but it is negligible except at La, where it contributes 25%. The statistical uncertainties of the total counts in a line are \( \sigma = \pm \sqrt{N} \); the small fluctuations in this plot, particularly at longer wavelengths, are due primarily to differences in adjacent bin widths. The dotted line represents the locus of emission-line peaks whose line intensity is 0.5 photons cm\(^{-2}\) s\(^{-1}\). The arrow indicates the nominal O I 1356 \AA{} line center. (b) A synthetic spectrum of the solar emission lines based on a rocket observation (Rottman 1975). The La emission has been reduced by a factor of 5. For both spectra, a sliding sum has been made over seven adjacent bins so that only every seventh bin contains completely independent data; the instrumental full width at half-maximum is also about seven bins.
the observed $\lambda 1356$ feature with the $\mathrm{O\:I\:}\lambda 1356, 1358$ doublet and not the $\mathrm{C\:I\:}\lambda 1356$ line for the following reasons: (1) In the Burton and Ridgeley solar spectrum there are several weak emissions due to $\mathrm{C\:I\:}$ between 1350 and 1360 Å in addition to the $\mathrm{C\:I\:}\lambda 1355.84$ line; all these lines are expected to have roughly the same low intensity (Moore 1950). Therefore, in the Sun, the $\mathrm{O\:I\:}\lambda 1355.6$ line must be the dominant component of the blend, since the intensity of the blend is much higher than the intensities of the other solar $\mathrm{C\:I\:}$ lines in this region. (2) The observed surface fluxes in the $\mathrm{O\:I\:}\lambda 1304$ and the $\lambda 1356$ features are about 0.6 that of the Sun, whereas upper limits for the surface fluxes of $\mathrm{C\:I\:}-\mathrm{C\:IV}$ lines are very much smaller (see Table 1). For example, the surface flux ratio of $\mathrm{O\:I\:}\lambda 1304$ to $\mathrm{C\:II\:}\lambda 1335.3$ is greater than 24, whereas in the Sun these features are of comparable intensity. A 1460 to 1560 Å feature is approximately 50% larger than that of the $\mathrm{Si\:I\:}$ line near 1510 Å, the $\mathrm{Si\:I\:}$ doublet at 1531 Å, the $\mathrm{C\:IV\:}$ doublet at 1549 Å, and other solar $\mathrm{C\:I\:}$ lines in this region. (3) The observed fluxes in the $\mathrm{O\:I\:}\lambda 1356.84$ line; all these lines are expected to have roughly the same low intensity.

In our case, as well, identification is difficult. The low resolution of our instrument does not permit the separation of lines which may be contributing to this detection; nevertheless, several conjectures are possible. They include a blend of $\mathrm{Si\:I\:}$ lines around 1455 Å, the $\mathrm{CO}$ fourth positive system near 1510 Å, the $\mathrm{Si\:II\:}$ doublet at 1531 Å, the $\mathrm{C\:IV\:}$ doublet at 1549 Å, and $\mathrm{C\:II\:}$ at 1561 Å. No one feature can explain the observation (Weinstein 1976). Selective population of the vibrational levels of the excited electronic state by special processes such as dissociative recombination of $\mathrm{CO}_2^+$ could produce an unusual intensity distribution (Rottman and Moos 1973; Gutcheck and Zipf 1973).

Another possibility is the effect of the silicon continuum. Vernazza, Avrett, and Loeser (1976) have calculated a solar model which shows the neutral silicon edge at 1525 Å in emission. When the Vernazza et al. results for their model M from 1300 to 1530 Å are processed through a computer simulation of the spectrograph and the resulting spectrum is normalized to the Arcturus data at 1510 Å, the broad shape of the low-wavelength portion of the feature from approximately 1450 Å to approximately 1520 Å is reproduced, but the shape falls short of matching the long-wavelength (>1520 Å) part. There is no a priori reason to suspect a simple constant of proportionality between the Sun and Arcturus, and detailed calculations are needed to ascertain whether the $\mathrm{Si\:I\:}$ bound-free continuum is a significant contributor to the observed flux.

It is clear that further observations with higher resolution and greater sensitivity are needed, together with detailed theoretical models for the identification of the feature(s).

The rise in the spectrum near 1650 Å could be interpreted as due to $\mathrm{He\:II\:}\lambda 1640$, $\mathrm{C\:I\:}\lambda 1657$, and/or $\mathrm{Al\:II\:}\lambda 1671$, which are prominent lines in the Sun. However, this is probably not so. Tests have shown that similar long-wavelength artifacts were caused by a shield above the microchannel plate (Weiser et al. 1976; Weinstein 1976). As a result, these data could be used only to obtain an upper limit for the flux and for the blackbody temperature.

Several synthetic spectra (see § IIIc) were generated by using the Planck blackbody radiation function. This served two purposes: it corroborated the negligible blackbody continuum radiation in our wavelength region, and it determined an upper limit (2σ) to a blackbody temperature of 4000 K in the wavelength region from 1600 to 1650 Å. McKinney, Moos, and Giles (1976) have obtained a blackbody temperature upper limit at 1900 Å of 4000 K.

c) Spectral Fluxes

Table 1 lists both the measured Arcturus fluxes and the upper limits obtained for emissions which are not statistically significant. The criterion used in determining whether a feature is statistically significant was that it must rise at least 2σ above adjacent background. Upper limits were obtained by attempting to fit the data with known parameters by using a computer simulation of the instrument (Weinstein 1976). This computer simulation utilized the experimentally determined sensitivities, wavelength position, and spectral resolution to synthesize candidate spectra which were then compared with the actual experimental data.

The values of the upper limits are very sensitive to the estimated value of the adjacent background; an uncertainty of a factor of 2 for these values, attributed solely to background determination, dominates any calibration or statistical uncertainties. Owing to the broad $\mathrm{L\:II\:}$ wings, the background was more difficult to determine for $\mathrm{Si\:III\:}\lambda 1206$ and $\mathrm{N\:V\:}\lambda 1240$ and, as a result, the upper-limit values were increased for these lines.

The line surface fluxes for Arcturus are given in Table 1 assuming a radius of 26 $R_\odot$ (Gezari, Labeyrie, and Stachnik 1972) and a distance of 11.1 pc (Hoffleit 1964). Also given are ratios of the surface flux at Arcturus to the surface flux at the Sun, calculated from the solar observations of Rottman (1975). Note that the upper limits in Table 1 are about a factor of...
2 smaller than the McKinney, Moos, and Giles (1976) rocket observations, the C iv A1549 upper limit a factor of 60 smaller than the Jamar, Macau-Hercot, and Praderie (1977) TD1 satellite upper limit, and the factor of 60 smaller than the McKinney, Moos, and Giles (1976) where in the spectrum, the comparison with the Si in A1206 upper limit comparable with the Mc-
trum processed through a computer simulation of the lines from the Rottman (1975) 1.2 Å resolution spec-
Clintock et al. (1975) Copernicus upper limit. Else-

The intensities of the corre-
sensitivity decreases rapidly longward of La. The magnitude more favorable, because the Copernicus

where in the spectrum, the comparison with the Coper-

for interstellar absorption.

appear anomalously large compared with other lines in this region of the spectrum.

4. The ratio for Si iii A1206 is high with respect to other Si lines, due to the bright La wing at this wavelength.

5. The S i upper-limit ratio is high; thus this feature is not likely to be a significant contributor in the 1460–1500 Å wavelength region.

IV. OUTER ATMOSPHERE EMISSION-LINE ANALYSES

Observations of both quiet and active regions of the Sun indicate a chromosphere within which the temperature rises slowly, then a narrow transition region with a steep temperature gradient, and then a corona with very high temperatures compared with the chromosphere (Goldberg 1974). The fundamental difference among these regions results from the different terms which enter the local energy balance. Crude models, using very simplified assumptions and guidelines provided by what has been learned from solar observations, have been developed to make predictions of emitted flux from lines which originate in stellar transition regions and coronae (Gerola et al. 1974; McClintock et al. 1975; Haisch and Linsky 1976).

These models are guides only; the neglect of magnetic fields and spatial inhomogeneities may make the assumptions used in the models questionable. In addition, there may be fundamental differences in the physics of the outer atmospheres of the Sun and Arcturus. For example, the thickness of the transition region may be comparable with or greater than a pressure scale height, in which case the coronal base...
pressure $P_{\text{cor}} < P_{\text{chv}}$, the pressure at the top of the chromosphere. In this section we compare the data with the predictions of simplified models to see whether such models lead to realistic results or whether the physical basis for these models must be altered.

a) Coronal Emission Lines

In this section predictions of coronal emission-line fluxes are compared with the data; the result is that certain coronal temperature ranges are excluded or the coronal base pressure is lower than the value estimated by Ayres and Linsky (1975) on the basis of $P_{\text{cor}} = P_{\text{chv}}$.

Coronal fluxes can be predicted by assuming a plane-parallel, isothermal corona in hydrostatic equilibrium and optically thin lines. The photon flux at the Earth as a function of coronal temperature is then

$$F_E = G \frac{P_{\text{cor}}^2}{g} b(T_{\text{cor}}),$$  \hspace{1cm} (1)$$

where $G$ is a geometrical gain factor which involves the stellar radius and distance and $g$ is the stellar surface gravity. The value of the geometrical gain factor $G$ for $\alpha$ Boo is 550, and we assume $P_{\text{cor}} = P_{\text{chv}}$, hence $P_{\text{cor}}^2/g = 4.5 \times 10^{-8}$ (cgs) (Ayres and Linsky 1975). The function $b(T_{\text{cor}})$ in equation (1) involves the temperature-dependent ionization equilibrium of the ion $N(\text{ion})/N(\text{el})$, the relative atomic abundance, $N(\text{el})/N(\text{H})$, and the electron collisional excitation strength, $\Omega$:

$$b(T_{\text{cor}}) = 1.81 \times 10^{16} \frac{N(\text{ion}) N(\text{el}) \Omega}{N(\text{el}) N(\text{H}) g T_{\text{cor}}^{3/2}} \times \exp \left(-\frac{E_0}{k T_{\text{cor}}} \right).$$  \hspace{1cm} (2)$$

Here $E_0$ is the excitation energy and $g_i$ is the statistical weight of the lower level of the transition (McClintock et al. 1975; Gerola et al. 1974).

Figure 2 shows the predicted coronal fluxes for $\alpha$ Boo in photons cm$^{-2}$ s$^{-1}$ as a function of coronal temperature for Si $\text{III} \lambda 1206$, Si $\text{IV} \lambda 1397$, C $\text{II} \lambda 1335$, C $\text{III} \lambda 1176$, C $\text{IV} \lambda 1549$, O $\text{V} \lambda 1218$, and O $\text{VI} \lambda 1032$ as functions of temperature (K). The horizontal dotted lines are the 2 $\sigma$ upper limits of this work, with the exception of the values for Si $\text{III} \lambda 1206$, O $\text{V} \lambda 1218$, and O $\text{VI} \lambda 1032$, which are obtained from Copernicus observations (McClintock et al. 1975; W. McClintock 1975; Anderson 1976).

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O vi λ1218, and O vi λ1032. Metal abundances for α Boo were obtained as follows: the solar abundances for carbon (Mount and Linsky 1975) and for silicon (Withbroe 1971) were multiplied by 0.6 (Conti et al. 1967) to reflect the metal deficiency of Arcturus. For O v and O vi, the solar oxygen abundance of Mount et al. has been multiplied by 0.6 to reflect the enhancement of oxygen with respect to other metals (Conti et al. 1967). Ionization equilibria of Jordan (1969) and collision strengths of Gabriel and Jordan (1971), Dupree (1972), and Bely (1966) were used in the calculations.

Since C iii λ175 arises from a metastable level, rather than the ground state, a relative population factor had to be included in the calculation of the flux (Munro, Dupree, and Withbroe 1971). In computing the flux for O v λ1218, we accounted for the depopulation of the ground state to the metastable level in the same way.

Table 2 lists the transitions depicted in Figure 2, the predicted maximum coronal fluxes, the observed flux upper limits, and values of some of the parameters used in the calculation. Included with the results of this observation are the upper limits obtained from the Copernicus satellite for Si iii λ1206 (McClintock et al. 1975), O v λ1218 (McClintock 1975), and O vi λ1032 (McClintock 1975; Anderson 1976). Scans of the O vi λ1032 line made by using the U2 detector on Copernicus give an upper limit of 0.031 photons cm⁻² s⁻¹ (0.2 Å slit)⁻¹ (Anderson 1976; McClintock 1975). Assuming a line width of 0.6 Å as a reasonable value, we find that the upper limit to the O vi λ1032 flux is 0.093 photons cm⁻² s⁻¹. Also included are the maximum values of b(T) and the corresponding temperature, T_max.

When the predicted fluxes as functions of temperature are compared with the upper limits in Table 1, certain temperature regions are excluded because for these temperature regions the predicted fluxes are larger than observed. As indicated in Figure 2, almost all regions of temperature from approximately 20,000 to 350,000 K are excluded except for a very narrow region from 160,000 to 200,000 K. It is very unlikely that the coronal temperature exists only within this small range (180,000 ± 20,000 K).

These coronal calculations depend explicitly on the value of P_cor²/g; a factor of 3 change in P_cor results in a change in the predicted coronal fluxes by a factor of 9. Ayres and Linsky (1975) have adopted a value for the mass column density at the top of the chromosphere log m_ch = –4.5 corresponding to P_cor²/g = 4.5 × 10⁻⁸ if P_cor = P_chr, but they conclude that log m_ch could be as small as –5.0 (P_cor²/g = 4.5 × 10⁻⁹). Subsequently, Ayres (1975) recomputed the Ca ii and Mg ii line cores with the use of a partial redistribution code. He concluded that the Ca ii flux is best explained by a model with log m_ch = –4.5, but that log m_ch = –5.0 is consistent with the Ca ii data and better explains the ratio of Mg ii to Ca ii emission.

The question can be inverted. From the observed upper limits for the flux and equation (1), one can compute values of P_cor²/g as functions of the coronal temperature. The results of these calculations are shown in Figure 3 and serve as upper limits to values of P_cor²/g. In the figure, the existing value of P_cor²/g of Ayres and Linsky (1975) is shown as well as this value and 1/4 this value. These curves are upper limits, and P_cor may be considerably lower. The implication is clear: the low upper limits require either a lower value of P_cor²/g and hence of P_cor or a coronal temperature outside the range 20,000–350,000 K (except for possibly 180,000 ± 20,000 K).

b) Transition-Region Emission Lines

If the coronal temperature exceeds 350,000 K, then most of the emission lines listed in Table 1 should be formed in an analog of the solar transition region.

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**Table 2**

<table>
<thead>
<tr>
<th>Ion</th>
<th>λ (Å)</th>
<th>g₀</th>
<th>N(e)</th>
<th>log (T_max)</th>
<th>Predicted Flux</th>
<th>Observed Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>N(H)</td>
<td>(photons cm⁻² s⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si ii</td>
<td>1263.3</td>
<td>6</td>
<td>13.2 (D)</td>
<td>1.18 (–5)(W)</td>
<td>4.5</td>
<td>9.5 (2)</td>
</tr>
<tr>
<td>Si iii</td>
<td>1206.5</td>
<td>1</td>
<td>11.1 (D)</td>
<td>4.8</td>
<td>1.8 (4)</td>
<td>0.45</td>
</tr>
<tr>
<td>Si iv</td>
<td>1396.7</td>
<td>2</td>
<td>19.7 (D)</td>
<td>4.9</td>
<td>4.1 (3)</td>
<td>0.1</td>
</tr>
<tr>
<td>C ii</td>
<td>1335.3</td>
<td>6</td>
<td>12.8 (D)</td>
<td>4.6</td>
<td>1.7 (4)</td>
<td>0.41</td>
</tr>
<tr>
<td>C iii</td>
<td>1175.7</td>
<td>9</td>
<td>23.3 (GJ)</td>
<td>4.9</td>
<td>5.8 (3)</td>
<td>0.14</td>
</tr>
<tr>
<td>C iv</td>
<td>1549.1</td>
<td>2</td>
<td>9.1 (B)</td>
<td>5.0</td>
<td>1.8 (4)</td>
<td>0.44</td>
</tr>
<tr>
<td>N v</td>
<td>1240.1</td>
<td>2</td>
<td>7.7 (GJ)</td>
<td>5.3</td>
<td>1.7 (3)</td>
<td>0.04</td>
</tr>
<tr>
<td>O v</td>
<td>1218.4</td>
<td>1</td>
<td>0.35 (GJ)</td>
<td>5.4</td>
<td>4.3 (3)</td>
<td>0.11</td>
</tr>
<tr>
<td>O vi</td>
<td>1031.9</td>
<td>2</td>
<td>3.9 (GJ)</td>
<td>5.5</td>
<td>5.6 (3)</td>
<td>0.14</td>
</tr>
</tbody>
</table>

‡ No correction for interstellar absorption.

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Haisch and Linsky (1976) have derived a scaling law for transition-region stellar surface fluxes,
\[
\frac{f_\star}{f_\odot} = \frac{A_\star}{A_\odot} \frac{P_{TR}(\star)}{P_{TR}(\odot)}
\]
where \(f_\star\) is the stellar surface flux, \(f_\odot\) is the solar surface flux, and \(A_\star\) and \(A_\odot\) are the stellar and solar abundances, respectively. For Arcturus, the ratio \(P_{TR}(\star)/P_{TR}(\odot)\) (\(P_{TR}\) = transition-region pressure) is \(9 \times 10^{-9}\) if \(P_{TR} = P_{cor}\) (Ayres and Linsky 1975). Thus, by using observed solar fluxes, it is possible to predict transition-region fluxes.

Table 3 presents quiet Sun surface fluxes (Rottman 1975) for lines which originate in the solar transition region (Dupree 1972; Gibson 1973), and the predicted \(\alpha\) Boo transition-region flux at Earth for several lines, assuming the abundances described above. In predicting the values for \(\mathrm{C\ II}\) \(\lambda\lambda 1335, \mathrm{C\ III}\ \lambda 1176, \mathrm{C\ IV}\ \lambda 1549, \mathrm{Si\ II}\ \lambda 1206, \mathrm{Si\ IV}\ \lambda 1397, \mathrm{N\ V}\ \lambda 1240, \mathrm{O\ V}\ \lambda 1218,\) and \(\mathrm{O\ VI}\ \lambda 1032\). The horizontal dotted lines represent the value of \(P_{0}/g\) where \(P_{0}\) is the pressure at the top of the chromosphere determined by Ayres and Linsky (1975) and the indicated fractions thereof.

Also listed in Table 3 are the predictions for the transition-region value of \(\mathrm{O\ V\ \lambda 1218}\) along with the observed solar value (Chipman and Bruner 1975) and observed upper limit for Arcturus (McClintock et al. 1975). The predicted value for \(\mathrm{O\ VI\ \lambda 1032}\) is included with the solar observation of Dupree and Reeves (1971) and the Copernicus upper limit for Arcturus (McClintock 1975; Anderson 1976). All of the predictions fall at least an order of magnitude lower than the upper limits inferred from this observation. Thus there is no direct evidence for or against the existence of a solar-like transition region on Arcturus, and future observations with sensitivity higher by one to two orders of magnitude are needed to determine the existence of such a region on Arcturus.
TABLE 3  
Arcturus Transition-Region Line Emission

<table>
<thead>
<tr>
<th>Ion</th>
<th>$\lambda$ (Å)</th>
<th>Solar Surface Flux* (photons cm$^{-2}$ s$^{-1}$)</th>
<th>Predicted Arcturus Surface Flux† (photons cm$^{-2}$ s$^{-1}$)</th>
<th>Predicted Arcturus Flux at Earth† (photons cm$^{-2}$ s$^{-1}$)</th>
<th>Observed Flux (photons cm$^{-2}$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O vi</td>
<td>1031.9</td>
<td>4.3 (13)(DR)</td>
<td>2.3 (11)</td>
<td>6.4 (−4)</td>
<td>&lt; 0.09†</td>
</tr>
<tr>
<td>C iii</td>
<td>1175.7</td>
<td>9.7 (13)</td>
<td>1.3 (11)</td>
<td>3.6 (−4)</td>
<td>&lt; 0.04</td>
</tr>
<tr>
<td>Si iii</td>
<td>1206.5</td>
<td>2.2 (14)</td>
<td>6.6 (11)</td>
<td>1.8 (−3)</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>O v</td>
<td>1218.4</td>
<td>4.3 (13)(CB)</td>
<td>2.4 (11)</td>
<td>6.7 (−4)</td>
<td>&lt; 0.06†</td>
</tr>
<tr>
<td>N v</td>
<td>1240.1</td>
<td>3.3 (13)</td>
<td>9.9 (10)</td>
<td>2.8 (−4)</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Si ii</td>
<td>1263.3</td>
<td>5.1 (13)</td>
<td>1.5 (11)</td>
<td>4.2 (−4)</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td>C iv</td>
<td>1335.3</td>
<td>3.6 (14)</td>
<td>1.1 (12)</td>
<td>3.1 (−3)</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td>Si iv</td>
<td>1396.7</td>
<td>1.8 (14)</td>
<td>5.4 (11)</td>
<td>1.5 (−3)</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td>Si ii</td>
<td>1531.2</td>
<td>1.2 (14)</td>
<td>3.6 (11)</td>
<td>1.0 (−3)</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>C iv</td>
<td>1549.1</td>
<td>5.1 (14)</td>
<td>1.5 (12)</td>
<td>4.2 (−3)</td>
<td>&lt; 0.05</td>
</tr>
</tbody>
</table>

* Rottman 1975, except CB (Chipman and Bruner 1975), DR (Dupree and Reeves 1971).
† No corrections for interstellar absorption.
‡ Copernicus, McClintock 1975, Anderson 1976.

c) Chromospheric Emission Lines

This paper reports observations of La and the O i $\lambda$1304 triplet as well as the O i $\lambda$1356 doublet. These lines are probably optically thick and should be formed in a chromosphere. The detailed chromospheric models necessary for analyzing these emissions are not discussed here.

As shown in Table 4, H i $\lambda$1216 and O i $\lambda$1304 have been observed a number of times. The present La observation is in agreement with previous observations with the exception of McKinney, Moos, and Giles (1976). In the case of O i $\lambda$1304, all three observations, including that of McKinney et al., are consistent. This strongly argues against a flat rejection of the McKinney et al. La flux. They discuss the possibility that variable chromospheric properties may be a cause of the low La flux.

Simultaneous observations of La from α Boo were made by the Princeton telescope aboard Copernicus (from 2h49m to 7h29m UT, 1975 March 15) and our rocket. Our uncertainty, including laboratory calibration and statistics, amounts to slightly less than 25% (1 σ) at La. The uncertainty in the Copernicus data cited by Snow (1975) is also 25%, based on a cross-calibration observation of η UMa. Our values agree to within 10% of each other, well within the uncertainties of the two instruments.

V. CONCLUSION

Several points can be inferred from our spectrum of Arcturus.
1. O i lines are anomalously strong on Arcturus.
2. Except for La and O i $\lambda$1304, the bright emission lines appearing in the solar spectrum between 1175 and 1700 Å are not observed in Arcturus.
3. A non-solar-like feature exists around 1500 Å.
4. There is no direct evidence for the existence of a transition region or a corona.

TABLE 4

Observations of Chromospheric Emissions

<table>
<thead>
<tr>
<th>Observation</th>
<th>La Observed Flux (photons cm$^{-2}$ s$^{-1}$)</th>
<th>O i $\lambda$1304 Observed Flux (photons cm$^{-2}$ s$^{-1}$)</th>
<th>Quoted Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rottman et al. 1971 (1970 June) sounding rocket</td>
<td>4.0</td>
<td>Factor of 2</td>
<td></td>
</tr>
<tr>
<td>Moos and Rottman 1972 (1971 January) sounding rocket</td>
<td>10.0</td>
<td>Factor of 1.5</td>
<td></td>
</tr>
<tr>
<td>McKinney et al. 1976 (1972 September) sounding rocket</td>
<td>1.2</td>
<td>±50% (≥ 2 σ)</td>
<td></td>
</tr>
<tr>
<td>McClintock et al. 1975 (1973 May) Copernicus satellite</td>
<td>5.35</td>
<td>Factor of 2</td>
<td></td>
</tr>
<tr>
<td>This work (1975 March) sounding rocket</td>
<td>4.33</td>
<td>±25% (1 σ)</td>
<td></td>
</tr>
<tr>
<td>Simultaneous observation (1975 March) Copernicus satellite</td>
<td>4.75</td>
<td>±25% (Snow 1975)</td>
<td></td>
</tr>
</tbody>
</table>

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5. Standard outer atmosphere assumptions coupled with our low upper limits indicate a value for the coronal base pressure that is lower than that which has been derived from chromospheric emission-line analysis (Ayres and Linsky 1975).

Future experiments with higher resolution and sensitivity should help to answer some of the questions raised herein. However, this work strongly suggests instruments of moderate resolution and high sensitivity would be useful in surveying a large number of cool stars to search for gross differences in the ultraviolet spectra such as those between Arcturus, on the one hand, and Capella and the Sun, on the other.

This work was supported by the National Aeronautics and Space Administration under grant NGR 21-001-001 to the Johns Hopkins University and under grant NGL 06-003-057 to the University of Colorado. The success of the instrument owes much to R. C. Vitz and H. Weiser of the Physics Department of the Johns Hopkins University. Helpful discussions with R. Shine of LASP and B. Haisch of JILA, both of the University of Colorado, and G. Mount of the Johns Hopkins University, as well as the cooperation of D. York of Princeton, in arranging the simultaneous Copernicus observation are gratefully acknowledged. W. McClintock and R. Anderson of the Johns Hopkins University generously made available their Copernicus results to provide a broader base for the discussion of the corona of α Boo. One of us (A. W.) wishes to thank the staff of JILA for their cooperation while he was a guest there.

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