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HIGH-SPECTRAL-RESOLUTION MEASUREMENTS OF THE H I λ1216 AND Mg II λ2800 EMISSIONS FROM ARCTURUS

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ABSTRACT

High-spectral-resolution scans of H I λ1216 and Mg II λλ2796, 2803 obtained using the ultraviolet spectrometer abroad the *Copernicus* satellite show broad and very asymmetrical emission profiles. The ratio of the line widths to the solar values is consistent with a law similar to the Wilson-Bappu relation for the calcium K reversal. A fit of the interstellar absorption profile indicates that the average H density toward this nearby star is low, 0.02–0.1 cm^{-3}.
Subject headings: late-type stars — line profiles — spectra, ultraviolet

I. INTRODUCTION

Excitation, ionization and line-width anomalies in the spectra of late-type stars imply the existence of stellar chromospheres, with associated nonradiative energy transport and mass loss (Praderie 1973). A rewarding spectral region for detecting and studying this phenomenon in stars is the ultraviolet where the continuum is low and many species have emission lines. Both accurate photometric and high-resolution spectral measurements are needed.

In the far-ultraviolet, rocket observations of Arcturus with low spectral resolution have measured the Lα line and the O I triplet near 1304 Å in emission with no detectable continuum (Moos and Rottman 1972). For the Mg II doublet at 2800 Å, data have been obtained for a number of stars by Doherty (1972), using the Wisconsin experiment on OAO-2; also high-resolution data for a few stars have been obtained by Kondo *et al.* (1972) using a balloon-borne instrument.

We report in this *Letter* high-spectral-resolution observations of the H I λ1216 and Mg II λλ2796, 2803 emission features of the bright giant Arcturus (α Boo) (K2 IIIp) obtain using the Princeton spectrometer on the OAO satellite *Copernicus* (Rogerson *et al.* 1973*a*). This star exhibits doubly reversed profiles of the Ca II H and K lines (Griffin 1968; Liller 1968) and Hε emission (Wilson 1938), but no absorption or emission in the He I 10,830 Å line (Vaughan and Zirin 1968).

II. OBSERVATIONS

Arcturus was observed on 1973 May 19 and 20. The raw data contained a background, of the same order as the signal, due primarily to cosmic rays and terrestrial trapped particles. This background, which varied slowly due to the motion of the satellite, was removed by fitting a straight line at wavelengths far from line center where there was no emission. This technique did not remove short time variations, which remain as noise and which would also remove any low-level continuum if it were present. (Measurements at higher spectral resolution and at other wavelengths were also made. In these, the background fluctuations are comparable with the signals and require more care in accounting for the background. They will be reported at a later date with a more detailed discussion of the present spectra.) The wavelengths reported are relative to the star: in vacuum for Lα and in air for Mg II. The spectral resolution was 0.2 Å for Lα and 0.4 Å for Mg II (Rogerson *et al.* 1973*a*).

Figure 1 shows the average of the eight Lα scans after subtracting the background. The observing time per 0.2 Å spectral element was 112 s. A check of the background subtraction was made by breaking the data into two sets: sweeps increasing in wavelength, and sweeps decreasing. The two sets gave essentially the same spectra in the line as figure 1, indicating that the background fitting procedure was valid and that the averaged spectrum was not dominated by a set of cosmic-ray events in a single spectrum.

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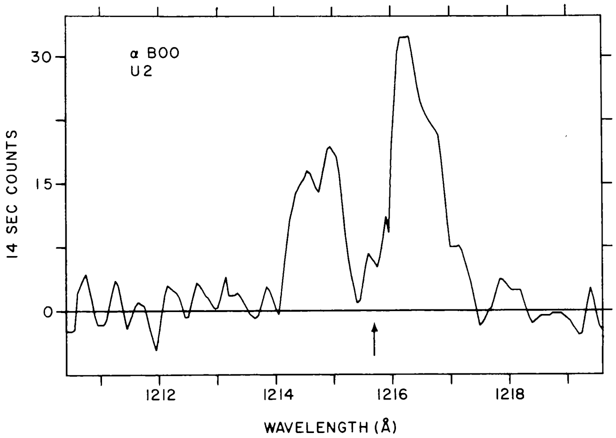

FIG. 1.—Observed H I λ1216 emission from Arcturus. The corresponding solar line has a width of about 0.9 Å. The abscissa is the number of photomultiplier pulses observed in a 14-s period. The arrow refers to nominal line center. The reversal is probably partially intrinsic and partially due to interstellar absorption.

Figure 1 shows three notable features: (*a*) The half-intensity width is quite broad, 2.3 Å. This is to be compared with a solar width of about 0.9 Å (Tousey 1967). (*b*) The line is very asymmetric about the center wavelength of 1215.66 Å, with the ratio of long- to short-wavelength intensity peaks equal to 1.7. (*c*) The center of the line is reversed, due at least in part to the interstellar H absorption.

The Mg II lines at 0.4 Å resolution, after removal of a sloping background, are presented in fig. 2. The observing time was 84 s per 0.4 Å spectral element. The average of the six scans is shown together with two subsets—namely, the three scans made toward longer wavelengths, and the three scans made toward shorter wavelengths. The subsets are included to show that the noise in the background decreases when the average is taken, but the short-wavelength feature on the edge of each of the doublet components remains. This fact, plus the striking resemblance between the two doublet components (insert in fig. 2), leads us to believe that the short-wavelength features are real. (It should be noted, however, that Kondo *et al.* [1972] report striking differences between the two Mg II components in α Ori.) If this is correct, each component has a major peak +0.30 Å from the nominal line center, a minimum near −0.35 Å, and a secondary maximum near −0.65 Å. In any case, the broad, very asymmetric shapes for both components are similar. The widths of the lines at their bases are about 2.2 Å, compared with about 1 Å in the Sun. The ratio of flux in the *k* (2796 Å) line to the *h* (2803 Å) is about 1.3, with the main emission feature of the *k* being slightly broader (∼0.7 Å full width at half-intensity) than that of the *h* line (∼0.6 Å). These widths are substantially greater than the instrumental width of 0.4 Å, indicating that the true width is very close to the measured width.

III. DISCUSSION

The precise sensitivity of the *Copernicus* instrument is in the process of being determined, and we are not able to report the photon flux at this time. Moos and Rottman (1972) have reported a flux of 10 photons cm^{-2} s^{-1} at the Earth for the total Lα emission line of Arcturus when observed in 1971 January. We do not know whether the H I emission from Arcturus is constant. However, if we assume the above value, the peak of the Lα emission corresponds to 1.4 photons s^{-1} cm^{-2} $(0.2\ Å)^{-1}$.

In the same way it is possible to calibrate the Mg II profiles by comparison with the OAO-2 observations of Arcturus (Doherty 1972). It should be noted that it is quite possible that there is a time variation in Mg II emission from Arcturus, as indicated by Liller's (1968) study of the Ca II lines. If the OAO-2 results are used, the maximum of the 2795.5 Å line is 21 photons cm^{-2} s^{-1} $(0.4\ Å)^{-1}$.

The asymmetrical line shapes for both Lα and Mg II are striking. Kondo *et al.* (1972) report that the 2795.5 Å line but not the 2802.7 Å line of α Ori shows an asymmetry. Modisette, Nicholas, and Kondo (1973) have discussed the possibility that Fe I λ2795.01 may be the cause of this effect. In the case reported here, the asymmetry appears in both Mg II lines as well as the Lα line, and accidental matches of absorption wavelengths are not likely to be the cause. The observed violet shift in the Mg II line-reversal centers and enhanced red emission peaks are consistent with the picture of a stellar wind which increases in velocity outward as the density decreases. This point will be considered in detail elsewhere, but the theoretical profiles of Hummer and Rybicki (1968) clearly show the effect. It should be noted that Griffin (1963) has reported short-term irregular changes in the shape of the Ca II H and K emission lines of α B00.

The absorption of Lα is sufficiently weak to suggest a low value for the density of interstellar hydrogen in this direction. This is not surprising in view of the high galactic latitude (69° N) of Arcturus, and the fact that Rogerson *et al.* (1973*b*) find a density of atomic hydrogen of 0.02 cm^{-3} for α Leo, only 60° away from Arcturus. Although it was not possible to completely distinguish the contribution to the observed profile of interstellar absorption from that of the intrinsic stellar emission, it was possible to set limits by the use of simple line-shape fitting. We have attempted to fit the profile of figure 1 using hydrogen column densities of from 6.8×10^{17} cm^{-2} (0.02 cm^{-3}) to 3.4×10^{18} cm^{-2} (0.1 cm^{-2}), interstellar turbulent velocities of 1–10 km s^{-1} and systematic interstellar cloud velocities of 0–35 km s^{-1}, and a Gaussian shape for the assumed stellar emission profile. The fits indicated that the low densities were of correct order of magnitude. However, no very satisfactory fit was achieved, indicating that unless extreme assumptions should have been made about the interstellar absorption, the emission line was not well

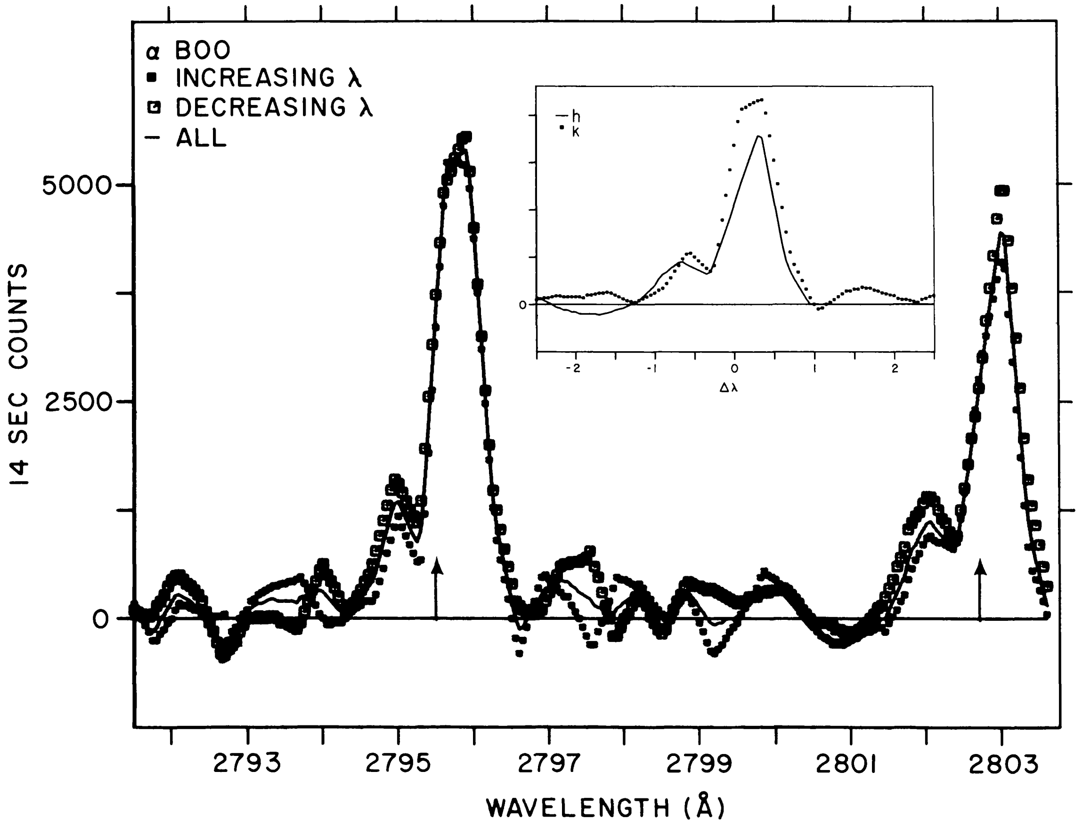

FIG. 2.—Observed Mg II λ2800 emission from Arcturus. Two independent sets of scans are shown, together with their mean (*solid line*). The inset compares the shape of the two components of the doublet.

approximated by a Gaussian shape (which is unsurprising) and was asymmetric about 1215.7 Å. Much better model testing would be possible if the profile were more precisely determined. The noise in the spectrum is largely due to particle background. It may be possible in the future to account for the background more precisely and thereby improve the signal-to-noise ratio.

The two line widths most unambiguously measured—the Lα half-intensity width and the Mg II total widths—are considerably greater than those in the Sun. For Lα, the Arcturus/Sun width ratio is ~2.6 (cf. Tousey 1967) and for the Mg II *k* line it is ~2.2 (cf. Lemaire and Skumanich 1973). A one-sixth power law in the luminosity is known to be applicable to the widths of the Ca II H and K lines (Wilson and Bappu 1957). It is of interest to compare the ratios above to the number 2.16, which results from taking the one-sixth power of the visual luminosity ratio of Arcturus to the Sun. For Mg II, this is consistent with the results of Kondo *et al.* (1972).

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