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HIGH-EXCITATION EMISSION LINES IN THE FAR-ULTRAVIOLET SPECTRUM OF THE LATE A STAR α CEPHEI

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ABSTRACT

The A7 V star α Cephei lies in a region of the Hertzsprung-Russell diagram that is generally thought to be devoid of solar-like magnetic activity. The far-ultraviolet spectrum of this star was observed with the Berkeley spectrograph during the 1996 *ORFEUS-SPAS II* mission. We detected emission lines of Si III, C III, and O VI in the 900–1200 Å interval, spanning formation temperatures of 2×10^4–3×10^5 K. The normalized strengths of these lines, $\mathcal{R}_L \equiv f_L/f_{\rm bol}$, are within a factor of 2 of solar values. Lines of two C III multiplets in the *ORFEUS* spectrum yield an electron density estimate, $n_e \approx 10^{9.4\pm0.3}$, at a temperature of $\sim 6 \times 10^4$ K. The corresponding electron pressure, $p \equiv n_e T \sim 10^{14.2\pm0.3}$, is similar to that of the average Sun, but several times smaller than previous estimates made for other late-type G–K stars. At higher temperatures, the normalized flux ratio for coronal soft X-rays is 20 times less for α Cep than it is for the Sun. This greatly reduced X-ray brightness suggests that the outer atmosphere of α Cep differs strikingly from that of the average Sun, being more akin to a low-density "coronal hole."

Subject headings: stars: activity — stars: individual (α Cephei) — ultraviolet: stars

1. INTRODUCTION

Alpha Cephei (HD 203280, A7 V$^+$n; Gray & Garrison 1989) is a rapid rotator ($v \sin i \simeq 250$ km s^{-1}; Slettebak 1966) and a low-temperature coronal soft X-ray source (Simon, Drake, & Kim 1995). Its luminosity in the 0.2–2.0 keV *ROSAT* PSPC band, $L_{\rm X} \sim 10^{27.3}$ ergs s^{-1}, is comparable to the X-ray luminosity of the average Sun at times of moderate magnetic activity (Ayres 1997), while its X-ray to bolometric luminosity ratio, $\mathcal{R}_{\rm X} \equiv L_{\rm X}/L_{\rm bol}$, is ~5% of solar by virtue of the much higher $L_{\rm bol}$ of the early-type star. The 1200–1600 Å ultraviolet (UV) spectrum of α Cep has been observed by the Goddard High Resolution Spectrograph (GHRS) on board the *Hubble Space Telescope* (*HST*) (Simon & Landsman 1997). Emission lines of H I λ1216, Si III λ1206, C III λ1176, and N V λ1239 were detected. Such features in the solar spectrum originate from the "transition zone" (TZ) in the temperature range of 2×10^4–2×10^5 K.

The UV emission lines of α Cep have surface fluxes 2–4 times larger than solar. A-type stars like α Cep have very thin outer convection zones, and the expectation is that they likely would have little or no magnetic dynamo activity (see, e.g., Parker 1970). The existence of the "hot" UV emissions demonstrates, nevertheless, that α Cep has significant levels of activity compared with the Sun, at least at TZ temperatures. At higher temperatures, it is conversely the Sun that has the larger X-ray surface flux, by a factor of 5 or more. Evidently, the amount of nonradiative heating in the atmosphere between 2×10^5 and 1×10^6 K declines much more steeply for α Cep than it does for the Sun.

Here, we delve further into the UV spectrum of α Cep, with observations obtained by the Berkeley spectrograph on the *ORFEUS-SPAS II*. Detection of O VI λ1032 allows us to extend the comparison with the Sun to 3×10^5 K. The density-diagnostic pair, C III λλ977 and 1176, are detected as well, permitting us to make the first estimate of the electron pressure in the outer atmosphere of an A star.

2. OBSERVATIONS

The *Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer–Shuttle Pallet Satellite* (*ORFEUS-SPAS II*) mission was conducted during the 1996 November/December flight of space shuttle Columbia (STS-80). Alpha Cep was observed for a total of 6 ks with the Berkeley spectrograph in four separate observing segments between November 30 and December 3. Descriptions of the mission, the Berkeley instrument, the normal data acquisition mode, and the standard extraction and calibration techniques (including the crucial corrections for contaminating airglow lines) can be found in Hurwitz et al. (1998) and Hurwitz & Bowyer (1986, 1996). The α Cep data discussed here are based on the pipeline processing scheme described in the first article.

Figure 1 illustrates the 950–1200 Å spectrum of α Cep, as extracted and supplied to us by the Berkeley Space Astrophysics Group. According to Hurwitz et al., in-flight measurements yield a spectral resolution of 0.33 Å. The trace is dominated by strong airglow lines from the near-Earth environment. The solid curve is the heavily smoothed background-corrected stellar spectrum, and the dashed lines are $\pm 2\,\sigma$ photometric error bounds.

Other than H I Lyα, the strongest lines present are those of C III λλ977 and 1176, O VI λ1032, and Si III λ1206. All are relatively free of airglow contamination. These also are the strongest lines observed in the average-Sun spectrum (aside from H I Lyβ λ1026, which is obscured by airglow emission in the stellar spectrum). The 1037 Å component of O VI is blended with the geocoronal O I emission, and its detection, although highly significant with respect to the photometric uncertainties, is less reliable than the other lines owing to possible systematic errors associated with the airglow subtraction.

Table 1 summarizes the line fluxes, measured by direct nu-

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[1] *ORFEUS-SPAS II* Guest Investigator.

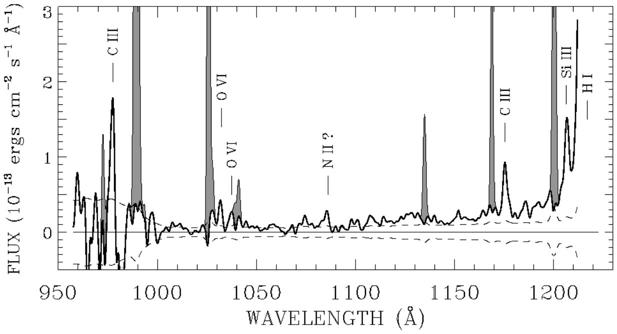

FIG. 1.—*ORFEUS* spectrum of α Cep from the pipeline processing. The solid line is our heavily smoothed background-corrected trace. The dashed lines are the 2 σ photometric error bounds. Strong airglow emissions are shown shaded.

TABLE 1

ULTRAVIOLET LINE FLUXES

Line	log T	α Cephei f_L	α Cephei R_L	Sun R_L	Ratio
C II λ1335	4.3	68	2.7	1.79	1.49
Si III λ1206	4.5	22	0.86	1.12	0.77
C III λ977	4.8	50	1.96	1.44	1.36
C III λ1176	4.8	15	0.59	0.62	0.95
N V λ1239	5.3	2.2	0.09	0.15	0.59
O VI λ1032	5.5	11	0.43	0.73	0.59
O VI λ1037	5.5	9	0.36	0.63	0.56
X-rays, 6–60 Å	6.2	7.5	0.29	5.6	0.05

NOTES.—f_L is the flux observed at Earth (10^{-14} ergs cm^{-2} s^{-1}). T is the temperature of line formation. Normalized flux, $R_L = f_L/f_{\rm bol}$, is in units of 10^{-7}. Ratio is R_L(α Cep)/R_L(Sun).

merical integrations (above an estimated local continuum if necessary), in order of increasing temperature of formation. The 1 σ internal errors in these measurements are ~10%. The *ORFEUS* fluxes cited here for Si III λ1206 and C III λ1176 are within 4% and 16%, respectively, of the earlier measurements obtained by *HST* (Simon & Landsman 1997), supporting the calibration of the Berkeley experiment, even at the current early stage of its refinement.

3. DISCUSSION

Column (4) of Table 1 lists the available UV line fluxes of α Cep from *HST* and *ORFEUS* and the *ROSAT* 6–60 Å X-ray detection. Solar normalized fluxes from Ayres (1997) are tabulated in column (5); ratios of α Cep to the Sun are in column (6). Ratios of the line *surface fluxes* would be 3 times larger than the entries in column (6); ratios of the line *luminosities* would be 17 times larger.

Over the *HST* temperature range, up to ~$10^{5.3}$ K in N V λ1239, the normalized fluxes of α Cep and the Sun are closely comparable, within a factor of 2 of each other. The same holds for the O VI lines in our *ORFEUS* spectrum at ~$10^{5.5}$ K. A dramatic difference is encountered in coronal X-rays, however: the $\mathcal{R}_{\rm X}$ of α Cep is only 1/20 that of the Sun, and thus substantially below the ratios of the normalized UV line fluxes. In that respect, α Cep is more like a solar coronal hole, having normal TZ emissions but greatly reduced soft X-rays. The same pattern of depressed $\mathcal{R}_{\rm X}$ compared with UV lines first was identified in a number of A and early F stars by Simon & Drake (1989). It was shown by those authors that the apparent "deficit" in the X-ray emission of main-sequence stars increases with decreasing thickness of the stellar convection zone. No satisfactory explanation has yet been found for the trend. The reader is referred to Ayres et al. (1998) for a more recent perspective.

Under optically thin conditions, the relative intensities of the C III resonance line at 977 Å and the 1176 Å multiplet are predicted to be sensitive to electron density over the range $8 \leq \log n_e \leq 11$ (Bhatia & Kastner 1993). Both features are detected at high confidence levels in the *ORFEUS* spectrum. The flux ratio, $f_{1176}/f_{977} = 0.3$, is plotted in the bottom panel of Figure 2, together with theoretical curves from Bhatia & Kastner (1993), which bracket the likely C III formation temperature, ~$10^{4.8}$ K. Also plotted in Figure 2 is the flux ratio for the average (moderately active) Sun, as deduced from the full-disk—Sun as a star—irradiance spectra described by Ayres (1997). The Sun and α Cep are examples of "quiet stars" in terms of their UV line strengths. Ratios for a group of more active RS CVn binaries and giant stars from the *ORFEUS-SPAS II* program from Dupree, Brickhouse, & Hurwitz (1997) are shown in the upper and middle panels for comparison. Schmitt et al. (1996) cite a C III line ratio of 0.3 for another star, the K dwarf ϵ Eri, which was observed during the *ORFEUS-SPAS I* mission. However, the 1176 Å line in this observation lies at the extreme long-wavelength edge of the spectrum, and accordingly its strength should probably be regarded as more uncertain than the line fluxes obtained from the *ORFEUS-SPAS II* flight, whose spectra are more advantageously centered.

The relatively small observational error for α Cep and the shape of the theoretical curves constrain the electron density

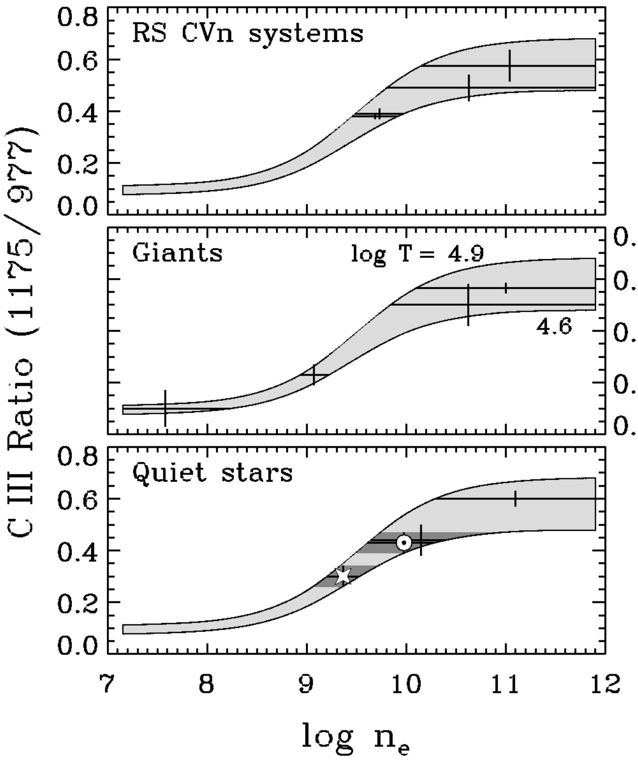

FIG. 2.—Ratio of C III line intensities, f_{1176}/f_{977}. Solid curves are derived from theoretical calculations by Bhatia & Kastner (1993). The star symbol in the bottom panel denotes α Cep, the Sun is shown by its center-filled symbol, and dark shaded areas represent density limits consistent with 1 σ measurement errors and the uncertain formation temperature. Crosses are line ratios cited for other late-type stars by Dupree et al. (1997) from *ORFEUS-SPAS II* observations.

to $n_e \sim 10^{9.4 \pm 0.3}$ cm^{-3}, or an electron pressure $p \equiv n_e T \sim 10^{14.2 \pm 0.3}$ cm^{-3} K. That density is lower than the values implied for all but two of the other stars in the figure, the "hybrid-chromosphere" supergiants α TrA and α Aqr, whose ratios are plotted in the middle panel of Figure 2. Hybrid stars show evidence for both hot coronae and massive cool winds; these are usually mutually exclusive, at least among luminosity class III K giants (see, e.g., Hartmann, Dupree, & Raymond 1980). In *Skylab* spectra of the Sun, equally low C III flux ratios, in the range of 0.07–0.19, were observed in solar prominences (Orrall & Schmahl 1976). For spatial features observed against the disk of the Sun, however, the ratios were generally much larger, ~0.3 above the quiet chromospheric network and 0.35–0.45 for active regions (Dupree, Foukal, & Jordan 1976). The latter values bracket the solar point we include in Figure 2. The only other estimates of transition-zone densities available for comparison are those obtained for a relatively few active late-type stars from UV line ratios in *HST* spectra, e.g., the O IV] multiplet near 1400 Å (Ayres et al. 1998; Linsky et al. 1995). These measurements all lead to higher densities and pressures ($n_e \geq 10^{10}$ cm^{-3} and $p \sim 10^{15.2}$ cm^{-3} K) at *higher* temperatures ($T \sim 10^{5.2}$ K) than we estimate here for α Cep.

By comparison with the Sun, α Cep has a similar TZ density and only somewhat larger (factor of ~4) surface flux in C III. This congruence with the Sun would seem to suggest that the two stars might have a similar TZ structure, whose foundation is presumably based on magnetic loops. That is a rather surprising inference to make in view of the widespread expectation that thinly convective A stars should be incapable of supporting the vigorous dynamo action that is thought necessary to manufacture the substantial-sized magnetic flux ropes such as those seen, for example, on the Sun.

It is possible that the high-excitation activity of α Cep occurs in a "fossil magnetosphere," as has been suggested recently for the not so distantly related Hertzsprung gap giants (Ayres et al. 1998). The minimal X-ray activity of α Cep might then be attributed to a relatively weak "shaking" of the magnetospheric flux tubes by horizontal flow fields, owing to the ineffective thin convective layer. Under such conditions, the deposited magnetoacoustic heating might largely be removed by radiation at TZ temperatures, without triggering the thermal instability that yields hot coronal loops in the more vigorously convective stars of later spectral type.

Elucidation of the surprisingly solar level of TZ activity but puzzling low-density, coronal-hole–like character found here for α Cep, and exploration of these properties in other A stars, now awaits future space observatories. *AXAF* and *FUSE*, in particular, promise to achieve much higher signal-to-noise ratios and spectral resolution in the soft X-ray and far-ultraviolet bands, respectively, while offering a greater array of density-diagnostic line pairs over a wider range in temperature. The A dwarfs, lying at the blueward boundary of activity in the H-R diagram, will be pivotal targets for these missions to address the origins and evolution of magnetocoronal phenomena in stars.

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