THE ASTROPHYSICAL JOURNAL, 555:L121–L124, 2001 July 10

FAR ULTRAVIOLET SPECTROSCOPIC EXPLORER OBSERVATIONS OF CAPELLA[1]

P. R. YOUNG,[2] A. K. DUPREE,[2] B. E. WOOD,[3] S. REDFIELD,[3]
J. L. LINSKY,[3] T. B. AKE,[4,5] AND H. W. MOOS[4]
Received 2001 March 16; accepted 2001 June 8; published 2001 June 25

ABSTRACT

Far Ultraviolet Spectroscopic Explorer observations of the binary system Capella reveal a rich emission-line spectrum containing neutral and ionic species, among them H I, O I, C III, O VI, S VI, Ne V, and Ne VI. In addition, Fe XVIII λ974.85, formed at temperatures of $\approx 6\times10^6$ K, is detected. Whereas the strong transition region lines principally come from the G1 giant, consistent with results from previous ultraviolet observations, Fe XVIII is formed largely in the G8 giant atmosphere. Line ratios from C III suggest densities of $(2–8)\times10^{10}$ cm^{-3}, although anomalous line profiles of the 1176 Å transition may signal optical depth effects.

Subject headings: stars: chromospheres — stars: coronae — stars: individual (α Aurigae) — stars: late-type — ultraviolet: stars

1. INTRODUCTION

The Capella system (α Aurigae = HD 34029), consisting principally of two nearby cool giant stars (G8 III + G1 III) forming a spectroscopic binary, has long been a popular object because it is a bright target at virtually all energies. Astrophysical interest derives from the different evolutionary states of the two stars that are of very similar mass. The cooler, more massive G8 star is an He-burning clump giant (Pilachowski & Sowell 1992), while the G1 star is a rapidly rotating giant located in the Hertzsprung gap (Barlow, Fekel, & Scarfe 1993). The physical parameters of the system are well established (Barlow et al. 1993; Hummel, Armstrong, & Quirrenbach 1994), making Capella a benchmark object to confront theoretical models of the evolution of magnetic activity and winds in stars. *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) spectra contain diagnostics to reveal chromospheric and transition region structure and dynamics. Additionally, the spectral resolution of *FUSE* enables line emission to be identified with each of the giant stars individually using velocity separation techniques.

2. *FUSE* OBSERVATIONS AND SPECTRA

Capella was observed by *FUSE* (Moos et al. 2000) on 2000 November 5 and 7 through the large ($30'' \times 30''$) aperture for 14.2 and 12.3 ks. Another observation of 21.2 ks was obtained on 2001 January 11 in the medium ($4'' \times 20''$) aperture in order to minimize airglow contamination of the spectra, although some loss of flux occurred in all channels as the target moved in the aperture. Data were processed with version 1.8.7 of the *FUSE* calibration pipeline. Orbital phases at the time of the *FUSE* observations were 0.34, 0.35, and 0.98 (using the Hummel et al. 1994 ephemeris), which convert to radial velocities of +7.1, +8.1, and +32.8 km s^{-1} (G8 giant) and +52.4, +51.3 and +25.4 km s^{-1} (G1 giant) with the radial velocity data of Barlow et al. (1993).

The absolute wavelength scale of *FUSE* is accurate to within 100 km s^{-1} (although relative wavelengths within a single channel are good to within 5–10 km s^{-1}), and so interstellar absorption lines that occur at known velocities are needed to fix the wavelength scale precisely. For cool stars, only two such lines (C III λ977.020 and C II λ1036.337) are typically seen, superposed on the stellar emission lines, and potentially allow the wavelength scale to be set for all channels except LiF2A and LiF1B. Caution must be exercised, however, since the 977 Å absorption may be intrinsic to the star in some cases.

Figure 1 shows spectra from 2000 November 5 with identifications based on the solar spectrum and predictions from CHIANTI (Dere et al. 2001) using the emission measure distribution and densities from UV and EUV observations of Capella (Brickhouse et al. 2000). The Capella spectrum is strikingly similar to the solar spectrum, the central differences lying in the broader line profiles and the presence of Fe XVIII λ974 in Capella. Some lines differ in the Capella spectrum; for example, N IV (922–924 Å) is stronger, which may indicate abundance anomalies in the G8 giant (Linsky et al. 1995). The broader lines found in Capella result from the combined emission from the two giants and the intrinsically larger broadening of the emission from the rapidly rotating G1 giant. The high sensitivity of *FUSE* is highlighted through the detection of the C I recombination continuum, which is seen over the region ≈1100–1000 Å and exhibits several absorption lines.

Table 1 contains fluxes and total counts in selected emission lines.[6] Although dominated by resonance lines of C III and O VI, the spectrum exhibits a wealth of weaker lines from other elements including H, He, C, N, O, Ne, Si, S, and Fe.

3. O VI EMISSION

O VI λ1032 is unblended, with broad wings extending to ≈±600 km s^{-1}, which could represent microflaring activity (Wood, Linsky, & Ayres 1997) or emission from regions extending well above the stars' surfaces. Use of C II λ1036 interstellar absorption to fix the wavelength of line λ1032 shows

[1] Based on observations made with the NASA-CNES-CSA *Far Ultraviolet Spectroscopic Explorer*, which is operated for NASA by Johns Hopkins University under NASA contract NAS5-32985.

[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

[3] JILA, University of Colorado, Campus Box 440, Boulder, CO 80309-0440; and National Institute of Standards and Technology, Physics Laboratory, 100 Bureau Drive, MS 8400, Building 221, B 160, Gaithersburg, MD 20899-8400.

[4] Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218.

[5] Computer Sciences Corporation, 7700 Hubble Drive, Lanham-Seabrook, MD 20706.

[6] A complete line list for the spectrum is available at http://fuse.pha.jhu.edu/analysis/cool_stars/capella_linelist.html.

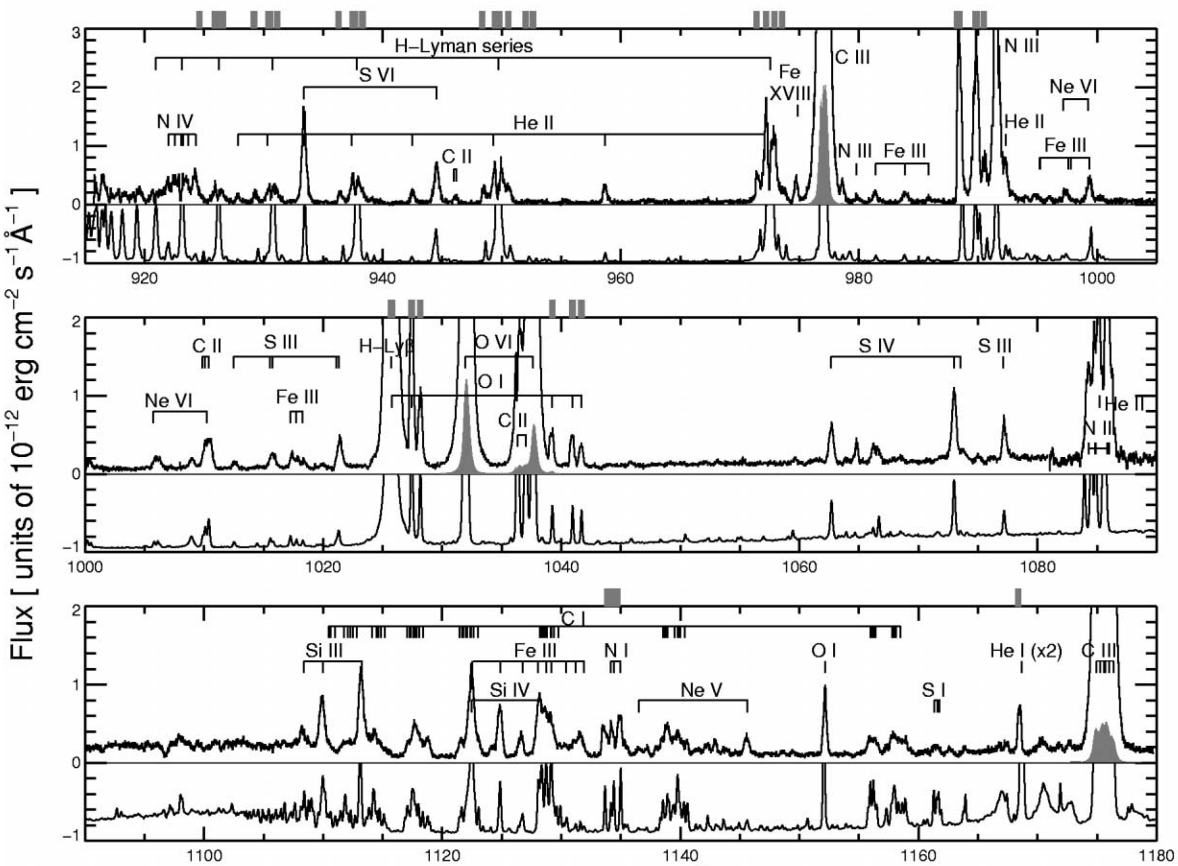

FIG. 1.—*FUSE* spectrum of Capella in the large aperture derived from the observation on 2000 November 5. The quiet-solar spectrum shown in each panel was obtained by the SUMER instrument on *SOHO* (Curdt et al. 1997; W. Curdt 2001, private communication). The shaded regions above each spectrum denote areas contaminated by airglow lines. The Capella C III λλ977, 1176 and O VI λλ1032, 1038 lines, reduced by a factor of 18, are plotted as shaded profiles.

that the G1 star dominates the λ1032 emission, consistent with lower temperature transition region lines (Ayres 1988; Linsky et al. 1995; Young & Dupree 2001). The ratio of the O VI doublet, λ1038/λ1032, is ≈1 : 2, indicating that the plasma is optically thin at these wavelengths.

4. C III AND ELECTRON DENSITY

The ratio of C III λ977 to λ1176 provides an excellent electron density diagnostic between 10^8 and 10^{11} cm^{-3} for optically thin plasmas (Dupree, Foukal, & Jordan 1976). The observed flux

TABLE 1
PARAMETERS OF SELECTED EMISSION LINES FROM THE 2000 NOVEMBER 5 OBSERVATION

Ion	Line (Å)	Flux ($\times 10^{12}$ ergs cm^{-2} s^{-1})	Photon Counts (in 14174 s)	FWHM$_{obs}$ (km s^{-1})
		SiC2A		
S VI	933.378	0.715[a]	4980	140
He II	958[b]	0.118	901	125
Fe XVIII	974.850	0.113	848	92
C III	977.020	29.4	219000	247
		LiF1A		
O VI	1031.926	14.4	267000	162
S IV	1062.664	0.236	4490	137
		LiF2A		
O I	1152.151	0.275	7420	72
C III	1176[c]	15.1	248000	453

[a] Includes a ≲10% contribution from a blending He II line.
[b] A blend of seven lines between 958.670 and 958.725 Å.
[c] A blend of six lines at wavelengths of 1174.933, 1175.263, 1175.590, 1175.711, 1175.987, and 1176.370 Å.

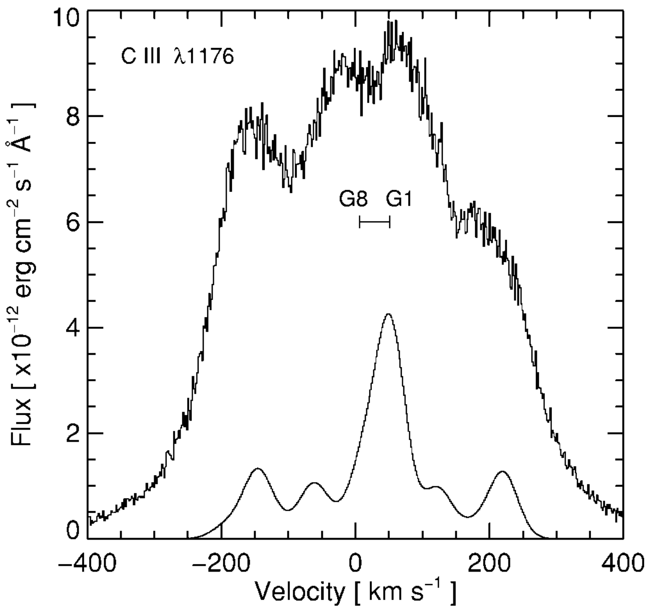

FIG. 2.—Comparison of the observed C III λ1176 profile (*upper line*) from the 2000 November 5 observation with a model profile (*lower line*) derived with CHIANTI with $N_e = 10^{10}$ cm^{-3}. At the orbital phase of 0.34 (Hummel et al. 1994), the radial velocities are +7.1 (G8) and +52.4 km s^{-1} (G1).

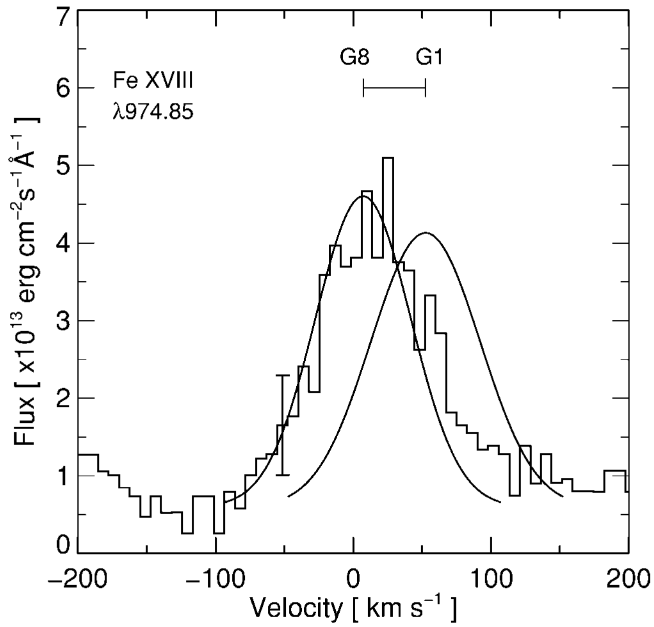

FIG. 3.—Fe XVIII λ974 profile from the SiC2A spectrum of the 2000 November 5 observation. The zero point of the velocity scale corresponds to the rest wavelength of the line, determined from interstellar C III absorption at 977 Å. The expected velocities of the Capella giants are shown, together with two model profiles centered at the two stars' velocities. These model profiles show the appearance of the Fe XVIII line if it originated solely in one of the two stars, and thus they demonstrate the dominant contribution from the G8 giant. The model profiles are broadened with the thermal width of line λ974 (79 km s^{-1}), the *FUSE* instrumental broadening (20 km s^{-1}), and the rotational broadenings of each star (3 km s^{-1} for the G8 giant and 36 km s^{-1} for the G1 giant). A 1 σ error bar is also shown.

ratio (in units of ergs) λ1176/λ977 from the 2000 November 5 observation is 0.51 ± 0.01, which translates to an electron density of 2×10^{10} cm^{-3} using atomic data from CHIANTI. This is in excellent agreement with the λ1176/λ977 ratio of 0.52 that we derive from publicly available *ORFEUS I* (the first mission of the *Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer*) spectra. A drop of 12% in the λ977 flux in the *FUSE* 2000 November 7 observation leads to a higher density of 8×10^{10} cm^{-3}. Corresponding electron pressures are ≈(2–8) × 10^{15} cm^{-3} K, which are values consistent with the C V pressure (Ness et al. 2001) that suggests constant pressure through the transition regions of the Capella giants. Much higher pressures are found at higher temperatures, based on EUV density diagnostics of Fe XIX and Fe XXI that yield densities of $\sim 10^{12}$ cm^{-3} (Dupree et al. 1993; Brickhouse 1996), indicating inhomogeneous coronal structures.

The derived density from the C III lines must be treated with caution since the lines show evidence of optical depth effects. Figure 2 compares the Capella λ1176 profile with a simulated, optically thin profile calculated using CHIANTI and assuming a cool-to-hot giant ratio of 1/5. The λ1176 feature comprises six transitions. Although the lower levels of the transitions belong to an excited configuration, they can have populations comparable to the ground level at electron densities $\gtrsim 10^{10}$ cm^{-3}, allowing the possibility of photoabsorption from these levels. Clearly, the strong peak expected from the 1175.71 Å transition (the strongest of the multiplet) is much weaker in Capella. This reduction in the observed strength of λ1175.71 compared with the optically thin case has been observed in solar spectra taken near the limb that indicate that the λ1175.71/λ1174.93 ratio can fall to 50% of the optically thin value (Doyle & McWhirter 1980).

5. CORONAL IONS: Fe XVIII

For stars with coronae extending to temperatures of $\sim 10^7$ K, emission lines from highly ionized ions arising from forbidden transitions within the ground configurations of the ions are expected at UV wavelengths. One of the strongest is Fe XXI λ1354.06, which has been observed in Capella (Linsky et al. 1998); another is Fe XVIII λ974.85, which has been seen previously in solar flare spectra (Feldman & Doschek 1991) and is now accessible with *FUSE*. We identify the weak line at 974 Å (Fig. 1) between H I Lyγ and C III λ977 with Fe XVIII. By comparing CHIANTI and APEC (Smith et al. 2001) models of the Fe XVIII ion with the *FUSE* flux, other Fe XVIII lines at 15.625 and 93.92 Å in *Chandra* (Canizares et al. 2000), and *EUVE* spectra (Brickhouse et al. 2000), we find that the *FUSE* λ974 flux is consistent, within a factor of 2, with the X-ray lines, confirming the Fe XVIII identification.

The line λ974 is narrow compared with cooler emission lines in the spectrum (Table 1), indicating that the emission originates principally from one of the two giants. If the nearby interstellar line C III λ977 (expected at a heliocentric radial velocity of ≈+22 km s^{-1}; Linsky et al. 1993) is used to determine the absolute wavelength scale, then Figure 3 shows that a stronger contribution (about 75% of the flux) arises from the G8 giant. To confirm this result, the centroids of C III λ977 and S VI λλ933, 944 were measured and found to be redshifted by between 44 and 51 km s^{-1}, relative to the Fe XVIII line, in the 2000 November 5 data. C III and S VI would be expected to be formed in the G1 atmosphere, and so this confirms both the association of Fe XVIII with the G8 giant and the interstellar origin of the C III λ977 absorption. This Fe XVIII result contrasts with a *Hubble Space Telescope*/Goddard High Resolution Spectrograph (*HST*/GHRS) observation obtained in 1995 September in which almost equal contributions to Fe XXI λ1354 from both stars were found (Linsky et al. 1998). The *FUSE* observation suggests variability in the relative contributions of the two giants to the high-temperature emission.

The ability of *FUSE* to resolve the individual stars' contributions to the Fe XVIII line is critical to the interpretation of the X-ray spectra of Capella, where emission lines from highly ionized species are found but where the spectral resolution is not high enough to resolve the stellar components (Brickhouse et al. 2000; Brinkman et al. 2000; Canizares et al. 2000; Audard et al. 2001). Fe XVIII is particularly important since it is formed in a region that gives rise to a prominent "bump" in the Capella emission measure distribution (Dupree et al. 1993; Audard et al. 2001; Mewe et al. 2001). The *FUSE* result shows that this region is dominated by the G8 star at the time of the 2000 November 5 observation.

6. VARIABILITY

Monitoring of Capella with the *International Ultraviolet Explorer* (*IUE*) revealed that chromospheric and transition region fluxes are variable only on the 5%–10% level (Ayres 1991). However, higher temperature coronal emissions observed in the EUV region are constant to within ∼30%, except for species formed above 6×10^6 K that can vary by a factor of 3–4 (Dupree & Brickhouse 1995; Brickhouse et al. 2000). *FUSE* fluxes can be compared with those from the *ORFEUS I* spectrum obtained in 1993 (Dupree, Brickhouse, & Hurwitz 1998), where we find λ977 and λ1032 fluxes of 2.52×10^{-11} and 1.11×10^{-11} ergs cm^{-2} s^{-1}, respectively, with measurement uncertainties of around 5%. These values are in reasonable agreement with the *FUSE* measurements (Table 1), although the ≈30% difference for line λ1032 is larger than the expected absolute flux accuracy of both instruments (≈10%). The line λ1176 has been measured with *IUE* and GHRS (Linsky et al. 1995) as well as with *ORFEUS I*, and consistency with *FUSE* is found to within 20%. Since the time of arrival of each photon was recorded during the *FUSE* Capella observations, variability can be sought during each observation; however, no significant variations in the λ977, λ1032, and λ1176 fluxes were found down to timescales of 30 s, consistent with a lack of flaring activity. No significant change occurred in the flux of Fe XVIII λ974 during or between the different *FUSE* observations.

7. SUMMARY

Spectra of Capella illustrate the diagnostic opportunities available for cool star research with *FUSE*. Line profiles and velocities can be measured accurately, while the large number of emission lines, many from species unavailable from *IUE* or *HST* spectra, allow the temperature structure from the chromosphere through to the upper transition region to be determined. Fe XVIII λ974 is measured for the first time in an astrophysical object other than the Sun, extending the *FUSE* temperature coverage to 6×10^6 K. The high spectral resolution of *FUSE* allows the line to be predominantly identified with the cool giant of Capella, a result crucial for the understanding of X-ray spectra obtained by *Chandra* and *XMM-Newton*, where the two giants cannot be resolved.

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