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# EXTREME ULTRAVIOLET SPECTROSCOPY OF CAPELLA

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## ABSTRACT

The X-ray active binary system Capella was observed with a moderate-resolution extreme ultraviolet spectrograph from 200 to 330 Å. Two low-level emission features were detected. One most likely is geocoronal He II 304 Å emission, while the other probably originates from the corona of Capella. The weak stellar emission at 304 Å is in direct conflict with predictions of the intrinsic stellar He II flux based on standard scaling arguments but is consistent with the only previous observation of Capella in the EUV. The most plausible explanation for the lack of stellar 304 Å emission is a warm wind from the active G0 III star.

*Subject headings:* stars: individual (α Aurigae) — ultraviolet: stars

## 1. INTRODUCTION

Capella (α Aurigae A: G8 III [Aa] + G0 III [Ab]) is a nearby binary (12.5 pc) that has been the subject of numerous investigations over the past several decades (e.g., Ayres 1988 and references therein). Capella is an intense X-ray and ultraviolet source with emission temperatures as high as $2.4 \times 10^7$ K (Cash et al. 1978; Holt et al. 1979). Observations with *IUE* indicate that the fast rotating G0 III star is responsible for most of the chromospheric ($T \leq 10^4$ K) and transition-zone ($T \approx 10^5$ K) emission (Ayres & Linsky 1980), although at coronal temperatures ($T \geq 10^6$ K) the soft X-ray emission from the G8 III star might be comparable to that of the G0 III component (Ayres 1988). *EXOSAT* spectroscopy observed a sharp drop in emission longward of 150 Å, but to date, there has been no detection of the EUV (200–900 Å) emission from Capella. Bobroff, Nousek, & Garmire (1984, hereafter BNG) reported a nondetection of 304 Å flux from Capella and concluded that the low level of emission at Earth resulted from interstellar absorption.

Models of the chromospheric and transition zone emission have indicated that a significant EUV signal should be detectable from Capella. The strongest emission was anticipated at 304 Å, but depending on the models, it was possible that additional lines could be observed in the interval 200–330 Å. For example, following arguments presented in BNG, the predicted 304 Å flux at Earth should scale relative to the solar He II 304 Å flux by the ratio of the emission measures at $10^5$ K. This results in an estimate of 2.8 photons $cm^{-2}$ $s^{-1}$ at Earth in the absence of interstellar absorption. Refinements to their simple model, such as the addition of ion diffusion (Shine, Gerola, & Linsky 1975) tend to increase the expected He II flux (BNG). More recent models by Dupree & Kenyon (1991) suggest that other lines should arise in this wavelength region, but their intensity is highly dependent on the emission measure near $10^6$ K. While X-ray and UV observations place constraints on the emission measure above $3 \times 10^6$ K and below $5 \times 10^5$ K, there are only weak observational constraints on the intermediate values (Lemen et al. 1989).

Nevertheless, given the expected strength of the 304 Å emission and the possibility of numerous other emission lines (particularly from iron) in this wavelength regime, Capella promised to be a productive target for our sounding-rocket EUV spectrograph.

## 2. THE OBSERVATION

The Extreme Ultraviolet Spectrograph (EUVS) was flown on a sounding rocket on 1992 February 22 at 03:30 UT from White Sands Missile Range. About 6 hr earlier, a 30 minute SWP high-dispersion exposure (SWP 44038) of Capella was obtained with *IUE*. The orbital phase at the time of the satellite and rocket observations was 0.27 in the ephemeris cited by Ayres (1988); $\phi = 0$ is the velocity crossing with the G8 III star in front. The *IUE* SWP-HI spectrum was completely normal and consistent with the 119 previous high-dispersion observations of Capella in the 1150–2000 Å band (Ayres et al. 1992). Six weeks prior to observing Capella the EUVS obtained a spectrum of the hot white dwarf G191-B2B from 200–330 Å (Wilkinson, Green, & Cash 1992a).

EUVS is a grazing incidence spectrograph incorporating a paraboloid-hyperboloid telescope for efficient EUV collection, a grazing incidence toroidal mirror for postaperture reimaging, a radial groove grating for dispersing the light, and a two-dimensional microchannel plate detector. The radial groove grating is a novel design that benefits from the enhanced efficiency of the conical diffraction mount while simultaneously controlling the aberrations incurred by performing spectroscopy in a converging light beam (Cash 1983). The spectrograph entrance aperture was a 37″ diameter circle.

Pre- and postflight calibration showed no significant performance degradation. The instrument was calibrated at the University of Colorado full beam facility (Windt & Cash 1986) and has a peak effective area of 3.7 $cm^2$ at 304 Å, and a resolution of ~2 Å. After correction for atmospheric attenuation during the flight, ~180 s of effective exposure was achieved on Capella at 304 Å. The sensitivity limit at 304 Å was ~50 times greater than that achieved by BNG. A complete description of the instrument is forthcoming (Wilkinson, Green, & Cash 1992b).

## 3. ANALYSIS

An image of all the valid flight data (including airglow and detector dark counts) is presented in Figure 1. The arc shown in Figure 1 defines the footprint of the spectrum. Virtually all of the counts shown result from detector dark noise. In Figure 2 we display the extracted spectrum, including all background, as a function of wavelength. The data have been summed in wavelength bins significantly larger than the instrumental

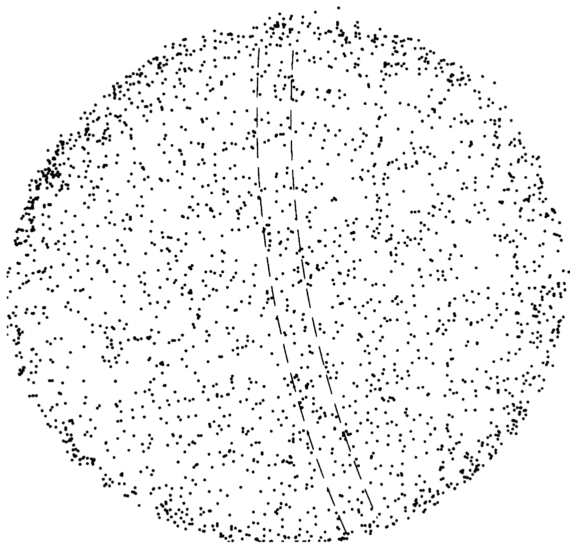

FIG. 1.—An image of all the events recorded during the observation of Capella. Most of the counts result from detector background. The dashed arc defines the region where the spectrum lies. The 304 Å enhancement is $\sim\frac{1}{4}$ of the way up from the bottom of the image. The 252 Å enhancement is $\sim\frac{2}{3}$ of the way up from the bottom. The increase in counts at the edge of the image is an instrumental effect.

resolution ($\sim$8.5 Å per bin) to enhance the signal-to-noise ratio. Maximum signal significance was achieved with binning of this size, which indicates but does not prove (due to the low total number of counts), that one or both of the significant features has a spectral width wider than that expected from a monochromatic line from a point source. If true, this implies that the emission is diffuse or represents more than one emission line. Both possibilities are discussed in detail later. Two

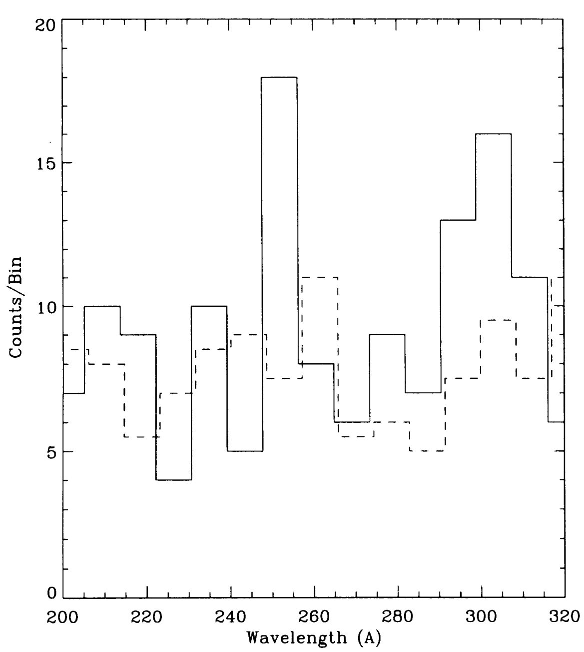


FIG. 2.—The solid line is a histogram of the counts in the arc shown in Fig. 1. No background has been subtracted. The dashed line is the background determined by averaging the counts in similar arcs on either side of the spectral footprint.

features are statistically significant: the one high bin centered at 252 Å, and the three high bins centered at 303 Å. The high bin at 252 Å is 3.9 $\sigma$ (significance = 0.9999) above the mean defined exclusive of the four high bins mentioned above. The statistical probability that *any* bin in the spectrum would show a deviation as large as that seen in the 252 Å bin is 3.2 $\sigma$. The excess counts in the three bins centered at 303 Å represents a 3.8 $\sigma$ (significance = 0.9998) deviation above the mean.

Prime candidates for sources that we could detect with our instrument are Capella itself and local diffuse sky background, either geocoronal emission or possibly interplanetary backscatter of solar lines. In principle, it is possible to distinguish between the uniform illumination of a sky background source and the peaked signature of a stellar feature. Unfortunately, the low level of source counts in our observation prevents a reliable assessment of the origin of the two significant features from their shape alone. Thus, we must rely on other considerations.

The three-bin feature centered at 303 Å has a spectral profile consistent with diffuse emission. We expect a bright geocoronal emission line at 304 Å, but we also expect a significant flux from Capella based on the arguments given above. On one hand, if we attribute the entire signal to local sky-background, we obtain a diffuse intensity of $9.6 \pm 3.6R$ ($1R = 10^6/4\pi$ photons cm$^{-2}$ s$^{-1}$ sr$^{-1}$). That value is consistent with expectations for an observation in the direction of the Earth's shadow. BNG reported a diffuse 304 Å airglow emission of 16$R$ and an earlier sounding rocket flight from our group measured 12$R$ in 1991 (Gallagher & Cash 1992). On the other hand, if we attribute the signal entirely to 304 Å emission from Capella, we obtain a stellar signal of $0.027 \pm 0.010$ photons cm$^{-2}$ s$^{-1}$ at Earth. Given that a significant fraction of the detected emission very likely is geocoronal we consider 0.027 photons cm$^{-2}$ s$^{-1}$ to be a firm upper limit on the 304 Å emission from Capella.

The one high bin centered at 252 Å raises different questions. Given the likely presence of diffuse emission at 304 Å, on first inspection it might seem reasonable that the 252 Å feature represents sky background as well. He II 256 Å would be the obvious candidate. The 252 Å feature represents $9.0 \pm 3.6R$ of diffuse emission, comparable to the 304 Å emission. While there has been no measurement of the 256 Å airglow, standard geocoronal emission models indicate that the 256 Å emission should be reduced compared to 304 Å emission by a ratio of $\sim$1/125 (EUVE Guest Observer Program Handbook 1992; R. Gladstone, private communication). Thus, it is highly unlikely that the observed 252 Å feature is geocoronal. The alternative is that the 252 Å represents one or more stellar emission lines in the interval 247–257 Å, with a total intensity of $0.024 \pm 0.010$ photons cm$^{-2}$ s$^{-1}$.

Over the rest of the spectrum no bin exhibits a $\geq 2\,\sigma$ deviation from the mean. Given the effective area of the EUVS and the effective exposure time, we can place a limit on the potential strength of any possible stellar emission features. Representative 2 $\sigma$ upper limits are 0.013 at 240 Å, 0.012 at 270 Å, and 0.016 at 320 Å in photons cm$^{-2}$ s$^{-1}$ at Earth.

## 4. DISCUSSION

Given the simplicity and robustness of the arguments concerning the expected level of stellar 304 Å flux, we were surprised by the low level of 304 Å emission detected during the EUVS flight. Our limit on the stellar 304 Å emission is completely consistent with, although considerably tighter than, the only previous observation of Capella in the EUV: 0.6 photons $cm^{-2}$ $s^{-1}$ at Earth (BNG). A further complication is our detection of a stellar emission line other than He II 304 Å while simultaneously failing to detect 304 Å emission. The first point to be resolved is the absence of 304 Å emission. Either Capella does not emit nearly as much 304 Å emission as we anticipated or there is a large amount of absorption along the line of sight.

The first possibility is that Capella is producing far less 304 Å emission than predicted. If we assume a H I column density of $2 \times 10^{18}$ $cm^{-2}$ and a 12/1 ratio of H I/He I in the local ISM (see below), our limit dereddens to 0.078 photons $cm^{-2}$ $s^{-1}$ at Earth, assuming negligible interstellar He II absorption. This is nearly 40 times less flux than expected from simply scaling the solar He II emission according to the ratio of Capella to solar emission measures in the He II temperature range. We have confidence in the scaling procedure because the He II 1640 Å subordinate line of the G0 III star has a surface flux of more than 10 times solar (Ayres & Linsky 1980; Ayres 1988). It is difficult to imagine an atmospheric stratification that would yield a suitably enhanced subordinate line flux but severely reduced resonance line emission. There is no indication from any other UV lines in the *IUE* range of a serious anomaly in the emission measure distribution of the G0 III star in the temperature range $3 \times 10^4$–$2 \times 10^5$ K. Indeed, because the lower level of the 1640 Å transition is the upper level of 304 Å and given that there is not likely to be any significant collisional or radiative disruption of cascades to the ground state, the photon flux of 1640 Å at Earth, 0.5 photons $cm^{-2}$ $s^{-1}$, sets a reasonable lower limit on the intrinsic unattenuated 304 Å flux of Capella at Earth. The actual flux of 304 Å should be substantially larger owing to direct collisional excitation of the resonance line: the solar ratio of 304 Å to 1640 Å in photon units is $\sim$4:1. Thus we conclude that the intrinsic He II 304 Å emission of Capella should be large enough to provide an easy detection and that the lack of flux must be attributed to intervening absorption.

The absorption could occur in Earth's upper atmosphere, the interstellar medium or in a wind localized to the vicinity of Capella. We will examine each of these possibilities. First, it seems unlikely that upper atmospheric He II is responsible. In particular, our observation of G191-B2B measured continuum emission at 304 Å with no detectable absorption. Second, consider interstellar absorption. Assuming for the moment that the scaling arguments of BNG are correct, we would expect 2.8 photons $cm^{-2}$ $s^{-1}$ at Earth in the absence of interstellar absorption. Therefore, we require at least 4.6 optical depths of attenuation along the line of sight to explain our observation. Candidate interstellar absorbers are: continuum absorption by H I, line absorption from He II, and continuum absorption by He I. The neutral hydrogen column density to Capella recently has been measured with the *Hubble Space Telescope* to be $1.8 \pm 0.2 \times 10^{18}$ $cm^{-2}$ (Linsky et al. 1992). This $N_{\rm H\,I}$ provides only 0.5 optical depths in the Lyman continuum at 304 Å. Interstellar He II in either the warm or hot phase is unlikely to provide sufficient absorption: if the He II is at a low temperature the absorption profile is too narrow; at high temperatures most of the He II becomes He III. A detailed analysis was performed by BNG: they found a very restricted temperature regime that could provide the attenuation needed to explain their observational limit while simultaneously satisfying the requirement of pressure equilibrium within the interstellar medium. Since our very conservative stellar 304 Å flux is more than 20 times smaller than the limit derived by BNG, it seems very unlikely that interstellar He II could account for the reduced signal. The remaining candidate is the He I continuum. However, a He I column density of at least $1.3 \times 10^{18}$ would be required for the necessary optical depths, yielding a H I/He I ratio of 3/2. To explain this ratio through differential ionization would require that the hydrogen along the line of sight be greater than 85% ionized, while the helium is neutral. Theoretical calculations (Bruhweiler & Cheng 1988) and arguments concerning the source of the ionizing radiation field in the local interstellar medium (Green, Jelinsky, & Bowyer 1990) indicate that such an ionization state is extremely unlikely. Observations of interstellar He I toward G191-B2B, a hot white dwarf whose sky position lies within 8° of Capella, indicates that the ratio of H I/He I in the local interstellar medium is cosmogonic (12/1) (Green et al. 1990; Kimble et al. 1992). Furthermore, the presence of a stellar signal at $\sim$252 Å rules out the possibility of interstellar continuum absorption, unless the 252 Å signal is intrinsically stronger than the stellar 304 Å emission. Therefore, we consider the local interstellar medium to be an unlikely source for the attenuation of the 304 Å signal from Capella.

The final candidate is the local environment of Capella. A warm ionized wind ($T \leq 10^5$ K) in the vicinity of Capella could provide the required resonant absorption of the 304 Å emission without significantly altering other emission lines (such as 252 Å. A large optical depth within such a wind could provide a sufficiently broad absorption profile without requiring the high temperatures that would ionize He II. There is a recent body of independent evidence that such a wind may be produced by the G0 III star (Ayres et al. 1992; Katsova 1992). Given the measured strength of its He II emission 1640 Å emission and the robustness and simplicity of the standard scaling arguments, we feel that the wind-absorption scenario is the most natural explanation for the curious lack of 304 Å emission from Capella.

The detection of the one emission feature near 252 Å is more problematic. However, one conclusion is clear; it is not stellar He II 256 Å emission. Whatever the reason for the low level of 304 Å emission, all possible explanations lead to the conclusion that He II 256 Å emission should be small as well. If the 304 Å emission is being absorbed by He II in a local warm wind, then 256 Å emission would be absorbed as well. If 304 Å emission is not being produced in the stellar environment, then one would not expect any strong 256 Å emission either.

Therefore, we feel that the observed line is not stellar He II 256 Å, but most likely is one or more coronal emission lines. The three strongest emission lines in the 200–260 Å region (excluding He II 256) of a solar flare are Ni XVII at 249.2 Å, Fe XVI at 251.1 Å and S XIII at 256.7 Å (Doschek 1991). These lines are absent in the quiet Sun (Hinteregger 1963); the high ionization states are characteristic of hot flare plasmas. Since the corona(e) of Capella are much hotter than the solar corona, it is plausible that such high excitation lines might exist routinely in the spectrum of Capella.

Our observation has important implications for future observations in this bandpass, primarily with the Extreme Ultraviolet Explorer. If warm ionized winds are a common feature in Hertzsprung-gap giants like the G0 star of Capella, then observations of He II 304 Å will be difficult; Our limit on the 304 Å flux from Capella is almost identical to the EUVE sensitivity to emission lines at 304 Å (EUVE Guest Observer Program Handbook 1992). However, it is always possible that Capella is not representative of stars of its type, and that bright

EUV emission may still be detected from many other stars with active coronae. Spectroscopy with EUVE might permit secure identification of the 252 Å feature and extend studies of it to many other targets.

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