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ULTRAVIOLET OBSERVATIONS OF ALPHA AURIGAE FROM *COPERNICUS*

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ABSTRACT

Emission lines of Lα (1215.67 Å) and O VI (1031.94 Å) were detected in the spectroscopic binary α Aur (Capella) with the Princeton experiment on *Copernicus*. Temperatures of the emitting regions are inferred to be in excess of 3×10^5 K. The temperature and emission measure are consistent with a variable source of soft X-rays. If the emission is attributed to the primary star (G5 III), the atmosphere is expanding with velocities $\sim$20 to 100 km s^{-1}. Such expansion can lead to material within the binary system. The density of interstellar hydrogen inferred from absorption of stellar Lα appears to be $\sim$0.01 hydrogen atoms cm^{-3}.

Subject headings: chromospheres, stellar — coronas, stellar— spectra, ultraviolet — stars, individual — stellar winds

I INTRODUCTION

Capella (α Aurigae) is a nearby spectroscopic and interferometric binary system that is classified G5 III+G0 III (Wright 1954) and might be expected to have a chromosphere and corona. The spectroscopic signatures of its chromosphere include weak Ca II K-line emission (Wright 1954) and strong He I 10830 Å absorption (Vaughan and Zirin 1968). This system is of particular current interest because Catura, Acton, and Johnson (1975) suggest that α Aur is a variable source of soft X-rays based on their detection of 0.25–3 keV X-rays from a region of the sky including the star. To investigate this system, we obtained some preliminary observations of Lα and O VI with the Princeton Experiment Package on board the *Copernicus* satellite. These results demonstrate the presence of high-temperature plasma with $T_e \gtrsim 3 \times 10^5$ K. The source of this emission could be a stellar corona or circumstellar material associated with the system.

II. OBSERVATIONS

The Princeton telescope/spectrometer on the *Copernicus* satellite (Rogerson *et al.* 1973) was used to obtain wavelength scans centered about the 1031.9 Å line of O VI and the Lα line of hydrogen (1215.67 Å) by using the U1 and U2 phototubes simultaneously. The observations were made during 5 hours of 1974 October 19 (mean UT 13$^{\rm h}$33$^{\rm m}$) when the phase of Capella was 38.2 days ($\sim$10 days past elongation).[1] X-rays were detected (Catura *et al.* 1975) at phase 48.7 days (1974 April 5).

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[1] The phases of α Aur were computed from the zero epoch (JD 2,433,459.856) and period (104.023 days) of Struve and Kilby (1953) with corrections to the zero epoch as noted by Wright (1954) and Heintz (1975).

a) The Lyman-α Line

Figure 1 shows the average of nine scans made with the U2 phototube covering the wavelength region 1210.7–1220.7 Å. At these wavelengths the exit slit of the U2 phototube is 0.185 Å—comparable to the step size of 0.174 Å. The nine scans have been stacked and averaged, and a linear baseline and Gaussian emission profile have been simultaneously fitted to the data with the central reversal deleted.

Lyman-α occurs in emission with a central reversal that may result in part from the optical thickness of the stellar chromosphere, and from absorption by interstellar hydrogen. The observed total flux in the line is obtained by summing the counts over the line profile (from 1213.85 to 1217.52 Å) and calibrated by assuming 0.0011 counts per photon at 1216 Å in U2 near orbit 7000 (Snow 1974); this yields an observed flux at the Earth of 13.64 photons cm^{-2} in Lα. The uncertainty in the absolute calibration could be as much as a factor of 2.

It is difficult to estimate the column density of neutral hydrogen without *a priori* knowledge of the intrinsic stellar profile. Although the apparent Lα profile is broader and asymmetric as compared to the solar profile (Tousey 1963), we nevertheless use the solar profile as a crude guide and require the stellar profile to have the solar value ($\sim$0.3) of the ratio of central intensity to (averaged) emission peaks. The observed stellar Lα profile was multiplied by exp $[+\tau(\lambda)]$, where $\tau(\lambda)$ is the optical depth of neutral hydrogen in the wing of a line dominated by radiation damping (Jenkins 1971), $\tau(\lambda) = (4.26 \times 10^{-20}$ atom^{-1} cm^2 Å^2) $N_{\rm H}(\lambda - \lambda_0)^{-2}$. Here $N_{\rm H}$ (cm^2) is the hydrogen column density. Such a procedure results in a stellar Lα profile (see Fig. 2) that mimics the Sun for $N_{\rm H} = 4 \times 10^{17}$ cm^2. (If we assume Voigt absorption profiles [Morton and Morton 1972] with Doppler velocity equal to 5 km s^{-1}, then a similar

Lα profile and essentially the same value of the hydrogen density result.) Using a distance of 14 pc (Hoffleit 1964) for α Aur, we infer a hydrogen density of 0.01 cm^{-3}. When the Lα profile is corrected for interstellar hydrogen absorption, the line emission from the α Aur system is 3.4×10^{41} photons s^{-1}. If the emission is attributed to the primary star of radius 14.1 $R_{\odot}$,[2] the surface brightness in Lα becomes 2.6×10^{16} photons cm^{-2} s^{-1}. This value is about twice the solar surface brightness (Dupree and Reeves 1971).

[2] We select the primary star because Ca K emission shows the velocity variation of the primary (Wright 1954), and the observed

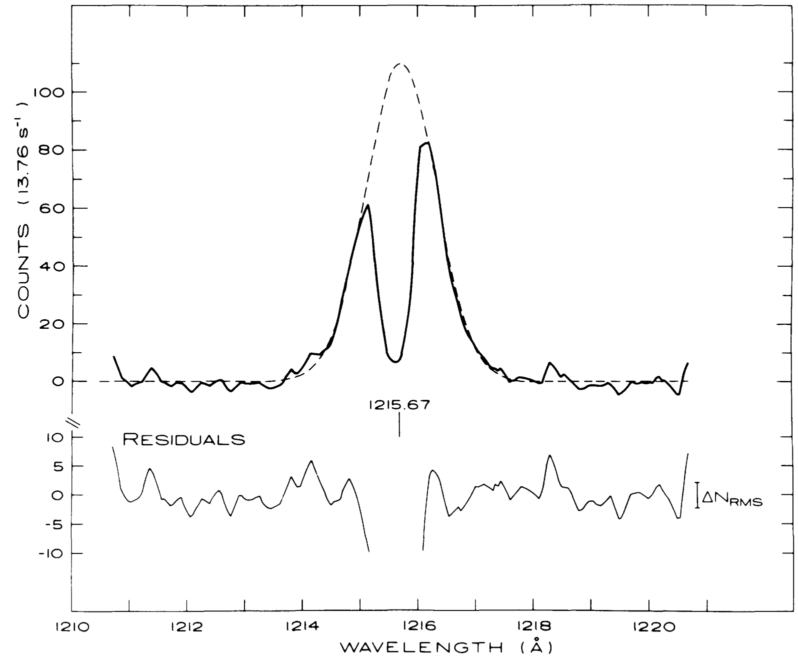

FIG. 1.—The Lα profile in α Aur (*heavy solid line*). A Gaussian profile (*broken line*) and linear baseline have been iterated on the data.

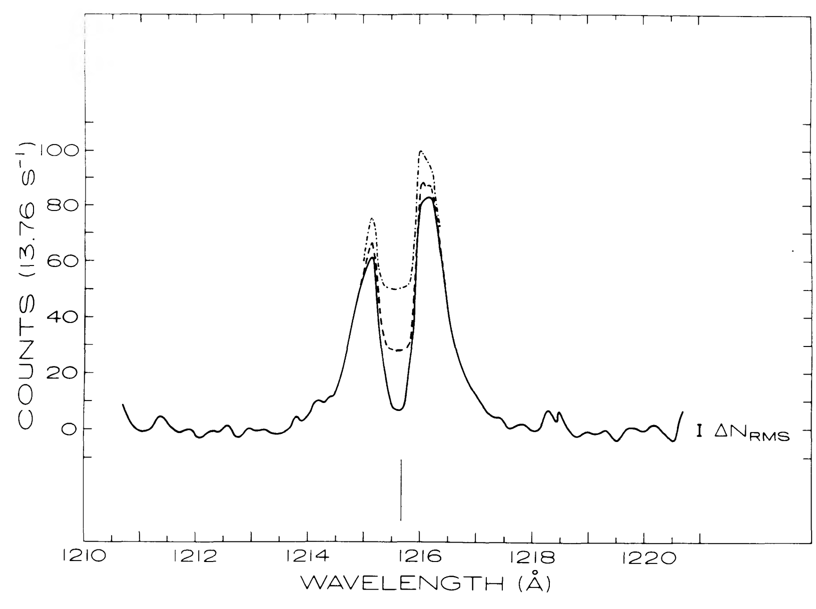

FIG. 2.—The Lα profile in α Aur (*heavy line*) as reconstructed for two values of the interstellar hydrogen column density: $N_H = 4 \times 10^{17}$ cm^2 (*broken line*) corresponding to $n_H = 0.01$ cm^{-3}; and $N_H = 10^{18}$ cm^2 (*dot-dash line*) corresponding to $n_H = 0.025$ cm^{-3}. The central minimum in the profile has been smoothly connected to eliminate the reconstruction of the Doppler core.

These results depend upon the assumed similarity of the stellar and solar profiles, and without detailed calculations we cannot exclude the possibility that the intrinsic stellar Lα line has a reversal deeper than the solar profile or perhaps has no central reversal, and that the observed central core is due solely to interstellar hydrogen absorption. In the first case the inferred density of hydrogen would be even less than 0.01 cm^{-3}. To explore the second possibility, we attribute the residual curve in Figure 1 entirely to interstellar absorption. However, this absorption profile does not agree well with predicted Voigt profiles obtained by assuming hydrogen column densities 10^{16} to 10^{19} cm^{-2} and Doppler velocities from 5 to 80 km s^{-1}.

There are indications of expansion in the atmospheric region producing the Lα line. The observed asymmetry, present also in other late-type stars (Dupree 1974; Moos *et al.* 1974), is indicative (Hummer and Rybicki 1968) of differential expansion. In addition, the Lα line may be blueshifted. The apparent center of the Gaussian profile, 1215.71 Å, is shifted by -0.04 Å, corresponding to -9 km s^{-1}. However, the uncertainty of ± 21 km s^{-1} in the absolute wavelength scale on the U2 phototube (York 1975) makes this a marginal displacement. The apparent minimum of the central reversal is shifted to shorter wavelengths by -35 ± 21 km s^{-1}, perhaps resulting from interstellar absorption.

It should also be noted that the value of the central intensity in the Lα profile is not clearly equal to zero. A value of 7 ± 2 ($1\ \sigma$) counts is present at the minimum of the profile which is slightly above the $2\ \sigma$ level of confidence. The data reduction procedure used here capitalizes on the lack of a stellar continuum away from the Lα profile by forcing this background to equal zero. In contrast, for early-type stars (Bohlin 1975), the net counts at line center are forced to approach zero when a correction for scattered light is constructed. The data for α Aur are then optimum for detecting extremely low column densities if they exist.

There is a feature at $\sim$1218.4 Å, occurring at two consecutive steps ($\Delta\lambda \sim 0.34$ Å), that corresponds in wavelength to the intercombination line of O V at 1218.406 Å. This line has been identified (Gerola *et al.* 1974) in the spectrum of β Gem (K0 III). In α Aur this feature is only $\sim$6 counts ($\sim 2\ \sigma$) at maximum intensity, may be narrower in comparison to the O VI line at 1032 Å (see below), and is more than an order of magnitude less intense relative to Lα than the corresponding feature found in β Gem.

b) The O VI *Line at 1031.94 Å*

The U1 detector was used to scan a restricted region near the O VI line where a broad emission feature was detected (see Fig. 3). The entrance slit of the spectrometer at this wavelength is $\sim$0.05 Å, a value about twice the step size. The nine scans were averaged, and a linear baseline and Gaussian line profile were simultaneously iterated on the data. Values of the background fluctuations, averaging 23 counts per step per scan, were provided by the Princeton experimenters. The peak flux in the line corresponds to 6 counts (13.76 s^{-1}) which amounts to $\sim 4\ \sigma$, an estimate based on the expected statistical noise in the averaged scans and on the errors in the fit of the profile and baseline to the data.

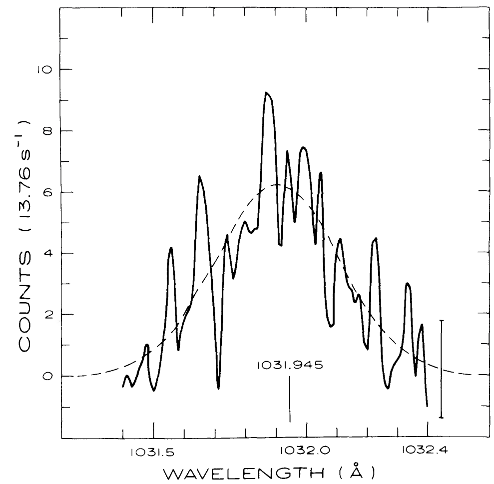

FIG. 3.—O VI emission from α Aur. The broken curve results from a simultaneous iteration of a linear baseline and a Gaussian profile to the data.

The total flux in the line is found by summing the data over the profile in Figure 3 and by using an efficiency factor of 0.0034 counts $photon^{-1}$ for U1 at 1032 Å (Snow 1974). The observed flux is 0.47 photons cm^{-2} s^{-1} at Earth. The distance to Capella is 14 pc (Hoffleit 1964), so that the total flux from the system is 1.1×10^{40} photons s^{-1}. If the emission is attributed to the primary star, the surface brightness corresponds to 9×10^{14} photons cm^{-2} s^{-1}. This value is an order of magnitude larger than the surface flux of the quiet Sun in the O VI line (Dupree and Reeves 1971).

The O VI line appears anomalously wide, having a full width at half-maximum intensity of 0.48 ± 0.08 Å. This width is a factor of 4 larger than the Doppler width at the "expected" temperature of formation, 3×10^5 K (Dupree 1972). If the increased width is ascribed to turbulence, then velocities $\sim$100 km s^{-1} are required; these velocities are about twice the sound speed which is 66 km s^{-1} at 3×10^5 K. If the width is attributed to thermal broadening, it corresponds to a temperature of 6.7×10^6 K.

The observed central position of the Gaussian profile is $1031.90 \pm .02$ Å, whereas the rest wavelength of O VI, 1031.945 Å corrected for the radial velocity of the primary star at the observed phase, should be 1032.01 Å. Hence the maximum of the line appears blueshifted by 0.11 ± 0.02 Å corresponding to -32 ± 6 km s^{-1}. The wavelength scale on the U1 phototube must be corrected by $+12$ km s^{-1} (York 1975); in addition, the

radial velocities of the ultraviolet emission lines indicate expansion from the primary as opposed to infall of material if the lines arise in the secondary.

uncertainty in the repeatability of this scale is ± 7 km s^{-1}. The corrected radial velocity for the line is thus -20 ± 7 km s^{-1}.

III. PHYSICAL CONDITIONS OF THE EMITTING REGIONS

Detection of both Lα and O VI resonance lines in emission indicates the presence of plasma at temperatures of $\sim 10^4$ K and $\sim 3 \times 10^5$ K or higher. Because the Lα line profile is probably optically thick, a straightforward interpretation of the line intensity is not possible in terms of the atmospheric parameters. The increased width with respect to the Sun could result from various causes, namely, a larger optical depth due to the increased path length compared with the Sun, the broadening effects of a differentially expanding atmosphere, and turbulent broadening.

The upper limit to the O V line at 1218.4 Å and the observed O VI transition give a lower limit to the temperature of O VI formation. Assuming that the O V and O VI lines are formed by collisional excitation from their respective ground levels followed by spontaneous emission, we find that the observed photon ratio of O VI (1031 Å)/O V (1218 Å) ≥ 1.5 corresponds to an electron temperature $T_e > 3 \times 10^5$ K. The collision strength for O V, ^1S–^3P, was set equal to 0.15 (Munro 1973), and other atomic data were adopted from Dupree (1972).

An upper limit to the temperature, 6.7×10^6 K, arises by attributing the width of the line totally to thermal broadening. Another upper limit can be found from the indirect argument that the stellar corona can not be so hot as to evaporate. In this case, the maximum coronal temperature corresponds to a near equality between the gravitational potential energy and the thermal kinetic energy for an ion in the corona (Parker 1963). For the Sun, the temperature that results is an order of magnitude higher than the observed average coronal temperature of 2×10^6 K. Inserting the parameters for the primary G5 III component of α Aur ($M_* = 3.03\, M_\odot$; $R_* = 14.1\, R_\odot$ [Wright 1954]), we find, by requiring the coronal temperature to be ~ 0.1 the gravitational potential energy, that $T_{\max} \sim 5 \times 10^5$ K. This value is consistent with the relative fluxes of O V and O VI, suggesting that a corona of about 5×10^5 K can be associated with the primary star.

To investigate the origin of the O VI and X-ray radiation, we can compare the required emission measures ($\int N_e^2\, dV$). The soft X-ray observations require an emission measure of 10^{53} to 10^{54} (cm^{-5}) (Catura 1974). If the O VI line is formed at the temperature of maximum ionic concentration, 3.2×10^5 K, then the emission measure needed is 1.4×10^{52} cm^{-5}. If there were such a low-temperature corona, the X-rays would be a transient phenomenon, occurring from a volume of the corona with different physical conditions from those producing O VI emission. If the temperature corresponds to the Doppler width, 6×10^6 K, the necessary emission measure for O VI is 3.6×10^{57} cm^{-5}, again suggesting that the O VI emission and the X-ray emission arise from different volumes.

While it is attractive to assign the X-ray (and O VI) emission to the corona of the primary star, an equally valid origin could be in gas streams between the stars or in a common envelope. The asymmetric Lα profile and the blueshifted O VI line suggest expansion with a velocity ~ 20 to 100 km s^{-1} in the atmosphere of the primary, making α Aur the earliest giant star in which a stellar wind has been detected. A consequence of this expansion may well be circumstellar material. If the velocities are maintained, the gas would cover a distance comparable to the semimajor axis of its orbit ($\sim 6R_*$) during a time (2×10^6 s) that is substantially less than its orbital period (10^7 s). With such a configuration the broadening in the O VI line could be attributed to the streaming motion of high-temperature circumstellar material. If this gas has a scale comparable to the stellar system, then the emission measure derived for O VI implies an electron density $\sim 10^7$ cm^{-3}, a value much lower than the densities of 10^{11} to 10^{14} cm^{-3} usually attributed to circumstellar material (Batten 1973). Observation of the velocity variation of the O VI line will be necessary in order to firmly identify the source.

The hydrogen column density of 4×10^{17} cm^{-2} has important implications for the opacity of the interstellar medium. Using the tabulations of Cruddace *et al.* (1974), we find the optical depth at 800 Å to be ~ 1 to 2— values that are substantially less than previously believed. These low values encourage the search for radiation from α Aur that is below the Lyman limit.

As this paper was completed, we received additional observations taken at phase ~ 51 days. There is clear evidence for emission from Mg II $\lambda\lambda$2795, 2803, Si III λ1206, and N V $\lambda\lambda$1238, 1242, as well as O VI and Lα. Thus a continuous distribution of temperatures between 10^4 and 5×10^5 K exists in the α Aur system. In addition, the emission characteristic of high temperatures has now been observed at several different phases, suggesting that the O VI emission is not a transitory phenomenon.

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