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EVIDENCE FOR A CORONA OF BETA GEMINORUM

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ABSTRACT

Using the Princeton spectrometer on the satellite *Copernicus*, a strong emission line has been detected in the K0 giant β Gem at 1218.4 Å, which is identified as the $^1S_0$–$^3P^o_1$ intercombination line of O v. The strength of the line is such that it is probably formed in a corona at temperatures near 260,000° K rather than in an analog of the solar chromosphere-corona transition region.

Subject headings: coronae, stellar — line identifications — ultraviolet

I. INTRODUCTION

Stellar chromospheres have been studied for many years through their calcium K-line emission, and more recently through their Mg II 2800 Å emission (e.g., Kondo *et al.* 1972 and Lα emission (Moos and Rottman 1972; Moos *et al.* 1974). Coronae, on the other hand, have never been detected for any normal star other than the Sun. In the course of observations of chromospheric Lα emission from K-type stars, we have discovered an emission line at 1218.4 Å in one star (out of three K giants and one K dwarf observed) which appears to be a coronal emission, since the ion it is identified with requires 77.4 eV to be produced.

II. OBSERVATION

Scans were made of the neighborhood of Lα in β Gem following the procedure of Moos *et al.* (1974). The Lα observation of β Gem consists of 18 low-resolution scans from 1212.2 Å to 1219.1 Å. The spectrometer has a fixed grating, and spectral scanning is accomplished by moving the exit slit and its detector in discrete steps along the exit plane. The integration period at each step is 14 s, and the step size for the present scans is 0.174 Å. The raw data contain a background due to cosmic rays and trapped terrestrial particles. Because of the weakness of the signal from β Gem, it was necessary to use the high-resolution channel of the spectrometer as a real-time background monitor. The details of this procedure, as well as a complete analysis of all β Gem spectra, are given in Linsky *et al.* (1974).

Figure 1 is a histogram average of 14 scans after background subtraction. The average background for the 18 scans varied between 16 and 54 counts per spectral step. The four scans which had average background levels above 50 counts per spectral step were deleted from the data. The baseline was further adjusted downward by 0.14 counts per spectral step so that the weighted mean of counts in the region 1212.2–1213.9 (11 spectral steps) is 0. Finally the data were degraded in resolution to 0.4 Å by averaging the counts in pairs of adjacent spectral steps. The error bars are $\pm 1\ \sigma$, where σ is the rms scatter among the 14 measurements at that wavelength.

Figure 1 clearly demonstrates the presence of Lα emission from β Gem. (For comparison, the Arcturus Lα profile of Moos *et al.* [1974], reduced a factor 5.2, is also shown). The two steps at the center of the line, severely contaminated by geocoronal Lα emission, are deleted. The total signal summed from 1214.6 Å to 1216.9 Å is 32.5 $\pm$ 9.3 counts per 14-s integration period.

In addition to the stellar Lα signal, an emission feature appears at 1218.35 $\pm$ 0.10 Å. The integrated strength of this feature is 12.5 $\pm$ 4.2 counts per 14-second integration period, i.e., about 0.38 the integrated strength of the stellar Lα signal.

There are a number of arguments which can be made for the reality of this 1218.4 Å feature. (*a*) The feature's intensity is 3.0 times the rms error, including the error in background determination. (*b*) We have broken the set of 18 independent spectral scans into four subsets of four or five each. The feature is present in all four subsets. We have also selected a subset of seven scans which have particularly flat low-level backgrounds; the feature is still present. (*c*) We have tested for the possibility that the λ1218.4 feature is a grating ghost of the geocoronal Lα emission by separating the data into two subsets according to the strength of the geocoronal emission. The λ1218.4 feature appears equally strong in each subset. (*d*) The feature does not appear in the spectrum of α Tau (K5 III) obtained with nearly equal observing time a day later (Linsky *et al.* 1974), or in the spectra of Arcturus (fig. 1), or in the K2 V star ϵ Eri (McClintock *et al.* 1974). We conclude that the λ1218.4 feature is a real stellar emission line.

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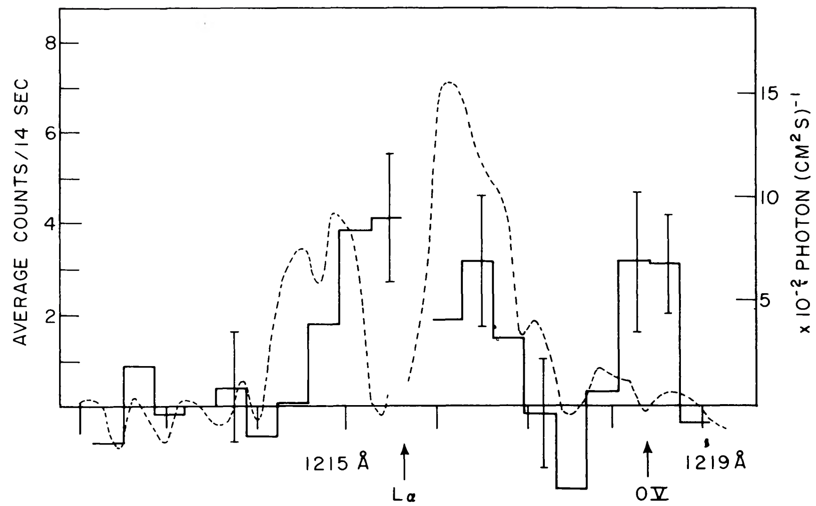

FIG. 1.—The average of 14 spectral scans of the Lα region of β Gem is shown (*solid histogram*) compared with scans for α Boo (Moos *et al.* 1974), reduced in intensity by a factor 5.2 (*dashed line*). The vertical scales are per 0.174 Å bin. A strong feature, present in the β Gem spectrum at 1218.4 Å but absent from the Arcturus spectrum, is identified as a coronal emission line of O^{+4}. Arrows indicate nominal Lα and O v wavelengths.

III. IDENTIFICATION

In the high-resolution solar limb spectra of Burton and Ridgeley (1970) a moderate-strength line is seen at a nominal wavelength of 1218.31 Å. They identify this line as the intercombination $2s^2\ ^1S_0$–$2s2p\ ^3P^o{}_1$ line of O v following Edlèn *et al.* (1969). In the compendium of emission lines of Kelly and Palumbo (1973) the only other lines close in wavelength are λλ1218.27 (Se II), 1218.430 (Cu IV), 1218.50 (V III), 1218.571 (S I), and 1218.595 (S I). The Se II, Cu IV, and V III line identifications are unlikely because of low atomic abundances and the lines originating in excited states. The S I lines are from the ground-state $3p^4\ ^3P$, but are extremely weak in S I spectra, probably because of high-lying upper states $3p^3(^4S^o)\ 9d\ ^3D^o$ and probable small oscillator strengths. They are also unreasonably far from the measured line center. We therefore identify the observed feature as the 1218.406 Å line of O v.

IV. LINE STRENGTH

The absolute efficiency of the spectrometer is not well known: the most recent calibration factor at Lα is 0.0011 counts per photon (Snow, private communication). Using a counting rate of 12.5 counts per 14 s for the region 1218.08–1218.71 Å, the total flux observed at the Earth is 0.28 photons $cm^{-2}\ s^{-1} = 0.46 \times 10^{-11}$ ergs $cm^{-2}\ s^{-1}$. This is converted to surface flux at the star by assuming a distance of 10.8 pc (Hoffleit 1964) and a radius of 11.3 $R_\odot$. (The radius was estimated using Wesselink's [1969] spectrophotometric method, and is similar to Gray's [1968] value of 11.9 $R_\odot$ for the K0 III star γ Tau.) The value of the surface flux is then 8.2×10^3 ergs $cm^{-2}\ s^{-1}$. Because of the uncertainty of the absolute calibration this value may be in error by as much as a factor of 2.

V. IS THE O V LINE FORMED IN A TRANSITION REGION?

We first consider whether the observed O v surface brightness is consistent with the line being formed in a chromosphere-corona transition region, as in the solar case. For our purposes the transition region is defined as that portion of the outer atmosphere in which the energy balance is dominated by conductive flux from above (the corona) and radiative losses. In the Sun this region is extremely narrow, and constant pressure is an excellent approximation. We assume constant pressure also for β Gem. The energy equation can then be written

$$\frac{d}{dz}\left(K\frac{dT}{dz}\right) = \frac{n_e}{n}\left(1 - \frac{n_e}{n}\right) n^2 L_r(T)\ , \qquad (1)$$

where K is the thermal conductivity and $L_r(T)$ the radiative loss term (cf. Cox and Tucker 1969). Equation (1) can be integrated

$$\frac{dT}{dz} = \frac{1}{K}\left[\int_{T_0}^{T} 2\frac{n_e}{n}\left(1 - \frac{n_e}{n}\right) n^2 L_r(T) K dT\right]^{1/2} \qquad (2)$$

such that assuming the perfect gas law ($n \propto P/T$) the temperature gradient is proportional to P.

In computing the surface brightness in the O v line we now assume the following: (*a*) Lambert's (1968) value of the solar oxygen abundance (5.9×10^{-4}), since there is no evidence that β Gem is deficient in metals (Gustaffson, Kjaergoard, and Anderson 1974; Conti *et al.* 1967); (*b*) Jordan's (1969) ionization equilibria; (*c*) that the excitation equilibrium is determined by collisions from the ground state ($2s^2\ ^1S_0$) to the three excited substates ($2s2p\ ^3P^o{}_{0,1,2}$), collisional de-excitations, and radiative de-excitation ($2s2p\ ^3P^o{}_1$–$2s^2\ ^1S_0$). (The collisional rates are from Gabriel and Jordan [1971], and the radiative de-excitation rate A = 2100

s^{-1} from Hummer and Norcross [1974]); (*d*) that the line profile is determined only by thermal broadening. This assumption does not affect our conclusions.

The integrated line flux (surface brightness) is then

$$F_* = \int\int S \exp(-\tau_\nu) d\tau_\nu d\nu = 200 \left(\frac{n_e T_e}{6 \times 10^{14}}\right)$$
$$= 200 \left(\frac{P}{0.16}\right) \text{ ergs cm}^{-2}\text{ s}^{-1}\,, \quad (3)$$

where S is the line source function computed from the excitation equilibrium at each optical depth. In the quiet-Sun transition region the reduced electron pressure $P_e = n_e T_e$ is 6×10^{14} (Dupree 1972) and total pressure 0.16 dyn cm^{-2} (for 10 % helium abundance). For this pressure the surface brightness would be a factor of 40 lower than observed. In fact, the transition region pressure for β Gem is probably lower than the solar value due to the generally lower densities associated with the lower gravity in a K giant compared with the Sun. No model for the upper atmosphere of β Gem presently exists, but Ayres and Linsky's (1973) model chromosphere for α Boo (K2 III) suggests a transition-region pressure of 0.018 dyn cm^{-2}, an order of magnitude lower. We therefore conclude that unless the physical situation in the transition region of β Gem is far different from the Sun, the O v line must be formed elsewhere in its atmosphere.

VI. IS THE O V LINE FORMED IN A CORONA?

We consider finally whether the λ1218 line is formed in an analog of the solar corona. Since there is at present only one datum to explain, we assume a very simple coronal model, namely, a plane-parallel isothermal region in hydrostatic equilibrium. In this case the mass column density is P/g, where P is the pressure at the base of the corona. If we also assume, as is valid for the Sun, that coronal lines are optically thin, then

$$F_*(\text{O v } \lambda 1218)$$
$$= 4.17 \times 10^{15} \left[\frac{R/R_\odot}{d(\text{pc})}\right]^2 \frac{1}{\lambda(\text{Å})} \frac{N(\text{O v})}{N(\text{H})} C_{lu} \frac{P^2}{gT}\,. \quad (4)$$

Here $N(\text{O v})/N(\text{H})$ includes both the oxygen abundance and temperature-dependent ionization ratio, and C_{lu} is the temperature-dependent collisional excitation rate. For the measured value of $F_*(\text{O v } \lambda 1218)$, equation (4) can be solved for P^2/g as a function of T. This curve is shown as a dashed line in figure 2, and has a minimum at 260,000° K, the temperature of maximum O v abundance (Jordan 1969). At this temperature $P^2/g = 2.76 \times 10^{-7}$ cgs or $P = 0.015$ dyn cm^{-2} ($n_e T_e = 5.8 \times 10^{13}$) for log $g = 2.9$ (Gustafsson *et al.* 1974), consistent with our previous estimate of $P = 0.018$ ($n_e T_e = 6.8 \times 10^{13}$).

Clearly, the coronal temperature need not be 260,000° K, in which case P^2/g would be somewhat larger, as given in figure 2. One way to test this model is to predict intensities of other lines formed at temperatures somewhat higher and lower than 260,000° K subject to the constraint on P^2/g versus T imposed by the λ1218 observations. Included in figure 2 are such predicted fluxes at the Earth for C III (λλ1247, 1176), Si III (λ1206), N v (λ1238), and O VI (λ1031) assuming the abundances of Lambert (1968) and the rates of Gabriel and Jordan (1971) and Dupree (1972). These lines are all observable by the *Copernicus* satellite, In Linsky *et al.* (1974) an upper limit for the Si III λ1206 line is estimated to be 0.25 photons cm^{-2} s^{-1} at the Earth, corresponding to a surface brightness of 7.0×10^3 ergs cm^{-2} s^{-1}. This upper limit places a lower limit of 140,000° K for the β Gem corona.

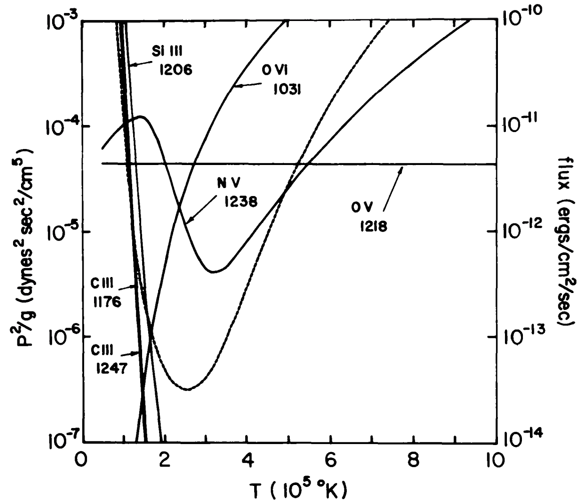

FIG. 2.—The dashed curve is the loci of points of P^2/g and T reproducing the observed intensity of the O v (1218 Å) line in β Gem. The left ordinate axis gives P^2/g. The other labeled curves give, as a function of T, the expected fluxes at the Earth of the indicated lines, for those values of P^2/g and T that give the observed intensity of the 1218 line. The right-side ordinate axis gives the flux.

VII. DISCUSSION

The main conclusion of this *Letter* is that β Gem has a corona characterized by temperatures near 260,000° K. This range of temperatures was unexpected because it is far cooler than the solar corona, typically estimated to be in the range 1.2–2.0 × 10^6 ° K, and the K1 III coronal model calculated by Ulmschneider (1967), which has a temperature of 2.8 × 10^6 ° K. The unexpected coolness of the β Gem corona suggests that this star has far weaker nonradiative heating than assumed by Ulmschneider.

Kuperus (1965) has also computed coronal temperatures for a grid of late-type stars using a somewhat different treatment of the heating term. For stars of 4400° K effective temperature he computes coronal temperatures of 2.0 × 10^6, 7.1 × 10^5, and 3.0 × 10^5 ° K for log g = 2.0, 3.0, and 4.0, respectively. Arcturus is similar to the log g = 2 model, β Gem to the log g = 3 model, and ϵ Eri to the log g = 4 model. As Kuperus points out, these coronal temperatures are uncertain due to our poor understanding of the heating function. Although the predicted coronal temperature for the

(4400,3) model appears high for β Gem, the predicted values of $P = 0.025$ dyn cm^{-2} and $P^2/g = 6.3 \times 10^{-7}$ cgs are similar to those derived in this *Letter*. Also the qualitative dependence of the coronal temperature on gravity for the Kuperus models suggests an explanation for the absence of detectable O v emission in Arcturus and ϵ Eri: namely, the corona of Arcturus is too hot and the corona of ϵ Eri is too cool.

We estimate the half-width at half-intensity for the O v line to be 0.30 Å corresponding to line-of-sight motions of 74 km s^{-1} or, for an assumed Gaussian line profile, a Doppler half-width of 90 km s^{-1}. Since the rms thermal velocity for oxygen at 260,000 °K is 20 km s^{-1}, the observed profile is formed mainly by nonthermal motions. However, the sound speed at this temperature is 85 km s^{-1}, so that turbulent motions with velocities of order the sound speed can account for the observed line width. The observed line center is displaced -0.06 ± 0.10 Å from the rest wavelength. We can estimate an upper limit for the stellar wind mass flux by assuming a velocity of 40 km s^{-1} corresponding to -0.16 Å at the base of the corona where the particle density is 4.5×10^8 cm^{-3}. This upper limit is 2×10^{-10} $M_\odot$ per year, but it should be increased if the coronal temperature is much different from 260,000° K.

It is interesting to note that a temperature of 260,000° K corresponds to the peak of the radiative power loss curve for cosmic abundances computed by Cox and Tucker (1969), so that additional nonradiative heating would likely make the β Gem corona thermally unstable until temperatures in excess of 10^6 ° K are reached as in the solar corona. Our estimate of the β Gem coronal temperature is based on a value of the pressure 1/10 that in the Sun. If we are in error by a factor of 10 so that the pressure is the solar value, then according to figure 2 the temperature is either 110,000° or 500,000° K. The first temperature is unlikely since Si III λ1206 was not observed, while the higher temperature is unlikely given the thermal instability argument cited above.

Finally, we discuss the assumptions used. The plane-parallel assumption is probably a good one since the coronal pressure scale-height $kT/\mu g \approx 0.07\ R_*$. The isothermal assumption is probably a poor one, however, as the thermal conductivity is only 2 percent that in a solar 1.2×10^6 ° K corona. At 260,000° K the optical depth at the center of the O v line is only 3.7×10^{-4}.

The proposed crude picture of the corona about β Gem should be tested and refined by other observations such as those proposed above for *Copernicus*.

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