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SEARCH FOR OPTICAL CORONAL LINE EMISSION FROM THE X-RAY SOURCES EPSILON ORIONIS (B0 Ia) AND KAPPA ORIONIS (B0.5 Ia)

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ABSTRACT

High signal-to-noise observations have been made at the wavelengths of the lines of [Fe X] 6574 Å and [Fe XIV] 5303 Å to search for evidence of a coronal region at the base of the winds of ϵ Ori (B0 Ia) and κ Ori (B0.5 Ia). These two stars have been detected as soft X-ray sources with the Imaging Proportional Counter (IPC) detector on board the *Einstein* X-Ray Observatory, and both stars also show anomalously strong O VI lines in the UV spectra, which has been explained as a product of Auger ionization in cool stellar wind. From the total X-ray flux and Auger-enhanced ionization, large coronal emission measures of a base corona were expected. The nondetection of the iron coronal lines places new upper limits on the emission measure if the coronal temperature is in the range $0.7 \times 10^6 < T_c < 3 \times 10^6$. The measured upper limits on the equivalent width of the Fe X and Fe XIV lines are 1 mÅ for narrow lines and 2.5 mÅ for lines assumed to be rotatonally broadened. This constrains the coronal temperatures to $T_c > 1 \times 10^6$ for κ Ori and $T_c > 2 \times 10^6$ for ϵ Ori. For ϵ Ori the constraints are then no longer compatible with the energy distribution measured with the IPC. It is suggested that at least some of the X-rays arise not from the base corona, but from source regions farther out in the wind.

Subject headings: stars: coronae — stars: individual — stars: supergiants — X-rays: sources

I. INTRODUCTION

It is now clear from *Einstein* satellite observations that essentially all O stars and early B supergiants have hot X-ray emitting regions somewhere in their outer atmospheres (Harnden *et al.* 1979; Long and White 1980; Vaiana *et al.* 1980). In a survey of O and B supergiants using the Imaging Proportional Counter (IPC) on the *Einstein* Observatory, ϵ Ori (B0 Ia) and κ Ori (B0.5 Ia) were found to have an emergent X-ray luminosity of about 10^{32} ergs s^{-1} (Cassinelli *et al.* 1981). The count rate from 0.2 and 3 keV was sufficiently large to derive some information concerning the emergent energy distribution from the pulse height spectra. The spectra peak at about 0.8 keV and are consistent with an attenuated thermal source with a temperature between 10^6 and 10^7 K. The emergent X-ray luminosity is sufficient to account for the anomalously high stages of ionization such as O VI seen in the UV spectra of the stars as had been proposed by Cassinelli and Olson (1979). However, neither the IPC spectra nor the presence of Auger-enhanced ionization in the outer wind gives firm evidence as to the location of the X-ray emitting material. The gas could be in a hot, slab corona at the base of the wind as suggested on the basis of Hα observations by Hearn (1975) and Cassinelli, Olson, and Stalio (1978), or the gas could be in hot wisps produced by shocks in the radiatively driven winds (Lucy and White 1980). The two possibilities differ in the amount of X-ray attenuation produced by the overlying wind material. As the wind opacity varies with frequency as ν^{-3}, the attenuation length and, hence, information concerning the location of the X-ray source could in principle be derived from the X-ray distribution. The low resolution IPC spectra are consistent with either (*a*) a relatively cool corona at the base of the wind with $T \approx 10^6$ K and emission measure EM $= N_e^2$ Vol $\approx 10^{58}$ cm^{-3} or (*b*) a hotter gas $T > 3 \times 10^6$ with EM $\sim 10^{55}$ in wisps farther out in the wind.

The large emission measures at T near 10^6 associated with the coronal option suggest that the material might be observable at the strong solar coronal lines of Fe X 6374 Å which peaks in abundance at 1.2×10^6 K or the Fe XIX 5303 Å line which peaks at 2.1×10^6 K. This paper concerns the search made for these two lines in the very bright OB supergiants ϵ Ori and κ Ori.

In § II the observational techniques are discussed, and limits on the line equivalent width are derived. The limits on the coronal emission measure imposed by the measurements are discussed in § III. The corresponding limits imposed by the X-ray emission and the O VI Auger-enhanced line are discussed in § IV, where it is shown that the Auger and total X-ray flux constraints on the base corona model are nearly redundant.

In the final section it is found that only a small zone in the EM versus T_c plot is not ruled out by the above constraints. Furthermore, for ϵ Ori the delimited region is not compatible with the IPC spectral information.

II. OBSERVATIONS

The observations have been obtained with the Washburn Observatory echelle spectrograph (Schroeder and Anderson 1971) attached to the 91 cm reflector of the

Pine Bluff Observing Station. The spectra were detected, recorded, calibrated, and reduced with the Observatory's intensified Reticon system (McNall and Nordsieck 1976; Percival and Nordsieck 1979, 1980; Nordsieck, Michalski, Percival, and Tobin 1981). The primary detector of the system is a Varian microchannel plate intensifier with an S-20 cathode and a P-20 phosphor output. The signal is recorded by means of a Reticon self-scanned photodiode array which is coupled to the intensifier by a fiber optics bundle.

The Reticon chip contains two parallel lines (called arrays A and B) of diodes separated by 2.5 mm. Each array contains 1872 individual photodiodes (pixels) which are 15 μm in width along the array and 0.75 mm long perpendicular to the array. In the present application one array measures the spectral signal while the other measures the inter-order, dark, and sky background. In the current application the highest possible resolution was not necessary, so in order to maximize the data collection rate a 200 μm entrance slit was used, corresponding to 3."2 at the f/13.5 focus of the 91 cm telescope. The dispersion of the system is 0.036 Å per pixel, and the various demagnifications in the spectrometer and detector result in a slit limited resolution (FWHM) of 9 pixels, 0.3 Å, or 15 km s^{-1} at 6000 Å.

Central to the detection of very weak lines is the precision with which the wavelength and flat-field calibrations can be performed. To this end the Pine Bluff 91 cm telescope has been equipped with an optical bench which can be inserted over the Cassegrain light baffle. The bench is equipped with both emission line and continuum sources so designed as to maintain collimation and beam geometry identity with respect to that of the telescope. During the course of this investigation a substantial improvement in the quality of flat-field calibration was realized by the application of antireflection coatings to the window which separates the detector thermal control cavity from the spectrograph.

During the observations both wavelength and flat-field calibration scans were interspersed with the stellar observations with the telescope pointed at the object to remove effects of flexure. The details of the data reduction procedure are discussed in detail in Anderson, Oliverson, and Nordsieck (1980).

Observations of ϵ Ori and κ Ori were obtained on the nights of 1980 January 6 and 14 and 1980 February 4 (Fe x λ6374) and 1980 March 2, 3, and 6 (Fe xiv λ5303). Each night's spectrum was wavelength calibrated and velocity shifted to the stellar rest frame, using the heliocentric correction and stellar radial velocities of $+26$ km s^{-1} for ϵ Ori and $+21$ km s^{-1} for κ Ori. Figures 1*a* and 1*b* show the mean of all spectra for each star, using linear intensity units which are arbitrarily normalized. Only the results from the A array are shown, since intercomparisons of the B array spectra showed the flat-field repeatability to be inferior. Data in the region λ5290 coincided with an image tube defect and are not plotted. The calibrated spectra were divided by a fitted fourth order polynomial to remove a smooth trend of amplitude $\sim 3\%$ which remained after the flat-field calibration. Each point represents the mean of 0.3 Å (about 9 pixels) of data, comparable to the resolution element.

No obvious emission lines are present at the predicted position. The only clear spectral feature is a photospheric absorption line in both ϵ Ori and κ Ori near 5314.5 Å. These have equivalent widths of 23 and 27 mÅ, respectively, and are tentatively identified as N III λ5314.45, possibly blended with N II λ5313.43; their widths are consistent with the rotational broadening of 85 and 81 km s^{-1} (Uesugi and Fukuda, 1970). One-sigma observational upper limits for the coronal emission lines were estimated to be 1 mÅ for a narrow line ($\Delta\lambda \lesssim 0.3$ Å) and 2.5 mÅ for a rotationally broadened line ($\Delta\lambda = 1.5$ Å). The former limit would apply if the coronal material were spatially confined in polar plumes or an evanescent loop. The minimum line width then would be 0.4 Å for material at 2×10^6 K. An examination of data from the individual night's observations showed no obvious variable wavelength features that might be consistent with evanescent loops. The rotationally broadened limit holds for a thin uniform corona rotating with the star and not participating significantly in the wind expansion. The limits were estimated by evaluating the mean of the equivalent widths (without regard to sign) of hypothetical lines distributed evenly over the spectrum. Only the λ5314 photospheric line was eliminated from this estimate; the possible presence of unidentified small lines would of course make this a pessimistic estimate.

Slightly larger upper limits would be obtained if the coronal rotational line broadening were enhanced by an appreciable coronal thickness or if part of the corona participated in the expansion at the base of the wind. Such upper limits were found to scale approximately as the square root of the expected line width. In one proposed coronal model (Lucy and White 1980) X-ray emitting wisps are distributed throughout the wind, thus reducing the X-ray attenuation and the required coronal material. Lines from such wisp material would be at least 15 Å wide and would be essentially undetectable in this data because of the difficulty of assigning the continuum. The Lucy and White model is discussed further in § V.

III. CORONAL LINE EMISSION

The red Fe x line and green Fe xiv line are two of the strongest lines in the solar corona, where temperatures are about 2–4 $\times 10^6$ K and electron densities are of order 10^9–10^{10} cm^{-3}. The postulated coronae of the OB supergiants have densities at least an order of magnitude larger as judged from observed mass loss rates. This higher density affects the expected thermal structure of the outer atmosphere. Hearn (1975) suggested that the higher densities in the coronae of OB supergiants should lead to a two component temperature structure. A rapid decrease in temperature should occur in a thin recombination layer on top of the corona, and thus there would be an abrupt transition from a corona zone to an cooler outer region. The recombination is proportional to N_e^2 and so is much more important in the OB supergiant winds than in the solar wind. Cassinelli, Olson, and Stalio (1978) studied the observational effects of a corona on the Hα

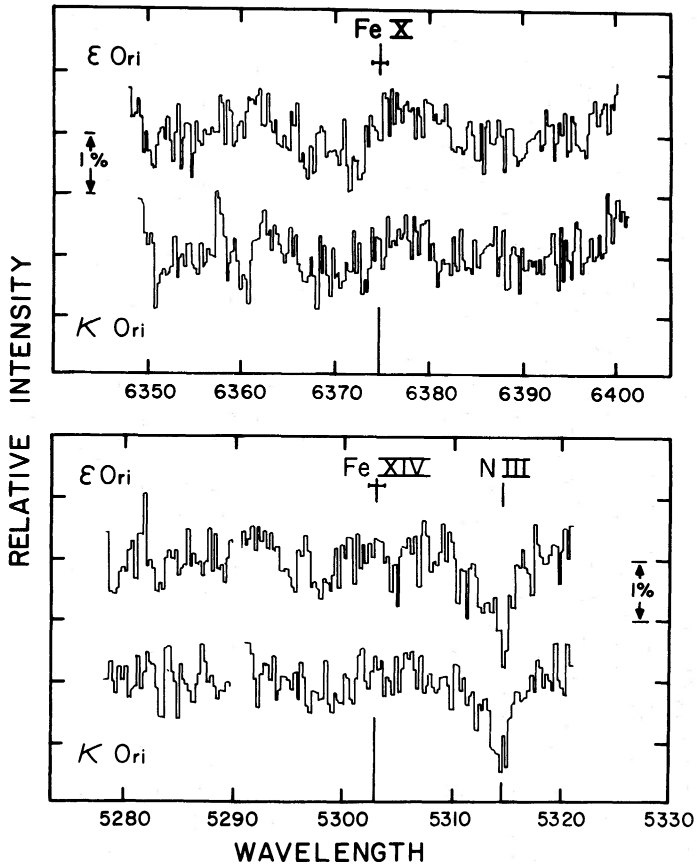

FIG. 1.—Reticon echelle spectra of ε Ori and κ Ori in the region of the coronal lines Fe X and XIV. Each point is a mean of 0.3 Å (9 pixels). The spectra have been shifted to the rest frames of the stars and the positions of Fe X λ6374.5 and Fe XIV λ5302.9 are shown lined up. The rotationally broadened line width used in one of the equivalent width estimates is shown. The only apparent feature is a photospheric line of equivalent width 25 mÅ, tentatively identified as N III 5314.5.

line in ζ Ori (O9.5 I). They deduced that the corona would have to be very thin ($\lesssim 0.1\ R_*$) and with a velocity at the base of the cool overlying wind of only about $\frac{1}{20}$ the terminal speed, v_∞, in order to avoid flat topped emission profiles. Flat topped emission features are not seen in the Hα profiles of either κ Ori or ε Ori (Ebbets 1981), so we again will presume that the coronae are thin and with velocities in the coronae of $v_c = \frac{1}{20} v_\infty$ (This is about two thirds the speed of sound in a corona at $T = 2 \times 10^6$). Given a mass loss rate of $\dot{M} = 3.1 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ for ε Ori (Abbott *et al.* 1980), the density in the corona must be $1.5 \times 10^{11}\ \mathrm{cm}^{-3}$, and using $\dot{M} = 1.0 \times 10^{-6}$ for κ Ori (Barlow and Cohen 1977; Abbott *et al.* 1980) gives $N_e = 4.1 \times 10^{10}\ \mathrm{cm}^{-3}$.

Another consequence of the higher densities is that the upper levels of the λλ6374, 5303 lines are nearly saturated, i.e., the population of the upper level is nearly that given by the Boltzmann distribution. In the saturated limit, the population of the upper level is proportional to the electron density N_e, instead of being proportional to N_e^2, as is the case in the low density limit in which collisions up are balanced by radiative transitions down.

The luminosity of a line is given by

$$L = N_2{}^i A_{21} h\nu V\,, \tag{1}$$

where V is the volume of the emitting material, A_{21} is the transition probability, and $N_2{}^i$ the population of the upper level in ion i, which depends on the excitation and ionization balance, and abundance of iron relative to electrons. We have used the calculations of Mason (1975) for the emissivity of the two lines as a function of N_e and T. The iron abundance assumed in those calculations was $[N(\mathrm{Fe})/N(\mathrm{H})] = 7 \times 10^{-5}$. Following Mason, we write

$$\begin{aligned} L &= 2\pi J(T, N_e) N_e f V \\ &= 2\pi J(T, N_e) f\,\mathrm{EM}/N_e\,, \end{aligned} \tag{2}$$

where the 2π indicates we are counting only the photons in the outward 2π steradians, EM is the emission measure, J is the emission per unit volume per steradian, and f is the coronal filling factor. We will assume the filling factor is unity in this paper. If the coronal material is clumped, the upper limits derived here for the emission measure will be higher, inversely proportional to f.

$J(T, N_e)N_e$ is tabulated by Mason for both Fe x and Fe xiv for the temperatures and coronal electron densities of interest here.

The equivalent width of the line (in Å) is $\mathrm{EW} = L/L_\lambda{}^*$ where $L_\lambda{}^*$ is the monochromatic luminosity of the stellar photosphere continuum in the neighborhood of the line. Thus, given the density and the observed line equivalent width, we get an expression for the coronal emission measure as a function of temperature,

$$\mathrm{EM} = \mathrm{EW} L_\lambda{}^* N_e / 2\pi J(T, N_e) \,. \tag{3}$$

This relation is shown in Figure 2 for both ϵ Ori and κ Ori. The results were calculated for the densities quoted above, and for an equivalent width of 1 mÅ, which is the approximate observational limit discussed earlier. Note our upper limit on the line strength implies an upper limit of about 10^{58} cm^{-3}, if the corona has a temperature in the broad range from 0.7 to 3×10^6 K.

IV. THE EMERGENT X-RAY FLUX AND AUGER-ENHANCED O VI

Here we consider the observations directly related to the X-ray emission of a corona—the emergent X-ray flux and the high ion stages that are produced in the wind by the Auger effect. The ultraviolet spectra of O-stars and OB supergiants through to B0.5 show strong P Cygni shaped lines of the anomalously high state of ionization O vi. The absorption on the shortward side of the line extends to large Doppler velocities, indicating that the ion exists even far out in the wind where the flow has reached terminal velocity. The presence of O vi and its persistence to B0.5 can be explained nicely by the Auger mechanism. As two electrons are ejected from C, N, or O after K shell absorption of an X-ray photon, O vi should be produced in measurable quantities as long as O iv is the dominant ion stage, i.e., until B0.5 (Cassinelli and Olson 1979). In a similar way, the persistence of N v as

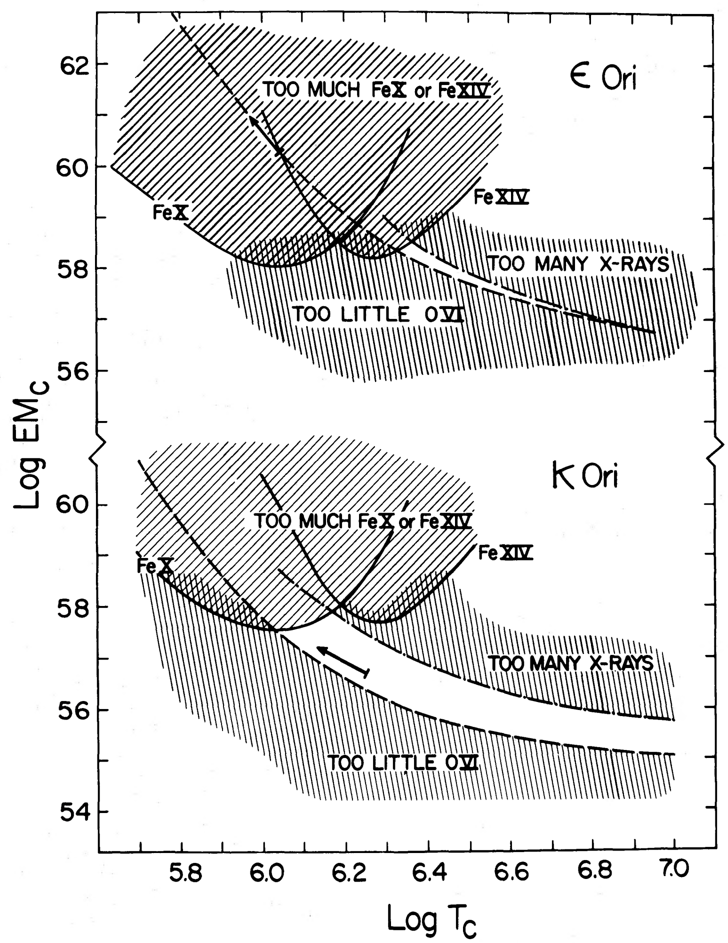

FIG. 2.—Summary of the observational constraints on the base corona emission measures and coronal temperatures of ϵ Ori and κ Ori that were derived from (*a*) the Fe x, and Fe xiv measurements reported in this paper; (*b*) the X-ray count rates from the *Einstein* satellite; and (*c*) the Auger produced O vi that is seen in *Copernicus* ultraviolet spectra. The limits shown for Fe x and Fe xiv correspond to an equivalent width of 1 mÅ. The limit for the X-ray flux is for a count rate 2 times the nominal rate, to account roughly for the instrumental uncertainty. The limit shown for O vi is for $g(\mathrm{O\ VI}) = 10^{-3}$. The unshaded region shows the net delimited region that is acceptable for all three types of observations. In each figure the arrow gives the emission measure and temperature limits determined from the IPC X-ray spectrum for base coronal models. Note that for ϵ Ori these X-ray spectral data are incompatible with the other constraints. This calls into question the assumption that all the hot gas is in a base corona.

late as B2.5 I and C IV as late as B6 I is understandable by the Auger model. The ultraviolet ionization anomalies inform us of the X-ray flux beyond the K shell ionization edge, which is at about 0.6 keV for oxygen. We shall see in this section that the information derivable from the Auger produced O VI is nearly redundant with the total X-ray flux seen by the IPC. This is because both are a measure of the emergent radiation at about 1 keV, and hence both are affected by the attenuation of the X-rays in the wind material above the corona. If the corona temperature is low, the attenuation of the emitted, predominantly soft, X-rays is very large and a correspondingly large coronal emission measure is required to produce the observed emergent radiation.

a) The Measured X-ray Flux

The two supergiants were observed at X-ray energies with the IPC for about 2000 seconds each. The count rate for ϵ Ori was $r = 0.40$ counts s^{-1}, while for κ Ori it was 0.10 counts s^{-1}. Using the nominal sensitivity of the IPC of $S = 2 \times 10^{-11}$ ergs cm^{-2} count^{-1}, these rates correspond to detected X-ray luminosities of $L_x = 2 \times 10^{32}$ ergs s^{-1} for ϵ Ori and 1×10^{32} ergs s^{-1} for κ Ori. The detected luminosity is related to the emission measure, the temperature, and the attenuation optical depth τ_ν through

$$L_x = S\,\mathrm{EM} \int \Lambda_\nu(T_c) e^{-\tau_\nu} \left(\frac{A_\nu d\nu}{h\nu}\right), \qquad (4)$$

where A_ν is the instrumental sensitivity function (Giacconi *et al.* 1979), and $\Lambda_c(T_c)$ is the thermal continuum plus line emissivity (ergs cm^3 s^{-1} Hz^{-1}) (Raymond and Smith 1977).

b) The O VI *Abundance*

Analyses of the UV spectra (Olson and Castor 1981) indicate that more than about 10^{-3} of oxygen must be in the form of O VI, and that an abundance greater than 10^{-2} would more than suffice. Therefore we assume that the relative abundance, $g = N(\mathrm{O\ VI})/N(\mathrm{O})$, lies in the range of $10^{-3} < g \leq 10^{-2}$. For a given abundance of O VI in the outer wind, the Auger ionization balance equation gives:

$$g = \frac{W}{N_e \alpha} \frac{4\pi}{h} \mathrm{EM} \int_{\nu_0}^{\infty} \Lambda(T_c) e^{-\tau_\nu} \left(\frac{a_0 \nu_0{}^3}{\nu^3}\right)\left(\frac{d\nu}{\nu}\right), \qquad (5)$$

where W is the dilution factor, α is the recombination coefficient from O VI to O V, $W/N_e \approx$ constant since both vary as $1/r^2$ in the outer regions of the wind, and a_0 is the absorption coefficient at the K edge of oxygen at ν_0. Assuming that $\Lambda = \Lambda_0(T) e^{-h\nu/kT}$ like a bremsstrahlung spectrum, we see that L_x and g are related by

$$\frac{L_x}{g} = \frac{S}{K} \int e^{-h\nu/kT} e^{-\tau_\nu} A_\nu \frac{d\nu}{\nu} \left[\int e^{-h\nu/kT} e^{-\tau_\nu} \frac{d\nu}{\nu^4}\right]^{-1}, \qquad (6)$$

where K is a constant depending on mass loss rates, $\alpha(T)$, and constants. For large temperatures, $h\nu/kT \ll 1$, and the temperature dependence of L_x/g cancels out, indicating that both L_x and g provide the same information concerning T. For small temperatures, the product of the two exponentials inside the integrals forms a sharply peaked pseudo–delta function, f_1, and the integrals may be solved by the method of steepest descent. The rate of L_x/g then depends on the value of A_ν at the peak of the function f_1, and we find again that the ratio is a relatively weak function of T. The net result is that the measurements of L_x and g are nearly redundant as far as deriving a temperature of a base corona, and because both are affected by attenuation in the same way, the emission measure required to produce a given value of L_x and g is a steep function of T_c for $T_c \lesssim 3 \times 10^6$. This is to be contrasted with the result derived for the Fe X and Fe XIV coronal line measurements, which over the temperature range $0.7 \times 10^6 < T_c < 3 \times 10^6$ is primarily a measure of the coronal emission measure.

c) The IPC Spectral Information

For sources with a sufficient count rate, the IPC pulse height distribution is given as a 15 bin spectrum covering the energy range 0.2 to 3 or 4 keV. The IPC spectra for ϵ Ori and κ Ori are displayed in Figure 3 of Cassinelli *et al.* (1981) and are analyzed there on the basis of the slab coronal model. The corona is assumed to emit continuum and line radiation as calculated by Raymond and Smith (1977, with more recent updates), and the emergent flux depends on the assumed coronal temperature, the emission measure of the corona, and the wind column density. After accounting for a 10% uncertainty in the IPC gain parameter, upper limits on the coronal temperatures are derived from fits to the observed spectrum. These upper limits (shown in Fig. 3 of Cassinelli *et al.* 1981) are $T_c < 1.1 \times 10^6$ K for ϵ Ori and $T_c < 1.8 \times 10^6$ for κ Ori. The coronal emission measure required to fit the spectra depends on the coronal temperature in the following way. As the assumed temperature of the corona is decreased, a larger fraction of the coronal emission is absorbed in the wind, and hence a larger emission measure is required to provide the observed flux. The limits derived for the coronal temperature and emission measure from the IPC analysis are shown by the arrows in Figures 2*a* and 2*b*.

V. DISCUSSION

The results of the constraints imposed on EM_c and T_c by the optical, ultraviolet, and X-ray observations discussed in the previous two sections are shown in Figure 2. We have assumed that there must be an abundance of at least 10^{-3} of O VI to derive a lower limit on the emission measure at any T_c. We assume that the count rate could be no larger than a factor of 2 more than the rates presented earlier for ε Ori and κ Ori. The factor should adequately cover the uncertainty in the sensitivity S and the gain at the time of the observation. This places an upper limit on EM_c over the range of T_c. Note in the figure that, as explained in the previous section, the information derived from L_x and g(O VI) is nearly redundant.

The upper limit of EM_c imposed by our Reticon observations of the iron coronal lines is also shown for the 1 mÅ "narrow line" upper limit. The net effect of these observations is to place a lower limit on the temperature of the coronae. For ϵ Ori the corona must have a temperature above 2.0×10^6 K, and for κ Ori the minimal temperature is 1.0×10^6 K. Relaxing the Reticon upper limits to 2.5 mÅ (the rotationally broadened limit) relaxes the temperature lower limits by about 10% to 1.8×10^6 (ϵ Ori) and 0.9×10^6 (κ Ori). The IPC spectral data for κ Ori is found to be consistent with the L_x, g, and Fe limits, in that the spectra require a temperature less than 1.8×10^6 K. However, for ϵ Ori the IPC spectral information is *not* compatible with the delimited regions as it must be less than 1.1×10^6 K. This would be the case, even if the attenuation column density were reduced by a factor of 4. The mass loss determination of Abbott *et al.* (1980) and other factors affecting the column density are not thought to be uncertain by such a large factor.

This disagreement in ϵ Ori is an indication that the slab coronal model of Cassinelli and Olson (1979) is not simultaneously consistent with the optical, UV, and X-ray observations. The most likely explanation is that at least some of the X-ray emission is coming from regions farther out in the wind, as had been postulated by Natta *et al.* (1975) in their explanation of the O VI enhancement. A model with hot wisps located in the outflowing wind has been worked out by Lucy and White (1980). The model explains the X-rays from O stars and OB supergiants as being produced in shocks at the interface of radiatively driven clouds and ambient, radiatively shielded wind material.

If the observed X-ray flux is to be derived wholly from unattenuated wisp material at the *top* of the wind, it would be insufficient to penetrate to the base of the wind to provide an Auger effect throughout the wind, as has been assumed here. Indeed, it is possible that the Auger effect is more complete in the outer part of the wind, as suggested in the Lamers *et al.* (1980) analysis of the Copernicus spectra of Snow and Jenkins (1977). They found that for ϵ Ori and κ Ori and for many similar OB supergiants, at least half the O VI line absorption occurs in "shells" with displacement velocities of the order 10^3 km s^{-1}. One possible picture is that these shells are Auger-ionized by wisp material in the outer part of the wind, which also provides the observed X-ray flux, while the rest of the inner wind Auger ionization is provided by a base corona whose X-ray flux does not penetrate the wind. The emission measure of the base corona component would then be subject to the coronal line limits discussed in this paper. In any case, our Fe X and Fe XIV line measurements unfortunately do not place useful constraints on the wisp component. Wisp material would be moving relative to the star, and the emission would be spread over a Doppler range of, say, 500 km s^{-1} and then would be undetectable by our measurement. Our measurements provide limits on only the amount of material in relatively stationary coronal components.

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