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X-RAY SPECTRA OF ORION OB SUPERGIANTS

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ABSTRACT

Observations from the *Einstein* satellite have been made of the three belt stars of Orion using the solid state spectrometer. The spectra are at a higher energy resolution than previous X-ray observations of OB supergiants, and this permits stronger constraints to be placed on the location of the emission source in the outer atmosphere. The spectra of all three stars are found to be consistent with thermal sources that are only slightly attenuated by stellar wind opacity and have temperatures of $\sim 10^{6.5 \pm 0.2}$ K. Several explanations of the soft X-ray flux distributions of early-type stars are tested. A model with the X-rays coming only from a corona in a slab at the base of the wind appears to be ruled out unless the ionization or density structure of the overlying material is significantly different from that usually assumed for a cool wind. A model with the X-rays produced by radiatively driven shocks, some of which must be strong, can explain the X-ray luminosity and satisfy upper limits on the absorption by oxygen that is derived from the data. There could be a high-energy (> 1 keV) contribution from a base coronal zone. The spectrum of ζ Ori shows emission near 2 keV, which may be interpreted as line emission of Si XIII and S XV from a very hot source component with $T = 1.5 \times 10^7$ K. This gas could be in magnetically confined regions at the base of the wind. A comparison is made with earlier X-ray observations made with the imaging proportional counter.

Subject headings: stars: early-type — stars: supergiants — stars: winds — X-rays: spectra

I. INTRODUCTION

Observations with the imaging proportional counter (IPC) on board the *Einstein Observatory* have shown that essentially all O stars are X-ray sources as are OB supergiants with spectral types at least as late as B2 Ia (Harnden *et al.* 1979; Long and White 1980; Cassinelli *et al.* 1981). Prior to the observations, Hearn (1975), Cassinelli, Olson, and Stalio (1978), and Cassinelli and Olson (1979) argued that there is a thin coronal region lying at the base of the stellar winds of these stars. Radiation from the corona could explain the presence of lines of highly ionized species, such as O VI and N V in the ultraviolet, by K shell ionization followed by the Auger effect. The X-ray spectra for such coronae were predicted by Cassinelli and Olson (1979). Because of attenuation in the stellar wind, little flux below 1 keV was predicted. However, even in the relatively low energy resolution spectra of the IPC, it was clear that there is far more flux below 1 keV than was predicted (Long and White 1980; Cassinelli *et al.* 1981).

There have been two approaches in the ideas of a better model: (1) to generate the X-rays far out in the wind and (2) to decrease the attenuation by the wind. Lucy and White (1980) and Lucy (1982) explored models with X-rays produced in shocks occurring in the wind. To estimate X-ray fluxes, Lucy and White conjectured that instabilities give rise to blobs that are radiatively driven through the envelope of the star. Lucy proposed that the outflow takes the form of periodic shocks that propagate far out into the flow and that the shocks survive until shadowing by following shocks compels their decay. On the other hand, Stewart and Fabian (1981) and Waldron (1983*a*) have argued that the X-rays are produced in a base corona, but the flux is not as heavily attenuated as calculated by Cassinelli and Olson (1979), because there is less wind material, or the gas in the wind is more highly ionized than had been assumed.

This paper presents the results of observations of the X-ray spectra of the three belt stars of Orion using the solid state spectrometer (SSS) on the *Einstein Observatory*. The stars were known to be strong stellar sources from earlier IPC observations and to have characteristic source temperatures of a few million degrees (Long and White 1980; Cassinelli *et al.* 1981). The SSS is well suited for the study of plasmas at a temperature of 5–20×10^6 K. In this range, the resonance lines of helium-like ions of Mg, Si, S, Ar, and Ca can, for some sources, have large equivalent widths that are easily observable with the SSS resolution. For lower temperatures, the dominant lines are below 1 keV and are too close in energy to be individually resolved. Nevertheless, the flux at these energies is sensitive to the source temperature and attenuating column density. The observations of the Orion stars occurred under optimal conditions, when the instrumental efficiency was good down to 0.5 keV. The data provide a measurement of the column density of stellar wind material absorbing at the K shell edge of oxygen at 0.6 keV. The SSS results much more narrowly define the apparent temperatures of the sources and put severe limits on any absorption at the K edge of oxygen. We discuss whether any of the recent models can explain these results.

II. OBSERVATIONS

The three stars were observed in 1979 September and October, the last months of operation of the SSS. The instrument consists of a cryogenically cooled Si(Li) detector at the focus of the *Einstein Observatory* telescope. It has a resolution of about 160 eV over the energy range from 0.5 to 4 keV. The SSS is described in detail by Joyce *et al.* (1978).

Stellar parameters for the three stars observed are given in Table 1. The stellar radii, R, and wind terminal velocity, v_∞, are from Abbott (1978). The mass loss rates, $\dot{M}$, are from the radio observations of Abbott *et al.* (1980). The stellar distance and interstellar column densities are from Savage *et al.* (1977). The "maximum wind column density", N_H(max) is an estimate of the column density through the wind to the top of a slab corona, and EM_w is an estimate of the emission measure (n_e^2 Vol) of that wind material, as discussed in Cassinelli and Olson (1979) and Cassinelli *et al.* (1981). The effective observing time and the dates of the observations are given in the last two rows of Table 1.

Figure 1 shows the SSS spectra of the three stars as a function of energy from 0.5 to 4 keV with the 1 σ uncertainties. We have tested whether the spectra can be characterized as resulting from one or two thermal sources, each source at some temperature and depth in the stellar wind. The procedure is to fold the model spectra through the detector response function and make a chi-square comparison with the data. We used the collisional equilibrium thermal models calculated by Raymond and Smith (1977, 1979), usually fixing the elemental abundances at solar values. The initial fits to the spectrum were carried out with single source models in which the source temperature, column density and emission measure are adjusted, free parameters. There are two contributions to the absorbing column density, N_H: the interstellar medium column density N_H (ISM) (taken as the fixed value given in Table 1) and the unknown wind column density, $N_H(W)$, which as the maximum value listed in Table 1. For the attentuation of X-rays by the interstellar gas, we have used the opacity per hydrogen nucleus given by Fireman (1974). The corresponding opacity for the wind material was calculated as described and illustrated in Cassinelli *et al.* (1981). The parameters for these fits are given in Table 2, and the best fitting single-component models are shown in Figure 1. More than 50% of the flux below 1 keV is due to lines which are too closely spaced to be resolved as separate features. Note in Figure 1 that none of the stars show noticeable absorption at the 0.6 keV K shell edge of oxygen. Figure 2 compares the 90% confidence contours for T and $N_H(W)$ of the fits for ε Ori in this model to those from the IPC data (Cassinelli *et al.* 1981). The comparison of the SSS results with the 90% confidence region derived from the IPC pulse-height spectrum with bins that are in the energy range from 0.5 to 4 keV shows satisfactory agreement. The IPC is also sensitive to X-rays with energies as low as 0.1 keV. Using this additional spectral data reduces the range of acceptable values of T and N_H such that the SSS region is not included. Perhaps this discrepancy indicates that the single-component thermal model is not fully consistent with all of the data. Note also in Figure 2 that, in

TABLE 1

STELLAR PARAMETERS

Parameter	ζ Ori A	ε Ori	δ Ori A
Spectral type	09.5Ia	B0Ia	09.5I
Distance (pc)	352	409	384
Radius ($R_\odot$)	24	33	20
Wind velocity v_∞ (km s^{-1})	2290	2010	2410
Mass loss rate ($M_\odot$ yr^{-1})	2.3×10^{-6}	3.1×10^{-6}	1.3×10^{-6}
Wind emission measure EM_W (cm^{-3})	$10^{58.5}$	$10^{58.7}$	$10^{58.0}$
Maximum wind N_H (cm^{-2})	$10^{22.38}$	$10^{22.44}$	$10^{22.19}$
Interstellar N_H (cm^{-2})	$10^{20.41}$	$10^{20.45}$	$10^{20.23}$
Eff. observing time (hr)	7.7	14.3	5.9
Date observed	1979 Sep 14	1979 Oct 3	1979 Oct 12
Count rate (ct s^{-1})	0.40	0.31	0.46

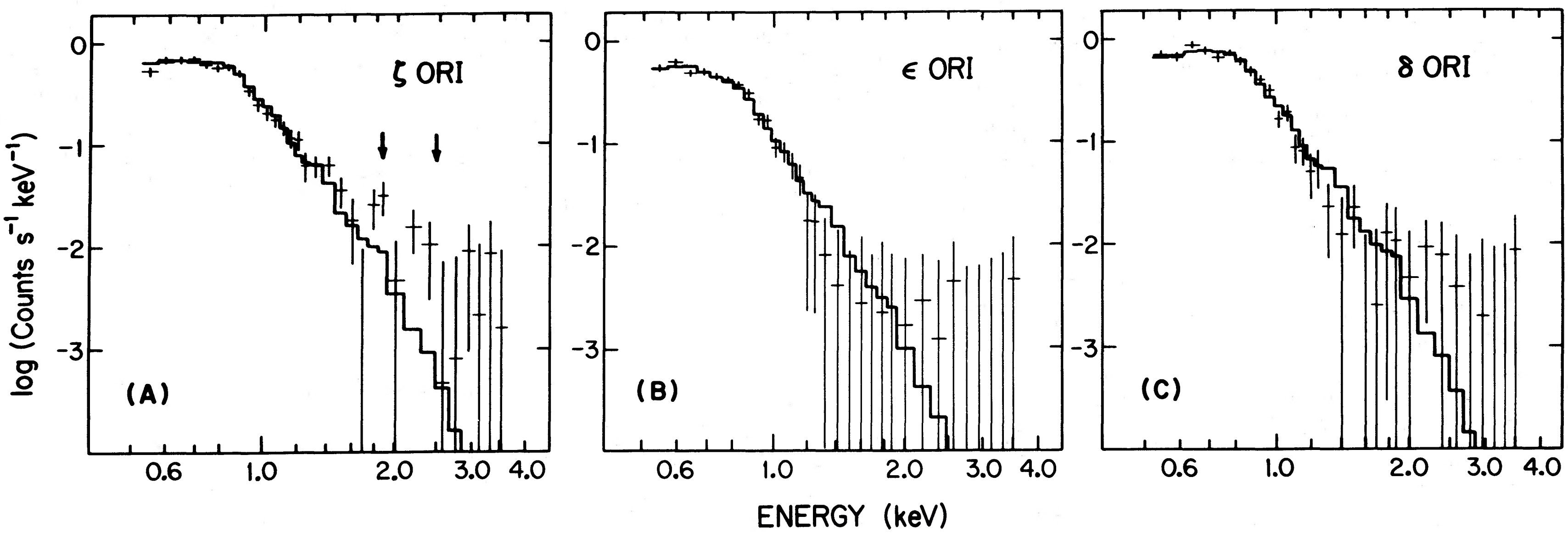

FIG. 1.—The SSS spectra of the three belt stars of Orion are shown with 1 σ error bars. The best fit single-component thermal source model is also shown for each spectrum. The arrows in the ζ Ori frame indicate the location of lines of Si XIII and S XV.

TABLE 2

SSS SPECTRAL FITTING RESULTS

	FIRST COMPONENT				SECOND COMPONENT				
SOURCE	T (10^6)	log N_H (cm^{-2})	EM (cm^{-3})[a]	L (ergs s^{-1})[b]	T (10^6 K)	log N_H (cm^{-2})	EM (cm^{-3})	L (ergs s^{-1})[c]	χ^2
ζ Ori O9.5 Ia:									
Single source	3.8	21.50	1.3×10^{55}	...	...	...	...	...	37
Outer source + slab corona[c]	4.7	21.16	0.7×10^{55}	...	1.4	22.38	1×10^{57}	...	31
Two sources	4.0	21.18	0.9×10^{55}	8.2×10^{31}	15.0	21.65	2×10^{54}	1.8×10^{30}	23
ϵ Ori B0 Ia:									
Single source	3.3	21.37	1.0×10^{55}	7.8×10^{31}	...	...	...	...	20
Outer source + slab corona[c]	3.3	21.37	0.8×10^{55}	...	1.4	22.44	1×10^{57}	4.0×10^{30}	28
δ Ori O9.0 II:									
Single source	4.0	21.18	0.9×10^{55}	1.1×10^{32}	...	...	...	...	26

[a] Source emission measure (EM) corresponding to the observed X-ray fluxes. The source EM could be up to 2 times larger, depending on the extent of the source and the occultation by the star.

[b] The 0.5–4 keV luminosity corrected for interstellar absorption.

[c] Here the slab is assumed to be relatively cool (1.4×10^6 K) in order to assess the emission measure of a hidden base corona.

contrast to the lower resolution IPC results, the SSS spectrum does not allow for a single component at the base of the wind, which would have an overlying column density in the range indicated on the figure by N_H(max).

III. COMPARISON WITH EXISTING SOURCE MODELS

a) *Slab Coronal Model*

In the corona plus cool wind model of Cassinelli and Olson (1979), it is assumed that there is a discontinuous drop in temperature at the top of the corona, and thus the corona has the form of a slab above the photosphere. Hearn (1975) argued that this should be a good approximation because the densities in the winds of OB supergiants are so large that radiative cooling in a recombination region should give rise to a very rapid decrease in the temperature. This structure was found by Cassinelli, Olson, and Stalio (1978) to be compatible with observed Hα line profiles.

The two-component temperature structure should lead to a maximal attentuation of coronal X-rays by the cool, overlying wind material. The attenuation should be especially large at the strong oxygen K shell edge at 0.6 keV. As the opacity decreases with energy as E^{-3}, the X-ray flux should increase at larger energies. Long and White (1980) showed that the predicted X-ray spectrum for ζ Pup did not agree with the observed IPC spectra. However, 90% confidence contours on a source temperature versus column density plot are very large and do not convincingly rule out a slab model (Long and White 1980; Cassinelli *et al.* 1981) (see Fig. 2).

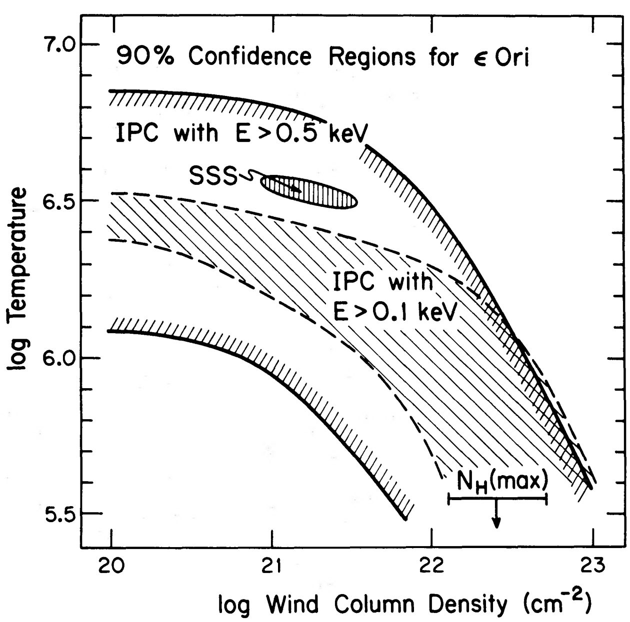

FIG. 2.—Limits on the source column density and wind column density derived from single-component thermal model fits to ϵ Ori. The 90% confidence regions are shown both for the fits to the SSS spectrum analyzed in this paper and the IPC spectrum analyzed by Cassinelli *et al.* (1981). The IPC results are shown for two energy ranges as indicated: the full range of sensitivity of the IPC (0.1–4 keV) and the range (0.5–4 keV) corresponding to the sensitivity energy band of the SSS. The range of likely hydrogen column densities through the wind is indicated at the base of the figure and is seen to be well beyond the range allowed by the SSS observations.

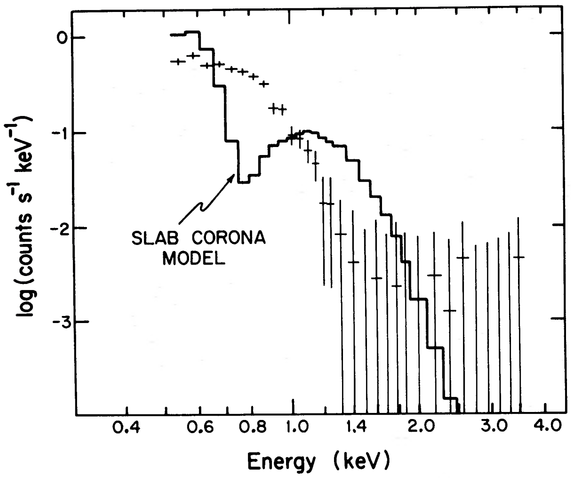

FIG. 3.—Shows a comparison of the SSS spectrum for ε Ori with the prediction of the slab corona plus cool wind model of Cassinelli and Olson (1979). The large absorption edge at 0.6 keV is caused by K shell ionization of oxygen occurring in the thick wind. The model shown corresponds to source parameters: $T = 1.7 \times 10^6$ K, $N_H = 10^{22.44}$ cm^{-2}, EM $= 10^{58}$ cm^{-3}.

Figure 3 shows the clearly incorrect predictions of the slab coronal model for ε Ori compared with the SSS spectrum of this star. Table 2 shows that the column densities of the best fit single-component models are about an order of magnitude smaller than the column density to the base of the wind (row [7] in Table 1). For ε Ori, N_H(best fit) $= 10^{21.37}$ versus $N_H(\max) = 10^{22.44}$. Using the standard velocity law discussed in Cassinelli and Olson (1979), $v^2 = v_0^2 + v_1^2(1 - R/r)$, it is possible to express the column density down to a given radius in terms of the velocity of the flow at that radius (see eq. [13] in that paper):

$$N_H(v)/N_H(\max) = [v_\infty - v(r)]/(v_\infty - v_0).$$

For a ratio of 0.1, this equation indicates that the X-rays arise from the regions where $v(r) \approx 0.9 v_\infty$, i.e., very far out in the wind.

There would, however, be other problems with taking this best fit single-component model literally. For example, the P Cygni profiles of O VI and N V indicate that these ions exist throughout the stellar winds of early-type stars (Lamers and Morton 1976; Olson and Castor 1981). X-rays from a single source at $v \sim 0.9 v_\infty$ and with an emission measure of $n_e^2 V = 10^{55}$ cm^{-3} could not be responsible for the production of O VI and N V in the deeper layers of the wind. The base coronal model calculations indicated that a single-component source would need a much larger emission measure of $\sim 10^{58}$ cm^{-3} to overcome the attenuation of the wind so as to account for the high ion stages at all levels in the wind. We are therefore led to consider distributed emission source models like that of Lucy and White (1980) or possibly two-component models, with one component being a corona at the base of the flow.

b) Radiation-Driven Shock Models

Lucy and White (1980) and Lucy (1982) have developed two versions of radiation-driven shock source models that lead to the production of hot regions in the accelerating regions of stellar winds. The initial growth

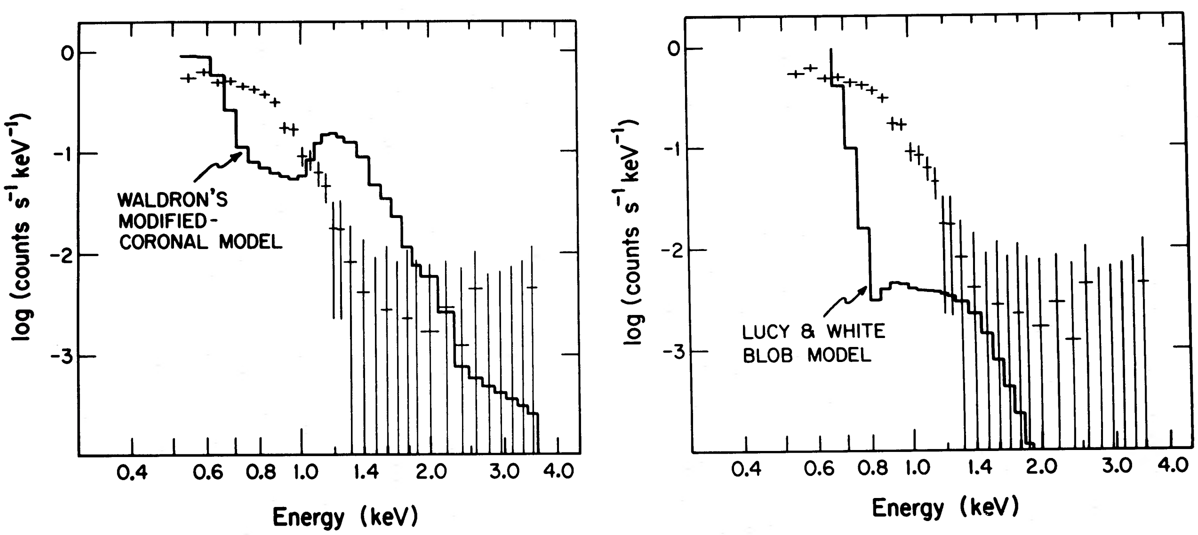

FIG. 4.—Shows the spectra predicted from two models to explain the X-ray spectra of O and OB stars. (*left*) Shows the Waldron (1983*a*) modified base coronal model, which has less opacity in the wind than the slab coronal model because of higher wind ionization. (*right*) Shows the spectrum predicted from the radiatively driven blob model of Lucy and White (1980) for ζ Pup in which X-rays are expected to be formed near the base of the wind.

of instabilities in line-driven winds has been discussed by Nelson and Hearn (1978), MacGregor, Hartmann, and Raymond (1979), Carlberg (1980), and Kahn (1981). Lucy and White (1980) proposed that the instabilities grow into radiatively driven blobs that produce a shock temperature of $\sim 10^6$ K at the interface between the blob and the gas in front of it. As in the coronal model, the X-rays can be attenuated by the wind material between the source and the observer. In the Lucy and White model, the shocks are at maximum strength very close to the star and the attenuation, while less than in the slab coronal model, is still appreciable. This is illustrated in Figure 4(*right*), where we compare the predictions of Lucy and White for ζ Pup with the SSS spectrum of ε Ori, a star which has about the same mass loss rate ($\sim 10^{-5.5}$ $M_\odot$ yr^{-1}, Abbott *et al.* 1980).

Lucy (1982) has proposed another form of the radiation-driven shock model that predicts much less attenuation of the X-rays because the shocks are assumed to persist much farther out into the flow than expected in the blob model. Lucy argues that the winds of luminous, hot stars are in fact driven to their high speeds by radiation pressure on gas just behind shock fronts. In his new type of radiation-driven wind model, the flow develops a sawtooth velocity structure that can be specified by the parameter ν. This is the difference in peak velocity in the sawtooth pattern between any two successive shocks, divided by the intershock sound speed, i.e., $\nu = \Delta v/a$. Lucy finds that ν should have a value in the range from 0.4 to 1.0. The shock strength and the temperature behind the shock in this model are expected to be higher at increasing distances from the star. Thus there is very little attenuation of the X-ray flux that is produced in the shocks, and the predicted spectrum has a negligible drop at the 0.6 keV edge of oxygen. In its original version, the model led to an X-ray spectrum that has an overall flux level that is too low to fit ζ Pup by an order of magnitude, and the spectrum is too soft, characterized by $T < 1 \times 10^6$ K instead of $\sim 3 \times 10^6$ K needed to fit the overall distribution. To improve the fit, Lucy suggested that there are rare (1 out of several hundred) shocks with much larger shock strengths ($\nu \gtrsim 2.0$) so that some gas at 3×10^6 K is produced. Because of the needed revision, Lucy suggested that the hard X-ray flux of early-type stars should vary sporadically.

Dr. Lucy has kindly run his periodic shock model for us so that we can compare the prediction of the model with the SSS spectrum of one of our stars. Figure 5 shows the comparison for ε Ori for two values of model parameter ν. For the model with $\nu = 0.4$, note that the X-ray spectrum is far too soft and the flux is many orders of magnitude too low to fit the SSS data. However, a model with $\nu = 3.4$ gives a result that is qualitatively similar to the observed spectrum. A statistically good fit probably could be made with minor adjustments in the model's emission measure versus temperature distribution. Linearly combining the two results for $\nu_1 = 0.4$ and $\nu_2 = 3.4$ as suggested in Lucy's paper, we get a fit also to the total X-ray flux $L_x = (1 - \varepsilon_2)L_1 + \varepsilon_2 L_2$ for $\varepsilon_2 = 1/25$. This means a relative frequency of strong to weak shocks of $[\varepsilon_2 \nu_1/(1 - \varepsilon_2)\nu_2] = 1/200$ is required. That is, if one out of two hundred shocks is a strong one, the X-ray luminosity and energy distribution can be accounted for.

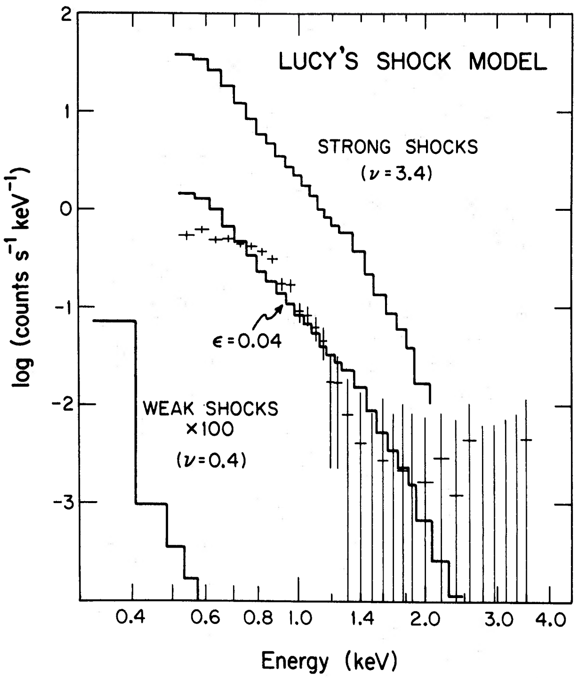

FIG. 5.—Compares the SSS spectrum of ε Ori with the fit derived from Lucy's (1982) periodic shock model. The shocks are parameterized by the quantity ν. Results for two values of ν are shown. The preferred value in the theory is $\nu = 0.4$, but this value is seen to yield a spectrum that is far below (even after multiplying by 100) the observed distribution. The model with $\nu = 3.4$ gives rise to a spectrum that is sufficiently hard but predicts more X-rays than are needed to fit the observation. If a fraction, $\varepsilon = 0.04$, of the X-rays are assumed to come from these strong shocks a reasonably good fit is achieved as is shown.

Some problems remain, however. First, the required shock value of $\nu = 3.4$ is far beyond the maximum of $\nu = 1.0$ predicted in the periodic shock model. Second, the relative frequency of strong shocks is so small that ε Ori should be a variable X-ray source on hourly time scales. This was not seen in ε Ori in the simultaneous X-ray ultraviolet variability search carried out by Cassinelli *et al.* (1983).

c) *Coronal Models*

Stewart and Fabian (1981) and Waldron (1983*a*) have reconsidered the possibility that all of the X-rays originate in a base coronal region. Stewart and Fabian do so because of doubts that a sufficient flux of X-rays could be produced in lower density sources embedded in a wind. X-ray production is shown by them to be most efficient in dense regions near the base of the flow where radiative cooling dominates cooling by expansion or Compton scattering. Waldron considers base coronae because there is interest in theoretical problems associated with the transition from one type of wind-driving mechanism to another, as might occur at the top of a corona in a luminous star. The winds in his models are driven initially by thermal pressure gradients, but as the gas cools and ions recombine there is a transition to a line-driven flow. Several of his models have extended regions with $T \approx 10^5$ K and hence are called "coronal warm wind models."

For a base coronal model to account for the soft X-ray flux observed with the IPC and the SSS spectra without the oxygen absorption, as illustrated in Figure 3, it is necessary that the optical depth of the wind material be reduced. Stewart and Fabian (1981) show that reduction of the opacity in the He^+ continuum ($E > 54$ eV) is crucial for explaining the X-ray data. A reduced He^+ continuum optical depth allows a larger flux of radiation to penetrate through the wind at energies below the carbon K edge at 0.35 keV. An increase in the soft X-ray flux allows good fits to be made to the IPC spectra which, unlike the SSS, is sensitive to X-rays at energies in the range from 0.1 to 0.5 keV. Figure 4 shows a spectrum calculated by Waldron (1983*a*) that was found to give a good fit to IPC data. It clearly does not fit the higher resolution SSS data, however. Stewart and Fabian also point out that an enhanced soft X-ray flux can affect the overall ionization equilibrium of C, N, and O. It is perhaps possible that this could lead to a decrease in the optical depth at the K shell edges of oxygen (0.53 to 0.6 keV) and thereby improve the fit to the SSS spectrum.

In both the Stewart and Fabian (1981) and Waldron (1983*a*) models, stellar parameters are adjusted to decrease the He^+ opacity. The papers differ in their choice of freely adjustable parameters.

Stewart and Fabian (1981) focus attention on the ionization of helium by the Wien tail of the photospheric radiation field and choose to adjust the mass loss rate, $\dot{M}$, to decrease wind opacity. They show that the optical depth in the He^+ continuum depends sensitively on mass loss rate, approximately with $\tau_\nu \propto \dot{M}^2$. They could fit the IPC spectrum of ζ Pup by assuming a mass loss rate a factor of 0.6 times that estimated from radio flux measurements. To resolve the discrepancy between the required and observed mass loss rates, they proposed that the winds are clumpy. This allows part of the base corona to be viewed through a small optical depth, while the clumps provide the radio and $H\alpha$ emission used in observational estimates of $\dot{M}$.

Waldron (1983*a*) treats the observed mass loss rates as fixed. His basic fitting parameter is the coronal emission measure, $EM_c (= n_e^2 \text{ Vol})$. If this is made sufficiently large, the coronal radiation can decrease the fractional abundance of He^+ relative to He^{+2} and thereby can decrease the opacity of the wind to soft X-rays.

As some combination of the two modified coronal models might possibly lead to acceptable fits to the SSS spectrum, it is of interest to consider the models in regard to our observations of the Orion OB supergiants. The optical depth of the wind in the He^+ ionizing continuum is

$$\tau_\nu = a_\nu \int_{R_c}^{\infty} n(\mathrm{He}^+)\, dr ,$$

where $a_\nu = 2.1 \times 10^{-18}\ (\nu_T/\nu)^3$ is the ionizing cross section with a threshold at ν_T(54 eV), and $n(\mathrm{He}^+)$ is the number density at r of once ionized helium. Assuming that helium is mostly doubly ionized (Stewart and Fabian 1981), we get from the ionization equilibrium, for the case in which the continuum is thin,

$$n(\mathrm{He}^+) \int_{\nu_T}^{\infty} \frac{4\pi}{h\nu} a_\nu J_\nu\, d\nu = n(\mathrm{He}^{+2})\, n_e \alpha ,$$

where α is the recombination rate ($= 1.54 \times 10^{-12}\ T_4^{0.7}$) in a wind at a temperature $T_4 \times 10^4$. Now let $J_\nu = WF_\nu$, where W is the dilution factor and πF_ν is the flux at the base of the wind. F_ν is composed of a photospheric contribution, that is emphasized by Stewart and Fabian (1982), and a coronal contribution that is emphasized by Waldron (1983*a*). For the photospheric part we follow Stewart and Fabian and assume the star is radiating with a Wien distribution at $T = T_B$. For the coronal part we use the approximate fit to coronal emissivity like that in Cassinelli and Olson (1979): $F_\nu(\text{coronal}) = EM_c F_0 e^{-h\nu/kT_c}$, where, for a temperature, $T_c = 5 \times 10^6$, $F_0 = 2 \times 10^{-40}/4\pi R^2$. The radiative ionization integral now becomes

$$\int_{\nu_T}^{\infty} \frac{4\pi}{h\nu} a_\nu J_\nu\, d\nu = W \frac{4\pi}{h} a_T \times \left[\frac{2h\nu_T^3}{c^2} E_1\left(\frac{h\nu_T}{kT_B}\right) + F_0 \mathrm{EM}_c E_4\left(\frac{h\nu_T}{kT_c}\right) \right],$$

where E_1 and E_4 are exponential integral functions. For $T_B \gtrsim 40{,}000$ K, as was considered by Stewart and Fabian in their model of ζ Pup, the first term dominates unless $EM_c > 10^{58}$. However, the E_1 function decreases rapidly for temperature appropriate for cooler stars, such as our OB supergiants, and the second term dominates for $T_B < 30{,}000$ K if $EM_c > 10^{55}$. Let us consider this latter case, in which the overall wind ionization is dominated by coronal emission. Assuming that $4\pi r^2 W \approx$ const, the optical depth can now be written

$$\tau_\nu = a_\nu A\alpha \int_{R_c}^{\infty} 4\pi r^2 n_e^2\, dr \times \left[(4\pi r^2 W)\mathrm{EM}_c \frac{4\pi}{h} a_T F_0 E_4\left(\frac{h\nu_T}{kT_c}\right)\right]^{-1},$$

where A is the abundance of helium. The quantity τ_ν is proportional to the emission measure of the wind overlying the corona, EM_w, and thus is proportional to $\dot{M}^2$, as mentioned earlier. For a given wind temperature, T_4, and coronal temperature, we see that

$$\tau_\nu \propto \mathrm{EM}_w/\mathrm{EM}_c \propto \dot{M}^2/\mathrm{EM}_c .$$

The modified coronal models reduce τ_ν either by decreasing $\dot{M}$ or increasing EM_c. Using $T_4 = 2$ and parameters appropriate for ϵ Ori, we find, on setting $\tau_\nu = 1$ at 0.3 keV, that

$$\mathrm{EM}_c \approx 0.1\ \mathrm{EM}_w \approx 10^{58}\ \mathrm{cm}^{-3} .$$

This is the typical coronal emission measure required in some of Waldron's models (Waldron 1983*b*). It is much larger than that required to explain the observed X-ray fluxes ($\sim 10^{55}$ cm^{-3}), and it points out a potential problem with even the modified coronal models. Waldron (1983*b*) finds that the emission measure must be finely tuned, along with changes in T_c, to achieve the required ionization equilibrium in the wind required to explain the observed soft X-ray flux. This need for fine tuning of the base coronal models implies that the X-ray flux should be strongly variable because of random fluctuations in EM_c, T_c, or $\dot{M}$. The result from Waldron's model shown in Figure 4, gives the right total X-ray flux and fits the IPC data, but it is clear that the wind is not sufficiently thin beyond the K edges of oxygen to fit the SSS data. The jump in τ_ν allowed by the data is $\lesssim 0.6$, or only a tenth that for the corona cool wind model shown in Figure 3.

Perhaps the allowance for the clumping suggested by Stewart and Fabian (1981) could lead to an acceptable fit, but that is not obvious and detailed models must be calculated. Although the optical depth below 0.35 keV is proportional to $\dot{M}^2$, the optical depth in the region of the K shell edges of oxygen at 0.53–0.6 keV may depend more linearly on $\dot{M}$. The dominant K shell opacity edge does not shift much in energy when the ionization state is increased. To first order, τ_ν is proportional to the total column density of oxygen, i.e., to the first power in $\dot{M}$, and very strong clumping may be needed.

In summary, both of the modifications of the base coronal model predict X-ray spectra that depend very sensitively on the primary model fitting parameters ($\dot{M}$ in the case of Stewart and Fabian and EM_c in the case of Waldron). It may be possible to get fits to the X-ray spectra by fine tuning these parameters. However, essentially all O and OB stars with massive winds have about the same IPC spectral distributions, and all three OB stars discussed here have about the same SSS spectra. It does not seem likely to us that all of the stars have $\dot{M}^2/\mathrm{EM}_c$ so precisely throttled to account for this. If they do, then the stars should show strong X-ray variability associated with random fluctuations in $\dot{M}$ or EM_c. The simpliest explanation is that at least the soft X-rays near 0.6 keV are associated with hot regions lying above the bulk of the wind opacity.

d) *Hidden Slab Component*

There could be a major contribution to the Auger ionization in the wind and to the harder X-ray spectral regions by gas in a base corona. Table 2 shows that ϵ Ori could have a very substantial base corona (EM $= 1 \times 10^{57}$ cm^{-3}) with a temperature of 1.4×10^6 K and not reduce the quality of the fit to the SSS spectrum. Such a region could provide a significant contribution to the Auger ionization in the lower parts of the wind. Nordsieck, Cassinelli, and Anderson (1981) have looked for optical coronal lines of Fe X and Fe XIV that might arise from such a corona but could only derive a rather large upper limit on the emission measure ($\mathrm{EM}_c < 10^{58}$ cm^{-3}).

A base coronal zone with a temperature much larger than the one discussed here might give rise to observable features at energies above 1 keV where the winds are optically thin. In fact, we see evidence in ζ Ori for a very hot component with a small emission measure.

IV. POSSIBLE Si AND S EMISSION FEATURES IN ζ ORI

The location of the strong X-ray lines of helium-like Si XIII and S XV are shown by the arrows in Figure 1 in the panel for ζ Ori. These correspond well with energies at which there is excess emission in the SSS spectrum. A fit to the spectrum of ζ Ori is improved over the single component model discussed earlier if we assume there is a second source component with a temperature of $\sim 1.5 \times 10^7$ K. This is not the case for the other two supergiants, for which the single component fit is very good.

The location of this hotter component is not well determined. This is because the wind is optically thin at the energies greater than 1.5 keV where the emission features appear. Our fitting procedure indicates that the hot source is deeper than the source(s) producing the bulk of the soft X-ray flux. For the "best fit" shown in Figure 6, it is at $N_{\mathrm{H}} \approx 0.2\ N_{\mathrm{H}}(\mathrm{max})$, not quite at the base of the wind, but again because of the low attenuation of the wind at 1.8 and 2.2 keV the fit is not particularly sensitive to N_{H} and the hot source could be at the base.

Let us assume that it is at the base. The maximum coronal temperature for a gravitationally bound plasma

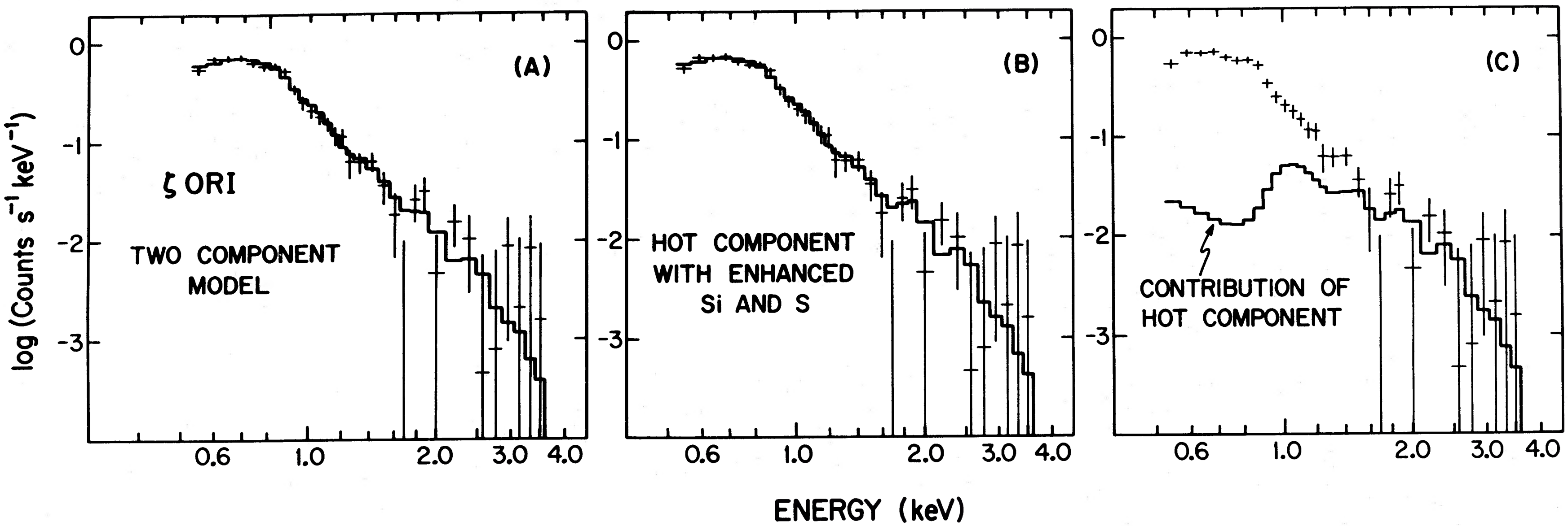

FIG. 6.—The emission features in ζ Ori shown in Fig. 1 are here better fitted using a hotter second component ($T \sim 1.5 \times 10^7$ K). (b) Shows the improvement made in the fit by enhancing the Si and S abundance by a factor of 3 over the solar values used in (a). (c) Shows the contribution from the hotter component to the emission features and to the harder X-ray continuum.

in basic Parker wind theory is $T_{max} = [\frac{1}{4}(\mu m_H/k)]v_{esc}^2$. For ϵ Ori this corresponds to 7×10^6 K. The temperature of the hot component, while not well determined, exceeds 10^7 K. In the case of late-type stars, gas at temperatures above the Parker limit are commonly considered to be magnetically confined in closed loop structures, as in the case of RS CVn stars (Holt *et al.* 1979; Walter *et al.* 1980; Swank *et al.* 1981). If that is the case for the OB stars as well, we can estimate the loop parameters following the approach of Walter *et al.* (1980). We assume that gas at 1.5×10^7 K of emission measure $\mathrm{EM} = n_e^2 V = 2\times10^{54}$ cm^{-3} is in magnetic loops with equilibrium between the pressure and magnetic stresses, $(B^2/8\pi) = p = 1.91\ n_e kT$. The volume is assumed to consist of n loops of half length l, for which $T = 1400\ (pl)^{1/3}$ (Rosner, Tucker, and Vaiana 1978), and the loop footpoints are assumed to cover a fraction, f, of the surface area. Then $p = 360\ (\mathrm{EM}_{54}/T_7)R^{-2}f^{-1} = 0.83\ f^{-1}$ and $B = 4f^{-1/2}$ gauss. The fraction of the star covered by the hot loops is not known, but letting $f = 1\%$ as a crude guess we find $B = 40$ gauss, $l = 0.13$ R_*, and with $A \le \pi l^2$, the number of loops is $n \ge 250$. Thus the observed line emission could be explained with a large number of small loops that have a modest magnetic field strength.

There is also the possibility that the Si XIII and S XV lines might be formed in strong shocks within the wind. As discussed earlier, the rare strong shocks that are required in Lucy's (1982) explanation for the X-ray flux are characterized by a value for the shock strength parameter of $\nu = 3.4$. This corresponds to a shock velocity relative to the mean flow of ~ 500 km s^{-1} and a temperature immediately behind the shock of $\sim 7\times10^6$ K. It is not clear whether the ions S^{+12} and S^{+14} could be abundant in the shocks especially under the nonequilibrium conditions expected in such shocks. Further calculations are required to see if in fact the radiation-driven shock mechanism can give rise to such strong shocks and, if so, whether the shocks could provide the observed flux in the Si XIII and S XV lines.

V. SUMMARY

The SSS observations provide important constraints on the various models proposed to explain the X-ray emission from early-type stars. Several models that can explain the IPC spectra are found to be inadequate for fitting the higher resolution SSS spectra. The shape of the spectra can be explained with Lucy's (1982) radiation-driven shock models but using a shock parameter outside the predicted range. The spectra do not rule out the possibility that there could be rather massive coronae at the base of the winds, for example with an emission measure of 10^{57} cm^{-3} and a temperature of 1.4×10^6 K or modest higher temperature components. There is a suggestion of Si and S emission lines in ζ Ori indicating that there is some very hot gas ($\sim 15\times10^6$ K) present, and it is located deeper in the wind than a source which can explain the soft X-rays. It appears to be difficult to explain the emission as coming from base coronal regions alone.

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