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SIMULTANEOUS X-RAY AND ULTRAVIOLET OBSERVATIONS OF ϵ ORIONIS AND κ ORIONIS

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ABSTRACT

Simultaneous observations were made with the *Einstein Observatory*, the *International Ultraviolet Explorer*, and the *Copernicus* satellite of the supergiant stars ϵ Ori (B0 Ia) and κ Ori (B0.5 Ia). The X-ray observations spanned periods of 7 hours and 10 hours, and the ultraviolet observations spanned 15 and 18 hours for ϵ Ori and κ Ori, respectively. For either star, no variations were detected in the X-ray flux or spectrum or in the ultraviolet line profiles of Auger enhanced ionization states. For ϵ Ori, the X-ray count rate was the same as it was during an observation 11 months earlier, while for κ Ori, the X-ray count rate was 46% larger than it was 11 months earlier. This change could be explained by an increase in the source temperature from $10^{6.3}$ K to $10^{6.4}$ K, or by an increase in the source emission measure of 46%, or by a decrease in the column density of the intervening matter of several times 10^{20} cm^{-2}. The ultraviolet line profiles are found to be insensitive to changes of X-ray flux which are less than 50%. Various constraints imposed on current models for the X-ray production in early-type stars are discussed.

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

I. INTRODUCTION

Ultraviolet observations of the winds of OB stars show strong, broad profiles of O VI λ1036 and N V λ1240 formed in the wind by ionization states higher than those expected from radiative equilibrium conditions. The presence of these "superionized" lines has led to several models for their production involving either collisions in a uniformly heated wind or radiative ionization by X-rays from high temperature zones in the outer atmosphere or wind (Lamers and Morton 1976; Lamers and Snow 1978; Cassinelli, Castor, and Lamers 1978). In the corona plus cool wind model of Cassinelli and Olson (1979), X-ray ionization of the K shell electrons of O^{+3} and N^{+2} in the wind, followed by Auger deexcitation, results in the observed P Cygni profiles for the O VI and N V lines. A further prediction of this model is that the star emits an appreciable X-ray flux. Soon after the mechanism was proposed, instruments on the *Einstein* (*HEAO 2*) X-ray Observatory detected X-rays at the predicted intensity level from several OB supergiants (Harnden *et al.* 1979; Seward *et al.* 1979). Subsequent observations have led to the detection of X-rays from all classes of early-type stars (Long and White 1980; Vaiana *et al.* 1981; Cassinelli *et al.* 1981; Pallavicini *et al.* 1981; Snow, Cash, and Grady 1981; Seward and Chlebowski 1981).

Although the basic idea of Auger ionization seems confirmed, the location(s) of the source(s) of X-rays is still uncertain. Hearn (1975) proposed that OB supergiants have a coronal zone in a slab at the base of the stellar winds. Several investigations of the observational constraints on such a model were discussed by Cassinelli (1979). The coronal zone would have to be thin (<0.1 of a stellar radius, R_*) to satisfy Hα and IR constraints. The coronal zone would need a sufficiently large emission measure ($n_e^2 V \geq 10^{58}$ cm^{-3}) to allow at least some of the ionizing X-rays to reach the outer parts of the wind. The *Einstein* observations show, however, that the soft X-ray flux at energies $E \leq 1$ keV is larger than would be expected from such a model (Long and White 1980; Cassinelli *et al.* 1981; Cassinelli and Swank 1983).

Lucy and White (1980) and Lucy (1982) have proposed an alternate model in which the X-rays are produced in shocks in the stellar winds. The shocks may result from the radiatively driven instabilities of line-driven winds that have been discussed by MacGregor, Hartmann, and Raymond (1979) and Carlberg (1980). In this radiatively driven shock model, the soft X-rays are not as heavily attenuated as in the slab coronal model. As a result, a much smaller volume emission measure ($n_e^2 V \approx 10^{55}$ cm^{-3}) is required to explain the observed X-ray luminosity of the stars.

Although the observation of a large soft X-ray flux is certainly consistent with the radiatively driven shock model, it does not rule out the possibility that hot gas also exists in a corona at the base of the wind. Evidence in favor of X-ray emission from other than radiatively driven shocks comes from the *Einstein Observatory* Solid State Spectrometer (SSS) observations of OB stars by Cassinelli and Swank (1983) and by Seward (1981, private communication). These observations find evidence for X-ray emission from gas at temperatures as high as 1.5×10^7 K. The radiatively driven shock models predict temperatures on the order 10^6 K.

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It has been realized for some time now that the outer atmospheres of OB supergiants display variability in Hα (Rosendhal 1973; Rusconi *et al.* 1980 and references therein). Snow (1979) discusses the variability that is seen in the P Cygni lines in the ultraviolet. From *Copernicus* (*0A0 3*) satellite observations of the superionized lines of O VI and N V in κ Ori, Stalio and Upson (1979) found line profile variability which may be attributable to variations of the source of the Auger ionizing radiation. Snow, Cash, and Grady (1981) have used *Einstein* to detect X-ray variability in three out of seven O stars over intervals of five days to a year.

There are several properties of the X-ray emitting regions that can, in principle, be deduced from simultaneous ultraviolet and X-ray observations of variability. For example, if there were a hot component at the base of the wind, variations in the base coronal X-ray emission would be seen primarily at higher X-ray energies, because the softer X-rays from that source would be absorbed in the wind. In this case we would expect variations of harder X-rays to be correlated with changes in the density of the superionization stages throughout the wind. As a result, the depth of the absorption trough of the P Cygni lines would change across the entire line profile.

Alternatively, if there were shocks in the outer parts of the wind, the observations require that the emission measure be only 10^{55} cm^{-3}, and there would be little attenuation by wind material. As a result, variations in X-ray flux could be seen also at soft X-ray energies, and these would affect the ionization over a much smaller fraction of the wind. This is because the X-rays could not penetrate inward to regions near the base of the flow where the velocity is low (recall that it requires a single source emission measure of 10^{58} cm^{-3} to provide sufficient X-rays to overcome the attenuation of the wind). Variations in X-ray flux might therefore affect only the high velocity portions of the line profiles.

Another possibility is the embedded shock model (Lucy and White 1980; Lucy 1982), which suggests that shocks of varying strengths are distributed throughout the flow. In this case, the shocks may lead to enhanced absorption over portions of the profile. Resonance lines often show highly shifted narrow absorption features or "shell components" superposed on wide P Cygni profiles (Snow 1979; Lamers 1981). It is quite plausible that these high velocity components indicate local density enhancements or locally enhanced Auger ionization conditions. The shell components might vary in step with variations in the soft X-ray flux from embedded shocked regions.

In this paper we discuss simultaneous X-ray and ultraviolet observations of ε Ori (B0 Ia) and κ Ori (B0.5 Ia) that have been made using the imaging proportional counter (IPC) on *Einstein* and the high resolution spectrometers on the *International Ultraviolet Explorer* (*IUE*) and *Copernicus*. Our goal is to study the location(s) of the hot X-ray emitting gas relative to the cooler wind material by examining the variability of X-ray flux and ultraviolet line profiles. These stars were chosen because they had been found in our 1979 *Einstein* survey to be relatively strong X-ray sources with a sufficient count rate to derive some information about the X-ray source temperature and attenuation (Cassinelli *et al.* 1981). Both stars are well studied at optical wavelengths and both show variability in their Hα profiles (Ebbets 1982).

In § II the observations of the IPC X-ray flux are discussed. In § III the analysis of the ultraviolet line profile observations is presented. In § IV, the discussion and conclusions are presented.

II. X-RAY OBSERVATIONS

To examine the X-ray time variability of each star, we have analyzed observations spanning intervals of 25,000 s obtained with the IPC on *Einstein*. The IPC is capable of arcmin spatial resolution, 63 μs time resolution and energy resolution $E/\Delta E \sim 1$ at 1.5 keV (Giacconi *et al.* 1979). We have also compared our data to earlier IPC observations of both stars (Cassinelli *et al.* 1981) to search for variations over a time span of a year.

The star ε Ori was observed on 1980 March 1 over an interval of 25,580 s with an effective exposure time of 13,494 s. After rejection of several brief intervals with telemetry problems, there remained 12,978 s of useful data. The star κ Ori was observed on 1980 March 14 over an interval of 36,611 s with an effective exposure time of 14,438 s. After rejection of data with telemetry problems, 13,848 s remained. In Figure 1, the shaded bands indicate the times when data were taken. The gaps between the bands indicate times when no data were taken because of Earth obscuration or the South Atlantic Anomaly.

Figures 2*a* and 3*a* show the net count rates as a function of time for ε Ori and κ Ori. Source counts are from a 6 arcmin radius circle, and background counts are from an annulus of inner radius 6 arcmin and outer radius 9 arcmin, each centered on the star. The counts are summed over IPC channels 1–9 (0.11–2.36 keV). Error bars on individual data points indicate the statistical uncertainty only.

Figures 2*b* and 3*b* show the "softness ratio," defined as S/H where S and H are count rates from IPC channels 1–4 (0.11–0.74 keV) and IPC channels 5–9 (0.74–2.36 keV), respectively, as a function of time. This particular division of IPC bins yields about the same number of counts in the S and H bands.

Changes in the X-ray spectrum should produce changes in the softness ratio. To see if the variations in S/H could be attributed to either temperature or absorption variation, we examined S/H as a function of the total count rate (R). Temperature variations at the source would cause an inverse relationship between S/H and R, whereas absorption variations would cause a direct relationship. However, the data for neither star showed any correlation between S/H and R.

a) *Analysis of X-Ray Observations of ε Orionis*

The ε Ori count rate data were tested for variability using a χ^2 test. The mean count rate with one standard deviation uncertainty is 0.356 ± 0.006 s^{-1}. Using 100 s

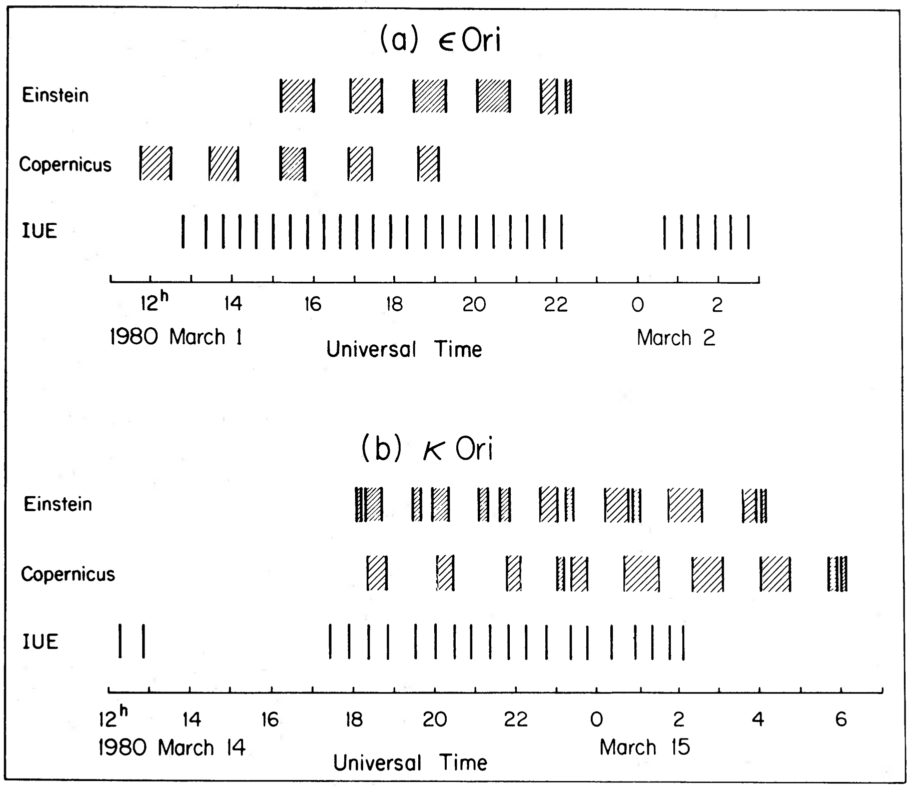

FIG. 1.—Times of observations of ϵ Ori and κ Ori with the *Einstein*, the *Copernicus*, and the *IUE* satellites. Continuous observations are indicated by shaded bands.

time bins, for a model with constant count rate of 0.356 s^{-1}, we find the χ^2 is 152 with 134 degrees of freedom. This value of χ^2 is within the 90% confidence limits. Other time scales ranging up to 5000 s were examined with similar results. We conclude that ϵ Ori shows no evidence for time variability of its X-ray emission on time scales from 100 s to 5000 s.

A χ^2 test was also performed on the softness ratio data. Using 100 s time bins, we found that a constant model produced a minimum χ^2 which fell outside the 90% confidence limits ($\chi^2 = 413$ with 134 degrees of freedom). For a model with a linear term added, the minimum χ^2 is 405 with 134 degrees of freedom. This is still an unacceptable fit. We made no attempt to fit a function more complicated than a straight line. Either ϵ Ori shows significant spectral variations on a time scale of 100 s, or IPC systematic uncertainties are responsible for this large value of χ^2. Dr. F. R. Harnden, Jr. (1981, private communication) indicates that pointing jitter may create a variation of $\sim 10\%$ in the gain of the IPC at the image of ϵ Ori. The variability in the gain does not significantly affect the total flux but it does create an additional uncertainty in S/H. This is indicated by the error bar labeled "B" on the right hand side of Figure 2*b*. The resultant uncertainty is so large that it masks any variation in the softness ratio. Even without allowance for the gain uncertainty, a constant model for S/H is consistent with the data at the 90% confidence level for time scales from 400 to 5000 s.

To study variability of ϵ Ori on an even longer time scale, we compared our data with those of Cassinelli *et al.* (1981), taken 11 months earlier on 1979 March 26. Our net count rate is the same as the previous value (see Table 1).

The pulse height distribution for ϵ Ori allowed an estimation of the X-ray source temperature and emission measure, and of the intervening column density of *wind* material. We assumed a column density of neutral interstellar material between us and ϵ Ori of $10^{20.4}$ cm^{-2} (Bohlin, Savage, and Drake 1978). We used the equilibrium thermal plasma spectral models of Raymond and Smith (1977, 1979, hereafter called thermal source models), the interstellar gas absorption cross-sections of Brown and Gould (1970), and the stellar wind absorption cross-sections of Cassinelli *et al.* (1981). The model with the best fit to 12,978 s of data had a temperature of $T = 10^{6.2}$ K and a wind hydrogen column density of $N_H = 10^{22.3}$ cm^{-2}. The best fit to the 1979 data of Cassinelli *et al.* was $T = 10^{6.1}$ K and $N_H = 10^{22.4}$ cm^{-2}. Furthermore, the 90% confidence region in the T versus N_H plane for our data is similar to that shown in Figure 3 of Cassinelli *et al.* (1981). (Note that this 90% confidence region also allows a negligible wind column density if $T = 10^{6.5}$ K and $EM = 10^{54.8}$ cm^{-3}.) The

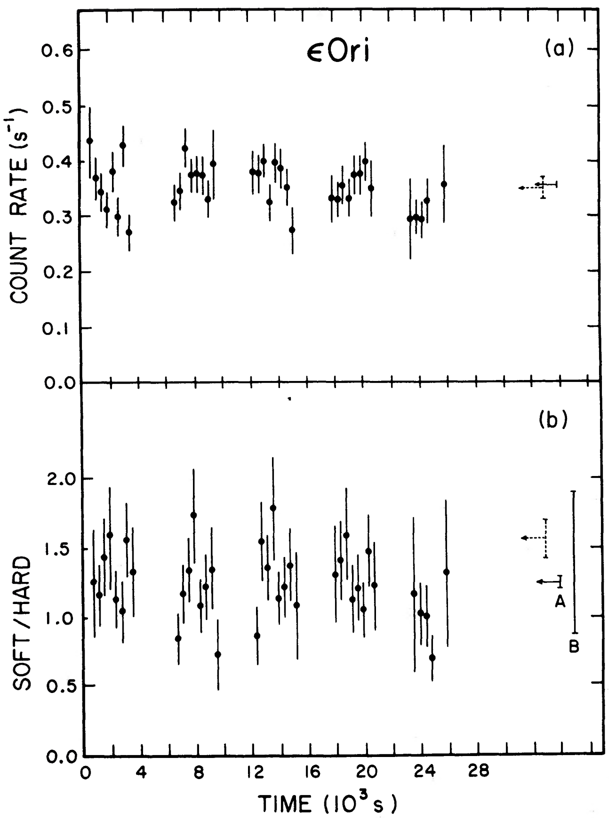

FIG. 2.—(*a*) Total count rate of ϵ Ori for the 1980 observation. Time bins are 400 s. The solid arrow indicates the mean rate and its error bar gives the statistical uncertainty of the mean. The dashed arrow indicates the mean rate and statistical uncertainty for the 1979 observation. (*b*) Softness ratio (*S*/*H*) of ϵ Ori, where the soft energy range (*S*) is 0.10–0.74 keV and the hard energy range (*H*) is 0.74–2.36 keV. Time bins are 400 s. The total soft to total hard ratio for the 1980 observation is given by the solid arrow and for the 1979 observation is given by the dashed arrow. The total soft to total hard ratio error bar for the 1979 observation and the error bar labeled "A" indicate statistical uncertainties only. The error bar labeled "B" shows the combined statistical and IPC gain uncertainties.

X-ray data show no evidence for either intensity or spectral variations over one year time scales.

b) Analysis of X-Ray Observations of κ Orionis

The κ Ori count rate data were tested for variability using a χ^2 test. The mean count rate with one standard deviation uncertainty is 0.143 ± 0.004 s^{-1}. Using 100 s time bins, for a model with a constant count rate of 0.143 s^{-1}, the χ^2 is 171 with 148 degrees of freedom. This value falls just within the 90% confidence limits. For longer time scales up to 5000 s, the χ^2 values are well within the 90% confidence limits. We conclude that κ Ori shows no evidence for variability of its X-ray flux on time scales from 100 s to 5000 s.

TABLE 1

OBSERVED X-RAY COUNT RATES (s^{-1})

Star	1979[a]	1980
ϵ Ori	0.35 ± 0.02	0.356 ± 0.006
κ Ori	0.098 ± 0.008	0.143 ± 0.004

[a] The count rates given in Table 2 of Cassinelli *et al.* (1981) are roughly 0.01 s^{-1} too low.

A χ^2 test was also performed on the κ Ori softness ratio data. Using 100 s time bins, a constant model produced an unacceptable fit, $\chi^2 = 274$ with 148 degrees of freedom. A linear model produced a minimum value with essentially the same χ^2. Using time bins up to 5000 s also failed to provide fits acceptable at the 90% confidence level for linear models. We made no attempt to fit a more complicated function. Either κ Ori shows significant spectral variations on a time scales of 100 s to 5000 s or variations in the effective IPC gain could be responsible for the apparent spectral variations, as discussed above.

Thermal source models were fitted to the pulse height distribution from κ Ori to estimate the source parameters. We assumed a column density of neutral interstellar material between us and κ Ori of $10^{20.5}$ cm^{-2} (Bohlin, Savage, and Drake 1978). The best fit parameters to 13,848 s of data were $T = 10^{6.4}$ K and $N_{\rm H} = 10^{19.7}$ cm^{-2}. The best fit parameters to the Cassinelli *et al.* data of 1979 were $T = 10^{6.3}$ K and $N_{\rm H} = 10^{20.7}$ cm^{-2}. The 90% confidence region in the T versus $N_{\rm H}$ plane for the current data is similar to that shown in Figure 3 of Cassinelli *et al.* (1981). The X-ray pulse height data of κ Ori shows no evidence for spectral variability over one year time scales.

Comparison with 1979 observations (see Table 1) shows an increase of 46% in the net count rate in one year. We can use the thermal source models to determine how each of three parameters, temperature, emission measure, and wind hydrogen column density, would have to vary if it were solely responsible for the flux increase. The change in a parameter is restricted in that all three parameters initially must produce an acceptable spectral fit to the 1979 data and the new parameter values must produce an acceptable spectral fit to the current data. We present the result of this comparison in terms of the changes in the parameters from the best fit 1979 values.

If the wind column density and the emission measure were fixed, an increase in the temperature of ~25% from $10^{6.3}$ K to $10^{6.4}$ K would account for the observed increase in X-ray flux. If only the attenuating wind column density has varied, which is equivalent to the location of emission having varied, $N_{\rm H}$ has decreased from $10^{20.7}$ cm^{-2} to $10^{19.8}$ cm^{-2}. This represents a decrease of only 5% of the entire column density to the base of the wind. If the temperature and the column density have not changed, the emission measure has increased by 46% from $10^{54.8}$ cm^{-3} to $10^{55.0}$ cm^{-3}. This last case is particularly useful for discussing effects of the changes of X-ray flux on line profiles of the superionization stages. This is because the relative density of a superionization state in the wind is directly proportional to the emission measure of the X-ray source.

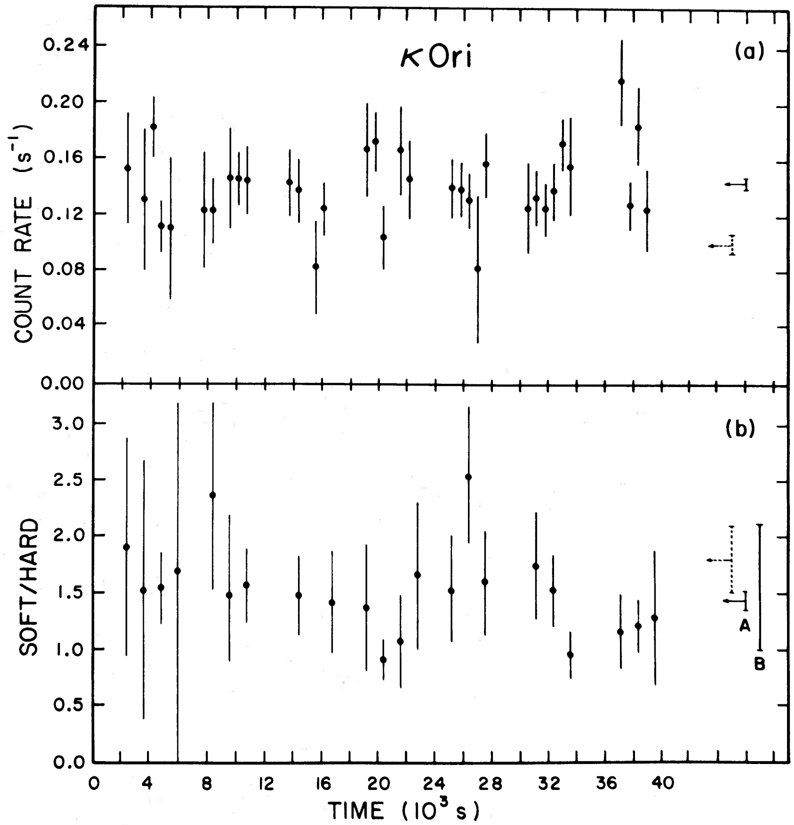

FIG. 3.—Same as Fig. 2, but for κ Ori with 600 s time bins for the count rate and 1200 s time bins for the softness ratio

III. ULTRAVIOLET OBSERVATIONS

The Princeton Experiment Package on the *Copernicus* satellite was used to scan the region from λ1020 to λ1052 with the U2 spectrometer in order to obtain simultaneous measurements of the O VI doublet. About six complete scans were made of this region for each star. The count level of 600 to 1000 counts per 14 s integration interval is of course lower than the early *Copernicus* spectra (because the instrumental sensitivity has been decreasing with time), but sufficient to make individual scans meaningful. Inspection of the stacked scans show that the deviation of the individual scans from each other are within the expected photon statistics. There is no indication of any variability in the O VI portion of the spectrum that is different from the nearby continuum and interstellar line profiles.

Although ε Ori exhibited two narrow absorption features in the Si IV (and to a lesser extent in the C IV and N V profiles), these features are not apparent in the O VI line.

The remaining ultraviolet data reported here were all acquired using the short-wavelength (1150–1950 Å), high-dispersion (resolving power = 1.2×10^4) echelle mode of the *IUE* satellite (Boggess *et al.* 1978). The exposures were taken through the small aperture. This may improve resolution and minimize the order overlap problem (see below). Absolute photometric behavior is not preserved when observing through the small aperture, so spectra must be normalized for meaningful comparison.

Thirty-one exposures of ε Ori were obtained on 1980 March 1, covering a total time baseline of approximately 15 hours as shown in Figure 1. The majority of spectra were obtained with 11 s exposure times. Twenty-one exposures of κ Ori were made on 1980 March 14 covering a baseline of almost 14 hours. Most spectra were 15 s exposures. The spectra presented here have all been reduced using the normal Goddard spectral extraction system. Corrections were made for the echelle blaze response by dividing by the function

$$R = (1 + aX^2)(\sin X/X)^2 , \qquad (1)$$

where X equals $\lambda - \lambda_m$ and $\lambda_m = K/m$ is the central wavelength of order m, and a and K are suitably chosen constants. The values of a and K used, chosen on the basis of the match between adjacent echelle orders, are listed in Table 2.

It is well known (cf. Cassatella, Ponz, and Selvelli 1981) that high-dispersion *IUE* spectra suffer from overlapping of adjacent echelle orders. The problem is worst at the shortest wavelengths where the orders are most crowded. The nominal extraction procedures subtract a background which is too large and possibly contaminates the extracted spectral order. By inspection of strong,

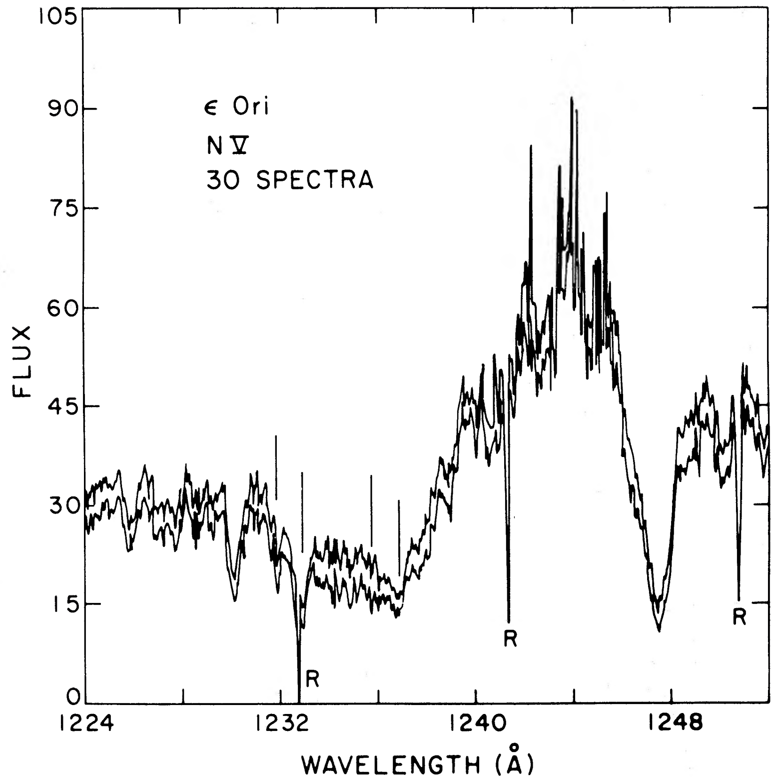

FIG. 4*a*

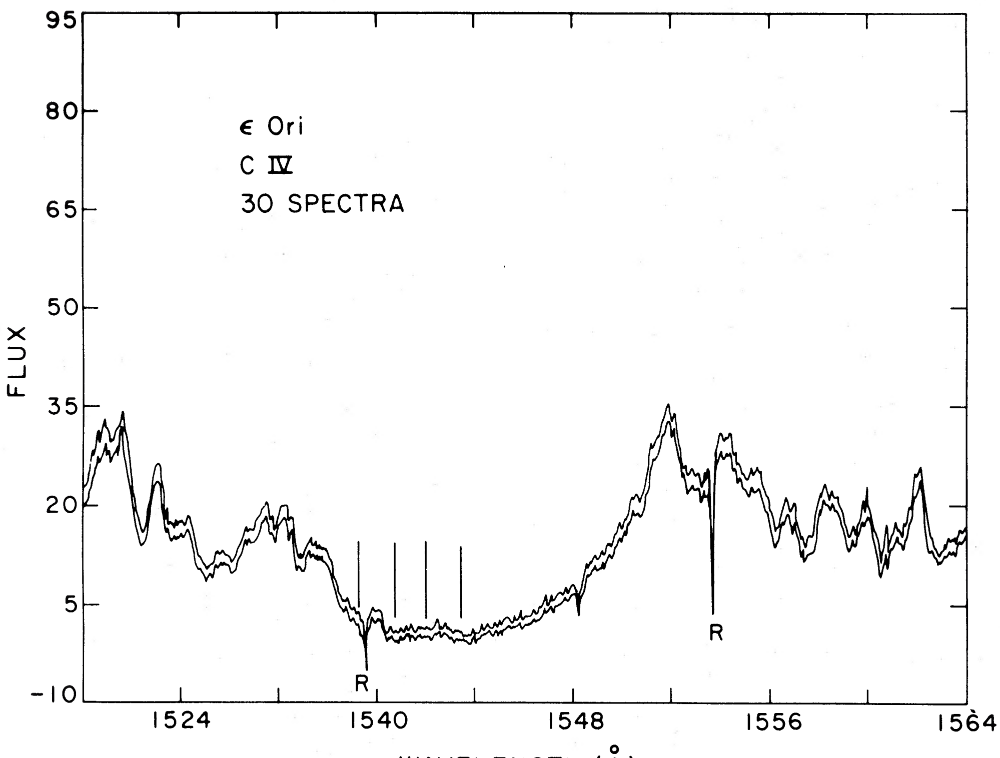

FIG. 4*b*

FIG. 4.—The N v, C iv, and Si iv profiles of ε Ori. For each profile, the mean plus one standard deviation and the mean minus one standard deviation are shown. The lines point out the location of prominent enhanced absorption features.

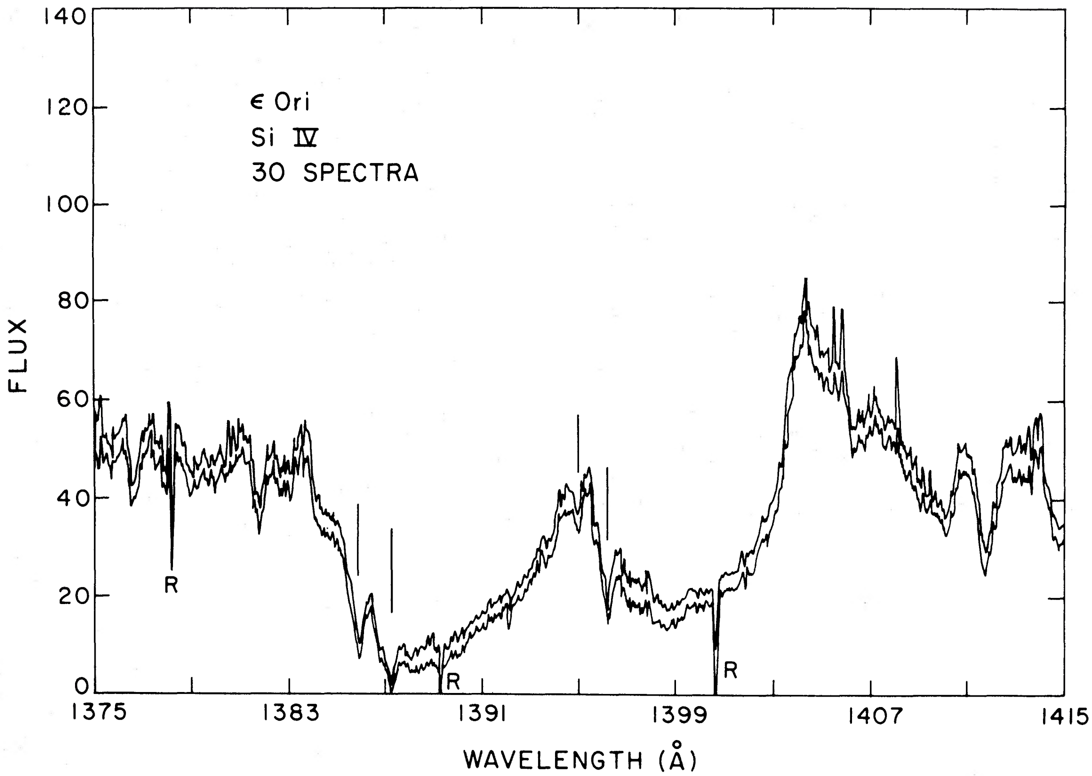

FIG. 4c

saturated interstellar lines such as Lyα and C II λ1335, and assuming zero residual intensity, it is possible to estimate the size of the background subtraction error. In this manner we estimate errors ∼10% in the N V λ1240 region, ∼5% at Si IV λ1400, and ≲5% at C IV λ1550. These uncertainties should have relatively little effect on the profiles. Since we are principally concerned with variability observed in spectra reduced in exactly the same fashion, we expect such errors to have no significant impact.

We shall concentrate on study of the N V, C IV, and Si IV doublets, as these lines are the strongest formed in the expanding wind as observed with *IUE*. C III λ1176 exhibits a well-developed P Cygni profile in both stars, but the sensitivity of the instrument is low and the overlap problem is severe in that wavelength region.

TABLE 2

REDUCTION PARAMETERS FOR *IUE* SPECTRA

A

a Values	LWR	SWP
Small aperture	0.09	0.10
Large aperture	0.13	0.31

B

Order	*K* value
87	137690
89	137680
98	137710
99	137715
110	137715
111	137735
112	137750

An assessment of stellar variability requires an estimate of instrumental repeatability. Since *IUE* does not operate in a direct photon-counting mode, the proper error analysis is uncertain. We estimate from our past experience on other objects that the low-dispersion mode repeatability is ∼2.8% (1 σ) for 100 A bins of "optimally" exposed spectra. If one assumes that the signal-to-noise ratio $S/N \sim S^{1/2}$, then the "standard deviation" of an individual resolution element of 6 Å would be ∼11% of the average flux level. This number would be expected to apply as well to a high-resolution element with approximately the same flux number per pixel. Thus, for well-exposed regions of our spectra we may expect repeatability ∼10% in a resolution element 0.12 Å as a beginning error estimate.

We have attacked the problem of repeatability by assuming that the photospheric portions of the spectrum are constant. Each spectrum is normalized in overall flux level to the same standard. The mean spectrum is then computed, from which the deviation of each pixel (at a specific wavelength) in a given exposure can be calculated.

The results of this procedure for the N V, C IV, and Si IV lines in ε Ori and κ Ori are exhibited in Figures 4 and 5. Plots of the mean plus one standard deviation and the mean minus one standard deviation are presented.

The figures show that the measured intensities in the well-exposed portions of the photospheric spectrum are repeatable at the level of 10%, as expected. Furthermore, there is no obvious variability which might be indicated by much larger deviations in the line profiles than in the neighboring continuum. The deviations are generally larger in the absorption components of the line profiles, but the amount of increase appears to be consistent with the fact that the exposure level is lower. No evidence is seen for anything like the large fluctuations of N v absorption in κ Ori observed by Stalio and Upson (1979). We would expect to see these variations in either of two ways: in larger standard deviations in the line than in the continuum or in large deviations of individual spectra from the mean. Deviations 2 σ from the mean in an individual spectrum are infrequent, and neighboring pixels are generally uncorrelated. There is no example of the correlated changes over wavelength scales ~1 Å or more detected by Stalio and Upson (1979).

In Table 3, we have computed the average standard deviation per pixel (two pixels per resolution element) in specified wavelength bins for κ Ori. The results clearly show repeatability ~5–10% in the continuum and generally ~10% in the lines. The only exception to this is in the very saturated portions of the C IV line where the residual flux is essentially zero. We conclude that the ultraviolet resonance line profiles of ϵ Ori and κ Ori exhibit stability ~10% per resolution element over timescales of 15 hours.

One interesting feature of the spectrum of ϵ Ori (Fig. 4) is the presence of two sharp components in the absorption line profiles. These components are most clearly seen in both members of the Si IV doublet at velocities of -1400 and -1670 km s^{-1}. No such features are present in the κ Ori spectrum (Fig. 5), so we conclude that the components originate in the wind of

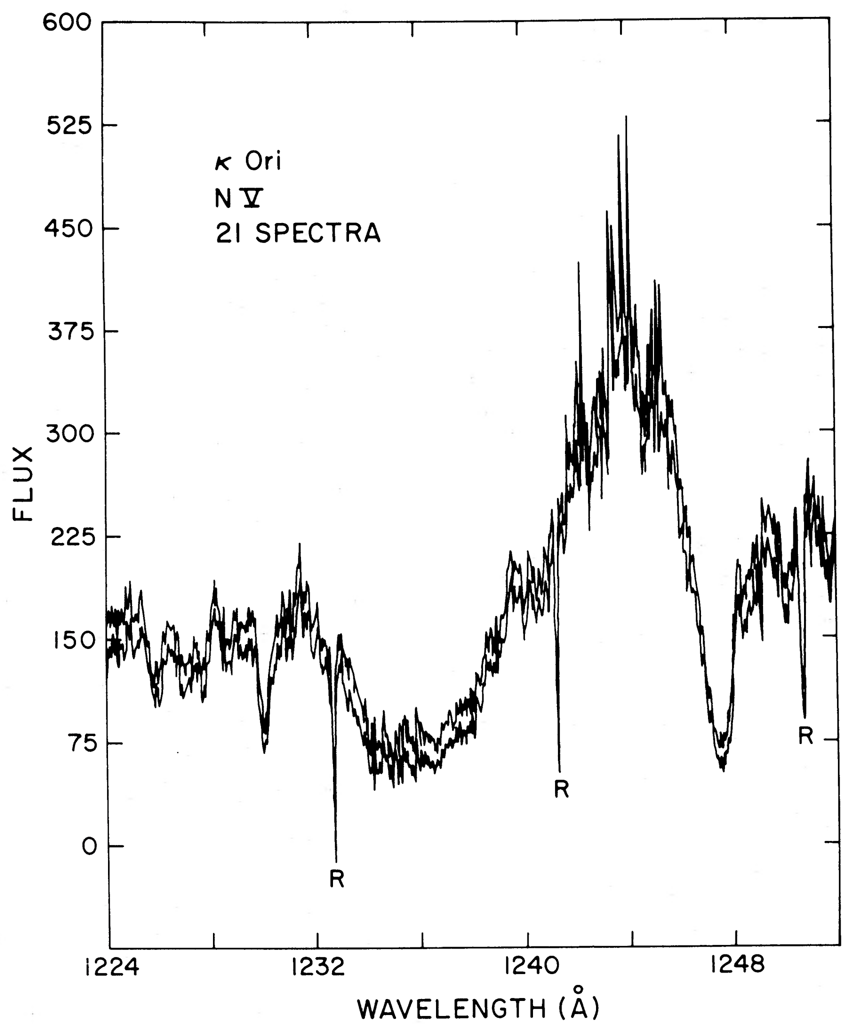

FIG. 5*a*

FIG. 5.—Same as Fig. 4, but for κ Ori

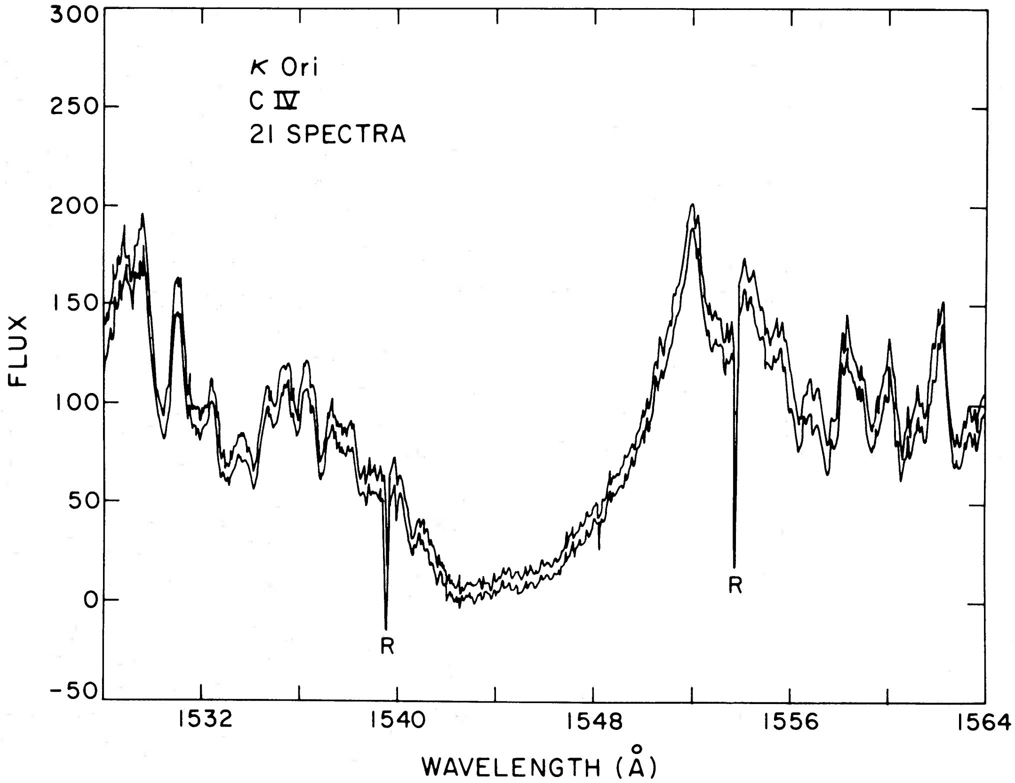
κ Ori
C IV
21 SPECTRA
FLUX
300
250
200
150
100
50
0
-50
1532
1540
1548
1556
1564
WAVELENGTH (Å)
R
R

FIG. 5b

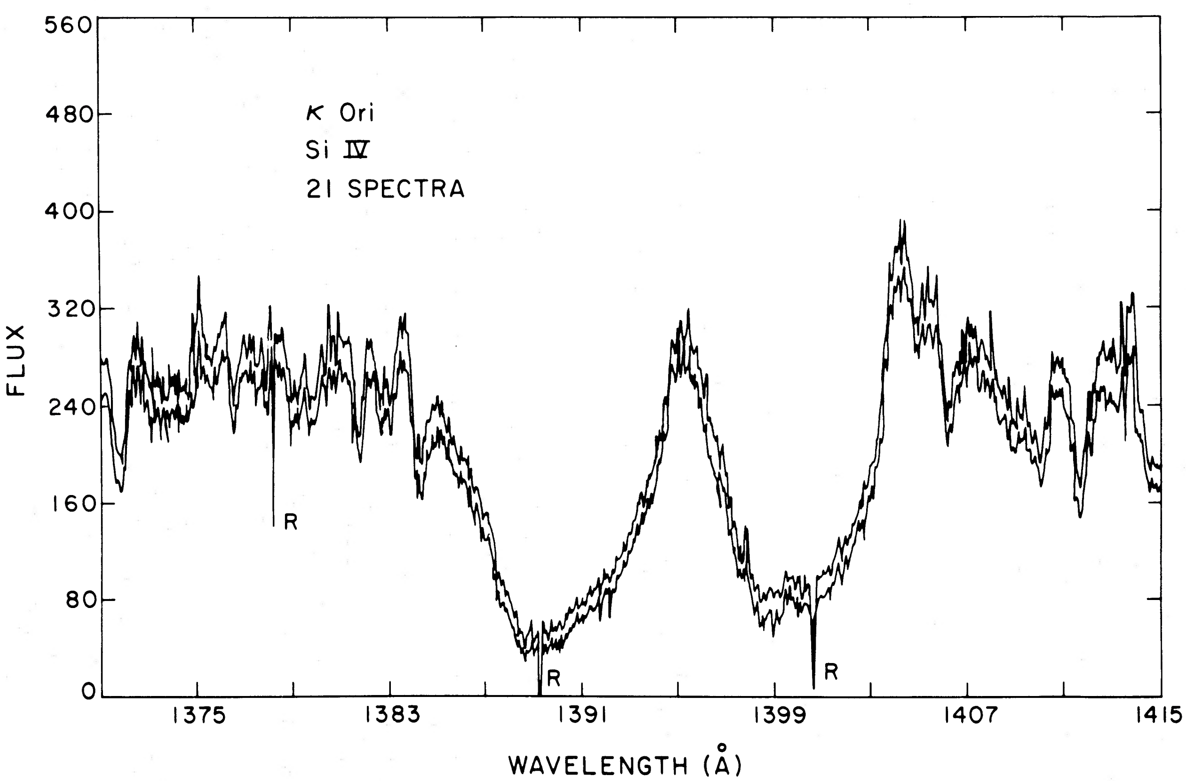
κ Ori
Si IV
21 SPECTRA
FLUX
560
480
400
320
240
160
80
0
1375
1383
1391
1399
1407
1415
WAVELENGTH (Å)
R
R
R

FIG. 5c

TABLE 3

VARIABILITY IN SELECTED WAVELENGTH REGIONS OF κ ORIONIS SPECTRUM

Spectral Line	Wavelength Interval (Å)	(σ/S)[a]
N v	1234.0–1236.0	0.13
N v	1239.5–1241.0	0.06
N v	1247.0–1248.0	0.10
N v	1248.0–1249.0	0.07
Si IV	1384.0–1386.0	0.06
Si IV	1391.0–1393.0	0.08
Si IV	1398.0–1400.0	0.12
C IV	1543.0–1545.0	0.39
C IV	1549.0–1551.0	0.06
C IV	1575.0–1577.0	0.10

[a] Ratio of the average standard deviation in the wavelength interval indicated to the mean flux level.

ϵ Ori. The N v doublet exhibits evidence for these components as well, as indicated in Figure 4. The features are visible on almost all of the 31 spectra and so are clearly real. The time coverage available shows that these features persist for time scales >15 hours. These absorption features are not apparent on the O VI line profiles in ϵ Ori, but the lower quality of the *Copernicus* data does not allow us to rule out their existence.

IV. DISCUSSION AND CONCLUSIONS

a) Variability of X-Ray Emission

The total X-ray flux from both ϵ Ori and κ Ori exhibited no variation over time scales of 100–5000 s. Compared to the observations in 1979, ϵ Ori had the same count rate, 0.36 s^{-1}, and the κ Ori count rate increased from 0.10 s^{-1} to 0.14 s^{-1}.

A model of constant softness ratio is unacceptable over the 10 hours of observations for either star. However, because of possible variations in the IPC gain, we cannot attribute the variations to actual changes of the source. Ultimately, the expected reprocessing of the IPC data base will reduce the IPC gain variation uncertainty.

The flux increase of κ Ori from 1979 to 1980 may be attributed solely to (a) a temperature increase from $10^{6.3}$ K to $10^{6.4}$ K, (b) a decrease of wind column density from $10^{20.7}$ cm^{-2} to $10^{19.8}$ cm^{-2} (a change of approximately 5% of the entire wind column density), or (c) an increase in the emission measure of 46%.

b) Variability of Ultraviolet Lines

The upper limits of ultraviolet variability observed here may be placed in the context of other studies. The first report of such variability was made by York *et al.* (1977), who detected variations in the O VI lines of ζ Pup (O4f), δ Ori (O9.5 II), and ι Ori (O9 III). The changes were of the order of up to several tens of percent, and fluctuations were observed over time scales of hours. A later study of ζ Pup was made by Snow, Wegner, and Kunasz (1980), who found variations <15% in O VI and Si IV. The changes were much weaker than seen by York *et al.*, and occurred over slightly longer time scales. Snow (1977) had previously found variations in the P Cygni profiles of several O and B stars over a few years.

More directly relevant is the study of κ Ori by Stalio and Upson (1979). Variations in the O VI and N v doublets were observed over time scales ~1–2 days. The changes in the profiles were approximately 20–50% over two spectral bands of ~2 Å width in the absorption part of the P Cygni profile. We would have detected variations of >10% over such bands in our observations of N v. The variations were not found, and therefore we conclude that either κ Ori was in a relatively quiescent state over the 14 hours observed with *IUE*, or that the substantial fluctuations observed by Stalio and Upson are characteristic of time scales of days rather than hours. If the time scale were hours, then the fluctuations would appear to represent organized, coherent variations of the wind.

It is useful to keep in mind the saturation of the ultraviolet profiles when considering translating line profile variations into possible mass-loss or X-ray emission measure fluctuations. Olson and Castor (1981) have determined an empirical wind model for ϵ Ori. Using their parameters in conjunction with the atlas of the theoretical wind models computed by Castor and Lamers (1979), it is possible to estimate the variation in $\dot{M}$ which results in a given profile change. For the N v doublet, the radial optical depth at a velocity $v = \frac{1}{2}v_\infty$ is estimated to be ~2 by Olson and Castor (1981). Comparing this to the atlas of theoretical profiles, a change in $\dot{M}$ of 50% leads to a variation in the line profile of <10% of the continuum. Even this is a relatively favorable situation, and it occurs in the line profile only for $0.5 < v/v_\infty < 0.9$; other portions of the line profile are much less sensitive. Thus the ultraviolet observations in this velocity range at best can indicate fluctuations ~50% in the local density over regions >1 R_*. The situation is considerably worse in terms of sensitivity to mass-loss rate fluctuation for the other lines observed here, which are much more saturated. Olson and Castor estimate $\tau_{\rm rad}(v = \frac{1}{2}v_\infty) = 5$ and 8 for Si IV and C IV, respectively, so that saturation effects preclude observing anything but very large reductions in $\dot{M}$.

The possible increase of 46% in X-ray source emission measure deduced above for κ Ori should not affect the ultraviolet profiles by more than ~10% of the continuum. Thus the change seen in the X-ray count rate of κ Ori is consistent with a change in ultraviolet profiles that would be only marginally detectable with the *IUE* spectrograph. Unfortunately, there were no *IUE* spectra of κ Ori taken near the time of the 1979 *Einstein* observation.

c) Stationary Features

As noted previously, ϵ Ori appears to exhibit two "shell" features in Si IV and N v which are stable over the 15 hours of *IUE* observations. Furthermore, one of these features appears to be present in the *Copernicus* data from 1975 (Snow and Jenkins 1977). Snow (1977) first called attention to such features. Similar observations led Lamers, Stalio, and Kondo (1978) to suggest that mass loss occurs in "puffs" (from stars with spectral types ranging from late B to early A supergiants), although this does not explain the stationary behavior. Snow (1977) cataloged various possible explanations such as ionization or velocity "plateaus." It was suggested that the plateaus appear because of chance patterns in the overlapping of absorption lines presumably driving the flow, but no quantitative support was presented for this idea. No clearly acceptable theoretical explanation is currently available.

d) *Constraints on X-Ray Models*

The lack of variability in our observations places constraints on the various models of X-ray emission from OB stars. Consider first the shock models. Lucy (1982) has found that in order to explain the hardness of the observed X-ray spectra, most of the X-ray flux must be produced in rare, but strong, shocks. (In the notation of his model, the shocks are characterized by $v = 3.4$ and $\epsilon = 1/25$ for the case of ϵ Ori. [Lucy 1982; Cassinelli and Swank 1983]). The magnitude of the X-ray flux from ϵ Ori can be explained by the passage of a strong shock through any point in the wind at a rate of 1 per 21 hours. However, the wind flushing time is only about 3 hours, so for steady X-ray emission at the observed luminosity, each strong shock should overlay no more than one-seventh of the star's surface. Furthermore, the statistical fluctuations in the number of the strong shocks present at any one time would cause variability in the X-ray flux. We estimate that variability on hourly time scales of greater than 20% would have been detected in our data. This places a lower limit of ~ 25 strong shocks in the wind at any one time. These are, of course, rough estimates, but they illustrate that nonvariability of the X-ray certaintly must be taken into account in further developments of the embedded shock model.

Constraints are also imposed on the recent base coronal explanations of the X-ray spectra. Stewart and Fabian (1981) and Waldron (1982) have proposed that the winds are of just the right optical depth or have just the right emission measure to explain the IPC X-ray spectra. Slight variations in the optical depth or coronal emission measure could result in greatly amplified change in the observed X-ray flux. In the context of those models, the steadiness of the X-ray flux implies constant mass-loss rates and X-ray production processes.

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