

THE VISUAL AND ULTRAVIOLET POLARIMETRIC DATA OF α CAMELOPARDALIS AND κ CASSIOPEIA: EVIDENCE OF SHOCKED REGIONS

GEOFFREY K. FOX, JOHN C. BROWN,¹ AND KAREN S. BJORKMAN

Space Astronomy Laboratory, University of Wisconsin, 1150 University Avenue, Madison, WI 53706;
 Fox@larry.sal.wisc.edu

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ABSTRACT

The OB supergiants α Cam and κ Cas are intrinsically very similar stars at comparable distances. Apart from a constant offset in the polarization of $\simeq 0.2\%$, both stars exhibit the same polarimetric variation between 1400 and 8000 Å. Several possible mechanisms to explain the polarimetric observations are investigated. We propose that the polarization mechanism may be due to grain formation in an extended shell where the stellar wind and the interstellar medium interact. If this interpretation is correct, then it implies that the physical process giving rise to grain formation is not strongly correlated to the stellar wind parameters.

Subject headings: polarization — stars: individual (κ Cassiopeia, α Camelopardalis) — stars: supergiants — ultraviolet: stars

1. INTRODUCTION

The OB supergiants α Cam and κ Cas possess very similar characteristics. Table 1 summarizes the main physical properties of both stars. The data were taken from Nugis (1989) with the exception of the polarization data (this paper) and the stellar association to which the star is believed to belong (Lennon, Dufton, & Fitzsimmons 1992). These stars differ spectroscopically by only one subclass and are estimated to be at approximately the same distance. The main differences between the stars are that κ Cas has a slower wind and lower mass-loss rate. It should be noted, however, that depending upon the method used the estimated values for v_∞ and \dot{M} may vary. For example, according to the literature v_∞ (km s⁻¹) lies in the range of 1150–2050 for α Cam and 1500–1650 for κ Cas, and \dot{M} (10⁻⁶ M_\odot yr⁻¹) lies in the range 0.8–5.1 for α Cam and 1.4–2.5 for κ Cas (Abbot 1978; Wilson & Dopita 1985; Groenewegen, Lamers, & Pauldrach 1989; Vilkoviskij & Tambovtseva 1992).

2. OBSERVATIONS

Both stars were observed in the UV during 1990 December using the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE) flown aboard the space shuttle Columbia as part of the Astro-1 mission. Ground-based support observations were taken at Pine Bluff Observatory (PBO). The dates on which κ Cas was observed are given in Taylor et al. (1991). Similarly, the observation dates for α Cam may be found in Clayton et al. (1992). A description of the instrument and data reduction procedure may be found in these references as well. The data presented here are based on the final calibration of WUPPE data rather than the preliminary calibrations used by Taylor et al. (1991) and Clayton et al. (1992).

The variation of the flux, polarization, and position angle versus wavelength are illustrated in Figures 1 and 2 for κ Cas and α Cam, respectively. The polarization of both stars is almost constant in the visual and decreases linearly with wavelength in the UV. The characteristic polarization variation of

the stars with wavelength is very similar. The only difference between the stars is a constant difference of $\simeq 0.2\%$ throughout the entire wavelength range and a small rotation in the position of κ Cas by 8° across the entire wavelength range.

3. INTERPRETATION OF THE DATA

In general, the observed (obs) normalized Stokes parameters are the sum of the intrinsic (int) and interstellar medium (ISM) components, given by

$$\begin{bmatrix} Q(\lambda) \\ U(\lambda) \end{bmatrix}_{\text{obs}} = \begin{bmatrix} Q(\lambda) \\ U(\lambda) \end{bmatrix}_{\text{int}} + \begin{bmatrix} Q(\lambda) \\ U(\lambda) \end{bmatrix}_{\text{ISM}}. \quad (1)$$

The observed polarization may, therefore, be dominated entirely by the interstellar or intrinsic polarization or be a combination of both components. Each of these three possibilities will be considered in turn.

3.1. Interstellar Dominates

McLean & Clarke (1979) demonstrated that it is possible to estimate the interstellar contribution from the polarimetric variability of a star. This method is not particularly useful here, however, since we require the wavelength dependence of the interstellar component while most of the observations of κ Cas and α Cam are comprised of broadband measurements (Hayes 1984; Lupie & Nordsieck 1987). There are three additional methods with which to determine the interstellar polarization component.

3.1.1. Polarization versus E_{B-V}

Serkowski, Mathewson, & Ford (1975) showed that there exists an upper limit to the V -band polarization,

$$P_{\text{max}} \leq 9.0 E_{B-V}. \quad (2)$$

Since both stars have similar values of E_{B-V} , then $P_{\text{max}} = 0.29\%$. Neither star exhibits a polarization much more than about half of this maximum value and so it is difficult to draw any conclusions from this information. Furthermore, this method yields only the maximum value for the polarization and does not give any information about the wavelength dependence of the interstellar component.

¹ Department of Physics and Astronomy, University of Glasgow, G12 8QQ, Scotland, UK.

TABLE 1
PHYSICAL PARAMETERS

Parameter	α Cam	κ Cas
Spectral type	O9.5 Ia	B1 Ia
V mag	4.29	4.16
Distance (Kpc)	1.2	1.0
E_{B-V}	0.32	0.31
\dot{M} ($10^{-6} M_{\odot} \text{ yr}^{-1}$)	4.6	1.1
v_{∞} (km s^{-1})	2050	1650
V pol (%)	1.61	1.45
Association	NGC 1502	Cas OB 14

3.1.2. Serkowski's Law

Serkowski et al. (1975) showed that the intrinsic polarization $P(\lambda)$ at a given wavelength λ in the visual range could be fitted by an empirical law of the form

$$P(\lambda) = P_{\max} \exp \left[-K \ln^2 \left(\frac{\lambda_{\max}}{\lambda} \right) \right], \quad (3)$$

where λ_{\max} is the wavelength at which the maximum polarization (P_{\max}) occurs and K is an adjustable constant of order unity.

A χ^2 fit to the visual data (and extrapolated to the UV) is shown for each star in Figures 1 and 2. In the UV the observed polarization is in excess of that predicted by the Serkowski law. It has been shown by Clayton et al. (1992) that other interstellar probes do obey the Serkowski law in the UV, so the excess UV polarization should be considered real rather than the Serkowski law being inappropriate in the UV range.

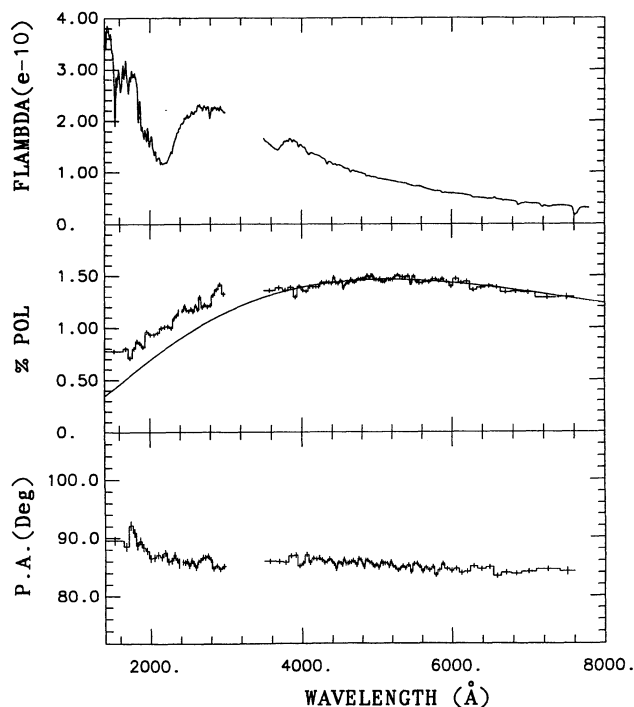


FIG. 1.—The observed WUPPE and PBO data for κ Cas. The data are binned to a constant polarization error of 0.02%. The WUPPE data were collected on 1990 December 9. The PBO data were collected on 1990 December 10. The smooth curve represents a Serkowski fit to the visual data and extrapolated to the UV. The Serkowski fit is given by the parameters $P_{\max} = 1.465$, $\lambda_{\max} = 5119 \text{ \AA}$, $\theta = 85^\circ 3$, and $K = 0.860$. There is no data coverage between 3500 and 3000 \AA . Due to an instrument problem there are no data around 2400 \AA .

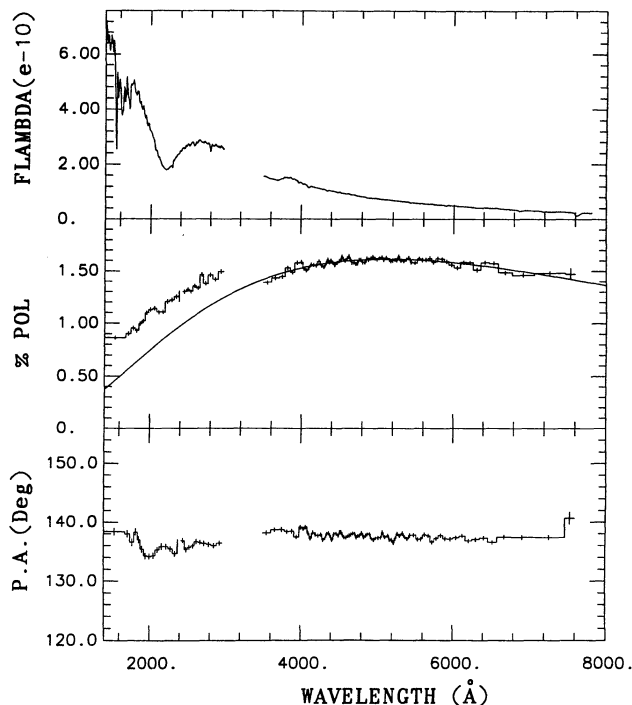


FIG. 2.—The observed WUPPE and PBO data for α Cam. The data are binned to a constant polarization error of 0.02%. The WUPPE data are the combined data collected on 1990 December 4 and 8. The PBO data were collected on 1990 December 7. The Serkowski fit is given by the parameters $P_{\max} = 1.613$, $\lambda_{\max} = 5147 \text{ \AA}$, $\theta = 137^\circ 6$, and $K = 0.864$. There is no data coverage between 3500 and 3000 \AA . Due to an instrument problem there are no data around 2400 \AA .

3.1.3. Comparison with Nearby Stars

As part of the Astro-1 mission, an extensive database of stellar polarization measurements was made from published and unpublished data. From this database, 66 stars have been measured within a 5° radius of κ Cas. A polarization map of the region is illustrated in Figure 3. A similar map is shown for the region around α Cam in Figure 4. Because α Cam lies in a relatively star-poor region of the sky a larger radius of 15° was required to obtain 21 stars. Qualitatively it appears that both stars have polarizations consistent with nearby stars. However, if the same data are plotted in the Q , U plane (Figures 5 and 6) it is evident that there is so much spread in both the degree of polarization and position angle that it is not possible to tell if the observed polarization is in fact consistent with an interstellar origin.

For κ Cas there may be some evidence that its polarization could be interstellar because several stars exhibit polarizations close to its value (Fig. 5). However, these stars are located some 3° away (Fig. 3) in a faint nebosity region that is visible on the Palomar Sky Survey plates (near HD 2011). In Figure 4 it appears that α Cam is highly polarized ($P \approx 1.6\%$) compared to its neighbors ($P < 1\%$). However, due to the real lack of stars near α Cam one can make no conclusions about its interstellar component based on the polarization measurements of stars over 5° away.

Of the three methods used to determine the interstellar polarization the only method from which firm conclusions can be drawn is from the Serkowski fit to the data. If the interstellar component is given by this fit, some intrinsic component is required to explain the UV excess polarization. This, however, raises a problem since one then requires a polarizing

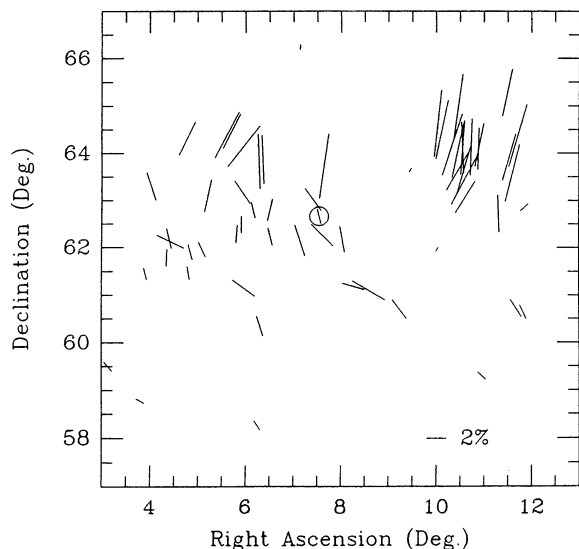


FIG. 3.—Polarization map for 66 stars within a 5° radius of κ Cas. κ Cas is indicated by the circled polarization vector. The right ascension is measured in degrees.

(or opacity) mechanism to operate solely in the UV. No such mechanism is known and so the interstellar component cannot be as much as is indicated by the Serkowski fits (Figs. 1 and 2). Since the observed polarization of κ Cas and α Cam cannot be explained as arising solely due to the ISM, then there must be some intrinsic polarization.

There is additional evidence against a pure interstellar origin for the observed polarization of either star. First, both stars are known to exhibit a random intrinsic polarimetric variability of up to 0.2% (Hayes 1984; Lupie & Nordsieck 1987). Second, from a close inspection of Figures 1 and 2 there is suggestive evidence (at the 3σ level) of a reduction in the polarization across emission lines (e.g., unidentified emission lines at, 2675 Å, 2800 Å, and 2950 Å), compared to the continuum, while

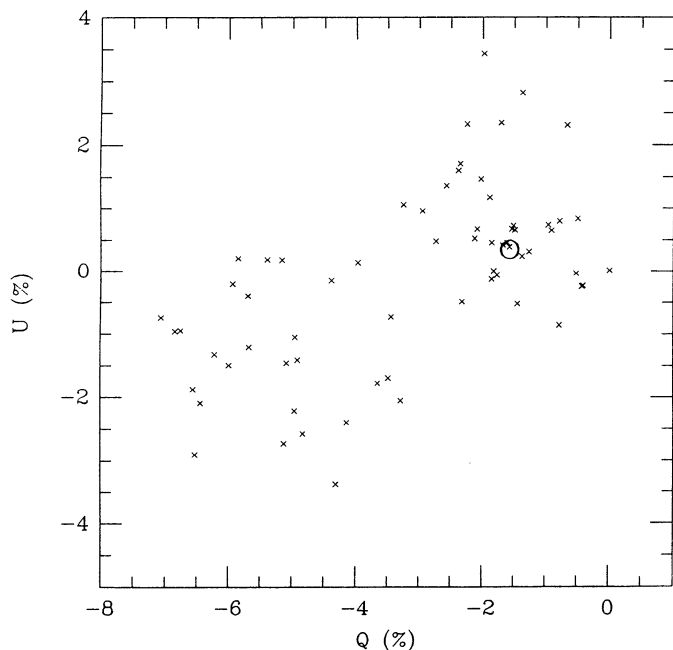


FIG. 5.—The polarization of the field stars from Fig. 3 in the Q, U plane. The circled point is κ Cas. The highly polarized star H62 ($P = 4.51\%$, $\theta = 6^\circ$) has been excluded.

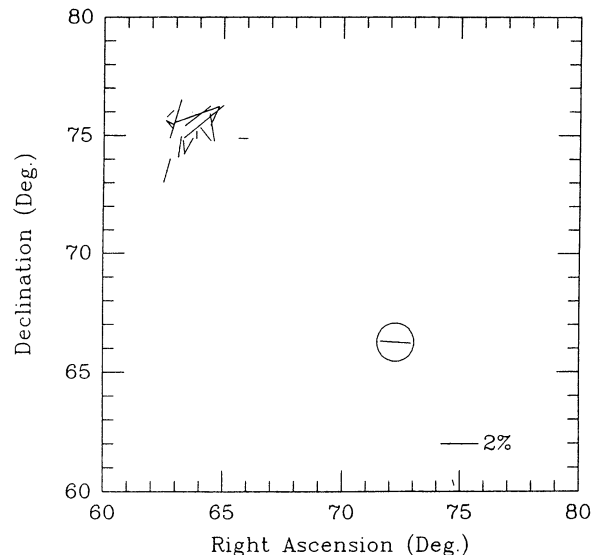


FIG. 4.—Polarization map for 21 stars within a 15° radius of α Cam. α Cam is indicated by the circled polarization vector.

stellar absorption lines are polarimetrically enhanced (e.g., the hydrogen Balmer lines). This implies that at least some of the polarization is intrinsic in origin. Third, although the E_{B-V} values for both stars are similar, the UV ISM features at 2200 Å are completely different (Figs. 1 and 2). This suggests that the distribution of interstellar material (e.g., grain size and types) along the two lines of sight is also different. There is also a lack of polarimetric variation (at the 3σ level) across this feature for either star. This suggests that the interstellar material responsible for this feature may be composed of nonpolarizing absorbers and implies that some of the observed polarization may be of intrinsic origin.

3.2. Intrinsic Only

The visual polarization data for both stars are approximately independent of wavelength. Together with the inferred

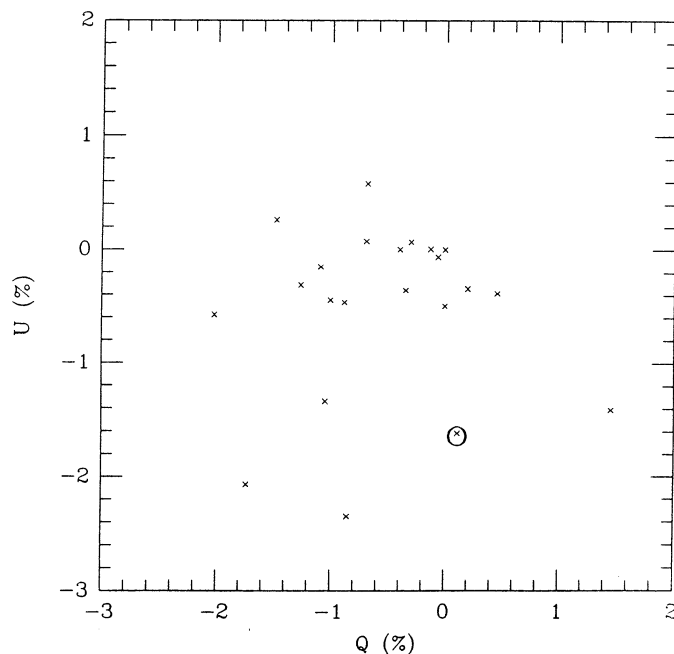


FIG. 6.—The polarization of the field stars from Fig. 4 in the Q, U plane. The circled point is α Cam.

temperatures of OB supergiants (typically 30,000 K; Prinja & Howarth 1986), we infer that the polarization is due to electron scattering. The UV data, on the other hand, decrease linearly with wavelength. The reduced UV polarization (with respect to the visual) suggests that there is additional UV emission and/or absorption present in the wind.

3.2.1. Opacity Effects

McLean (1979) has shown that the polarization from an axisymmetric envelope in which photons undergo single scattering and continuous absorption processes close to the star can be approximated by

$$P = e^{-\bar{\tau}_a(\lambda)} P_{\text{BM}}, \quad (4)$$

where $\bar{\tau}_a(\lambda)$ is some mean optical depth due to absorption and P_{BM} is the degree of polarization predicted by Brown & McLean (1977) when absorption is neglected. If the maximum polarization (P_{max}) occurs when there is no absorption ($P_{\text{max}} = P_{\text{BM}}$), then the relative mean optical depth $\bar{\tau}_a(\lambda)$ can be inferred from observations.

The change in the mean optical depth with wavelength is illustrated in Figure 7 for α Cam. (The results for κ Cas, which are very similar, are not reproduced here.) There is no absorption in the visual region of 4000–6000 Å. At longer and shorter wavelengths the optical depth increases reaching maximum values of 0.43 at 1900 Å and 0.23 at 7000 Å. For illustration purposes the inferred optical depth is compared to the most commonly occurring opacity mechanisms, namely electron and Rayleigh scattering. While it is clear that none of these opacity mechanisms matches the inferred optical depth at all wavelengths, Rayleigh scattering does appear to fit the data at short wavelengths ($\lambda < 5000$ Å). If Rayleigh scattering is important at short wavelengths, then the data require an additional opacity mechanism to be important only at longer wavelengths ($\lambda > 5000$ Å). Such a mechanism is not known.

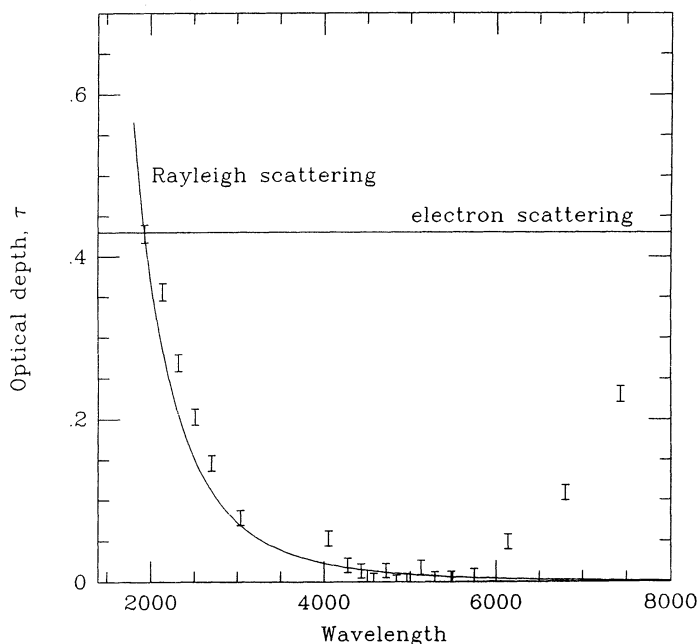


FIG. 7.—The inferred optical depth of the stellar wind of α Cam, if the polarization is assumed to be entirely intrinsic. The polarimetric data of Figure 1 were rebinned to a constant polarization error of 0.01%. The optical depth increases outside of the visual range of 4000–6000 Å. For comparison purposes the mean optical depth due to electron and Rayleigh scattering are illustrated. Each is defined to have an optical depth of 0.43 at 1900 Å.

Furthermore, no single opacity mechanism is known to give rise to the parabolic variation depicted in Figure 7.

3.2.2. Emission in the Wind

Another possible cause for the decrease in the UV polarization is additional unpolarized emission of radiation within the wind, for example, due to shocks (Gies & Wiggs 1991; Usov 1992; Bychkov & Cherespashchuk 1993). In this case (assuming an optically thin electron scattering envelope),

$$P(\lambda) = \frac{P_{\text{BM}}}{1 + J(\lambda)}, \quad (5)$$

where $J(\lambda)$ is the ratio of the intensity due to the wind relative to that of the star.

If we assume that there is no emission from the wind at visual wavelengths, then the emission in the UV (due to recombination, collisional excitation) must reach up to $J(\lambda) \simeq 1$. This is not only physically impossible, but there is also no evidence for this claim in the UV flux of either star.

3.2.3. Other Mechanisms

Another possibility is that the effective radius of the star (defined at $\tau = \frac{2}{3}$) may vary significantly with wavelength, like W-R stars. Cassinelli, Nordsieck, & Murison (1987) have shown that if the effective radius of the star changes with wavelength so will the polarization (even for a pure electron scattering envelope, Fox 1991). A wavelength-dependent stellar radius, however, is not supported by the photometry of eclipsing OB supergiants (Landolt 1964; Koch 1972; Mandore 1975).

3.3. Interstellar and Intrinsic Contributions

The preceding sections have shown that the observed polarization of α Cam and κ Cas cannot be interpreted as arising solely due to either an interstellar or intrinsic origin. One must therefore conclude that the polarization is a combination of both. If this is the case, one must expect a rotation of the position angle with wavelength. However, α Cam does not exhibit such a dependence and the position angle of κ Cas only rotates by 8° over the entire wavelength range (or about 1° per 1000 Å). Such a small rotation of position angle implies that either one component (interstellar or intrinsic) dominates the observed polarization, which has been shown not to be the case (§§ 3.1 and 3.2) or the interstellar and intrinsic polarizations are almost co-aligned.

4. AN EXTENDED REGION

The probability that the interstellar and intrinsic polarization could be co-aligned by chance for both stars is small and therefore one must investigate the possibility that there exists some underlying physical mechanism to explain this co-alignment.

A possible explanation is that massive luminous stars are known to possess winds that interact with the ISM (Castor, McCray, & Weaver 1975), causing an expanding bubble to form around the star. Over a period of 1 million years or so (approximately the age of OB supergiants), the bubble will typically have a radius of ~ 20 pc and a thickness of ~ 6 pc. At the boundary, where the stellar wind interacts with the ISM, the density increases and the temperature decreases, allowing grain formation to occur. Since the ram pressure at the shock boundary ($\propto Mv_\infty$) for the two stars differs by a factor of 5, the polarization data imply that the physical mechanism giving rise to grain formation cannot be very sensitive to the values of the wind parameters (e.g., v_∞ and \dot{M}). If this interpretation is

correct we expect that OB giant and supergiant stars will exhibit a polarimetric variation similar to that of α Cam and κ Cas; i.e., they will exhibit an excess UV polarization compared to that predicted by the Serkowski fit to the visual data.

Independent evidence for the existence of such a shocked region is evident in the *IRAS* data, from which Van Buren & McCray (1988) have shown that a bow-shocked region exists around both stars, and de Vries (1985) has shown that α Cam is associated with a warm (40° K) dust cloud some 25 pc in diameter.

To test the possibility that shocked regions give rise to a peculiar UV polarization signature, we note that WUPPE also observed the supergiant P Cyg (Taylor et al. 1991), two B type giants, and three main-sequence B stars (Clayton et al. 1992). Due to the temporal polarimetric variability of P Cyg no UV excess polarization could be observed. Of the two giants, HD 25443 definitely exhibits an excess of UV polarization, while HD 197770 appears to exhibit only an excess around the 2200 Å ISM feature. The three main-sequence stars appear to fit the Serkowski law at all wavelengths. This would suggest that while OB giants and supergiants have sufficiently strong winds to interact with the ISM, main-sequence stars do not.

A quantitative estimate of the mean number density of the dust in the shock region can be obtained from Spitzer (1978, p. 176) if we assume the dust is composed of aligned ice grains with an average size of 1×10^{-7} m in a shell 6 pc thick at a distance of 20 pc from the star. One finds the mean number density to be $n_0 \simeq 400 \text{ m}^{-3}$. With this value the shell has a mass about $7.5 M_\odot$, consistent with the estimate given by Castor et al. (1975).

If we assume that the underlying physical mechanisms giving rise to the observed polarization are the same for both stars then (independent of the mechanisms) the constant offset of $\sim 0.2\%$ in the polarization (Figs. 1 and 2) can be explained only by either one or both stars possessing an electron scattering axisymmetric envelope (since this offset is independent of wavelength).

To summarize, we illustrate in Figure 8 a cartoon of the global environment of the two OB supergiants based on our interpretation of the polarization data. The OB supergiant loses mass at a rate of $\sim 10^{-6} M_\odot \text{ yr}$, to form an axisymmetric electron scattering envelope with a net polarization of $\leq 0.2\%$ (from the constant offset value). The mass loss is presumably asymmetric, giving rise to a temporal polarimetric variability of $\leq 0.2\%$ (Hayes 1984; Lupie & Nordsieck 1987). At a distance of ~ 20 pc from the star the stellar wind interacts with the ISM to form a shocked region ~ 6 pc thick (Castor et al. 1975). Within this region the low temperature and high density are conducive to the formation of grains. At these distances the grains are presumably aligned by the interstellar magnetic field. This is where most of the polarization is formed. The

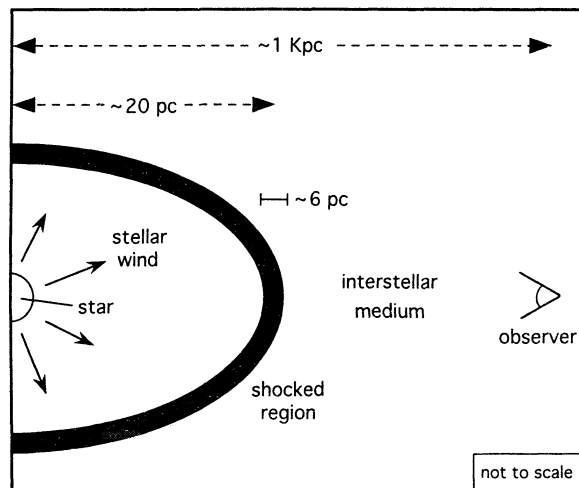


FIG. 8.—Cartoon of the global environment of an OB supergiant; not to scale. See text for details.

polarized radiation is then further modified by the ISM (though its contribution may be small, judging by the lack of a polarimetric variation across the 2200 Å ISM feature and also by the relatively high density of the shocked region compared to the ISM) until it reaches the observer ~ 1 kpc away.

5. DISCUSSION AND CONCLUSIONS

The similar polarization properties of κ Cas and α Cam suggest a common underlying physical mechanism. We have proposed that the polarization may be produced by grain formation in a shocked region where the stellar wind and ISM interact. We predict that other OB giants and supergiants will exhibit the same excess UV polarization compared to that predicted by a Serkowski fit to the visual data.

It is clear that our speculation requires more UV polarimetric measurements before the origin of the excess UV polarization can be determined as arising due to the interaction of a stellar wind with the ISM. In particular, a better determination of the interstellar polarization from field stars is required over a longer wavelength range. A second flight of WUPPE is scheduled for 1995 March during which a variety of OB stars will be observed.

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