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NEAR-INFRARED OBSERVATIONS OF INTERSTELLAR POLARIZATION

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ABSTRACT

We have observed interstellar linear polarization at three wavelengths between 1 and 2.2 μ for seven stars. We find that the polarization tends to decrease much less rapidly to wavelengths longward of that at which maximum polarization occurs than predicted by Serkowski's empirical relation. The observations appear to be consistent with a model in which the polarization is produced by a mixture of graphite and silicates rather than by pure silicates.

I. INTRODUCTION

Measurements of linear interstellar polarization between 1 and 2.2 μ have been small in number and of lower precision than those in the visual. To date, observations exist of VI Cyg No. 12 and HD 183143 (Dyck 1974), ξ Oph (Gehrels 1974), and o Sco (Cox *et al.* 1976). Yet these data are potentially of great value for testing Serkowski's empirical relation (e.g., Serkowski *et al.* 1975) and theoretical models computed by Martin (1974). Greenberg (1968) and, more recently, Martin (1975) have pointed out that near-infrared observations should be generally valuable for determining the contribution to interstellar polarization by metals such as graphite. The sensitivity to composition occurs because the refractive indices for graphite change rapidly between 1 and 4 μ (e.g., Greenberg 1968) while those for most dielectrics (e.g., silicate minerals) change slowly (Pollack *et al.* 1973; Steyer *et al.* 1974). Thus, for an optically-thin medium of aligned submicron grains, the wavelength dependence of polarization in the infrared will tend to reflect these differences.

Until recently linear polarization measurements have been limited to only the brightest stars by relatively poor detectors. With the advent of high-quality InSb detectors the polarimetry is no longer limited by detector noise and a vast number of heavily-reddened stars has become available for observation. We report here new, high-precision observations of seven stars at three wavelengths between 1 and 2.2 μ and comment upon the data in light of the foregoing discussion.

II. OBSERVATIONS

The data were all obtained with a rotating-analyzer polarimeter employing either a Polaroid HR sheet or a Cambridge Consultants model IGP 225 wire grid on BaF_2 substrate. The analyzer was placed in front of all beam-splitters and beam-directing mirrors and was used most of the time with a quartz Lyot depolarizer to eliminate any spurious effects introduced by these mirrors. Small residual effects were found which are attributable to variable transmission across the analyser and to beam wander at the detector. These effects were found to be constant by measurement of unpolarized stars and corrections have been applied to the published data. Corrections for system efficiency have also been applied. Calibration of the analyser position angle was carried out using the published visual position angles for VI Cyg No. 12 and HD 183143; since neither shows strong rotation with wavelength, we expect no significant error from this method. The filters were close approximations to the Arizona JHK photometric system having central wavelengths of 1.25, 1.65, and 2.2 μ. All observations were obtained during 1976–1977 on the Mauna Kea 2.2-m telescope equipped with an f/35 chopping secondary for sky cancellation.

The data are listed in Table I with additional information about the program stars. The tabulated values are means of several observations taken on at least two different nights and the errors are the standard errors of those means. We have also plotted the data in Figs. 1 and 2 along with published visual polarimetry taken from several sources. The solid lines in the figures are fits of Serkowski's empirical formula

$$P/P_{\max} = \exp\left[-1.15 \ln^2(\lambda_{\max}/\lambda)\right]$$

to the observations. The parameters $P_{\max}$, the maximum value of the polarization, and $\lambda_{\max}$, the wavelength at which the maximum occurs, have been taken from Serkowski *et al.* (1975). For o Sco our data are systematically lower than those of Cox *et al.* (1976) by about 20% at 1.25 μ and 10% at 2.2 μ. For VI Cyg No. 12 our data agree reasonably with those published by Dyck (1974); and for HD 183143 our 2.2 μ value is about a factor of 2 higher than that published by Dyck (1974). Our new observations have approximately two to three times higher precision than those in the literature.

III. DISCUSSION

The noteworthy results from our investigation can be summarized: (a) the observed ratio P_J/P_K does not show a large dispersion; (b) the observed ratio P_J/P_K is gen-

TABLE I. The observational data.

Star	$\lambda_{\max}$	$P_{\max}$	$\theta_{\max}$	$P_J \pm \epsilon$ (%)	θ_J(°)	$P_H \pm \epsilon$ (%)	θ_H(°)	$P_K \pm \epsilon$ (%)	θ_K(°)
o Sco	0.67	4.30	32	2.28 ± .09	34	...	...	0.92 ± .16	32
HD 147889	0.80	4.06	175	2.80 ± .22	170	...	...	1.19 ± .14	170
HD 154445	0.57	3.74	90	1.77 ± .06	91	...	...	0.84 ± .11	92
HD 160529	0.53	7.20	20	3.08 ± .16	19	...	...	1.35 ± .15	15
HD 183143	0.56	6.07	179[a]	2.77 ± .05	176	1.65 ± .16	176	1.06 ± .07	174
VI Cyg No 12	0.45	9.48	116[a]	3.31 ± .17	117	2.15 ± .12	127	1.22 ± .12	113
HD 204827	0.46	5.62	60	2.34 ± .15	64	...	...	1.34 ± .12	72

[a] $\theta_{\max}$ used to calibrate polarimeter position angle.

erally smaller than that predicted from Serkowski's relation for the best fit $\lambda_{\max}$ and $P_{\max}$; and (c) the observed P_K values tend to lie above Serkowski's relation extrapolated to 2.2. In order to illustrate these aspects of the data, we have listed the important points in Table II, where the superscripts o and p refer to observed values and to predicted values from Serkowski's relation, respectively. The first point is that the predicted values of the near-infrared slopes $(P_J/P_K)^{\mathrm{p}}$ range from 2.6 for HD 147889 to 5.7 for VI Cyg No. 12. In contrast to those predicted values the observed slopes $(P_J/P_K)^{\mathrm{o}}$ range from 1.8 for HD 204827 to 2.7 for VI Cyg No. 12, having a mean value 2.3 ± .3 (rms). There is no correlation between the observed slopes and $\lambda_{\max}$ as there is for the predicted values; the highest and lowest values of $(P_J/P_K)^{\mathrm{o}}$ correspond to the two stars having the smallest values of $\lambda_{\max}$. A second related point is that the ratio of observed to predicted slopes $(P_J/P_K)^{\mathrm{o}}/(P_J/P_K)^{\mathrm{p}} < 1$ and, for this case, there is a correlation with $\lambda_{\max}$. This correlation is not unexpected since $(P_J/P_K)^{\mathrm{p}}$ is well correlated with $\lambda_{\max}$. We have shown this correlation in Fig. 3 where one can clearly see that the largest discrepancies between observed and predicted slopes occur for the smallest values of $\lambda_{\max}$ and conversely. The third point is that the ratio of observed to predicted polarization at 2.2 μ, $P_K{}^{\mathrm{o}}/P_K{}^{\mathrm{p}}$ ranges from 1 to 4 indicating that the observed values tend to lie above the predicted ones. If the value for $\lambda_{\max}$ is changed in an effort to improve the fit for the infrared data, the relation makes a serious departure from the data in the visible. It may be noted that the effects are small in an absolute sense, being less than about 1%, but that the significant departures between observed and predicted values are large compared to the observational errors. In Table II we have computed

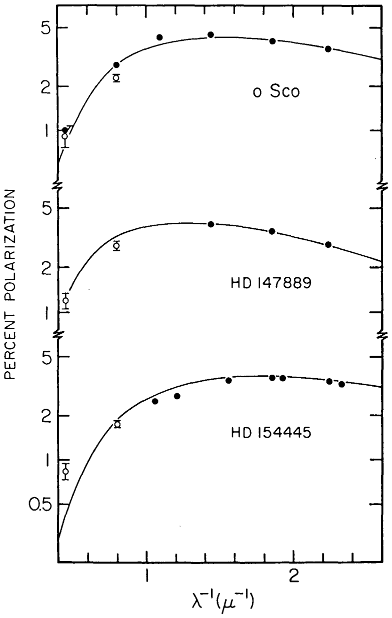

FIG. 1. Wavelength dependence of polarization for three stars. The open circles (○) are data from this program; the filled circles (●) are data from Coyne and Wickramasinghe (1969), Cox *et al.* (1976), and Serkowski *et al.* (1975). The solid lines are graphs of Serkowski's empirical relation fitted to the observations using $P_{\max}$, $\lambda_{\max}$ taken from Serkowski *et al.* (1975).

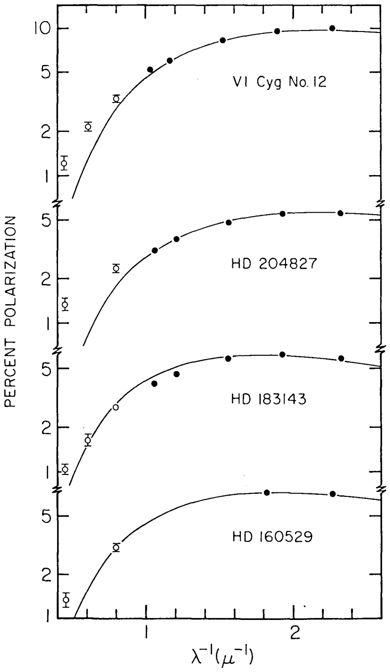

FIG. 2. Wavelength dependence of polarization for four stars. The open circles (○) are data from this program; the filled circles (●) are data from Coyne and Wickramasinghe (1969), Dyck (1974), Kruszewski (1971), Serkowski *et al.* (1969), and Serkowski (1968). The solid lines are graphs of Serkowski's empirical relation fitted to the observations using $P_{\max}$, $\lambda_{\max}$ taken from Serkowski *et al.* (1975).

TABLE II. Comparison of observations to Serkowski's empirical relation.

Star	$\lambda_{\max}$	$(P_J/P_K)^{\mathrm{p}}$	$(P_J/P_K)^{\mathrm{o}}$	$(P_K{}^{\mathrm{o}} - P_K{}^{\mathrm{p}})/\epsilon$	$P_K{}^{\mathrm{o}}/P_K{}^{\mathrm{p}}$
o Sco	0.67	3.3	2.5	0.6	1.1
HD 147889	0.80	2.6	2.4	−0.2	1.0
HD 154445	0.57	4.1	2.1	3.6	1.9
HD 160529	0.53	4.6	2.3	4.5	2.0
HD 183143	0.56	4.2	2.6	5.4	1.6
VI Cyg No 12	0.45	5.7	2.7	6.0	2.4
HD 204827	0.46	5.5	1.8	8.5	4.2

the difference between the observed and predicted values at 2.2 μ divided by the observational error $(P_K{}^{\mathrm{p}} - P_K{}^{\mathrm{o}})/\epsilon$, which is a measure of the significance of the departure. Two stars—o Sco and HD 147889—show less than 1 σ departure. The remaining five stars show departures ranging from about 3.5 σ to about 8 σ, all significant in a statistical sense. We rule out that the separation is caused by any systematic errors in correction of instrumental polarization because such a vectorial subtraction should produce low values as well as high ones given the wide distribution of position angles among the program stars. We conclude, therefore, that the departure is real and significant for some stars. We summarize by saying that the linear polarization generally declines less rapidly in the near infrared than is predicted by Serkowski's relation.

It is well known that the maximum of the wavelength dependence of polarization changes with changing grain size (Greenberg 1968). However, Martin (1974) has stated that the shape will remain constant with changing grain size only if the refractive index is independent of wavelength. If the interstellar particles were pure silicates, for example, this condition would be approximately fulfilled in the visible and near infrared and one might expect to be able to find an empirical relation to fit the polarization data. However, the observed ratio of visual extinction to 9.7 μ silicate absorption optical thickness $(A_v/\tau_{9.7\mu})$ in VI Cyg No. 12 (Gillett *et al.* 1975) cannot be accounted for on the basis of pure silicates. Pure silicates yield too little extinction in the visible per unit absorption at 9.7 μ. Hence one requires the addition of more extinction in the visible which will not produce an absorption band in the infrared. Metals, notably graphite, satisfy this requirement. Given a mixture of graphite and silicates one can qualitatively understand the behavior of the linear polarization in the infrared: small silicate grains (size $\simeq$ 0.1–0.2/μ), which have a small imaginary part of the index of refraction, will produce polarization primarily by scattering. In the infrared (where size $\ll \lambda$) the polarization would scale approximately as (size $\lambda)^4$; small graphite grains (size $\simeq$ 0.05–0.08 μ), which have a large imaginary part of the index of refraction, will produce polarization primarily by absorption. In the infrared the polarization would scale approximately as (size/λ). Hence, as the particle size of a mixture of graphite and silicates decreases, the role of graphite becomes more dominant in the infrared. One would expect to observe a progressively larger departure between observations and an empirical relation (valid only if the polarization were produced by silicates) as $\lambda_{\max}$ decreases. This behavior is in agreement with the observations reported here.

Small $\langle a \rangle \sim 0.03$ μ graphite grains appear to be a necessary constituent of the interstellar medium if the 2200 Å absorption feature is to be reproduced (Mathis *et al.* 1977; Kunkle 1978). Since these grains are small, they cannot contribute significantly to the interstellar extinction or polarization in the infrared unless they are present in quantities much larger than necessary to fit the 2200 Å feature. Kunkle (1978) has been able to reproduce the observed interstellar extinction longward of 1 μ with grain composition and size distributions similar to Mathis *et al.* (1977) but with the addition of a small quantity (~0.7%) of larger, $\langle a \rangle \sim 0.15$ μ, graphite grains. These few larger graphite grains do not contribute a significant amount to the extinction in the *UV* but are the dominant absorber in the infrared. The addition of these larger graphite grains may cause a discrepancy with the observed peak in the interstellar circular polarization and circular polarization calculations should be made to check this.

IV. CONCLUSION

We conclude, based upon near-infrared linear polarization observations of seven stars, that:

(1) the polarization falls less rapidly longward of $\lambda_{\max}$ than predicted by Serkowski's relation, and

(2) the observations can be explained, qualitatively, by assuming that the polarization is produced by a mixture of graphite and silicates.

Clearly one needs to increase the sample size and to pay special attention to stars for which $\lambda_{\max} \lesssim 0.5$. Observations at 3.5 μ would also be important. Further insight into the interpretation will come when models are calculated for graphite–silicate mixtures which take

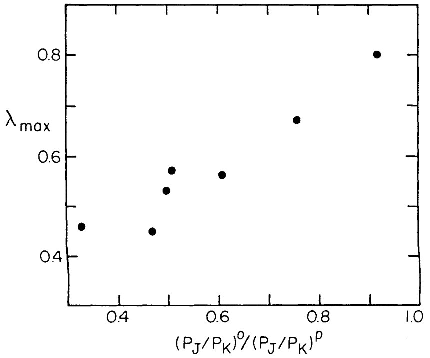

FIG. 3. The ratio of the slope of the observed near infrared λ-dependence of P $(P_J/P_K)^{\mathrm{o}}$ to that predicted from Serkowski's relation $(P_J/P_K)^{\mathrm{p}}$ versus $\lambda_{\max}$.

account of the wavelength dependence of the refractive index (Martin 1975).

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