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THE FIRST SPECTROPOLARIMETRIC STUDY OF THE WAVELENGTH DEPENDENCE OF INTERSTELLAR POLARIZATION IN THE ULTRAVIOLET

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ABSTRACT

The first ultraviolet spectropolarimetry along six lines of sight with significant interstellar polarization is reported. The observations were obtained with the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE) during the Astro-1 mission. HD 37903, HD 62542 and HD 99264 show a wavelength dependence which follows the Serkowski relation extrapolated into the ultraviolet. HD 25443 and α Cam have UV polarization well in excess of the Serkowski extrapolation. HD 197770 clearly shows a polarization bump which closely matches the 2175 Å extinction feature. This bump polarization can be fitted by small aligned graphite disks. The differences along various lines of sight might be the result of differences in the environments which affect the size and alignment of the grains.

Subject headings: dust, extinction — polarization — ultraviolet: interstellar

1. INTRODUCTION

The extinction by interstellar dust in the visible and infrared (IR) is well behaved and characterized by one parameter, R_V, the ratio of total-to-selective extinction. However, in the ultraviolet (UV) the extinction curve shows large variations from one line of sight to another, and at least six parameters are needed to fit the wavelength dependence from 3200 to 1200 Å (Fitzpatrick & Massa 1986). The visible and IR interstellar polarization curve behaves similarly. It is characterized by one parameter, λ_{max}, the wavelength at which the polarization peaks. R_V and λ_{max} are proportional to one another and both are thought to be related to the average size of interstellar dust grains (Serkowski, Mathewson, & Ford 1975, hereafter SMF; Clayton & Mathis 1988). There is no physical reason to expect this simple polarimetric wavelength dependence to continue into the UV.

The wavelength dependence was first characterized in the 1970s (SMF; Codina-Landaberry & Magalhães 1976). The semiempirical Serkowski relation was extended to longer wavelengths when IR polarimetry became available (Wilking, Lebofsky, & Rieke 1982). The Serkowski relation is $p(\lambda)/p_{max} = \exp[-K \ln^2(\lambda_{max}/\lambda)]$, where $K = 0.01 \pm 0.05 + (1.66 \pm 0.09)\lambda_{max}$, and p_{max} is the magnitude of the polarization at λ_{max}. The value of K was determined from fits to 105 stars with visible and IR polarimetry (Whittet et al. 1991). Interstellar polarization is now generally thought to be produced by nonspherical dust grains aligned by the Galactic magnetic field. The Davis-Greenstein (1951) mechanism involving paramagnetic relaxation of spinning grains, modified by either or both of suprathermal rotation or superparamagnetic damping, can produce the alignment efficiency needed to account for the observed polarization (Hildebrand 1988). However, since the nature of the grains is uncertain, the details of the alignment also remain poorly understood.

Several models have been put forward that attempt to fit most or all of the known extinction and polarization features, but no one model is completely successful (Mathis 1990). Silicates are present in all models because the polarization of the 10 μm feature is attributed to aligned silicate grains (Hildebrand 1988). In most models the 2175 Å extinction bump is produced by small graphite grains. The exception is the Williams (1989) model in which very small magnesium silicate grains produce the bump by $(OH)^-$ ion absorption. Recent studies have shown that the wavelength dependence of the extinction (Cardelli, Clayton, & Mathis 1989) and polarization (Martin & Whittet 1990) in the red and infrared may be the same from one line of sight to another. The observed variations seem to be confined to the blue and UV wavelength regions. Observations of the wavelength dependence of interstellar polarization in the UV and its behavior across the 2175 Å feature can play an important role in distinguishing among the competing models for interstellar dust.

The only UV polarimetry previously reported was the pioneering work of Gehrels (1974). His balloon-borne, wide-band polarimeter observed ζ Oph at 2860 Å and 2250 Å and κ Cas at 2250 Å. This small amount of data was roughly consistent with an extrapolation of the Serkowski curve into the UV. In this *Letter* we report observations by the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE) which obtained spectropolarimetry between 1400, and 3200 Å along five lines of sight specifically for the study of interstellar polarization.

2. OBSERVATIONS

The observations were made during the 1990 December 2–9, Astro-1 mission of the space shuttle Columbia. WUPPE is a 0.5 m telescope with a Cassegrain spectrograph and polarization analyzing optics. Polarization modulation is accomplished by switching between half-wave plates at six different orientations which are located in a filter wheel just behind the entrance aperture. The light is then separated into two beams

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of orthogonal linear polarization by a MgF_2 Wollaston prism. A Monk-Gilleson spectrometer images the two spectra on a CsTe photocathode microchannel plate intensifier. The intensifier output is integrated and read out by parallel Reticon self-scanned diode arrays. The flux, percent polarization, and position angle as a function of wavelength are obtained between 1400 and 3200 Å. Spectroscopic resolution is about 10 Å. The polarization spectra are binned in wavelength to obtain a specified constant polarization error, typically 0.1%. Calibrations of instrumental polarimetric efficiency, residual polarization, position angle registration, and flux sensitivity were performed by a combination of preflight laboratory measures and inflight standard star observations. The data are corrected for telemetry errors, thermal background, cosmic-ray hits, second-order contamination, and instrumental polarization which is roughly 0.05%. The preliminary calibration and reductions are described in detail in Nordsieck et al. (1992a). Further review of all flight science and engineering data might lead to minor changes in flat field, flux, and especially the wavelength calibrations, the latter due to pointing errors. These are not expected to alter significantly the results presented here.

Nearly simultaneous observations in the visible were made for all the northern hemisphere stars with the spectropolarimeter on the 0.9 m telescope of the Pine Bluff Observatory (PBO), Madison, Wisconsin (Nordsieck et al. 1992b). Ground-based polarimetry for the southern hemisphere objects was obtained from the literature (Serkowski 1968) and elsewhere Magalhães and Rodrigues (1991) and Schulte-Ladbeck & Hillier (1992). The combined UV and visible spectra are plotted in Figure 1 and the percent polarization in Figure 2.

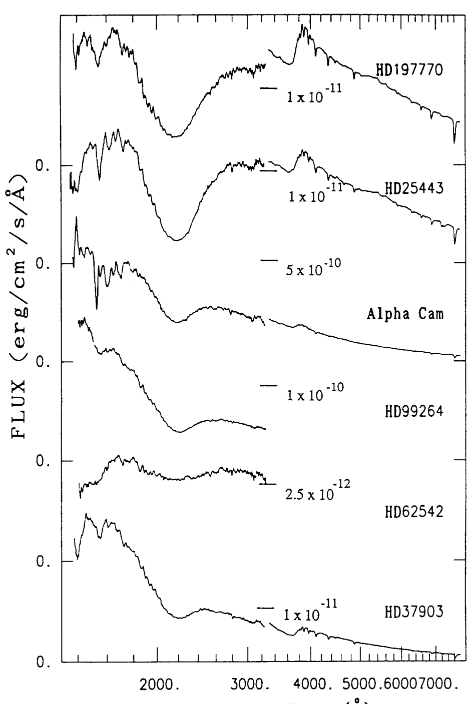

FIG. 1.—The flux spectra of the six stars discussed in the text. The ultraviolet data from WUPPE are normalized to the *ANS* fluxes while those in the optical from PBO are normalized to the flux at *V*. The zero points of the flux scale have been displaced vertically and are indicated at the left. Near the center of the wavelength scale a tick mark and numerical value indicate a flux value (ergs cm^{-2} s^{-1} $Å^{-1}$) for each object.

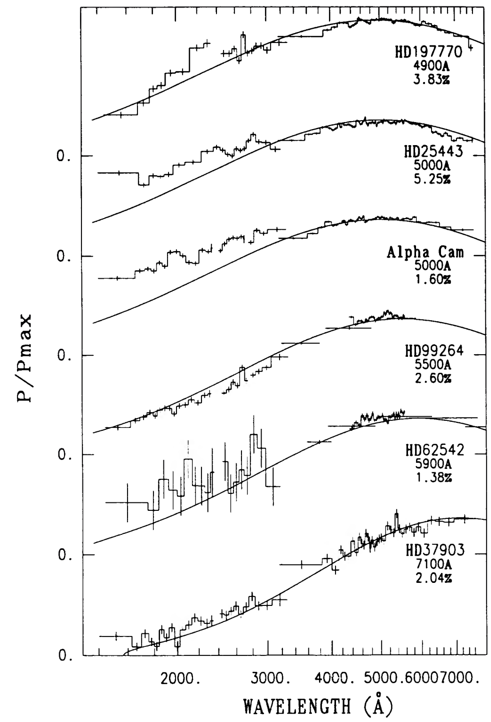

FIG. 2.—The polarization spectra, normalized to p_{max}, of the six stars discussed in the text. The stars are arranged in order of increasing λ_{max}. The solid line is the Serkowski fit discussed in the text. The gap in the data at approximately 2400 Å is due to a defect in the image intensifier affecting one array.

Details of the observing program are listed in Table 1. The stars were chosen to have significant interstellar polarization in the visible with a variety of polarization and extinction characteristics, and spectral types such that intrinsic polarization is expected to be insignificant. Small (<0.5%) polarization variations have been reported in HD 25443, HD 37903, and HD 197770 (Coyne 1974; Bastien et al. 1988; SMF; and Lupie & Nordsieck 1987). However, observations made at PBO before and after the WUPPE observations show no evidence at the ± 0.01% level of variability in any of these objects. In addition to the five interstellar probes listed in Table 1, α Cam is also included. This star is a supergiant and has shown intrinsic polarization of up to 0.1% (Lupie & Nordsieck 1987). The results for this star must be treated with care but it appears that the intrinsic component of polarization in α Cam is currently at the ± 0.05% level.

3. DISCUSSION

3.1. *The λ Dependence of the UV Polarization*

Figure 2 shows that although all six stars are reasonably well represented by the Serkowski relation in the visible, the stars do not all have the same $p(\lambda)$ dependence shortward of 2800 Å. The Serkowski fits shown in Figure 2 were made with the K-λ_{max} relation from Whittet et al. (1991). The values of p_{max} and λ_{max} are given in Table 2. The Serkowski relation, extrapolated into the UV, fits HD 37903 and HD 99264 very well and HD 62542 adequately. However, HD 25443, HD 197770, and α Cam show larger polarization than the extrapolated Serkowski $p(\lambda)$ shortward of 2800 Å. The $p(\lambda)$ for HD 25443 and α Cam is relatively smooth and remains above the Serkowski $p(\lambda)$ down to 1400 Å, but neither star shows any

TABLE 1

NEW INSTELLAR PROGRAM OBSERVATIONS

Object	SpT	$E(B-V)$	E(bump)	$E(1500-V)$	JD −2,440,000	Exposure (minutes)	Aperture (arcsec)	Instrument
HD 197770	B2 III	0.57	1.18	2.77	8230.87	11.2	6 × 12	WUPPE
					8230.94	4.7	6 × 12	WUPPE
					8240.47	136	12 × 12	PBO
HD 25443	B0.5 III	0.61	1.50	3.08	8234.95	14.4	40 square	WUPPE
					8235.95	188	12 × 12	PBO
α Cam	O9.5 I	0.30	0.71	1.50	8230.34	7.6	6 × 12	WUPPE
					8234.27	7.6	40 square	WUPPE
					8232.65	133	12 × 12	PBO
HD 99264	B2 IV–V	0.30	0.74	1.14	8230.56	14.9	6 × 12	WUPPE
HD 62542	B5 V	0.33	0.21	2.18	8234.21	14.9	6 × 12	WUPPE
HD 37903	B1.5 V	0.35	0.54	1.13	8234.88	30.3	40 square	WUPPE
					8298.30	136	12 × 12	PBO

polarization signature at 2175 Å in spite of having large extinction bumps. HD 197770 shows a well-defined polarization bump at 2175 Å, returning to the Serkowski fit below 1800 Å. Two good observations were made of this star; the bump is evident in both data sets. Several other objects in the observing program, most notably κ Cas and P Cyg, have quite strong 2175 Å extinction features but show no signature in polarization at this wavelength (Taylor et al. 1991). These stars are known to have intrinsic polarization, and thus Serkowski fits are inappropriate. Similarly, α Cam is an early-type supergiant and excess short-wavelength intrinsic polarization cannot be ruled out.

There does not appear to be any significant variation of the position angle (PA) of the polarization in any of the stars observed. In Table 2 we list the results of a linear least squares fit to the PA as a function of wavelength across the entire available wavelength range. The marginally detected slopes for HD 25443 and α Cam are of the same order as the uncertainty in the relative calibration between the optical and the UV.

3.2. *Dust Models*

The various dust models outlined in the introduction have been optimized to fit visible and IR polarization data. Wolff (1991) has shown that the polarization efficiency of astronomical silicate grains (Draine & Lee 1984) can also fit an extrapolation of the Serkowski law into the UV. However, it is not possible to reproduce both the visible/IR and the non-Serkowski UV behavior in HD 25443 and HD 197770 with a single component. Using a superparamagnetic (SPM) inclusion model (Balcells & Mathis 1986; Mathis 1986), Wolff (1991) predicts the UV polarization by fitting the visible/IR and extrapolating into the UV. These models predict polarization in the UV which is in excess of that found from an extrapolation of the Serkowski curve by 30%–50% at 1500 Å. Very small grains are not aligned and do not contribute to the polarization in this model. Therefore, it is possible that polarization larger than that predicted by the Serkowski relation can be achieved without finding a mechanism for aligning the very small silicates. In the Balcells & Mathis (1986) model, if the very small grains are aligned by some means, they cause an upturn in the polarization in the far ultraviolet.

The polarization signature near 2175 Å in HD 197770 seems to require an additional grain component. Most extinction models invoke small graphite grains, which must be small, to fit the 2175 Å extinction feature (Draine 1989). Draine (1988) used the discrete dipole approximation to model the extinction and polarization by graphite grains in the UV. He found that graphite, if aligned, produces polarization at wavelengths near the extinction peak. Disks with $a = 100$ Å and axial ratio $a/b = 0.647$ produce polarization in the vicinity of 2175 Å which has the same position angle as that produced by the large silicate grains. Graphite rods with $a = 200$ Å and $a/b = 1.47$ also produce a 2175 Å feature, but the position angle is orthogonal to the polarization resulting from disks. This would result in a decrease in net polarization contrary to the observation. Witt et al. (1987) find enhanced scattering in the long-wavelength wing of the 2175 Å feature in two reflection nebulae which could be related to the polarization feature in HD 197770.

3.3. *The Alignment Problem*

In general, the enhancement of the extinction in the UV relative to that produced by those grains important in the visual/IR requires an additional population of smaller grains.

TABLE 2

POLARIZATION CURVE CHARACTERISTICS

Object	p_{max}	λ_{max}	p (1800)	p (3000)	PA	PA slope (degrees per 1000 Å)
HD 197770	3.83	0.49	1.81 ± 0.15	2.78 ± 0.15	131.1 ± 0.4	−0.21 ± 0.10
HD 25443	5.25	0.50	3.09 ± 0.10	4.36 ± 0.10	137.3 ± 0.4	−0.36 ± 0.07
α Cam	1.60	0.50	1.03 ± 0.04	1.42 ± 0.04	134.7 ± 0.5	+0.53 ± 0.12
HD 99264	2.60	0.55	0.72 ± 0.07	1.72 ± 0.07	121.6 ± 1.1	−0.37 ± 0.27
HD 62542	1.38	0.59	0.49 ± 0.20	0.72 ± 0.20	30.8 ± 2.9	−0.93 ± 0.67
HD 37903	2.00	0.71	0.23 ± 0.07	0.72 ± 0.07	120.6 ± 1.9	−0.12 ± 0.46

Since interstellar polarization can be thought of as directionally selective extinction (Hildebrand 1988), a requirement for a small population of aligned grains may apply to UV polarization. It is not obvious that small grains can be aligned in the same way that large grains are. For instance, in the SPM model (Mathis 1986), a grain can only be aligned if it contains one or more SPM inclusions. However, there is a lower limit, a' proportional to λ_{max}, on the size of grains which have a non-negligible probability of having an inclusion. The range in a' implied by the observed range in λ_{max} does not significantly change the essentially zero probability of alignment for the very small grains (<0.10 μm). Whether a similar consideration applies to suprathermal rotation (Purcell 1979) needs to be investigated. Nevertheless, the polarization bump in HD 197770 shows that an additional small grain component associated with the feature must be aligned.

3.4. *The Dust Environments*

Just as with the variations in UV extinction seen along different lines of sight, the variations in UV polarization are an indication of grains responding to different environments. Therefore, it is important to link these variations to specific environmental conditions such as the following:

1. The six lines of sight considered here contain dust in a wide variety of environments. Three of the stars, HD 37903 in the reflection nebula NGC 2023 (Massa, Savage, & Fitzpatrick 1983), HD 62542 in the Gum nebula (Cardelli & Savage 1988), and HD 99264 in the Scorpio-Centaurus OB association (de Geus, de Zeeuw, & Lub 1989), are lines of sight along which the grains might be subjected to large radiation fields, high temperatures, and other activity which may affect them in various ways. The other two stars, HD 25443 which lies in front of the cluster NGC 1502 (Reimann & Pfau 1987), and HD 197770 which lies in the Local spiral arm (Dixon 1967), are lines of sight which seem to contain diffuse ISM dust undisturbed by regions of high activity. α Cam lies only 7° away from HD 25443 on the sky in a similarly undisturbed line of sight.

2. UV extinction data from *ANS* (Savage et al. 1985) is available for all six stars. These data indicate that HD 25443, HD 197770, and α Cam have UV extinction curves very close to the Galactic average which is based on mostly diffuse lines of sight and does not include dark clouds and star-forming regions (Mathis 1990; Cardelli & Clayton 1991). HD 37903 and HD 62542 show significant deviations from the average, and HD 99264 shows mild deviations. The extinction parameters indicate fairly quite lines of sight for HD 25443, HD 197770, and α Cam in agreement with condition (1), above.

3. The high values of $p_{max}/E(B-V)$ indicate that large grains are well aligned for HD 25443, HD 197770, and α Cam. HD 99264 also has a large value of $p/E(B-V)$.

4. The large visible and UV extinction for HD 25443 and HD 197770 indicate that there are more grains of all sizes available to polarize light if aligned. These two stars are also distinguished by having the largest values of p_{max}. The amount of excess polarization over the extrapolated Serkowski relation is $>0.8\%$ for HD 25443 and HD 197770, but for HD 37903, HD 62542, and HD 99264 it is $<0.2\%$. However, the reddening in the visible and the UV of the former pair is about twice that toward the latter three. Therefore, if there were identical grains with the same alignment along all the lines of sight, only about a factor of 2 difference in the measured excess polarization would be expected.

5. HD 197770, HD 25443, and α Cam have the lowest measured values of λ_{max} in the sample. As discussed above, λ_{max} is physically related to the average size of the aligned silicate grains. Therefore, small values of λ_{max} may indicate that small aligned grains are relatively more important along these lines of sight.

6. The density of the clouds along the lines of sight to the sample stars is not known, but extinction per kpc gives a rough indication. HD 197770 has the largest $E(B-V)$/kpc in the sample. HD 25443 has only the fourth highest. In the general ISM, the average reddening per kpc is $\langle E(B-V)/r \rangle = 0.61$ mag kpc^{-1}; therefore, HD 197770 has a value of this parameter about 2 times the average. The other stars in the sample are near or below the average value.

4. CONCLUSIONS

Even with the small number of observations reported here, it is evident that there is substantial variation in the wavelength dependence of interstellar polarization in the UV. For all the stars in the sample the interstellar polarization continues to decrease in the UV qualitatively similar to the extrapolation of the empirical Serkowski relation. Quantitatively HD 37903, HD 62542, and HD 99264 are consistent within the errors with the extrapolated empirical Serkowski relation. These three objects are the ones in the sample with the largest values of λ_{max}. The stars with shortest λ_{max}, α Cam and HD 25443, show excess UV polarization with respect to the Serkowski law at the 35%–40% level. HD 197770 is roughly consistent with the Serkowski extrapolation at the short- and long-wavelength limits of WUPPE coverage but clearly shows a polarization bump at 2175 Å. Within the errors, there is no wavelength dependence in the position angle of the polarization for any of these stars.

While various interstellar grain models can account for the individual features of the UV polarization, each model encounters some difficulties when confronted with extinction and polarization data spanning the spectral range from 1400 Å to the visual and near-IR. Similarly, there are a number of differences in the dust environments along the sampled lines of sight, but which environmental condition is most important and how the grains themselves are affected remains to be determined.

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