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ULTRAVIOLET INTERSTELLAR POLARIZATION OBSERVED WITH THE *HUBBLE SPACE TELESCOPE*[1]

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ABSTRACT

We have used the Faint Object Spectrograph of the *Hubble Space Telescope* to observe interstellar linear polarization from 1300 to 3300 Å in two stars with well-studied interstellar polarization at visible wavelengths. The wavelength dependence of linear polarization declines smoothly with decreasing wavelength and is devoid of structure associated with the prominent 2175 Å absorption bump in the interstellar extinction curve. The data for one star (HD 161056) are consistent with an extrapolation based on the Serkowski formula of a fit to the ground-based polarization; the other star (HD 7252) shows excess (super-Serkowski) polarization relative to this extrapolation. Out of a total of 10 stars now studied by means of spectropolarimetry in the satellite ultraviolet, including eight observed with the Wisconsin Ultraviolet Photopolarimeter, five (those of longest λ_{max}) show Serkowski behavior, and four others show super-Serkowski behavior; only one (HD 197770) shows evidence for polarization associated with the 2175 Å bump. These results place important constraints on the nature of the bump feature.

Subject headings: dust, extinction — stars: individual (HD 7252, HD 161056) — techniques: polarimetric — ultraviolet: ISM

1. INTRODUCTION

The physical nature and chemical composition of interstellar dust grains are as yet poorly understood. From various types of observation it has become clear that they consist mainly of a mixture of silicates and some form of solid carbon, perhaps graphite, with the addition of ice mantles in molecular clouds, but a unique model for interstellar extinction has yet to emerge (see Whittet 1992 for a review). The extinction curve is dominated by the dramatic and ubiquitous "bump" centered at 2175 Å. The bump is often attributed to graphite, but there are significant problems with this identification: indeed, the identity of the particles responsible for the bump is amongst the most significant unsolved problems in astronomical spectroscopy (Draine 1989; Draine & Malhotra 1993; Mathis 1994).

Spectropolarimetric observations in the satellite ultraviolet (UV) have the potential to provide unique insight into both the optical properties of grains which contribute to extinction at these wavelengths and their ability to align in the ambient magnetic field (Somerville 1991). The overall shape of the continuum polarization is closely related to the grain size distribution. The wavelength dependence of polarization across a dust-related absorption feature is a general diagnostic of the shape, size distribution, refractive index and alignment properties of the carrier. A spectral signature in the polarization is expected for significant alignment of aspherical carrier grains, and this has been observed, for example, in the infrared at wavelengths corresponding to the principal vibrational resonance in silicates near 10 μm (e.g., Whittet 1992), indicating that silicate particles are alignable and may contribute to the general continuum polarization. Whether or not this property is shared by the carrier of the bump is a key question with important implications for grain models: Draine (1988) pointed out that aspherical graphite grains, if appreciably aligned, would produce distinctive linear polarization in the UV and that the predicted polarization is an important constraint on graphite as a component of grain models. Spectropolarimetric results available to date are intriguing. An early experiment (Gehrels 1974) suggested a lack of significant excess above the continuum predicted by an extrapolation of the visible polarization curve to ultraviolet wavelengths. In the recent past, data from the Wisconsin Ultraviolet Photopolarimeter Experiment (WUPPE) have become available, which suggest the presence of a 2175 Å interstellar polarization excess in one star out of eight observed (Taylor et al. 1991; Clayton et al. 1992; Schulte-Ladbeck et al. 1992). Here, we present the first observations of UV interstellar polarization to be made with the *Hubble Space Telescope* (*HST*). These observations represent an advance in quality over those previously available.

2. OBSERVATIONS AND RESULTS

Observations of three program stars were made in Cycle 1 of the *HST* Guest Observer program in September, 1992. Results for two of them are presented here (see Table 1). Observation of the third target, HD 98695, suffered from a spacecraft pointing error (it was recently reobserved in one grating segment). Early-type stars were selected on the basis of previous observations of UV extinction and visible polarization to give varia-

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TABLE 1

PROGRAM STARS

HD	Spectral Type	E_{B-V}	l, b	d (pc)	p_{max}	λ_{max} (μm)	2175 Å	FUV	Grating	Exposure (minutes)
7252	B1 V	0.34	125.7, −1.9	824	3.49% ± 0.02%	0.52 ± 0.01	Strong	Strong	G130H	83.4
									G190H	36.3
									G270H	12.3
161056	B1.5 V	0.63	18.7, +11.6	295	4.03% ± 0.01%	0.59 ± 0.01	Normal	Normal	G130H	124.6
									G190H	64.6
									G270H	16.9

tion in bump amplitude, far-UV extinction amplitude, and the wavelength (λ_{max}) of maximum polarization. Table 1 lists spectral types and reddening (E_{B-V}) for the program stars (from Carnochan 1986), together with Galactic coordinates and distances (derived assuming $A_V = 3.1E_{B-V}$ and the absolute magnitude calibration from Gottlieb 1978). Polarization parameters (see below) and comments on the UV extinction curve are also given. The latter indicate the strengths of the 2175 Å feature and the far-UV extinction rise, relative to the mean extinction curve, using data from the S2/68 telescope on the *TD-1* satellite (Carnochan 1986).

The *HST* Faint Object Spectrograph (FOS) was used in spectropolarimetric mode (see Allen et al. 1993 for a description), using the blue digicon and wave plate B. Data were acquired at eight position angles of the wave plate. Gratings and total exposure times are listed in Table 1. The spectral range 1300–3300 Å was covered in three overlapping segments at a nominal spectral resolution of 2–4 Å. The segment ranges were 1279–1603 Å (G130H grating), 1575–2324 Å (G190H grating) and 2224–3295 Å (G270H grating). Exposure times were chosen to give the same nominal accuracy in the percentage polarization p in each grating segment, using S2/68 fluxes. All observations were made through the 4.3 arcsec square aperture. The data were processed independently using standard STSDAS pipeline procedures at ST-ECF and dedicated software available at the university of Arizona (Allen & Smith 1992). All of the FOS linear polarization measurements have been adjusted to allow for the bias that occurs when the expected error is more than a small fraction of the measurement itself (Wardle & Kronberg 1974). The data were binned to give 10 points per grating segment, as plotted in Figure 1; only error bars in excess of 0.04% polarization (1 σ) are shown. Note that both the signal-to-noise ratio and the spectral resolution, especially at the shortest wavelengths, are superior to those achieved with WUPPE. The FOS also reaches down to shorter wavelengths, 1279 Å compared with 1400 Å for WUPPE.

New ground-based linear polarimetry covering the spectral range 3500–7400 Å was obtained for the two program stars with the 0.9 m telescope and spectropolarimeter of the Pine Bluff Observatory, Madison, Wisconsin (PBO) (see Nordsieck et al. 1992; Nook 1990). Additional ground-based visible and near-infrared data are available from the literature (HD 7252, Coyne & Gehrels 1967; HD 161056, Coyne & Gehrels 1966; Coyne & Wickramasinghe 1969; Wilking et al. 1980; Nagata 1990). Ground-based and UV polarization data were combined to plot polarization curves (Fig. 1) extending in wavenumber from 0.4 to 8.0 μm^{-1}. Standard empirical curves represented by the Serkowski law $p(\lambda)/p_{max} = \exp[-K \ln^2(\lambda_{max}/\lambda)]$ (Serkowski, Mathewson, & Ford 1975)

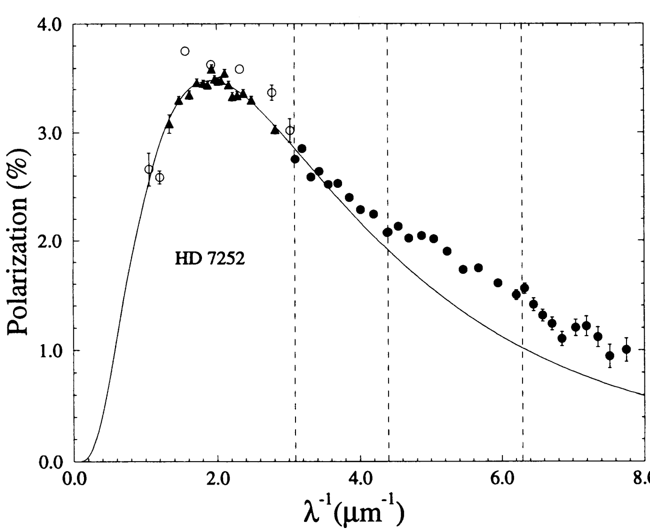

FIG. 1*a*

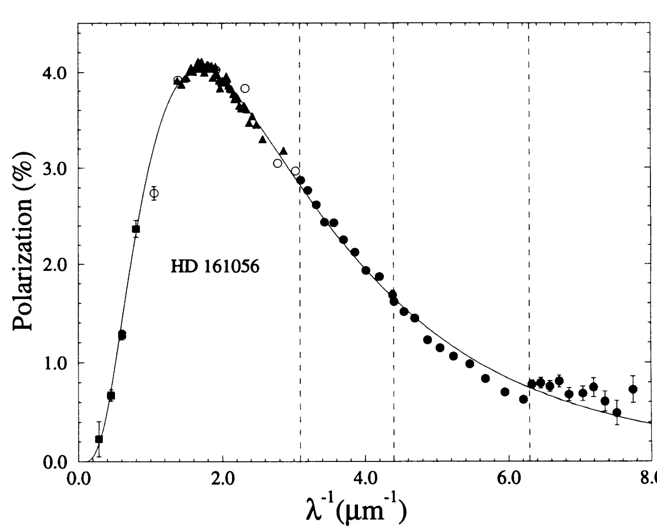

FIG. 1*b*

FIG. 1.—Interstellar polarization curves for the program stars: (*a*) HD 7252; (*b*) HD 161056. *HST* data are represented by filled circles, and the vertical dashed lines indicate the approximate division by grating segment (see § 2). Ground-based data are represented by filled triangles (previously unpublished observations from the PBO), open circles (from Coyne & Gehrels 1966, 1967; Coyne & Wickramasinghe 1969), and filled squares (near-infrared data from Wilking et al. 1980; Nagata 1990). The curves are least-squares fits to selected ground-based data (see text) using the Serkowski formula with $K = 1.66\lambda_{max}$(Whittet et al. 1992). Values of p_{max} and λ_{max} derived from the fits are given in Table 1.

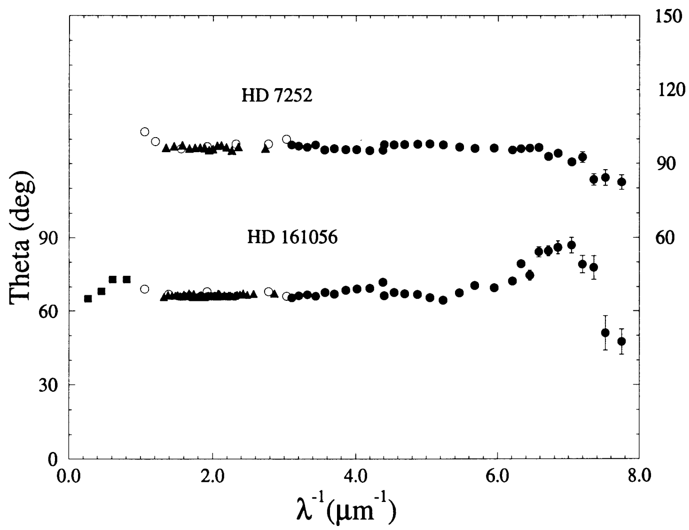

FIG. 2.—The wavelength dependence of the position angle θ of polarization for the two program stars. The right and left vertical scales refer to HD 7252 and HD 161056, respectively. Symbols have the same meaning as in Fig. 1.

with $K = 1.66\lambda_{max}$ (Whittet et al. 1992) were fitted to the ground-based data. In the case of HD 7252, the data of Coyne & Gehrels (1967; *open circles* in Fig. 1*a*) are excluded from the fit because of scatter and systematic inconsistency with the more recent ground-based data. Similarly, in the case of HD 161056, the data of Coyne & Gehrels (1966) and Coyne & Wickramasinghe (1969) (*open circles* in Fig. 1*b*) are excluded from the fit, but the near-infrared data (*filled squares*) are included, along with the PBO data (*filled triangles*). Values of p_{max} and λ_{max} derived from the fits are listed in Table 1: in both cases, these are in reasonable agreement with previous values quoted in the literature (Serkowski et al. 1975; Wilking et al. 1980).

The position angle (θ) of polarization was examined for systematic variability with wavelength, comparing UV and ground-based data. Results are presented in Figure 2. In the visible, the individual values of θ are consistent with the mean value to an accuracy of better than $\pm 2°$ in each line of sight. The dispersion is somewhat higher in the UV, particularly at the shortest wavelengths, where the degree of polarization is low, but there is no evidence for significant systematic dependence of θ on wavelength toward either of the program stars, except possibly below 1350 Å.

3. QUALITY OF THE DATA

In this section we discuss possible systematic effects in FOS polarimetry which are not included in the errors indicated in the figures. Examination of the wavelength regions which overlap between two gratings provides an internal check. The degree of linear polarization shows satisfactory agreement (within 1 σ error bars), except for the G190H to G130H transition in HD 161056, where the polarization jumps from $0.63\% \pm 0.04\%$ at 1611 Å to $0.78\% \pm 0.04\%$ at 1585 Å, opposite to the trend of a decrease in polarization with wavenumber. Systematic behavior can be seen in θ as well. These discontinuities probably result from the effects of geomagnetic distortion. The diode array in the FOS digicon is overfilled by the stellar image because of the spherical aberration in the telescope primary mirror. The spillover losses vary slightly with the orientation of the spacecraft to Earth's magnetic field; this introduces spurious polarization that varies as a function of wavelength. Since the amount of polarization depends on the accuracy of the grating mechanism, the effects are slightly different whenever the grating is moved.

The level of instrumental polarization for the FOS has been discussed by Allen et al. (1993), on the basis of observations of the unpolarized standard star BD $+28°4211$ at two roll angles separated by 45 degrees. Their results indicate that the FOS instrumental polarization is less than 0.1% over the entire wavelength range of our observations. However, because the detector counts are lowest in the G130H range, it contained only two wavelength bins: G130H is a region of particular concern because the polarization for the program stars is smallest there, and the detected counts are low on account of the falling sensitivity of the detector to short wavelengths, so we have made an independent analysis using the two sets of observations of BD$+28°4211$ in the G130H grating. We confirm the result of Allen et al. (1993) but caution that any polarizations below 0.2% must be considered highly uncertain; therefore, any interpretation of the data judged only from the formal statistical errors that depends on the errors being less than 0.1% is unwise.

A case in point is the G130H data for HD 161056, where the measured linear polarization is only slightly above 0.5% and is therefore most susceptible to both types of systematic error. The change in θ seen below 1350 Å seems well established because it appears in all five sets of data (because of its length, the exposure had to be divided between five orbits of the spacecraft). However, if there are systematic errors of the order of 0.2% in polarization, then the accompanying errors in θ could be at least 10°, lowering our confidence in the reality of this change. While the linear polarization of HD 7252 declines smoothly over all three gratings, a slight decrease in θ is seen below 1350 Å. This change in θ is also only marginally significant.

Finally, there is some structure seen in the linear polarization of HD 7252, in association with its super-Serkowski behavior. This structure, which is within the data for a single grating, appears to be real.

4. DISCUSSION

The empirical fits to ground-based data are shown in Figure 1 with extrapolation to shorter wavelengths. There is, of course, no a priori reason to suppose that this extrapolation will provide a good fit to the observed polarization (Martin 1989). From their analysis of WUPPE data, Wolff, Clayton, & Meade (1993) recognized three types of behavior: (1) stars with UV data well-matched by the extrapolated fit (Serkowski behavior); (2) stars exhibiting excess continuum polarization with respect to the extrapolated fit (super-Serkowski behavior); and (3) one star with excess polarization apparently associated with the 2175 Å bump. Examination of Figure 1 suggests that one of the two stars observed with the *HST* (HD 161056) exhibits Serkowski behavior, and the other (HD 7252) exhibits super-Serkowski behavior. It might be significant that the latter star also has the stronger far-UV extinction. However, we note that the "Serkowski excess" extends across the UV spectrum from $\lambda^{-1} \sim 3.8\ \mu m^{-1}$ to the far-UV (Fig. 1*a*), whereas the far-UV extinction rise sets in only at $\lambda^{-1} > 6.0\ \mu m^{-1}$. Perhaps of greater significance is the fact that HD 7252 has the lower λ_{max} value. This is in qualitative agreement with WUPPE results: Wolff et al. find Serkowski behavior for four stars with $\lambda_{max} \geq 0.55\ \mu m$ and super-Serkowski behavior for three stars with $\lambda_{max} \leq 0.51$ μm. We note that members of the latter class should have relatively large "Serkowski" polarization in the UV by virtue of both smaller λ_{max} and the wider polarization curve (systematically decreased K with λ_{max}); the "excess" is perhaps simply another manifestation of this behavior, and the failure of the Serkowski curve to describe it adequately is certainly no particular surprise.

An important conclusion is that neither of our program stars exhibits a polarization signature that can be attributed to the 2175 Å (4.6 μm^{-1}) extinction bump. Of a total of 10 stars now studied in the UV with WUPPE or *HST*, only one, HD 197770, shows any evidence for polarization structure associated with the bump. On the basis of its λ_{max} value, 0.51 μm, HD 197770 might be expected to show super-Serkowski behavior. One may thus argue that the anomaly could be characterized not as a polarization excess at 4.6 μm^{-1} but instead as unusually low polarization at $\lambda^{-1} > 5$ μm^{-1} (see Fig. 5 of Wolff et al. 1993). Further observations of this star are needed to settle this issue.

Limits on the amplitude of polarization structure, Δp, are of quantitative interest. For example, from our data for HD 161056 (Fig. 1*b*), we estimate that $\Delta p/p < 0.06$ near 4.6 μm^{-1}, whereas for the extinction bump in this line of sight $\Delta\tau/\tau \simeq 0.6$ using extinction parameters from Carnochan (1986). In other combinations $p/\tau \simeq 0.004$ and $\Delta p/\Delta\tau < 0.0004$. The latter can be compared to Draine's (1988) models of the potential bump polarization which give $\Delta p/\Delta\tau \sim 0.3$–$0.8$ for perfect alignment of small prolate or oblate graphite particles with axial ratio 1.5. Our observations therefore place tight constraints on some combination of the degrees of asphericity and alignment of these particles. Wolff et al. (1993) found that the excess polarization in the region of the 2175 Å bump for HD 197770 can be fitted well by small aligned graphite disks. We estimate that $\Delta p/\Delta\tau \sim 0.004$ for that line of sight, an order of magnitude larger than the upper limit for HD 161056 (the limit for HD 7252 is 0.001), but still much less than the maximum possible.

Observations of UV interstellar polarization are providing impetus for theoretical work designed to test existing models for the wavelength dependence of extinction, and the degree of grain alignment as a function of grain size. Wolff et al. (1993) have investigated the applicability of existing grain models to WUPPE data. They conclude that both Serkowski and super-Serkowski behavior can be understood in terms of the model of Mathis (1986) by varying the adjustable parameters of the size distribution. This model is based on the bare graphite/silicate extinction model (Mathis, Rumpl, & Nordsieck 1977), with the additional assumption that only the silicate component becomes aligned. A crucial feature of this model is a prediction that the degree of alignment should decrease systematically toward smaller particles, and hence that the polarization should decline to shorter ultraviolet wavelengths, where the polarization is most sensitive to small particles. This prediction is in good agreement with observations from both WUPPE and *HST*.

If interstellar polarization is produced primarily by silicate grains, as in the Mathis (1986) model, then structure in the polarization curve is expected to occur in the far-UV. This arises because of the onset of electronic absorption in the adopted silicate: in olivine, for example, it takes the form of a downturn in the predicted polarization beyond ~ 6 μm^{-1} (see, e.g., the MRN curve in Fig. 3 of Wolff et al. 1993). Kim & Martin (1994) discuss this effect and find that the downturn continues to larger wavenumbers, making it difficult to fit stars with super-Serkowski behavior. However, olivine might not be very representative of interstellar silicates, and other forms may have optical constants that lead to acceptable fits. We conclude that our data may be used to constrain the optical constants of interstellar silicates.

Independent of a specific model, Kim & Martin (1994) have shown how systematic changes in the underlying size distribution of the aligned grains can produce the varying behavior with λ_{max}. Compared to the size distributions of grains that give extinction, the aligned grain size distributions are very much lacking in small particles; in particular, there is no evidence so far that the grains that cause the far-UV extinction rise make an appreciable contribution to the polarization. Such investigations benefit from extension of the polarization data as far as possible to short wavelengths, as we are attempting to do with *HST*.

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REFERENCES

Allen, R. G., & Smith, P. S. 1992, FOS IDT Report CAL/FOS-078
Allen, R. G., Smith, P. S., Angel, J. R. P., Miller, B. W., Anderson, S. F., & Margon, B. 1993, ApJ, 403, 610
Carnochan, D. J. 1986, MNRAS, 219, 903
Clayton, G. C., et al. 1992, ApJ, 385, L53
Coyne, G. V., & Gehrels, T. 1966, AJ, 71, 355
———. 1967, AJ, 72, 887
Coyne, G. V., & Wickramasinghe, N. C. 1969, AJ, 74, 1179
Draine, B. T. 1988, ApJ, 333, 848
———. 1989, in IAU Symp. 135, Interstellar Dust, ed. L. J. Allamandola & A. G. G. M. Tielens (Kluwer: Dordrecht), 313
Draine, B. T., & Malhotra, S. 1993, ApJ, 414, 632
Gehrels, T. 1974, AJ, 79, 590
Gottlieb, D. M. 1978, ApJS, 38, 287
Kim, S.-H., & Martin, P. G. 1994, ApJ, in press
Martin, P. G. 1989, in IAU Symp. 135, Interstellar Dust, ed. L. J. Allamandola & A. G. G. M. Tielens (Kluwer: Dordrecht), 55
Mathis, J. S. 1986, ApJ, 308, 281
———. 1994, ApJ, 422, 176
Mathis, J. S., Rumpl, W., & Nordsieck, K. H. 1977, ApJ, 217, 425
Nagata, T. 1990, ApJ, 348, L13
Nook, M. A. 1990, Ph.D. thesis, Univ. of Wisconsin, Madison
Nordsieck, K. H., Babler, B., Bjorkman, K. S., Meade, M. R., Schulte-Ladbeck, R. E., & Taylor, M. J. 1992, in Nonisotropic and Variable Outflows from Stars, ed. L. Drissen, C. Leitherer, & A. Nota (ASP Conf. Ser., 22), 114
Schulte-Ladbeck, R. E., et al. 1992, ApJ, 391, L37
Serkowski, K., Mathewson, D. S., & Ford, V. L. 1975, ApJ, 196, 261
Somerville, W. B. 1991, Vistas Astron., 34, 51
Taylor, M., et al. 1991, ApJ, 382, L85
Wardle, J. F. C., & Kronberg, P. P. 1974, ApJ, 194, 249
Whittet, D. C. B. 1992, Dust in the Galactic Environment (Bristol: Inst. of Physics)
Whittet, D. C. B., Martin, P. G., Hough, J. H., Rouse, M. F., Bailey, J. A., & Axon, D. J. 1992, ApJ, 386, 562
Wilking, B. A., Lebofsky, M. J., Martin, P. G., Rieke, G. H., & Kemp, J. C. 1980, ApJ, 235, 905
Wolff, M. J., Clayton, G. C., & Meade, M. R. 1993, ApJ, 403, 722