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INTERSTELLAR EXTINCTION, POLARIZATION, AND GRAIN ALIGNMENT IN THE HIGH-LATITUDE MOLECULAR CLOUD TOWARD HD 210121

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ABSTRACT

We present near-infrared photometry and optical and near-infrared polarimetry for the line of sight toward HD 210121, obscured by the high-latitude cloud DBB 80. From the data, we determine remarkably small values of the ratio of total to selective extinction, $R_V = 2.1 \pm 0.2$, and the wavelength of maximum polarization, $\lambda_{max} = 0.38 \pm 0.03$ μm, as compared to average values in the diffuse Galactic interstellar medium. These values nevertheless follow the linear relationship between R_V and λ_{max} seen closer to the Galactic plane. Our results imply an abundance of small grains, which we interpret as evidence for lack of grain growth in this high-latitude cloud. This is consistent with previous observations of high molecular abundances and extremely steep far-ultraviolet extinction toward the star and also with the presence of mid-infrared emission in the foreground cloud. We show that populations of small grains responsible for extinction and polarization in DBB 80 respond to prevailing physical conditions in a correlated way. Based on its extremely short value of λ_{max}, we predict that the line of sight to HD 210121 will be highly polarized in the ultraviolet.

Subject headings: dust, extinction — ISM: clouds — ISM: individual (DBB 80) — polarization — stars: individual (HD 210121)

1. INTRODUCTION

The presence of molecular gas in high-latitude clouds (HLCs) in our Galaxy is a topic of much current interest and debate (e.g., Reach et al. 1995; Caillault, Magnani, & Fryer 1995). As well as contributing a significant fraction of the total inventory of molecular material in the Galaxy, HLCs provide a laboratory in which to study interstellar matter and processes in controlled, quiescent environments and thus give new insight into the conditions which lead to star formation. Observations of interstellar extinction and polarization in HLCs permit us to characterize their interstellar dust content by constraining the optical properties and alignment of the dust grains as functions of environment. Physical conditions far from the Galactic plane may radically change the evolution of interstellar dust. In this paper, we examine an extreme case of environmental variation in the size distribution of grains toward HD 210121.

The B3 V star HD 210121 is a particularly suitable target for such an investigation. Existing information on this well-studied line of sight include 21 cm H I data (Heiles & Habing 1974), 100 μm maps of thermal dust emission (Désert, Bazell, & Boulanger 1988), optical absorption spectra of atomic (Na I, Ca II, K I) and molecular (CH, CN, C_2) species (Welty & Fowler 1992; de Vries & van Dishoeck 1988; Gredel et al. 1992), and emission-line spectra of CO (Gredel et al. 1992; van Dishoeck et al. 1991). Analysis by Welty & Fowler (1992) of spectral velocity components shows that the line of sight is particularly simple: more than 90% of the total hydrogen ($H + H_2$) and a wide variety of molecular species are contained in a single foreground cloud, DBB 80 (Désert et al. 1988). DBB 80 is located at $(l, b) \sim (57°, -45°)$, about 150 pc from the Galactic plane. Molecular abundances, particularly of CO, are high in this cloud with respect to the relatively low value of absolute visual extinction, $A_V \sim 1$ mag (Gredel et al. 1992). Like many molecular HLCs, the cloud toward HD 210121 is translucent, but with density and temperature more typical of dark clouds ($n_H \sim 500$–5000 cm^{-3}, $T_K \sim 10$–25K; Stark & van Dishoeck 1994). In translucent clouds such as this, photochemical processes are important, yet molecules can be formed in abundance.

Given the distance from the Galactic plane and the lack of nearby hot stars, it can be expected that the intensity of the interstellar radiation field (ISRF) incident on the surface of DBB 80 is less than that of the average ISRF. This is suggested by the relatively low observed ratio $I(100\ \mu m)/N(H_{tot})$, which, for given grain properties, is a measure of the strength of the field heating the grains (Welty & Fowler 1992). Recent observations of C I (Stark & van Dishoeck 1994) indicate that its inferred column density is consistent with detailed models of chemistry in translucent clouds if it is assumed that the external ultraviolet (UV) ISRF is reduced by a factor of 2 with respect to the average at low latitudes. The depth to which incident radiation can penetrate a cloud depends on the extinction properties of the grains, gas-grain chemistry as a function of density, and molecular self-shielding (Roberge, Dalgarno, & Flannery 1981; van Dishoeck 1994). Rapid attenuation of energetic photons accompanying a steep rise in far-UV extinction may significantly alter the equilibrium abundances of molecules with photoionization and photodissociation potentials in this region of the spectrum (Cardelli 1988; van Dishoeck & Black 1989). The depth-dependent models of van Dishoeck & Black (1989), for example, predict relatively high CO and CN abundances at low A_V assuming high UV extinction. Thus, increased molecular column densities per unit A_V seen toward HD 210121 are likely due to reduced photodissociation in a HLC shielded by relatively large UV extinction.

To explore this relationship between gas phase abundances and UV extinction, Welty & Fowler (1992) determined the extinction curve of HD 210121 by the standard

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"pair" method, using low-resolution UV spectra taken with the *International Ultraviolet Explorer* (*IUE*) satellite and ground-based *B* and *V* photometry. Their result is illustrated in Figure 1 (augmented with infrared data reported below in § 2). The UV segment is calculated from the empirical fit based on the formulation of Fitzpatrick & Massa (1990). For comparison, the fit to the Seaton (1979) average extinction curve for the diffuse interstellar medium (ISM) close to the Galactic plane and the fit to the average extinction curve of ρ Oph, representative of the dark cloud environment, are also shown (Fitzpatrick & Massa 1990). The extinction curve of HD 210121 has a somewhat anomalous 2175 Å feature that is weaker and broader than the diffuse average but not significantly shifted. Most notably, the continuum extinction toward HD 210121 rises extremely steeply into the far-ultraviolet (FUV). Comparing with other stars fitted by the Fitzpatrick & Massa formula, the linear continuum coefficients are the highest known, and the FUV polynomial coefficient is among the highest known (see Welty & Fowler 1992). Very steep FUV extinction implies a relatively high abundance of small grains, which provide a larger surface area per volume for molecular formation (Cardelli 1988).

Observations of normal Ca and Ti depletions and low CH^+ column density suggest an absence of recent shocks or other causes of rapid grain destruction in DBB 80 (Gredel et al. 1992). One cannot therefore easily account for the bias toward small grains in terms of destruction mechanisms such as sputtering or shattering due to shock-driven grain-grain collisions. The observations may be better interpreted in terms of *lack of growth* compared with more typical regions of the ISM. Correlated variations in the UV and blue-visible regions of the extinction curve (Cardelli, Clayton, & Mathis 1989, hereafter CCM) are generally interpreted in terms of varying degrees of grain coagulation (e.g., Mathis 1996). These variations may be characterized to some degree in terms of a single parameter, the ratio of total to selective extinction ($R_V = A_V/E_{B-V}$). Corresponding variations in the polarization due to aligned grains may be similarly characterized in terms of the wavelength of maximum polarization (λ_{max}). Both R_V and λ_{max} are dependent on the average size of the grains, but the latter is sensitive only to the aligned component, which will in general be a subset of all grains along any given line of sight. Moreover, small grains may tend to align much less efficiently than large grains (e.g., Mathis 1986). Evaluation of R_V and λ_{max} toward HD 210121 is therefore of considerable interest, as a means of investigating the effect of the unusual environment inside DBB 80 on both the grain size distribution and the alignment mechanism.

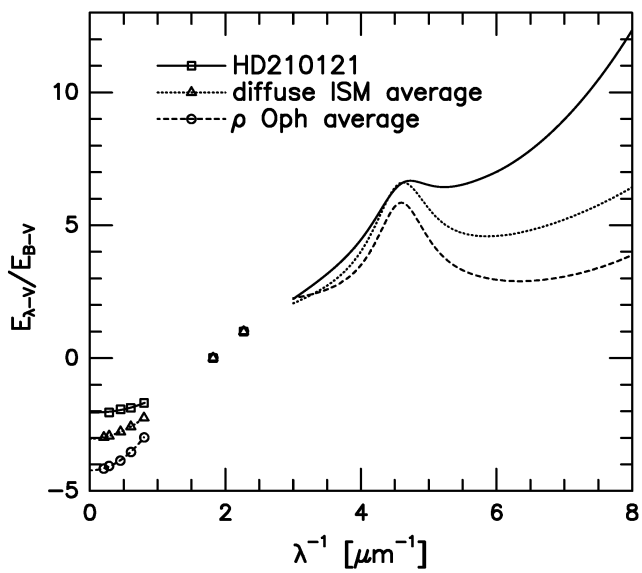

FIG. 1.—Interstellar extinction curve of HD 210121 from 0 to 8 μm^{-1}. The ultraviolet segment is represented by the Fitzpatrick & Massa (1990) formula (*solid curve*) fitted to the data by Welty & Fowler (1992). Infrared data are from our observations (*squares*) fitted with a power law (*solid curve*). Error bars on our observations are equal to or smaller than the size of the squares. The average extinction curves for the diffuse ISM (*dotted curve and triangles*) and ρ Oph dark cloud (*dashed curve and circles*) are also shown for comparison.

2. EXTINCTION

Photometric observations of HD 210121 were obtained at the South African Astronomical Observatory (SAAO) on 1994 July 15 and 16. The Mark III InSb Infrared Photometer was used on the 1.9 m telescope to give magnitudes in standard *JHKL* passbands. An 18″ aperture was used with a 30″ north-south chop. Results were reduced to the standard photometric system of Carter (1990). Data from the two nights were averaged, with each measurement weighted by its formal statistical error. Deviations due to systematic errors between the two nights, while more than formal statistical uncertainties, are consistent with the variances from the mean and the accepted uncertainty in photometric measurement. Results are listed in the second column of Table 1.

Based on UV and visual spectra, Welty & Fowler (1992) adopt a spectral type of B3 V for HD 210121, and report previously unpublished optical photometry by Penprase of $V = 7.67$ and $B - V = +0.20$. We calculate color excesses,

$$E_{\lambda-V} = (\lambda - V) - (\lambda - V)_0 = A_\lambda - A_V ,$$

where the zero subscript indicates intrinsic color indices from Wegner (1994). The blue-visual reddening is deduced to be $E_{B-V} = 0.38$. Relative extinction normalized to unit E_{B-V} is shown as squares in Figure 1. Data for HD 210121 are compared with average extinction for the diffuse ISM (*triangles*) and also with extinction for ρ Oph (*circles*), representative of the dense dark cloud environment (Martin & Whittet 1990).

To determine the ratio of total-to-selective extinction, $R_V = A_V/E_{B-V}$, we follow the procedure of Martin & Whittet (1990). Assuming the absolute extinction, A_λ, has a

TABLE 1

OBSERVATIONAL DATA FOR HD 210121

Band (λ) (μm)	m_λ (mag)	p_λ (%)	θ_λ (deg)
U (0.36)......	...	1.35 ± 0.07	154 ± 1
B (0.43)......	7.87 ± 0.03[a]	1.27 ± 0.05	154 ± 1
V (0.55)......	7.67 ± 0.03[a]	1.21 ± 0.05	154 ± 1
R (0.63)......	...	1.17 ± 0.08	155 ± 2
I (0.78).......	...	0.94 ± 0.04	157 ± 2
J (1.25)......	7.42 ± 0.02	0.53 ± 0.05	156 ± 2
H (1.65)......	7.41 ± 0.02	0.32 ± 0.05	163 ± 7
K (2.20)......	7.43 ± 0.03	0.18 ± 0.03	168 ± 8
L (3.50)......	7.42 ± 0.05	...	...

[a] Unpublished data of Penprase quoted by Welty & Fowler 1992.

power-law form in the infrared where variations in grain size are least important, we apply a nonlinear least-squares weighted fit of an offset power law to the relative extinction data. The power-law fit obtained agrees with the "universal" power law of index 1.8 (Martin & Whittet 1990). Extrapolating to $\lambda^{-1} = 0$, we obtain R_V from the intercept (Whittet 1992). For the line of sight to HD 210121,

$$R_V = -\left(\frac{E_{\lambda-V}}{E_{B-V}}\right)_{\lambda\to\infty} = 2.1 \pm 0.2 .$$

Variation in this parameter due to the sensitivity of the fit to the choice of weights for the data is within the formal statistical uncertainty. The value of R_V obtained by this method is consistent with the less rigorous method of evaluating R_V from the E_{V-K} color excess (Whittet & van Breda 1978),

$$R_V \simeq 1.1 \frac{E_{V-K}}{E_{B-V}} = 2.1 .$$

With R_V determined, we can deduce the absolute visual extinction $A_V = R_V E_{B-V} = 0.80 \pm 0.09$ mag in this line of sight, which is reasonably consistent with values of $A_V \sim 1$ mag used in previous efforts to determine column densities and in models of cloud chemistry.

Fits of offset power laws to the diffuse ISM and ρ Oph extinction curves in *JHKLM* passbands yield R_V values of 3.04 ± 0.05 and 4.22 ± 0.09, respectively. From this comparison, we first conclude that the value of R_V in DBB 80 is substantially lower than the average for diffuse regions of the ISM closer to the Galactic plane. Indeed, we believe it to be the lowest known at this level of precision. For example, the lowest value found in a set of some 200 reddened OB stars studied by Whittet & van Breda (1980) is $R_V \simeq 2.4$. Second, we conclude that processes leading to evolution of the grain size distribution in ρ Oph (and other dark clouds) affect R_V in the *opposite* sense to that observed in DBB 80.

3. POLARIZATION

Polarimetry of HD 210121 was obtained at the 3.9 m Anglo-Australian Telescope (AAT), Siding Spring Observatory, on 1995 September 13. The Hatfield Polarimeter (see Hough, Peacock, & Bailey 1991) was used to measure the degree (p_λ) and position angle (θ_λ) of linear polarization in eight passbands from the near-ultraviolet to the near-infrared (*UBVRIJHK*). The observational procedure and methods of data reduction were similar to those described by Whittet et al. (1992). Repeat measurements were averaged, weighted by formal statistical uncertainties. Data were corrected for noise biasing, but the corrections are below the precision of the data. Results are given in Table 1 (third and fourth columns), and a plot of p_λ versus λ^{-1} is shown in Figure 2. Error bars represent scatter in the measurement and are more conservative than strict statistical errors. Position angles were calibrated relative to the polarized standard *o* Sco (Serkowski, Mathewson, & Ford 1975) and show no significant rotation with wavelength.

The Serkowski-Wilking empirical relation for optical interstellar polarization,

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

(e.g., Whittet et al. 1992), was fitted to the data. The result of a three-parameter nonlinear least-squares weighted fit are $p_{\max} = 1.32 \pm 0.04\%$, $\lambda_{\max} = 0.38 \pm 0.03$ μm, and

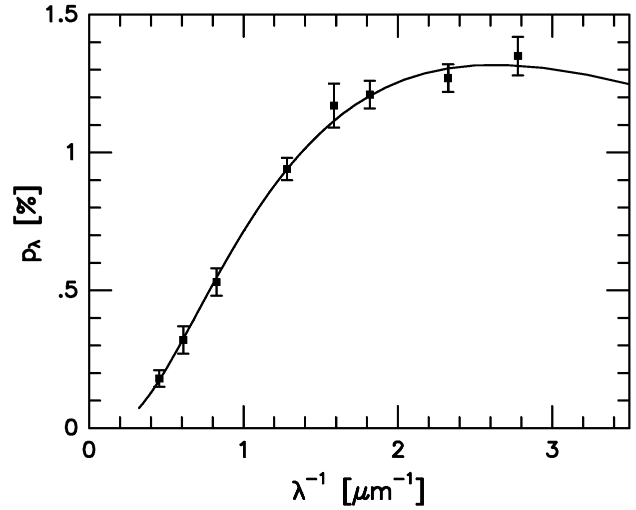

FIG. 2.—Interstellar polarization curve for HD 210121, based on data from Table 1 (*squares with error bars*). The curve is the best three-parameter fit obtained with the Serkowski formula ($p_{\max} = 1.32 \pm 0.04\%$; $\lambda_{\max} = 0.38 \pm 0.03$ μm ; $K = 0.66 \pm 0.09$).

$K = 0.66 \pm 0.09$. This fit is shown as a solid curve in Figure 2. Variation in $\lambda_{\max}$ when different subsets of points are included in the fit is within the statistical uncertainty. We contrast this notably low value of $\lambda_{\max}$ with values in the diffuse ISM, typically in the range 0.4–0.8 μm with an average value of $\lambda_{\max} = 0.55$ μm (Serkowski et al. 1975). However, the width of the polarization curve for HD 210121 is well within the expected range, based on the average Galactic correlation of K and $\lambda_{\max}$ (Whittet et al. 1992), which predicts

$$K = (1.66 \pm 0.09)\lambda_{\max} + (0.01 \pm 0.05) = 0.64 \pm 0.09$$

for HD 210121, in excellent agreement with the value of K deduced from the fit.

Our result for $\lambda_{\max}$ toward HD 210121 is consistent with its R_V value determined in the previous section. These independently determined parameters are correlated, as first shown by Serkowski et al. (1975). Although both have extreme values toward HD 210121, they nevertheless follow an extrapolation of the linear correlation described by a fit to the data set of Whittet & van Breda (1978); using $\lambda_{\max}$ to predict R_V, we obtain

$$R_V = (5.6 \pm 0.3)\lambda_{\max} = 2.1 \pm 0.2$$

for HD 210121, in remarkable agreement with the measured value. Our data also allow us to evaluate the polarization efficiency p/A toward HD 210121, which we express in the form $p_{\max}/A_V \simeq 1.65\%$ mag^{-1}. This value is comparable to the average for stars in the Galactic plane ($p_{\max}/A_V \simeq$ 1.6% mag^{-1}) and less than that for optimum alignment ($p_{\max}/A_V \simeq$ 3%–4% mag^{-1}; see Serkowski et al. 1975; Whittet et al. 1994).

4. DISCUSSION

As described in § 1 and shown in Figure 1, the extinction curve toward HD 210121 has among the highest FUV continua and nonlinear rises known. This observation, along with observations of large molecular column densities, is consistent with an abundance of small dust grains in the foreground cloud. In this discussion, we will explore the relationship between these previous observations and the photometric and polarimetric observations presented in this paper. In addition, we will show how the values of the parameters R_V and λ_{max} support the hypothesis of small grain abundance in this cloud. Understanding the meaning of these parameters and the observed correlation between them is important for determining the relationship between extinction and polarization in a broad spectral range.

The general convergence of interstellar extinction to a common behavior in the infrared (Martin & Whittet 1990; Martin et al. 1992) indicates that variations in relative extinction (as measured by R_V) depend on environmental variations of the properties of grains responsible for *blue-visual* extinction. Extinction in this spectral region is due to particles smaller than those causing extinction in the region of convergence; low values of R_V are therefore consistent with a low mean grain size due to relatively large numbers of smaller classical grains. Furthermore, steep FUV extinction suggests an abundance of even smaller grains. The FUV nonlinear rise is produced primarily by small particles (radius less than 0.05 μm) the extinction cross sections of which peak at wavelengths below 0.1 μm (Joseph et al. 1986). Increases in the extinction rise relative to the Galactic average are due to relatively large numbers of grains with very small radius. In this paper, we have shown that these two measures of extinction, R_V and the FUV rise, qualitatively agree in the line of sight to HD 210121. Over many lines of sight, CCM find a relationship between R_V and the wavelength dependence of UV extinction, which suggests that there is correlated evolution of these grain size populations. However, we find that the UV extinction curve for HD 210121 cannot be completely represented by the R_V parameterization that CCM describe. Cardelli & Clayton (1991) discuss "dark cloud" lines of sight, for which the extinction is not adequately matched by the CCM curve, which tends to average out variations in the FUV for a given visual extinction. Lines of sight with large deviations from the CCM average emphasize and set limits on environmental processes which modify the small grain population producing UV extinction. We propose that HD 210121 is one such line of sight.

Steep FUV extinction and other indicators of small grains toward HD 210121 predict excess emission in the 12 μm and 25 μm bands of the *Infrared Astronomical Satellite* (*IRAS*). In general, grains are heated by absorbing ultraviolet radiation and cooled by emitting in the infrared. Thermal emission from classical grains (radius greater than 0.1 μm) is detected in the far-infrared, dominating the 100 μm intensity measured by *IRAS*. However, variation in the shorter *IRAS* colors cannot be explained entirely with changes in grain excitation by the UV radiation field (Boulanger et al. 1990). Instead, these colors trace the abundance of small grains that are transiently heated, where observed emission depends on the time-averaged temperature. Welty & Fowler (1992) show excess $I(12\ \mu\text{m})/I(100\ \mu\text{m})$ emission toward HD 210121 relative to the three-component model of Désert, Boulanger, & Puget (1990). In this model, the very small grains that contribute to the FUV extinction rise (as well as a fraction of the gray visible and UV extinction) will emit at 12 μm. We show in Figure 3 the spectral energy distribution of HD 210121 and foreground cloud, plotting ground-based photometry from Table 1 and *IRAS* flux measurements of a 3′ square region around the star (Welty & Fowler 1992). Three blackbody calculations scaled to fit the data are also shown in the figure for illustration. The reddened profile of the background star is shown with the *JHKL* photometry in the blackbody Rayleigh-Jeans limit. A cool component peaking near 100 μm corresponds to large grains at 30 K in the foreground cloud. Excess emission at 12 and 25 μm, which cannot arise either in the star or in cold large grains, is clearly seen and emphasized in the figure by a blackbody curve at 300 K. This result strengthens the case for an abundance of small grains in the line of sight toward HD 210121.

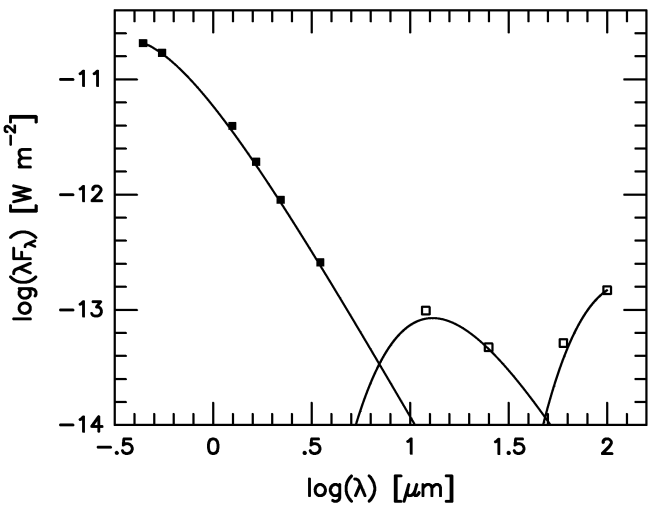

FIG. 3.—Spectral energy distribution for HD 210121 and DBB 80. Optical and infrared data (*filled squares*) are from Table 1. *IRAS* data (*open squares*) are from Welty & Fowler (1992). Three blackbody curves scaled to fit the data are shown at 11,000, 300, and 30 K, from left to right, respectively.

Because interstellar polarization is caused by directional extinction, it is most appropriate and useful to compare polarimetry with extinction. The models of Kim & Martin (1994) confirm that we can treat λ_{max} as a size parameter; variations in λ_{max} arise due to changes in the mean size of aligned grains along different lines of sight, such that there are more grains producing polarization in the blue-visible when λ_{max} is low. However, fewer small particles are needed to satisfy observations of polarization than observations of extinction, which implies that smaller particles are either not well aligned or more spherical. Star-to-star differences in λ_{max} may result from changes in the polarization efficiency of small grains (which is a function of both their shape and alignment efficiency), but such changes will not, in general, reflect corresponding effects in the extinction curve. On the other hand, variations in λ_{max} may also occur due to global changes in the abundance of *all* small grains, irrespective of their shape or how well they are aligned, and these changes will reflect corresponding effects in the extinction curve. The existence of correlations between λ_{max} and R_V (§ 3) and between λ_{max} and the level of UV continuum extinction at 6 μm^{-1} (He et al. 1996) provide convincing evidence that, at least in some lines of sight, low values of λ_{max} arise because of a general abundance of alignable small grains. Toward HD 210121 in particular, available evidence suggests that the high abundance of small grains implied by the shape of its extinction curve and spectral energy distribution is primarily responsible for short λ_{max}. Though R_V and λ_{max} may not be equally sensitive to mean grain size if the small grains are inefficiently aligned, the consistent linear relationship between these parameters indicates that populations of small grains responsible for extinction and polarization in DBB 80 respond to prevailing physical conditions in a correlated way. In this way, the dust grains in the line of sight to HD 210121 show behavior consistent with that of dust in clouds closer to the Galactic plane.

A similar case to HD 210121 is provided by the well-studied line of sight to HD 204827, which has a qualitatively similar extinction curve (Fitzpatrick & Massa 1990) with $R_V \simeq 2.6$ (CCM). The linear continuum is less steep and the 2175 Å bump is stronger in HD 204827, but the FUV polynomial coefficient is nearly identical to that of HD 210121. The line of sight to HD 204827 is one of the "dark cloud" regions discussed by Cardelli & Clayton (1991) which deviates from the CCM R_V-parameterized extinction curve. Furthermore, HD 204827 has a very short value of $\lambda_{\max} = 0.43$ μm, accompanied by a high degree of continuum polarization in the satellite UV (Clayton et al. 1995). Our $\lambda_{\max}$ value for HD 210121 therefore suggests that the level of UV polarization will be exceptionally high in this line of sight. Adopting the linear relationship of Clayton et al. (1995; see their Fig. 4) between UV polarization and $\lambda_{\max}^{-1}$ on 14 lines of sight and extrapolating to $\lambda_{\max}^{-1} = 2.6$ μm^{-1}, the UV polarization of HD 210121 at $\lambda^{-1} = 6$ μm^{-1} is predicted to be $\sim 0.9 p_{\max} \sim 1.2\%$. We therefore conclude that HD 210121 is an excellent candidate for future observation of interstellar polarization in the UV. Not only is it likely to be highly polarized in the UV, but data in this short $\lambda_{\max}$ line of sight should help define the functional form of the correlation between $\lambda_{\max}^{-1}$ and degree of UV polarization.

Although both HD 204827 and HD 210121 have extremely steep FUV extinction and small values of $\lambda_{\max}$ and R_V, it should be noted that there are lines of sight for which this correlation does not hold. The best example is HD 62542, which has a dramatic nonlinear FUV rise, with amplitude the highest known (Cardelli & Savage 1988), as well as a weak, highly shifted 2175 Å bump. Like HD 210121, the spectrum of HD 62542 yields large CH and CN column densities at $A_V \sim 1$ mag in the foreground cloud (Cardelli et al. 1990), indicating effective screening of dissociating radiation by the steep UV extinction curve. However, in complete contrast to HD 210121, $R_V = 3.24$ and $\lambda_{\max} = 0.58$ μm are unexceptional (somewhat above normal) toward HD 62542 (Whittet et al. 1993; Clayton et al. 1995), indicating a dichotomy between the very small grains producing the FUV rise and the small to medium-sized grains producing blue-visible extinction and polarization. This dichotomy may be related to the exceptional nature of the line of sight toward HD 62542, which contains a cometary globule swept by strong stellar winds (see Whittet et al. 1993 and references therein for further discussion). Compared with HD 62542, the dust toward HD 210121 seems likely to be relatively unprocessed. We attribute its steep FUV extinction curve to an abundance of very small grains and its exceptionally low values of R_V and $\lambda_{\max}$ to a lack of growth by coagulation of the small to medium-sized grains.

Future observations along these and other "anomalous" lines of sight with observable parameters far beyond average values are needed. Our goal is to establish correlations between grain populations responsible for extinction and polarization, and the sensitivity of each population to physical conditions. Determining such relationships and evaluating their wavelength dependence as a function of environment (or verifying universality across a range of environmental conditions) will constrain models for the evolution of dust grains in the ISM. Our observations of HD 210121 are part of an ongoing study of the optical properties and alignment efficiency of grains in translucent molecular clouds at high Galactic latitude.

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