Observations of the weak polarization of light from nearby stars, reported by Tinbergen, are consistent with polarization by small (radius <0.14 μm) interstellar dust grains entrained in the magnetic wall of the heliosphere. The region of maximum polarization is toward ecliptic coordinates (λ, β) ~ (295°, 0°), corresponding to (l, b) = (20°, −21°). The direction of maximum polarization is offset along the ecliptic longitude by ~3° from the nose of the heliosphere and extends to low ecliptic latitudes. An offset is also seen between the region with the best-aligned dust grains, λ ~ 281°–330°, and the upward direction of the undeflected large grains, λ ~ 259°, β ~ +8°, which are observed by Ulysses and Galileo to be flowing into the heliosphere. In the aligned-grain region, the strength of polarization anticorrelates with ecliptic latitude, indicating that the magnetic wall is predominantly at negative ecliptic latitudes. An extension of the magnetic wall to β < 0°, formed by the interstellar magnetic field \( B_{IS} \) draped over the heliosphere, is consistent with predictions by Linde (1998). A consistent interpretation follows if the maximum-polarization region traces the heliospheric magnetic wall in a direction approximately perpendicular to \( B_{IS} \), while the region of best-aligned dust samples the region where \( B_{IS} \) drapes smoothly over the heliosphere with maximum compression. These data are consistent with \( B_{IS} \) being tilted by 60° with respect to the ecliptic plane and parallel to the Galactic plane. Interstellar dust grains captured in the heliosheath may also introduce a weak, but important, large-scale contaminant for the cosmic microwave background signal with a symmetry consistent with the relative tilts of \( B_{IS} \) and the ecliptic.

Subject headings: cosmic microwave background — dust, extinction — polarization — solar system: general

1. INTRODUCTION

Tinbergen’s detection of weak (2± σ) polarization of light for ~15 nearby stars, caused by magnetically aligned interstellar dust grains in the Galactic center hemisphere, has long been intriguing (Tinbergen 1982, hereafter T82; Frisch 1990). Instrumental noise may introduce random weak polarization, and the significance of these polarization data results partially from the consistent polarization position angles for objects in a small region near the ecliptic plane (see Fig. 6 of T82 and Fig. 2 of Frisch 2003). T82 found the position angles to be consistent with a Galactic magnetic field directed toward \( l \sim 70° \), similar to the \( l \sim 80° \) field direction found from polarization data for distant stars (Heiles 1976). The location of these magnetically aligned interstellar dust grains (ISDGs) coincides with nearby interstellar material (ISM) in the Galactic center hemisphere (Frisch & York 1983).

Previous discussions of the T82 data found little increase in polarization with star distance, indicating that the grains are close to the Sun (Frisch 1990; Frisch & Slavin 2005). The regions of strongest polarization and most uniform position angle are concentrated in the ecliptic plane near the heliosphere nose region (Frisch 2003). Ulysses, Galileo, and Cassini observe interstellar dust grains flowing into the heliosphere from the heliosphere nose. The grains capable of polarizing starlight, radius \( a > 0.05 \) μm, are part of the population of grains with \( a < 0.1–0.2 \) μm that are filtered at the heliopause (Baguhl et al. 1996; Linde 1998; Landgraf 2000, hereafter L00; Frisch et al. 1999, hereafter F99).

In this Letter I argue that the T82 polarization data are consistent with polarization by charged interstellar dust grains trapped in, and diverted by, the interstellar magnetic field \( B_{IS} \) draped over the heliosphere. Conventional grain alignment theories will need evaluation for the unique outer heliosheath magnetohydrodynamic (MHD) configuration, where interstellar fields may be compressed by factors of 4 or more and field-aligned currents are present (e.g., Lazarian 2000; Linde 1998; Ratkiewicz et al. 1998; Pogorelov et al. 2004). The T82 data, together with the 3 kHz signals detected by Voyager in the outer heliosphere (Kurth & Gurnett 2003), represent the primary evidence for the interstellar magnetic field direction at the solar location and are both consistent with a field direction toward \( l \sim 80° \). If my interpretation is correct, sensitive polarization observations over the 22 yr magnetic solar cycle should monitor the outer heliosheath and detect variations in the interactions of these charged grains with the heliosphere.

Small charged grains capable of polarizing starlight are coupled to the interstellar magnetic field excluded from the heliosphere. For reasonable estimates of the far-ultraviolet radiation field, which causes photoelectric charging of the ISDGs, and interstellar field strengths greater than 1.5 μG, dust grains with radii \( a \sim 0.05 \) μm provide the most polarization in the diffuse ISM (Mathis 2000). Linde (1998) estimates that ISDGs with radii \( a < 0.14 \) μm will be deflected through large angles at the heliosphere magnetic wall, which is formed by compressed interstellar field lines draped over the heliosphere nose. For the case where \( B_{IS} \sim 1.5 \) μG and a field angle of 60° with respect to the ecliptic plane, field strength increases by factors of ~4–5 or more in the resulting magnetic wall. An even stronger \( B_{IS} \) is expected if magnetic and thermal energies are approximately equal in the ISM surrounding the heliosphere. For thermal energy density \( E_{th}/k = 1.5nT \sim 3700 \) cm\(^{-3} \) K, magnetic energy density \( E_{B}/k = B_{IS}^2/8\pi \) cm\(^{-3} \) K, and \( E_{th} \sim E_{B} \), \( B_{IS} \sim 3.6 \) μG for the local ISM, which has temperature and densities \( T = 6340 \) K, \( n(H^+) \sim 0.20 \) cm\(^{-3} \), \( n(H^+) \sim 0.09 \) cm\(^{-3} \), and \( n(e^-) \sim 0.1 \) cm\(^{-3} \) (Slavin & Frisch 2002; Frisch & Slavin 2005).

Larger ISDGs flow into the heliosphere at ~26.3 km s\(^{-1} \) (~5 AU yr\(^{-1} \)) from the upwind direction \( \lambda \sim 259°, \beta \sim +8° \) and
have been measured at all ecliptic latitudes in the inner 5 AU of the heliosphere (e.g., Baguhl et al. 1996; L00). ISDG trajectories depend on the charge-to-mass ratio and polarity of the solar magnetic cycle. The magnetic polarity of the Sun was north-positive during ~1971.6–1980.2, when the T82 data are likely to have been acquired, and again when the Ulysses and Galileo (U/G) and Voyager 3 kHz data were acquired in the 1990s (Frisch et al. 2005). Intermediate-sized charged grains, \(a \sim 0.2\ \mu m\), couple to the solar wind by the Lorentz force and are alternately focused and defocused by the changing solar cycle polarity. These observing periods coincided with defocusing cycles for positively charged grains (L00). Large grains (\(a > 0.5\ \mu m\)) are gravitationally focused downwind of the Sun, leaving a trail ("focusing cone") of interstellar dust extending for >10 AU, similar to the interstellar \(He^0\) focusing cone (Witte 2004; Möbius et al. 2004).

2. TINBERGEN POLARIZATION DATA

Tinbergen observed \(\sim 180\) stars at 1 \(\sigma\) levels of degree of polarization of \(7 \times 10^{-5}\) and concluded that there is a region of interstellar dust creating weak polarization of the light from nearby (<40 pc) stars, with the dust centered around the Galactic interval of \(l \sim 340^\circ \pm 40^\circ\), \(b \sim 0^\circ\). This direction is consistent with the upwind direction of the flow of ISM past the Sun, or \(l = 331^\circ.4\), \(b = -47^\circ.9\) (Frisch et al. 2002). The upwind direction is the value after correcting for the standard solar apex motion. The LSR velocity and ecliptic position are \(V \sim -19.4\ \text{km s}^{-1}\) and \(\lambda = 255^\circ.6\), \(\beta = -32^\circ.6\). The discussion here is restricted to \(\sim 160\) stars within 40 pc of the Sun. T82 reported Stokes parameters \(Q\) and \(U\) for three channels, I, II, III, based on filters centered near 5400, 6100, and 8000 \(\AA\), respectively, along with the averages of channels I and II. The channel I, II averages for \(Q, U\) are used in this Letter (as listed in cols. [10] and [11] of Table 5 of T82). Polarization is given by \(P = (Q^2 + U^2)^{1/2}\), and position angle in celestial coordinates \(\theta_c = 0.5\ \text{arctan}(U/Q)\). Note that the standard convention for defining the polarization angle, \(\theta_c\), is that \(Q\) is positive and \(U\) is zero when the electric vector is north-south in the equatorial (celestial) coordinate system. I now show that the T82 data show the distinct signature of the ecliptic and are consistent with predictions of a magnetic wall near the heliosphere nose.

The T82 results were not confirmed by a later survey of \(\sim 400\) stars at an accuracy of \(\sigma \sim 2 \times 10^{-4}\) (Leroy 1993, hereafter L93). Eleven stars in the T82 patch were observed in both surveys, with declinations down to \(-30^\circ\). However, the L93 data are not inconsistent with the T82 results. Observation dates are unclear in the T82 and L93 papers, but it appears that the T82 data were acquired in the years surrounding or following the 1975 solar minimum, while the L93 data were acquired near the 1990–1992 solar maximum, when the outer heliosheath configuration would have been different.

The strength of the anticorrelation between polarization and ecliptic latitude is shown in Figure 1. It has been determined from the covariance, \(C_{P,\beta}\), of polarization \(P\) and ecliptic latitude \(\beta\), where

\[
C_{P,\beta} = \frac{1}{(N - 1)(\sigma_{P,\beta})^2} \sum_{i=1}^{N} (P_i - \bar{P})(\beta_i - \bar{\beta}).
\]

Here \(\bar{P}\) and \(\sigma_{P,\beta}\) (and \(\bar{\beta}\) and \(\sigma_{\beta}\)) are the mean and variance of \(P\) (and \(\beta\)), respectively, calculated for stars in the interval \(\lambda_0 \pm 20^\circ\) centered at an arbitrary ecliptic longitude \(\lambda_0\), while \(N\) is the number of stars in that interval. \(N\) ranges from 5 to 17 for the points plotted in Figure 1. A covariance factor of roughly \(-0.5\) is found for stars near the upwind direction, but in addition offsets between inflowing and polarizing dust grains reveal details about the interaction of the heliosphere and interstellar magnetic field (see below). The significance of this covariance is tested by performing a similar analysis, using the same star sample, but with different assumptions. In the first case, an equivalent calculation of \(C_{P,\beta}\) is completed using Galactic instead of ecliptic coordinates, and the only features appearing simultaneously (for the same \(\lambda_0\)) in \(C_{P,\beta}\), \(P\), and \(\theta_c\) are toward the Galactic center (corresponding to the heliosphere nose direction) and a group of polarized stars near \((l, b) \sim (55^\circ, +55^\circ)\). For the second test, a set of values were generated for the Stokes parameters, \(Q\) and \(U\), with values randomly distributed between 0 and 35 (corresponding to a 5 \(\sigma\) polarization, \(P = 35 \times 10^{-5}\) deg polarization). These random polarizations were subjected to the same analysis as the real data, and the equivalent of Figure 1 is essentially a scatter plot for \(P\), \(\theta_c\), and \(C_{P,\beta}\), with no coherent patterns that depend on \(\lambda_0\). A third test uses the 25 stars contributing to the points in the interval \(\lambda_0 = 280^\circ-325^\circ\), which dominate the observed anticorrelation. The polarization for 13 stars with \(\beta < 0\) is \(P = (16.3 \pm 6.4) \times 10^{-5}\) deg, while the average polarization for the 12 stars with \(\beta > 0\) is \(P = (8.0 \pm 6.1) \times 10^{-5}\) deg. Applying the Stu-
dent’s $t$-test to these two samples gives an estimate, at the 98% confidence level, that the polarizations for these two samples are not drawn from a single sample with randomly distributed polarizations. Thus, the anticorrelation between polarization and $\beta$ for $\lambda = 280^\circ$–$325^\circ$ appears real and indicates that the polarization signal is dominated by stars with $\beta < 0^\circ$.

Figure 1 summarizes the properties of the polarization data for stars within 50° of the ecliptic plane. Each plotted point represents properties averaged over a 40° longitude interval, centered at an ecliptic longitude $\lambda_0$. The longitude, $\lambda_0$, is stepped along the ecliptic plane at intervals of 3° in order to display variations that depend on ecliptic longitude. The top panel of Figure 1 shows the variation in polarization, $P$, as a function of $\lambda_0$. The middle panel of Figure 1 shows that an interval extending from $\lambda_0 = 281^\circ$ to $330^\circ$ exhibits highly aligned grains (where $\theta_c \sim -35^\circ$; for the polarization angle in celestial coordinates) and encompasses the direction of maximum polarization observed toward $\lambda_0 \sim 295^\circ$. The position of ($\lambda, \beta$) = (295°, 0°) corresponds to ($l, b$) = (20°, $-21^\circ$). In the interval showing the strongest and most consistent polarization angle ($\lambda_0 = 281^\circ$–$330^\circ$), the correlation coefficient between $P$ and $\beta$ is $C_{P\beta} \sim -0.5$ (Fig. 1, bottom panel). The strength of the $P - \beta$ anticorrelation for only those stars with $\beta < 0^\circ$ gives $C_{P\beta} \sim -0.7$, a maximum smoothed value of $P \sim 20 \times 10^{-5}$ deg, and a direction of maximum $P$ toward $\lambda_0 \sim 294^\circ \pm 4^\circ$. The anomalously high values of $C_{P\beta} \sim +0.5$, found at $\lambda_0 \sim 60^\circ$, are dominated by the two nonvariable F stars HD 38393 and HD 40136, located near ($l, b$) = (223°, $-22^\circ$), with $P \sim 15 \times 10^{-5}$ deg. The He$^0$ cone central direction (Fig. 1, top panel) corresponds to a $\sim 15^\circ$ wide minimum in the polarization strength. Since grains in the dust cone are larger than typical grains that polarize optical light (LO0), this minimum, although marginally significant, could be explained if real.

In contrast, if one assumes a purely interstellar origin for the polarization and applies standard ISM values [$P/B < 0.03$, $A_v/E(B-V) = 3.1$, and $N(H)/E(B-V) = 5.8 \times 10^{-2}$ cm$^{-2}$], then a 1 $\sigma$ polarization corresponds to a cloud column density of $N(H) \sim 4 \times 10^{19}$ cm$^{-2}$ for a magnetic field perpendicular to the sight line. This value is consistent with the expected amount of nearby upward interstellar gas; for instance, toward 36 Oph $N(H) = 7.1 \times 10^{17}$ cm$^{-2}$ (Wood et al. 2000), and the gas in this sight line may be partially ionized. This argument, in turn, implies a purely interstellar origin for the polarization, with a possible small polarization enhancement in heliosheath currents. However, in this case it is difficult to explain the ecliptic signatures on starlight polarization as shown in Figures 1 and 2. The gas-to-dust mass ratio is, in any case, uncertain for such small reddening values.

### 3. DISCUSSION

ISDG interactions with the outer heliosheath may depend on solar cycle phase. During solar minimum phases, the heliospheric H i Ly$\alpha$ glow should show a pronounced groove from the asymmetric momentum flux of the solar wind (Bzowski 2003), compared to the more symmetric (although smaller overall) heliosphere during solar maximum. These differences in heliospheric morphology will affect the interstellar magnetic field and dust interactions with the heliosphere and may explain the lack of confirmation of the T82 data by L93.

For magnetically aligned ISDGs in space, the plane of polarization is parallel to $B_{hs}$, and maximum polarization will be seen for directions perpendicular to the field lines (Heiles 1976). The polarization maximum is offset by roughly $+30^\circ \pm 5^\circ$ from the heliosphere nose and should trace regions of the magnetic wall where the sight line is relatively perpendicular to the field direction. The region of maximum polarization is centered near $\lambda \sim 295^\circ$, but strongly polarized stars are seen at low ecliptic latitudes between ($\lambda, \beta$) = ($280^\circ$, $-10^\circ$) and ($320^\circ$, $-40^\circ$). This region near $\beta \sim -40^\circ$ may originate in the low-latitude extension of the magnetic wall caused by the relative tilt of $B_{hs}$ and the ecliptic. Linde (1998) modeled the magnetic wall for the 1996 solar minimum and found it stronger at southern latitudes where the azimuthal components of the interstellar and interplanetary fields are parallel, as compared to the northern hemisphere where they were antiparallel. The best-aligned grains ($\lambda = 281^\circ$–$330^\circ$) should trace compressed $B_{hs}$ field lines draping smoothly around the heliosphere (Linde 1998; Pogorelov et al. 2004; Rakitewicz et al. 1998). Alignment mechanisms are uncertain, but polarization may be enhanced by heliosheath grain charging (e.g., the Barnett effect) and the tight coupling between the small grains and compressed $B_{hs}$ (see Lazarian 2000). Detailed models of the distribution and trapping of small grains in the heliosheath are required.

In Figure 2, the distribution of polarization strengths is plotted in ecliptic coordinates, together with the upward direction of the interstellar dust, $H^0$, and $\text{He}^+$ flows. The positions of the 3 kHz bursts are also plotted. Both the distribution of 3 kHz bursts and the alignment of the polarization directions (Fig. 2 of Frisch 2003 and Fig. 6 of T82) suggest that $B_{hs}$ is parallel to the Galactic plane. This orientation corresponds to a tilt of $\sim 60^\circ$ with respect to the ecliptic plane, which is consistent with...
the direction of the global nearby $B_{IS}\sim 70^\circ$–80$^\circ$ (T82; Heiles 1976). The inflowing $U/G$ dust grains (Fig. 1, top panel) are larger than grains captured in the heliosheath, with an upward direction within $\sim 5^\circ$ of the value indicated by the He$^+$ cone antipode (F99). The 2 $\sigma$ uncertainties on the $U/G$ flow direction extend to smaller $\lambda$-values, or $\lambda = 210^\circ$–285$^\circ$. Figure 1 shows clearly that the region of maximum dust inflow (large grains) is offset from the region of maximum dust alignment (deflected small grains). Figure 2 shows that the direction of maximum polarization, which should trace the magnetic wall, is inclined by a large angle to the ecliptic plane. This offset between aligned and inflowing grains also indicates that dust filtration reflects the asymmetric heliosphere configuration caused by $B_{IS}$, with the large-grain inflow showing the heliosphere nose and the small grains showing the magnetic configuration of the outer heliosheath.

In principle, the relative distributions of the aligned dust, dust inflow, and He$^+$ and H$^+$ upward directions (see Fig. 2) will be understood if we impose the requirement that the filtration factors for dust, H$^+$, and other charged species vary with their gyroradius in the magnetic wall. Small dust grains are excluded (radii less than $\sim 0.05$–0.1 $\mu$m) and yield maximum polarization in directions perpendicular to $B_{IS}$. Large grains (radii $>0.2$ $\mu$m) experience minimal filtration. About 50% of the H$^+$ is filtered in the outer heliosphere. Protons are initially deflected perpendicular to $B_{IS}$ but become diverted around the heliosphere along with $B_{IS}$ in the magnetic wall. In Figure 2, the stars with the strongest polarization form a band that makes an angle of $\sim 65^\circ$ with respect to the ecliptic plane, and similar angles are seen between the offsets of the H$^+$ and He$^+$ upward directions. It seems a good guess that this alignment traces the magnetic wall orientation caused by the distortion of $B_{IS}$ at the heliosphere. The IBEX data on fast H$^+$ and O$^+$ neutral atoms formed in the heliosheath (McComas et al. 2004) may map out this heliosphere asymmetry driven by the interstellar magnetic field through observations of H$^+$ and O$^+$ fast neutrals, which have formation rates that depend on filtration factors.

Future precise observations of very weak polarization signals, with duplicate observations and using rotatable telescopes in the Northern and Southern Hemispheres, may provide a useful monitor of the outer heliosheath region and of the interaction between the solar and interstellar magnetic fields.

Removing contributions from foreground emission is an important element in analyzing WMAP composite maps (Bennett et al. 2003). The possibility of weak large-scale contributions from the heliosphere indicates that further modeling of this emission is warranted (P. C. Frisch & A. J. Hanson 2004, unpublished). The infrared emission from heliospheric interstellar dust appears much weaker than zodiacal emission, by factors of $\sim 10^2$ (F99). However, the observed correlation with the ecliptic of the combined quadrupole-octopole signature, found by Schwarz et al. (2004) in the WMAP data, supports a possible contamination from ISDGs interacting with the heliosphere. Candidates for contamination include the small polarizing grains trapped in the magnetic wall and discussed here, current sheets in the outer heliosheath regions, or alternatively from larger heated interstellar dust interacting with the solar wind. Any contribution to the cosmic microwave background from small grains in the outer heliosheath regions should reflect the complex asymmetry of the heliosphere interacting with $B_{IS}$, including the magnetic wall, rather than echoing the more simple symmetry of the ecliptic plane. If the smaller grains, radii $a<0.2$ $\mu$m, are responsible, the spatial distribution may show a variation with the solar cycle, such that the heliospheric contribution to the cosmic microwave signal could be recovered from sensitive polarization observations spaced throughout the 22 yr magnetic solar cycle.2

The author acknowledges NASA grants NAG5-11005 and NAG5-13107 for research support.

2 After this Letter was submitted, a discussion of the interstellar magnetic field direction based on Ly$\alpha$ interplanetary glow data was presented by Lallement et al. (2005).

REFERENCES

Baguhl, M., Gruen, E., & Landgraf, M. 1996, Space Sci. Rev., 78, 165
Bennett, C. L., et al. 2003, ApJS, 148, 97
Bzowski, M. 2003, A&A, 408, 1155
Frisch, P. 1990, in Physics of the Outer Heliosphere, ed. S. Grzedzielski & D. Page (Oxford: Pergamon), 19
———. 2003, J. Geophys. Res., 108, 11
Frisch, P. C., Grodnicki, L., & Welty, D. E. 2002, ApJ, 574, 834
Frisch, P. C., Müller, H. R., Zank, G. P., & Lopate, C. 2005, in Astrophysics of Life, ed. M. Livio, I. N. Reid, & W. B. Sparks (Cambridge: Cambridge Univ. Press), 21
Frisch, P. C., & Slavin, J. D. 2005, Adv. Space Res., in press
Frisch, P. C., & York, D. G. 1983, ApJ, 271, L59
Frisch, P. C., et al. 1999, ApJ, 525, 492 (F99)
Heiles, C. 1976, ARA&A, 14, 1
Kurth, W. S., & Gurnett, D. A. 2003, J. Geophys. Res., 108, 2
Lallement, R., Quémerais, E., Bertaux, J. L., Ferron, S., Koutchouma, D., & Pellinen, R. 2005, Science, 307, 1147
Landgraf, M. 2000, J. Geophys. Res., 105, 10303 (L00)
Lazarian, A. 2000, in ASP Conf. Ser. 215, Cosmic Evolution and Galaxy Formation: Structure, Interactions, and Feedback, ed. J. Franco et al. (San Francisco: ASP), 69
Leroy, J. L. 1993, A&A, 274, 203 (L93)
Linde, T. 1998, Ph.D. thesis, Univ. Michigan, http://hpcc.engin.umich.edu/CFD/publications
Mathis, J. S. 2000, J. Geophys. Res., 105, 10269
McComas, D., et al. 2004, in AIP Conf. Proc. 719, Physics of the Outer Heliosphere, ed. V. Florinski, N. V. Pogorelov, & G. P. Zank (Melville: AIP), 162
Möbius, E., et al. 2004, A&A, 426, 897
Pogorelov, N. V., Zank, G. P., & Ogino, T. 2004, ApJ, 614, 1007
Ratkiewicz, R., Barnes, A., Molvik, G. A., Spreiter, J. R., Stahara, S. S., Vinokur, M., & Venkateswaran, S. 1998, A&A, 335, 363
Schwarz, D., Starkman, G., Huterer, D., & Copi, C. 2004, Phys. Rev. Lett., 93, 221301
Slavin, J. D., & Frisch, P. C. 2002, ApJ, 565, 364
Tinbergen, J. 1982, A&A, 105, 53 (T82)
Witte, M. 2004, A&A, 426, 835
Wood, B. E., Linsky, J. L., & Zank, G. P. 2000, ApJ, 537, 304