COMPARISONS OF THE INTERSTELLAR MAGNETIC FIELD DIRECTIONS OBTAINED FROM THE IBEX RIBBON AND INTERSTELLAR POLARIZATIONS

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ABSTRACT

Variations in the spatial configuration of the interstellar magnetic field (ISMF) near the Sun can be constrained by comparing the ISMF direction at the heliosphere found from the Interstellar Boundary Explorer (IBEX) spacecraft observations of a “Ribbon” of energetic neutral atoms (ENAs), with the ISMF direction derived from optical polarization data for stars within ∼40 pc. Using interstellar polarization observations toward ∼30 nearby stars within ∼90° of the heliosphere nose, we find that the best fits to the polarization position angles are obtained for a magnetic pole directed toward ecliptic coordinates of λ, β ∼ 263°, 37° (or galactic coordinates of ℓ, b ∼ 38°, 23°), with uncertainties of ±35° based on the broad minimum of the best fits and the range of data quality. This magnetic pole is 33° from the magnetic pole that is defined by the center of the arc of the ENA Ribbon. The IBEX ENA ribbon is seen in sight lines that are perpendicular to the ISMF as it drapes over the heliosphere. The similarity of the polarization and Ribbon directions for the local ISMF suggests that the local field is coherent over scale sizes of tens of parsecs. The ISMF vector direction is nearly perpendicular to the flow of local interstellar material (ISM) through the heliosphere and is 15° above the galactic center and 5° above the ecliptic plane. The 0.05–6 keV ENAs detected by IBEX are formed in regions where charge exchange between interstellar neutral hydrogen and energetic ions creates inward flowing particles that reach the IBEX detectors. The ENAs formed inside the solar wind termination shock propagate away from the Sun, but the subsonic solar wind and pickup ions outside of the termination shock, with momentum components directed back toward the Sun, can create the ENAs measured in the inner heliosphere by IBEX (e.g., Izmodenov et al. 2009; Heerikhuisen et al. 2008). The subset of ENAs that propagate back toward IBEX at 1 AU is proving an excellent diagnostic of the heliosphere boundary conditions. The center of the Ribbon arc defines a value for the direction of the ISMF in the interstellar material (ISM) that is interacting with the heliosphere. The ISMF directions traced by the IBEX Ribbon and weak interstellar polarization observations of nearby stars together provide a unique constraint on the local ISMF direction, the outer boundary conditions of the heliosphere, and the global magnetic turbulence in the low density ISM near the Sun. In this paper, we compare the available data on the ISMF direction from optical polarization of local starlight, with the ISMF direction signified by the IBEX Ribbon.

ISM sets the outer boundary conditions of the heliosphere, including the thermal and ram pressures of the gas, and magnetic pressures (Davis 1955; Parker 1961; Holzer 1989). The heliosphere nose is defined by the upward direction of the flow vector of interstellar gas through the heliosphere and is 15° above the galactic center and 5° above the ecliptic plane. The 0.05–6 keV (∼50–1000 km s⁻¹) ENAs detected by IBEX are formed in regions where charge exchange between interstellar neutral hydrogen and energetic ions creates inward flowing particles that reach the IBEX detectors. The ENAs formed inside the solar wind termination shock propagate away from the Sun, but the subsonic solar wind and pickup ions outside of the termination shock, with momentum components directed back toward the Sun, can create the ENAs measured in the inner heliosphere by IBEX (e.g., Izmodenov et al. 2009; Heerikhuisen et al. 2008). The subset of ENAs that propagate back toward IBEX at 1 AU is proving an excellent diagnostic of the heliosphere boundary conditions. The center of the Ribbon arc indicates an ISMF direction toward ecliptic coordinates λ, β = 221°, 39° (or in the galactic coordinates toward ℓ, b = 33°, 55°, Funsten et al. 2009; Fuselier et al. 2009). The Ribbon’s arc does not follow the equator of the ISMF defined by the arc center, but rather traces the distortion of the ISMF by the heliosphere (Schwadron et al. 2009). For magnetic field B and radial direction R, the length and width of the B · R region depend on magnetic pressure and the limit set on B · R, respectively. The Ribbon latitude, in comparison to the magnetic pole defined by the arc center, depends on the distance beyond the heliopause of the Ribbon formation.

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1. INTRODUCTION

The recent unexpected discovery by the Interstellar Boundary Explorer (IBEX; McComas et al. 2009b) mission of a “Ribbon” of energetic neutral atoms (ENAs) provides the first direct evidence, and indirect measurement, of the interstellar magnetic field (ISMF) embedded in the low-density partially ionized cloud surrounding the Sun (McComas et al. 2009a; Fuselier et al. 2009; Funsten et al. 2009; Schwadron et al. 2009; Möbius et al. 2009). The IBEX Ribbon is visible at 1 AU for directions where the sight line is perpendicular to the ISMF draping over the heliosphere. The center of the Ribbon arc defines a value for the direction of the ISMF in the interstellar material (ISM) that is interacting with the heliosphere. The ISMF directions traced by the IBEX Ribbon and weak interstellar polarization observations of nearby stars together provide a unique constraint on the local ISMF direction, the outer boundary conditions of the heliosphere, and the global magnetic turbulence in the low density ISM near the Sun. In this paper, we compare the available data on the ISMF direction from optical polarization of local starlight, with the ISMF direction signified by the IBEX Ribbon.

ISM sets the outer boundary conditions of the heliosphere, including the thermal and ram pressures of the gas, and magnetic pressures (Davis 1955; Parker 1961; Holzer 1989). The heliosphere nose is defined by the upward direction of the flow vector of interstellar gas through the heliosphere and is 15° above the galactic center and 5° above the ecliptic plane. The 0.05–6 keV (∼50–1000 km s⁻¹) ENAs detected by IBEX are formed in regions where charge exchange between interstellar neutral hydrogen and energetic ions creates inward flowing particles that reach the IBEX detectors. The ENAs formed inside the solar wind termination shock propagate away from the Sun, but the subsonic solar wind and pickup ions outside of the termination shock, with momentum components directed back toward the Sun, can create the ENAs measured in the inner heliosphere by IBEX (e.g., Izmodenov et al. 2009; Heerikhuisen et al. 2008). The subset of ENAs that propagate back toward IBEX at 1 AU is proving an excellent diagnostic of the heliosphere boundary conditions. The center of the Ribbon arc indicates an ISMF direction toward ecliptic coordinates λ, β = 221°, 39° (or in the galactic coordinates toward ℓ, b = 33°, 55°, Funsten et al. 2009; Fuselier et al. 2009). The Ribbon’s arc does not follow the equator of the ISMF defined by the arc center, but rather traces the distortion of the ISMF by the heliosphere (Schwadron et al. 2009). For magnetic field B and radial direction R, the length and width of the B · R region depend on magnetic pressure and the limit set on B · R, respectively. The Ribbon latitude, in comparison to the magnetic pole defined by the arc center, depends on the distance beyond the heliopause of the Ribbon formation.
The ISM in the low column density sky is formed into filamentary anisotropic structures, whether it is neutral gas seen in the 21 cm H\textsuperscript{I} line, ionized gas observed in H\textalpha{} emission, or dust traced by infrared emission or the optical polarizations of starlight. Magnetic fields are a candidate force for controlling this observed filamentary structure, since they generate anisotropic forces on the ISM through pressure that acts perpendicular to the field lines, and tension that acts parallel to the field lines (Heiles 2009). Prior to the heliospheric diagnostics of the very local ISMF, such as the \textit{IBEX} Ribbon, the only data capable of constraining the ISMF within ∼50 pc were high-sensitivity measurements of the polarization of starlight by magnetically aligned interstellar dust grains. The \textit{IBEX} Ribbon is a feature that can be simulated with full heliosphere models, that simultaneously give the pressure of the ISM, and the orientation and strength of the ISMF. In the upwind direction (near the galactic center), the Sun appears to be at or close to the boundary of the surrounding cloud (Frisch et al. 2009). The ENA production simulation of Heerikhuisen et al. (2010), which is unconfirmed, predicts that \textit{IBEX} is capable of detecting variations in the Ribbon configuration that would be caused by variations in the interstellar density or magnetic field, such as expected when the Sun exits the cloud now around the heliosphere (Frisch et al. 2010). The relation between the ISMF directions traced by the \textit{IBEX} Ribbon and the observations of the weak interstellar polarizations of light from nearby stars provides a powerful tool for understanding both the distortion of the ISMF at the heliosphere and deviations from a homogeneous ISMF field over the nearest tens of parsecs.

The magnetic configuration traced by the ENA Ribbon, together with the asymmetry of the heliosphere, is a function of the angle between the interstellar gas flow vector and the ISMF direction. The flow of interstellar He\textsuperscript{0} through the heliosphere was measured by the Ulysses probe, and showed a warm cloud $T \sim 6300 \pm 340$ K, with velocity $26.3$ km s$^{-1}$ and an upwind direction toward $\lambda, \beta \sim 255.5, 5.1$ (or $\ell, b = 3.6, 15.1$, Witte 2004, after converting to J2000 coordinates). The Ribbon data therefore indicate an angle of ∼45° between the He\textsuperscript{0} flow velocity and field direction. The gaseous component of the heliosphere boundary conditions has been determined from models of the cloud ionization state based on interstellar absorption lines, which indicate that the surrounding interstellar gas is partially ionized with hydrogen ∼25% ionized, and low density, $n_{{\text{tot}}} \sim 0.27$ cm$^{-3}$ (Slavin & Frisch 2008, e.g., model 26). The ratio of thermal and magnetic pressures, $\beta$, is unknown for the surrounding cloud. If the local ISM is near the boundaries of an evolved superbubble, which is not yet clear, $\beta \sim 1$ might be expected. For the assumption of $\beta = 1$, the interstellar field strength is ∼2.8 \mu G (model 26). For comparison, Zeeman splitting of H\textsuperscript{0} 21 cm lines shows that superbubble shells with filamentary structures have high ISMF strengths and small $\beta < 0.1$, although column densities are over 100 times values in the local ISM (Heiles 1989). Low $\beta$ values are also found for the Local Bubble walls foreground of the Coalsack Nebula based on a Chandrasekhar–Fermi analysis of the polarization component in the plane of the sky (Andersson & Potter 2006).

The ISMF direction at the heliosphere is predicted by self-consistent heliosphere models (e.g., Ratkiewicz et al. 2000; Pogorelov et al. 2004, 2009; Opher et al. 2009; Izmodenov 2009) that are constrained by the interstellar neutral and plasma density in the circumbellospheric ISM (Slavin & Frisch 2008), the 10 AU difference between the \textit{Voyager} 1 and \textit{Voyager} 2 measurements of the termination shock distance (of which 3–4 AU could arise from variable solar wind, Stone et al. 2008), and the ∼5° offset between the directions of interstellar H\textsuperscript{0} and He\textsuperscript{0} flowing into the heliosphere (Witte 2004; Lallement et al. 2005, after precessing the He\textsuperscript{0} and H\textsuperscript{0} directions into a common coordinate system). Heerikhuisen et al. (2010) models reproduce the \textit{IBEX} Ribbon for an ISMF direction directed toward $\lambda, \beta \sim 223°, 40°$ (or $\ell, b \sim 35°, 54°$; hereafter $\ell, b$ are galactic coordinates). This direction is in good agreement with the ISMF direction $\ell, b \sim 30° \pm 5°, 33° \pm 4°$, for $B \sim 3.8$ \mu G, from magnetohydrodynamics (MHD) models of heliospheric asymmetries of Ratkiewicz & Grygorczuk (2008). Opher et al. (2009) use the heliosphere asymmetries from \textit{Voyager} data and the H\textsuperscript{0}–He\textsuperscript{0} offset to conclude that the ISMF field direction is inclined by ∼60°–90° with respect to the galactic plane. Several heliosphere models suggest that the very local ISMF is directed toward the southern solar magnetic pole, such as Swisdak et al. (2010) who base their conclusion on the assumption that the 3 kHz emissions detected by the \textit{Voyager} satellites during the early 1990s are formed by reconnection. The general agreement between the ISMF determined from the ENA Ribbon, the Heerikhuisen et al. model, and the Ratkiewicz & Grygorczuk (2008) model suggest directions for the ISMF at the heliosphere near the center of the Ribbon arc.

The new Ribbon diagnostic of the ISMF at the heliosphere provides an opportunity to evaluate the large-scale distortion or turbulence of the local ISMF, e.g., over ∼40 pc, through comparisons with the polarization of starlight caused by magnetically aligned interstellar dust grains. Optical polarization data show that once the curvature of spiral arms is taken into account, the global ISMF beyond ∼0.3 kpc is oriented toward $\ell \sim 83°$ (Heiles 1996). Faraday rotation data show that the polarity of the global ISMF is directed toward $\ell \sim 83°$ (Taylor et al. 2009). The Loop I magnetic superbubble, centered about 100 pc away, is a local large distortion of the global field with an angular diameter of ∼160° (e.g., Heiles 1976, 1998; Wolk 2007). It is prominent in dust, gas, synchrotron emission, optical polarization, and Faraday rotation data. Loop I is the best candidate for the phenomena that links the ISMF at the heliosphere with the ISMF causing nearby star polarizations (Frisch 2010). The overall geometry of Loop I, and the “$S$1” subshell, indicate that $S1$ has expanded to the solar location if it is approximately spherical, and the ISMF direction appears consistent with nearby polarization data for a field direction near $\ell, b \sim 71°, 48°$, with uncertainties of ∼±30°.

The ISM within ∼20 pc of the Sun has very low column densities, typically <10$^{18.5}$ cm$^{-2}$, and therefore low extinctions. Pioneering efforts to measure polarized starlight caused by magnetically aligned interstellar dust grains found that nearby space is very empty of the ISM, except for a patch of nearby dust, within 40 pc, primarily in the fourth Galactic quadrant between 270° and 360°, and in the southern hemisphere (Pirola 1977; Tinbergen 1982). This dust “patch” has a very local component, as the 2.5σ detection of polarization toward the star 36 Oph, 5 pc beyond the heliosphere nose, shows. (It is remarkable that many of these weak polarizations line up along the \textit{IBEX} Ribbon, see Figure 1.) The cloud giving rise to the polarization toward 36 Oph is not the circumbellospheric ISM, since the velocities of the two clouds differs by ∼2 km s$^{-1}$ (Frisch et al. 2009), so that the polarizations in this patch potentially trace a different ISMF direction than the Ribbon arc. The next set of studies of the polarization of nearby starlight was conducted by Leroy (1993), from the northern hemisphere. Leroy made a catalog of
observations of 1000 stars within 50 pc, with different sensitivity levels, and reconfirmed the emptiness of nearby space. However, he was unable to either confirm or disprove the existence of the polarization patch observed by Tinbergen. More recently, polarization observations with high measurement accuracy have been made with the PlanetPol instrument, primarily in the northern sky (Bailey et al. 2010). The Tinbergen, Piirola, and PlanetPol data are used in this study.

The goal of this study is to test the ISMF direction indicated by the center of the arc of the IBEX Ribbon with the ISMF direction traced by the polarization of light from nearby stars, using mainly polarization data from the literature with a range of sensitivity levels. These results are preliminary, in the sense that more and better high-sensitivity polarization data may affect the conclusions.

2. LOCAL MAGNETIC FIELD DIRECTION FROM INTERSTELLAR POLARIZATIONS

Magnetically aligned dust grains in the ISM create a birefringent medium with lower opacities parallel to the ISMF direction (e.g., Davis & Berge 1968; Lazarian 2003). The position angles of weakly polarized light, \( \lesssim 0.02\% \), from nearby stars can then be used to trace the local ISMF direction. A distance limit of 40 pc is selected for polarization measurements of the local ISM, since the “boundary” of the Local Bubble is at about 50 pc for galactic longitudes \( 300^\circ - 360^\circ \) and positive latitudes (e.g., Barstow et al. 1997). We assemble polarization data for nearby stars, omitting stars with known intrinsic polarization or circumstellar disks, and systematically evaluate the polarization position angles for a grid of \( i \) possible ISMF directions, \( \hat{\mathbf{k}}_{R,i} \), in order to determine the ISMF direction (e.g., rotated coordinate system) that provides the best alignment between polarization position angles and the meridians of the ISMF. The polarization data used for these comparisons consist of three sets of archival starlight polarization data, and new unpublished observations for three stars. The star sample is restricted to objects within \( \sim 40 \) pc of the Sun. The combined data sets of Tinbergen (1982)\(^{11} \) and Piirola (1977) provide data on \( \sim 140 \) stars, at 1 \( \sigma \) sensitivity levels of \( \sim 7 \times 10^{-5} \) degree of polarization (or equivalently 0.007% or 70 parts per million), and in both the northern and southern hemispheres. The strongest polarizations are seen toward the heliosphere nose region, with strengths of \( \sim 0.02\% \). Recent PlanetPol measurements at sensitivities of a few parts per million by Bailey et al. (2010) add additional data in the northern galactic and ecliptic hemispheres, where polarizations are typically very weak (<0.004%). Unpublished observations of several stars are also available, including of \( \beta \) Oph (HD 161096), with polarization \( P = 0.00506\% \pm 0.00008\% \), and equatorial position angle \( \theta_{R.A.} = 166.2 \pm 0.8 \) (S. Wiktorowicz; data acquired with the POLISH instrument, Wiktorowicz & Matthews 2008), where \( \theta_{R.A.} \) is the polarization position angle in equatorial coordinates. We add measurements of polarizations toward \( \lambda \) Sgr (HD 169916) and \( \tau \) Sgr (HD 177716), that were acquired by Berdyugin and Piirola in the \( R \)-band with the DIPOL polarimeter (Piirola et al. 2005) on the KVA-60 remotely operated telescope. For \( \lambda \) Sgr, \( P = 0.036\% \pm 0.007\% \) and \( \theta_{R.A.} = 109^\circ \pm 7^\circ \). For \( \tau \) Sgr, \( P = 0.028\% \pm 0.007\% \) and \( \theta_{R.A.} = 113^\circ \pm 7^\circ \). There are several stars with data from multiple sources (e.g., \( \lambda \) Sgr, \( \tau \) Sgr, and \( \beta \) Oph). In these cases all of the data were included with equal weight in the analysis.

The optical polarization position angles are plotted in galactic and ecliptic coordinates on Aitoff projections in Figures 1 and 2. The plotted size of the polarization vector is not related to the polarization strength, which spans over an order of magnitude for these stars (see Figure 5). The position angle of a vector is defined with respect to the north-south meridian passing through the position of the object, with the position angle increasing in the direction of increasing longitude.

To derive the orientation of the local ISMF, we used a minimization procedure in which we assumed that the local ISMF has a dipole configuration, so that the variations in the magnetic field strength are relatively small. The dipole model is characterized by two parameters: the dipole axis position angle \( \theta_{R.A.} \) and the dipole inclination \( \beta \). The dipole inclination is the angle between the dipole axis and the line of sight to the Sun. The dipole axis position angle is the angle between the dipole axis and the meridian of the Sun. The dipole model is the simplest model of the magnetic field, and it is the most common model used to describe the magnetic field in the ISM.

\( ^{11} \) During 1973–1974 when the southern hemisphere Tinbergen data were acquired, the solar magnetic polarity was north pole positive (\( A > 0 \), field lines emerging at the north pole). The solar polarity should have no effect on the optical polarization, as long as the grains are truly interstellar and outside of the heliopause.
orientations of the observed polarizations are due to the location of the field poles in the sky. If this assumption is correct, there should be a coordinate transformation that transforms all of the observed polarization vector directions into vectors that are parallel to a meridian of the transformed coordinate system. Following Appenzeller (1968), the position angle is transformed to the coordinate system \( \hat{k}_{B,i} \) using the relation

\[
\cot(\theta_{R.A} - \theta_i) = \frac{\cos(b_i) \tan(b_N) - \cos(\ell_i - \ell_N) \sin(b_i)}{\sin(\ell_i - \ell_N)},
\]

where \( \theta_{R.A} \) is the position angle in the equatorial coordinate system, and \( \theta_i, \ell_i, \) and \( b_i \) are the polarization position angle and star coordinates in the \( i \)th coordinate system corresponding to \( \hat{k}_{B,i} \). The north pole of the equatorial coordinate system is located at \( \ell_N, b_N \) in the \( i \)th coordinate system. Equation (1) is used to transform between both equatorial and ecliptic or galactic coordinates, and between the equatorial coordinates and the rotated ISMF frame \( \hat{k}_{B,i} \).

The ISMF direction that provides the best fit to the polarization position angles is selected by testing the polarization vector directions against the \( \hat{k}_{B,i} \) grid of possible ISMF directions. It is assumed that the “correct” ISMF direction will be parallel to the polarization vectors. The grid of possible ISMF directions are spaced by 1° in galactic longitude, \( \ell \), and latitude, \( b \), over the intervals \( 0° < \ell_i < 360° \) and \( |b_i| < 85° \). This comparison between polarization position angles and the ISMF direction was restricted to the subset of stars that have polarizations larger than \( 3\sigma \), where \( 1\sigma \) is the measurement uncertainty, and that are located within \( \sim 90° \) of the heliosphere nose. Since the heliosphere nose is \( \sim 15° \) from the galactic center, the fitting region is essentially restricted to the first and fourth galactic quadrants where ISM and the magnetic sky are dominated by the magnetic shell of Loop I. Polarization position angles for each star \( j \) were first rotated into the \( \hat{k}_{B,i} \) coordinate system using Equation (1), to obtain the new position angle \( \theta_{j,i} \) relative to the new ISMF direction corresponding to the grid point \( \hat{k}_{B,i} \). Polarization position angles are degenerate with respect to the north and south meridian directions, and the values of \( \theta_{j,i} \) were corrected to be between \( 0° \) and \( 180° \) by adding or subtracting \( 180° \).

The best-fitting ISMF then becomes the direction where the rotated ISMF (the \( i \)th grid point) yields a minimum of some function that describes a good match between the rotated polarizations and the rotated field direction. The process adopted here for determining the best-fitting ISMF is to determine the direction where the ISMF pole corresponds to the \( i \)th grid point that yields the minimum value for the function \( F_i \), where \( F_i = \sin(\theta_{j,i}) \) is the mean sin of \( j \) polarization position angles \( \theta_{j,i} \), in the rotated coordinates. All data points are weighted equally, rather than by measurement accuracy, since otherwise data sampling the Ribbon region would have lower weights since the older data (from Tinbergen 1982, see Figure 1) have lower measurement accuracies. The position angle is the angle between the polarization vector and a meridian, so that for a perfect fit the rotated position angles will be \( 0° \) or \( 180° \), and \( F_i = 0 \). Figures 3 and 4 show the color-coded map of \( F_i \). The best-fitting ISMF direction, \( \hat{k}_{B,best} \), that is determined where the minimum of \( F_i = 0.46 \), is directed toward the ecliptic coordinates \( \lambda, \beta \sim 263°, 37° \), or the galactic coordinates \( \ell, b \sim 38°, 23° \) (Table 1). The broad minima shown in Figures 3

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**Figure 2.** Same as Figure 1, except the figure is in galactic coordinates, and centered on the galactic center.

**Figure 3.** Value of the function \( F_i = \sin(\theta_{j,i}) \) evaluated over a regular grid of \( i \) possible interstellar field directions (see Section 2). The function is color coded and plotted in the ecliptic coordinate system, centered on the ecliptic nose, at \( \lambda \sim 255° \). The gray-dotted grid shows the best fit in the ecliptic coordinate system to the ISMF, \( B_{best} \), which is directed toward \( \lambda, \beta = 263°, 37° \). Polarization vectors for the stars used in the fit are shown as either black or white bars, for visual clarity.
and 4, together with the range of data quality, suggest that a more accurate uncertainty for the best fit is $\pm 35^\circ$. Figures 3 and 4 also display (only) the polarization position angles that were used in the ISMF fitting process.

Several tests of the fitting process were made. When the stellar data set was restricted to stars within 35 pc, the best fit ISMF direction changed by $\sim 10^\circ$–$20^\circ$ because four measurements near the ecliptic equator were removed from the sample, leaving a bimodal sample biased toward stars in the northern ecliptic hemisphere. The fitting function based on $F_i = \sin(\theta_i^2)$ was also tried, and it gave a best-fitting ISMF direction toward $\ell, b = 38^\circ, 23^\circ$; however, this function overweighted position angle values near the equator of the rotated ISMF, and so seems less suitable for this small set of data. The fitting procedure was repeated by varying the initial coordinate system used in the fit (e.g., equatorial, ecliptic, or galactic), and the results agreed to within $\sim 1^\circ$. Another check was made by omitting the step of converting the rotated $\theta_i$, values to the range $0^\circ$–$180^\circ$, yielding as expected the same result.

The polarization position angles in the rotated frame have been constrained to be between $0^\circ$ and $180^\circ$, so that the best fit value $F_{\text{min}} = 0.46$ corresponds to mean position angles of $27^\circ$. When the standard deviation of the position angles is included, the best-fit mean position angle in the rotated frame is $27^\circ \pm 23^\circ$. In principle, the dispersion in the position angles for the best-fitting ISMF direction could either be due to variations in the global configuration of the nearby ISMF over scale lengths comparable to typical scales of energy injection, or to small-scale turbulence at scale lengths typical of the plasma and magnetic properties of the partially ionized gas. However, the intrinsic measurement accuracies of the data from the northern versus southern hemisphere data sets differ substantially, so that understanding small-scale magnetic turbulence will require higher precision data in the southern hemisphere.

For a uniform distribution of interstellar dust near the Sun, and constant grain alignment efficiency, the polarization strengths will increase as the angular distance between the star and the poles of the ISMF increase, i.e., the polarizations are strongest where the sight line is more perpendicular to the ISMF direction. These data do not show such an effect (Figure 5). Instead, stars with ecliptic latitudes $\beta > +10^\circ$ consistently show much smaller polarizations than stars with ecliptic latitudes below $+10^\circ$. This statement is also nearly true when galactic latitudes are used instead. All stars with polarizations less than $0.01\%$ have ecliptic latitudes greater than $\beta = 10^\circ$. All stars with polarizations larger than $0.01\%$, except for HD 150997, are located at more negative latitudes, $\beta < 10^\circ$. This effect follows from the distribution of ISM very close to the Sun, within $\sim 15$ pc, which has higher column densities toward negative galactic latitudes than toward positive galactic latitudes in the galactic center hemisphere (e.g., Frisch et al. 2009). The ecliptic latitude of HD 150997 is $+60^\circ$, and it is $26^\circ$ from the ISMF pole at $\ell = 38^\circ, b = 23^\circ$. A single isolated clump of dust toward HD 150997 is possible, or the polarization may be intrinsic to the stellar system. In Figure 5, the stars used in the fit are color coded according to the data source. Other significant data points, with polarizations larger than the $3\sigma$ data uncertainties but not used in the fit are plotted as open squares.

Based on the above discussions we estimate uncertainties of $\pm 35^\circ$ on the best-fit ISMF direction of $\lambda, \beta = 263^\circ, 37^\circ$ in ecliptic coordinates, or $\ell, b = 38^\circ, 23^\circ$ in galactic coordinates. This direction is $33^\circ$ from the ISMF direction at the heliosphere determined from the arc of the IBEX Ribbon.

### Table 1

| Coordinate System | Longitude | Latitude |
|-------------------|-----------|----------|
| Polarization data–interstellar magnetic field: | | |
| Galactic | 38° | 23° |
| Ecliptic | 263° | 37° |
| Center of Ribbon arc: | | |
| Galactic | 33° | 55° |
| Ecliptic | 221° | 39° |

**Notes.**

- Galactic coordinates are denoted by $\ell$, $b$ and ecliptic coordinates by $\lambda$, $\beta$. The estimated uncertainties on the best-fit direction are $\pm 35^\circ$, based on the broad minimum for the best-fit function, $F_i$.
- This direction makes an angle of $\sim 71^\circ$ with respect to the vector motion of the flow of ambient local ISM past the Sun, in the LSR, which is from $\ell, b = 331^\circ, -5^\circ$ with a velocity of $-19.4$ km s$^{-1}$ (Frisch & Slavin 2006).
- This direction makes an angle of $\sim 46^\circ$ with respect to the heliocentric vector motion of the flow of interstellar He$^0$ into the heliosphere, which is from $\lambda, \beta = 255^\circ, 5^\circ$ with a velocity of $\sim 26.3$ km s$^{-1}$ (Witte 2004).

### 3. DISCUSSION

The ISMF direction of $\ell, b \sim 38^\circ, 23^\circ$, found from local polarization data, is directed toward the tangential region of Loop I at the North Polar Spur (NPS), that rises $50^\circ$ vertically from the galactic plane near $\ell \sim 30^\circ$–$40^\circ$. The NPS is a region of radio intense synchrotron emission, that Wolleben (2007) attributes to the collision of the S1 and S2 subshells of Loop I. Positive Faraday rotation measures for distant pulsars and extragalactic sources toward the NPS indicate an ISMF that is directed toward the Sun (Taylor et al. 2009). However, at the southern galactic latitudes for the same longitudes, where Wolleben’s model suggests the S1 subshell has expanded to the solar location, Faraday rotation measures are negative as is consistent with an ISMF direction pointing away from the Sun and toward the azimuthal field direction $\ell \sim 83^\circ$. Salvati (2010) analyzed Faraday rotation measure and dispersion data toward four pulsars, 150–300 pc away in the low-density sunlight background.
third galactic quadrant, and found an ISMF directed toward \( \ell = 38^\circ, b = 5^\circ \), with strength 3.3 \( 10^4 \) G, and with polarity directed into the northern galactic hemisphere. These data give the ISMF in the downwind direction, and it is within 33\(^\circ\) of the best-fitting polarization ISMF direction and within 22\(^\circ\) of the ISMF direction indicated by the center of the Ribbon arc. The good agreement between these three independent methods of obtaining the ISMF direction suggests that the three kinds of measurements are tracing the same ISMF, and that it is relatively smooth.

The formation mechanism for the Ribbon must be understood in order to relate the magnetic field direction derived from the Ribbon configuration, with the magnetic field derived from polarization data. The 26.3 km s\(^{-1}\) relative motion between the heliosphere and circumhelsiosphere ISM displaces the ISMF so that it drapes over the heliosphere, and the geometry of the outer heliosphere depends on the angle between the ISMF and interstellar flow vectors (e.g., Ratkiewicz et al. 2000; Pogorelov et al. 2009; Opher et al. 2009; Izmodenov 2009). The center of the Ribbon arc defines a magnetic field direction that makes an angle of 45\(^\circ\) with the gas flow vector (Table 1). Heerikhuisen et al. (2010) reproduce the Ribbon figuration using three-dimensional MHD models of the heliosphere plasma, coupled to interstellar neutrals described by a kinetic distribution, and ions with a Lorentzian distribution. In this model, the ENAs originate upstream of the heliopause in the region where the ISMF angle varies with the distance beyond the heliopause.

The model reproduces the location of the IBEX Ribbon quite well for the ISMF direction of \( \lambda, \beta = 22^4^\circ, 41^\circ \), which is close to the center of the Ribbon arc. The details of the Heerikhuisen et al. model are not yet substantiated, because the pitch–angle distribution of the underlying pickup ion ring-beam may scatter much more rapidly than the charge-exchange lifetime (McComas et al. 2009a; Florinski et al. 2010). These same MHD models also show that the Ribbon moves toward the equator of the distant ISMF as the ENA origin pushes further upstream of the heliopause. Several alternative scenarios have been discussed for the Ribbon formation, including an origin in

the inner heliosheath (McComas et al. 2009a; Schwadron et al. 2009; McComas et al. 2010). Comparisons between magnetic field directions derived from the Ribbon arc and polarization data will yield information on large-scale magnetic turbulence in the solar vicinity, once the formation of the Ribbon is fully understood.

The ISM toward the star 36 Oph (5 pc away and 10\(^\circ\) from the heliosphere nose) provides insights into the ISMF and gas forming the polarizations observed in the upwind direction. Tinbergen (1982) observed a polarization of 0.02% toward 36 Oph, a strength that is unusually high compared to the mean polarizations found over long sight lines. A single interstellar cloud, the “G” cloud, is present in front of both 36 Oph (5 pc) and the nearest star \( \alpha \) Cen (1.3 pc), with a velocity that differs by 2 km s\(^{-1}\) from the ISM velocity inside of the heliosphere (e.g., Frisch et al. 2009, and references therein). This suggests that there is a single polarization screen within 1.3 pc of the Sun in the upwind direction, and allows the possibility that the ISMF direction derived from the polarization data is sampling a different magnetic field than the Ribbon arc. Heliosphere models predict that the configuration of the IBEX Ribbon is sensitive to 20\(^\circ\) variations in the direction of the ISMF, so that a solar transition between the two field directions should be readily apparent in the configuration of the IBEX Ribbon (Frisch et al. 2010). The Ribbon models are not yet proven, and the uncertainties on the ISMF direction obtained from the polarization data are large. Nevertheless, it appears that the different ISMF directions obtained from the center of the Ribbon arc and starlight polarizations can provide information on the large-scale variations in the local ISMF, and ultimately on small-scale magnetic turbulence.

The local ISMF direction derived from polarization data can be used to test the possibility that the ISMF is perpendicular to the flow of ISM past the Sun. The interstellar cloud surrounding the heliosphere is part of a cluster of local interstellar cloudlets (CLIC) that has a mean flow velocity directed away from the center of the Loop I magnetic superbubble (e.g., Frisch et al. 2009). For comparing the kinematical CLIC with the geometrically defined configuration of Loop I, the interstellar velocities are first converted into the local standard of rest (LSR). The standard LSR conversion generally assumed for converting radio velocities to the LSR is used here, e.g., a solar apex velocity of 19.5 km s\(^{-1}\), 56\(^\circ\), 23\(^\circ\). The result is an LSR upwind direction for the CLIC that is toward \( \ell, b = 331^\circ, -5^\circ \), and an LSR upwind direction for the circumhelsiospheric cloud that is directed toward \( \ell, b = 318^\circ, 0^\circ \). Both of these directions are toward the central regions of Loop I. A value of \( \sim 71^\circ \) is found for the angle between the mean LSR flow velocity vector of the CLIC and the best-fitting ISMF direction from polarization data, \( \ell, b \sim 38^\circ, 23^\circ \). The ISMF direction is therefore nearly perpendicular to the cloud motions, similar to what might be expected for the expansion of an evolved superbubble shell in pressure equilibrium with ambient ISM. For the ISM around the heliosphere, the angle between the ISMF direction from the Ribbon arc and the heliocentric He\(^{0}\) flow vector is \( \sim 46^\circ \). The spatial regions sampled by starlight polarization and CLIC features are similar, since stars within 30–40 pc of the Sun are utilized in both comparisons. Additional information on magnetic turbulence in the flow of ISM past the Sun might be obtained from the Chandrasekhar–Fermi method, by comparing the velocity dispersion of clouds with the dispersion of polarization position angles (e.g., Andersson & Potter 2006).
There may be some contribution to the polarizations from interstellar grains in the outer heliosheath, which will tightly follow the ISMF that interacts with and is deflected around the heliosphere. The magnetic field upstream of the heliopause filters out grains with large charge-to-mass ratios, Q/M, and gyroradii that are smaller than the characteristic lengths between the heliosphere bow shock and heliopause (e.g., Slavin et al. 2010). The radii of the magnetically excluded grains are <0.01–0.1 μm, and are comparable to the sizes of interstellar polarizing grains (e.g., Mathis 1986). The strongest polarizations occur for stars located on the northern edge of the IBEX Ribbon, which is 15°–30° above the equator of the ISMF direction toward the arc center, corresponding to the blue points in Figure 5. For truly interstellar polarization and a uniform dust distribution, the strongest polarizations are expected at the equator of the ISMF, so perhaps additional contributions to starlight polarizations from nanosized grains in the heliosheath regions are possible.

The local ISMF direction found here has a curious coincidence with the cosmic microwave background (CMB) dipole (as found previously, Frisch 2007). The great circle midway between the hot and cold poles of the CMB dipole moment bifurcates the heliosphere nose region and is aligned with the direction of the local ISMF direction found here, to within the uncertainties. The ISMF direction of \( \ell, b \sim 38^\circ, 23^\circ \) is at an angle of 90° \( \pm 8^\circ \) from the dipoles at \( \ell, b = 264^\circ, +48^\circ \) and 83°, −48°.

4. CONCLUSIONS

In this exploratory study we find the best fit to the polarization position angles toward \( \sim 30 \) stars within 40 pc of the Sun and 90° of the heliosphere nose (16° above the galactic center), using mainly data from the literature, is \( \ell, b \sim 38^\circ, 23^\circ \) (or \( \lambda, \beta \sim 263^\circ, 37^\circ \), Table 1), with uncertainties of \( \pm 35^\circ \) based on the flat minimum of the best-fit direction. The ISMF direction indicated by the center of the IBEX Ribbon arc is \( \ell, b \sim 33^\circ, 55^\circ \). The difference between the two, \( \sim 33^\circ \), is marginally significant given the uncertainties. The sensitivity of the IBEX Ribbon to variations of \( \leq 20^\circ \) in the ISMF direction, and the fact that the Sun is in a cloud that is different from the nearest upwind ISM, support the possibility that the different ISMF directions obtained from the Ribbon and polarization data are tracking either large-scale distortion of the magnetic field direction, or possibly small-scale magnetic turbulence. This comparison is possible because the Ribbon is observed where the ISMF draping over the heliosphere is perpendicular to the sight line. Better constraints on the distortion of the ISMF in the solar vicinity will be possible once the formation of the ENA Ribbon is understood, and more high sensitivity polarization data toward the Ribbon are available.

There are several implications of the ISMF direction found here. The ISMF vector direction is perpendicular to the bulk LSR velocity of the cluster of local interstellar clouds flowing past the Sun, which is consistent with an origin in an evolved expanding magnetized superbubble shell. The similarity of the ISMF directions found from the ENA Ribbon and optical polarization data suggests that the nearby ISMF is coherent over scale sizes of decades in parsecs, and that variations in the ISMF direction due to large-scale distortion or magnetic turbulence are on the order of 35° or smaller. A curious coincidence is that the direction of the local ISMF is within 8° of the great circle that divides the hot and cold poles of the CMB dipole moment, which also passes through the heliosphere nose.

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