THE VELOCITY DISTRIBUTION OF THE NEAREST INTERSTELLAR GAS

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ABSTRACT

The bulk flow velocity for the cluster of interstellar cloudlets within \( \sim 30 \) pc of the Sun is determined from optical and ultraviolet absorption line data, after omitting from the sample stars with circumstellar disks or variable emission lines and the active variable HR 1099. A total of 96 velocity components toward the remaining 60 stars yield a streaming velocity through the local standard of rest of \( \sim -17.0 \pm 4.6 \) km s\(^{-1}\), with an upstream direction of \( l = 273, b = -5^\circ2 \) (using Hipparcos values for the solar apex motion). The velocity dispersion of the interstellar matter (ISM) within 30 pc is consistent with that of nearby diffuse clouds, but present statistics are inadequate to distinguish between a Gaussian or exponential distribution about the bulk flow velocity. The upstream direction of the bulk flow vector suggests an origin associated with the Loop I supernova remnant. Groupings of component velocities by region are seen, indicating regional departures from the bulk flow velocity or possibly separate clouds. The absorption components from the cloudlet feeding ISM into the solar system form one of the regional features. The nominal gradient between the velocities of upstream and downstream gas may be an artifact of the Sun’s location near the edge of the local cloud complex. The Sun may emerge from the surrounding gas patch within several thousand years.

Subject headings: ISM: structure — solar neighborhood

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1. INTRODUCTION

A number of studies have searched for correlations between the velocity of interstellar gas observed inside the solar system and toward external stars (Adams & Frisch 1977; McClintock et al. 1978; Lallement & Bertin 1992, hereafter LB92). Adams & Frisch (1977) showed that the velocity of interstellar gas inside the solar system differs by several kilometers per second from interstellar cloud velocities toward stars located in the upstream direction. The discovery that the \( \text{H}^0 \) \( \text{Ly} \alpha \) line is redshifted by several kilometers per second from the \( \text{D}^0 \) line toward the nearest star (\( \alpha \) Cen, 1.3 pc) confused the identification of the cloud velocity in this direction (Landsman et al. 1984). This shift has since been successfully modeled by including the \( \text{Ly} \alpha \) absorption from compressed \( \text{H}^0 \) in the heliosheath (Linsky & Wood 1996; Gayley et al. 1997). However, the heliosheath is observed only in the strong \( \text{Ly} \alpha \) line. The \( \text{D}^0, \text{Mg}^+, \) and \( \text{Fe}^+ \) line velocities toward \( \alpha \) Cen (roughly \( -19 \) km s\(^{-1}\); Lallement et al. 1995; Linsky & Wood 1996) disagree by \( \sim 2 \) km s\(^{-1}\) with interstellar gas and dust velocities found inside the solar system (e.g., Weller & Meier 1981; Witte, Banaszkiewicz, & Rosenbauer 1996; Flynn et al. 1998; Frisch et al. 1999) when projected toward \( \alpha \) Cen. Optical and ultraviolet (UV) data show that the bulk flow of the closest interstellar material (ISM) has an upstream direction toward the Loop I supernova remnant and a velocity of \( \sim 20 \) km s\(^{-1}\) in the local standard of rest (LSR; Frisch 1981, 1995; Crutcher 1982). This bulk flow is similar to ISM expanding around OB associations (e.g., Münch 1957). Following Slavin & Frisch (2002, hereafter SF02), the ISM within 30 pc is referred to as the complex of Local Interstellar Clouds (CLIC), while the cloudlet feeding ISM into the solar system is denoted the Local Interstellar Cloud (LIC). Optical Ca\(^+\) and UV absorption data show that the CLIC is inhomogeneous on subparsec scales and that multiple absorption components are present toward the nearest stars (e.g., Münch & Unsöld 1962; Ferlet, Vidal-Madjar, & Lallement 1986; Lallement, Vidal-Madjar, & Ferlet 1986; Lallement et al. 1994; Valeraga et al. 1993; Crawford & Dunkin 1995; Welty, Morton, & Hobbs 1996; Frisch 1995, 1996; Crawford, Craig, & Welsh 1997; Crawford, Lallement, & Welsh 1998). The kinematics of the CLIC provides the opportunity to probe the history of a diffuse cloud and the relevance of small-scale structure to ISM physics and to gauge the past and future Galactic environment of the Sun (Frisch 1997\(^1\)).

Nearby ISM provides a unique set of constraints for determining diffuse cloud physics. Observations of both pickup ions inside the solar system (formed by interactions of interstellar neutrals with the solar wind) and interstellar absorption lines toward nearby stars have been used to constrain the first full radiative transfer model of nearby ISM (SF02). These results indicate that the interstellar properties at the solar location are \( T \sim 7000 \) K, \( n(\text{H}^0) \sim 0.24 \) cm\(^{-3}\), \( n(\text{e}^-) \sim 0.13 \) cm\(^{-3}\), and fractional ionizations \( X(\text{H}) \sim 31\% \) and \( X(\text{He}) \sim 48\% \), with both density and ionization levels varying toward the cloud surface (model 17). The model includes emission from a conductive interface, which yields an excess of helium compared to hydrogen ionization (SF02). If the density \( n(\text{H}^0) \sim 0.24 \) cm\(^{-3}\) is typical for all cloudlets near the Sun, then \( N(\text{H} i) \) toward \( \alpha \) Cen (1.3 pc; Linsky & Wood 1996) suggests a filling factor \( f \sim 0.4 \). Enhanced refractory element abundances in warm nearby gas provide evidence that local ISM has been shocked (Frisch et al. 1999). The presence of cold Ca\(^+\) and Na\(^0\) absorption components (Doppler width \( b_p \leq 0.8 \) km s\(^{-1}\)) toward \( \alpha \) Pav (56 pc) and \( \delta \) Cyg (52 pc) indicates at least an order of magnitude variation for ISM temperatures within 50 pc (see references in Table 1).

The sensitivity of heliosphere properties (Zank & Frisch 1999)—and astrospheres in general (including extrasolar

\(^{1} \) Available at http://xxx.lanl.gov/ps/astro-ph/9705231.
| HD       | Name          | l   | b   | d   | Spectral Type | N(X)a | Velocity | dV/| (km s⁻¹) | References |
|----------|---------------|-----|-----|-----|--------------|-------|----------|----|----------|------------|
| 128621   | α CenB        | 315.7 | −0.7 | 1.4 | GLpl         | 3.89E17 | −18.9   | −3.8 | 1        |            |
| 48915    | α CMa         | 227.2 | −8.9 | 2.6 | A1 V         | 2.5E17 | 13.7   | −9.5 | 2        |            |
| 22049bc  | ε Eri         | 196.0 | −48.0 | 3.2 | K2 V         | 7.50E17 | 21.3   | −1.3 | 4        |            |
| 61421    | α CMi         | 213.7 | 13.0 | 3.5 | F5 IV/V      | 7.59E17 | 20.8   | −3.0 | 5        |            |
| 201092   | 61 CygA       | 82.3  | 8.3  | 3.5 | K5 V         | 7.08E17 | −9.0   | 0.0  | 6        |            |
| 209100   | ε Ind         | 336.2 | −48.0 | 3.6 | K4.5 V       | 1.00E18 | −9.2   | 1.5  | 7        |            |
| 26965    | 40 EriA       | 200.8 | −38.0 | 5.0 | K1 V         | 8.71E17 | 21.6   | −3.4 | 6        |            |
| 155886   | 36 OphAB      | 358.3 | 6.9  | 6.0 | K1 V/K0 V    | 7.08E17 | −28.4  | −1.2 | 8        |            |
| 187642   | α Aql         | 47.7  | −8.9 | 5.1 | A7 V         | 0.3E10 | −26.9  | −5.5 | 3        |            |
| 17216bc  | α Lyr         | 67.5  | 19.2 | 7.6 | A0 V         | 6.5E12 | −18.3  | −1.5 | 9        |            |
| 21695bc  | α PsA         | 20.5  | −64.9 | 7.7 | A3 V         | 3.8E12 | −3.2   | 3.3  | 10       |            |
| 17925    | EP Eri        | 192.1 | −58.3 | 10.4 | K2 V         | 8.9E17 | 19     | −0.3 | 11       |            |
| 62509    | β Gem         | 192.2 | 23.4 | 10.6 | K0 II        | 1.15E18 | 21.9   | −1.2 | 4        |            |
| 10264bc  | β Leo         | 250.6 | 70.8 | 11.0 | A3 V         | ...  | −0.8   | −0.3 | 9        |            |
| 34029    | α Aur         | 162.6 | 4.6  | 12.9 | G5 IIIipl    | 1.74E18 | 22.0   | −1.4 | 5        |            |
| 159561   | α Oph         | 35.9  | 22.6 | 14.3 | A5 III       | 1.00E11 | −23.6  | 1.9  | 12       |            |
| 203280   | α Cep         | 101.0 | 9.2  | 15.0 | A7 IV        | 0.7E10 | 0.2    | 1.8  | 13       |            |
| 432      | β Cas         | 117.5 | −3.3 | 16.7 | F2 IV        | 1.51E10 | 10     | 2.5  | 1        |            |
| 11443    | α Tri         | 138.6 | −31.4 | 17.5 | F6 IV        | 1.15E10 | 17.6   | 0.8  | 4        |            |
| 82443    | DX Leo        | 201.2 | 46.1 | 17.7 | K2 V         | 5.0E17 | 11     | −3.8 | 11       |            |
| 115892   | ε Cen         | 309.4 | 25.8 | 18.0 | A2 V         | 2.5E10 | −18.2  | −4.5 | 14       |            |
| 82558    | LQ Hya        | 244.6 | 28.4 | 18.3 | K2 V         | 5.62E18 | 6    | −6.2   | 11       |            |
| 39066bc  | β Pic         | 258.4 | −30.6 | 19.3 | A5 V         | ...  | −3.2   | −15.7 | 10       |            |
| 220140   | V368 Cep      | 118.5 | 16.9 | 19.7 | K2 V         | 8.9E17 | 5     | −0.6   | 11       |            |
| 12311    | α Hyi         | 289.5 | −53.8 | 21.9 | F9 V         | 2.88E10 | 9.8   | 7.3  | 14       |            |
| 139006   | α CrB         | 41.9  | 53.8 | 22.9 | A0 V         | 1.03E10 | −17.4  | 1.3  | 3        |            |
| 87901    | α Leo         | 226.4 | 48.9 | 23.8 | B7 V         | 0.50E10 | 10.5   | −0.3 | 3        |            |
| 156164   | δ Her         | 46.8  | 31.4 | 24.1 | A3 IV        | 3.1E10 | −19.7  | 2.7  | 3        |            |
| 74956    | δ Vel         | 272.1 | −7.4 | 24.4 | A1 V         | 0.86E10 | 15.6   | 10.0 | 15       |            |
| 106591   | δ UMa         | 132.6 | 59.4 | 25.0 | A3 V         | 0.91E10 | 3.8    | 1.6  | 3        |            |
| 40183    | β Aur         | 167.5 | 10.4 | 25.2 | A2 IVipl     | 1.01E10 | 22.3   | −1.3 | 3        |            |
| 177724   | ζ Aql         | 46.9  | 3.3  | 25.5 | A0 Vn        | 0.60E10 | −24.5  | −1.5 | 3        |            |
| 103287   | γ UMa         | 140.7 | 61.4 | 25.6 | A0 V         | 0.80E10 | 4.4    | 1.2  | 3        |            |
| 222107   | Λ And         | 109.9 | −14.5 | 25.8 | G8 III       | 2.81E18 | 6.5    | 1.6  | 7        |            |
| 18978    | τ3 Eri        | 213.5 | −60.3 | 26.4 | A4 V         | 2.00E10 | 15.9   | −1.7 | 16       |            |
| 108767   | δ CrV         | 295.5 | 46.1 | 26.9 | B9.5 V       | 3.4E10 | −0.5   | 7.9  | 17       |            |
| 22468    | HR 1099       | 184.9 | −41.6 | 29.0 | G5 IV/K1 IV  | 7.9E17 | 21.9   | −2.3 | 1        |            |
| 161868   | γ Oph         | 28.0  | 15.0 | 29.1 | A0 V         | 3.0E10 | −33.1  | −6.0 | 14       |            |
| 4128     | β Cet         | 111.3 | −80.7 | 29.4 | K0 III       | 5.9E16 | 1      | −5.3 | 1        |            |

**TABLE 1**

Velocity Components of Unrestricted Sample
| HD     | Name   | l     | b     | d     | Spectral Type | N(X) | Velocity | dV/(96) | References |
|--------|--------|-------|-------|-------|---------------|------|----------|---------|------------|
| 120418 | θ Peg  | 67.4  | −38.7 | 29.6  | A2 IV         | 3.0E10 | −4.2     | 4.6     | 15         |
| 358    | α And  | 111.7 | −32.8 | 29.8  | B8 IVp        | 1.99E10 | 13.0     | 6.2     | 15         |
| 8538   | δ Cas  | 127.2 | −2.4  | 30.5  | A5 III–IV     | 0.51E10 | 12.9     | 1.1     | 13         |
| 120315 | υ UMa  | 100.7 | 65.3  | 30.9  | B3 V          | 0.9E10  | −3.4     | 2.1     | 3          |
| 209952 | α Gru  | 350.0 | −52.4 | 31.1  | B7 IV         | 2.0E10  | 13.0     | −1.9    | 12         |
| 213558 | α Lac  | 101.3 | −6.6  | 31.4  | A1 V          | 1.0E10  | 3.5      | 3.4     | 13         |
| 88955  | HR 4023| 274.3 | 11.9  | 31.5  | A2 V          | 2.38E10 | −1.7     | −4.4    | 15         |
| 112413 | α2 CVn | 118.3 | 78.8  | 33.8  | A0 spe        | 0.51E10 | −1.9     | 2.2     | 18         |
| 177756 | Λ Aql  | 30.3  | −5.5  | 38.4  | B9 Vn         | 0.41E10 | −21.9    | 3.7     | 3          |
| 215789 | ε Gru  | 338.3 | −56.5 | 39.7  | A3 V          | 1.58E10 | −12.2    | −4.3    | 14         |
| 218045 | α Peg  | 88.3  | −40.4 | 42.8  | B9 III        | 0.8E10  | −4.7     | −3.2    | 3          |
| 1014Abd | α Eri  | 290.8 | −58.8 | 44.0  | B3 Vpe        | 0.50E10 | 18.9     | 16.2    | 12         |
| 141003 | β Ser  | 26.0  | 47.9  | 46.9  | A2 IV         | 1.0E10  | −16.7    | 5.5     | 3          |
| 212061 | γ Aqr  | 62.2  | −45.8 | 48.4  | A0 V          | 7.94E9  | −4.5     | 3.9     | 14         |
| 135742 | β Lib  | 352.0 | 39.2  | 49.1  | B8 V          | 0.8E10  | −33.7    | −10.1   | 3          |
| 106625 | γ Crv  | 291.0 | 44.5  | 50.0  | B8 IIIp       | 1.5E10  | 1.6      | 8.5     | 17         |
| 148857 | γ Oph  | 17.1  | 31.8  | 50.9  | A0 Vpl        | 4.7E10  | −24.8    | 1.5     | 3          |
| 160613 | β Ser  | 13.3  | 9.2   | 51.5  | A2 Va         | 5.6E10  | −29.0    | −0.9    | 3          |
| 222439 | κ And  | 109.8 | −16.7 | 52.0  | B9 IVn        | 1.1E10  | 0.8      | −4.2    | 18         |
| 186882 | δ Cyg  | 78.7  | 10.2  | 52.4  | B9.5 IV       | 2.8E10  | −18.8    | −6.9    | 17         |
| 62044  | β Gem  | 191.2 | 23.3  | 55.5  | K1 III        | 5.85E17 | 32.0     | 8.9     | 4          |
| 193924 | α Pav  | 340.9 | −32.5 | 56.2  | B2 IV         | 1.24E10 | −19.6    | −2.8    | 15         |
| 213998 | δ Aqr  | 66.8  | −47.6 | 56.3  | B9 IV–Vn      | 2.70E10 | −2.1     | 4.6     | 18         |
| 156928 | δ Ser  | 10.6  | 13.5  | 59.3  | A0/A1 V       | 4.4E10  | −27.7    | 0.4     | 3          |
| WD 0501+527 | G191–B2B | 156.0 | +7.1  | 68.8  | DAw           | 1.86E18 | 19.3     | −2.0    | 19         |
| 111812 | 31 Com | 114.9 | 89.6  | 90.9  | G0 II         | 7.66E17 | −2.4     | 3.2     | 4          |
| 52089  | ω CMa  | 239.8 | −11.3 | 132. | A1 V          | 4.0E17  | 9.2      | −10.2   | 20         |

_{Note:}—Table 1 is also available in machine-readable form in the electronic edition of the Astrophysical Journal.

^{a}_Column densities less than 10^{13} are for Ca+, and values greater than this are based on N(H i) measurements.

^{b}_Star omitted from restricted sample used for determining V_{flow}(93); see text.

^{c}_Star α Eri is the brightest known Be emission line star, with evidence of variable chromosphere and variable stellar radial velocities (Porri & Stalio 1988).

^{d}_Star with infrared excess indicating dust disk (e.g., Habing et al. 2001).

^{e}_Velocities are from GJ01 text and not GJ01 table.

References.—(1) Piskunov et al. 1997. (2) Hebrard et al. 1999. (3) P. C. Frisch & D. E. Welty 2002, in preparation. (4) Dring et al. 1997. (5) Linsky et al. 1995. (6) Wood & Linsky 1998. (7) Wood, Alexander, & Linsky 1996a. (8) Wood et al. 2000b. (9) Lallement et al. 1995. (10) Ferlet et al. 1995. (11) Wood et al. 2000a. (12) Crawford & Dunkin 1995. (13) LB92. (14) Crawford et al. 1997. (15) Crawford et al. 1998. (16) Bertin et al. 1993. (17) Welty et al. 1996. (18) Vallerga et al. 1993. (19) Sahu et al. 1999. (20) GJ01.
planetary systems; Frisch 1993)—to the physical conditions of the surrounding ISM motivates this exploration of small-scale structure in the nearby ISM using cloud velocity as a structure proxy. Understanding small-scale structure in the CLIC will also help decipher the signature that astrospheres structure proxy. Understanding small-scale structure in the surrounding ISM motivates this exploration of small-planetary systems; Frisch 1993)—to the physical conditions of the ISM within \( \sim 30 \) pc of the Sun. Anticipating a conclusion, the CLIC appears to consist of an ensemble of cloudlets at velocities consistent with a random distribution about a mean bulk flow velocity. The first results of this study were presented by Frisch (2001).

2. VELOCITIES OF ABSORPTION COMPONENTS

2.1. Method

In this analysis we assume that the motions of nearby interstellar clouds (i.e., the CLIC) in the LSR can be described by a linear flow vector \( V_{\text{flow}} \), which is characterized by the flow velocity and the Galactic coordinates of the direction from which the gas flows (implying that the flow velocity is less than 0). Our approach is to calculate a best-fitting flow vector for a set of observed interstellar cloud component radial velocities that sample interstellar gas within \( \sim 30 \) pc (§ 2.2) and then to determine the distribution of component velocities about this bulk flow vector. If the CLIC \( (d < 30 \) pc) is part of an expanding shell feature from Loop I (§ 3.1), it will subtend a total angle equivalent to about 10% of the expanding shell and yield less than 5% deviations from a linear flow velocity (i.e., \( \sim 1 \) km s\(^{-1}\) for uniform expansion). Therefore, over the scale length of the CLIC, the linear assumption is sufficient. The bulk flow velocity vector is determined from a fitting procedure that varies \( V_{\text{flow}} \) in order to minimize the sum, \( \Phi_m \), over \( m \) observed interstellar absorption line components, of the square of the difference between the projected flow and observed velocity toward each star; i.e., to minimize,

\[
\Phi_m = \sum_{i=1}^{m} dV_i^2 ,
\]

where

\[
dV_i = v_{i,\text{obs}} - V_{\text{flow}} \cdot \hat{k}_{\text{star}} .
\]

For a flow vector calculated from a set of \( m \) components \([V_{\text{flow}}(m)]\),

\[
dV_i(m) = v_{i,\text{obs}} - V_{\text{flow}}(m) \cdot \hat{k}_{\text{star}} .
\]

where \( dV_i(m) \) is the scalar radial velocity (at the solar location) of component \( i \) in the rest frame of \( V_{\text{flow}}(m) \). Here \( \hat{k}_{\text{star}} \) is the unit position vector toward each star and \( v_{i,\text{obs}} \) is the observed heliocentric (HC) radial velocity for an interstellar velocity component toward that star (here denoted \( i \), where \( i = 1, m \)). The fits were performed using the FindMin function in Mathematica, which determined the local minima of the function \( \Phi_m \) as a function of the three variables \( V, l, \) and \( b \) that define \( V_{\text{flow}} \). Note that since many stars show more than one interstellar absorption component, the number of components \( (m) \) is greater than the number of stars. An unweighted fit was employed since there is no obvious weighting function. Line broadening is not suitable since instrument resolutions and thermal broadening vary (artificially blending velocity components). Column densities are unsuitable since they vary between species. Note that since we are interested in the distribution of the deviation of component velocities in the rest frame of \( V_{\text{flow}} \), the component data set includes all measured components for each star. We find that this procedure yields a predicted flow velocity \( V_{\text{flow}} \), which is relatively insensitive to the detailed set of the selected velocity components, provided that sky coverage is good and that several stars with components at anomalous velocities are removed from the sample (next section).

In principle, the full three-dimensional flow vector \( V_{\text{flow}} \) is calculated correctly for cases in which the perturbations from the flow \( (dV_i) \) are random, since the Sun is immersed in the flow. Alternative cases in which perturbations in the flow have a directional dependence (or preference), or the flow is decelerated (Frisch 1995), are not considered here. However, we make an elementary attempt to identify systematic regional patterns in the velocity components.

2.2. Component Set and Bulk Velocity

The velocities of optical and ultraviolet absorption lines toward nearby stars, and toward more distant stars that sample primarily the CLIC gas, are used to evaluate the velocity distribution of the CLIC. Interstellar absorption line data for 67 stars that sample the CLIC are listed in Table 2, with component information in Table 1. This component set forms the “unrestricted sample.” A range of data sources was used in order to cover as much of the sky as possible. Observations of the optical interstellar Ca\(^+\) lines represent the primary source of cloud velocity data, but the optical data do not adequately sample the downstream region where column densities are low over the first \( \sim 30 \) pc [e.g., \( N(\text{Ca}^+) < \times 10^{10} \) cm\(^{-2}\); Bruhweiler & Kondo 1982; Frisch & York 1983; Frisch 1995; Lallement et al. 1995]. Observations of the intrinsically stronger UV lines of Fe\(^+\), Mg\(^+\), D\(^0\), and H\(^0\) are available for several stars in the downwind direction and toward the north Galactic pole (where column densities are also low).

The component sample results primarily from fits to optical and UV absorption lines observed at relatively high resolution \(<3 \) km s\(^{-1}\); medium-resolution UV data were used for a few stars. When both optical and UV data exist, the optical Ca\(^+\) data (resolution 0.5–3 km s\(^{-1}\)) are the first choice and the UV data the second choice since about 50% of the optical spectra were acquired with resolution FWHM < 1.5 km s\(^{-1}\). Component velocities are generally obtained from a process that iteratively fits each discernible component in the absorption-line profile with a population of atoms with a Maxwellian velocity distribution about the central component velocity, with a projection in the radial line of sight toward the Sun of \( v_{\text{obs}} \) (denoted \( v_{i,\text{obs}} \) in eqs. [2] and [3]). The number of components and the component descriptors (column density, \( v_{i,\text{obs}} \), and Doppler broadening constant \( b_d \)) are sensitive to instrument resolution, signal-to-noise ratio, and the judgment of the observer.

The component sample used here is not of uniform quality. For example, the star \( \alpha \) Oph (14 pc) has been observed at resolutions of 0.3 and 1.2 km s\(^{-1}\) by Crawford & Dunkin (1995) and Welty et al. (1996), respectively. The 0.3 km s\(^{-1}\) resolution profiles were fitted with four components with velocities \(-32.0 \pm 0.5, -28.4 \pm 0.3, -26.2 \pm 0.2, \) and \(-23.6 \pm 0.5\) km s\(^{-1}\). The 1.2 km s\(^{-1}\) resolution profiles were
fitted with three components with velocities $-33.03$, $-26.25$, and $-22.16$ km s$^{-1}$. While temporal variations in interstellar Ca$^+$ absorption profiles are seen in a few cases (e.g., Hobbs et al. 1991), comparisons between the two absorption profiles suggest that the component at $-28.4$ km s$^{-1}$ was unresolved in the lower resolution data.

The derived flow vector depends on the component set used in the fitting procedure, and the unrestricted sample is small enough that lines incorrectly identified as interstellar may alter the results. Therefore, the basic star sample was restricted to omit stars with either identified circumstellar disks or strong emission-line spectra (where misidentification of circumstellar features is possible). Thus, the stars $\epsilon$ Eri (3.2 pc), $\beta$ Pic (19.3 pc), $\beta$ Leo (11.0 pc), $\alpha$ Lyr (7.6 pc), and $\alpha$ PsA (7.7 pc), which have circumstellar disks identified at 60 $\mu$m (e.g., Habing et al. 2001), were omitted from the sample. Although interstellar components can in principle be distinguished from circumstellar disk components since stellar velocities are known, we considered the sample to be more reliable when stars with circumstellar disks are omitted. The emission-line star $\alpha$ Eri (44 pc) was also omitted, as it shows variable He$^+$ and Mg$^+$ chromospheric features indicating that weak circumstellar absorption features may be present. The active RS CVn variable HR 1099 (Wood et al. 1996b) was also omitted from the sample because the inclusion of the components toward this star yielded results that are inconsistent with fits toward the other stars (see below). With the above omissions, the remaining restricted sample consists of 60 stars with a total of 96 components. Star distances range from 1.3 ($\alpha$ Cen) to 132 pc ($\epsilon$ CMa). Components toward the two stars beyond 70 pc, $\epsilon$ CMa and 31 Com, were included because these stars primarily sample ISM within 30 pc (Gry & Jenkins 2001, hereafter GJ01; Dring et al. 1997) and fill a gap in the spatial coverage.

This basic component sample was fitted for the flow vector $V_{\text{flow}}$, yielding an HC vector $V_{\text{flow}}(96)$ with radial velocity $-28.1 \pm 4.6$ km s$^{-1}$, flowing from the upstream direction $l = 12^\circ.4$, $b = 11^\circ.6$. The uncertainty is the 1 $\sigma$ value of the velocity component distribution about the bulk flow velocity. Figure 1a shows the deviations $dV_{96}$ plotted against the stellar distance (omitting the two stars more distant than 70 pc). Note that 76 of these 96 components originate in the upstream direction, while the remaining components originate downstream, reflecting the higher column densities of nearby ISM found upstream (e.g., Frisch 1995).

The positions of the stars forming the 96-component set are plotted in Figure 2a. Most of the sky is well sampled, except for the interval $l = 150^\circ-180^\circ$ in the direction of the third Galactic quadrant void (also known as the Puppis window or the $\beta$ CMa tunnel), where mean interstellar column densities are low out to $\sim 100$ pc ($n_{H^1} < 0.003$ cm$^{-3}$). Figure 3a shows $dV_{96}$ as a function of the Galactic longitude of the star; no strong systematic spatial dependence is seen. For comparison, the LSR velocities of the 96 components [$dV_{\text{LSR}}(96)$] are plotted against Galactic longitude in Figure 3b, illustrating the expected behavior for an incorrect vector describing the flow. Throughout this paper we use the solar apex motion based on Hipparcos data, corresponding to a solar motion toward the Galactic coordinates $l = 27^\circ.7$, $b = 32^\circ.4$ at the velocity $V = 13.4$ km s$^{-1}$ (Dehnen & Binney 1998).

The robustness of $V_{\text{flow}}(96)$ was tested in several ways. The first test was to restrict the star sample to stars within 29 pc of the Sun (except for $\epsilon$ CMa and 31 Com, which sample the nearest ISM and are required for completeness in low column density directions). This restriction gives 46 components toward 31 stars. The best-fit HC flow vector for this 46-component sample, $V_{\text{flow}}(46)$, corresponds to an

### Table 2: Data Sources

| Reference | Nominal Resolution (km s$^{-1}$) | Star List |
|-----------|---------------------------------|-----------|
| Optical data: | | |
| P. C. Frisch & D. E. Welty 2002, in preparation | 1.3–1.5 | $\alpha$ CMa, $\alpha$ Leo, $\gamma$ UMa, $\gamma$ UMa, $\delta$ UMa, $\beta$ Lib, $\alpha$ CrB, $\lambda$ Oph, $\delta$ Her, $\nu$ Ser, $\beta$ Ser, $\sigma$ Ser, $\lambda$ Aql, $\zeta$ Aql, $\alpha$ Aql, $\beta$ Aur, $\alpha$ Peg |
| Crawford et al. 1998 | 0.35 | $\alpha$ And, $\delta$ Vel, $\delta$ Pav, $\theta$ Peg |
| Crawford et al. 1997 | 0.35 | $\alpha$ Hyl, $\zeta$ Cen, $\eta$ Gru, $\gamma$ Aqr, $\gamma$ Oph |
| Welty et al. 1996 | 1.2 | $\gamma$ Cyg, $\delta$ Cyg, $\epsilon$ Cyg |
| Crawford & Dunkin 1995 | 0.3 | $\alpha$ Oph, $\alpha$ Gru, $\alpha$ Eri |
| Vallerga et al. 1993 | 1.9 | $\alpha$ Cng, $\gamma$ Aqr, $\alpha$ And |
| Bertin et al. 1993 | 3.0 | $\gamma$ 3 Eri, HR 4023 |
| LB92 | 3.0 | $\alpha$ Cep, $\delta$ Cas, $\alpha$ Lac |
| Ultraviolet data: | | |
| GJ01 | 2.7 | $\epsilon$ CMa |
| Wood et al. 2000b | 2.7 | 36 Oph |
| Wood et al. 2000a | $\sim 15$ | EP Eri, DX Leo, LQ Hya, V368 Cyg |
| Sahu et al. 1999 | 2.7 | G191-B2B |
| Hebrard et al. 1999 | 2.7 | $\alpha$ CMa |
| Wood & Linsky 1998 | 3.5 | 61 Cyg, 40 Eri A |
| Dring et al. 1997 | 3.5 | $\epsilon$ Eri, $\beta$ Gem, $\alpha$ Tri, $\sigma$ Gem, 31 Com |
| Wood, Alexander, & Linsky 1996a | 3.5 | $\epsilon$ Ind, $\lambda$ And |
| Piskunov et al. 1997 | 3.5 | $\beta$ Cet |
| Ferlet et al. 1995 | 3.5 | $\alpha$ PsA |
| Linsky et al. 1995 | 3.5 | $\alpha$ CMi, $\alpha$ Aur |
| Lallement et al. 1995 | 3.5 | $\alpha$ Lyr, $\beta$ Leo, $\beta$ Pic |
upstream direction of \( l = 12^\circ 5, b = 12^\circ 5 \), with an inflow velocity of \( -28.1 \pm 4.3 \text{ km s}^{-1} \). The fact that \( V_{\text{flow}}(46) \) is virtually identical to \( V_{\text{flow}}(96) \) is not a coincidence, since the initial selection of stars in Table 1 was restricted to stars that did not appear to contain neutral ISM more distant than \( \sim 30 \) pc. The closeness of the \( V_{\text{flow}}(96) \) and \( V_{\text{flow}}(46) \) vectors supports the validity of eliminating HR 1099 from the component sample, since had HR 1099 been retained in the restricted sample the resulting fitted vector \([V_{\text{flow}}(96)]\) would have differed from \( V_{\text{flow}}(46) \) by 0.6 km s\(^{-1}\) and 2\(^\circ\).

The second test was a search for spatially correlated variations in \( dV_{\text{flow}}(96) \). Star positions are replotted in Figure 2b, with symbols coded for \( dV_{\text{flow}}(96) \). No systematic positional dependence appears for components with \( |dV_{\text{flow}}(96)| > 5 \text{ km s}^{-1}\). However, when the components with \( |dV_{\text{flow}}(96)| < 5 \text{ km s}^{-1}\) are plotted with symbols that code the sign of \( dV_{\text{flow}}(96) \), stars in the interval \( l = 150^\circ-250^\circ \) are found to show components with systematically small but negative \( dV_{\text{flow}}(96) \) values (Fig. 2c; note several components are overplotted). The best-fitting flow vector, \( V_{\text{flow}}(20) \), for the 20 components toward 14 stars located in the interval \( l = 150^\circ-250^\circ \) corresponds to a vector velocity \(-25.8 \pm 4.3 \text{ km s}^{-1}\) from the upstream direction \( l = 62^\circ, b = 10^\circ 4 \). If only a single component per star is selected for the fit, biasing toward components with small \( dV_{\text{flow}}(96) \) values, the resulting fitted vector \( V_{\text{flow}}(14) \) corresponds to a velocity \(-25.6 \pm 1.3 \text{ km s}^{-1}\) from the upstream direction \( l = 64^\circ, b = 13^\circ 1 \), which is close to \( V_{\text{flow}}(\text{He}) \) (Table 3, §3.3.1). The dispersion of the same 14 components around \( V_{\text{flow}}(\text{He}) \) is \( \pm 1.7 \text{ km s}^{-1} \). Gas near the LIC velocity (Table 3) dominates in the downwind direction \( (l \sim 180^\circ) \), as found previously. The LIC and other regional variations in \( V_{\text{flow}}(96) \) are discussed in §3.3.

2.3. Component Velocity Dispersion

The randomness of interstellar cloud velocities has long been of considerable interest, with early arguments presented for random motions of \( \sim 20 \text{ km s}^{-1} \) for interstellar particles (Spitzer 1942), compared to recent data showing rms velocity dispersions of \( \sim 0.5 \text{ km s}^{-1} \) in individual cold clouds. Early studies of diffuse cloud kinematics found an exponential distribution for cloud velocities, suggestive of a turbulent ISM (Blaaauw 1952; Münch 1957).

The functional form of the velocity distribution of the CLIC gas was tested, but the results prove inconclusive. A plot of the number of components (\( N \); ordinate) binned for a given value of \( dV_{\text{flow}}(96) \) (abscissa) is shown in Figure 4. Here \( N \) is determined with \( dV_{\text{flow}}(96) \) binned with 1 km s\(^{-1}\) bin sizes. The histogram is “noisy” because the sample is small.

For a purely random distribution of individual components about the central flow velocity \( V_{\text{flow}}(96) \), the form of the \( dV \) distribution should be Gaussian:

\[
\Psi(V) = \frac{c_{\text{g}}}{b\sqrt{\pi}} \exp\left(-\frac{(V - V_{\text{flow}})^2}{b^2}\right).
\]
The Blaauw (1952) and Münch (1957) results for Ca\(^+\) and Na\(^0\) lines, based on low-resolution data (FWHM > 5 km s\(^{-1}\)), are consistent with an exponential distribution for cloud velocities:

\[
\Psi(V) = \frac{c_e}{2\eta} \exp\left( -\frac{|V - V_u|}{\eta} \right),
\]

such as is expected for a turbulent flow. Here b = \(\sigma\sqrt{2}\), \(c_d\) and \(c_e\) are normalizing constants, and \(\sigma\) and \(\eta\sqrt{2}\) are the rms deviations of the Gaussian and exponential distributions, respectively.

The 96-component sample was tested for the distribution of \(dV(96)\), assuming alternatively Gaussian and exponential distributions. The best-fit Gaussian distribution yields \(b = 6.2\) km s\(^{-1}\), and the best-fit exponential distribution yields \(\eta = 5.1\) km s\(^{-1}\). The present data do not distinguish between these two distributions (see overplotted functions in Fig. 4). Blaauw concluded that an exponential function with mean speed \(\eta \sim 5 \pm 1\) km s\(^{-1}\) provided the best fit to Ca\(^+\) K line data toward 300 stars observed by Adams (1949) with instrumental resolution \(\sim 9\) km s\(^{-1}\). Münch inferred that an exponential form fitted observations of the Ca\(^+\) and Na\(^0\) doublets toward 112 stars, with \(\eta \sim 5\) km s\(^{-1}\) for Ca\(^+\) in the Orion arm and a somewhat smaller value for Na\(^0\). Münch concluded that turbulence dominates the velocity distribution of these components. These early low-resolution data undersampled blended components at low velocity and therefore probably enhance component statistics in the distribution wings with respect to the central region. It is therefore puzzling that we find a similar value from higher resolution data. This issue is discussed further in a subsequent paper (P. C. Frisch & D. E. Welty, in preparation 2002).

3. DISCUSSION

3.1. Upstream Direction and Loop I

The best-fit HC velocity vector, \(\mathbf{V}_{\text{flow}}(96)\), corresponds to a bulk velocity \(-28.1\) km s\(^{-1}\) flowing from the upstream direction \(l = 12\degree 4, b = 11\degree 6\) (\(\S 2.2\)). However, in order to compare \(\mathbf{V}_{\text{flow}}(96)\) with morphological features in the astronomical sky, the solar apex motion through the LSR must be subtracted. Subtracting the solar apex motion from

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TABLE 3
STREAMING MOTIONS IN HC AND LSR REST FRAMES

| PARAMETER | HC VECTOR | LSR VECTOR |
|-----------|-----------|------------|
|           | Velocity | l | b | Velocity | l | b | Sample |
|           | (km s\(^{-1}\)) | (deg) | (deg) | (km s\(^{-1}\)) | (deg) | (deg) |          |
| Bulk fits: |          |     |    |          |     |    |          |
| \(V_{\text{flow}}(96)\) |          |     |    | \(-17.0\) |     |    | 60 stars |
| \(V_{\text{flow}}(46)\) |          |     |    | \(-18.1\) |     |    | 31 stars, \(d < 29\) pc |
| Upstream: |          |     |    |          |     |    |          |
| \(V_{\text{flow}}(76)\) |          |     |    | \(-14.7\) |     |    | 46 stars |
| \(V_{\text{flow}}(G)\) |          |     |    | \(-18.1\) |     |    | G cloud (LB92) |
| Downstream, \(l = 150\degree -250\degree\): |          |     |    |          |     |    |          |
| \(V_{\text{flow}}(\text{He})\) |          |     |    | \(-14.7\) |     |    | 14 stars |
| \(V_{\text{flow}}(20)\) |          |     |    | \(-14.7\) |     |    | 14 stars |
| \(V_{\text{flow}}(584 \text{ Å})\) |          |     |    | \(-14.7\) |     |    | Backscattered He\(^0\) 584 Å (Flynn et al. 1998) |

\(^a\) Galactic coordinates correspond to upstream directions. The velocity uncertainty is the 1 \(\sigma\) value of the component distribution about the bulk flow velocity.

\(^b\) Based on Hipparcos solar apex motion (Dehnen & Binney 1998).

\(^c\) Sample stars are listed in Tables 1 and 2.

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The sinusoidal appearance shows that the ISM within 30 pc of the Sun is not near the rest velocity of the LSR (e.g., see also Frisch 1995).

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**Fig. 3.**—(a) \(dV(96)\) plotted against Galactic longitude for the restricted sample of stars. (b) \(dV(\text{He})\) plotted against Galactic longitude for same stars. The sinusoidal appearance shows that the ISM within 30 pc of the Sun is not near the rest velocity of the LSR (e.g., see also Frisch 1995). (c) \(dV(\text{He})\) plotted against Galactic longitude for same stars.
$V_{\text{flow}(96)}$ gives a "true" upstream direction (in LSR) in Galactic coordinates of $l = 2^{3}/3$, $b = -5^{5}/2$, with flow velocity $-17.0$ km s$^{-1}$. The $V_{\text{flow}(96)}$ upwind direction is shown plotted against the filamentary H$^0$ structure associated with Loop I (21 cm data; Fig. 5; Hartmann & Burton 1997).)

The position of the radio continuum Loop I shell, defined from the discovery 408 MHz radio continuum data, is marked (from Berkhuijsen 1971; Haslam et al. 1982).

Low column densities in the CLIC components [$N(H) < 10^{18.5}$ cm$^{-2}$, typically] prevent linking CLIC velocities to individual features in the 21 cm H$^0$ sky maps. The relation between the flow of interstellar gas past the Sun and the Loop I superbubble has been discussed from several viewpoints (e.g., Frisch 1979, 1981, 1995; Crutcher 1982; Crawford 1991; de Geus 1992). The Loop I superbubble remnant (the brightest segment of which is the North Polar Spur) is centered near $l = 320^\circ$, $b = 5^\circ$, with distance $\sim 130$ pc and radius $\sim80^\circ$ (based on H$^0$ 21 cm data; Heiles 1998). The radio continuum Loop I is centered at $l = 329^\circ$, $b = 17^\circ5$, radius $58^\circ$, and is strongly limb brightened in the tangential direction near $l = 35^\circ$ (Berkhuijsen 1973). The center of Loop I defined from H$^0$ data is offset from the radio continuum center by $\sim15^\circ$. The H$^0$ shell shows a polar cap at $v_{\text{LSR}} \sim -30$ km s$^{-1}$ and $l \approx 300^\circ$, $b \approx -10^\circ$ (Heiles 1989), where the cold component seen at $-19.6$ km s$^{-1}$ toward $\alpha$ Pav may originate (Table 1). This expansion velocity implies a projected velocity of approximately $-14$ km s$^{-1}$ for the $V_{\text{flow}(96)}$ LSR upwind direction, versus the best-fit LSR velocity of $-17.0$ km s$^{-1}$. The filamentary structure and likely asymmetric expansion of the H$^0$ shell make it difficult to identify the approaching portion of the H$^0$ shell, so the $\sim 20\%$ difference between the projected polar cap velocity and the LSR bulk velocity of the CLIC gas possibly is within uncertainties. However, the H$^0$ shell regions traced by the 21 cm polar cap emission are denser and colder than the CLIC gas appears to be. Alternatively, models of

![Diagram](https://example.com/diagram.png)
shell expansion from the Sco-Cen association Upper Scorpius subgroup place an H\(^0\) shell with LSR velocity approximately \(-22\) km s\(^{-1}\) and age \(\approx 4\) Myr at the solar location (Crawford 1991; de Geus 1992; Frisch 1995).\(^3\)

### 3.2. Comparison with Previous Models

The bulk flow of nearby interstellar gas has been determined from optical absorption lines observed toward nearby stars (primarily Ca\(^+\); e.g., Crutcher 1982; Frisch 1986, 1995, 1997; Lallement et al. 1986; LB92; Vallerga et al. 1993). The velocity vectors determined from these earlier studies are summarized in Table 4 and shown in Figure 7. Since column densities in the downstream direction are low [log \(N(H^0)\) < 18 cm\(^{-2}\)], optical lines do not easily sample this interval. This causes bulk flow vectors based primarily on Ca\(^+\) data to be strongly weighted toward upstream gas and quite sensitive to the details of the star sample. The inclusion of UV data provides an adequate sample of downstream gas, but at lower resolution (3 km s\(^{-1}\)). LB92 used UV data to identify the ISM in the downstream direction, denoting it the “anti-Galactic” (AG) cloud (Table 4), which is the same as the LIC. ISM identified in the upstream direction, generally toward the Galactic center hemisphere, was denoted the “Galactic” (G) cloud (Table 4). The velocity difference between the G and AG clouds is smaller than found by Adams & Frisch (1977), based on backscattered Ly\(\alpha\) \(H^0\) data, because of the deceleration and compression of \(H^0\) in the heliosheath regions (which was unknown in 1977). LB92 concluded that either the Sun is located in a patch of gas with velocity intermediate between the G and AG clouds or \(H^0\) is decelerated in the heliosheath (or both). The \textit{Ulysses} He and 584 A\(^\circ\) backscattering data confirm the velocity of ISM inside the solar system, so that the general velocity difference between the upstream and downstream ISM is real. However, the fact that the velocities of CLIC cloudlets are consistent with a random distribution about the mean bulk flow velocity suggests that the upstream/downstream velocity gradient locally displayed by the G versus LIC vectors may be an artifact of the location of the Sun with respect to the “edge” of the CLIC complex. Alternatively, the presence of a blueshifted cloud toward CMa (Lallement et al. 1994; GJ01) is also consistent with a velocity gradient.

For comparison with the LB92 G-AG two-flow model, a separate bulk flow velocity was calculated for downstream components. The 20 LIC components originating in the interval \(l = 150^\circ-250^\circ\) were removed from the 96-component sample. The fit to the resulting 76 components yields \(V_{flow}(76) = -29.3 \pm 4.0\) km s\(^{-1}\), from HC upstream direction \(l = 13.1^1, b = 11.2^2\). The velocities of \(V_{flow}(76)\) and the G vector \([V_{flow}(G)]\) coincide, although the upstream directions differ by \(\approx 12^\circ\). The observed 3.5 km s\(^{-1}\) difference between \(V_{flow}(76)\) and \(V_{flow}(20)\) and the near coincidence of upward directions (within \(\approx 8^\circ\)) suggest a deceleration of the bulk flow. The two-flow model with the two vectors \(V_{flow}(20)\) and \(V_{flow}(76)\) [or alternatively with \(V_{flow}(He)\) and \(V_{flow}(G)\)] is not a unique description of CLIC gas. For example, the velocity dispersion of \(V_{flow}(76)\) is about equal to the difference between the \(V_{flow}(76)\) and \(V_{flow}(20)\) velocities (\(\approx 4\) km s\(^{-1}\)). The second shortcoming is that six stars in the \(l = 150^\circ-250^\circ\) interval show two absorption components, and the second components are not accommodated by the two-flow model. The dispersion of the entire 20 components about \(V_{flow}(96)\) is 5.4 km s\(^{-1}\). The dispersion around \(V_{flow}(He)\) of the 14 components best matching the LIC velocity (1.5 km s\(^{-1}\)) is only slightly better than the dispersion of these components about \(V_{flow}(96)\) (1.6 km s\(^{-1}\)).

### 3.3. Regional Properties

The small filling factor of nearby ISM, combined with the component distribution, led to attempts to understand the positions of nearby “cloudlets” (e.g., Lallement et al. 1986; Frisch 1996), the clouds toward \(\alpha\) Oph and \(\alpha\) Aql (Münch & Unsöld 1962; Frisch 1981; Ferlet et al. 1986), and the “shape” of the cloud around the solar system (Frisch 1996; Redfield & Linsky 2000). These earlier approaches used velocities grouped in either the observed HC velocity or the LIC velocity. Here we use an alternative approach and evaluate cloud membership in the rest frame of \(V_{flow}(96)\). Using the \(dV(96)\) values, we identify regional clumps of ISM based on similar \(dV(96)\) values for stars sampling a relatively compact region of the sky, except for the LIC, which is identified by \(dV(He)\) [or \(dV(20)\)]. The component groups that appear to represent subsets of the flow are listed in Table 5 and are discussed in order below. The positions of the clouds are plotted in Figure 6 as symbols overlying star positions.

#### 3.3.1. Cloud Surrounding the Solar System

The velocity of the interstellar cloud surrounding the solar system, the LIC, has been determined from observations of the resonance fluorescence of the 584 Å transition from interstellar He\(^0\) inside the solar system (e.g., Weller & Meier 1981; Flynn et al. 1998) and from \textit{Ulysses} in situ.

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3 Note that the age given for the most recent shell-forming event should be 4 Myr, not 400,000 yr (Frisch 1995).

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**Table 4**

| Vector             | \(V\) (km s\(^{-1}\)) | \(l\) (deg) | \(b\) (deg) | Basis             | Reference |
|--------------------|-----------------------|-------------|-------------|-------------------|-----------|
| Crutcher (C)........| -28±2                 | 25          | +10         | Optical Ti\(^+\), \(d < 100\) pc stars | 1         |
| Frisch & York (FY) | -27                   | 34          | +15         | Optical Ca\(^+\), \(d > 100\) pc stars | 2         |
| LIC ..................| 26±1                  | 6±3         | 16±3        | Ca\(^+\)          | 3, 4      |
| G .....................| 29                    | 4.5         | 20.5        | Ca\(^+\)          | 4         |
| Frisch (F)..........| -26.8±1.3             | 6.2         | 11.7        | Ca\(^+\), \(d < 50\) pc stars | 5         |
| Bulk flow (BF).....| -28.1±4.6             | 12.4        | 11.6        | UV, optical       | 6         |

References.—(1) Crutcher 1982. (2) Frisch & York 1986, pp. 83–100. (3) LB92. (4) Bertin et al. 1993. (5) Frisch 1995. (6) This paper.
measurements of interstellar He$^0$ (Witte et al. 1996). Since
the trajectories of interstellar H atoms inside the solar system
are subject to radiation pressure, these He$^0$ data yield
the best LIC velocity. The Ulysses GAS detector data give $V_{\text{flow}}(\text{He}) = -25.3 \pm 0.5 \text{ km s}^{-1}$, $l = 3\text{9}° \pm 1\text{0}$, $b = 15^\circ8 \pm 1^\circ3$ (and $T = 6550 \pm 1050$ K) for the HC
upstream direction (Witte et al. 1996; M. Witte 2001, private communication), which is within the uncertainties of the He$^0$ 584 Å backscattered radiation vector (Flynn et al. 1998). When this He motion is converted to a vector in the LSR using the Hipparcos solar apex motion (Dehnen & Binney 1998), the upstream direction corresponds to a velocity of $-14.7 \text{ km s}^{-1}$, arriving from the upwind direction $l = 345^\circ9$, $b = -1^\circ1$. In the LSR, this differs by $-2 \text{ km s}^{-1}$ and $20^\circ$ in direction from the bulk velocity vector. Pure deceleration of the flow would not alter the upstream direction, so shear motions may be present in the bulk flow.

Copernicus, IUE, and Hubble Space Telescope (HST) observations of interstellar D$^0$, Fe$^+$, and Mg$^+$ toward $\alpha$ Cen (1.3 pc) indicate an HC velocity for the ISM in the range $-17.7 \pm 0.1$ to $-18.2 \pm 0.1 \text{ km s}^{-1}$, versus the value $-16.1 \text{ km s}^{-1}$ predicted by the projection of the Ulysses vector

(Levshakov et al. 1994; Lallement et al. 1995; Linsky & Wood 1996). This difference has been interpreted as indicating that the cloud surrounding the solar system terminates within $\sim 10,000$ AU of the Sun in the direction of $\alpha$ Cen. The $\alpha$ Cen cloud shows $dV_{\text{flow}}(\text{He}) \sim -2.8 \text{ km s}^{-1}$ [and $dV_{\text{flow}}(\text{He}) \approx -3.8 \text{ km s}^{-1}$]. This evidence for a cloud boundary close to the Sun in the direction of $\alpha$ Cen is consistent with column densities measured toward the nearest stars, which indicate that less than 40% of space is filled with ISM for volume density $n(H^0) \sim 0.24 \text{ cm}^{-3}$ as found for the LIC (SL02).

A total of 30 CLIC components have velocities consistent with the velocity of interstellar He inside the solar system $[V_{\text{flow}}(\text{He})]$ using the criterion $|dV_{\text{flow}}(\text{He})| < 1.5 \text{ km s}^{-1}$. However, components toward stars beyond 15 pc (Fig. 1b) have predominantly negative $dV_{\text{flow}}(\text{He})$ values since these stars are generally located in the upstream direction. The stars showing these 30 $V_{\text{flow}}(\text{He})$ components are distributed relatively uniformly across the sky (Fig. 2d). Refitting the 30 components essentially reproduces $V_{\text{flow}}(\text{He})$ and does not alter the distance dependence, suggesting that the more distant components with $|dV_{\text{flow}}(\text{He})| < 1.5 \text{ km s}^{-1}$ either are blends of local and distant gas or are formed in independent cloudlets with no local contribution. The five stars within 15 pc with $V_{\text{flow}}(\text{He})$ components are $\alpha$ CMa (2.7 pc), 61 CygA (3.5 pc), $\epsilon$ Ind (3.6 pc), 40 EriA (5 pc), and $\alpha$ Aur (13 pc). The UV absorption lines toward $\alpha$ CMa (3.5 pc) have been fitted with both single-component and two-component models (Linsky et al. 1995). With the single-component fit (Table 1), $dV_{\text{flow}}(\text{He}) = 1.8 \text{ km s}^{-1}$; however, $dV_{\text{flow}}(20) = 0.5 \text{ km s}^{-1}$, so that $V_{\text{flow}}(20)$ provides a better fit for local gas toward this star. (A second component redshifted by $2.6 \text{ km s}^{-1}$ [with $\sim 50\%$ of the column density of the main component] is not coincident with either flow vector.)

The velocity vector of the cloud within the solar system provides poor agreement with the restricted sample of 96 components, as seen in Figure 3c, where $dV_{\text{flow}}(\text{He})$ is plotted for all 96 components. The fact that $|V_{\text{flow}}(\text{He})| < |V_{\text{flow}}(96)|$ yields the effect that nearby ISM in the downstream direction is blueshifted in the rest frame of $V_{\text{flow}}(96)$.

Several studies have noted the small distance to the upstream cloud edge for the ISM surrounding the solar system (<10$^4$ AU; e.g., LB92). The relative Sun-cloud velocity

![](image.png)
Wood, Linsky, & Zank 2000b). The LIC is reliably identified only in the $l = 150^\circ$–$250^\circ$ interval where slightly more distant gas is absent, and in this interval $V_{\text{flow}}$(He) is an excellent descriptor of component velocities. The inability to identify the LIC reliably in sideline and upstream directions indicates that the two-flow model must be evaluated with caution in most sight lines, and in particular where velocity information is unavailable. In addition, since the CLIC represents a cluster of comoving clouds with a velocity dispersion of $\sim 5$ km s$^{-1}$, simple closed surface LIC models that can be topologically deformed to a sphere may not realistically represent the LIC cloudlet.

3.3.2. Other Regional Component Groups

3.3.2.1. Blue Cloud

The “blue cloud” (BC) has been identified toward $\alpha$ CMa and $\epsilon$ CMa, placing the cloud within 3 pc of the Sun (Lallement et al. 1994; Hebrard et al. 1999; GJ01). The BC has $V_{\text{BC}}(96) \sim -10$ km s$^{-1}$ and is blueshifted from the LIC by $\sim 6.5$ km s$^{-1}$. The filling factor of the LIC toward $\alpha$ CMa is $f \sim 0.3$, suggesting that the BC is a spatially separate feature. Toward $\alpha$ CMa the BC appears to be cooler and denser than the LIC (Hebrard et al. 1999), while toward $\epsilon$ CMa it appears warmer and denser than the LIC (GJ01).

3.3.2.2. Aquila-Ophiuchus Cloud

The Aquila-Ophiuchus cloud (AOC) is disclosed by a set of Ca$^+$ components with $V_{\text{AOC}}(96) = -6.1 \pm 0.9$ km s$^{-1}$ toward stars located in the interval $l = 28^\circ$–$48^\circ$, $b = -5^\circ$ to $23^\circ$. The stars $\alpha$ Aql, $\alpha$ Oph, $\zeta$ Aql, $\gamma$ Oph, and $\lambda$ Aql show the AOC component, and the 5.1 pc distance of $\alpha$ Aql places the cloud close to the Sun. For each of these five background stars, the component formed in the AOC is the weakest and most blueshifted component seen toward the star. The similarity between the AOC velocity and the velocity of weakest and most blueshifted component toward $\delta$ Cyg [$V_{\text{AOC}}(96) = -6.9$ km s$^{-1}$] may be a coincidence since the $\delta$ Cyg component originates in a cold cloud ($b_\text{HI} = 0.47$ and 0.42 km s$^{-1}$ for Ca$^+$ and Na$^+$, respectively; Welty et al. 1996), and cold clouds are not expected within 5 pc. The AOC is located near the solar apex direction, $l = 277^\circ$, $b = 32^\circ$. If the unobserved tangential velocity component is $\sim 0$ km s$^{-1}$, the Sun may encounter this cloud within the next $\sim 160,000$ yr. Components from this cloud are seen clearly in Figure 3a.

3.3.2.3. Pegasus-Aquarius Cloud

The Pegasus-Aquarius cloud, with $V_{\text{Peg}}(96) = 4.2 \pm 0.5$ km s$^{-1}$, is seen toward stars grouped in the interval $l = 75^\circ$ $\pm 13^\circ$, $b = -44^\circ$ $\pm 5^\circ$. Background stars are $\theta$ Peg, $\alpha$ Peg, $\gamma$ Aqr, and $\eta$ Aqr, and this cloud must be within 30 pc of the Sun.

3.3.2.4. North Pole Cloud

A group of components with velocity $1.7 \pm 0.6$ km s$^{-1}$ is found toward stars at high Galactic latitudes, $b > 53^\circ$, including the Ursa Majoris region. The nearest star with a component in this group is $\alpha$ CrB, at 23 pc.

3.3.2.5. South Pole Cloud

A cloud with $V_{\text{flow}}(96) = 2.4 \pm 1.0$ km s$^{-1}$ occupies an irregularly shaped region covering the south Galactic pole ($b \leq 48^\circ$). The south pole cloud (SPC) is seen toward $\epsilon$ Ind, $\alpha$ Hyi, $\tau$ Eri, and $\beta$ Cet. However, two of these components (toward $\epsilon$ Ind and $\beta$ Cet) also have $|V_{\text{flow}}(\text{He})| < 0.1$ km s$^{-1}$, indicating that they also could be formed in the LIC (which is seen toward two other low-latitude stars, 40 Eri and EP Eri). If so, the SPC is not a separate cloudlet. The nearest star in this sample is $\epsilon$ Ind at 3.6 pc, indicating that the SPC, if real, is quite nearby. Additional data are required to test for the SPC.

3.3.2.6. Filamentary-like Feature

Perhaps the most puzzling of the component groups suggests a filamentary structure, with $V_{\text{flow}}(96) = 6.9 \pm 1.5$ km s$^{-1}$. Since this feature has a large angular extent ($\sim 90^\circ$: Fig. 6), it represents a single cloudlet only if the tangential (unobserved) velocity is $\sim 0$ km s$^{-1}$ for all of the stars, similar to a fragment of an expanding ring. This feature is at $l = 284^\circ \pm 12^\circ$, $b = -4^\circ \pm 50^\circ$, and it is seen toward $\delta$ CrV, $\gamma$ CrV, HR 4023, $\delta$ Vel, and $\alpha$ Hyi.

4. CONCLUSIONS

The principal conclusions of this paper are as follows:

1. The bulk flow velocity for interstellar matter within $\sim 30$ pc of the Sun is determined from optical and UV absorption line data. A self-consistent flow vector is determined if stars with infrared-emitting circumstellar disks ($\epsilon$ Eri, $\beta$ Pic, $\beta$ Leo, $\alpha$ Lyn, and $\alpha$ PsA), variable emission lines ($\alpha$ Eri), and HR 1099 are omitted from the sample. Fits to the remaining 96-component sample (60 stars) yield a bulk flow velocity [$V_{\text{flow}}(96)$] through the LSR (using Hipparcos data on the solar apex motion) of magnitude $-17.0$ km s$^{-1}$, with an upstream direction of $l = 23^\circ$, $b = -52^\circ$ (Table 3, Fig. 7). In the HC velocity frame (i.e., with respect to the Sun), $V_{\text{flow}}(96)$ = 28.1 km s$^{-1}$, approaching from the direction $l = 124^\circ$, $b = 11^\circ$ (the $\sigma$ velocity uncertainty is $\pm 4.6$ km s$^{-1}$, based on the component distribution about the bulk flow velocity).

2. The CLIC gas is defined by this ensemble of velocity components, which show a Gaussian or exponential distri-
bution in the rest frame of the central flow velocity, and the dispersion of this distribution is typical for dispersions determined from lower resolution observations of diffuse clouds. The dispersion in the velocities of the individual CLIC components partaking in the bulk flow explains the difference between the velocity of the interstellar cloud inside the solar system (25.3 km s\(^{-1}\), HC) and the overall bulk flow velocity (–28.1 km s\(^{-1}\), HC).

3. This LSR upstream direction suggests that the CLIC gas may be part of a superbubble shell expanding from the Loop I supernova remnant or from an earlier epoch of superbubble formation in the Sco-Cen association. The cold absorption component formed in the polar cap of Loop I appears to be present in front of α Pav.

4. The velocity of the interstellar cloud observed inside the solar system and in the downstream direction toward nearby stars \(V_{\text{flow}}(\text{He})\) differs from both \(V_{\text{flow}}(96)\) and the velocity of ISM toward the nearest star α Cen. However, 85% of the observed components consistent with \(V_{\text{flow}}(\text{He})\) are probably formed in unrelated parts of the CLIC. This complexity suggests that simple smooth closed-surface models for local interstellar gas are unlikely to be accurate in detail. The components within 1.5 km s\(^{-1}\) of the velocity of interstellar He within the solar system \(V_{\text{flow}}(\text{He})\) dominate the Galactic longitude interval \(l = 150° - 250°\), suggesting a deceleration of the flow in the third Galactic quadrant. The Sun is likely to emerge from the gas patch now surrounding it within the next several thousand years.

5. Several spatially distinct groups of components sharing a common \(dV_f(96)\) suggest that the bulk flow is composed of cloudlets (Table 5), including the previously known LIC and BC in the downstream direction. Distinct cloudlets in the upstream direction include the AOC with components at \(dV_f(96) \approx -6\) km s\(^{-1}\). This cloud may extend within 5 pc of the Sun since it is seen toward α Aql. Components in this cloud form the weakest and highest velocity Ca\(^+\) component for each star in which it is observed. This cloud is in the solar apex direction, and if the nonradial component of the cloud velocity is small, the Sun will encounter this cloud in less than 200,000 yr. A distinct cloud is seen toward Pegasus/Aquarius, at \(dV_f(96) = 3.8 \pm 0.3\) km s\(^{-1}\). Another distinct cloud is found within 22 pc toward the north Galactic pole, with \(dV_f(96) = 1.7 \pm 0.6\) km s\(^{-1}\).

6. These results show that the kinematics of CLIC components is consistent with early studies showing macroscopic turbulence in the ISM within ~500 pc (Blauw 1952; Münch 1957). Low filling factors for nearby ISM (<40%) and mean cloudlet speed \(\gamma \approx 5\) km s\(^{-1}\) in the flow reference frame \(V_{\text{flow}}(96)\) suggest that the CLIC is a cluster of comoving cloudlets. If this velocity dispersion is due to turbulence (as the larger samples considered by Blaauw and Münch suggest), then it is distinct from the microscopic turbulence that broadens absorption lines toward nearby stars \((b\gamma = 2kT/m + 2\nu^2_{\text{turb}},\text{where } V_{\text{turb}} \sim 1\) km s\(^{-1}\)).

7. A two-flow model of the velocity components is not a unique description of CLIC gas. For example, the velocity dispersion of \(V_{\text{flow}}(76)\) is about equal to the difference between the \(V_{\text{flow}}(76)\) and \(V_{\text{flow}}(20)\) velocities (~4 km s\(^{-1}\)). In addition, multiple components in the downstream gas are not accommodated by a two-flow model. The result is that morphological models of the LIC must include velocity information for accurate results.

Studies of the CLIC, where individual cloudlets can be studied in high-resolution UV data and in some sight lines in optical data, offer the best opportunity for reliably determining the relation between the kinematical and spatial characteristics of diffuse interstellar clouds.

*Note added in manuscript.*—The bulk flow vector presented here is consistent with the results of Bzowski (1988).

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