The galactic environment of the Sun

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Short title: GALACTIC ENVIRONMENT OF THE SUN
Abstract. The interstellar cloud surrounding the solar system regulates the
galactic environment of the Sun and constrains the physical characteristics of the
interplanetary medium. This paper compares interstellar dust grain properties observed
within the solar system with dust properties inferred from observations of the cloud
surrounding the solar system. Properties of diffuse clouds in the solar vicinity are
discussed to gain insight into the properties of the diffuse cloud complex flowing past the
Sun. Evidence is presented for changes in the galactic environment of the Sun within
the next $10^4$–$10^6$ years. The combined history of changes in the interstellar environment
of the Sun, and solar activity cycles, will be recorded in the variability of the ratio of
large- to medium-sized interstellar dust grains deposited onto geologically inert surfaces.
Combining data from lunar core samples in the inner and outer solar system will assist
in disentangling these two effects.
1. Introduction

The interstellar cloud surrounding the solar system regulates the galactic environment of the Sun and constrains the physical characteristics of the interplanetary medium enveloping the planets. In addition, the daughter products of the interaction between the solar wind and the interstellar cloud surrounding the solar system, when compared with astronomical data, provide a unique window on the chemical evolution of our galactic neighborhood, reveal the fundamental processes that link the interplanetary environment to the galactic environment of the Sun, and constrain the history and physical properties of one sample of a diffuse interstellar cloud. The combined history of variability in the solar galactic environment and activity cycles will be recorded in the variability of the ratio of large- to medium-sized interstellar dust grains deposited onto geologically inert surfaces within the solar system and, if this record could be accessed (and has not been destroyed), will witness the journey of the Sun through space. Oort cloud comets will sweep up pristine interstellar dust outside of the heliosphere.

The first effort to identify the interstellar cloud feeding gas and dust into the solar system found a difference of several kilometers per second between the velocity of the nearest interstellar gas in the upwind direction and interstellar gas inside the solar system identified spectrally by H$^\circ$ Lyman -$\alpha$ backscatter radiation [Adams and Frisch, 1977]. We now know that this discrepancy is due to a velocity gradient across the complex of interstellar clouds surrounding the solar system (section 5), possibly reflecting its fractal nature (section 4). On the basis of evidence of shock-front destruction of dust grains in nearby interstellar material, and the fact that the bulk velocity of the local interstellar matter (LISM) is consistent with the outflow of interstellar matter (ISM) from the Loop I superbubble (a curved radio-emission feature seen in the galactic center hemisphere of the sky; section 4), I concluded that interstellar matter inside and immediately outside of the solar system was part of an expanding superbubble shell around Loop I [Frisch, 1981, 1996]. On the basis of detailed models of star formation
in the Scorpius-Centaurus Association, the superbubble shell formed with the creation of the Scorpius subgroup appears to have expanded to the location of the Sun [De Geus, 1992; Frisch, 1995]. Alternative explanations place the Sun at the boundary of two merged superbubbles [e.g., Egger, 1998], but this alternative fails to explain the flow of nearby ISM from the Scorpius-Centaurus region. The conclusion that enhanced gas-phase abundances of refractory elements (Ca, Fe, Mg) in nearby interstellar clouds is caused by grain destruction in shock fronts is now supported by detailed calculations (see section 2). The recent successes of the Ulysses and Galileo dust detectors (see following section) in observing the mass distribution of “typical” interstellar dust grains have now opened new possibilities for understanding interstellar dust.

The interstellar cloud in which the solar system is currently embedded, also known as the local interstellar cloud (LIC, see section 5), is low density and warm \( n(\text{H}^0+\text{H}^+) \sim 0.3 \text{ cm}^{-3}, T \sim 6900 \text{ K} \). The physical properties of the cloud around the solar system, including temperature, electron density and magnetic field strength, have been summarized elsewhere [e.g., Frisch, 1990; Lallement, 1998] and are listed in Table 1. The interplanetary environment is subject to the physical conditions of the cloud surrounding the solar system, and currently \( \sim 98\% \) of the diffuse gas within the heliosphere (by number) is interstellar, with the densities of the solar wind and interstellar matter equal near the orbit of Jupiter.

Today, the solar wind effectively prevents most interstellar atoms, low-energy cosmic rays (energy/nucleon \( \leq 300 \text{ MeV} \)), and small dust grains from reaching the inner solar system. Over the history of the solar system the outer planets, comets, and Kuiper Belt objects are more likely to be immersed in pristine interstellar material than are inner objects. It has been shown that if the density of the surrounding cloud increases moderately, both the properties of the heliosphere and the density of \( \text{H}^0 \) and \( \text{He}^0 \) in the inner solar system change dramatically. For instance, if the density of the surrounding cloud is increased to \( n_\text{H}=10 \text{ atoms cm}^{-3} \) (above the current value of \( n_\text{H} \sim 0.3 \text{ atoms} \))...
cm$^{-3}$; Table 1) the termination shock contracts to 10–14 AU upstream and is highly dynamical, while the density of H$^+$ increases to $\sim$2 cm$^{-3}$ at 1 AU [Zank and Frisch, 1999]. Arguments about the fractal nature of the interstellar medium, within the boundaries set by the global structure imposed by forces shaping cloud morphology, predict maximum density contrasts of $\sim$10$^4$ within a cloud complex [Elmegreen, 1998]. If similar density contrasts are present in the cloud complex sweeping past the Sun, the interplanetary medium at Earth orbit potentially could change dramatically on short timescales.

2. Comparison of Gas and Dust in the Local Interstellar Cloud

Comparisons of interstellar dust grains observed within the heliosphere by the Ulysses and Galileo spacecraft [e.g., Baguhl et al., 1996; Landgraf, this issue; Landgraf et al., this issue] with interstellar dust properties inferred from observations of gas in the LISM [Frisch et al., 1999] provide a unique tool that can be used to probe the origin and evolution of interstellar dust grains, to constrain galactic chemical evolution, and to evaluate the behavior of interstellar dust in the inner heliosphere were the Sun to encounter a denser interstellar cloud. Interstellar dust grain models have been formulated to predict the extinction and polarization of optical starlight by interstellar dust grains and do not tightly constrain the numbers and properties of large dust grains (radius $a_{gr} \geq 0.3$ $\mu$m) [e.g., Mathis, this issue; Witt, this issue; Kim et al., 1994; Li and Greenberg, 1997], so that spacecraft observations of interstellar dust with $a_{gr} \geq 0.3$ $\mu$m add new information to our understanding of interstellar dust. The bulk of the discussion in this section is taken from Frisch et al., [1999] (hereinafter referred to as F99).

The population of dust grains found in interstellar space includes grains with a range of mass, charge, size and composition properties [e.g., see Witt, this issue; Mathis, this issue] and each population interacts differently with the heliosphere. The derivation
of the mass distribution of inflowing interstellar dust grains from in situ spacecraft observations relies on modeling the interaction of these grains with the heliosphere and heliosheath regions. Very small ($a_{gr}<0.01\ \mu m$) charged interstellar dust grains are excluded by Lorentz force interactions with the compressed interstellar magnetic field (when present) in the heliosheath region between the heliopause (HP) and bow shock (F99). (In this paper, all conversions between grain mass and radii are made assuming spherical grains with density 2.5 g cm$^{-3}$, giving $m_{gr} \sim 10.5\ a_{gr}^3$, where $a_{gr}$ is measured in centimeters.) Grains with mass $m_{gr}<10^{-14}\ g$ ($a_{gr}\leq0.1\ \mu m$) are excluded by Lorentz force interactions with the solar wind, while the spatial distribution within the heliosphere of somewhat larger grains is modulated by the solar wind cycle [see Landgraf, this issue; Mann and Kimura, this issue]. The strength of the interstellar magnetic field in the interstellar cloud surrounding the solar system is not known, and if the field strength is zero, the Lorentz force deflection of very small grains in the “hydrogen wall” pileup will not be effective. In this case, alternative filtering mechanisms within the heliosheath and outer heliosphere regions occur, but the distribution of small dust grains in the outer heliosphere and heliosheath regions will differ distinctively from the case where the interstellar magnetic field strength is nonzero.

Comparisons between the gas-to-dust mass ratio value ($R_{g/d}$) derived from the in situ versus astronomical data provide insight into the reference abundance for the interstellar medium and grain history. The in situ value yields $R_{g/d}=94^{+46}_{-38}$, from comparisons of the mass of interstellar dust grains observed by the Ulysses and Galileo satellites with the gas mass densities for the surrounding interstellar cloud. However, since small grains ($a_{gr}\leq0.1\ \mu m$) are excluded from the inner heliosphere where the data were acquired, the true value of $R_{g/d}$ for the cloud material flowing into the heliosphere should be smaller than this value. The exception to this conclusion would be if small and large dust grains are not mixed homogeneously in space, because of grain processing within molecular clouds, in the cloud disruption process, and in diffuse gas [Witt, this
The gas-to-dust mass ratio can also be found from observations of absorption lines in nearby stars. Grain mass builds up in molecular clouds by the accretion of gas atoms onto the surfaces of small grains (which have most of the surface area of interstellar grains and are negatively charged so that ions will stick) [e.g., Weingartner and Draine, 1999]. The dust mass of a cloud can then be determined by applying a “missing mass” argument, which is based on the assumption that the sum of the atoms of a given element in the combined gas and dust phase is equal to the “reference abundance” of that atom. This logic is developed and applied to observations of the cloud surrounding the solar system, in order to determine the gas-to-dust ratio from astronomical data (F99). In principle, comparisons between the spacecraft and astronomical results should allow the reference abundance of the gas to be removed as a variable if this logic is correct. In reality, the disruption of the molecular cloud that is parent to the cloud surrounding the solar system occurred millions of years ago, and the application of this argument requires the assumption that gas and dust in the cloud have remained closely coupled over this time (by collisions and coupling to an embedded magnetic field) with no new grains captured in the expanding material.

The gas-to-dust mass ratio in the LIC cloud, based on observations of interstellar absorption lines in the ultraviolet region of the spectrum and observed in the spectrum of the star $\epsilon$ CMa, is larger than the ratio based on the spacecraft data, with the exact value depending on the assumed reference abundance, which is unknown. If solar reference abundances are assumed, $R_{g/d}=427^{+72}_{-207}$ for the LIC, while $R_{g/d}=551^{+61}_{-251}$ if B-star reference abundances are assumed. In either case, the gas-to-dust mass ratios derived from in situ versus astronomical observations of the LIC differ by large amounts. (The quoted uncertainties on the astronomical determinations represent $2\sigma$ or better uncertainties (see F99).) These differences suggest that the interstellar dust grains observed in situ include a population which has not exchanged dust with the LIC-gas,
thereby invalidating the missing-mass argument. This extra population may be dust particles from any source, including circumstellar material, which has a separate history from the LIC. For example, any population of dust grains captured by a magnetic field embedded in the moving LIC cloud (which is moving through space at \( \sim 19 \) km s\(^{-1}\)) would not have exchanged atoms with the LIC and therefore would enrich the dust population and invalidate the missing-mass argument. Alternatively, the metallicity of the LISM may be inhomogeneous.

The classic view for ISM reference abundances in the solar neighborhood is that solar abundances apply (even though the Sun has long since decoupled from its parent protosolar nebula). More recently, it has been shown that a wide range of abundances are found in solar type stars \([Edvardsson et al., 1993]\), and that reference abundances for both ISM and young B-stars appear to be metal-poor in comparison with solar values \([Snow, this issue; Mathis, this issue]\). If the reference abundances for metals are reduced, that leaves intrinsically less mass for the formation of interstellar dust grains, in comparison with assumed solar abundances, when missing-mass arguments are invoked \([e.g., Savage and Sembach, 1996]\) (hereinafter referred to as SS). The dust grain core-mantle composition can be inferred by assuming that the grain core composition is the same as the grain composition found for the most weakly depleted clouds observed, which are typically in the direction of halo stars. After the core composition is subtracted from the grain mass, the remaining material in the grains is then attributed to the grain mantles (SS). This logic depends on the missing-mass argument, which effectively argues that the total mass of any seed grains injected from either asymptotic giant branch stars (AGBs) or supernova is negligible over the lifetime of the grain population.

Over 80\% of refractory elements Mg and Fe in the interstellar medium are condensed onto dust grains, and the refractories found in the gas phase result from the destruction of dust grains by sputtering in shock fronts \([Jones et al., 1996]\). The high abundances of
refractory elements in shocked clouds indicates that sputtering of refractory-rich small grains occurs in shocks (although the small grain population also reforms from the shattering of large grains) [Jones et al., 1996]. The gas-phase abundances of Fe, Mg, and Si in the velocity component corresponding to the LIC velocity projected toward \( \epsilon \) CMa, which is believed to be the interstellar cloud surrounding the solar system, indicate grain destruction of the parent dust grains by a shock of velocity of 100–200 km s\(^{-1}\). The relatively good correlation between the Mg and Fe column densities in the LISM gas indicates Fe and Mg originate from destruction of the same dust component. (The “column density” of an element is the number of atoms seen in a column that has a cross-section of 1 cm\(^{-2}\) and a length equal to the distance of the background star. The units of column density are per square centimeter.) In the LIC, comparison between gas-phase abundances (using \( \epsilon \) CMa data) and grain core (SS) models indicates that the destroyed mantle material was silicon rich in comparison with the cores. The lack of Si in LIC dust indicates grain mantles have been mostly eroded. The enhanced abundance of refractories in the LIC are also consistent with cosmic-ray acceleration models which require small refractory-rich dust grains \((a_{gr} \sim 0.1 \mu m)\) to be accelerated and destroyed by shocks in order to provide the initial injection of refractory atoms into shocks for acceleration up to cosmic-ray energies [e.g., Ellison et al., 1997]. (Volatiles are accelerated to cosmic-ray energies directly from the gas phase.)

If a significant fraction of the LIC dust mass is contained in small and very small dust grains, such as found elsewhere in the ISM, then the discrepancy between the \( R_{g/d} \) value determined from in situ and astronomical data is exacerbated. Alternatively, it is possible that the shock front which destroyed the small grains, and returned the refractory elements to the gas-phase, entirely removed these small grains. Grains with radii \( a_{gr} > 1 \mu m \) survive in interstellar shocks because of the underabundance of particles capable of fragmenting them [e.g., Jones et al., 1996]. This scenario would explain the relatively large mass of interstellar grains observed by the spacecraft.
3. The LIC Among Diffuse Clouds

The interstellar cloud surrounding the solar system is part of a complex of diffuse interstellar clouds flowing past the Sun, and an analogous system should be present elsewhere in the galaxy. The identification of a LIC-type diffuse cloud toward an external star is more likely in regions which either have been disturbed by star formation and supernova activity or which show high-velocity clouds from infalling halo gas, causing low column density components to be separated in velocity from other clouds in the sight line. (High spectral resolution observations are required to resolve individual velocity components in complex sight lines, which in turn mandates a relatively bright background star with minimal reddening by foreground interstellar dust.) Such rapidly moving clouds have long been known to show enhanced abundances of refractory elements \cite{Routly1952}, a property shared by the LIC \cite{Frisch1981, Bertin1993, Gry1996, Gry1995}.

The identification of a cloud is based on fitting an absorption line formed by an ensemble of interstellar atoms (or ions) in the cloud with a Maxwellian velocity distribution, characterized by a kinetic temperature and turbulent velocity. Improvements in instrumental spectral resolution when observing cold clouds always reveal additional clouds unresolved at lower spectral resolutions. (For instance, at a resolution of 0.5 km s$^{-1}$, $\sim$40\% of the clouds contributing to Na° absorption lines are missed because of blending with adjacent velocity components \cite{Welty1993}.) In warm diffuse gas this may not be the case since the velocity dispersion increases and theoretical line widths are about 8 times as wide as in the cold gas. Low column density velocity components are always difficult to identify, unless they are separated in velocity from adjacent components or are seen in a nearby star.

LIC-type clouds were originally identified as high-velocity clouds in halo stars. For example, the halo star HD 215733 \cite{Fitzpatrick1997} shows warm and diffuse clouds. Component 5, at $-54$ km s$^{-1}$, has $T=7000\pm4100$ K and log $N$(H°)=19.63.
cm$^{-2}$. The electron density is $n(e^-)=0.05$ cm$^{-3}$, based on the ionization equilibrium of Ca$^+$. If the electron density is instead found from the collisional excitation of C$^+$, $n(e^-)=0.0014-0.095$ cm$^{-3}$ (depending on the detailed assumptions). In this component, the depletion of Mg is comparable to depletions in the LIC toward the stars $\alpha$ Aur, $\alpha$CMi, and GD191-B2B (e.g., F99), however the total column density is larger than the LIC value. Component 2, at $-83$ km s$^{-1}$, has a kinetic temperature comparable to the LIC, $T=6000^{+5000}_{-3100}$ K and log $N$(H$^\circ$))=18.40 cm$^{-2}$. Many absorption lines are too weak to be visible in this weaker component. The LIC has less Fe depletion than either components 2 or 5, indicating the LIC is one of the least depleted sight lines [e.g., Gry and Dupin, 1996; Dupin, 1998].

The group of diffuse cloud components found in front of 23 Orionis samples a region disturbed by an expanding superbubble shell (although it is younger than the $\sim4$ million year old shell near the Sun). A recent study of this sight line by Welty et al. [1999] presents puzzling contradictions in our understanding of diffuse clouds. Two cloud complexes dominate the sight line: the “weak low velocity” (WLV) and the “strong low velocity” (SLV) groups. The column densities of the WLV and SLV groups are log $N$(H$^\circ$)=19.61 cm$^{-2}$ and log $N$(H$^\circ$)=20.71 cm$^{-2}$, respectively. The WLV cloud complex yields insight into LIC-type clouds, although it is cooler (possible temperature $\sim3000$ K), higher column density, and more depleted than the LIC.

Welty et al. [1999] have shown that no unique electron density can be derived for these clouds, with different methods yielding different values. For the WLV complex, the ionization equilibrium for C, Na, and Mg gives values ranging from $n(e^-)=0.11$ to 0.22 cm$^{-3}$ (for $T=3000$ K). The properties of each individual component within the WLV complex vary, preventing the determination of $n$(H$^\circ$), and intrinsically weak spectral features cannot be observed in this component because of low column densities. The higher column density SLV cloud complex is not a good model for the LIC but illustrates the limitations of our understanding. The SLV is denser ($n_H\sim10-15$ cm$^{-3}$)
than the LIC, and \(\sim 1\%\) ionized, with less than 1\% of the gas in the form of molecular hydrogen. For the SLV, evaluating the ionization equilibrium of 12 separate elements yields electron density values ranging from \(n(e^-)=0.04\) to 0.95 cm\(^{-3}\). The puzzling result that a consistent electron density is not found from different methods indicates either that we do not yet understand the physics of diffuse clouds or that atomic or rate constants are wrong. On the basis of observations of the 23 Orionis sight line, LIC-type clouds are not expected to have molecular material.

4. Time-Variable Galactic Environment of the Sun

The galactic environment of the Sun changes with time. In the rest velocity frame defined by the average motion of cool stars in our neighborhood of the galaxy (the “local standard of rest,” or LSR), nearby interstellar material is sweeping past the Sun from the galactic center hemisphere. Hence the solar environment during the next few years will be dominated by the physical properties of nearby gas in this hemisphere of the sky.

The LSR space motion of the LIC cloud can be found by removing the vector motion of the Sun through the LSR. The solar motion has been rederived recently using precise astrometric data from the Hipparcos satellite, giving a new solar velocity of 13.4 km s\(^{-1}\) toward galactic longitude and latitude 28\(^\circ\), +32\(^\circ\) [Dehnen and Binney, 1998]. This new value represents a significant change from the previous value (see footnotes to Table 1) and is not skewed by velocities of very young stars (which may retain the motion of the parent molecular cloud) or very old stars (which lag galactic rotation).

The morphology, flow direction, and dust grain destruction evident in the LISM suggest that the cloud complex is part of a superbubble shell associated with star-formation in the Scorpius-Ophiuchus Association [Frisch, 1995] (hereinafter referred to as F95). Within the global morphological structure set by the boundary conditions on a given volume of interstellar material, the ISM is fractal with a fractal dimension characteristic of turbulence [Elmegreen, 1998]. The fractal structure allows density
contrasts over short spatial scales.

The galactic environment of the Sun over the past several \( \sim 10^6 \) years has been dominated by two types of material, both of which should have yielded a heliosphere with about the same dimensions. Within the past \( \sim 10^5 \) years the Sun emerged from the hot low-density interior of the Local Bubble and entered the cloud complex now sweeping past the Sun from a direction near the central region of the expanding Loop I superbubble. The absence of neutrals within the Local Bubble, combined with high temperatures, indicates the heliosphere was large in that region, providing solar wind characteristics were similar to today. More recently, the Sun was probably in the warm “blue-shifted” cloud seen toward Sirius and \( \epsilon \) CMa, although the three-dimensional space trajectory of this cloud is unknown. These two regions have pressure characteristics yielding heliosphere radii of \( \sim 130 \) and \( \sim 120 \) AU, providing the solar wind was unchanged from today [Frisch, 1999]. An early statistical analysis of the distribution of diffuse and molecular interstellar clouds concluded that over its lifetime, a typical disk star such as the Sun would have encountered over 16 dense interstellar clouds with radii \( \geq 3 \) pc and density \( n_H > 10^3 \) cm\(^{-3}\), with more frequent encounters with clouds of lower densities [Talbot and Newman, 1977]. An encounter with a molecular cloud would produce severe changes in the heliosphere and accretion of ISM onto solar system surfaces. Dust grains would accrete directly onto outer solar system surfaces, such as on moons, comets, and Kuiper Belt objects. The number of interstellar dust grains successfully deposited onto these surfaces provides a record of the combination of the solar galactic environment and activity cycles. The ratio of large to small dust grains in the deposits provides a measure of stellar activity cycles. In addition, cometary surfaces will accrete interstellar dust and the size distribution of accreted grains will be a function of the orbital parameters.

The distribution of nearby interstellar material \((d<30\) pc\) is highly asymmetric; there is an an order of magnitude more material within 30 pc of the Sun in the galactic-center hemisphere, from which the material is flowing, than is found in the
anticenter hemisphere. This distribution is also skewed, so that nearby stars at high galactic latitudes have little foreground ISM \((N(\text{H}) \sim 10^{18}\ \text{cm}^{-2})\), while stars at low galactic latitudes \((b < -30^\circ)\) generally show more nearby gas \((N(\text{H}) \sim 10^{18.6}\ \text{cm}^{-2})\).

A body of observations indicates that 10–15% of cool diffuse interstellar gas is contained in very small dense structure. Multiepoch observations of the H\(^\circ\) 21-cm line in absorption against high-velocity pulsars show structure with scale-sizes 5–100 AU and inferred densities of \(10^3–10^5\ \text{cm}^{-3}\) [Frail et al., 1994]. Both members of binary star systems have been observed in search of spatial variations in the optical interstellar Na\(^\circ\) D lines, also indicating diffuse cloud density variations on small scales. The ubiquitous presence of small \((<7000\ \text{AU})\) dense \((>10^3\ \text{cm}^{-3})\) structures in cold interstellar gas is supported by the these optical data [Meyer and Blades, 1996; Watson and Meyer, 1996]. Ultraviolet observations in \(\mu\) Cru find that Zn\(^+\) (which is undepleted and traces both the H\(^\circ\) and H\(^+\) column densities) does not vary between the binary components, so that the small-scale variations in Na\(^\circ\) and other neutrals do not represent changes in the total amount of material present. Pockets of cooler and denser material, with enhanced recombination, would explain the neutral enhancements [Lauroesch et al., 1999]. Limits on the density \(n_{\text{H}} < 50\ \text{cm}^{-3}\), for temperature \(\sim 100\ \text{K}\), were derived from the absence of C\(^\circ\) fine-structure lines. The pressure equilibrium of these tiny dense structures is not understood because the geometry is unknown, but they would be pressure equilibrium in two-component systems where the second component is somewhat warmer than the tiny cold structures [Heiles, 1997].

Small-scale high-density ionized components are found near large loops of radio continuum emission (such as Loop I) and are consistent with postshock, radiatively cooled gas with electron density \(\sim 500\ \text{cm}^{-3}\) and sizes \(\sim 20\ \text{AU}\) [Heiles, 1997].

In the LISM cloud complex, observations of the nearest stars indicate that about one velocity component is seen per 1.7 pc; toward \(\alpha\) Aql at 5 pc, three clouds are seen [Ferlet et al. 1986] and toward Sirius at 2.7 pc, two clouds are seen [Bertin et al.,...
In the direction of \( \epsilon \) CMa, which samples the same nearby gas as Sirius, the second interstellar cloud is slightly cooler (\( T=3800 \) K versus \( T=7200 \) for the LIC) and somewhat denser (electron density \( n(e^-)=0.46 \) cm\(^{-3} \)) than the LIC [Gry et al., 1995]. The second cloud toward \( \epsilon \) CMa, with log column density \( \log N(H_\odot)=16.88 \) cm\(^{-2} \), would be impossible to observe in distant regions unless the cloud is well separated in velocity from other material in the sight line. The ISM (\( Fe^+ \), \( Mg^+ \), \( D_\odot \)) in the spectrum of \( \alpha \) Cen, 1.3 pc from the Sun (and near the LSR upwind direction of the LISM flow), is not moving with the LIC cloud velocity, suggesting the LIC has a boundary within 10,000 AU of the Sun in this direction (see next section).

The bulk of the LISM cloud complex will be flowing past the solar location during the next 10\(^6 \) years, with the first transition of a cloud “boundary” within 3000 years if the LIC and solar velocities are correctly identified. Therefore a worthy question is whether small dense structures, similar to those found in cool ISM, might be embedded in the LISM gas. This question cannot be answered by existing observations. Limits on the presence of small dense structures can be placed by assuming that the LISM is a fractal cloud, within the confines of its overall morphology (e.g., a superbubble shell expanding from the Scorpius-Centaurus Association). The maximum density contrast expected for a fractal medium is \( \sim 10^4 \) [Elmegreen, 1998], which when compared to the \( n_H=0.3 \) cm\(^{-3} \) of the LIC gives a maximum density for a fractal component of \( n_H=300 \) cm\(^{-3} \) (where \( n_H \) is the cloud density). Also, \( n_H \times L < 10^{19} \), where \( L \) is the length of the fractal structure, and the upper limit is set by the approximate maximum column density of \( H_\odot \) through the LISM gas complex in the upwind direction. With this constraint, the upper limit on the sizes of the densest possible fractal structures in the LISM would be \( L<0.01 \) pc. Lower density structures could be larger. An encounter with a dense structure cannot be ruled out observationally, and a structure of this size, moving at \( \sim 15 \) km s\(^{-1} \), would pass over the Sun in less than 700 years. Such a cloud would shrink the heliosphere radius by an order of magnitude.
5. Velocity Gradient in LISM

The velocity of the interstellar gas immediately surrounding the solar system (the LIC) is found from observations of He\textsuperscript{o} within the solar system (Table 1) [Witte et al., 1996; Flynn et al., 1998]. However, the bulk flow of nearby ISM differs slightly and can be found from the ensemble of observations of interstellar gas in nearby stars, where a dispersion of \(\sim 2\) km s\(^{-1}\) about the bulk flow velocity is found (see below).

Bulk cloud motions derived from optical interstellar absorption lines are subject to uncertainties because of line weakness in some directions and higher column densities in the galactic center hemisphere where individual clouds usually are not spectrally resolved. Observations of the nearest star \(\alpha\) Cen show several velocity components (interstellar clouds) within 1.4 pc of the Sun in this direction, and limits on gas at the LIC velocity place the boundary of the LIC in this direction at less than 10,000 AU [Landsman et al., 1984, 1986; Lallement et al., 1995; Linsky and Wood, 1996].

The bulk motion of the LISM cloud complex has been determined by observations of interstellar Ca\textsuperscript{+} absorption lines in nearby stars (see references of F95). The average LISM flow, in the velocity rest frame of the Sun, corresponds to an inflow velocity \(-26.8\) km s\(^{-1}\) from the position \(l=6.2^\circ, b=+11.7^\circ\) (galactic coordinates), without distinguishing any velocity between the upwind and downwind directions. This corresponds to a bulk LISM LSR motion of \(-15\) km s\(^{-1}\), from the direction \(l=344^\circ, b=-2^\circ\), for the new Hipparcos value for the solar motion (see Table 1 for other values). This average motion for nearby interstellar clouds provides a better description for the LISM than does the assumption that nearby clouds are at rest in the LSR, as can be seen in Figure 1 and Figure 2. Data on Ca\textsuperscript{+} absorption lines in 17 nearby stars show 36 absorption line components (see \url{http://xxx.lanl.gov/astro-ph/9705231}, hereinafter referred to as F97, for data sources). In Figures 1 and 2 only one interstellar absorption Ca\textsuperscript{+} component for each of the 17 stars is plotted in two separate reference frames. The abscissa gives the component velocity in the LSR rest frame, while the ordinate gives the component
velocity in the heliocentric local flow velocity frame. In Figure 1 the plotted component is selected to be the component which has the smallest velocity in the local flow velocity frame. These 17 components have an average velocity in the local flow frame of $-0.05 \pm 2.24$ km s$^{-1}$ (1$\sigma$ dispersion). In Figure 2 the plotted component is selected to be the component which has the smallest velocity in the LSR; an average velocity of $-5.46 \pm 9.82$ km s$^{-1}$ is found. From these plots it is immediately obvious at least one cloud in front of these stars is moving at the local flow velocity, and this flow velocity provides a better description of LISM cloud kinematics than does the assumption that these clouds are at rest in the LSR.

Small regional deviations from an average local flow vector have been interpreted as indicating the presence of separate clouds (e.g., the “LIC” versus the “G” cloud components) [Lallement and Bertin, 1992], perhaps indicating a velocity gradient. The gradient is such that nearby interstellar matter in the galactic-center hemisphere is moving toward the LIC gas at a relative velocity of about 3 km s$^{-1}$. The LIC may represent the deceleration of the leading edge of the LISM cloud complex as it expands into the hot pressurized plasma interior to the Local Bubble (F95). Turbulence, associated with the fractal nature of the ISM, may also explain the observed velocity dispersion of $\pm 2.24$ km s$^{-1}$ about the flow velocity. If the LISM gas is warm, the cloud-cloud velocity differences are subsonic.

These velocities and dispersions can be compared with the average mass-weighted LSR velocity of molecular clouds found in the solar vicinity, of $2.9 \pm 0.6$ km s$^{-1}$, where the uncertainty represents 1$\sigma$ (F97). In contrast, it has been shown that globally, diffuse clouds with enhanced abundances of the refractory Ca have much larger velocity dispersions (average velocity $0.9 \pm 11.3$ km s$^{-1}$ in the LSR) [Vallerga et al., 1993] than do cool clouds, so the general property of rapidly moving warm clouds with enhanced refractory abundances is a global characteristic of the ISM. Given the relatively rapid space motions of diffuse clouds with enhanced refractory abundances, and the large
dimensions associated with evolved superbubbles, it is not surprising that the Sun is currently located in warm material with enhanced refractory abundances. The LISM bulk motion originates in a region near the center of the H$^\circ$ 21-cm shell forming the Loop I superbubble ($l,b=320^\circ, +5^\circ$) [Heiles, 1998], supporting the view that this material represents an outflow from the Scorpius-Centaurus Association.

6. Interstellar Micrometeorites

Interstellar micrometeorites with masses $\sim 10^{-6.5}$ g have been detected by radar measurements of ionospheric ion trails; these micrometeorites have inflow directions preferentially concentrated in the southern ecliptic hemisphere [Taylor et al., 1996; Baggaley, this issue; Landgraf et al., this issue]. The total mass of the detected micrometeorites is a significant fraction of the dust mass in the LIC (for particle velocities of 25–50 km s$^{-1}$). The distribution of nearby interstellar gas is asymmetric, and the regions of highest nearby column densities are found in the southern hemisphere (in both ecliptic and galactic coordinates). For example, the total column densities toward the stars $\eta$ UMa (ecliptic coordinates $\lambda,\beta=150^\circ, +48^\circ$) and $\alpha$ Gru ($\lambda,\beta=317^\circ, -33^\circ$) are $N$(H)$\sim 10^{18}$ cm$^{-2}$ and $N$(H)$\sim 10^{19}$ cm$^{-2}$, respectively. Both stars are located 31 pc from the Sun, but in opposite hemispheres. Therefore both nearby ISM distribution and the micrometeorite fluxes show the same broad spatial asymmetries, suggesting that the micrometeorites may be spatially related to the interstellar cloud complex which is flowing past the Sun. This comparison is not a detailed comparison, since the effects of the solar motion through space have not been considered.

Large particles ($m_{gr}>10^{-9}$ g) are decoupled from the interstellar magnetic field, so these micrometeorites may originate several hundred parsecs away (F99). The parent molecular clouds disrupted by star formation in the Scorpius-Centaurus Association, are suggested by one model to be the source of the local interstellar cloud complex flowing past the Sun (F95). The observed asymmetry in the micrometeorite flux suggests that
these molecular clouds may also be the source of the observed micrometeorites. An alternative origin for the micrometeorites would be in the atmospheres of evolved stars, since AGBs are a formation site for SiC presolar grains. The main argument against an AGB origin is that it does not explain the observed spatial asymmetry. An origin in the debris from Type II supernova would also be tenable since \( \sim 10 \) supernova explosions have occurred during the 15-Myr evolution period of the Scorpius-Centaurus Association [De Geus, 1992].

7. Future Outlook

In principle, the deposition of interstellar dust grains on geologically inert surfaces in the solar system will provide a record of changes in the galactic environment of the Sun. The heliosphere will contract and expand as the properties of the interstellar cloud in which it is immersed change, with outer planets, comets, and Kuiper Belt objects more likely to be exposed to pristine interstellar material than inner planets. When the solar system is embedded in denser interstellar clouds than at present, the heliosphere will be smaller than it currently is, exposing the surfaces of outer objects to the full flux of interstellar dust grains. These surfaces may contain a record of these variations in the interstellar dust flux. Periods when the heliosphere is large would provide a solar-wind-modulated mass spectrum. The Earth’s Moon will also provide a record of encounters with interstellar clouds containing large (radii > 0.1 \( \mu \)m) grains. If it were possible to obtain and analyze an unmixed core sample of the lunar surface, the ratio of large to small interstellar grain, as a function of time, should record a combination of solar activity and the dust mass spectrum of the cloud in which the Sun was immersed. If a similar core sample could be obtained from a surface in the outer solar system, a comparison with the lunar record would permit disentangling the effects of galactic environment versus solar activity. Surfaces of Oort cloud comets will accrete interstellar dust. Thus the changing galactic environment of the Sun on its journey through space
may be recorded by the deposition of interstellar dust grains on solar system surfaces. Accessing this record will enrich our understanding of the physical changes which may have affected the Earth’s climate in the past.

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**Figure 1.** The velocities of Ca$^+$ components in 17 nearby stars are plotted in the local standard of rest (LSR) versus the local interstellar flow velocity frames. Only one component per star is plotted. The plotted components are selected to be the components with the smallest velocity in the local flow velocity frame. These components have average velocities of $-0.05 \pm 2.24 \text{ km s}^{-1}$. Figure is from [http://xxx.lanl.gov/astro-ph/9705231](http://xxx.lanl.gov/astro-ph/9705231). The “LISW” label on the ordinate is an abbreviation for the “local interstellar wind,” which is the flow of interstellar gas within the solar system (see Table 1).

**Figure 2.** Same as Figure [1], except that the plotted components are selected to be the components with the smallest velocity in the LSR. These components have average velocities of $-5.46 \pm 9.82 \text{ km s}^{-1}$. Figure is from [http://xxx.lanl.gov/astro-ph/9705231](http://xxx.lanl.gov/astro-ph/9705231).
Table 1. Properties of the Interstellar Cloud which Surrounds the Solar System

| Item | Adopted Values | References |
|------|----------------|------------|
| $n(\text{He}^o)$ | 0.015 cm$^{-3}$ | 1          |
| $N(\text{H}^o)/N(\text{He}^o)$ | 14.7 | 2, 3, 4 |
| $n(\text{H}^o+\text{H}^+))/(n(\text{He}^o+\text{He}^+))$ | 10 | 10 |
| $n(\text{H}^o)$ | 0.22 cm$^{-3}$ | inferred, 15 |
| $n(\text{H}^+)$ | 0.10 cm$^{-3}$ | 5, 6, 7, 12, 15 |

Downstream direction in solar rest frame

Ecliptic coordinates

$\lambda=74.7^\circ\pm1.3^\circ$, $\beta=-4.6^\circ\pm0.7^\circ$

$V=24.6\pm1.1$ km s$^{-1}$

Upstream directions

Solar rest frame, galactic coordinates

$l=2.7^\circ$, $b=+15.6^\circ$

$V=-24.6\pm1.1$ km s$^{-1}$

LSR rest frame, galactic coordinates

$l=344^\circ$, $b=-2^\circ$

$V=-14.7$ km s$^{-1}$

Temperature

6,900 K

11

Turbulent velocity

$\sim1-1.5$ km s$^{-1}$ K

16

Magnetic field

1.5–6 $\mu$G

9, 13

Table based on Frisch et al. [1999]. The flow of interstellar gas through the solar system is referred to as the local interstellar wind (LISW). References are 1, Witte et al. [1996], A. N. Witte (private communication, 1999), and Flynn et al. [1998]; 2, Dupuis et al. [1995]; 3, Frisch [1995]; 4, Vallerga [1996]; 5, Slavin and Frisch [1998]; 6, Gry
and Dupin [1996]; 7, Wood and Linsky [1997]; 8, present paper, section 1; 9, Frisch [1990] (estimated value); 10, Savage and Sembach [1996]; 11, Flynn et al. [1998]; 12, Lallement and Ferlet [1997]; 13, T. Linde (private communication, 1997). 14, present paper, section 4 (This value is based on the removal of solar motion based on by recent Hipparcos data: 13.4 km s$^{-1}$ toward the direction $l=28^\circ$, $b=32^\circ$ from the observed LISW heliocentric velocity vector (see text). Earlier estimates of the solar motion yield different results. Removing “standard” solar motion of 19.5 km s$^{-1}$ toward the direction $l=56^\circ$, $b=+23^\circ$, instead, gives $V=-24.6$ km s$^{-1}$, from $l=315^\circ$, $b=-3^\circ$ for the observed LISW heliocentric velocity vector. If the “best” solar motion of 16.5 km s$^{-1}$ toward $l=53^\circ$, $b=+25^\circ$ had been subtracted instead, the local standard of rest inflow direction of the local interstellar wind would be $V=-18.2$ km s$^{-1}$ from $l=324^\circ$, $b=-1^\circ$ [e.g., Frisch, 1995].) 15, Puyoo and Jaffel [1998]; and 16, Linsky et al. [1995]. The turbulent velocity is defined such that the line broadening, $b$ (where full width at half maximum=1.6×$b$) is given by the root-mean-square of the thermal and turbulent velocities.
