The Local Interstellar Medium

Seth Redfield[1]

Department of Astronomy and McDonald Observatory, University of Texas, Austin, TX, USA

Abstract. The Local Interstellar Medium (LISM) is a unique environment that presents an opportunity to study general interstellar phenomena in great detail and in three dimensions. In particular, high resolution optical and ultraviolet spectroscopy have proven to be powerful tools for addressing fundamental questions concerning the physical conditions and three-dimensional (3D) morphology of this local material. After reviewing our current understanding of the structure of gas in the solar neighborhood, I will discuss the influence that the LISM can have on stellar and planetary systems, including LISM dust deposition onto planetary atmospheres and the modulation of galactic cosmic rays through the astrosphere — the balancing interface between the outward pressure of the magnetized stellar wind and the inward pressure of the surrounding interstellar medium. On Earth, galactic cosmic rays may play a role as contributors to ozone layer chemistry, planetary electrical discharge frequency, biological mutation rates, and climate. Since the LISM shares the same volume as practically all known extrasolar planets, the prototypical debris disks systems, and nearby low-mass star-formation sites, it will be important to understand the structures of the LISM and how they may influence planetary atmospheres.

1. Introduction

The interstellar medium (ISM) is a critical component of galactic structure. Its role in the lifecycle of stars, mediating the transition from stellar death to stellar birth, evokes a sense of a "galactic ecology" (Burton 2004). The ISM provides a platform for the recycling of stellar material, by transferring and mixing the remnants of stellar nucleosynthesis and creating environments conducive for the creation of future generations of stars and planets. It also transfers energy and momentum, absorbing flows from supernovae blasts and strong winds from young stars and coupling these peculiar motions with galactic rotation and turbulence. Ultimately, when a dense interstellar cloud collapses, it is the conservation of momentum from the parent cloud that leads to the formation of a protostellar disk from which stars and planets are formed.

The local interstellar medium (LISM) is the interstellar material that resides in close ($\lesssim 100\,\mathrm{pc}$) proximity to the Sun. For a discussion on more distant ISM structures, see McClure-Griffiths, in this volume. Proximity is a special characteristic that drives much of the interest in the LISM. First, proximity provides an opportunity to observe general ISM phenomena in great detail, and in three

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[1]Hubble Fellow.

dimensions. ISM structures and processes are repeated almost *ad infinitum* in our own galaxy (Dickey & Lockman 1990), and beyond in other galaxies (McCray & Kafatos 1987), even at high redshift (Rauch et al. 1999). Knowledge of general ISM phenomena in our local corner of the galaxy, discussed in §2, can be applied to more distant and difficult to observe parts of the universe.

Second, proximity implies an interconnectedness. The relationship between stars and their surrounding interstellar environment will be discussed in §3, with particular attention paid to the interaction of the Sun with the LISM. In §4, the consequences of the relationship between stars and the LISM on planetary atmospheres are discussed, and the LISM-Earth, or more generally, the ISM-planet connection is explored in more detail.

This manuscript should not be considered a comprehensive review of the subject of the LISM, but an individual, and biased, thread through a rich research area. I certainly will not be able to explore many LISM topics to the level they deserve, nor will I be able to highlight all the work done by the large number of researchers in this area. Hopefully, this short review will introduce you to some new ideas, and the references provided can escort you to even more work that was not specifically mentioned in this manuscript.

2.   Properties of the Local Interstellar Medium

Measuring the morphological and physical characteristics of the nearest interstellar gas has long been of interest to astronomers. Observations of the general ISM via interstellar extinction of background stars (Neckel et al. 1980), the 21 cm H I hyperfine transition (Lockman 2002), or foreground interstellar absorption in optical resonance lines (Cowie & Songaila 1986) typically focus on more distant ISM environments due to the observational challenges inherent in measuring the properties of the LISM (see §2.2). Recent reviews that focus specifically on the LISM by Ferlet (1999) and Frisch (1995, 2004) also provide some discussion on the history of the field.

2.1.   Our Cosmic Neighborhood

The LISM is a diverse collection of gas. The outer bound of what I consider to be "local" in the context of the LISM, is the edge of Local Bubble (LB), coincident, by definition, with the location of the nearby dense molecular clouds, such as Taurus and Ophiuchus (Lallement et al. 2003). Figure 1 is a schematic illustration of the volume populated by the LISM, adapted from a similar figure by Mewaldt & Liewer (2001). Within the LISM volume, our cosmic neighborhood so to speak, resides the nearest 10^4 to 10^5 stars, including almost all known planetary systems (see Ford, in this volume) and the prototypical debris disk stars (see Chen, in this volume). Among these stars drifts interstellar gas known as the LISM. Several warm partially ionized clouds, such as the Local Interstellar Cloud (LIC) and the Galactic (G) Cloud, are observed within the Local Bubble.

The LIC is the material that directly surrounds our solar system. The internal pressure and ram pressure of the LIC, functions of its density and velocity relative to the Sun, balance the force of the outward-moving solar wind to define the boundary and shape of the heliosphere (see §3.1). The heliospheric structure is not unique to the Sun, but is observed around other stars, including the near-
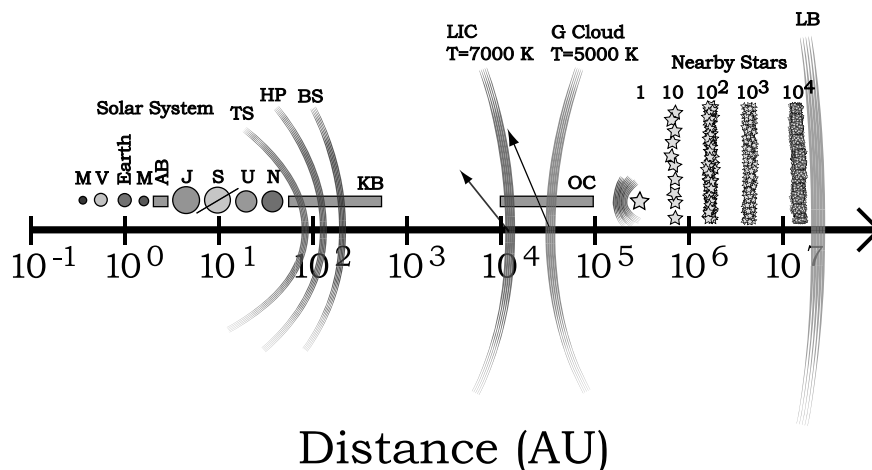
Distance (AU)

Figure 1.   Our cosmic neighborhood, shown on a logarithmic scale. The Solar System includes the major planets, the asteroid belt (AB), the Kuiper belt (KB), and the Oort cloud (OC). As of October 2005, Voyager 1 was 97.0 AU from the Sun. The heliospheric structure consists of the termination shock (TS), the heliopause (HP), and the bow shock (BS). The Local Interstellar Cloud (LIC) is the warm, partially ionized cloud that directly surrounds our solar system and currently determines the size and shape of the heliosphere. Our nearest neighboring cloud is the Galactic (G) Cloud which directly surrounds the α Cen stellar system. Analogous to the heliosphere, the α Cen system includes an astrosphere. The LISM resides in a larger ISM structure, the Local Bubble (LB). Within the Local Bubble, which extends ~ 100 pc from the Sun, lie the nearest 10^4–10^5 stars. This figure is inspired by a diagram in Mewaldt & Liewer (2001).

est stellar system, α Cen (Wood et al. 2001). Nor is the heliospheric structure static. The heliosphere will expand and contract, in response to the density of the LISM material surrounding the Sun (see §3.2).

The boundary between the LISM and the solar system is not an obvious one. The Oort cloud contains the most distant objects that are gravitationally bound to the Sun, which reside at a third of the distance to α Cen. The Oort cloud is completely enclosed by LISM material, and due to the short extent of the LIC in the direction of α Cen (Redfield & Linsky 2000), Oort cloud objects in that direction may be surrounded by a different collection of gas (G Cloud material) than surrounds our planetary system (LIC material). Currently, even much of the Kuiper belt (KB) extends beyond the bow shock (BS) into pristine LISM material (see Sheppard, in this volume). Some neutral LISM material can penetrate well into the solar system. This material is utilized to make *in situ* measurements of properties of the LIC (see §2.2). The interconnectedness of our solar system with our surrounding interstellar medium could have important consequences for planetary atmospheres (see §4).

Hot Gas: Local Bubble The Local Bubble refers to the apparent lack of dense cold material within approximately 100 pc of the Sun. Therefore, the distance to the edge of the Local Bubble cavity is equal to the distance at which cold dense gas is first observed. Lallement et al. (2003) were able to map out the contours of the Local Bubble by tracing the onset of the detection of foreground

Na I absorption lines in the spectra of ∼1000 early type stars. In general, the interstellar material within the Local Bubble is too hot for neutral sodium, and therefore none is detected until the edge of the Local Bubble is reached. The edge of the Local Bubble can be as close as 60 pc, and as far as ∼250 pc, or even unbound, as toward the north and south galactic poles (Lallement et al. 2003).

The hot gas within the Local Bubble is notoriously difficult to observe. Early direct detections of million degree gas came from diffuse soft X-ray emission (Snowden et al. 1998), although part of this emission is now thought to be caused by charge exchange reactions in the heliosphere, the same process that causes comets to emit X-rays (Lallement 2004). Absorption lines of highly ionized elements are generally weak or not detected, as Oegerle et al. (2005) found when looking for O VI absorption toward nearby white dwarfs. Detecting emission from highly ionized atoms has also been more difficult than expected. Using the *Cosmic Hot Interstellar Plasma Spectrometer* (*CHIPS*), Hurwitz et al. (2005) do not detect the array of extreme ultraviolet emission lines that are predicted from the "standard" Local Bubble temperature and density. Canonically, it is thought that the Local Bubble is filled with $T \sim 10^6$ K, $n \sim 5 \times 10^{-3}$ cm^{-3} gas that extends about $R \sim 100$ pc. However, much work remains to be done to understand the nature of the hot Local Bubble gas.

Warm Gas: Local Interstellar Clouds Within the hot Local Bubble substrate are dozens of individual accumulations of diffuse gas that are warm and partially ionized ($T \sim 7000$ K, $n \sim 0.3$ cm^{-3}, $R \sim 0.5$–5 pc). It is most commonly this material that is being referenced with the term "local interstellar medium." It is warm, partially ionized material that directly surrounds our solar system, and which can be measured with *in situ* observations and high resolution optical and ultraviolet (UV) spectroscopy (see §2.2). The warm LISM will dominate the remainder of this review, because it is the best studied of the different phases of LISM material, and the most significant with regards to interaction with stars.

Typical properties of the local warm interstellar clouds are given in Table 1. Absorption line spectroscopy and *in situ* observations often provide independent measurements of the same quantity (e.g., T, v_0, l_0, b_0). In addition, the two techniques are often complementary, as when parameters derived from absorption spectra of nearby stars (e.g., $N_{\mathrm{HI}}/N_{\mathrm{HeI}}$) are combined with *in situ* measurements (e.g., n_{HeI}) to determine a third physical quantity that would be difficult or impossible to determine using either technique alone (e.g., n_{HI}). The LISM is a diverse collection of gas. For example, individual temperature determinations of LISM material can be made to the precision of ± 200 K, although temperatures ranging from 2000–11000 K are observed (Redfield & Linsky 2004b). The value given for the LISM in Table 1 is a weighted LISM mean.

Despite the diversity, there are several observational clues that indicate a coherence in the LISM. First, LISM absorption features in high resolution spectra can almost always be fit by one to three individual, symmetric, well-separated, Gaussian profiles, as opposed to a broad asymmetric feature that would result from multiple absorption features with a gradient of velocities. Second, the projected velocities of LISM features toward nearby stars can be characterized by a single bulk flow (Lallement & Bertin 1992; Frisch et al. 2002) that matches the observed ISM flow into our solar system (Witte 2004). However, small deviations from this bulk velocity vector are observed in the direction of the leading

Table 1.   Properties of Warm Local Interstellar Clouds

Property	Value	Ref.	Comments[a]
Temperature (T)	6680 ± 1490 K	1	LISM, AL
	6300 ± 340 K	2	LIC, *IS*
Turbulent Velocity (ξ)	2.24 ± 1.03 km s^{-1}	1	LISM, AL
Velocity Magnitude (v_0)	25.7 ± 0.5 km s^{-1}	3	LIC, AL
	28.1 ± 4.6 km s^{-1}	4	LISM, AL
	26.3 ± 0.4 km s^{-1}	2	LIC, *IS*
Velocity Direction (l_0, b_0)	$186°1, -16°4$	3	LIC, AL
	$192°4, -11°6$	4	LISM, AL
	$183°3 \pm 0°5, -15°9 \pm 0°2$	2	LIC, *IS*
HI Column Density ($\log N_{\mathrm{HI}}$)	17.18 ± 0.70 cm^{-2}	5	LISM, AL
HeI Volume Density (n_{HeI})	0.0151 ± 0.0015 cm^{-3}	6	LIC, *IS*
HI and HeI Ratio ($N_{\mathrm{HI}}/N_{\mathrm{HeI}}$)	14.7 ± 2.0	7	LISM, AL
Electron Volume Density (n_e)	$0.11^{+0.12}_{-0.06}$ cm^{-3}	8	LIC, AL
HI Volume Density (n_{HI})	0.222 ± 0.037 cm^{-3}	6,7	$n_{\mathrm{HI}} = n_{\mathrm{HeI}} \times N_{\mathrm{HI}}/N_{\mathrm{HeI}}$
Thermal Pressure (P_T/k)	3180^{+1850}_{-1130} K cm^{-3}	1,6,7	$P_T = nkT$
Turbulent Pressure (P_ξ/k)	140^{+140}_{-130} K cm^{-3}	1,6,7	$P_\xi = 0.5\rho\xi^2$
Hydrogen Ionization (X_{H})	$0.33^{+0.24}_{-0.13}$	6,7,8	$X_{\mathrm{H}} = n_{\mathrm{HII}}/(n_{\mathrm{HI}} + n_{\mathrm{HII}})$
Absorbers per sightline	1.8	9	LISM, AL
Cloud size (r)	~2.3 pc	10	LIC, AL
Cloud mass (M)	~0.32 $M_\odot$	10	LIC, AL

[a] LISM = average of several LISM sightlines; LIC = quantity for LIC material only; AL = derived from absorption line observations; *IS* = derived from *in situ* observations.

REFERENCES.—(1) Redfield & Linsky 2004b; (2) Witte 2004; (3) Lallement & Bertin 1992; (4) Frisch, Grodnicki, & Welty 2002; (5) Redfield & Linsky 2004a; (6) Gloeckler et al. 2004; (7) Dupuis et al. 1995; (8) Wood & Linsky 1997; (9) Redfield & Linsky 2002; (10) Redfield & Linsky 2000;

edge of the LIC, where the gas appears to be decelerated, possibly due to a collision of LIC material with neighboring LISM material (Redfield & Linsky 2001). Third, chaotic small scale structure in the LISM has not been detected. In one example, a collection of 18 Hyades stars, separated by only $1°$–$10°$, shows a smooth slowly varying gradient in column density with angular distance, as opposed to a chaotic, filamentary geometry. However, an extensive database of observations is required to fully study the three dimensional structure of the LISM (see §2.3).

Several properties of warm LISM clouds are not well known. Except for the material currently streaming into the solar system, volume densities are very difficult to measure. Inherent in absorption line observations are: (1) the ignorance of a length scale to the absorbing material, other than the limit set by the distance of the background star, and (2) the ignorance of density variations within a single collection of gas, since only the total column density is observed.

Measurements of the magnetic field in the LISM have also been difficult to make. For lack of better measurements, observations of distant (several kpc) pulsars give a "local" galactic magnetic field strength of $\sim1.4\,\mu$G (Rand & Lyne 1994), although this value may have little to do with the magnetic fields entrained in the LISM. Polarization measurements of nearby (<35 pc) stars are weak, but seem to indicate an orientation parallel to the galactic plane (Tinbergen 1982; Frisch 2004). The same orientation is derived from heliospheric observations of 1.78–3.11 kHz radio emission by Voyager 1 (Kurth & Gurnett 2003). The orientation and strength of the local magnetic field will have important consequences on the structure and shape of the heliosphere (e.g., Gloeckler

et al. 1997; Pogorelov et al. 2004; Florinski et al. 2004; Lallement et al. 2005). Additionally, since the magnetic pressure goes as B^2, the strength of the LISM magnetic field (B) could have important consequences for the relationship between the hot Local Bubble gas and the warm LISM clouds. The apparent pressure imbalance between the warm ($P_{tot}/k \sim 3300\,\mathrm{K\ cm^{-3}}$, see Table 1) and hot ($P_T/k \sim 10000\,\mathrm{K\ cm^{-3}}$, see "Hot Gas" section above) components of the LISM has been a persistent topic concerning the structure of our local interstellar environment (Jenkins 2002). Possible scenarios include: (1) the presence of a LISM magnetic field of $\sim 4.8\,\mu$G to match the hot Local Bubble pressure, (2) refinement of Local Bubble observations and models that may reduce the Local Bubble pressure, in particular refining the X-ray and extreme ultraviolet observations of nearby hot gas (Hurwitz et al. 2005; Lallement 2004), or (3) the hot and warm components of the LISM are not in pressure equilibrium. It will be important to resolve this issue in order to understand the interaction between the hot Local Bubble gas and warm local interstellar clouds.

Cold Gas? Although the volume of the Local Bubble is defined by the scarcity of cold dense gas, there are some indications that collections of cold gas may reside within the Local Bubble. Observations of Na I by Lallement et al. (2003), which define the morphology of the Local Bubble, also identify a number of isolated dense clouds, just inside the Local Bubble boundary. Magnani et al. (1996) identify several small molecular clouds that are thought to be relatively nearby ($\leq 200\,$pc), although their precise distances are not often known. These clouds have $T \sim 20\,$K, $n \sim 30\,\mathrm{cm^{-3}}$, and sizes of about $R \sim 1.4\,$pc. One such nearby molecular cloud, MBM 40 ($\sim 100\,$pc), contains molecular cores, although they are not massive enough for star formation (Chol Minh et al. 2003). MBM 40 is likely an example of a dense cloud that resides within the Local Bubble boundary.

2.2.   How do we Measure the Properties of the LISM?

The proximity of the LISM presents unique challenges and opportunities for measuring the properties of nearby interstellar gas, which is too sparse to cause measurable reddening or be detected in atomic hydrogen 21 cm emission. One unique observational technique is *in situ* measurements of ISM particles, which stream directly into the inner solar system. These observations complement the traditional ISM observational technique of high resolution absorption line spectroscopy. Observing the closest ISM provides many advantages, such as simple absorption spectra, well known distances to background stars, and large projected areas that allow multiple observations through different parts of a single cloud, enabling a probe of its properties in three dimensions.

In Situ Measurements A powerful observational technique, absent in the vast majority of astrophysical research, is the ability to send instruments to physically interact with, collect, and measure the properties of the material of interest directly, instead of relying on photons. Due to the close proximity of the LISM, interstellar particles are continually streaming into the interplanetary medium. Neutral helium atoms, and helium "pick-up" ions (neutral helium atoms ionized as they approach the Sun and are "picked-up," or entrained, in the solar wind plasma), are observed by mass spectrometers onboard the *Ulysses* spacecraft. Möbius et al. (2004) review these measurements, together with He I UV-backscattered emission, collected and analyzed by several groups over many

years. These observations give consistent measurements of the temperature, velocity, and density of the interstellar medium directly surrounding the solar system (see Table 1). LISM dust particles collected in the interplanetary medium are among the sample onboard the *Stardust* mission, scheduled to return to Earth in January 2006 (Brownlee et al. 2003). Laboratories will be able to analyze the collected particles in detail. Not only will this provide information about the nature of dust in the LISM, but may answer questions about the origin of ISM dust and its role in circumstellar and disk environments (see Chen, in this volume). Both Voyager spacecraft, launched in 1977, are still functioning and returning data as part of the Voyager Interstellar Mission (VIM). On 16 December 2004, Voyager 1 provided a long sought-after measurement of the distance to the termination shock, at 94.01 AU. With enough power to last until 2020, Voyager 1 should provide measurements of its encounter with pristine interstellar material once it crosses the heliopause around 2015 (Stone et al. 2005).

High Resolution Absorption Line Spectroscopy A standard technique used to measure the physical properties of foreground interstellar material along the line of sight toward a background star is high resolution absorption line spectroscopy. This kind of work has a long and rich history, but has typically been dominated by more distant ISM environments, with large column densities and strong absorption signatures (Cowie & Songaila 1986; Savage & Sembach 1996). The challenge inherent in absorption line spectroscopy of the LISM is the low column density along sightlines to nearby stars. This limits the number of diagnostic lines to only the strongest resonance line transitions. In Figure 2, the hydrogen column density sensitivities are shown for the 100 strongest ground-state transitions at wavelengths from the far-ultraviolet (FUV), through the ultraviolet (UV), to the optical. The lower sensitivity limit indicates a 3σ detection in a high signal-to-noise observation with modern high resolution instruments. The upper sensitivity limit marks the column density at which the transition becomes optically thick and leaves the linear part of the curve of growth, where, although absorption is detected, limited information can be obtained from the saturated absorption profile. Ionization structure typical for warm LISM clouds is incorporated (Slavin & Frisch 2002; Wood et al. 2002), although typical LISM depletion is not; only solar abundances are assumed (Asplund et al. 2005). The range of LISM absorbers ($16.0 \leq \log N_{\mathrm{H}}\,(\mathrm{cm}^{-2}) \leq 17.7$) is such that less than 100 transitions are available to study the LISM. Taking into account such issues as blending or continuum placement, which can limit the diagnostic value of an individual transition, reduces the number of useful transitions even more. Most of the transitions lie in the FUV and UV, with only a few transitions available in the optical, most importantly Ca II resonance lines at $\sim$3950 Å. (Other notable optical transitions, such as Na I and K I, probe more distant and higher column density ISM environments, see Lallement et al. 2003 and Welty & Hobbs 2001.) Recent LISM absorption line observations of these transitions have been made in the FUV with the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) (e.g., Lehner et al. 2003; Wood et al. 2002), in the UV with the *Hubble Space Telescope* (*HST*) (e.g., Redfield & Linsky 2004a, 2002), and in the optical with ultra-high resolution spectrographs, such as those at McDonald Observatory and the Anglo-Australian Observatory (e.g., Crawford 2001; Welty et al. 1994).
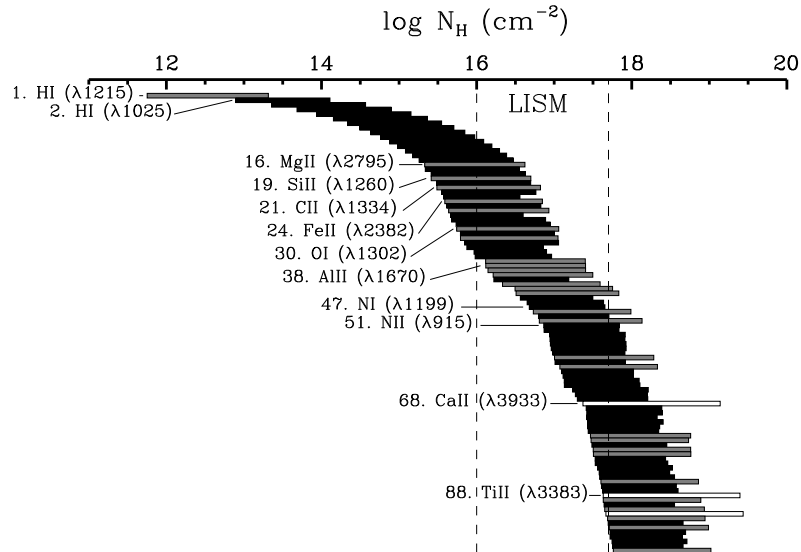
Figure 2.   The 100 strongest resonance lines, ranked in order of their hydrogen column density sensitivity. White bars indicate those that fall in the optical (3000-10000Å), gray for ultraviolet (1200-3000Å), and black for far-ultraviolet (900-1200Å). The top 15 lines are H I transitions from Lyman-α to Lyman-o, only Lyman series lines to Lyman-ω are shown. The vertical dashed lines indicate the typical range of hydrogen column densities observed for warm LISM clouds. Those transitions with sensitivities left of this range will be optically-thick and saturated, whereas those transitions to the right will not be sensitive enough to detect absorption from warm LISM clouds.

2.3.   Future Directions

Absorption line analyses, supported by *in situ* observations of the LIC, have resulted in numerous single sightline measurements of projected velocity, column density, and line width for several dozens of sightlines, leading to individual measurements of various physical properties of the LISM, including temperature and turbulence (Redfield & Linsky 2004b), electron density (Wood & Linsky 1997), ionization (Jenkins et al. 2000), depletion (Lehner et al. 2003), and small scale structure (Redfield & Linsky 2001). However, with the recent accumulation of significant numbers of observations, it is possible to go beyond the single sightline analysis and develop a global morphological and physical model of the LISM. Initial steps have been made toward this end with global bulk flow kinematic models of the LIC and G Clouds produced by Lallement & Bertin (1992), and a global morphological model of the LIC by Redfield & Linsky (2000).

Future LISM research will synthesize the growing database of LISM observations, taking advantage of the information contained in the comparison of numerous individual sightlines. A global morphological model would enable the development of global models of various physical properties, such as kinematics, ionization, depletion, density, etc. Ultimately, these global models are required to tackle larger issues that cannot be fully addressed by single sightline analyses, such as the interactions of clouds, the interaction of the warm LISM clouds with the surrounding hot Local Bubble substrate, the strength and orientation of magnetic fields, and the origin, evolution, and ages of clouds in the LISM.

Such work will not only be important in understanding the structure of gas in our local environment, but will be applicable to other, more distant and difficult to observe interstellar environments in our galaxy and beyond.

CLOSE: Ca II LISM Optical Survey of our Environment A global morphological model of the LISM requires high spatial and distance sampling. The development of a morphological model for the LIC by Redfield & Linsky (2000) was possible because LIC absorption is detected in practically every direction, since the material surrounds the solar system. More distant LISM clouds will subtend smaller angles on the sky, and will require higher density sampling of LISM observations in order to be morphologically characterized. The CLOSE (Ca II LISM Optical Survey of our Environment) project is a large scale, ultra-high resolution survey of ∼500 nearby stars that will enable a global morphological model of the LISM (work in collaboration with M.S. Sahu, B.K. Gibson, C. Thom, A. Hughes, N. McClure-Griffiths, P. Palunas). Previous Ca II surveys (Vallerga et al. 1993; Lallement et al. 1986; Lallement & Bertin 1992; Welty et al. 1996, and see summary, Redfield & Linsky 2002) only accumulated ∼50 nearby sightlines, but detected LISM Ca II absorption in 80% of the targets. Our survey will provide extensive coverage. The maximum angular distance between any two adjacent targets will be <10°, including more than 45 target pairs that will be <1° apart, providing an interesting study of small scale structure in the LISM. When combined with past and future observations, this survey will provide a significant baseline with which to search for long-term LISM absorption variation, as the sightlines to these high proper motion nearby stars vary over timescales of decades. Ultimately, the CLOSE project will provide a valuable database for the development of a global morphological model of the LISM.

3.   Relationship Between Stars and their Local Interstellar Medium

As discussed in reference to Figure 1, the interaction between the LISM and solar/stellar winds is mediated by the heliospheric/astrospheric interface. This interface is defined by the balance between the solar/stellar wind and the LISM. Reviews of heliospheric modeling include Zank (1999) and Baranov (1990), and the detection of astrospheres around nearby stars is reviewed by Wood (2004).

3.1.   The Heliosphere and Astrospheres

In the standard picture of the heliosphere, discussed by Zank (1999), Baranov (1990) and Wood (2004), the magnetized solar wind is shocked to subsonic speeds ("termination shock"), as is the ionized LISM material ("bow shock"). The interface in between ("heliopause") is where the plasma flows of the solar wind and LISM are deflected from each other. It was originally thought that neutral atoms from the LISM pass through the heliosphere unimpeded and therefore have a negligible influence on the structure of the heliosphere. However, charge exchange reactions between ionized hydrogen in the solar wind and neutral hydrogen in the LISM act to heat and decelerate LISM hydrogen atoms just prior to the heliopause. The resulting structure, referred to as the "hydrogen wall," is an accumulation of hot hydrogen between the heliopause and the bow shock.

   At the same time that heliospheric simulations were indicating an enhancement of hydrogen just beyond the heliopause, it was becoming clear that observations of LISM absorption in H I Lyman α were discrepant with other LISM

absorption lines along the same line of sight. In particular, excess H I absorption was required on the red and blue sides of the LISM H I absorption feature, in order to be consistent with the optically thin D I absorption profile, which is only $82 \, \mathrm{km \, s^{-1}}$ to the blue of the H I absorption. The models predicted a column density for the "hydrogen wall" of log $N_\mathrm{H} \, (\mathrm{cm^{-2}}) \sim 14.5$. From Figure 2, it is clear that only the Lyman series hydrogen lines are sensitive enough to detect these low column densities. Indeed, heliospheric H I absorption was first detected using the Lyman-α profile, when Linsky & Wood (1996) measured excess absorption redshifted with respect to the LISM absorption. The blueshifted excess absorption is associated with an astrosphere. Because we observe the decelerated heliospheric hydrogen from the inside, the heliospheric absorption is redshifted, whereas the decelerated hydrogen in an astrosphere is observed exterior to the astrosphere, and therefore is blueshifted, see Figure 6 of Wood (2004).

It should be noted that if the interstellar absorption gets to be too large, log $N_\mathrm{H} \, (\mathrm{cm^{-2}}) \geq 18.7$, the saturated ISM absorption will obliterate any sign of a slightly offset heliospheric or astrospheric absorption. So, these measurements are only possible within the low column density volume of the LISM. Among a sample of nearby stars, heliospheric and astrospheric absorption has been detected for many stars (Wood et al. 2005b). Multiple heliospheric detections sample the structure of our heliosphere in three dimensions, while multiple astrospheric detections provide measurements of weak solar-like winds around other stars. More than 50% of stars within 10 pc that have high resolution UV Lyman-α spectra show signs of astrospheric absorption (Wood et al. 2005a).

3.2.   Heliospheric Variability

Short Term   The solar wind strength and distribution fluctuate with the 11-year solar cycle (Richardson 1997). These variations slowly propagate out to the heliospheric boundary and it is expected that the heliopause will expand and contract on a comparable timescale. The stochastic injection of energy into the solar wind in the form of flares and mass ejections leads to variability on even shorter timescales. This dynamic wind is constantly buffeting the magnetospheres of planets in its path as well as the heliospheric boundary. Voyager 1 may have detected such short-term variability when over a 7-month period in 2003 the termination shock contracted inward, over Voyager 1, and then expanded back outward over Voyager 1 yet again, a year before Voyager 1 unambiguously crossed the termination shock (Krimigis et al. 2003; McDonald et al. 2003).

Long Term   Long-term variations in the solar wind strength are not well known, but observations of astrospheres around young solar analogs provide clues as to what kind of wind the Sun had in its distant past. The solar wind, 3.5 billion years ago, may have been $\sim 35\times$ stronger than it is today (Wood et al. 2005a). In contrast, density variations spanning 6 orders of magnitude are commonly observed throughout the general ISM. Since the Sun has likely encountered a number of different ISM environments with extreme variations in density, it seems quite intuitive to expect that the variation in density of our surrounding interstellar environment plays the dominant role in long-term variations of the heliosphere. Detailed models support this intuition. Zank & Frisch (1999) model the modern heliosphere surrounded by a LISM density $50\times$ the current value and find that the termination shock shrinks from $\sim 100 \, \mathrm{AU}$ to $\sim 10 \, \mathrm{AU}$. In the

next section, we will explore the possible consequences for planets, such as Earth, caught in the midst of such a dramatic change in the structure of the heliosphere.

4.   The LISM-Earth or ISM-Planet Connection

Discussion of a LISM-Earth connection has an incredibly long history. Shapley (1921) and Hoyle & Lyttleton (1939) are among the earliest references. Research has intensified as of late; observations and models have improved, geologic and climatic events remain unexplained, and it is becoming clear that the habitability of planets may be dependent on subtle astrobiological parameters (e.g., Fahr 1968; Begelman & Rees 1976; Thaddeus 1986; Frisch 1998; Florinski et al. 2003; Yeghikyan & Fahr 2004; Wallmann 2004; Pavlov et al. 2005; Gies & Helsel 2005).

4.1.   Planetary Consequences of Heliospheric Variability

It appears inevitable that the heliosphere has and will continue to expand and contract as the Sun passes through different ISM environments. The Sun is now surrounded by a relatively modest density cloud, the LIC, and the heliopause stands well beyond the planets at $\sim$100 AU. However, when the Sun encounters more dense ISM clouds, the heliosphere will shrink, perhaps to within the inner solar system. The question then arises: What are the consequences, on Earth and on other planets, of a compressed heliosphere/astrosphere?

Cosmic Rays   The solar wind is magnetized and extends out to the heliopause. Energetic charged particles, or cosmic rays, interact with this magnetic field and if they are not too energetic (≤ 1 GeV), the cosmic rays are partially or completely prevented from penetrating far into the heliosphere. The heliosphere is one of three screens, together with the Earth's magnetic field and the Earth's atmosphere, that modulate the cosmic ray flux at the surface of the Earth. The loss of heliospheric modulation would lead to flux increases of 10–100$\times$ at energies of 10–100 MeV at the top of the terrestrial magnetosphere (Reedy et al. 1983), and could have serious consequences for several planetary processes.

Cosmic rays are important sources of ionization in the upper atmosphere, creating showers of secondary particles, ultimately leading to muons, which dominate the cosmic ray flux in the lower atmosphere. Ions in the atmosphere may serve as cloud nucleation sites, increasing low altitude clouds and ultimately increasing the planetary albedo (Carslaw et al. 2002). A connection between cosmic rays and clouds was suggested by Svensmark & Friis-Christensen (1997) and a correlation between cosmic ray flux and low cloud cover over the course of a solar cycle was found by Marsh & Svensmark (2000), even though the global cosmic ray flux varied by only $\sim$15%. The 1–2 orders of magnitude variation that would result from the loss of the heliospheric screen could have a tremendous impact on the formation of clouds in the Earth's atmosphere. The ionization caused by cosmic ray secondaries may also trigger lightning production (Gurevich & Zybin 2001). Cosmic rays increase the production of NO and NO_2 in the upper stratosphere, which significantly influences ozone layer chemistry. Randall et al. (2005) tracked the enhancement of nitric oxide and nitrogen dioxide that resulted from an injection of low energy cosmic rays following a series of intense solar storms. In some locations within the polar vortex, the increased levels of NO and NO_2 led to 60% reductions in terrestrial ozone over several months.

Muons, electrons, and other cosmic ray products are significant natural radiation sources, accounting for 30–40% of the annual dose from natural radiation in the United States (Alpen 1998). Muons ionize atoms in our bodies, producing hydroxyl radicals, which can cause DNA mutations. The cosmic muon flux can be significant even at depths of 1 km below the Earth's surface, and is therefore a source of mutation even for deep-sea or deep-earth organisms. The loss of the heliospheric screen, and the subsequent increase in cosmic ray flux on the Earth's atmosphere, could have important implications for the long-term evolution of the Earth's climate, and for long-term mutation rates in terrestrial organisms.

Dust Deposition   Passage through dense ISM environments will compress the heliosphere while also depositing a significant amount of interstellar dust onto the top of the Earth's atmosphere. Pavlov et al. (2005) presented atmospheric models in which large amounts of interstellar dust cause a reverse greenhouse effect, blocking or scattering incident visible light while being transparent to infrared thermal radiation. McKay & Thomas (1978) also find that increased deposition of interstellar H_2 onto Earth's atmosphere would decrease mesospheric ozone levels, decrease the mesospheric temperature, and cause high altitude noctilucent ice clouds, which would ultimately increase the planetary albedo. Dust deposition could be a natural trigger for "snowball" Earth episodes, periods of $\sim$200,000 years in which the Earth is entirely glaciated (Hoffman et al. 1998).

4.2.   Future Directions

Most of the work on the LISM-Earth or ISM-planet connection has been theoretical. The few observational tests of this relationship have focused on correlating the largest ISM fluctuations with the largest climatic or geological fluctuations. For example, Shaviv (2003) claimed a correlation between the passage through spiral arms, the glaciation period, and the cosmic ray flux derived from iron meteorites. The most significant hurdles that these kinds of empirical tests must overcome are the extreme systematic errors that plague long-term astronomical, climatic, and meteoritic timescales that are so vital to demonstrating a convincing correlation. Invoking passage through spiral arms and major glaciations requires accurate temporal calibration back more than a billion years.

Although it is intuitive to attach the largest fluctuations in the ISM to the largest fluctuations in the climatic record, with respect to the modulation of the cosmic ray flux, modest density clouds may have a significant influence. As demonstrated in the model by Zank & Frisch (1999), a modest density LISM has a dramatic effect on the structure of the heliosphere. Although higher density environments would compress the heliosphere still further, there will be a point of diminishing returns as the incident cosmic ray flux on Earth's atmosphere approaches the galactic cosmic ray flux level. Future work will explore the evolution of the heliosphere through a variety of ISM environments, besides our current LISM surroundings and intermediate to the extremes of giant molecular clouds in the heart of spiral arms.

Historical Solar Trajectory   Linking the long-term timing of ice ages with spiral arm passages will continue to be an interesting test of the ISM-planet connection, but the LISM provides a provocative alternative empirical test (work in collaboration with J. Scalo and D.S. Smith). As discussed in §2, we know precisely the nature of the LISM that directly surrounds our solar system now from

in situ measurements of the LIC. If we look at a very nearby star, in the direction of the historical solar trajectory (Dehnen & Binney 1998), the observed LISM absorption should provide information on the nature of the LISM that the Sun encountered only a short time ago. (The Sun travels 1 pc in approximately 73,000 years.) If we continue this exercise, looking out the rearview mirror, so to speak, it should be possible to reconstruct a deterministic history of the ISM that the Sun experienced in the not-too-distant past. The Sun's ISM history could then be converted into a cosmic ray flux history, based on the heliospheric response to the historical interstellar density profile. As we sample more distant environments, and therefore more distant times, the peculiar motions of the Sun and the ISM cease to make a true deterministic history of the Earth's cosmic ray flux possible, but would still represent a possible and plausible cosmic ray history of the Earth, or any other planet orbiting a nearby star. Although the most recently experienced ISM environments may not include dense molecular clouds, nor the most recent climatic history include dramatic periods of global glaciations, such a short-term test does not suffer the systematics that make long-term correlations difficult. Both the astronomical (*Hipparcos* distances to nearby stars) and climatic (Zachos et al. 2001) records of the most recent past are sampled at high temporal resolution and are well calibrated.

5. Conclusions

The LISM is a unique conduit that connects large scale galactic and extragalactic structures with planetary atmospheres. Although every observation of an astronomical object outside our solar system (and even some "within" our solar system) peers through the LISM, we do not, as of yet, have a detailed three-dimensional global understanding of the morphological or physical properties of our own interstellar environment. The challenges of observing the properties of the LISM are slowly being met with larger databases of high resolution spectra taken from the FUV to the optical, along sightlines toward nearby stars. Due to the limited number of transitions that are sensitive to the low column densities of LISM material, it is critical to have access to high resolution spectrographs from the FUV to the optical. With the recent loss of the Space Telescope Imaging Spectrograph (STIS) on *HST*, no high resolution astronomical spectrograph ($R \equiv \lambda/\Delta\lambda \geq 50,000$) is currently operating in the ultraviolet. A new high resolution UV instrument is needed in order to preserve and expand our observational capabilities in the UV. Without such a facility, among other losses, we will no longer have the ability to observe gas in the LISM, and risk being ignorant of our most immediate interstellar surroundings. The LISM interacts with stellar and planetary systems and as we explore the subtle astrobiological parameters that control the degrees of habitability of planets, the role of the LISM may turn out to be significant.

Since the LISM, and the ISM in general, is an important part of a grand "galactic ecology," research on the LISM touches many different areas of astrophysics, often at a profound level. Carl Sagan once said that "we are made of star-stuff" (Sagan 1980). Created in stars, our "stuff" was mixed and transported from across the galaxy by the ISM and, eventually, it is likely that this "stuff" will return there to be recycled yet again.

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