The Warm Local ISM: Structure, Properties, and Theory

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Abstract. Ultraviolet spectra of interstellar absorption lines for lines of sight to nearby stars are providing new information about the physical properties and structure of the Local Interstellar Cloud (LIC) and other warm clouds within about 100 pc of the Sun. We summarize these results for the LIC and eight other warm clouds. These clouds typically have temperatures of 5600–7500 K and subsonic turbulent velocities. The locations and sizes of these clouds are being determined from the analysis of high resolution spectra from HST. The observed high degree of hydrogen ionization is inconsistent with the predictions of theoretical models of the ISM that assume steady state ionization and pressure equilibrium amoung the various components of the ISM.

Since HST's launch in 1990, we have exploited the high spectral resolution and excellent photometric qualities of its two spectrographs (GHRS and STIS) to study the interstellar medium along lines of sight toward nearby late-type stars. Our objectives have been to measure the D/H ratio and its spatial variations, to study the interaction of stellar winds with the interstellar gas flows, and to determine the physical properties and structure of warm clouds near the Sun. The first topic was reviewed by Linsky (1998), and the second by Wood, Linsky, & Zank (2000) and by Wood, Müller, & Zank (2000). In this talk, we will summarize what we have learned about the nearby warm clouds.

High resolution ultraviolet spectroscopy permits us to measure the column depths and broadening parameters for resonance lines of the many atoms and ions present in this spectral region. Of particular importance are the Lyman α (Lα) lines of H I (1215.67 Å) and D I (1215.34 Å). Analysis of the H I line plays a key role because its broadening parameter is primarily thermal and, since neutral hydrogen is the dominant constituent in warm clouds, the H I column density measures the cloud mass independent of abundances and depletions on to grains. To measure these quantities accurately we must infer the intrinsic stellar Lα emission or absorption line that forms the "continuum" against which the interstellar absorption is measured, and also determine the H I absorption in the heliosphere and astrosphere. Most of the work to date has used nearby late-type stars as background sources for which the intrinsic stellar Lα emission line must be assumed or reconstructed (for stars with high or variable radial velocities). Examples of these studies include Linsky et al (1995) and Wood et al (1996). Early-type stars and hot white dwarfs also prove background "continua" against which to measure interstellar absorption although typically for longer lines of sight which are more complicated. Examples of these studies include Vidal-Madjar et al (1998) and Sahu et al (1999).

Figure 1 (top) shows observed Lα lines for lines of sight toward five nearby late-type stars and one early-type star (Sirius). Absorption by models of the interstellar H I and D I absorption are shown as dashed lines. Figure 1 (bottom) shows in more detail the interstellar absorption toward α Cen B (1.35 pc, $l = 316°$, $b = -01°$) and the absorption due to the pileup of heated, decelerated H I in the "hydrogen wall" of the heliosphere (cf. Baranov & Malama 1995; Zank 1999), and the corresponding hydrogen wall absorption in the astrosphere around α Cen B. The latter is blue-shifted relative to the interstellar absorption because the astrosphere is viewed from outside. Note that if one mistakenly ascribes all of the absorption to the interstellar medium rather than separating out the heliosphere and astrosphere absorption, the effect would be to overestimate the interstellar H I column density $N_{\rm HI}$ and underestimate the D/H ratio by large factors given the very saturated H I Lα line.

Interstellar absorption by heavy elements like Mg II (2796, 2803 Å), Fe II (2599 Å), and C II (1335 Å) provide important complementary information. The optical depths of these lines are usually less than or of the order of unity, and the broadening is small, $b = \sqrt{2kT/m + \xi^2}$, where m is the atomic mass and ξ is the turbulent (nonthermal) broadening parameter. These lines play a crucial role in measuring ξ and in identifying individual velocity components produced in separate clouds. Figure 2 shows how the comparison of broadening parameters for elements with different atomic weights can measure T and ξ very accurately for the line of sight to 36 Oph A, which has only one velocity component and thus only one cloud (the G cloud). Table 1 lists the T and ξ parameters for the 9 clouds that we have studied so far. For most of the clouds T lies in the range 5600–7000 K and the nonthermal motions are very subsonic.

Table 1. Properties of nearby warm clouds in the local ISM

Cloud Name	Center l	Center b	d (pc)	Δd (pc)	$N_{\rm HI}$ (10^{18})	T (K)	ξ (km s^{-1})	D(Mg) (log)
LIC	149	–27	2.9	6.8	2.1	7000	1.7	–1.1
G	315	+25	1.15	2.3	0.7	5600	1.7	–0.5
NGP	–	+90	5.6	2.9	0.9	7500	< 1.5	–1.4
SGP	–	–90	5.6	11.0	3.4	6600	< 2.0	+0.3
+32	191	+23	5.1	2.0	0.63	6300	1.0	–1.3
–22	010	–38	5.0	6.5	2.0	–	–	–
+12	189	–50	5.2	0.9	0.28	11100	0.7	–1.4
BC	230	–11	1.3	0.7	0.22	–	–	(–1.0)
CMa	233	–12	65.	–	–	–	–	–

We define a "cloud" as a structure characterized by a single bulk velocity vector, T, ξ, and metal depletion. Lallement & Bertin (1992) and Lallement et al (1995) showed that interstellar velocities for many lines of sight to nearby stars are consistent with a single velocity vector of the Local Interstellar Cloud (LIC). Furthermore, the Sun must be located inside the LIC as the flow vector of H I in the heliosphere is consistent with the LIC flow vector (Witte et al 1993). Linsky et al. (2000) and Redfield & Linsky (2000) computed a model for the LIC based on values of $N_{\rm HI}$ at the projected LIC velocity for 16 lines of sight studied by HST, 3 lines of sight for which the analysis of EUVE spectra

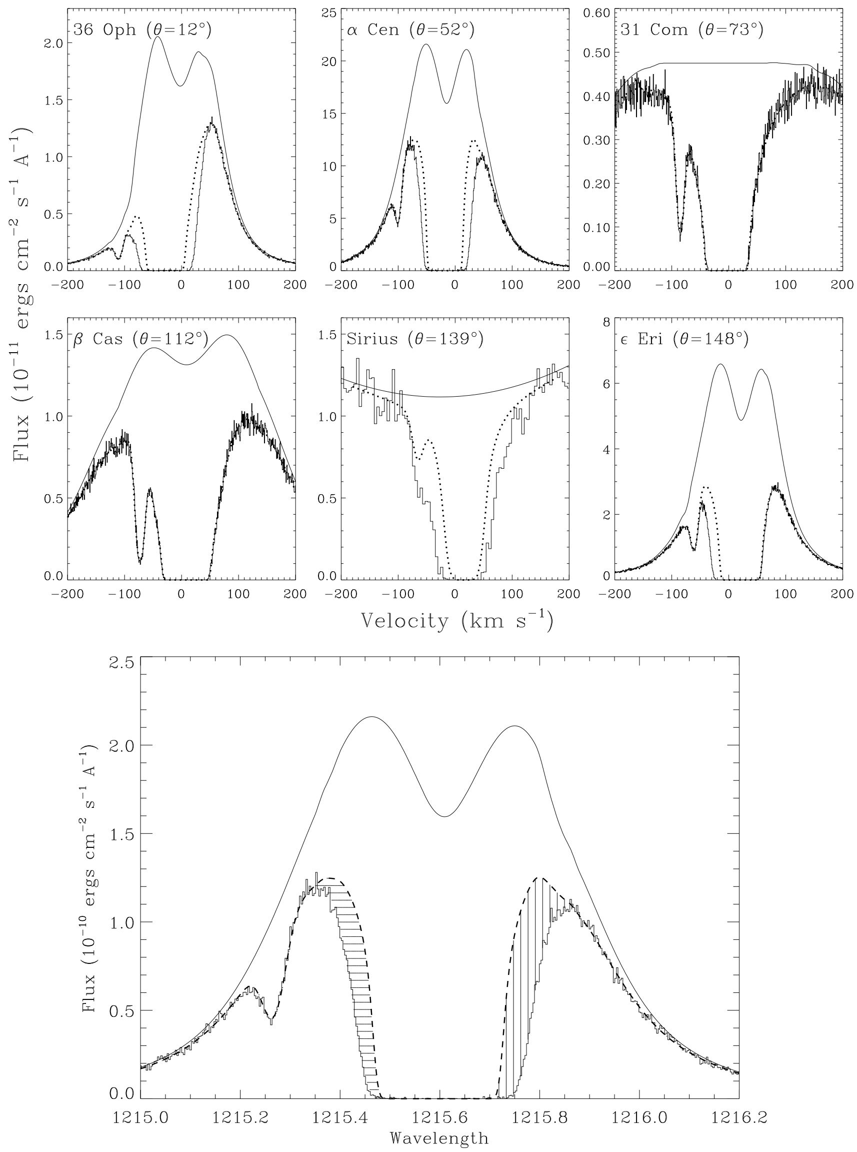

Figure 1. (top) Lα line profiles for lines of sight toward a representative sample of nearby stars with spectral types A1 V (Sirius) to K2 V (36 Oph A). θ is the angle between the star and the upwind direction of the interstellar flow. The smooth solid lines are the assumed intrinsic stellar emission lines, the noisy lines are the GHRS or STIS data, and the dotted lines show the absorption by interstellar H and D Lα. From Wood, Müller, & Zank (2000). (bottom) Fitting the Lα profile of α Cen B (K1 V). The smooth solid line is the assumed intrinsic stellar emission line, the noisy line is the GHRS data, and the dashed line shows absorption by interstellar H and D Lα. The vertically hatched area to the red of line center is heliospheric absorption, and the horizontally hatched area to the blue of line center is astrospheric absorption. From Wood, Müller, & Zank (2000).

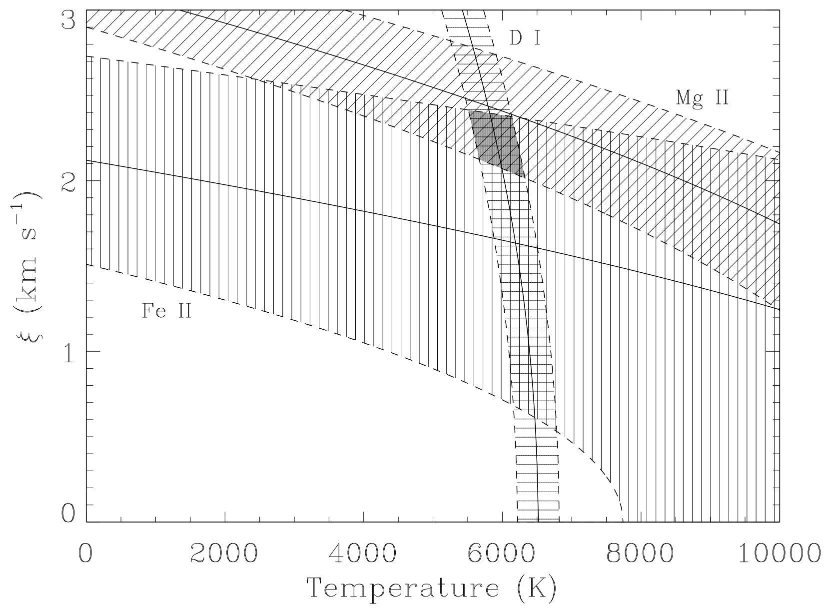

Figure 2. Nonthermal velocities (ξ) are plotted versus temperature (T), based on the Doppler parameters (solid lines) and their uncertainties (dashed lines) measured from interstellar absorption lines of Fe II, Mg II, and D I. The shaded area where the three curves overlap indicates that for the G cloud toward 36 Oph A, $T = 5900 \pm 500$ K and $\xi = 2.2 \pm 0.2$ km s^{-1}. From Wood, Linsky, & Zank (2000).

measured the total $N_{\rm HI}$, and 13 lines of sight with high resolution spectra in the Ca II 3933 Å line. Figure 3 shows this model as veiwed from the North Galactic Pole. We find that the Sun is located just inside the LIC ($<$ 0.05 pc from the edge) and that the flow inside the LIC is in nearly the same direction as the flow from the Sco-Cen Association, suggesting that the LIC is a warm condensation in the hot expanding gas produced by stellar winds and supernovae in Sco-Cen.

Figure 4 (top) shows contours of $N_{\rm HI}$ in the LIC projected on to the sky in Galactic coordinates. The maximum co0lumn density $N_{\rm HI} = 2.1 \times 10^{18}$ cm^{-2} is approximately in the direction of the Pleiades. Also shown are the stars used in creating the model. There is very little LIC absorption toward the Galactic Center or the North Galactic Pole. This map and a tool for computing $N_{\rm HI}$ and flow velocity along any line of sight through the LIC can be found in our web site http://casa.colorado.edu/∼sredfiel/ColoradoLIC.html.

Several velocity components are typically observed in high resolution spectra even for lines of sight toward nearby stars. In many cases we can identify other warm clouds from several lines of sight that show similar velocities. Figure 4 (bottom) shows approximate contours for these other clouds. The largest is the G (or Galactic Center) cloud originally identified by Lallement and Bertin (1992), but there are also clouds near the North Galactic Pole (NGP) and South Galactic Pole (SGP). Other smaller clouds are identified by their heliocentric radial velocities. Table 1 lists the directions and distances (d) of the inferred cloud centers, cloud thicknesses (Δd in pc and $N_{\rm HI}$), T, ξ, and logarithmic depletion of magnesium, D(Mg). Except for the LIC and G clouds, these parameters are first approximations based on only a few lines of sight. Analyses of recent and

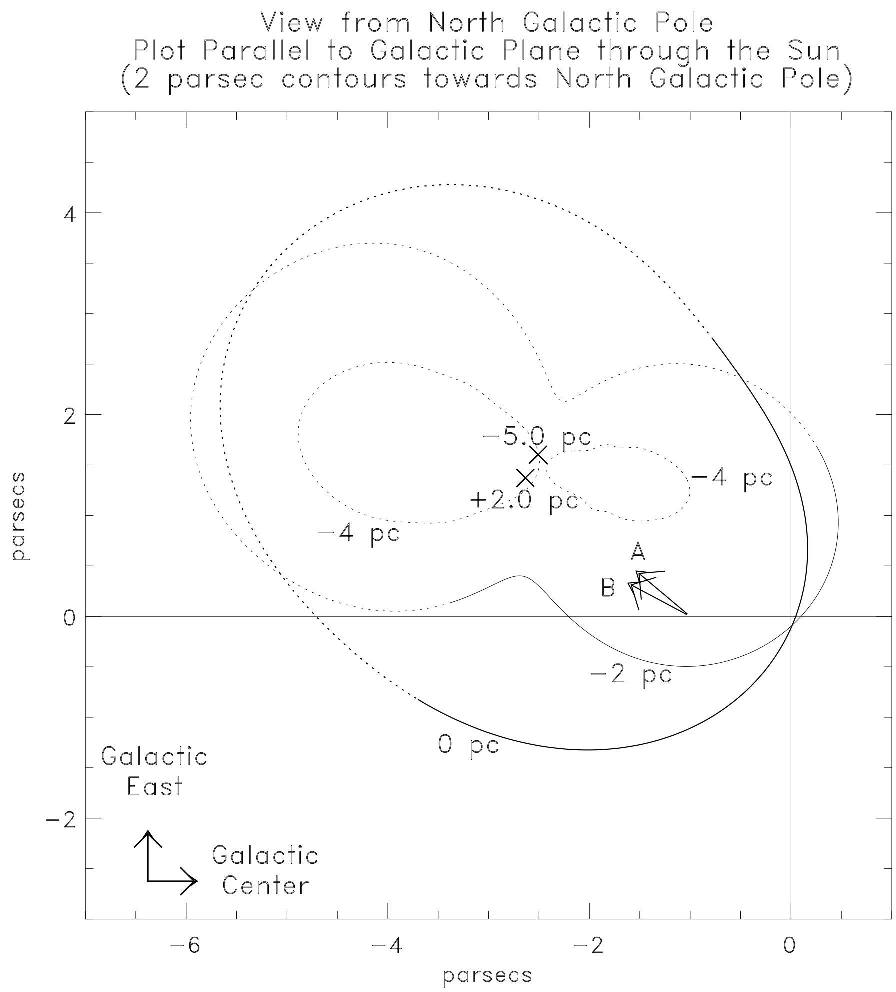

Figure 3. View of the LIC from the north Galactic pole. The Sun is located at (0,0). The x symbols mark the northernmost and southernmost points of the LIC. The solid portions of the contours indicate where the model is well constrained, and the dotted regions are where the model is poorly constrained. The arrow marked A indicates the direction from the center of the Sco–Cen association ($l = 320°, b = +15°$). The arrow marked B is the direction of the flow vector within the LIC in the local standard of rest ($l = 331.9°, b = +4.6°$). From Redfield & Linsky (2000).

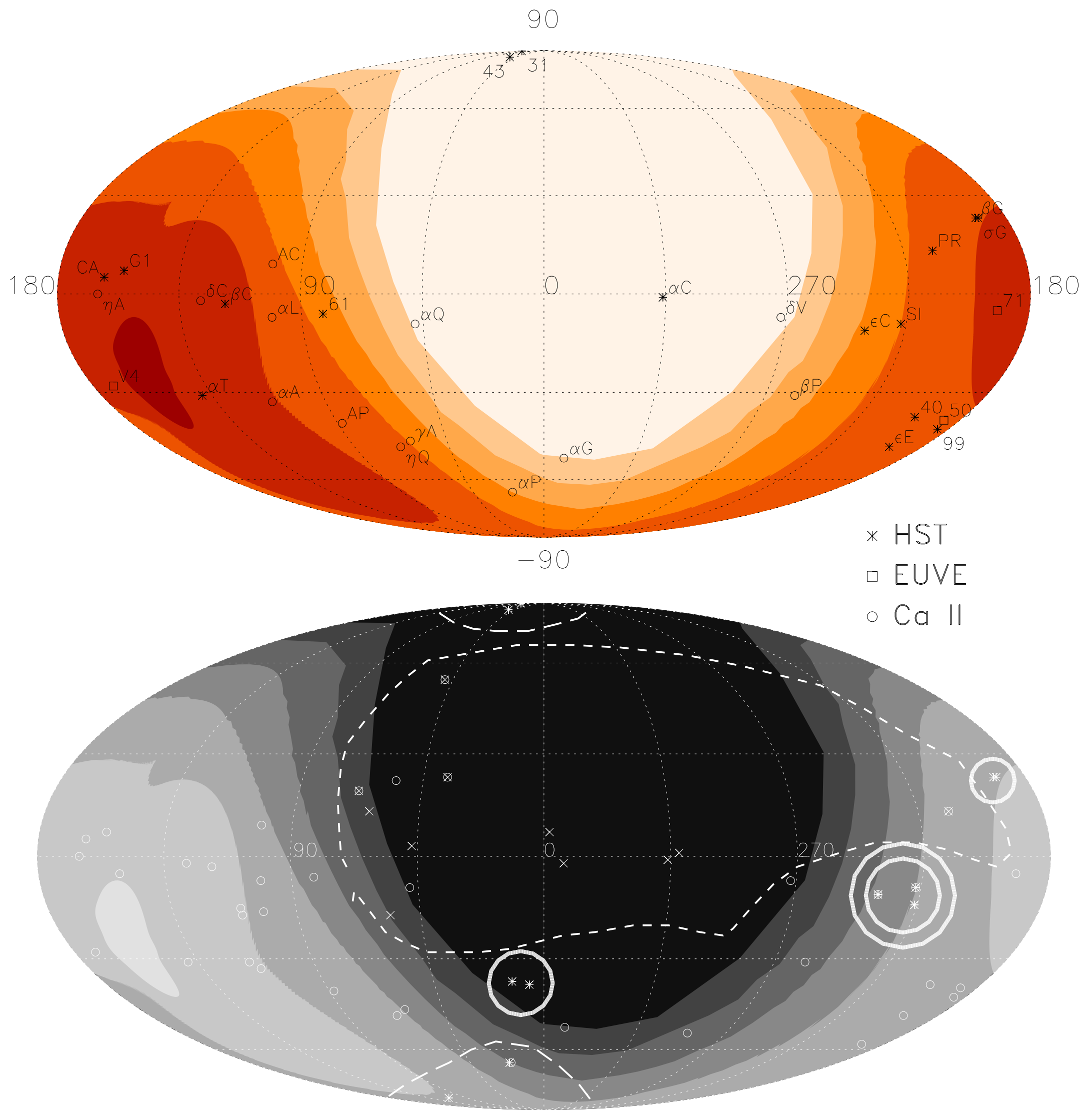

Figure 4. (top) Projection of the LIC model on the sky in Galactic coordinates. The shadings indicate the values of $N_{\rm HI}$ in units of 10^{18} cm^{-2} from the Sun to the edge of the LIC. From darkest to lightest, the shadings designate > 2.0, 1.0–2.0, 0.5–1.0, 0.25–0.5, 0.10–0.25, 0.05–0.10, and < 0.05 in these units. The symbols identify the stars used in making the LIC model. From Redfield & Linsky (2000). (bottom) Same as top (with reversed shading), except that the approximate locations of other nearby clouds are indicated using additional lines of sight. The large dashed contour indicates the location of the G cloud, and the smaller dashed contours indicate the locations of the North Galactic Pole and South Galactic Pole clouds. Solid lines indicate the contours of four other clouds (see Table 1).

future observations of new lines of sight by the STIS instrument on HST and the FUSE instrument will determine the properties and structures of these and other clouds more accurately. The cloud thicknesses are estimated from the largest value of $N_{\rm HI}$ for the cloud and the assumption that $n_{\rm HI} = 0.10$ cm^{-3}. The volume of the LIC is about 93 pc^3 and its mass is about 0.32 M$_\odot$. The velocity vectors for the G, NGP, and SGP clouds are similar to that of the LIC and these clouds may also be warm condensations in the Sco-Cen outflow. We cannot yet determine the velocity vectors for the other clouds.

The electron density in the LIC, derived from the ratio of C II column densities from the ground state (1335 Å) and the first excited state (1336 Å), is about $n_e = 0.11$ cm^{-3} for the lines of sight to Capella (Wood & Linsky 1997) and the white dwarf REJ1032+535 (Holberg et al 2000). The neutral hydrogen number density is more difficult to estimate. Linsky et al (2000) estimate $n_{\rm HI} = 0.10$ cm^{-3} as this is the largest average density determined by assuming that the LIC fills the line of sight to the nearest stars. Other estimates for $n_{\rm HI}$ lie in the range 0.15–0.20 cm^{-3} as inferred from space observations of scattered solar Lα photons by heliospheric H I (e.g., Quémerais et al 1995).

Hydrogen is significantly ionized in the LIC (cf. Vallerga 1996). Frisch & Slavin (1996) argue that ionizing photons from hot stars like ϵ CMa and a conductive interface with hot gas surrounding the LIC can explain the observed hydrogen ionization, whereas Lyu & Bruhweiler (1996) argue that the LIC is a recombining plasma following complete ionization by a supernova in Sco-Cen that may have occured a few million years ago. On the basis of new FUSE observations of the A I 1048 Å line, however, Jenkins et al (2000) maintain that the hydrogen ionization in the LIC is consistent with the local EUV radiation field.

For $n_{\rm HI} = 0.10$ cm^{-3}, the LIC gas pressure is $P/k = 2240^{+1280}_{-630}$ cm^{-3} K, which is consistent with $P/k = 1700$–2300 cm^{-3} K determined by Vallerga (1996) from the analysis of EUVE spectra of white dwarfs. Standard theoretical models of the multicomponent ISM assume steady–state ionization equilibrium and pressure equality among the three of more components. In the Wolfire et al (1995) models, for example, these assumptions lead to very low ionization ($n_e/n_{\rm H} = 0.046$–0.11 cm^{-3}) and $T = 9380$ K for the range of $N_{\rm HI}$, $n_{\rm HI}$, and photoionization rates consistent with measured LIC parameters. Clearly either the LIC ionization is transient or there is an additional source of ionization (perhaps produced in a conductive interface) that is not included in the standard theoretical calculations. We asked M. Wolfire to compute a model in which the ionization is specified to be the empirical value. The higher ionization led to more cooling, reducing T to 6590–6900 K depending on the value of $N_{\rm HI}$. Our empirical results and these calculations point to the importance of including more realistic assumptions in the next generation of theoretical models.

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