THE REMARKABLE HIGH PRESSURE OF THE LOCAL LEO COLD CLOUD

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Received 2011 December 15; accepted 2012 April 22; published 2012 June 4

ABSTRACT

Using the Space Telescope Imaging Spectrograph (STIS) on board the Hubble Space Telescope, we have obtained high-resolution ultraviolet spectra of the C I absorption toward two stars behind the Local Leo Cold Cloud (LLCC). At a distance (∼20 pc) that places it well inside the Local Bubble, the LLCC is the nearest example of the coldest known (T ≈ 20 K) diffuse interstellar clouds. The STIS measurements of the C I fine-structure excitation toward HD 85259 and HD 83023 indicate that the thermal gas pressure of the LLCC is much greater than that of the warm clouds in the Local Bubble. The mean LLCC pressure measured toward these two stars (60,000 cm−3 K) implies an H i density of ∼3000 cm−3 and a cloud thickness of ∼200 AU at the 20 K cloud temperature. Such a thin, cold, dense structure could arise at the collision interface between converging flows of warm gas. However, the measured LLCC pressure is appreciably higher than that expected in the colliding-cloud interpretation given the velocity and column density constraints on warm clouds in the HD 85259 and HD 83023 sightlines. Additional STIS measurements of the Zn II, Ni II, and Cr II column densities toward HD 85259 indicate that the LLCC has a modest “warm cloud” dust depletion pattern consistent with its low dust-to-gas ratio determined from H i 21 cm and 100 μm observations. In support of the inferred sheet-like geometry for the LLCC, a multi-epoch comparison of the Na I absorption toward a high-proper-motion background star reveals a 40% column density variation indicative of LLCC Na I structure on a scale of ∼50 AU.

Key words: ISM: atoms – ISM: clouds – ISM: structure – solar neighborhood

1. INTRODUCTION

The Local Leo Cold Cloud (LLCC; Peek et al. 2011b) is the predominant central component (22 deg2 centered near l = 223°, b = +44°) of a narrow (∼2°), broken ribbon of diffuse cold gas stretching over 70° of the sky at high Galactic latitude (Haud 2010). The LLCC was discovered by Verschuur (1969) through its very narrow H I 21 cm emission indicative of a kinetic temperature below 30 K. Utilizing 21 cm observations of three background extragalactic radio sources, Heiles & Troland (2003) revisited the LLCC as part of their Arecibo Millennium H I survey and measured spin temperatures of ≈20 K and column densities of ≈3 × 1019 cm−2 for the intervening gas. The combination of such temperatures and column densities is remarkable in that they imply an extremely thin (<0.1 pc), sheet-like geometry for the cloud if it is in thermal pressure equilibrium.

In the first optical absorption-line study of the LLCC, Meyer et al. (2006) obtained high-resolution observations of interstellar Na I toward 33 stars in the region and were able to place a firm upper limit of 45 pc on the cloud distance. This distance constraint places the LLCC well inside the Local Bubble of low-density gas surrounding the Sun out to distances of ~100 pc or more (Cox & Reynolds 1987). Based on measurements of the soft X-ray background (Fried et al. 1980), it has long been thought that the Local Bubble is filled with a highly ionized, hot (∼106 K) plasma. Recently, Peek et al. (2011b) tested this hypothesis through a multi-wavelength study utilizing the LLCC in an X-ray shadowing experiment. Key steps included tightening the LLCC distance to between 11.3 ± 0.2 and 24.3 ± 0.2 pc based on additional optical absorption-line measurements and mapping the LLCC H I 21 cm emission at spatial and velocity resolutions of 4′ and 0.184 km s−1 through the Galactic Arecibo L-Band Feed Array H I (GALFA-H I) survey (Peek et al. 2011a). In comparing this map (with a peak H I column density of 2.5 × 1020 cm−2) to the ROSAT soft (1/4 keV) X-ray data (Snowden et al. 1997) in the LLCC region, Peek et al. (2011b) find appreciably less X-ray shadowing than expected from a standard Local Bubble model. Based on this result and other evidence (Welsh & Shelton 2009), they argue that the isotropic component of the observed soft X-ray background is mostly a foreground effect due to solar wind charge exchange with neutral interstellar matter at the ~100 AU distant heliopause (Stone et al. 2005; Koutronampa et al. 2009).

Given the LLCC’s location deep inside the Local Bubble, a measure of its thermal gas pressure would provide a key physical diagnostic of this cold cloud and its environment. The warm, partially ionized clouds that are known to inhabit the Local Bubble collectively have an average temperature of 6700 K and a mean thermal pressure (P/k) of 2300 cm−3 K (Redfield & Linsky 2004). If the LLCC is in pressure equilibrium with these warm clouds and their environment, one would expect it to have a similar mean pressure. However, Redfield & Linsky (2008) have suggested that this cold cloud is the result of an impact between warm clouds in the Local Bubble and subsequent compression at the cloud interface. Models of the transonic compression of colliding flows of warm gas have yielded cold, sheet-like structures at the collision interface characterized by significant overpressures with respect to the surrounding medium (Audit &
Hennebelle 2005; Heitsch et al. 2006; Vazquez-Semadeni et al. 2006). Thus, if the LLCC is the product of such a collision, its pressure should clearly exceed the mean pressure of the warm clouds in the Local Bubble.

Ultraviolet spectroscopy of the C I absorption produced by the LLCC in its background stars has the potential to provide an accurate measure of the cloud’s thermal gas pressure. Since the fine-structure states of interstellar C I are primarily populated by collisions with hydrogen atoms in diffuse clouds, their excitation is sensitive to the local gas pressure (Jenkins & Shaya 1979). The many C I transitions observable in the far-UV (key multiplets centered near 1277, 1280, and 1329 Å) include lines with a large range in oscillator strength arising from each of the J = 0, 1, and 2 fine-structure levels. A number of other diagnostic transitions through which the physical character of the LLCC can be evaluated are also only observable in the ultraviolet. However, due in part to a lack of bright UV background sources, there has been no previous UV absorption-line study of this cloud.

In this paper, we present high-resolution UV spectra of the LLCC C I absorption in two sightlines observed with the Space Telescope Imaging Spectrograph (STIS) on board the Hubble Space Telescope (HST). These observations conclusively show that the thermal gas pressure of the LLCC is well above that of the warm clouds in the Local Bubble. Indeed, the measured LLCC pressure is higher than that expected in the colliding-cloud interpretation of the LLCC as a sheet-like structure at the collision interface. Nevertheless, in support of this interpretation, we find that a multi-epoch comparison of the Na I absorption toward a high-proper-motion background star reveals signifcant variation indicative of LLCC structure on a scale of ≈50 AU.

2. OBSERVATIONS

Among the 16 stars found by Meyer et al. (2006) to exhibit narrow Na I absorption corresponding to the LLCC, three (HD 83023, HD 85259, and HD 84722) were targeted for HST/STIS observations of their UV interstellar absorption lines. These specific stars were selected because they are the brightest UV background sources with appreciable LLCC absorption and they are all rapid rotators (v sin i > 100 km s⁻¹) well suited for interstellar absorption-line measurements. HD 83023 (d = 209.5±5.0 pc; van Leeuwen 2007) and HD 85259 (239.3±5.3 pc) have sky positions behind the periphery of the LLCC while HD 84722 (84.8±3.3 pc) is located behind the cloud interior about 52' away from HD 85259 (which corresponds to a sightline separation of 0.3 pc at the cloud distance of ≈20 pc).

The STIS observations of HD 83023, HD 84722, and HD 85259 were obtained in 2010 April, November, and December, respectively. HD 83023 and HD 85259 were both observed using the E140H and E230H echelle gratings to cover the 1242–1444 Å and 1824–2101 Å wavelength regions at a velocity resolution of 2.75 km s⁻¹. Due to the faintness of HD 84722 in the far-UV, this star was only observed with the E230H setup. The observed wavelength regions were chosen to cover key interstellar transitions of C I, C II*, C II**, C II*, Si I, Si II, Cl I, and Ni II with the E140H setup and Mg I, Cr II, and Zn II with the E230H setup. The raw two-dimensional STIS echelle spectra were flat-fielded, wavelength-calibrated, and scattered-light-corrected using the standard STSDAS data reduction software. With net exposures ranging from 1750 s (E230H) for HD 84722 to 4650 s (E140H) for both HD 83023 and HD 85259, the final extracted spectra are characterized by continuum signal-to-noise ratios (S/Ns) ranging from ≈15 at 2050 Å for HD 84722 and at 1260 Å for HD 83023 to ≈80 at 1315 Å for HD 85259. All of the STIS observations for this program (GO 11736) were obtained in a total of seven HST orbits.

In support of our STIS data analysis, we re-observed the interstellar Na I D₂ λ5889.951 and D₁ 5895.924 absorption toward HD 83023, HD 84722, and HD 85259 using the same 0.9 m coude feed telescope and spectrograph setup as the Meyer et al. (2006) observations at Kitt Peak National Observatory (KPNO). These observations were obtained with the purpose of determining the absorption-line profile of the LLCC as accurately as possible at higher S/N and velocity resolution than the STIS observations. The new exposures were reduced in the same manner as the earlier data and summed with these data to achieve final spectra with significantly enhanced S/Ns at a measured velocity resolution of 1.3 km s⁻¹. Specifically, HD 83023 was observed for an additional 7 hr in 2009 January to produce a net Na I spectrum (10 hr total exposure) characterized by a continuum S/N of 320. The high S/N ratio (340) of the final HD 84722 spectrum (14.75 hr total exposure) was achieved through new exposures spanning 12.75 hr in 2007 January and 2008 March. HD 85259 was observed for an additional 9 hr in 2008 March and 2011 February to produce a net Na I spectrum (10 hr total exposure) characterized by an S/N of 250.

In 2009 January, we also conducted new KPNO Na I observations of the star HD 84937 to compare with the 2006 January measurements of Meyer et al. (2006) and probe the small-scale Na I structure of the foreground LLCC. This star is located behind the outer periphery of the LLCC at a distance of 72.7±4.4 pc and it is distinguished by a very large proper motion of 0.860 arcsec yr⁻¹ (van Leeuwen 2007). The new exposures of HD 84937 (9 hr net integration) were reduced in the same manner as the earlier data (4.5 hr net integration) and the resultant summed spectra both have S/Ns of 100 at a velocity resolution of 1.3 km s⁻¹. HD 84937 was not selected as a UV interstellar absorption target for our STIS observations due to its late spectral type (F5) and faintness (V = 8.28).

3. RESULTS

3.1. Na I

In modeling their multi-star observations of the Na I absorption-line profiles corresponding to the LLCC, Meyer et al. (2006) found that a single-component solution provided an excellent fit to the data. Our significantly higher S/N observations of the LLCC Na I D₂ and D₁ profiles toward HD 83023, HD 85259, and HD 84722 shown in Figures 1–3 indicate that a double-component fit is more appropriate. The fits to these profiles were made with the FITS6p iterative Voigt profile fitting program (Welty et al. 1994) and took into account the hyperfine splitting of the Na I D lines (Δν = 1.05 km s⁻¹). Table 1 lists the resulting Na I column densities, line widths (b-values), and LSR velocities for both the single- and double-component models of the measured line profiles. The double-component fits are characterized by a very narrow dominant core superposed on a much broader, shallower component with a central velocity offset of no more than 0.4 km s⁻¹. Due to its high S/N, moderate Na I line strength, and modest component separation, the HD 83023 spectrum provides the most accurate measure of the line width (b = 0.24±0.01 km s⁻¹) of the narrow Na I component. This b-value was adopted for the stronger narrow Na I components toward HD 85259 and HD 84722 in optimizing the double-component fits to their Na I profiles.
In the case of the broader secondary Na\textsc{i} component, there are also hints of this feature in other LLCC sightlines observed by Meyer et al. (2006), but nothing definitive due to the lower S/N of their data. However, as shown in Figure 4, our re-observation of HD 84937 yields a net spectrum of sufficiently enhanced S/N (140) to provide further evidence of this secondary Na\textsc{i} component. The existence of a weak broader component at nearly the same velocity as that of the narrow LLCC Na\textsc{i} absorption toward multiple background targets suggests that the clouds responsible for these features may be related. Furthermore, we detect this broader component in the spectra of HD 84722 (84.8 pc) and HD 84937 (72.7 pc) which are both located inside the Local Bubble. Among the LLCC background stars observed by Meyer et al. (2006), none within 157 pc exhibits the additional Na\textsc{i} components seen at LSR velocities ranging from −11.5 to −1.5 km s\(^{-1}\)) toward some of their more distant stars. Meyer et al. interpret this additional Na\textsc{i} absorption as arising from the neutral gas boundary of the Local Bubble at a distance between 100 and 150 pc in the direction of the LLCC.

Interestingly, Peek et al. (2011b) also find that a double-component solution provides the best fit to their H\textsc{i} 21 cm emission-line observations of the LLCC. In Table 1, we list the H\textsc{i} column densities, line widths (\(b\)-values), and LSR velocities derived from their optically thin, two-component fits to the LLCC H\textsc{i} emission observed at 4\’ resolution toward HD 83023, HD 85259, and HD 84722 (no LLCC H\textsc{i} emission was detected toward HD 84937). In comparing the Na\textsc{i} and H\textsc{i} measurements in these sightlines, it is important to note that the 4 arcmin H\textsc{i} emission-line beam is much larger than the 10\’ arcsec Na\textsc{i} absorption-line beam. Also, as a trace neutral, Na\textsc{i} (ionization potential of 5.14 eV) is not the dominant ion of Na in H\textsc{i} clouds. Consequently, the column density of Na\textsc{i} is a function of both the H\textsc{i} column and environmental parameters such as the cloud temperature, electron density, and radiation field governing the Na ionization equilibrium. Nevertheless, as compared to Na\textsc{i} observations of other Galactic H\textsc{i} clouds (Welty 2007), the stronger LLCC components toward HD 83023, HD 85259, and HD 84722 all have among the highest Na\textsc{i} columns measured in such low N(H\textsc{i}) sightlines. Since the recombination of trace neutrals scales with cloud temperature as \(T^{-1.5}\) for a given N(H\textsc{i}) and constant pressure (Heiles 2007), such high Na\textsc{i} columns would be expected in an H\textsc{i} cloud as cold as the LLCC. Assuming that the turbulent Na\textsc{i} and H\textsc{i} motions in the stronger LLCC components are similar, a comparison of the Na\textsc{i} (0.24 km s\(^{-1}\)) and H\textsc{i} (mean value of 0.59 km s\(^{-1}\)) line widths through the expression \(b^2 = (2kT/m) + 2\upsilon_t^2\) yields a cloud kinetic temperature of 18 K and a one-dimensional rms turbulent velocity (\(\upsilon_t\)) of 0.16 km s\(^{-1}\).

The principal differences between the LLCC Na\textsc{i} and H\textsc{i} profiles lie in the weaker of the two fitted components. In all three sightlines, the weaker Na\textsc{i} component is much broader than the...
weaker H\textsc{i} component. Furthermore, the velocity separations between the stronger and weaker components are greater for H\textsc{i} than Na\textsc{i} and the column density differences between the components are more pronounced in the Na\textsc{i} fits than those for H\textsc{i}. The most likely explanation for these differences is that the weaker Na\textsc{i} and H\textsc{i} components are not sampling the same parcels of gas. In the case of the weaker Na\textsc{i} component, its low column and broad width would make the corresponding H\textsc{i} emission difficult to detect in the Peek et al. (2011b) data. Such a weak H\textsc{i} feature would have an FWHM of \(\approx 13\) km s\(^{-1}\) and blend in with the broad red wing of the H\textsc{i} emission associated with the neutral gas boundary of the Local Bubble. Peek et al. (2011b) interpret the similarly narrow H\textsc{i} components in their two-component fits to the LLCC H\textsc{i} profile as arising from two colliding clouds. In this picture, the absence of Na\textsc{i} absorption corresponding to the lower H\textsc{i} column cloud could reflect an environmental factor such as a lower electron density. Alternatively, the narrow Na\textsc{i} absorption could arise from high-density gas at the collision interface between the two clouds. In either case, the broad Na\textsc{i} component could arise from warmer diffuse gas associated with the two H\textsc{i} clouds or the post-shock material just outside the cold interface layer.

3.2. C\textsc{i}

The STIS observations of the LLCC C\textsc{i} absorption toward HD 85259 and HD 83023 support the two-component solution to the optical Na\textsc{i} profiles. As illustrated in Figures 5 and 6, spectra of the 1329 Å multiplet reveal significant C\textsc{i} absorption arising from each of the J = 0, 1, 2 fine-structure states toward both HD 85259 and HD 83023. In the case of HD 85259, the C\textsc{i} lines are strong enough and the spectral S/N is high enough to fully utilize the C\textsc{i} multiplets centered near 1277 and 1280 Å along with the 1329 Å data in measuring the C\textsc{i}, C\textsc{i}* and C\textsc{i}** profiles and column densities. The best simultaneous FITS6P fit to these data yields a two-component solution for the C\textsc{i} profile characterized by a dominant narrow (\(b = 0.4 \pm 0.1\) km s\(^{-1}\)) component and a weaker broad (\(b = 2.6 \pm 0.4\) km s\(^{-1}\)) component with the same velocity separation as the Na\textsc{i} profile fit. The C\textsc{i} and C\textsc{i}** profiles were fitted by a single component with the same b-value as the narrow C\textsc{i} component. In the case of HD 83023, the low S/N (<25) of its STIS spectra shortward of 1300 Å makes the C\textsc{i} 1277 and 1280 Å multiplets of limited utility in fitting the C\textsc{i}, C\textsc{i}*, and C\textsc{i}** profiles. Nevertheless, we find that a two-component solution consisting of a narrow (\(b = 0.4\) km s\(^{-1}\)) component and a weaker broad (\(b = 3.1 \pm 0.6\) km s\(^{-1}\)) component with the same velocity separation as the Na\textsc{i} fit provides an excellent fit to the LLCC C\textsc{i} absorption toward HD 83023. As in the case of HD 85259, the C\textsc{i} and C\textsc{i}** profiles toward HD 83023 are also best fit by a single narrow component with a b-value of 0.4 km s\(^{-1}\). Figures 5 and 6 display all of these fits along with the observed profiles near 1329 Å. The resultant C\textsc{i}, C\textsc{i}*, and C\textsc{i}** column densities for both the narrow and broad LLCC components toward HD 85259 and HD 83023 are listed in Table 2. These column densities were calculated using the

### Table 1

| Star       | Column Density\(^a\) (cm\(^{-2}\)) | \(b\)-value\(^b\) (km s\(^{-1}\)) | LSR Velocity (km s\(^{-1}\)) |
|------------|-----------------------------------|---------------------------------|------------------------------|
|            |                                   |                                 |                              |
| HD 83023   | 2.39 \times 10^{11}               | 0.84                           | +4.10                        |
| HD 85259   | 3.73 \times 10^{11}               | 0.46                           | +3.85                        |
| HD 84722   | 7.55 \times 10^{11}               | 0.71                           | +3.38                        |
| HD 84937   | 1.77 \times 10^{11}               | 0.86                           | +3.01                        |
|            |                                   |                                 |                              |
| HD 83023   | 2.23 \times 10^{11}               | 0.24                           | +4.23                        |
| HD 85259   | 8.99 \times 10^{10}               | 1.83                           | +3.87                        |
| HD 84722   | 5.69 \times 10^{11}               | 0.24                           | +3.87                        |
| HD 84937   | 2.12 \times 10^{12}               | 0.24                           | +3.44                        |
| HD 84722   | 2.29 \times 10^{11}               | 1.35                           | +3.37                        |
| HD 84937   | 1.43 \times 10^{11}               | 0.24                           | +2.95                        |
| HD 84722   | 6.95 \times 10^{10}               | 1.70                           | +3.37                        |

\(a\) The measured Na\textsc{i} column densities are based on single- and double-component Voigt profile fits to the 1.3 km s\(^{-1}\) resolution optical spectra. The measured H\textsc{i} column densities are based on double-component Gaussian profile fits to the 0.184 km s\(^{-1}\) resolution 21 cm spectra (Peek et al. 2011b).

\(b\) The measured b-values represent the Gaussian line widths of the profile components (\(b = \text{FWHM}/1.665\)).

#### Notes.

- The measured Na\textsc{i} column densities are based on single- and double-component Voigt profile fits to the 1.3 km s\(^{-1}\) resolution optical spectra. The measured H\textsc{i} column densities are based on double-component Gaussian profile fits to the 0.184 km s\(^{-1}\) resolution 21 cm spectra (Peek et al. 2011b).

- The measured b-values represent the Gaussian line widths of the profile components (b = FWHM/1.665).
updated C\textsc{i} oscillator strengths determined by Jenkins & Tripp (2001, 2011).

### 3.3. Other Neutrals and Ions

In addition to C\textsc{i}, the STIS spectra reveal weak LLCC absorption arising from other trace neutrals such as S\textsc{i}, Mg\textsc{i}, and Cl\textsc{i}. Figures 7 and 8 compare the S\textsc{i} λ1425.030, Mg\textsc{i} λ2026.477, and Cl\textsc{i} λ1347.240 profiles to those of C\textsc{i} and Na\textsc{i} toward HD 85259 and HD 83023. The C\textsc{i} λ1276.483 and λ1280.135 profiles illustrated in Figures 7 and 8 are respectively the weakest C\textsc{i} lines detected in the HD 85259 and HD 83023 spectra and are fit with the same two-component solutions shown for the strong C\textsc{i} λ1328.833 line in Figures 5 and 6. There is no evidence of a broad component in the weak S\textsc{i}, Mg\textsc{i}, and Cl\textsc{i} absorption toward either star. These lines were all fitted using a single component with the same b-value (0.4 km s\(^{-1}\)) as the narrow C\textsc{i} component. The resultant S\textsc{i}, Mg\textsc{i}, and Cl\textsc{i} column densities are listed in Table 2. Given the weakness of the lines, these column densities are relatively insensitive to the profile fit. They were derived utilizing the S\textsc{i}, Mg\textsc{i}, and Cl\textsc{i} oscillator strengths compiled by Morton (2003).

Figures 9 and 10 compare the interstellar absorption profile of C\textsc{i} with those of the other dominant ions S\textsc{ii}, Cr\textsc{ii}, Ni\textsc{ii}, and Zn\textsc{ii} plus that of the excited fine-structure fraction of C\textsc{ii} (C\textsc{ii}*\textsuperscript{+}) toward HD 85259 and HD 83023. The C\textsc{ii}*\textsuperscript{+} and dominant ion profiles clearly exhibit multiple velocity components at LSR velocities blueward of the narrow LLCC absorption benchmarked by C\textsc{i}. These blue components are especially strong toward HD 85259 and are detectable in its Na\textsc{i} spectrum (see Figure 7). As discussed earlier, these components presumably arise from clouds associated with the neutral gas boundary of the Local Bubble through which HD 85259 and HD 83023 are distant enough to sample in absorption. Although the STIS spectrum of the nearer star HD 84722 is more limited in wavelength coverage and S/N, it does tend to support this interpretation. Specifically, as shown in Figure 11, the Zn\textsc{ii} λλ2026.136, 2062.664 doublet observed toward HD 84722 does not exhibit the strong components seen blueward of the LLCC absorption toward HD 85259 and HD 83023. At the same time, there is a hint of Zn\textsc{ii} absorption corresponding to a very weak Na\textsc{i} component seen at \(v_\lambda = -8.1\) km s\(^{-1}\) in the high S/N optical spectrum of HD 84722. Whether this component is associated with the LLCC, the HD 84722 environment, or somewhere in between, it most likely arises from gas inside the Local Bubble. In general, due to their velocity separation, the strong non-LLCC components are typically not a major complication in fitting the LLCC portion of the dominant ion profiles toward HD 85259 and HD 83023. The LLCC S\textsc{ii}, Cr\textsc{ii}, Ni\textsc{ii}, Zn\textsc{ii}, and C\textsc{ii}*\textsuperscript{+} column densities derived from these fits (using f-values from Jenkins & Tripp 2006 for Ni\textsc{ii} and from Morton 2003 for S\textsc{ii}, Cr\textsc{ii}, Zn\textsc{ii}, and C\textsc{ii}*) are tabulated in Table 2.

Among the dominant ion lines observed toward HD 85259 and HD 83023, the Zn\textsc{ii} doublet provides the best profile model of the LLCC absorption due to its modest strength and saturation. In the case of HD 85259, its LLCC Zn\textsc{ii} absorption is well fitted by a single narrow component with a b-value of 0.4 ± 0.1 km s\(^{-1}\). In contrast, the weaker LLCC Zn\textsc{ii} absorption toward HD 83023 is best fit with a two-component model consisting of a narrow (b = 0.4 km s\(^{-1}\)) core and a shallower broad (b = 2.8 km s\(^{-1}\)) component with the same velocity separation as its Na\textsc{i} and C\textsc{i} fits. Fitting the much stronger S\textsc{ii} λλ2150.584, 2153.811, 1259.519 triplet is more problematic, particularly for HD 83023 due to the low S/N of its far-UV spectrum. Nevertheless, we find that the best fits to the LLCC S\textsc{ii} absorption toward HD 85259 and HD 83023 both require a narrow and a broad component. Due to the saturation of the narrow component, these fits are relatively insensitive to its column density. Consequently, we adopted a b-value of

### Table 2

**The LLCC Column Densities**

| Species | HD 85259 | HD 83023 | HD 84722 |
|---------|----------|----------|----------|
| **Narrow Component** | | | |
| C\textsc{i} | 1.27 ± 0.17 × 10\(^{13}\) | 7.89 ± 1.30 × 10\(^{12}\) | ... |
| C\textsc{i}* | 9.42 ± 0.84 × 10\(^{12}\) | 5.40 ± 0.58 × 10\(^{12}\) | ... |
| C\textsc{i}** | 1.65 ± 0.13 × 10\(^{12}\) | 1.47 ± 0.24 × 10\(^{12}\) | ... |
| Na\textsc{i} | 5.69 ± 0.17 × 10\(^{11}\) | 2.23 ± 0.05 × 10\(^{11}\) | 2.12 ± 0.17 × 10\(^{12}\) |
| Mg\textsc{i} | 7.09 ± 1.21 × 10\(^{11}\) | 4.99 ± 1.33 × 10\(^{11}\) | 3.87 ± 1.19 × 10\(^{12}\) |
| S\textsc{i} | 7.37 ± 0.93 × 10\(^{11}\) | 4.21 ± 1.05 × 10\(^{11}\) | ... |
| Cl\textsc{i} | 1.67 ± 0.12 × 10\(^{12}\) | 6.44 ± 0.92 × 10\(^{11}\) | ... |
| Cu\textsc{i} | ~3 × 10\(^{13}\) | ~1 × 10\(^{13}\) | ... |
| Cr\textsc{ii} | 1.25 ± 0.57 × 10\(^{11}\) | <1.3 × 10\(^{11}\) | <5.1 × 10\(^{11}\) |
| Ni\textsc{ii} | 9.22 ± 1.52 × 10\(^{11}\) | <8.0 × 10\(^{11}\) | ... |
| Zn\textsc{ii} | 3.55 ± 0.37 × 10\(^{11}\) | 1.41 ± 0.42 × 10\(^{11}\) | 1.47 ± 0.44 × 10\(^{12}\) |
| **Broad Component** | | | |
| C\textsc{i} | 2.38 ± 0.30 × 10\(^{12}\) | 3.16 ± 0.50 × 10\(^{12}\) | ... |
| Na\textsc{i} | 7.54 ± 0.36 × 10\(^{10}\) | 8.99 ± 0.34 × 10\(^{10}\) | 2.29 ± 0.13 × 10\(^{11}\) |
| C\textsc{ii}* | 2.57 ± 0.26 × 10\(^{13}\) | 4.66 ± 0.41 × 10\(^{13}\) | ... |
| S\textsc{ii} | 1.94 ± 0.20 × 10\(^{14}\) | 2.82 ± 0.28 × 10\(^{14}\) | ... |
| Zn\textsc{ii} | ... | ... | ... |

**Notes.**

a The column densities are listed in units of cm\(^{-2}\). The quoted errors in the column densities are ±1σ values. All upper limits are 2σ values.

b The broad-component S\textsc{ii} column densities toward HD 85259 and HD 83023 were fitted assuming respective narrow-component S\textsc{ii} column densities of 1.6 × 10\(^{14}\) and 6.44 × 10\(^{13}\) cm\(^{-2}\) (based on the measured narrow-component Zn\textsc{ii} columns, the solar S/Zn abundance ratio, and a Zn depletion into dust of 0.1 dex relative to S).
Figure 4. High-resolution ($\Delta v = 1.3$ km s$^{-1}$) KPNO coude feed spectra of the interstellar Na I D$_1$ $\lambda 5895.924$ and D$_2$ $\lambda 5889.951$ absorption profiles toward HD 84937. The dotted lines through the data represent the best single velocity component Voigt fit to both of the observed profiles (the oscillator strength of the D$_2$ line is twice that of the D$_1$ line). The smooth lines through the data constitute the best two-component Voigt fit to the observed profiles. The central LSR velocities, Na I column densities, and line widths of the components associated with both fits are listed in Table 1.

0.4 km s$^{-1}$ for this S II component toward both stars and fixed its column density based on the measured Zn II columns, the solar S/Zn elemental abundance ratio ($\log(S/Zn) = 2.56$; Lodders 2003), and a Zn depletion into dust of 0.1 dex relative to S (Welty et al. 1999; Jenkins 2009a). The resulting S II column densities listed in Table 2 for the broad LLCC component were determined using fits with the same component separations as the Na I and C I models. In the case of the strong C II* $\lambda 1335.708$ ($f = 0.115$) absorption toward HD 85859 and HD 83023, a double-component LLCC solution with a narrow saturated core is also warranted. Unfortunately, the adjacent C II* $\lambda 1335.663$ ($f = 0.0128$) line does not provide much of a fitting constraint on the column density of this narrow component due to its blend with the strong non-LLCC C I 1335.708 components. Thus, the resulting column densities listed in Table 2 for the narrow LLCC C II* components toward HD 85259 and HD 83023 are very uncertain.

4. DISCUSSION

4.1. The LLCC C I Fine-structure Excitation

With excitation energies ($E/k$) of 23.6 and 62.4 K, the $J = 1$ and $J = 2$ fine-structure states of C I are predominantly populated through collisions with hydrogen atoms in cold interstellar H I clouds. Since the collision rates are a function of the H I density and temperature, the measured C I excitation reflects the thermal gas pressure of these clouds. The most thorough analysis to date of the C I fine-structure excitation in the Galactic interstellar medium has been carried out by Jenkins & Tripp (2011) who show that this excitation quickly equilibrates to its environmental pressure on a timescale of less than one year. Utilizing high-resolution HST/STIS observations of the far-UV C I multiplets, they measure the C I, C I*, and C I** column densities as a function of velocity in the interstellar absorption-line profiles of 89 stars. Building upon the smaller sample of their earlier work (Jenkins & Tripp 2001), Jenkins & Tripp (2011) calculate the thermal pressures of 2416 parcels of interstellar gas based on these column densities. Following the approach of Jenkins & Shaya (1979), they utilize the quantities $f_1 = N(C I*)/N(C I\text{ total})$ and $f_2 = N(C I**)/N(C I\text{ total})$ to relate the measured C I excitation to a grid of derived gas pressures as a function of cloud temperature. They find that the excitation of their large sample of clouds averages out to $f_1 = 0.209$ and $f_2 = 0.068$ with a derived mean gas pressure ($p/k$) of 3800 cm$^{-3}$ K.
Figure 7. Comparison of the LLCC Na\textsc{i} D\textsc{2} absorption profile with those of other trace neutrals observed in the STIS spectra of HD 85259. The Na\textsc{i} absorption blueward of the strong LLCC feature at \( v_{\text{LSR}} = 3.9 \text{ km s}^{-1} \) arises from the neutral gas boundary of the Local Bubble at a distance between 100 and 150 pc. The C\textsc{i} \( \lambda 1276.483 \) profile represents the weakest LLCC C\textsc{i} line detectable in the HD 85259 STIS spectra. Its oscillator strength is 7.6 times smaller than that of the C\textsc{i} \( \lambda 1328.833 \) line shown in Figure 5. The illustrated fits to the S\textsc{i}, Mg\textsc{i}, C\textsc{i}, Cl\textsc{i}, and Na\textsc{i} profiles reflect the LLCC column densities listed in Table 2 for the HD 85259 sightline.

Our measurements of the LLCC C\textsc{i}, C\textsc{i}\textsuperscript{*}, and C\textsc{i}\textsuperscript{**} column densities toward HD 85259 and HD 83023 yield respective \( (f_1, f_2) \) values of \((0.396 \pm 0.036, 0.069 \pm 0.008)\) and \((0.366 \pm 0.041, 0.100 \pm 0.018)\). In Figure 12, we plot these points plus their weighted mean value \((0.383 \pm 0.027, 0.074 \pm 0.007)\) amidst three curves denoting the derived \( (f_1, f_2) \) values for a range of gas pressures in clouds with temperatures of 15, 20, and 30 K (as cloud temperatures rise above these values, the curves remain closely spaced at low pressure (low \( f_1 \)) and pull back to the left at high pressure (high \( f_2 \))). These curves were calculated in a manner similar to that of Jenkins & Tripp (2011) using the same collision, radiative decay, and optical pumping rates along with the average stellar radiation field appropriate for the solar vicinity (Mathis et al. 1983). As noted by Jenkins & Tripp (2001), the \( (f_1, f_2) \) values are relatively insensitive to uncertainties in the radiation field when the pressure is greater than 10,000 cm\textsuperscript{−3} K. Given that the LLCC has a temperature of \( \approx 20 \) K, Figure 12 clearly indicates that its gas pressure toward both HD 85259 and HD 83023 is well in excess of 10,000 cm\textsuperscript{−3} K. Specifically, the HD 83023 data point falls 1.6\sigma above the 20 K curve at a pressure of 40,000 cm\textsuperscript{−3} K and that of HD 85259 falls 1.8\sigma below the 20 K curve at a pressure of 80,000 cm\textsuperscript{−3} K. Their weighted mean \( (f_1, f_2) \) value falls almost exactly on the 20 K curve at a pressure of 60,000 cm\textsuperscript{−3} K. In contrast, the vast majority of the Jenkins & Tripp (2011) data points have \( (f_1, f_2) \) values that place them above and/or left of the theoretical curves for individual clouds. They interpret these values as arising from mixtures of low-pressure and high-pressure C\textsc{i} components in their long-path sightlines that unresolvably overlap in velocity. In the cases of HD 83023 and HD 85259, the narrow LLCC C\textsc{i} component stands out in the spectra of these nearby stars with an excitation that closely matches the theoretical expectations for a very cold, highly pressurized cloud. Such conditions are very rare among the 2416 C\textsc{i} parcels sampled by Jenkins & Tripp (2011)—less than 1% of these clouds have \( (f_1, f_2) \) excitation values corresponding to temperatures less than 30 K and pressures greater than 10,000 cm\textsuperscript{−3} K.

The highly pressurized nature of the LLCC is particularly intriguing given its location deep inside the Local Bubble. As reviewed by Jenkins (2009b) and Welsh & Shelton (2009), the pressure balance of interstellar gas in this environment has long been a contentious issue. Since the discovery of the diffuse soft X-ray background in the 1970s, numerous studies through the 1990s interpreted it in terms of hot gas filling the Local Bubble with a pressure somewhere between 10,000 and 20,000 cm\textsuperscript{−3} K. Yet studies of cooler clouds within the Bubble have consistently yielded pressures below these values. Jenkins (2002) utilized
**Figure 9.** Comparison of the Cl $\lambda 1347.2396$ absorption profile with those of selected dominant ions in the STIS spectra of HD 85259. Unlike the Cl profile where the LLCC absorption stands alone, the Cr $\text{II}$, Ni $\text{II}$, Zn $\text{II}$, S $\text{II}$, and C $\text{II}$ profiles all show significant blueward absorption arising from gas beyond the LLCC. The illustrated fits to these profiles reflect the LLCC column densities listed in Table 2 for the HD 85259 sightline.

**Figure 10.** Comparison of the Cl $\lambda 1347.2396$ absorption profile with those of selected dominant ions in the STIS spectra of HD 83023. Unlike the Cl profile where the LLCC absorption stands alone, the Zn $\text{II}$, S $\text{II}$, and C $\text{II}$ profiles all show significant blueward absorption arising from gas beyond the LLCC. The illustrated fits to these profiles reflect the LLCC column densities listed in Table 2 for the HD 83023 sightline.

_HST C_1 observations to constrain the thermal pressures of four clouds inside or near the edge of the Local Bubble to values between 1000 and 10,000 cm$^{-3}$ K. Redfield & Linsky (2004) measured the temperatures of 50 warm, partially ionized clouds within the Bubble and determined their mean thermal pressure to be 2300 cm$^{-3}$ K. Recently, measurements of the foreground X-ray emission from solar wind charge exchange (Robertson et al. 2010) and the Peek et al. (2011b) finding of weak X-ray shadowing by the LLCC have weakened the case for a higher-pressure hot Local Bubble. Although some hot gas is undoubtedly present, its thermal pressure is most likely in a range (3000–7000 cm$^{-3}$ K) consistent with that of the warm clouds (Frisch et al. 2011). In contrast, the much higher mean LLCC pressure of 60,000 cm$^{-3}$ K measured toward HD 83023 and HD 85259 clearly indicates that the LLCC is not in thermal pressure equilibrium with either the hot gas or the warm clouds in the Local Bubble. Given the LLCC temperature of $\approx 20$ K and a typical H$\text{I}$ column density of $\approx 10^{19}$ cm$^{-2}$, this pressure
infalling warm gas by factors of 1.5–5. In contrast, the C at the collision interface is overpressured with respect to the Local Bubble. Vazquez-Semadeni et al. (2006) show that the cold, dense gas interface layer should balance the total (thermal plus ram) pressure of the colliding flows. In their analytical model of two oppositely directed warm gas streams (with \( T = 7100 \) K and \( n = 0.34 \) cm\(^{-3}\)), Vazquez-Semadeni et al. (2006) find that an inflow Mach number of 3.7 is required of each stream relative to the interface layer to produce a pressure of 60,000 cm\(^{-3}\) K in that layer. Such an inflow would correspond to a velocity difference of 60 km s\(^{-1}\) between the streams given an 8.4 km s\(^{-1}\) sound speed in the 7100 K gas. In terms of radial velocity, there is no evidence of warm clouds in the LLCC vicinity with such a large velocity differential. In Figure 13, we compare the HD 84722 21 cm emission and the C\( \text{ii} \) λ1334.532 absorption in the HD 85259 and HD 83023 sightlines. This strong C\( \text{ii} \) line is a very sensitive tracer of both warm and cold interstellar gas due to its high \( j_f \) Value, the abundance of C, and the C\( \text{ii} \) ionization potential (24.38 eV). The maximum velocity width of the single saturated C\( \text{ii} \) λ1334.532 absorption feature observed toward HD 83023 and HD 85259 is about 35 km s\(^{-1}\). The absence of any other C\( \text{ii} \) absorption lines in these spectra indicates that there are no foreground warm cloud pairs in the LLCC vicinity with hydrogen column densities greater than \( 10^{16} \) cm\(^{-2}\) and a radial velocity differential greater than 35 km s\(^{-1}\). As noted by Redfield & Linsky (2008), the LLCC sky position is near the boundaries of the nearby Gem, Leo, and Aur warm clouds. Although the Leo and Aur clouds both have radial velocities similar to that of the LLCC, the Gem cloud’s radial motion is only faster by 12 km s\(^{-1}\). Furthermore, the upper limits on the distances of the Gem, Leo, and Aur clouds are all below the lower bound (11.26 ± 0.21 pc) on the LLCC distance (Peek et al. 2011b).

Other factors may help to provide a better match of the observed LLCC pressure with that expected in a colliding flow scenario. For example, the colliding warm clouds might have a significant difference in their transverse velocities. Given the measured radial velocity gradient along the long cold cloud ribbon centered on the LLCC (Haud 2010), U. Haud (2012, private communication) has calculated a transverse LLCC LSR velocity of 16 km s\(^{-1}\) based on a ring model of the cloud ribbon.
Although this value is not a serious constraint on the transverse velocity differential of any parent warm cloud collision, it is four times greater than the radial LLCC LSR velocity. Other factors to consider are the temperature and density of the warm clouds themselves. If the temperature assumed by Vazquez-Semadeni et al. (2006) is decreased with a corresponding increase of the density (to maintain the same warm cloud pressure), the velocity flow differential needed to produce a pressure of $10^{16}$ cm$^{-3}$ K in the cold interface layer is reduced by the square root of the temperature reduction factor. Although such adjustments and transverse component considerations can close the gap, there is no question that the observed radial velocity constraints are a key hurdle toward fully understanding the high LLCC pressure in terms of a warm cloud collision. It is also important to note that the peak LLCC H$_1$ column density would require warm source clouds of appreciably higher column density than any previously identified in the nearby Local Bubble. Although the broad absorption component seen in our Na I and UV spectra attests to an appreciable column of warm gas in the LLCC sightlines, it could be associated with post-shock gas just outside the 20 K interface layer rather than the warmer source clouds.

A common feature of the colliding warm flow models (Audit & Hennebelle 2005; Gazol et al. 2005; Heitsch et al. 2006; Vazquez-Semadeni et al. 2006) is the turbulent fragmentation of the cold interface layer into clumpy structures. Some of the simulations (Audit & Hennebelle 2005; Gazol et al. 2005) have shown that localized regions within these structures can reach pressures up to $10^5$ cm$^{-3}$ K even when the collision is transonic (Hennebelle et al. 2007). It is quite likely that the different C I LLCC pressures measured toward HD 83023 (40,000 cm$^{-3}$ K) and HD 85259 (80,000 cm$^{-3}$ K) (both assuming $T = 20$ K) are due in part to real localized pressure variations rather than measurement errors alone. Both sightlines are located on the periphery of the LLCC (4.4 (1.4 pc) apart) with H I column densities that are more than 10 times below the peak interior value. Given the narrowness of their C I absorption beams and the pressure-implied thinness of their cloud regions, the HD 83023 and HD 85259 sightlines clearly provide extremely localized pressure samples of the LLCC. Consequently, the agreement of their significant overpressures within a factor of two argues for a large-scale LLCC explanation like a warm cloud collision. At the same time, the turbulent fragmentation expected in the wake of such a collision could push these localized overpressures above the limiting values implied by the measured velocity constraints on the colliding clouds.

4.2. The Elemental Dust Depletion of the LLCC

The abundance and elemental composition of dust in diffuse interstellar clouds can be estimated by comparing the gas-phase column density ratios of various dominant ions measured from their UV absorption lines to a set of reference elemental abundance ratios such as the solar values. As reviewed by Savage & Sembach (1996), a number of interstellar UV studies have shown that some elements such as Zn are only weakly depleted from the gas phase into dust grains while others such as Ni and Cr exhibit strong depletions. Recently, Jenkins (2009a) has systematically analyzed the dust depletion patterns of 17 elements based on UV absorption-line measurements toward 243 stars and the Lodders (2003) solar reference abundances. He interprets the depletion of each element relative to hydrogen in terms of a “line-of-sight depletion strength factor” ($F_*$) applicable to all of the elements in a given sightline plus two other element-specific parameters. $F_*$ is a dimensionless parameter that Jenkins has normalized to equal 0.0 for the lowest collective depletions in his sample and to equal 1.0 for the strong depletions observed in the cold ζ Oph cloud that has long been considered the prototype for the cold neutral medium. The Jenkins (2009a) results allow us to analyze the measurements of the LLCC gas-phase elemental abundances and interpret their dust depletion in the comparative context of a large sample of other Galactic sightlines. In our analysis, the cold hydrogen gas comprising the LLCC is entirely in the form of H I (we show in Section 4.4 that the H$_2$ concentration is very low) and the LLCC column density ratios of dominant ions are taken to reflect their gas-phase elemental abundance ratios.

As listed in Table 2, the Zn II and Ni II lines observed toward HD 85259 provide the best-measured dominant ion column

![Figure 13. Comparison of the C II λ1334.532 absorption and H I 21 cm emission in the HD 85259 and HD 83023 sightlines. The GALFA-H I spectra have spatial and velocity resolutions of 4′ and 0.184 km s$^{-1}$. The LSR velocity of the LLCC Na I absorption toward HD 85259 and HD 83023 is denoted with a dotted line through the displayed spectra. The absence of any C II absorption lines outside the single saturated feature in these spectra indicates that there are no foreground warm cloud pairs in the LLCC vicinity with H column densities greater than $10^{16}$ cm$^{-2}$ and a radial velocity differential greater than 35 km s$^{-1}$.](image-url)
densities from our STIS spectra for the gas associated with the narrow LLCC absorption component. Since Ni is depleted much more strongly into dust than Zn, the logarithmic ratio of their column densities relative to the solar Ni/Zn abundance ratio yields a relative depletion \( [\text{Ni}/\text{Zn}] = \log((N(\text{Ni}))/N(\text{Zn})) - \log(\text{Ni}/\text{Zn})) \) that is very sensitive to the depletion strength factor \( F_c \). Although such elemental comparisons can be compromised by photoionization to higher ionization stages in sightlines with H \( i \) columns below \( 10^{19.5} \) cm\(^{-2} \) like HD 85259 and HD 83023 (Jenkins 2009a), it is unlikely in the case of Ni \( i \) and Zn \( i \) since they have nearly identical ionization potentials. The corresponding value of \( -1.18 \pm 0.10 \) for \([\text{Ni}/\text{Zn}] \) in the HD 85259 sightline indicates a factor of \( F_c = 0.2 \pm 0.1 \) for the LLCC. In the case of HD 83023, the 2\( \sigma \) upper limit on its LLCC Ni \( i \) column density leads to an upper limit on \([\text{Ni}/\text{Zn}] \) that is too large to seriously constrain \( F_c \). Since Cr is also depleted more strongly into dust than Zn, the [Cr/Zn] ratio can provide an additional indicator of \( F_c \). Unfortunately, our measurements of the Cr \( i \) column density in the LLCC consist only of a marginal result toward HD 85259 and upper limits toward HD 83023 and HD 84722. Nevertheless, the resulting [Cr/Zn] values of \( -1.47 \pm 0.28, < -1.05 \pm 0.15, \) and \( < -1.48 \pm 0.16 \) for the LLCC in the HD 85259, HD 83023, and HD 84722 sightlines correspond to respective \( F_c \) factors and lower limits of \( 0.7 \pm 0.3, > 0.2 \pm 0.2, \) and \( > 0.7 \pm 0.2 \). Collectively, these [Cr/Zn] constraints indicate a somewhat higher \( F_c \) for the LLCC than the more accurate value provided by [Ni/Zn] toward HD 85259. Specifically, the [Ni/Zn] and [Cr/Zn] depletions taken together yield a weighted mean \( F_c \) of 0.3 for the LLCC in the HD 85259 sightline.

The modest dust content implied by a low depletion strength factor for the LLCC is consistent with the infrared dust emission measured by Peek et al. (2011b). In comparing the 100 \( \mu \)m emission and H \( i \) column density over the sky area of the LLCC, they find a best-fit value of \( 4.8 \times 10^{-21} \) MJy sr\(^{-1} \) cm\(^{-2} \) for the LLCC dust-to-gas ratio. This value is lower than the standard Galactic (\( 1.0 \times 10^{-20} \) MJy sr\(^{-1} \) cm\(^{-2} \)) and high-latitude (\( 6.7 \times 10^{-21} \) MJy sr\(^{-1} \) cm\(^{-2} \)) dust-to-gas ratios measured by Boulanger & Perault (1988) and Schlegel et al. (1998), respectively. As indicated by \( F_c \), the LLCC [Ni/Zn] and [Cr/Zn] depletions toward HD 85259 are also below those expected for cold, dense clouds. They are more consistent with the [Ni/Zn] \( \approx -1.2 \) and [Cr/Zn] \( \approx -1.0 \) values typical of warm clouds (Welty et al. 1999). Such a pattern would support the idea that the LLCC is the product of a warm cloud collision. Whether or not the collision itself disrupts some grain material into the gas phase, the LLCC should not exhibit higher dust depletions than the warm clouds feeding it.

Since Zn is weakly depleted into grains, the value of [Zn/H] is relatively insensitive to \( F_c \) and can be used with the measured Zn \( i \) column densities to calculate the corresponding H \( i \) column densities of the gas associated with the narrow LLCC component. Applying the [Zn/H] depletion (\( -0.1 \) dex) appropriate for an \( F_c = 0.3 \), the Zn \( i \) columns toward HD 85259, HD 83023, and HD 84722 indicate respective LLCC \( N(\text{H}) \) columns of \( 8.9 \pm 0.9 \times 10^{18} \), \( 3.5 \pm 1.0 \times 10^{18} \), and \( 3.7 \pm 1.1 \times 10^{19} \) cm\(^{-2} \). Within the errors, these \( N(\text{H}) \) values are consistent with those measured for the strongest 21 cm component in the Peek et al. (2011b) two-component fit (Table 1) to the LLCC H \( i \) emission in the three sightlines. Although there is no evidence of another narrow component in the Zn \( i \) profiles corresponding to the weaker of the two closely spaced 21 cm components, the STIS spectra are not definitive in this regard due to their lower velocity resolution. However, for the broad secondary LLCC component observed in Na \( i \) and C \( i \), the STIS data do provide well-measured column densities of S \( ii \) and Zn \( ii \) toward HD 83023 and of S \( ii \) toward HD 85259. The S \( ii \) and Zn \( ii \) columns are particularly interesting to compare because both S and Zn are weakly depleted into grains in diffuse clouds (Savage & Sembach 1996). Assuming that Zn is depleted into dust by 0.1 dex with respect to S (Welty et al. 1999; Jenkins 2009a) and that none of the hydrogen in the broad-component cloud is ionized, the value of log \( N(\text{S} \ i)/N(\text{Zn} \ i) \) in the cloud should equal 2.66. In the case of the HD 83023 sightline, the measured value of this logarithmic column density ratio is 3.00 \( \pm 0.09 \). This enhancement of the S \( i \) abundance relative to that of Zn could reflect a partial ionization of hydrogen in the broad-component cloud. Since S \( i \) (23.34 eV) has a higher ionization potential than Zn \( ii \) (17.96 eV), the ionized fraction of the cloud could raise the net \( N(\text{S} \ i)/N(\text{Zn} \ i) \) ratio above that expected from the neutral fraction. Such a possibility would be consistent with the idea of the broad LLCC component arising from warm post-shock gas or one of the colliding warm clouds producing the LLCC. Given the \( N(\text{S} \ i)/N(\text{Zn} \ i) \) ratio observed for the broad component toward HD 83023, the non-detection of the corresponding Zn \( ii \) component toward HD 85259 is consistent with its lower S \( ii \) column density.

4.3. The Electron Density of the LLCC

Given how the LLCC stands out among diffuse clouds in terms of its temperature and gas pressure, an evaluation of its electron density provides another key parameter for comparison. As reviewed by Welty et al. (2003), the electron density of a diffuse H \( i \) cloud can be estimated by comparing the trace neutral and dominant ion column densities of various elements under the assumption of photoionization equilibrium. This comparison is quantified through the expression \( n_e = \Gamma(\alpha/\alpha_X)N(X \ i)/N(\text{H} \ i) \) where \( \Gamma \) represents the photoionization rate appropriate for element X and the local radiation field while \( \alpha \) is the temperature-dependent radiative recombination coefficient associated with the dominant ion. Various absorption-line studies utilizing this approach have found that the electron densities derived from different elements in the same diffuse cloud sightline can differ by as much as a factor of 10 (Fitzpatrick & Spitzer 1997; Welty et al. 1999, 2003). Also, these derived electron densities are typically higher than the \( n_e \sim 10^{-3} n_{\text{H}} \) value expected under the simplest assumption that the photoionization of carbon is the predominant source of electrons in the cloud. Indeed, Welty et al. (2003) have found no significant relationship between \( n_e \) (as determined from the photoionization equilibrium of C, Na, and K) and \( n_{\text{H}} \) (as determined from the C \( i \) fine-structure excitation) in their sample of diffuse cloud sightlines. Apart from uncertainties in the input parameters (rate coefficients, radiation field, etc.), they concluded that “... additional processes besides photoionization and radiative recombination commonly and significantly affect the ionization balance of heavy elements in diffuse interstellar clouds.” Such processes include charge exchange between the dominant ions and dust grains (or polycyclic aromatic hydrocarbons (PAHs)) in the cloud which would raise the trace neutral abundances and the inferred electron densities (Lepp et al. 1988).

In evaluating the electron density of the LLCC, our focus is on the HD 85259 sightline due to the greater accuracy of its narrow-component column density measurements. We consider first the photoionization balance of C, S, Na, and Mg. Although we have measured only the trace neutral column densities for these species (Table 2), the corresponding dominant ion...
columns can be estimated utilizing the measured Zn II column, the Lodders (2003) solar abundances, and the appropriate dust depletions. In the case of the latter, our evaluation of the LLCC dust depletion toward HD 85259 indicates that Zn, C, Na, and Mg are depleted by 0.10, 0.14, 0.40, and 0.57 dex with respect to S (which is assumed to be undepleted; Welty et al. 1999; Jenkins 2009a). The resulting gas-phase C II, S II, Na II, and Mg II column densities are 1.80 × 10^{15}, 1.62 × 10^{14}, 7.75 × 10^{12}, and 9.93 × 10^{13} cm^{-2}, respectively. The radiative recombination rate coefficients (α) appropriate for C II (2.27 × 10^{-11} cm^{3} s^{-1}), S II (2.06 × 10^{-11} cm^{3} s^{-1}), Na II (1.83 × 10^{-11} cm^{3} s^{-1}), and Mg II (2.84 × 10^{-11} cm^{3} s^{-1}) at the LLCC temperature of 20 K are taken from the compilation of Verner (1999). The photoionization rates (γ) adopted for C I (2.58 × 10^{-10} s^{-1}), S I (9.25 × 10^{-10} s^{-1}), Na I (7.59 × 10^{-12} s^{-1}), and Mg I (5.39 × 10^{-11} s^{-1}) were calculated by Draine (2011) utilizing the Mathis et al. (1983) estimate of the local interstellar radiation field. Assuming photoionization equilibrium governed by these rates and coefficients, the measured trace neutral and inferred dominant ion column densities of C, S, Na, and Mg in the HD 85259 sightline indicate respective LLCC electron densities of 0.15, 0.20, 0.030, and 0.014 cm^{-3}.

Although the spread in the \( n_e \) values toward HD 85259 is similar to those derived from the photoionization balance of C, S, Na, and Mg in other diffuse cloud sightlines (Welty et al. 2003), there is an unusual pattern in the LLCC numbers. Specifically, the species (C I and S I) with the highest photoionization rates and ionization potentials yield significantly larger electron densities than the two (Na I and Mg I) with the lowest rates and potentials. Possible explanations for such a pattern range from a softer-than-expected local radiation field to biased trace neutral formation associated with a sharp density peak within the cloud. As discussed by Lauroesch & Meyer (2003), the latter possibility could produce ionization-dependent spatial variations in the distribution of trace neutrals due to the distance differences that various neutrals could travel on average from their predominant density-peak origin before photoionization. Consequently, in the presence of a sharp density peak, the trace neutrals with the highest photoionization rates will be more localized near the peak than those with lower rates and thus, their photoionization balance with density-dependent recombination will yield higher inferred electron densities. The potential attraction of this idea in the case of the LLCC is that such a density peak would be expected in the colliding warm cloud model.

The mean LLCC electron density determined from the photoionization balance of C, S, Na, and Mg toward HD 85259 is 0.1 cm^{-3}. In comparison, an electron density of ~0.4 cm^{-3} would be expected based on the LLCC hydrogen density \( n(H) \approx 4000 \) cm^{-3} determined from the C I fine-structure excitation in this sightline and the assumption that the photoionization of carbon is the predominant source of electrons \( (n_e \sim 10^{-4} n(H)) \) in this cloud. The contrast between the LLCC and similarly measured diffuse clouds is especially striking in terms of \( n_e / n(H) \). The LLCC value of 2.5 × 10^{-5} for this quantity is well outside the \( n_e / n(H) \approx 0.0002–0.02 \) range typical of other clouds (Welty et al. 2003). Given the modest dust content of the LLCC, it is certainly possible that the LLCC lacks the grains (and PAHs) to elevate its trace neutral abundances and inferred electron density through charge exchange with dominant ions. It is more likely that the low LLCC \( n_e / n(H) \) value is due to density inhomogeneities in the cloud such as a sharp density peak. The value of \( n(H) \) is determined from the C I fine-structure excitation and, thus, is biased toward high-density regions along the sightline where C I is most abundant. The value of \( n_e \), on the other hand, is weighted by the broader sightline distribution of the dominant ions and represents more of an average throughout the cloud. Consequently, one would expect a lower value of \( n_e / n(H) \) in a cloud with a sharp density peak than one that is more homogeneous.

Another approach to estimating the electron density of a diffuse cloud is through the analysis of its C II fine-structure excitation (Fitzpatrick & Spitzer 1997; Welty et al. 1999; Welty 2007; Draine 2011). At the temperature \( (T \approx 80 \text{K}) \) and density \( (n(H) \approx 10 \text{~cm}^{-3}) \) typical of cold diffuse clouds, this excitation is dominated by collisions with electrons. However, in a high-density cloud like the LLCC, the contribution from collisions with hydrogen atoms is also significant. In evaluating the LLCC C II fine-structure excitation in the HD 85259 sightline, the largest source of error is the C II* column density. As discussed in Section 3.3, the profile fit to the narrow C II* \( \lambda \lambda 1335.663,1335.708 \) absorption arising from the LLCC is complicated by heavy saturation and blending issues. Our best estimate of \( 3 \times 10^{13} \text{~cm}^{-2} \) for \( N(C(\text{II}*)) \) in this LLCC sightline is thus quite uncertain. Nevertheless, utilizing the appropriate excitation rates (Welty et al. 1999) for a cloud temperature of 20 K and assuming that \( n(H) = 4000 \text{~cm}^{-3} \), this level of C II fine-structure excitation \( (N(C(\text{II}^*)) / N(C(\text{II})) = 0.0167) \) indicates an electron density of 8.8 cm^{-3}. A much smaller value \( (n_e \sim 0.1 \text{~cm}^{-3}) \) consistent with the photoionization balance of C, S, Na, and Mg would only reduce the C II* excitation by 30%—an amount well within the uncertainty of \( N(C(\text{II}^*)) \). In other words, the high LLCC hydrogen density in the HD 85259 sightline makes its C II fine-structure excitation relatively insensitive as an indicator of the cloud’s electron density.

### 4.4. Molecular Hydrogen in the LLCC

Unlike the cases of C, S, Na, and Mg, the ionization balance of Cl in diffuse clouds is complicated by an exothermic reaction between Cl I and H2 which can lead to the predominance of the “trace” neutral Cl I if the abundance of H2 is significant (Jura & York 1978; Mooney et al. 2011). Based on the measured Cl I and Zn II columns (Table 2), the Lodders (2003) solar Cl abundance, and the Cl dust depletion (+0.07 dex) appropriate for an \( F_r = 0.3 \) cloud (Jenkins 2009a), the LLCC Cl II column density in the HD 85259 sightline is \( 5.70 \times 10^{13} \text{~cm}^{-2} \). Assuming an H2-free cloud where the Cl photoionization equilibrium is governed by \( \alpha(C(\text{II})) = 9.91 \times 10^{-11} \text{~cm}^{3} \text{~s}^{-1} \) (Verner 1999) and \( \Gamma(C(\text{I})) = 3.59 \times 10^{-10} \text{~s}^{-1} \) (Draine 2011; Mathis et al. 1983), the Cl I and Cl II column densities toward HD 85259 would indicate an LLCC electron density of 10.6 cm^{-3}. Although this electron density leads to a value of \( n_e / n(H) \approx 0.003 \) that is consistent with those of other diffuse clouds (Welty et al. 2003), it is \( \approx 100 \) times greater than the mean LLCC electron density determined from the photoionization balance of C, S, Na, and Mg. Alternatively, a modest abundance of H2 could explain the observed LLCC Cl I column toward HD 85259. Assuming \( n_e = 0.1 \text{~cm}^{-3} \) and utilizing a rate constant of \( k = 7 \times 10^{-10} \text{~cm}^{3} \text{~s}^{-1} \) for the reaction between Cl I and H2 (Welty et al. 1999), the required H2 density would be 1.5 cm^{-3}. This H2 density is certainly modest in comparison to the hydrogen density \( (n(H) \approx 4000 \text{~cm}^{-3}) \) measured from the Cl fine-structure excitation and would indicate an LLCC H2 column density of \( \approx 3 \times 10^{15} \text{~cm}^{-2} \) in the HD 85259 sightline.

The modest LLCC H2 column density inferred from the Cl ionization balance toward HD 85259 is consistent with the lack
of ultraviolet CO absorption in this sightline. Specifically, we measure a 2σ upper limit of 2.5 × 10^{12} cm^{-2} on the CO column density based on the absence of the [A-X](4-0)R(0) λ1419.044 line in our STIS spectra of HD 85259. The interstellar CO/H_2 column density ratio has been found to vary from ≈10^{-4} for dense clouds to ≈10^{-5} for translucent clouds to ≈10^{-7} for diffuse clouds (Burgh et al. 2007). Even with the assumption of the highest of these values for the LLCC, the inferred H_2 column density toward HD 85259 implies a CO column density (≈3 × 10^{11} cm^{-2}) that is well below our STIS upper limit.

4.5. Solar-system-scale Na i Structure in the LLCC

A key implication of the high LLCC gas pressures measured toward HD 85259 and HD 83023 is that the densest region of the cloud must be very thin. In the case of the HD 85259 sightline, a comparison of the pressure-inferred hydrogen volume density (n_H ≈ 4000 cm^{-3}) and the measured H i column density yields an LLCC H i thickness of ≈200 AU. However, it is important to note that the spatial distribution of trace neutrals like C i in diffuse clouds is not likely to match that of H i. As discussed by Lauroesch & Meyer (2003), since trace neutrals are biased by the recombination rates to form most abundantly near the peaks of the hydrogen density distribution within a cloud, their abundances will fluctuate more strongly on smaller length scales than those of H i and dominant ions. Consequently, in the presence of a sharp density peak, the LLCC gas pressure measured by the C i fine-structure excitation toward HD 85259 would be more representative of the density peak where C i is most abundant than that of the full H i extent of the LLCC. In other words, the C i thickness of the LLCC toward HD 85259 could be somewhat less than 200 AU while the H i thickness could be appreciably greater. If the trace neutral “layer” is indeed this thin, one would expect to observe column density fluctuations in the trace neutrals on very small transverse scales across the LLCC. Testing for such solar-system-scale structure is possible through multi-epoch Na i absorption-line observations of high-proper-motion background stars.

As reviewed by Lauroesch (2007), about 15% of the 40 diffuse cloud sightlines studied for temporal Na i absorption variations have revealed evidence for structure on scales of 50 AU or less. The sightlines exhibiting such variations appear to be preferentially associated with intervening H i shells. Variations in dominant ion absorption on these scales have been observed in only one case to date—the CPD -59 2603 sightline through the Carina Nebula (Danks et al. 2001). Among the clouds exhibiting solar-system-scale Na i structure, those in the sightlines toward HD 32040 (Lauroesch et al. 2000), ρ Leo (Lauroesch & Meyer 2003), and HD 219188 (Welty 2007) have been evaluated through observations of their C i fine-structure excitation. The derived pressures of these clouds range from 2000 cm^{-3} K to an upper limit of 20,000 cm^{-3} K with inferred hydrogen densities (n_H) between 20 cm^{-3} and 200 cm^{-3}. In the case of the HD 219188 cloud, Welty (2007) was able to measure the C i excitation multiple times with HST over a nine-year time span and found that n_H increased from 20 cm^{-3} to 45 cm^{-3} as N(C i) and N(Na i) increased over a transverse spatial scale somewhere between 10 and 200 AU (scale uncertainty due to unknown distance of the intervening cloud). Based on these results and the lack of dominant ion differences, observations of temporal Na i variations have generally been interpreted as arising from solar-system-scale cloud fluctuations in n_H and/or n_e rather than in N(H i).

Among the 16 stars found by Meyer et al. (2006) to exhibit narrow Na i absorption corresponding to the LLCC, HD 84937 has by far the largest proper motion (0.860 arcsec yr^{-1}). In Figure 14, we compare the initial 2006 January Na i spectrum of this star with that taken in 2009 January. While the broader stellar Na i absorption at v_{LSR} = −21 km s^{-1} is identical in both spectra, the narrow LLCC Na i absorption exhibits a significant difference in strength between the two epochs. This difference corresponds to a 40% increase in the LLCC Na i column density over the course of three years in the HD 84937 sightline. Given the 0.860 arcsec yr^{-1} proper motion of HD 84937 and a distance estimate of 17.8 pc for the LLCC, this increase occurred over a transverse distance of 46 AU across the cloud.

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translate to respective transverse distances of only 1.4, 2.2, and 2.0 AU across the LLCC over the course of our observations. Also, the greater strength of the LLCC Na i lines in these sightlines compared to those toward HD 84937 makes their equivalent widths less sensitive to comparable column density differences. Nevertheless, the HD 84937 results provide ample motivation to continue monitoring the Na i absorption toward the highest proper-motion LLCC background stars among the Meyer et al. (2006) sample.

The detection of Na i structure on a scale of 46 AU toward HD 84937 indicates that the trace neutrals in this LLCC sightline are abundant in a very thin layer. It is thus consistent with the sharp density peak and sheet-like LLCC geometry implied by the high gas pressures measured toward HD 85259 and HD 83023. At the assumed 17.8 pc distance of the LLCC, the HD 85259 and HD 83023 sightlines are separated by 1.4 pc (4:4), the HD 83023 and HD 84937 sightlines are separated by 1.0 pc (3:2), and the HD 85259 and HD 84937 sightlines are separated by 0.6 pc (2:0). Given these separations, it certainly appears that the cold, highly pressurized, low N(H i) gas observed toward HD 85259 and HD 84937 is representative of the LLCC and not a localized fluctuation within the cloud. Understanding the global overpressure of the LLCC gas with respect to the Local Bubble environment then requires either a non-equilibrium solution where the LLCC is a transient phenomenon or something like the Vazquez-Semadeni et al. (2006) colliding-cloud model where the LLCC can be sustained indefinitely as a thin, cold, dense interface between converging flows of warmer gas.

From a broader perspective, it is interesting that the coldest, densest, low-column-density interstellar cloud now known in the Galaxy is located only ≈20 pc away from the Sun. It is either just a fortunate coincidence to have such an unusual cloud nearby for close study or a manifestation of a selection effect that works against detecting such clouds at greater distances. In support of the former, the characteristics of the LLCC not only stand out in comparison with samples of many diffuse clouds (such as the comprehensive C1 study of Jenkins & Tripp 2011), its overpressure could be interpreted in terms of a transient phenomenon. Yet, Jenkins & Tripp (2011) have found evidence for a weak, but pervasive contribution from high-pressure (log(p/k) > 5.5), high-temperature (T > 80 K) gas in their measured distribution of interstellar pressures. The weak admixture of this high-f1, high-f2 gas stands out in their C1(f1,f2) diagnostic plot by pulling the net (f1,f2) values of the measured gas parcels above the theoretical curves for the dominant lower-pressure gas. It is important to note that a similar weak, pervasive admixture of high-pressure, low-temperature gas (like that of the LLCC) would not stand out in the Jenkins & Tripp (2011) C1 diagnostics. This high-f1, low-f2 gas would pull the net (f1,f2) values of the measured gas parcels to the right on slopes similar to that of the theoretical curves for individual clouds of lower-pressure gas. In other words, it is possible that LLCC-type clouds may not be uncommon in the Galaxy.

In support of this possibility, it is vital to recognize that the radio, optical, and UV study of the nearby LLCC has been aided by the modest interstellar gas background toward the Galactic halo—identification of LLCCs at greater distances in the Galactic disk would be greatly complicated by both foreground (radio, optical, UV) and background (radio) gas with overlapping velocity signatures. Furthermore, despite its large angular size, the total H i mass of the LLCC is only ≈1 M⊙. A distant, similar-sized LLCC would have a much less noticeable angular extent. For example, at 1000 pc, the LLCC would cover only a 12′ × 2′5 patch of sky. Given the observation of solar-system-scale Na i structure toward HD 84937, it is tempting to consider this characteristic as a potential LLCC-type signature in the other sightlines where it has been observed. However, none of these sightlines have yet revealed C i pressures as high as those measured in the LLCC despite their preferential association with H i shells. A key step toward a broader understanding of the LLCC will come with the measurement of the distances, pressures, and structure of the other cold clouds comprising the 70°-long Haud (2010) H i ribbon stretching from Gemini through Leo to Sextans.

We are especially grateful to the referee, Edward Jenkins, whose detailed and constructive review was very helpful in improving the paper. We also thank Urmas Haud for his calculation of the LLCC transverse velocity, Enrique Vazquez-Semadeni for his valuable comments on the manuscript, and Daryl Willmarch for his assistance with the KPNO observations. Support for program GO 11736 was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555. J.E.G.P. was supported by HST-HF-51295.01A, provided by NASA through a Hubble Fellowship grant from STScI, which is operated by AURA under NASA contract NAS5-26555.

Facilities: HST (STIS), KPNO:CFT (Coude Feed)

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