We study the effects of an asymmetric radiation field on the properties of a molecular cloud envelope. We employ observations of carbon monoxide ($^{12}\text{CO}$ and $^{13}\text{CO}$), atomic carbon, ionized carbon, and atomic hydrogen to analyze the chemical and physical properties of the core and envelope of L1599B, a molecular cloud forming a portion of the ring at $\approx 27$ pc from the star $\lambda$ Ori. The O8 star provides an asymmetric radiation field that produces a moderate enhancement of the external radiation field. Observations of the [C II] fine structure line with the GREAT instrument on SOFIA indicate a significant enhanced emission on the side of the cloud facing the star, while the [C i], $^{12}\text{CO}$ and $^{13}\text{CO}$ $J = 1–0$ and 2–1, and $^{12}\text{CO}$ $J = 3–2$ data from the Purple Mountain Observatory and APEX telescopes suggest a relatively typical cloud interior. The atomic, ionic, and molecular line centroid velocities track each other very closely, and indicate that the cloud may be undergoing differential radial motion. The H I data from the Arecibo GALFA survey and the SOFIA/GREAT [C II] data do not suggest any systematic motion of the halo gas, relative to the dense central portion of the cloud traced by $^{12}\text{CO}$ and $^{13}\text{CO}$.

Key words: ISM: cloud envelope – photon-dominated region (PDR)
The most massive cloud in the Λ Ori ring is B30, while the bright-rimmed cloud B35 projects from the ring toward the central star. The L1599 region is number 11 in Figure 3 of Maddalena & Morris (1987) and number 8 in Figure 2 of Lang et al. (2000). Figure 1 gives an overview of the Λ Ori ring, with the magenta cross denoting L1599B. The L1599B cloud was one of those observed in CO and H I by Wannier et al. (1983), who were investigating an apparent H I halo surrounding this object. Irrespective of the details of the origin of the Λ Ori ring, L1599B and other clouds on the ring’s periphery are bordered on the one side by the H I region, which is kept ionized by the radiation from the O- and B-stars. Consequently, the cloud is subjected to a highly asymmetric radiation field, which makes it an ideal environment for studying the radiation field dependence of the interface between molecular and atomic/ionized gas regions.

In this paper we report an observational study of the L1599B cloud. [C II] emission was observed with the GREAT3 instrument (Heyminck et al. 2012) on board SOFIA® (Young et al. 2012). The 12CO J = 3–2 transition, the 3P1–3P0 transition of [C II], and the J = 2–1 transition of 12CO and 13CO were observed using the APEX telescope (Güsten et al. 2006). The 12CO and 13CO 1–0 lines were observed with the 13.7 m Purple Mountain Observatory (PMO) telescope. In Section 2 we describe the SOFIA, APEX, and PMO observations, and in Section 3, we present the observational data and fitted spectral line parameters. In Section 4 we discuss the environment of L1599B and derive the column densities of the various tracers. In Section 5 we discuss the cloud kinematics and evaluate the structure of the cloud boundaries, including comparing a two-sided slab PDR model with the data, and in Section 6 we summarize the results of our study.

2. OBSERVATIONS

We observed the five positions listed in Table 1, comprising a strip (more or less oriented on a line pointing toward Λ Ori) across the narrow axis of L1599B. The “Center” (CEN) position is approximately in the middle of the strip, and was chosen based on the data from Wannier et al. (1983). Figure 2 shows the spectra obtained at the five positions across the strip. The frequencies of the observed transitions are given in Table 2.

2.1. HCO+

We observed the five positions given in Table 1 with the 21 m Yonsei telescope (Kim et al. 2011) of the Korean VLBI Network (KVN) on 2015 September 7. The FWHM beam size and beam efficiency were 32″ and 0.041, respectively. Smoothing the data to 0.42 km s$^{-1}$ yielded an rms antenna temperature uncertainty of 0.03 K. A signal above the noise level was seen only at the CEN position, where the peak line intensity was 0.11 K, the line width 2.3 km s$^{-1}$, and the central velocity 10.1 km s$^{-1}$. Despite the marginal (≥5σ in integrated intensity) detection, the line parameters agree well with those of the other species detected at this position, so we do feel this represents a detection of HCO+. We discuss the significance of this observation in terms of a possible high-density component of the cloud in Section 5.1.

2.2. CO

The 12CO and 13CO J = 1–0 lines were observed with the 9-beam receiver (Shan et al. 2012) on the PMO 13.7 m telescope on 2015 October 15. The data were converted to a main beam temperature scale by using main beam efficiencies of 0.52 for 115 GHz and 0.56 for 110 GHz (T. Liu 2016, private communication). The FWHM beam size was ∼50″. The spectra shown in Figure 2 were part of small maps of the region in each isotopologue. Figure 3 displays the 12CO image and Figure 4 the 13CO image. The locations of the 5 positions studied in detail are also indicated in these figures. The higher-J carbon monoxide observations were carried out using the 12 m APEX telescope (Güsten et al. 2006) on several nights in 2014 September under good weather conditions. The J = 2–1 rotational transition of 12CO and 13CO were observed using the APEX-1 (SHFI) receiver (Vassilev et al. 2008) and

| Designation | R.A.      | decl.  |
|-------------|-----------|--------|
| Center (CEN)| 05:49:27.40| +07:22:07.0 |
| O1         | 05:49:03.80| +07:29:46.0 |
| O2         | 05:48:19.60| +07:37:42.7 |
| O3         | 05:49:48.57| +07:16:25.0 |
| O4         | 05:50:34.51| +07:04:24.7 |
the extended bandwidth Fast Fourier Transform Spectrometer (XFFTS) backend (Klein et al. 2012). The \( J = 3–2 \) rotational transition of \(^{12}\text{CO} \) was observed with the FLASH+ receiver (Klein et al. 2014) also on APEX and the XFFTS backend. Only the center and the two closest offset positions were observed in all of the lines after obtaining nondetections at the outer positions. Position switching observations with a clean reference position (\( \alpha(J2000) = 05:52:30, \delta(J2000) = 06:39:00 \)) were used to achieve the observed signal-to-noise ratio. For both sets of observations, the focus was checked at the beginning of each observation; pointing was checked every hour and found to be better than 2”. The data from APEX were calibrated in units of \( T_A^* \) using the standard APEX calibration tools, which provide a error of \( \pm 10\% \). A beam efficiency of 0.76 was used for analysis of the \( J = 2–1 \) \(^{12}\text{CO} \) and \(^{13}\text{CO} \) lines observed with SHFI and 0.69 for the \( J = 3–2 \) \(^{12}\text{CO} \) lines observed with FLASH+. The FWHM beam sizes were \( 27''–28'' \) for the \( J = 2–1 \) observations and \( 17''–18'' \) for the \( J = 3–2 \) observations.

2.3. \([\text{C} \text{I}]\)

The [\text{C} \text{I}] \(^3\text{P}_1–^3\text{P}_0 \) observations were carried out using the APEX telescope in parallel with the CO \( J = 3–2 \) observations discussed above, using the FLASH+ receiver. The FWHM beam size was \( 12''–14'' \). A beam efficiency of 0.57 was used for analysis of the [\text{C} \text{I}] data.

2.4. \([\text{C} \text{II}]\)

Observations of the 1900.537 GHz \(^2\text{P}_3/2–^2\text{P}_1/2 \) [\text{C} \text{II}] fine structure line were carried out as part of SOFIA Cycle 1 project 01_0040US on 2013 November 2, using the GREAT (Heyminck et al. 2012) instrument on the SOFIA airborne

| Species | Transition | Frequency (GHz) |
|---------|------------|-----------------|
| \( \text{HCO}^+ \) | 1–0 | 89.1885 |
| \( ^{13}\text{CO} \) | 1–0 | 110.2014 |
| \( ^{12}\text{CO} \) | 1–0 | 115.2712 |
| \( ^{13}\text{CO} \) | 2–1 | 220.3987 |
| \( ^{12}\text{CO} \) | 2–1 | 230.5380 |
| \( ^{12}\text{CO} \) | 3–2 | 345.7960 |
| [\text{C} \text{I}] | \(^3\text{P}_1–^3\text{P}_0 \) | 492.1607 |
| [\text{C} \text{II}] | \(^3\text{P}_1/2–^3\text{P}_1/2 \) | 1900.5369 |

Figure 2. Spectra of ionic, atomic, and molecular species observed toward the five positions in the strip through L1599B. The species and transition are identified in the left-most column (corresponding to position 4). The spectra are presented in units of antenna temperature corrected for atmospheric absorption. The vertical red line denotes a velocity of 10 km s\(^{-1}\), highlighting the systematic velocity shifts that occur in all species as one moves across the cloud. Positions 01 and 02 are in the direction toward the star \( \Lambda \) Ori.

Table 2

| Species | Transition | Frequency (GHz) |
|---------|------------|-----------------|
| \( \text{HCO}^+ \) | 1–0 | 89.1885 |
| \( ^{13}\text{CO} \) | 1–0 | 110.2014 |
| \( ^{12}\text{CO} \) | 1–0 | 115.2712 |
| \( ^{13}\text{CO} \) | 2–1 | 220.3987 |
| \( ^{12}\text{CO} \) | 2–1 | 230.5380 |
| \( ^{12}\text{CO} \) | 3–2 | 345.7960 |
| [\text{C} \text{I}] | \(^3\text{P}_1–^3\text{P}_0 \) | 492.1607 |
| [\text{C} \text{II}] | \(^3\text{P}_1/2–^3\text{P}_1/2 \) | 1900.5369 |
other species are indicated by the designations given in Table 1.

of better than a few arcsec. The forward and main beam efficiencies were 0.97 and 0.67, respectively, and the FWHM beam size 15″. The data were calibrated with the KOSMA/GREAT calibration procedure (Guan et al. 2012), removing residual telluric lines. The calibrated data were reduced with the CLASS software removing a first order polynomial baseline from an rms-weighted average of the data.

2.5. H\textsc{i}

The H\textsc{i} data were obtained from the GALFA survey (Peek et al. 2011), carried out with the Arecibo 305 m telescope. The angular resolution is 4′ and the velocity resolution 0.2 km s\textsuperscript{-1}.

3. DATA

Table 3 gives the basic parameters of the spectral lines observed at the five positions in the strip through L1599B. The line parameters are obtained from Gaussian fits of one or two components as appropriate for the spectrum in question. The H\textsc{i} is not included as Gaussian fitting is not helpful due to the complex line profiles with multiple emission components as well as possible self-absorption (discussed further in Section 4.2.4).

4. CLOUD ENVIRONMENT AND COLUMN DENSITIES

4.1. Environment

We adopt a distance of 425 pc for L1599B and Λ Ori. This distance is slightly less than the value of 445 pc suggested by Lombardi et al. (2011), slightly greater than the 400 pc used by Maddalena & Morris (1987), but close to the distance to the clouds in the Λ Ori ring of 420 pc derived by Schlafly et al. (2014).

The radiation flux at L1599B is enhanced by Λ Ori and the lower-mass stars in the Collinder 69 stellar cluster. The mass of Λ Ori is 26.8 M\odot (Dolan & Mathieu 2001). From Table 1 of Parravano et al. (2003), we find that the star’s output in the far-UV (FUV)-H\textsc{ii} range (912–2070 Å) is $2.2 \times 10^{38}$ erg s\textsuperscript{-1}. For a distance from Λ Ori to L1599B of 27 pc, we find a flux in the FUV-H\textsc{ii} range of about 1.6 times that of the Habing field. Given the contributions of the other moderately luminous stars in the cluster (Murdin & Penston 1977), we adopt an enhancement factor of 5 for modeling the physics and chemistry of the surface layers of L1599B facing Λ Ori. This may be an overestimate due to dust extinction between the star and the cloud. The oppositely oriented surface of L1599B is subject to the standard ISRF.

4.2. Column Densities

4.2.1. Carbon Monoxide

We have measurements of the three lowest transitions of 12CO at the CEN and 03 positions. From each line, assuming that the transition is optically thick, we can derive the excitation temperature. The stronger component at the CEN position is at 10.2 km s\textsuperscript{-1} (in all three transitions), and to obtain the excitation temperature we employ the expression for the antenna temperature produced by an optically thick line (e.g.,

\footnote{http://www.iram.fr/IRAMFR/GILDAS}
The velocity and line width of the components are indicated by double dashes. For positions where two Gaussian components were indicated, the two sets of fitted parameters are given sequentially. Positions where observations were not carried out are indicated by a single dash (—). Positions where no detection was made (or only a single component could be fitted) are indicated by a single dash (−). The velocity and line width of the [C II] line at position 02 could not be reliably determined. The identification of two components at position 04 is marginal but is a better fit than a single wide component.

Penzias 1975; Garden et al. 1991), expressed as

\[ T_{ex} = \frac{T^*}{\ln \left(1 + \frac{T^*}{T_{mb} + B}\right)}, \]  

(1)

where \( T^* = hf/k \) with \( f \) the frequency of the transition, \( T_{mb} \) is the source minus reference main beam peak temperature and \( B = T^*/(\exp(T^*/T_{bg}) - 1) \), where \( T_{bg} = 2.73 \) K is the background temperature. From these data we obtain \( T_{ex} = 11.4, 11.8, \) and 9.7 K for the 1–0, 2–1, and 3–2 transition, respectively, for the CEN position. The excitation temperatures for the dominant 8.7–8.9 km s\(^{-1}\) component at the 03 position for the three transitions are 10.9, 12.8, and 12.4 K, respectively. The three temperatures for each position are in quite close agreement, and suggest that we can adopt mean values of 11 K for CEN and 12 K for 03. With the additional assumption that the three lines are all thermalized, this leads to kinetic

### Table 3

| Spectral Line | Position | O4 | 03 | CEN | 01 | 02 |
|--------------|----------|----|----|-----|----|----|
| [C II] \(^3\)P\(_{1/2}\)–\(^3\)P\(_{1/2}\) | T\(_A\) max | 0.42 ± 0.07 | 0.56 ± 0.26 | 0.37 ± 0.07 | 0.63 ± 0.11 | 0.1 ± 0.1 |
| | T\(_A\) int | 0.50 ± 0.15 | 0.70 ± 0.15 | 1.25 ± 0.13 | 1.17 ± 0.13 | 0.1 ± 0.1 |
| | V\(_{lsr}\) | 12.4 ± 0.2 | 8.7 ± 0.12 | 10.3 ± 0.17 | 11.0 ± 0.11 | … |
| | \(\delta V_{FWHM}\) | 1.1 ± 0.4 | 1.2 ± 0.3 | 3.1 ± 0.4 | 1.8 ± 0.3 | … |
| 12CO J = 1–0 | T\(_A\) max | – | 4.32 ± 0.34 | 1.15 ± 0.24 | 1.50 ± 0.23 | – |
| | T\(_A\) int | – | 5.60 ± 0.18 | 0.57 ± 0.17 | 1.18 ± 0.13 | – |
| | V\(_{lsr}\) | – | 8.79 ± 0.02 | 11.27 ± 0.05 | 11.14 ± 0.04 | – |
| | \(\delta V_{FWHM}\) | – | 1.22 ± 0.05 | 0.52 ± 0.07 | 0.74 ± 0.08 | – |
| 12CO J = 2–1 | T\(_A\) max | – | 0.35 ± 0.12 | 0.68 ± 0.13 | – | – |
| | T\(_A\) int | – | 0.40 ± 0.07 | 0.66 ± 0.08 | – | – |
| | V\(_{lsr}\) | – | 9.04 ± 0.10 | 10.36 ± 0.05 | – | – |
| | \(\delta V_{FWHM}\) | – | 1.07 ± 0.19 | 0.91 ± 0.14 | – | – |
| 12CO J = 3–2 | T\(_A\) max | – | 5.86 ± 0.09 | 3.01 ± 0.09 | 1.76 ± 0.09 | 0.09 ± 0.03 |
| | T\(_A\) int | – | 6.49 ± 0.38 | 3.39 ± 0.15 | 1.02 ± 0.13 | 0.074 ± 0.029 |
| | V\(_{lsr}\) | – | 8.93 ± 0.03 | 11.29 ± 0.02 | 11.39 ± 0.01 | 11.01 ± 0.13 |
| | \(\delta V_{FWHM}\) | – | 0.68 ± 0.04 | 1.06 ± 0.03 | 0.54 ± 0.02 | 0.77 ± 0.45 |

Note.

* Peak intensities are antenna temperature (K), integrated intensities are antenna temperature integrated over velocity (K km s\(^{-1}\)), and velocities and line widths are in km s\(^{-1}\). For positions where two Gaussian components were indicated, the two sets of fitted parameters are given sequentially. Positions where observations were not carried out are indicated by double dashes (—). Positions where no detection was made (or only a single component could be fitted) are indicated by a single dash (−).
temperatures, $T_k$, between 11 and 12 K in the region where the $^{12}$CO becomes optically thick. As will be seen below, this solution is critically dependent on there being sufficient radiative trapping for this isotopologue.

We have detected the two lowest transitions of $^{13}$CO at the CEN and 03 positions. For this species, the ratio of the two lowest transitions is a good tracer of the volume density, in particular when the emission is optically thin, as we find is the case for L1599B. From Table 3, we find that the ratio of the integrated main beam temperatures, $R(2/1)$, is 0.61 for the CEN position and 0.85 for the 03 position, with errors of approximately 20%. The ratio is directly expressible in terms of the ratio of the upper level column densities, which in turn can be expressed in terms of the excitation temperature of the $J = 2$–1 transition

$$R(2/1) = \frac{\int T_{mb}(J = 2–1) dv}{\int T_{mb}(J = 1–0) dv} = 4e^{-10.6/T_k(J=2-1)}, \quad (2)$$

where 10.6 K is the energy difference between the $J = 2$ and $J = 1$ levels expressed as a temperature. We see that to obtain the observed ratios, excitation temperatures are very low; $\approx 5.6$ K for CEN and $\approx 6.8$ K for 03. Thus a local thermal equilibrium (LTE) population distribution cannot be assumed for calculating the $^{13}$CO emission.

For the moderate radiation fields present here, the hydrogen will be almost entirely molecular (see, e.g., discussion in Section 5.2). Using the RADEX code (van der Tak et al. 2007), we find that solutions for $R(2/1)$, given the above kinetic temperatures, are restricted to the range $1000 \leq n(H_2) \leq 3000$ cm$^{-3}$. We find the closest agreement between the data and model with $T_k = 12$ K, $n(H_2) = 1200$ cm$^{-3}$, and $N^{(13)CO} = 1.3 \times 10^{15}$ cm$^{-2}$ for the CEN position, while for the 03 position, $T_k = 11$ K, $n(H_2) = 2500$ cm$^{-3}$, and $N^{(13)CO} = 7 \times 10^{14}$ cm$^{-2}$.

With these $^{13}$CO column densities and assuming a $^{12}$CO/$^{13}$CO abundance ratio of 65 (Langer & Penzias 1993; Liszt 2007), we find $^{12}$CO column densities between 5 and $9 \times 10^{16}$ cm$^{-2}$. Taking a representative value of $6 \times 10^{16}$ cm$^{-2}$ and a line width of 1 km s$^{-1}$, with $n(H_2) = 2000$ cm$^{-3}$ and $T_k = 12$ K, gives optical depths of 8, 17, and 11 for the three lowest $^{12}$CO transitions. These are sufficiently large to give excitation temperatures of 11.0, 10.4, and 8.8 K. The assumption that the $^{12}$CO yields the kinetic temperature is thus confirmed for the two lowest transitions, but is somewhat marginal for the $J = 3$–2 transition. This difference may suggest that the single density model is not correct in detail, but that using the kinetic temperatures derived above for analysis of the carbon monoxide emission should be adequate for the present discussion.

4.2.2. Atomic Carbon

We have detected the $^{[C\ i]}$ 492 GHz transition at the 01, CEN, and 03 positions. With the reasonable (and finally self-consistent) assumption of optical thinness, the upper level ($^3P_1$) column density is given by $N_u = (8\pi \times 10^5v^2/A_{gh}) \int T_{mb} dv (K\ km\ s^{-1}) = 6.0 \times 10^{15}\int T_{mb} dv (K\ km\ s^{-1})$. The total column densities depend on the excitation conditions; the three-level problem can be solved analytically yielding the fractional population of each level (e.g., Goldsmith et al. 2015). The results for the $^3P_1$ level are shown in Figure 5. In a cloud with modest total column density such as L1599B, there will be a significant atomic carbon abundance throughout the cloud, and while it may be depressed just at the center due to conversion to carbon monoxide, the abundance of C will not be enhanced in the warm, outer layers, where the carbon is primarily $^3P_1$.

In considering the results shown in Figure 5, we see that the fractional population of $^3P_1$ is between 0.15 and 0.45. If we assume a characteristic value of 0.3, which is the value appropriate for 20 K and $n(H_2) = 1000$ cm$^{-3}$, we will be making an error of less than a factor of 2. With the assumption that the $H_2$ density in the region producing the $^{[C\ i]}$ emission is the same as that determined from $^{13}$CO, we find atomic carbon column densities of 1.0, 2.9, and $3.6 \times 10^{16}$ cm$^{-2}$ for the 01, CEN, and 03 positions, respectively.

4.2.3. Ionized Carbon

The $^2P_{3/2}$–$^2P_{1/2}$ fine structure line of $^3P_1$ ($^3P_1$) was detected at all five positions observed, albeit with a limited signal-to-noise ratio, particularly at the 02 position. The line profiles at the three inner positions are surprisingly similar to those of both the molecular and atomic species in terms of line width and central velocity. This similarity indicates that the conditions and extent of the emitting region are not vastly different from those of the other species observed.

In order to determine the excitation and column density of $^3P_1$, we assume that the thermal pressure in the region responsible for the $^{[C\ i]}$ emission is the geometric mean of the ISM pressure and the pressure of the internal molecular zone (Wolff et al. 2003; Pineda et al. 2013). For the ISM pressure, we adopt the mean value of the range found by Goldsmith (2013), $5700$ K cm$^{-3}$, determined for translucent clouds with low extinctions, which are assumed to be in pressure equilibrium with the surrounding ISM. For the molecular zone pressure, we use the average of the values found at the CEN ($p/k = 18,000$ K cm$^{-3}$) and 03...
(p/k = 27,500 K cm\(^{-3}\)) positions discussed above, yielding
\(p/k = 20,950\) K cm\(^{-3}\). Taking the geometric mean yields a
thermal pressure in the C\(^+\) layer of 10,900 K cm\(^{-3}\). Based on
expectations of cloud-edge thermal structure, we adopt
conditions \(n(H_2) = 100\) cm\(^{-3}\), and \(T^\parallel = 100\) K for analyzing the
[C II] emission.

Inverting Equation (26) of Goldsmith et al. (2012) yields

\[
N(C^+) = 2.9 \times 10^{15} \left[ 1 + 0.5 e^{0.1/\Theta} \left( 1 + \frac{2.4 \times 10^{-6}}{nR_{ul}} \right) \right] \int T_{mb} dv,
\]

where the column density is in cm\(^{-2}\), the integrated temper-
ature in K \(km\ s^{-1}\), \(n\) is the volume density of colliding particles
in cm\(^{-3}\), and \(R_{ul}\) is the collisional deexcitation rate in cm\(^3\) s\(^{-1}\).
Throughout almost all the C\(^+\) region, hydrogen will be
molecular, so we use the \(R_{ul}\) rate coefficient from Wiesenfeld
\& Goldsmith (2014), assuming a LTE H\(_2\) ortho-to-para ratio.
For 100 K kinetic temperature \(R_{ul} = 5.1 \times 10^{-10}\) cm\(^3\) s\(^{-1}\), and we
obtain \(N(C^+) = 1.8 \times 10^{17}\) integrated \(T_{mb} dv\). The C\(^+\) column
densities are 2.4, 1.9, 3.4, 3.2, and 0.3 \(\times 10^{17}\) cm\(^{-2}\) at
positions 04, 03, CEN, 01, and 02, respectively.

4.2.4. Atomic Hydrogen

Analysis of the H\(_i\) data is problematic due to the difficulty of associating
atmospheric data specifically with the L1599B region,
given that the H\(_i\) emission is widespread throughout the Λ Ori
ring as indicated by early observations of Wade (1957).
The extended H\(_i\) is confirmed by the GALFA observations, from
which the spectra in Figure 2 were extracted. There are multiple
velocity components present, as seen in Figure 2, but also one
at \(-20\) km s\(^{-1}\). The velocities of peak emission do shift
slightly with position, presumably reflecting the complex
motions of gas in the expanding ring (e.g., Maddalena
\& Morris 1987).

In the region of L1599B studied in detail, the H\(_i\) profiles are
unusual in that the spectra at the three central positions have
two maxima, which could reflect the presence of two velocity
components, or could be the result of H\(_i\) self-absorption. If we
adopt the latter interpretation, the line widths of the absorption
features are between 1 and 2 km s\(^{-1}\), similar to that of the
molecular emission lines, and the velocities agree very well.
Thus, this can be considered to be an example of “H\(_i\) narrow
self-absorption,” or HINSA (Li \& Goldsmith 2003). The very
close tracking of the \(^1\text{CO}, \ ^{13}\text{CO}, \) and \([\text{C II}]\) emission velocities
with that of the minimum of the H\(_i\) intensity (see Figure 2), is a
strong indication that this is indeed absorption produced by the
cold H\(_i\) in the central region of L1599B.

If we assume that the absorption is produced by atomic hydrogen
at a temperature of 12 K, we can determine the column density of “cold” atomic hydrogen to be 1–3 \(\times 10^{19}\) cm\(^{-2}\). This value is within the range found in cold dark
clouds by Li \& Goldsmith (2003). If this cold atomic hydrogen
is located in a path length of 1–2 \(\times 10^{18}\) cm determined from
the size of the \(^{13}\text{CO}\) emission, the density of cold atomic hydrogen must be \(\approx 10^{19}\) cm\(^{-3}\). This density is significantly
higher than the \(n(H_0) \approx 1–2\) cm\(^{-3}\) expected in steady-state
from cosmic ray destruction of H\(_2\) (Goldsmith \& Li 2005). For
the density of L1599B, achieving steady state requires

approximately \(10^7\) years, somewhat longer than the age of a
few My estimated for the Λ Ori ring (Maddalena
\& Morris 1987). It is thus not surprising that the density of cold
atomic hydrogen is significantly greater than the steady-state
value, so that the HINSA interpretation of the H\(_i\) profiles
is plausible. In this picture, the L159B cloud is a “transition”
object between purely atomic and fully molecular form.

5. DISCUSSION

In this section, we discuss the kinematics of the L1599B
cloud, and analyze the cloud structure focusing on the
photochemistry of the cloud edges.

5.1. Cloud Kinematics

The spectra in Figure 2 and the fitted velocities of the peak
emission in Table 3 show clear evidence of large-scale
kinematic structure in the transverse cut through L1599B. In
Figure 6 we plot the peak emission velocities and the velocity
of the H\(_i\) minimum (HINSA interpretation) for the three central
positions.

The key parameters of the different lines at each position
follow each other remarkably closely, generally agreeing in
velocity within the fitted uncertainty. It is interesting that the
C\(^+\) has line parameters similar to those of C\(_0\) and CO even
though it is almost certainly present only in the “envelope”
surrounding the atomic and molecular constituents of the cloud.
The lack of velocity shifts between the C\(^+\) and the molecular
component traced by CO argues against any clear motion of the
exterior portion of the cloud relative to its center, as would be
expected if the envelope were expanding away from or
contracting onto the cloud.
Figure 7. First moment image of $^{13}$CO in L1599B with velocities displayed according to the color bar at the right. The positions studied in detail are indicated. The main beam temperature cutoff is $3 \times \sigma$ of the mean value of 0.23 K. The black contours show the main beam temperature integrated from 7 to 13 km s$^{-1}$. The contour levels are from 10% to 90% in steps of 20% of the peak value of 7 K km s$^{-1}$.

Such a lack of relative velocity shifts among the species we have observed could be explained if the emission were largely coming from an ensemble of clumps or condensations, with the outer layer of each responsible for the [C II] and successively more highly shielded layers providing the [C I] and carbon monoxide. The overall ensemble of such condensations could exhibit the observed velocity changes. The presence of significant atomic hydrogen in excess of that expected in steady-state conditions (discussed in Section 4.2.4 above) argues against the dominance of high-density clumps that would have very short timescales for conversion of H$^+$ to H$_2$. The marginal detection of very weak HCO$^+$ J = 1–0 emission (Section 2.1) suggests that high-density condensations are relatively unimportant, but since we have only this single transition, we cannot make an unambiguous determination of possible clump densities and filling factors. The observational data on L1599B seem at this point to be satisfactorily reproduced by a smoothly varying density profile and central density much greater than those derived from the carbon monoxide observations discussed in Section 4.2.1.

The Maddalena & Morris (1987) expanding ring model for the Λ Ori region indicates that with an average velocity of 10 km s$^{-1}$, compared to the 6 km s$^{-1}$ central velocity of the ring, L1599B is located on the more distant portion of the ring. The 01 position is closer to Λ Ori, and its velocity is redshifted by 2 km s$^{-1}$ relative to that of the 03 position. If we take the CEN position as a reference, the 01 position is redshifted by 1 km s$^{-1}$ and the 03 position is blueshifted by the same amount. If these velocity differences are due to differential motions within the cloud, it appears to be contracting. While this may appear to be inconsistent with the suggestion of Andersson & Wannier (1993) that the H I halo of L1599B is expanding, their measurements of H I were of the enhanced 21 cm emission surrounding the cloud and not to the absorption features we have observed that presumably trace the denser, primarily molecular cloud core.

Table 4

| Species or Ratio | 04 | 03 | CEN Column Density (10$^6$ cm$^{-2}$) | 01 | 02 |
|-----------------|----|----|-------------------------------------|----|----|
| $^{13}$CO x 65  | ... | 5  | 9                                  | ... | ...|
| C$^+$           | 24 | 19 | 34                                  | 32 | 3  |
| $^{13}$CO       | 24 | 28 | 46                                  | 33 | 3  |
| C$^+/C^0$      | ... | 5  | 11                                  | 32 | ...|

Figure 7 is a first moment image of $^{13}$CO in L1599B showing the overall behavior of the velocity field. While there is a velocity shift from one side of the cloud to the other, a significant gradient is largely restricted to the central portion of the cloud, which includes the strip studied in detail. However, the quite different behavior seen in the southwest portion suggests that while the cloud may have been compressed by the H II region and Λ Ori, it is apparent that the overall velocity field is complex. Whether the denser portion of the cloud is contracting while the halo is expanding cannot yet be answered.

The velocity field between δ(J2000) = 7°20’ and 7°30’ seen in Figure 7 shows a velocity gradient which is consistent with rotation of the central portion of the cloud about its long axis. This region includes the positions studied in detail with the separation of the 01 and 03 positions being 2.15 pc at the assumed distance of 425 pc. The velocity difference of 2.4 km s$^{-1}$ corresponds to a velocity gradient of 1.1 km s$^{-1}$ pc$^{-1}$. If interpreted as rigid body rotation, the angular velocity $\omega = 3.4 \times 10^{-14}$ s$^{-1}$, which is within the range found for a number of rotating clouds (e.g., Arquilla & Goldsmith 1986). However, this behavior is restricted to the central portion of the cloud.

5.2. Cloud Edges

While the observed positions only partially sample the structure of L1599B and are not perfectly aligned with the cloud due to the initial lack of high resolution molecular data, comparing position 02 (toward the star) with 03 (away from the star), we do see an enhancement of the [C II] emission from the edge of the cloud facing Λ Ori. Without fully sampled maps in all species we need to be cautious in our conclusions. We summarize the column density information from Section 4.2 in Table 4, in which the column densities have been rounded off to the nearest integer multiple of 10$^{16}$ cm$^{-2}$. The column densities and the ratio of $N(C^+)/N(\Sigma C)$, where $N(\Sigma C) = N(C^+) + N(C^0) + 65N(^{13}CO)$, is the total carbon column density shown in Figure 8. Ionized carbon dominates throughout the cloud, but most strongly at the cloud edges. The enhanced [C II] emission results from the combination of increased gas temperature and the increased ionized carbon abundance, produced by the stronger radiation field. The [C II] line, with $\Delta E/k = 91.2$ K, is very sensitive to the gas temperature found in cloud edges subjected to radiation fields with modest enhancement factors relative to the standard ISRF.

To examine this issue in more detail, we have used the PDRLight version of the Meudon PDR code (Le Petit et al. 2006). We are not modeling the entire cloud, but rather only the cloud boundaries responsible for the [C II] emission.
We thus adopt a total proton density of 200 cm$^{-3}$ derived above as reasonable value for this portion of the L1599B cloud. The model is a plane parallel slab with radiation field enhanced by a factor of 5 on one side relative to the standard ISRF incident on the other side. The model computes the steady-state thermal balance and species abundance as a function of optical depth, which is chosen to be 5 mag through the slab. Due to the modest densities and relative youth of the L1599B cloud, we do not consider any grain surface depletion. The results are shown in Figure 9.

The most significant results, as shown in Figure 9, are that the cloud surface exposed to the enhanced radiation field is warmer, 120 K versus 70 K at the boundaries, and that the C$^+$ layer is thicker. The greater thickness results in somewhat larger C$^+$ column density, 2.5 versus $1.8 \times 10^{15}$ cm$^{-2}$ within 1 mag. of the cloud surface. The higher temperature results in much larger fractional population of the upper level of the transition; $f_n = 0.028$ in the enhanced ISRF side compared to 0.012 in the standard ISRF side. The combination results in a column density in the $^3P_3/2$ state equal to $6.4 \times 10^{15}$ cm$^{-2}$ compared to $2.1 \times 10^{15}$ cm$^{-2}$ on the low-radiation field side, a factor of 3.1 increase. The total column densities of C$^+$ necessarily differ slightly relative to those given in Section 4.2.3 that were derived assuming a single set of cloud boundary conditions, but the overall agreement is satisfactory.

The model does not satisfactorily explain all aspects of our data. In particular, the present model is not realistic in that the total visual extinction is larger than derived from stellar reddening, computed from infrared reddening using the NICER code (Lombardi & Alves 2001; Chapman 2007) following the procedure described in Pineda et al. (2010). This technique yields a maximum extinction of 1.25 mag. Such low extinction regions are “translucent” clouds having ionized carbon on the outside, and neutral carbon, or a mix of neutral and ionized carbon, on the inside, with little or no CO. The consequence of the low extinction is a much lower predicted $^{13}$CO column density than observed. This result may well be connected to the well-known problem of the formation rate of carbon monoxide in diffuse clouds (see e.g., the discussion in Goldsmith 2013). Another issue is that with an extinction as low as indicated by submillimeter and infrared observations, the kinetic temperature (even for $n$(H$_2$) as high as 1500 cm$^{-3}$) does not fall below 30 K, significantly higher than that implied by the three observed $^{12}$CO transitions discussed in Section 4.2.1 above.

The [C$^+$] emission peaks toward the 03 position, in the direction away from the star. Using the column densities from Sections 4.2.2 and 4.2.3, the ratio $N$(C$^+$/N(CO) is 32, 12, and 5, at positions 01, CEN, and 03, moving from the side of L1599B facing Λ Ori to the side facing away. This change is largely due to the reduction of the column density of neutral carbon by the enhanced radiation field produced by the star, together with a modest enhancement of the ionized carbon column density.

6. SUMMARY

We have carried out an observational study of the L1599B cloud, located in the ring surrounding the O8 star Λ Ori. We have made images in the $J = 1$–0 transitions of $^{12}$CO and $^{13}$CO but focus on five positions for which we have an extensive set of spectral diagnostics of the gas properties, cutting through the cloud on a line directed toward the star. At these positions we have observed the 2–1 transitions of $^{12}$CO and $^{13}$CO, the 3–2 transition of $^{13}$CO, the $^3P_1$–$^3P_0$ transition of [C$^+$], the $^3P_{3/2}$–$^3P_{1/2}$ transition of [C$^+$], and used 21 cm H$_1$ profiles from the GALFA survey. All are seen in emission with the possible exception of the H$_1$, which may be showing self-absorption by cold atomic gas in the molecular cloud.
The line centroid velocities and also the line widths for the emission lines agree very closely, and all exhibit a systematic velocity shift as one moves across the cloud. This shift could be indicative of rotation but is more likely the result of contraction of the cloud, comprising molecular, atomic, and ionic components, due to compression by the HII region.

Using the two lowest transitions of $^{13}\text{CO}$, we have determined the H$_2$ volume density in the shielded portion of the cloud to be 1000 and 2500 cm$^{-3}$ at the 03 and CEN positions, respectively. This range delineates the density in the central portion of the cloud, where from the three lowest transitions of $^{12}\text{CO}$, we find kinetic temperatures of 12 and 11 K, respectively.

The visual extinction through the cloud is modest, $\lesssim 1.25$ mag, and the $^{13}\text{CO}$ column densities are $0.7-1.3 \times 10^{15}$ cm$^{-2}$. These column densities are greater than expected from a PDR model of the L1599B cloud which includes a radiation field enhancement of a factor of 5 on the side facing the star Λ Ori. The $^{13}\text{CO}$ emission peaks on the side of L1599B facing away from L1599B.

The [CII] emission is enhanced and the [C I] emission reduced at the position of the cloud facing Λ Ori, and the ratio $N(\text{C}^-)/N(\text{CO})$ at positions 01, CEN, and 03, moving from the side of L1599B facing Λ Ori to the side facing away is 32, 12, and 5. While comparisons with a uniform density slab PDR model should be treated with caution, it appears that the model does predict the enhancement of C$^-$ and the diminution of C$^0$ reasonably well. While the C$^+$ emission from regions with such modest radiation field is obviously weak, our study confirms that relatively extended regions even quite far from massive young stars can contribute significantly to the [CII] emission and should be included in calculating the total C$^+$ luminosity and cooling of star-forming regions.

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