Neutral carbon in translucent regions of the dark cloud L 183

Ronald Stark1, *, Paul R. Wesselius2, Ewine F. van Dishoeck3, and R.J. Laureijs4

1 Institut d'Astrophysique de Paris, UPR 341 du CNRS, 98bis Boulevard Arago, F-75014 Paris, France
2 Space Research Organisation of the Netherlands, Postbus 800, 9700 AV Groningen, The Netherlands
3 Sterrewacht Leiden, Postbus 9513, 2300 RA Leiden, The Netherlands
4 Space Science Department, ESTEC, Postbus 299, 2200 AG Noordwijk, The Netherlands

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Abstract. Observations of the [C i] \(^3\)P\(_1\) – \(^3\)P\(_0\) 492 GHz fine structure line and isotopic CO(2 – 1, 3 – 2) rotational lines have been made at six positions along an east-west strip through the centre of the high-latitude dark cloud L 183 using the James Clerk Maxwell Telescope. The [C i] spectra have line strengths varying between \(T_{\text{MB}} = 0.8 – 3.4\) K. The lines appear broad due to a blend of two kinematically different components around \(V \approx 1\) km s\(^{-1}\) and \(V \approx 2.3\) km s\(^{-1}\) which can be resolved at some positions. If the [C i] emission originates in the warmer, translucent envelopes (\(A_V \approx 1 – 5\) mag) of L 183 we derive total column densities in both components in the range \(7 	imes 10^{15} – 3 	imes 10^{17}\) cm\(^{-2}\). In case it would come primarily from the cold dark core (\(A_V > 5\) mag) we calculate lower limits of about \(10^{16} – 10^{17}\) cm\(^{-2}\). The component around \(V \approx 1\) km s\(^{-1}\) is most likely entirely translucent. We argue that most of the observed [C i] emission from the \(V \approx 2.3\) km s\(^{-1}\) component also originates in the translucent regions of L 183 and has an optical depth in the range \(\tau = 0.1 – 6\). We find a good correlation between the [C i] and \(^{13}\)CO(3 – 2, 2 – 1) measurements but not with C\(^{18}\)O(2 – 1). The derived C/CO column density ratio along the cut varies between 0.08 – 0.7 and remains constant within the uncertainty. Chemical model calculations are used to study the [C i] column density as well as the C/CO ratio as a function of density and total hydrogen column density. A close inverse correlation is found between \(N(C)/N(\text{CO})\) and \(A_V\) for \(N(\text{H}_2) \approx 10^{20} – 5 	imes 10^{21}\) cm\(^{-2}\), which is consistent with the generally observed correlation between C and CO from diffuse clouds to dense photon dominated regions.

Key words: ISM: abundances; atoms; molecules; clouds; L 183 – radio lines; ISM

1. Introduction

The L 183 cloud is an isolated quiescent dark cloud and its dense molecular core has been studied extensively for many years. Together with L 1780 it is part of the L 134 cloud complex and is therefore often referred to as L 134N. This complex lies at a distance of about 100 pc (Mattila 1979, Franco 1989). It is located at high galactic latitude (\(b = 36^\circ\)), so no confusion with unrelated background or foreground emission occurs. Detailed observations of this cloud have been performed in the CO(1 – 0) line (Snell 1981), IRAS far-infrared emission (Laureijs et al. 1991), submillimetre continuum (Ward-Thompson et al. 1994), and in various molecules other than CO by Swade (1989a, b) and Swade & Schloerb (1992). The angular resolution of the above mentioned molecular spectroscopic measurements ranges between 40 – 100 arcsec. The kinetic temperature of the dense core derived from ammonia observations is \(T_K \approx 9 ± 1\) K (Ungerechts et al. 1980) and it has a peak molecular hydrogen density \(n(\text{H}_2) = 3 	imes 10^9\) cm\(^{-3}\) as derived from HC\(_3\)N observations (Swade 1989b). Laureijs et al. (1991) delineate cold (\(\approx 15\) K) dust in dense \(n(\text{H}_2) = 10^9\) cm\(^{-3}\) parts of L 183 which coincide with the \(^{13}\)CO peak mapped by Snell and by Swade, but not with the high density region traced by NH\(_3\). This means that the dust in the dense core could have a much lower temperature. Indeed, Ward-Thompson et al. derive \(T_{\text{dust}} \approx 8_{-4}^{+4}\) K and a density \(n \approx 2 	imes 10^6\) cm\(^{-3}\) from submillimetre continuum photometry (0.8 – 1.1 mm) at the peak of the ammonia emission.

The dense core of L 183 is embedded in an extended envelope with a visual extinction \(A_V < 1\) mag (Franco 1989). This envelope as well as the edge of L 183 with \(A_V \approx 1 – 5\) mag are translucent regions where UV photons can penetrate and photoprocesses control the physics and chemistry. In translucent regions the transition of carbon from predominantly ionized carbon to CO occurs, C\(^+\) \(\rightarrow\) C \(\rightarrow\) CO (van Dishoeck & Black, 1988, Stark & van Dishoeck 1994), similar to the H\(_1\) \(\rightarrow\) H\(_2\) transition in diffuse regions around \(A_V = 0.5\) mag. So far, the low density regions of L 183 have not been studied in much detail. This is mainly because the observations do not only sample the envelope but also the shielded inner part. Therefore species which trace both parts like low level CO and \(^{13}\)CO transitions suffer from saturation and self-absorption effects.

* Present address: Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
Table 1. Observations of the $^{13}$CO(2 – 1), and C$^{18}$O(2 – 1) lines in L 183 together with the inferred column densities

<table>
<thead>
<tr>
<th>$\Delta \alpha$, $\Delta \delta$ (arcmin)</th>
<th>$V_{\text{LSR}}$ (km s$^{-1}$)</th>
<th>$T_{\text{MB}}$ (K)</th>
<th>$\Delta V$ (km s$^{-1}$)</th>
<th>$I$ (erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$)</th>
<th>$N(^{13}\text{CO})^b$ (cm$^{-2}$)</th>
<th>$N(\text{CO})^c$ (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0, 0</td>
<td>2.83 ± 0.03</td>
<td>2.0 ± 0.1</td>
<td>2.00 ± 0.07</td>
<td>(4.7 ± 0.4)</td>
<td>(2)</td>
<td>(2)</td>
</tr>
<tr>
<td>13CO(2 – 1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(5)</td>
<td>(5)</td>
</tr>
<tr>
<td>13CO(3 – 2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(15)</td>
<td>(15)</td>
</tr>
<tr>
<td>C$^{18}$O(2 – 1)</td>
<td>2.66 ± 0.04</td>
<td>2.1 ± 0.2</td>
<td>1.17 ± 0.09</td>
<td>(9.7 ± 0.4)</td>
<td>(3)</td>
<td>(3)</td>
</tr>
<tr>
<td>2, 0</td>
<td>2.44 ± 0.01</td>
<td>1.8 ± 0.2</td>
<td>0.66 ± 0.03</td>
<td>(1.4 ± 0.2)</td>
<td>(7)</td>
<td>(7)</td>
</tr>
<tr>
<td>13CO(2 – 1)</td>
<td>2.41 ± 0.04</td>
<td>1.5 ± 0.1</td>
<td>1.81 ± 0.09</td>
<td>(3.2 ± 0.3)</td>
<td>(2)</td>
<td>(2)</td>
</tr>
<tr>
<td>13CO(3 – 2)</td>
<td>2.55 ± 0.02</td>
<td>2.3 ± 0.2</td>
<td>0.72 ± 0.05</td>
<td>(7 ± 1)</td>
<td>(1)</td>
<td>(1)</td>
</tr>
<tr>
<td>C$^{18}$O(2 – 1)</td>
<td>2.42 ± 0.01</td>
<td>1.9 ± 0.1</td>
<td>0.60 ± 0.03</td>
<td>(1.3 ± 0.2)</td>
<td>(7)</td>
<td>(7)</td>
</tr>
<tr>
<td>4, 0</td>
<td>2.16 ± 0.03</td>
<td>1.8 ± 0.1</td>
<td>1.84 ± 0.07</td>
<td>(3.9 ± 0.3)</td>
<td>(2)</td>
<td>(2)</td>
</tr>
<tr>
<td>13CO(2 – 1)</td>
<td>1.10 ± 0.06</td>
<td>0.6 ± 0.1</td>
<td>0.5 ± 0.1</td>
<td>(1.2 ± 0.5)</td>
<td>(3)</td>
<td>(3)</td>
</tr>
<tr>
<td>13CO(3 – 2)</td>
<td>2.12 ± 0.04</td>
<td>1.1 ± 0.1</td>
<td>0.9 ± 0.1</td>
<td>(3.9 ± 0.8)</td>
<td>(1)</td>
<td>(1)</td>
</tr>
<tr>
<td>C$^{18}$O(2 – 1)</td>
<td>2.30 ± 0.03</td>
<td>0.8 ± 0.1</td>
<td>0.6 ± 0.1</td>
<td>(6 ± 1)</td>
<td>(3)</td>
<td>(3)</td>
</tr>
<tr>
<td>6, 0</td>
<td>2.05 ± 0.04</td>
<td>1.5 ± 0.1</td>
<td>2.6 ± 0.1</td>
<td>(4.5 ± 0.5)</td>
<td>(2)</td>
<td>(2)</td>
</tr>
<tr>
<td>13CO(2 – 1)</td>
<td>2.16 ± 0.09</td>
<td>1.0 ± 0.2</td>
<td>1.4 ± 0.2</td>
<td>(6 ± 2)</td>
<td>(1)</td>
<td>(1)</td>
</tr>
<tr>
<td>13CO(3 – 2)</td>
<td>&lt; 0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8, 0</td>
<td>2.20 ± 0.04</td>
<td>1.4 ± 0.1</td>
<td>2.0 ± 0.1</td>
<td>(3.3 ± 0.4)</td>
<td>(2)</td>
<td>(2)</td>
</tr>
<tr>
<td>13CO(2 – 1)</td>
<td>2.4 ± 0.2</td>
<td>0.7 ± 0.2</td>
<td>1.2 ± 0.4</td>
<td>(3 ± 2)</td>
<td>(4)</td>
<td>(4)</td>
</tr>
<tr>
<td>13CO(3 – 2)</td>
<td>&lt; 0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10, 0</td>
<td>1.1 ± 0.1</td>
<td>0.5 ± 0.1</td>
<td>1.1 ± 0.3</td>
<td>(6 ± 4)</td>
<td>(3)</td>
<td>(3)</td>
</tr>
<tr>
<td>13CO(2 – 1)</td>
<td>2.1 ± 0.1</td>
<td>0.7 ± 0.1</td>
<td>1.1 ± 0.2</td>
<td>(9 ± 3)</td>
<td>(4)</td>
<td>(4)</td>
</tr>
<tr>
<td>13CO(3 – 2)</td>
<td>&lt; 0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C$^{18}$O(2 – 1)</td>
<td>&lt; 0.2</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

$^a$ offset with respect to $\alpha(1950)=15:51:32; \delta(1950)=-2:43:00$

$^b$ range in column densities for $T = 10 - 20$ K and $n_H = 10^{4} - 2 \times 10^{4}$ cm$^{-3}$ for $^{13}$CO, and $n_H = 2 \times 10^{3} - 2 \times 10^{4}$ cm$^{-3}$ for C$^{18}$O

$^c$ range in $^{12}$CO column densities derived from the abundance ratios $^{12}$Cl/$^{13}$Cl = 65 and $^{16}$O/$^{18}$O = 500

With the advent of new millimetre receivers equipped with sensitive Si SIS junction mixers it becomes possible to carry out more detailed studies of the translucent envelope of dark molecular clouds by observations of higher level isotopic CO transitions as well as the neutral carbon [C I] $^{3}$P$_1 - ^{3}$P$_0$ line. In combination with large millimetre telescopes with a high surface accuracy such studies can be done at an angular resolution of 10 – 20 arcsec. In this paper we present such observations in order to determine the position of the C – CO transition layer, and to study the cooling rate in L 183. Together with chemical models, constraints will be put on the extent of the neutral carbon transition layer and its relation to the molecular distributions of the inner parts.

[C I] 492 GHz emission was already detected in L 183 at one position by Phillips & Huggins (1981) using the Kuiper Airborne Observatory. More recently, ground-based [C I] observations at higher angular resolution have been presented for a number of high-latitude translucent and dark clouds, including that toward HD 210121 (Stark & van Dishoeck 1994), MBM 12 (Ingalls, Bania & Jackson 1994), and TMC-1 (Schilke et al. 1995; Keene 1995). Since these regions have different total visual extinctions and physical conditions, comparison with L 183 will be interesting. Keene (1995) also presented some [C I] data for L 183.

2. Observations

The observations of the [C I] $^{3}$P$_1 - ^{3}$P$_0$ line at 492.1607 GHz were obtained using the 15 m James Clerk Maxwell Telescope* (JCMT) on Mauna Kea, Hawaii, in June 1993. The beam size at this frequency is 10 arcsec full width at half-maximum (FWHM) and the main beam efficiency $\eta_{\text{MB}} = 0.4$. We used the 450 – 505 GHz SIS receiver RxC2 which has a double side band receiver noise temperature of 200 K**. The weather conditions resulted in system temperatures including the atmosphere of about 4200 – 4500 K. The backend consisted of the Acousto Optical Spectrometer AOSC which has a bandwidth of 500 MHz and a spectral resolution of 330 kHz corresponding to 0.2 km s$^{-1}$ at 492 GHz. The $^{13}$C$^{16}$O (hereafter abbreviated to CO), $^{13}$CO, and C$^{18}$O $J = 2 – 1$ lines were obtained with the 208 – 280 GHz SIS receiver RxA2 in July 1994. The CO and $^{13}$CO $J = 3 – 2$ lines were observed with the 300 – 380 GHz SIS receiver RxB3i. The CO observations were carried out in December 1994, while $^{13}$CO was observed in June 1993 and

* The James Clerk Maxwell Telescope is operated by The Observatories on behalf of the Particle Physics and Astronomy Research Council of the United Kingdom, the Netherlands Organisation for Scientific Research, and the National Research Council of Canada.

** The junctions for this mixer were fabricated by the University of Groningen and SRON.
Table 2. Observations of the \([\text{C} \text{i}] \, ^3\text{P}_1 - ^3\text{P}_0\) 492 GHz line in L 183 together with the inferred column densities, and C/CO column density ratios

<table>
<thead>
<tr>
<th>(\Delta \alpha, \Delta \delta^a) (arcmin)</th>
<th>(V_{\text{LSR}}) (km s(^{-1}))</th>
<th>(T_{\text{MB}}) (K)</th>
<th>(\Delta V) (km s(^{-1}))</th>
<th>(I) (erg cm(^{-2}) s(^{-1}) sr(^{-1}))</th>
<th>(N(\text{C})^d) (cm(^{-2}))</th>
<th>(N(\text{CO})/N(\text{C}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0, 0</td>
<td>2.2 ± 0.2</td>
<td>1.6 ± 0.5</td>
<td>1.7 ± 0.3</td>
<td>(4 ± 2)(-7)</td>
<td>3(16) - 2(17)</td>
<td>&gt; 8(16)</td>
</tr>
<tr>
<td>2, 0</td>
<td>1.6 ± 0.2</td>
<td>1.6 ± 0.6(^b)</td>
<td>2.2 ± 0.4</td>
<td>(5 ± 2)(-7)</td>
<td>4(16) - 3(17)</td>
<td>&gt; 9(16)</td>
</tr>
<tr>
<td>0.6 ± 0.1</td>
<td>2.0 ± 0.6(^c)</td>
<td>0.7 ± 0.3</td>
<td>(2 ± 1)(-7)</td>
<td>2(16) - 1(17)</td>
<td>&gt; 4(16)</td>
<td>0.08 - 0.1</td>
</tr>
<tr>
<td>2.1 ± 0.1</td>
<td>2.5 ± 0.6(^c)</td>
<td>0.9 ± 0.2</td>
<td>(3 ± 1)(-7)</td>
<td>3(16) - 2(17)</td>
<td>&gt; 1(17)</td>
<td>0.3 - 0.5</td>
</tr>
<tr>
<td>4, 0</td>
<td>2.2 ± 0.1</td>
<td>2.5 ± 0.6(^b)</td>
<td>1.6 ± 0.3</td>
<td>(5 ± 3)(-7)</td>
<td>5(16) - 3(17)</td>
<td>&gt; 2(17)</td>
</tr>
<tr>
<td>1.0 ± 0.2</td>
<td>1.4 ± 0.6(^c)</td>
<td>0.6 ± 0.3</td>
<td>(13 ± 1)(-8)</td>
<td>7(15) - 6(16)</td>
<td>2(16) - 5(17)</td>
<td>0.1 - 0.4</td>
</tr>
<tr>
<td>2.3 ± 0.1</td>
<td>2.8 ± 0.6(^c)</td>
<td>1.2 ± 0.3</td>
<td>(4 ± 2)(-7)</td>
<td>5(16) - 3(17)</td>
<td>&gt; 2(17)</td>
<td>0.2 - 0.7</td>
</tr>
<tr>
<td>6, 0</td>
<td>1.6 ± 0.1</td>
<td>2.4 ± 0.7</td>
<td>1.8 ± 0.3</td>
<td>(6 ± 3)(-7)</td>
<td>5(16) - 3(17)</td>
<td>&gt; 2(17)</td>
</tr>
<tr>
<td>8, 0</td>
<td>2.4 ± 0.1</td>
<td>2.1 ± 0.5</td>
<td>1.4 ± 0.3</td>
<td>(4 ± 2)(-7)</td>
<td>4(16) - 3(17)</td>
<td>&gt; 1(17)</td>
</tr>
<tr>
<td>10, 0</td>
<td>&lt; 1.2</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

\(^a\) offset with respect to \(\alpha(1950) = 15:51:32; \delta(1950) = -2:43:00.0\)
\(^b\) one component gaussian fit
\(^c\) two components gaussian fit
\(^d\) range in column densities for \(n_H = 10^3 - 2 \times 10^4\) cm\(^{-3}\)

July 1995. The main beam efficiencies were 0.72 (A-band) and 0.53 (B-band) and the corresponding beam sizes were 22 and 15 arcsec FWHM respectively.

For the observations of the CO molecule and its isotopes the Digital Autocorrelation Spectrometer (DAS) was used, except for the \(^{13}\text{CO}(3 - 2)\) observations in June 1993 which were done with the AOSC backend with a spectral velocity resolution of 0.3 km s\(^{-1}\) at 331 GHz. The adopted DAS bandwidth was 250 MHz with a velocity resolution corresponding to 0.1 km s\(^{-1}\) for both the A and B band. The observations were carried out in position switching mode, switching to an offset \((\Delta \alpha, \Delta \delta) = (0, 20)\)' with respect to the (0, 0) position. The offset position was carefully selected on the basis of existing CO maps (Laureijs et al. 1995). The calibration was performed with the chopper-wheel method carried out every 10 - 30 minutes. For the \([\text{C} \text{i}]\) observations the total integration time at each position was 30 min, resulting in an rms noise around \(T_A^* = 0.3\) K per spectral resolution element. The rms of the CO, \(^{13}\text{CO}\), and \(^{18}\text{CO} J = 2 - 1\) observations is 0.2, 0.15, and 0.1 K respectively. The rms of the CO and \(^{13}\text{CO} J = 3 - 2\) observations is 0.15, and 0.07 - 0.10 K respectively. The absolute calibration was checked by observing the H \(\alpha\) region W51 in the \([\text{C} \text{i}]\) line which showed \(T_A^* = 6.1\) K. The isotopic CO measurements were calibrated by observations of IRAS 1629-2422 for which we found agreement within 20% with the standard observatory values. The \([\text{C} \text{i}]\) and (isotopic) CO \(J = 2 - 1\) data were smoothed to a resolution of 0.4 km s\(^{-1}\) and 0.2 km s\(^{-1}\) respectively. This does not lead to a loss in spectral information since the spectral resolution is limited for narrow lines observed with RxA2 and RxC2 by the Gunn’s intrinsic phase stability which causes an instrumental broadening by 0.45 km s\(^{-1}\). All spectra are corrected for cold spillover. The intensities were converted to \(T_{\text{MB}}\), the main beam brightness temperature. The main beam efficiencies, and thus \(T_{\text{MB}}\), are referred to Jupiter (size \(\approx 40\)'). Since the emission is extended it would perhaps be more adequate to convert the observations to the radiation temperature \(T_A^*\) by means of the forward spillover and scattering efficiency \(\eta_{\text{fss}}\) (the Moon efficiency). On the \(T_A^*\) scale the intensities would be about 14, 17, and 26% lower than given here as \(T_{\text{MB}}\) for the A2, B3i, and C2 receiver, respectively.

3. Results

We observed the \([\text{C} \text{i}]\) and isotopic CO lines at six positions along an east-west cut through the centre of L 183; the spectra are presented in Fig. 1. The results of a gaussian analysis of the \(^{13}\text{CO}\) and \(^{18}\text{CO}\) spectra together with the calculated line intensities are listed in Table 1. For non-detections we list 2\(\sigma\) upper limits, the uncertainties are the 1\(\sigma\) errors from the gaussian fits. Table 2 shows the corresponding \([\text{C} \text{i}]\) parameters. In the comparison of the data no correction has been made for the different beamizes.

The optically thick CO \((3 - 2)\) and \((2 - 1)\) spectra are broad and often show a double peaked profile (see Fig. 1) with a dip at a local standard of rest (LSR) velocity of about 2.5 km s\(^{-1}\). This might be attributed to two closely spaced velocity components along the line of sight around 1.5 - 2 km s\(^{-1}\) and 3 - 3.5 km s\(^{-1}\). However, the double structure is not present in the \(^{13}\text{CO} J = 2 - 1\) profiles and the dip coincides with the LSR velocity of the single peaked \(^{18}\text{CO} J = 2 - 1\) spectra (see Table 1) as well as with the velocity of the cloud core as determined from other molecular species (e.g. Swade 1989a, b). This implies that the double structured CO profiles are due to self-absorption, caused by excitation gradients in a non-homogeneous physical and/or chemical cloud structure, such as commonly seen in high-mass star-forming regions (e.g. Phillips et al. 1979). Van Dishoeck et al. (1991) studied the effects of temperature, density, and molecular abundance gradients on a single component in a more diffuse cloud. They found that derived density and
isotope abundances of CO depend strongly on the assumptions about the cloud structure and internal kinematics, especially for thicker translucent regions. Therefore we have not used the saturated CO profiles of L 183 in our analysis.

The $^{13}$CO(2–1) emission peaks at the (0, 0) position and decreases gradually toward the east. Contrary to CO, the less optically thick (see Sect. 4.1) $^{13}$CO spectra show an asymmetric profile which we attribute to two kinematically different components closely spaced in velocity. These two components are resolved in the $^{13}$CO(3 – 2) spectrum at $\Delta \alpha = 4$ arcmin. They have central velocities around 1.1 km s$^{-1}$ and 2.1 km s$^{-1}$ and differ significantly in velocity from the above described double peaked $^{12}$CO self-absorption profiles. The C$^{18}$O profiles show only one component around 2.4 km s$^{-1}$ which peaks at the (0, 0) position and vanishes rapidly toward the east. Note that the $^{13}$CO(3 – 2) and the C$^{18}$O(2 – 1) spectra clearly have an asymmetric profile at the (0, 0) position.

Finally, the [C i] spectra show a double peaked profile at $\Delta \alpha = 2$ arcmin and $\Delta \alpha = 4$ arcmin with central velocities around 1.0 km s$^{-1}$ and 2.3 km s$^{-1}$ which correlate very well with the $^{13}$CO(3 – 2) components. The $^{13}$CO(3 – 2) spectrum at $\Delta \alpha = 2$ arcmin shows a 2.5$\sigma$ component around $V \approx 0.4$ km s$^{-1}$ which may be associated with the [C i] emission at $V = 0.6 \pm 0.3$ km s$^{-1}$, but a deeper integration is needed to find out if this component is real. A double structured [C i] profile may also be present at the other positions which have an asymmetric profile, but the signal-to-noise ratios are too low to make such a decomposition. The [C i] emission profile is also correlated with that of $^{13}$CO(2 – 1) (see Table 1 and Fig. 1). But the low intensity of the [C i] line and the blended $^{13}$CO(2 – 1) and [C i] profiles do not allow a detailed quantitative analysis at this stage. The C$^{18}$O emission is not correlated with [C i] in velocity width and extent.

The earlier [C i] $^{3}P_{1} - ^{3}P_{0}$ line emission measurement by Phillips & Huggins (1981) in L 183 with the Kuiper Airborne Observatory at 2.5 arcmin FWHM resolution shows a double peaked profile around $V \approx 3.5$ km s$^{-1}$ and $V \approx 2.0$ km s$^{-1}$. These velocities agree with ours if we adopt an offset between the velocity scales of about 1 km s$^{-1}$. Such an offset is consistent with the difference between the [C i] and CO central velocity in the L 183 spectra of Phillips & Huggins. Keene (1995) has also presented ground-based observations of [C i] along a strip through L 183 obtained with the Caltech Submillimeter Observatory. The absolute strength of the lines (converted to the same intensity scale) agree within 20% with our results. At positions in common, the line profiles are similar, and the second veloc-
ity component can be distinguished in her data as well. The $^{13}$CO($2 - 1$) lines appear somewhat stronger than those measured at the JCMT and show a double peaked profile at some positions. This structure is washed out in the JCMT data because of the local oscillator frequency instability.

4. Analysis

4.1. Abundances

We performed statistical equilibrium calculations to determine the population distribution over the ground triplet levels of [C i] and the twelve lowest CO, $^{13}$CO, and C$^{18}$O rotational levels, using an escape probability method for the radiative transfer. These calculations include collisional excitation and de-excitation as well as spontaneous and stimulated radiative transitions. This set of equations has been solved to find the level populations for a range of carbon and isotopic CO column densities, kinetic temperatures and H$_2$ densities (the main collision partner), including a background radiation field with $T_{bg} = 2.7$ K. For collisions of carbon with H$_2$ the de-excitation cross sections were taken from Schröder et al. (1991), while those for collisions of CO with H$_2$ were adopted from Schinke et al. (1985) for $T = 20$ K. Since the carbon and CO column densities are sensitive to both the kinetic temperature and molecular hydrogen density, a large range of the parameters ($N$(C, or $^8$CO), $n$(H$_2$), $T_K$) matches a given combination of main beam brightness temperature and velocity width. In Table 1 and 2 we list the derived column densities for $T = 10$ K, and $T = 15$ K for $n_{H_2} \approx 2n(H_2) = 10^3 - 2 \times 10^6$ cm$^{-3}$. The upper limits on the column density range correspond to the low end of the kinetic temperature and density range. The lower limits correspond to the high temperature and high density range, where the excitation temperatures approach the kinetic values. The excitation energy for the [C i] $J = 1$ level is $\Delta E/k = 23.6$ K, where $k$ is the Boltzmann constant. Since the [C i] intensity depends exponentially on $\Delta E$, very high densities are needed to excite the [C i] line at kinetic temperatures below $T_{K} < \Delta E/2k = 12$ K. In this temperature regime the observed [C i] line profiles are strongly saturated, consequently in most cases only lower limits on the column densities can be derived, see Table 2.

The optical depth of all lines may reach high values at the low end of the considered density and temperature range, while the lines become rapidly optically thin toward higher kinetic temperatures and/or densities. Table 3 lists the optical depths at $\Delta v = 4$ arcmin from the statistical analysis. For kinetic temperatures of about 10 K the optical depth of the [C i] line ranges from $\tau = 0.5 - 3.0$ for densities $n \approx 10^4$ cm$^{-3}$ and $T_{MB} < 2$ K, but may reach optical depths $\tau > 40$ for densities of about $n_{H_2} = 10^3$ cm$^{-3}$. At higher temperatures $15 < T_{K} < 20$ K, the optical depth of the [C i] line lies between $\tau = 0.1 - 6$. The $^{13}$CO and C$^{18}$O ($2 - 1$) lines have optical depths between $\tau = 0.1 - 6$ and $\tau = 0.1 - 0.7$ respectively. The C$^{18}$O($2 - 1$) line becomes optically thin at $T_{K} = 10$ K for densities $n \gtrsim 5 \times 10^3$ cm$^{-3}$, while the $^{13}$CO($2 - 1$) line needs densities $n \gtrsim 2 \times 10^3$ cm$^{-3}$. The $^{13}$CO($3 - 2$) line is found to have an optical depth $\tau = 0.1 - 7$ for the above listed range in physical parameters. We find that each corresponding component of the $^{13}$CO($3 - 2$) and the [C i] line profiles has the same range in optical depth for $15 < T < 20$ K.

Estimates of the CO column densities are listed in Table 1. These have been obtained by applying the terrestrial abundance ratio [O]/[H$^0$] = 500 and the local interstellar medium ratio [C]/[C$^13$] = 65 (e.g. Stahl & Wilson 1992, Langer & Penzias 1993). The constraints on the $^{13}$CO column densities derived from the $^{13}$CO($2 - 1$) observations are much tighter than those derived from the $^{13}$CO($3 - 2$) observations, except at $\Delta v = 4$ arcmin. This is due to the lower noise levels of the ($2 - 1$) measurements. The excitation conditions cannot be constrained by combining our $^{13}$CO($3 - 2$) and $^{13}$CO($2 - 1$) observations since in the latter observations the double component structure is blended through instrumental effects (Sect. 3). Observations have shown that in translucent regions the $^{13}$CO/C$^{18}$O column density ratio can exceed the terrestrial abundance ratio $^{13}$C]/[C$^{18}$O] = 5.5 (e.g. Bally & Langer 1982; White & Sandell 1995). At $\Delta v = 4$ arcmin the $^{13}$CO/C$^{18}$O column density ratio ranges between $3 - 30$ for $15 < T < 20$ K and $8 - 40$ for $T = 10$ K. This can be understood from two competing CO-isotope selective processes. First, isotope selective photodissociation causes C$^{18}$O to be more easily destroyed than $^{13}$CO, since C$^{18}$O is less self-shielding (van Dishoeck & Black 1988). Second, the carbon-isotope exchange reaction

$$^{13}$C$^+$ + $^{12}$CO $\rightarrow$ $^{13}$CO + $^{12}$C$^+$ + 36 K

leads to an enhancement of $^{13}$CO at low temperatures which may easily be a factor of ten at $T_{K} = 10$ K (van Dishoeck & Black 1988). These effects can explain why the CO column densities derived via $^{13}$CO are somewhat larger than those derived from C$^{18}$O, although this comparison is only allowed at $\Delta v = 4$' where the $^{13}$CO($3 - 2$) emission is resolved. Also, for high optical depths, the escape probability method may no longer give reliable results.

4.2. Cooling

The intensity of the [C i] $^3$P$_1 - ^3$P$_0$ 492 GHz line varies between $10^{-7} - 10^{-6}$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$, see Table 2. These values are comparable with those found for high-latitude translucent
clouds such as those toward HD 210121 and MBM12 (Stark & van Dishoeck 1994; Ingalls, Bania & Jackson 1994). In order to compare the total cooling by [C i] and CO, we have estimated the intensities of the [C i] \(3P_2 - 3P_1\) line and the twelve lowest CO transitions from excitation calculations (Sect. 4.1). The intensity ratio [C i] \(3P_2 - 3P_1\)/[C i] \(3P_1 - 3P_0\) ranges between 0.5 at \(T_K = 15\) K and \(n = 10^3\) cm\(^{-3}\) and unity at the high density and temperature limit. The corresponding CO intensities range between \(1 \times 10^{-6} - 4 \times 10^{-6}\) erg cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). At kinetic temperatures below 10 K the intensity of the [C i] \(3P_2 - 3P_1\) line is negligible. At the lowest density the cooling by carbon and CO becomes comparable, while for higher temperature and/or densities the cooling is always dominated by CO.

### 4.3. Chemical modelling

The derived carbon column densities for kinetic temperatures \(15 \leq T \leq 20\) K are comparable to those found in translucent clouds (Stark & van Dishoeck 1994), while for \(T = 10\) K only lower limits can be derived for the cold carbon abundance along the line of sight through the translucent envelope and the dark core. The calculated \(N(C)/N(CO)\) column density ratio has values between 0.08 – 0.7 for kinetic temperatures \(T \geq 15\) K, and has a lower limit of about 0.02 for \(T_K = 10\) K (see Table 2). Note that the C/CO column density ratio is better determined than the individual column densities since \(N(C)\) and \(N(CO)\) scale similarly with physical parameters like density and temperature. Thus, most of the observed carbon in L 183 is bound in CO. These values are comparable to those found in the translucent cloud MBM12 (Ingalls, Bania & Jackson 1994), which range between 0.1 and 1.5. However, they are an order of magnitude lower than those found in the high-latitude translucent cloud toward HD 210121 (Stark & van Dishoeck 1994). Recently Tauber et al. (1995) and White & Sandell (1995) have found a close inverse correlation between the C/CO column density ratio and the extinction over more than three orders of magnitude toward the Orion Molecular Cloud and Orion Bar: for \(A_V\) ranging from 0.1 to 500 mag, C/CO ranges from 10 to 0.01. A correlation between [C i] and \(^{13}\)CO emission in dense photon-dominated regions was already found by Keene et al. (1985).

Below we investigate the sensitivity of the carbon column density to the physical conditions as well as the large range in \(N(C)/N(CO)\) column density ratio and its anti-correlation with H\(_2\) column density. To this end we have extended the high-latitude cloud models of Stark & van Dishoeck (1994), which are based on the methods of van Dishoeck & Black (1988), to column densities of \(N(H_2) = 4 \times 10^{21}\) cm\(^{-2}\). Figure 2 (upper panel) shows the carbon column density as a function of total H\(_2\) column density for densities between \(n_{H_2} = 500 - 10^4\) cm\(^{-3}\). We assumed a gas-phase carbon, oxygen, and nitrogen fraction \(\delta_C = 0.4, \delta_O = 0.5,\) and \(\delta_N = 0.6,\) respectively. The gas-phase fraction of the other elements have been taken the same as those found in the \(\zeta\) Oph cloud (see Jansen et al. 1995). The radiation field is taken to be \(I_{UV} = 0.5\) which is representative for the high-latitude cloud regime. Higher values as large as three times the strength of the local interstellar radiation field (ISRF) may apply to the south-east side of L 183 (Laureijs et al. 1995; Sect. 5.2). At low H\(_2\) column densities the carbon column density increases strongly with \(N(H_2)\), as well as with density due to the enhanced C\(^+\) recombination rate. At high molecular hydrogen column densities most of the gas-phase carbon will be transformed into CO, and the C column density reaches a constant value of about \(3 \times 10^{17}\) cm\(^{-2}\). The observed atomic carbon column densities toward L 183 for the range \(15 \leq T \leq 20\) K can readily be obtained for visual extinction between \(A_V \approx 1\) mag \((N(H_2) \approx 8 \times 10^{20}\) cm\(^{-2}\)) and \(A_V \approx 5\) mag \((N(H_2) \approx 4 \times 10^{21}\) cm\(^{-2}\)) for densities larger than about \(500\) cm\(^{-3}\). If the radiation field is enhanced to \(I_{UV} = 3\), the limiting C column density is not changed significantly. Similar results are found in the models of e.g. Le Bourlot et al. (1993a).

In Fig. 2 (lower panel) we have plotted the column density ratio \(N(C)/N(CO)\) as a function of the total H\(_2\) column density. A close inverse correlation is found for \(N(H_2) = 10^{20} - 4 \times 10^{21}\) cm\(^{-2}\). For comparison we have also plotted the observed C/CO and (independently derived) H\(_2\) column density ratios for \(\zeta\) Per, (Savage et al. 1977, Smith et al. 1991) and HD 210121 (Stark & van Dishoeck 1994). Figure 2 clearly shows that the ratio...
N(C)/N(CO) ranges between 20–100 for N(H$_2$) = 10$^{20}$ cm$^{-2}$, and decreases to values between 0.2–0.4 at N(H$_2$) = 3 × 10$^{21}$ cm$^{-2}$.

For thicker clouds such as L 183 it is more appropriate to compare the observed N(C)/N($^{13}$CO) ratio with the model calculations, since only the $^{13}$CO column density is accurately derived and the conversion to CO column density is not straightforward because of isotopic-selective effects. In Fig. 3, we have plotted the model N(C)/N($^{13}$CO) ratio as a function of N(H$_2$). Note that in these particular calculations, the temperature structure was not explicitly solved for, but was kept constant at T = 40 K for the $n_H$ = 500 cm$^{-3}$ models and T = 15 K for the higher density models. The behaviour of the C/CO ratio is similar to that of C/C(O) (see Fig. 2, lower panel), except that $^{13}$CO is relatively enhanced in the higher density (lower temperature) models in the regime up to A$_V$ ≈ 2 mag. We have included in Fig. 3 the observed C/CO and H$_2$ column density ratios of the translucent clouds HD 210121 (Stark & van Dishoeck 1994) and MBM 12 (Ingalls, Van der Tak & Jackson 1994), and the dark cloud L 183 (this paper). For L 183, the plotted H$_2$ column density range corresponds to the translucent regime A$_V$ = 1–5 mag.

The behaviour of the C/CO and C/CO$_3$ column density ratio at a constant density, e.g. $n_H$ = 500 cm$^{-3}$, can be understood as follows. At low H$_2$ column densities, N(H$_2$) < 4 × 10$^{20}$ cm$^{-2}$, most of the carbon is still in the form of C$^+$, and the C/CO ratio decreases gradually with increasing N(H$_2$) while the C$^+$ → C → CO transition gradually shifts toward neutral atomic and molecular form. At a certain N(H$_2$) the atomic carbon column density has reached a maximum, while the CO column density is still increasing. Consequently from there on the C/CO ratio will decrease linearly. At higher densities the behaviour of the N(C)/N(CO) ratio is analogous. The C → CO transition zone will shift to lower H$_2$ column densities and becomes steeper. For the total hydrogen density range considered, it is seen that the range in the C/CO ratio becomes narrower toward higher H$_2$ column densities, where CO becomes the dominant carbon carrier.

5. Discussion

5.1. Atomic carbon distribution

The good correlation between the [C i] and the $^{13}$CO(3 - 2, 2 - 1) emission in linewidth and optical depth (Sects. 3, 4.1) suggests that both originate in the same regions of L 183. Most chemical models predict that the [C i] emission originates in the translucent outer regions of a cloud. The temperature in the core is estimated at T$_K$ = 10 K on the basis of the strength of the optically thick CO lines and the NH$_3$ observations of Ungerechts et al. (1980). We have also calculated the temperature structure in some of our models, as described in Jansen et al. (1995). These models show that for $I_{UV}$ = 0.5 and higher densities, the temperature is 20–30 K at the edge, decreasing to 10 K at A$_V$ ≈ 1 mag. For $I_{UV}$ = 3, this warmer layer extends somewhat deeper into the cloud. Thus, over the region where most of the carbon exists, the temperature is larger than 10 K, especially on the south-east side.

It is striking that two kinematically different components are seen in the [C i] and $^{13}$CO(3 - 2) spectra. Such a double structure has not been reported by Swade in his $^{13}$CO(1 - 0) data. Laureijis et al. (1995) mapped the L 134 complex in the CO(2 - 1) line at 2.7 arcmin resolution. From their channel maps it is clear that the 1.1 km s$^{-1}$ component belongs to the extended low brightness envelope of a distinct cloud which peaks east of L 183. This component does not have a counterpart in the molecules tracing the dense core such as NH$_3$. We attribute this to a second cloud which is completely translucent. The neutral carbon abundance N(C) that we derive for the translucent layer around the dark core and for the translucent cloud at V = 1.1 km s$^{-1}$ is constant along the cut and lies between 7 × 10$^{14}$ - 1 × 10$^{17}$ cm$^{-2}$, see Table 2. The derived C/CO column density ratio along the cut varies between 0.08–0.7 and remains constant within the uncertainty. Deeper integrations are necessary to get tighter constraints and to reveal a possible variation in N(C) and the C/CO column density ratio.

Recently it has been suggested that the neutral carbon abundance deep inside dark clouds may be high due to a bistability in the chemistry (Le Bourlot et al. 1993a, 1993b, 1995) which causes an incomplete carbon chemistry. Schilke et al. (1995) studied the [C i] line in TMC-1. They find similar line widths $\Delta V = 1.5–2$ km s$^{-1}$ for both the [C i] $\lambda\lambda$ 158.1–217.2 km s$^{-1}$ and $^{13}$CO(2 - 1) emission. This similarity suggests similar optical depths, and they derive values of the order $\tau = 10–20$ from analysis of the $^{13}$CO(2 - 1) emission. They use a low kinetic temperature $T = 10$ K and a density $n_H = 10^3$ cm$^{-3}$ in their large velocity gradient (LVG) calculations, and derive lower limits $N(C) > 10^{17}$ cm$^{-2}$. Consequently, their steady-state model.
with a maximum density $n_H = 2000 \text{ cm}^{-3}$ at $A_V \approx 0.3 \text{ mag}$ (A) fits their C\textsuperscript{18}O observations better than a model with a continuously increasing density $n_H \sim 1/r^2$ (B). The difference between the two models is an enhancement of the carbon abundance by an order of magnitude deep inside the cloud in the first model. But, at low kinetic temperatures ($T < 12 \text{ K}$) the intensity of the [C\textsc{i}] line decreases rapidly and high densities ($n \geq 10^4 \text{ cm}^{-3}$) are necessary to get a detectable intensity. On the other hand, the bistable chemical models predict a large atomic carbon abundance in the ‘Low-Ionization Phase’ at low density regions (Le Bourlot et al. 1993b). Therefore, even if atomic carbon is present in cold dense cores it does not contribute much to the observed [C\textsc{i}] emission. Schilke et al. find a carbon intensity for their model A only about a factor two higher than for model B. Note also that Shalabiea & Greenberg (1995) find that the bistability shifts to much lower density if different assumptions about elemental abundances are used and a different (gas-grain) chemical network is employed. Schilke et al. argue on the basis of similar line shapes that the optical depth of the [C\textsc{i}] lines in TMC-1 must be very high. For the case of L 183, this argument does not hold because of the two closely spaced velocity components. The line shapes of the spectra of Schilke et al. are often non-gaussian. Very high resolution and S/N data of both [C\textsc{i}] and $^{13}$CO(3 – 2) are needed to test their hypothesis.

5.2. Model of L 183

Because of the proximity of the Sco OB2 association and the star $\zeta$ Oph, Laurejs et al. (1995) estimate that the UV field illuminating L 183 is anisotropic and at most three times the global ISRF from the south-east direction. They studied the whole L 134 complex at a resolution of 5 arcmin in CO, $^{13}$CO, C\textsuperscript{18}O $J = 1 – 0$, IRAS emission, and extinction measurements from star counts. Slices through L 134 and L 1780 clearly show a correlation of the molecular and IR data with the anisotropy of the radiation field: stronger and more extended IR emission is found on the illuminated south-east side of the cloud than on the shadowside in the north-west. Also the ratio of the integrated $^{13}$CO and C\textsuperscript{18}O emission is high on the illuminated side of the cloud and remains low on the shadow side.

Large differences in the distribution of various molecules in the L 183 cloud core have been found by Swade (1989a, b). While emission of C\textsuperscript{18}O and CS is similar and extended in the east-west direction, the distribution of NH\textsubscript{3} and H\textsuperscript{13}CO$^+$ emission is different and elongated in the north-south direction. The emission of CS\textsubscript{2}H\textsubscript{2} peaks in the northern part at the maximum of the NH\textsubscript{3} and H\textsuperscript{13}CO$^+$ emission, but no emission is found at the corresponding southern peaks. In contrast, the SO emission peaks more to the west than all the other molecules. A similar behaviour is found for the distribution of molecules in the TMC-1 cloud (Olano et al. 1988). These differences in cloud structure can be due to abundance variations of the different molecular species, or they can be caused by variations in physical parameters. Although some density variations are seen across the L 183 and TMC-1 core, most of the structure in the maps is due to a true variation in chemical abundances (Swade 1989b, Olano et al. 1988). Swade & Schloerb suggest that the different distributions of SO and CS may be caused by an oxygen abundance effect across the core, with atomic oxygen being depleted by a factor five at the highest density core around the (0,0) position compared to the SO peak position. Alternative explanations include time-dependent effects (Suzuki et al. 1992) and cold, low luminosity protostars which do not show up as IRAS point sources but may affect the chemistry (van Dishoeck et al. 1993).

We propose the following 3-D cloud model for L 183. A dark core is traced by NH\textsubscript{3}, H\textsuperscript{13}CO$^+$, and CS\textsubscript{2}H\textsubscript{2} and completely shielded from the anisotropic radiation field. Around the dark core a translucent outer layer is present which is traced by emission of [C\textsc{i}] and CO isotopes. The distribution of these molecules is affected by the anisotropic radiation field, since the extent and chemistry in the translucent layer is very sensitive to the strength of the ISRF. At the north-west shadow side where $I_{UV}$ is lower, this translucent layer is shifted to smaller $A_V$ (van Dishoeck & Black 1988) whereas on the bright south-east side it is shifted to larger $A_V$ values. Molecules like CS, CO, and SO appear both in the dark core and translucent layer, consequently their emission suffers from self-absorption (Swade 1989a, Sect. 3). In addition, the anisotropic ISRF may cause chemical abundance variations. Therefore it is hard to disentangle true and apparent cloud structure by using these species. In particular, the suggested oxygen abundance variation by Swade & Schloerb (1992) may be apparent and caused by variations of the physical parameters in the translucent parts of L 183. The outermost parts form a diffuse veil at low density and higher temperature, wherein most of the carbon will be in the form C$^+$ at the south-east side. This layer may become a translucent C$^+$ → C, CO region at the shadow side of the cloud. Observations of the [C\textsc{i}] line at 158 $\mu$m along a cut in the direction of Sco OB2 will help to constrain the strength and anisotropy of the radiation field.

6. Summary and conclusions

The [C\textsc{i}] emission is well correlated with the $^{13}$CO(3 – 2, 2 – 1) emission in L 183. The lines are broad due to a double component structure caused by two kinematically different components along the line of sight. Such structure has not been resolved in earlier studies and may also be present in other dark clouds. It weakens the argument that the optical depth in the [C\textsc{i}] lines is very high based on the correspondence with $^{13}$CO. The existence of atomic carbon deep inside is not required to explain the observed [C\textsc{i}] emission. Most of the [C\textsc{i}] emission may come from the translucent outer envelopes of L 183, where the kinetic temperature is higher than in the dark core. The derived abundance of neutral carbon varies between $7 \times 10^{15} – 3 \times 10^{17}$ cm$^{-2}$, and is sensitive to small variations of the physical parameters (Stark & van Dishoeck 1994). The C/CO column density ratio is well below unity. Most of the gas phase carbon is bound in CO, and the cooling by CO dominates the cooling by [C\textsc{i}].

Observations of the (isotopic) [C\textsc{i}] $^3$P$\textsubscript{1} – ^3$P$\textsubscript{0}$ and [C\textsc{i}] $^3$P$\textsubscript{2} – ^3$P$\textsubscript{1}$ (hyper) fine structure lines accompanied by higher level
isotopic CO transitions at high signal-to-noise ratio in the north-south direction along the ammonia core as well as extension of our cut toward the west are highly desired. These are necessary to study the carbon content and extent of the translucent layer, as well as to separate a possible contribution from the cold core. Since [C I] delineates the edges of denser regions, mapping of the [C I] and $^{13}$CO lines will give important information on the structure of the translucent layer. The $^{13}$CO(2 − 1) and $^{13}$CO(3 − 2) spectra at the (0,0) position have an asymmetric profile and may be due to fragmentation. High resolution (interferometric) spectroscopy of this pre-protostellar core will be very valuable.

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