CARBON IN THE N159/N160 COMPLEX OF THE LARGE MAGELLANIC CLOUD

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ABSTRACT

We present a study of carbon in N159/N160, an H II region complex in the low-metallicity Large Magellanic Cloud. We have mapped this region, which comprises four distinct molecular clouds spanning a wide range of star formation activity, in four transitions: $^{13}$CO ($J = 1 \rightarrow 0$), $^{12}$CO ($J = 2 \rightarrow 1$) and ($J = 4 \rightarrow 3$), and [C I] ($^3P_1 \rightarrow ^3P_0$). Combining these data with existing [C II] ($^2P_{3/2} \rightarrow ^2P_{1/2}$) observations provides a complete picture of the predominant forms of carbon in the gas phase of the ISM. The new CO ($J = 2 \rightarrow 1$) data show that the complex is immersed in an envelope of extended, low-level emission, undetected by previous ($J = 1 \rightarrow 0$) mapping efforts. The $^{12}$CO ($J = 2 \rightarrow 1$)/($J = 1 \rightarrow 0$) ratio in this envelope is $\gtrsim 3$, a value consistent with optically thin CO emission. The envelope is also relatively bright in [C I] and [C II], and calculations show that it is mostly photodissociated: it appears to be translucent ($A_V < 1$). Neutral carbon emission in the complex unexpectedly peaks at the quiescent southern cloud (N159S). In the northern portion of the map (the N160 nebula), the H II regions prominent in [C II] correspond to holes in the [C I] distribution. Overall we find that, while the $I_{[CII]}/I_{CO}$ ratio is enhanced with respect to similar complexes in the Milky Way, the $I_{[CII]}/I_{CO}$ ratio appears to be similar or reduced.

Subject headings: galaxies: irregular — galaxies: ISM — ISM: clouds — Magellanic Clouds — radio lines: ISM — submillimeter

1. INTRODUCTION

The Magellanic Clouds are especially interesting systems for the study of the interstellar medium (ISM). Their low heavy element abundances and low dust-to-gas ratios, coupled with their proximity and their active star formation, make them ideal laboratories for understanding how metallicity and strong radiation fields influence the composition and structure of the ISM. Furthermore, in several important aspects they resemble prameval galaxies: they are morphologically irregular, metal-poor, and very actively forming massive stars. It is, however, worthwhile to point out that the Magellanic Clouds are not pristine systems. Their irregular morphologies refer mostly to the young populations (massive stars, OB associations, and H II regions), probably influenced by recent encounters with the Milky Way: the distribution of old stars and overall mass is not irregular (Cioni, Habing, & Israel 2000). Nevertheless, because of a relatively low time-averaged star formation rate the Magellanic Clouds are considerably less developed that the Milky Way. Therefore, their study will advance the understanding of the interaction between star formation and the ISM in primordial systems.

The H II regions in the N159/N160 complex were first cataloged by Henrize (1956) in a survey of emission-line nebulae in the Large Magellanic Cloud (Davies, Elliot, & Meaburn 1976 give them the numbers 271 and 284). These nebulae are two of the brightest H II regions in the immediate vicinity of 30 Doradus, located ~40' to its south.

In this region the star formation activity appears to be progressing from the (relatively) evolved starburst of 30 Doradus, where most of the enshrouding molecular cloud has been dissipated (Johansson et al. 1998), toward the quiescent southern CO arm region where little or no star formation is currently taking place (Cohen et al. 1988; Kutner et al. 1997). Located at such a transitional place the N159/N160 complex is one of the best studied star-forming regions of the Large Magellanic Cloud in molecular and atomic transitions (e.g., Johansson et al. 1994; Israel et al. 1996; Stark et al. 1997a; Pak et al. 1998; Johansson et al. 1998; Heikkilä, Johansson, & Olofsson 1999).

The N159/N160 complex features three distinct and spatially well separated regions: (1) the northern region, chiefly associated with the N160 nebula, where massive star formation is well evolved and the parent clouds have been mostly, albeit not completely, photodissociated and dissipated. (2) The central region, associated with the N159 nebula, which is undergoing strong star formation activity but still wrapped in molecular gas. This region includes two giant molecular clouds (GMCs) known as N159-east and N159-west (N159E and N159W, respectively). And (3) the southern region, featuring the molecular cloud N159-south (N159S). This cloud is actually the beginning of the 30 Doradus CO ridge region, a ~900 pc (~1°) long spur of molecular material extending southward of the 30 Doradus nebula.
The 30 Doradus CO ridge is the largest concentration of CO in the LMC (Cohen et al. 1988). Because the ridge is located on the leading edge of the LMC’s movement through the hot Galactic halo (Mathewson & Ford 1984), its formation has been attributed to ram pressure compression of the Magellanic interstellar medium (de Boer et al. 1998; Kim et al. 1998). The entire ridge region (including N159S) is quiescent, with little or no star formation activity as evidenced by its faint far-infrared (FIR), Hα emission of the Magellanic interstellar medium (de Boer et al. 1998).

Because the ridge is expected to be associated with C0 and photoionization products (C0 and C+), an increasingly large fraction of the molecular gas is relatively intact because of its strong self-shielding (Abgrall et al. 1992; Pak et al. 1998). Therefore, in metal-poor systems an increasingly large fraction of the molecular gas is dissociation regions (PDRs). In these regions the UV radiation dissociates most molecular species, but leaves Hα relatively intact because of its strong self-shielding (Abgrall et al. 1992; Pak et al. 1998). Therefore, in metal-poor systems an increasingly large fraction of the molecular gas is dissociation regions (PDRs). In these regions the UV radiation dissociates most molecular species, but leaves Hα relatively intact because of its strong self-shielding (Abgrall et al. 1992; Pak et al. 1998). Therefore, in metal-poor systems an increasingly large fraction of the molecular gas is dissociation regions (PDRs). 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times simultaneously in $^{12}$CO ($J = 1 \to 0$) and ($J = 2 \to 1$) (boxes in Fig. 1). Pointing and focus on a nearby SiO maser were performed before each observing session. The SEST pointing accuracy is $3^\prime$ rms.

2.2. Submillimeter Data

The $^{12}$CO ($J = 4 \to 3$) AST/RO observations were made with a system temperature $T_{sys} \approx 3500$ K. They were acquired on 1998 May 15 using the lower frequency side of AST/RO’s 460/810 GHz dual SIS waveguide receiver. The [C I] ($^3P_1 \to ^3P_0$) observations had a system temperature $T_{sys} \approx 1700$ K. The region was observed twice, on 1998 July 1 and August 10, using the AST/RO SIS quasi-optical receiver. The backend in both cases was the 2048 channel low-resolution AOS providing a spectral resolution $\Delta v \approx 0.4$ km s$^{-1}$ over a bandpass of $\sim 350$ km s$^{-1}$. The spectra were acquired in position switching mode, chopping 15' in azimuth (which is the same as R.A. at the pole).

The telescope was later determined to have HPBW(461) $\sim 34' \pm 0.3$ and HPBW(492) $\sim 38' \pm 0.3$, using scans across the limb of the Full Moon. The difference between the measured beams and the diffraction limited beam size for the telescope was caused by a 2° angular misalignment of the tertiary. No successful beam maps were acquired during the season, however, and the precise beam shape for either receiver is not actually known. Some of the source elongation manifested in the peaks of Figure 4, for example, may not be intrinsic but caused by a distorted beam shape in that particular receiver.

The forward efficiency for AST/RO was determined from skydips to be 70%, and it is assumed to be identical to the main beam efficiency as the telescope is an off-axis, unblocked aperture dish. Thus, we assume $\eta_{ab} \approx 0.7$ for 461 and 492 GHz. The maps were observed on a 30' grid, considerably oversampling the beam. A few of the spectra were contaminated by strong noise spikes that occasionally occur in two specific regions of the passband, possibly associated with electrical cross-talk between digital and analog signals in the AOS. These problematic spectra were discarded. Some grid points are therefore missing, but because of the oversampling this does not compromise the quality of the maps. The sensitivity of the [C I] map is $\sigma \approx 0.1$ K km s$^{-1}$ in the central area, but somewhat worse at the edges because there the spatial averaging cannot take advantage of the heavy beam oversampling.

AST/RO’s receivers sit on a static optical bench, located in the warm room below the dish, that does not track with the telescope. As a result any optical misalignment translates into precession of the receiver beam in the sky, a problem for faint sources that require long integrations. AST/RO’s radio pointing was carefully controlled during the 1998 season by repeatedly observing a set of compact line emitting sources at different elevations and fitting a model that compensates for elevation-dependent pointing offsets and beam precession. Thus, we are confident that the pointing accuracy out of our observations was better than $\sim 30'$ rms.

3. DISCUSSION

3.1. The Molecular ISM as Revealed by CO Observations

The CO data set is composed of new $^{13}$CO ($J = 1 \to 0$), $^{12}$CO ($J = 2 \to 1$), and $^{12}$CO ($J = 4 \to 3$) maps, as well as a preexisting $^{12}$CO ($J = 1 \to 0$) map obtained by the SEST Magellanic Clouds key program. Figure 1 shows the $^{12}$CO ($J = 2 \to 1$) and $^{13}$CO ($J = 1 \to 0$) SEST data. The four main molecular peaks (Table 1) are apparent in both transitions: N160 to the north is a relatively weak and elongated cloud, N159W is the strongest peak in the complex, N159E appears to break up into three clumps at this resolution, and N159S is a triangular cloud with the smallest ($J = 2 \to 1$)/($J = 1 \to 0$) intensity ratio in the complex. The cloud at offset $\bar{z}[+2', +5']$ is another member of the complex, which we will refer to as N160E. This cloud has very narrow lines (FWHM $\sim 2.6$ km s$^{-1}$). In addition to the bridge connecting N159S with the northern portion of the complex, there is a wealth of extended, faint emission throughout the mapped region. It is important to stress this point: even below the 2 K km s$^{-1}$ contours essentially every position in this map shows a significant CO ($J = 2 \to 1$) line if neighboring spectra are averaged. We will investigate the character of this extended, low-level emission in § 3.1.2.

The overall correspondence of these data with the published $^{12}$CO ($J = 1 \to 0$) map (Johansson et al. 1994, 1998) is extremely good, although some differences are apparent in the relative intensities and positions of the individual peaks. The shift in position is most noticeable for N159S, which at 1.3 mm appears to be $\sim 21'$ eastward of its nominal 2.6 mm position. This offset is most probably not real but caused by undersampling. These regions were mapped on a 30' grid at ($J = 1 \to 0$), while the SEST beam size at 115 GHz is 45' (Johansson et al. 1998). Our own ($J = 2 \to 1$) data are only sampled every 230 GHz beam (24'
grid) for N159S (N159E, N159W and N160 were observed on a 12′ grid). The CO \((J = 2 \rightarrow 1)\) peak in N159S falls almost precisely halfway between the \((J = 1 \rightarrow 0)\) samplings, and its position agrees very well with the fully sampled \(^{13}\text{CO} \,(J = 1 \rightarrow 0)\) map. This suggests that the \((J = 2 \rightarrow 1)\) position for this core may be better than the \((J = 1 \rightarrow 0)\) location. Excitation gradients within N159S may also explain this positional discrepancy. Fortunately, the shifts in the position of the peaks are much smaller for the remaining clouds. To maintain consistency with previous work (e.g., Heikkilä et al. 1999) we use the CO \((J = 1 \rightarrow 0)\) positions tabulated in Table 1. Because the submillimeter data have much lower angular resolution the precise position of the peaks will not greatly affect the ratios in Table 3.

3.1.1. Physical Conditions

What are the physical conditions in the different clouds of the complex? Figure 2 compares the \(^{12}\text{CO} \,(J = 1 \rightarrow 0)\), \((J = 2 \rightarrow 1)\), and the \(^{13}\text{CO} \,(J = 1 \rightarrow 0)\) observations. All three data sets have been spatially smoothed to a common 60′ resolution, and the results for the regions of interest are summarized in Table 2. The \(^{13}\text{CO}/^{12}\text{CO}\) integrated intensity ratio is commonly used to estimate column density. The \(^{13}\text{CO} \,(J = 2 \rightarrow 1)/(J = 1 \rightarrow 0)\) line ratio is sensitive to density in the low-density, optically thick limit, and to temperature for high densities (e.g., Kaufman et al. 1999). In the optically thin regime this ratio is sensitive to temperature, assuming that the emission is thermalized (for an exhaustive discussion of CO excitation see, however, Warin, Benayoun, & Viala 1996).

The centers of the N160 and N159W clouds have the highest \(^{13}\text{CO}/^{12}\text{CO}\) \((J = 1 \rightarrow 0)\) ratios and therefore the largest opacities, while at N159E this ratio is smaller by a factor of \(\sim 2\). Conversely, N160 has the largest \(^{13}\text{CO} \,(J = 2 \rightarrow 1)/(J = 1 \rightarrow 0)\) ratio and therefore appears to be the hottest, while N159S is the coldest cloud in the complex. These conclusions agree broadly with a much more detailed multiline excitation analysis performed toward the main molecular peaks in the complex by Heikkilä et al. (1999), who find kinetic temperatures of 20, 25, and 10 K for N159W, N160, and N159S, respectively.

The distribution of the warm and dense gas in the complex is elucidated by Figure 4. Recall that the \(^{12}\text{CO} \,(J = 4 \rightarrow 3)\) transition requires \(T \gtrsim 50\) K and \(n \sim 10^5\) cm\(^{-3}\) to be excited (§ 2). The angular resolution of the \((J = 4 \rightarrow 3)\) observations is \(\sim 4′\), therefore all of the clouds are beam

![Image of carbon monoxide main beam integrated intensity maps acquired at SEST.](image-url)
diluted and it is necessary to consider their beam-filling fractions to understand their relative intensities. All else being equal, larger clouds would appear brighter in Figure 4. The peak of the CO ($J = 4 \rightarrow 3$) map is N159W, due to a combination of intense emission and beam filling. Although there is an extension of ($J = 4 \rightarrow 3$) emission in the southward direction, a peak at the position of N159S is most noticeably absent. Because N159W and N159S have similar sizes and intensities in the CO ($J = 1 \rightarrow 0$) transition, this implies that the CO ($J = 4 \rightarrow 3$)/($J = 1 \rightarrow 0$) ratio is much smaller for N159S.

Conversely, there is a hint of an emission peak at the position of N160, a small cloud in $^{12}$CO ($J = 1 \rightarrow 0$). The presence of this peak suggests that the CO ($J = 4 \rightarrow 3$)/($J = 1 \rightarrow 0$) ratio for N160 is large. These results for the ratios are confirmed by convolving the CO ($J = 1 \rightarrow 0$) map to the resolution of the ($J = 4 \rightarrow 3$) data (Table 3). The CO ($J = 4 \rightarrow 3$)/($J = 1 \rightarrow 0$) ratio strongly depends on temperature and density, but the analysis performed by Heikkilä et al. (1999) shows that both clouds have volume densities above the ($J = 4 \rightarrow 3$) transition critical density. Therefore, the deficit of ($J = 4 \rightarrow 3$) emission in N159S is mostly due to the much lower temperature of the southern cloud. In the optically thick, LTE limit the observed CO ($J = 4 \rightarrow 3$)/($J = 1 \rightarrow 0$) ratio corresponds to $T_{\text{kin}} \approx 8$ K. This low temperature is probably due to the absence of star formation activity in N159S.

Figure 3 reveals the sources of heating and photodissociating radiation in the N159/N160 complex. The optical N159 nebula is centered between the N159E and N159W clouds. Portions of these clouds are in the foreground of the nebula and show themselves as obscurations against the bright background. The N160 cloud, however, appears to be behind its nebula. Part of the N160 nebulosity fills in the gap between the N160 and N160E molecular clouds and is neatly delineated by them. N159S is seen here only as a subtle obscuration against the field stars, with no associated nebulosity. While all the other clouds have apparent embedded sources visible as peaks in the 60 $\mu$m IRAS HIRES picture, N159S appears completely devoid of such sources. This lack of 60 $\mu$m emission confirms the complete absence of any massive star-forming activity in the southern cloud.

3.1.2. The Nature of the Extended CO Emission

To investigate the faint extended emission apparent in the $^{12}$CO ($J = 2 \rightarrow 1$) map, two small subregions at the edges of the complex (squares in Fig. 1) were mapped simul-
taneously in $^{12}\text{CO}$ ($J = 2 \rightarrow 1$) and ($J = 1 \rightarrow 0$). This permitted us to obtain reliable line ratios for these two transitions. The average spectra for these two regions are shown in Figure 5. The $^{12}\text{CO}$ ($J = 2 \rightarrow 1$)/($J = 1 \rightarrow 0$) ratio is $\sim 3$ for both positions; about a factor of 2–4 larger than for the molecular peaks (see Table 2). For thermalized, optically thick CO, we expect a line ratio close to 1. Larger ($J = 2 \rightarrow 1$)/($J = 1 \rightarrow 0$) ratios can be produced by essentially only four mechanisms: (1) self- or foreground-absorbed ($J = 1 \rightarrow 0$) emission, (2) optically thick CO gas with temperature gradients, (3) different beam filling fraction for the ($J = 1 \rightarrow 0$) and ($J = 2 \rightarrow 1$) transitions, or (4) thermalized but optically thin CO emission.

In the first of these cases the lower transition is absorbed by either a cold cloud along the line of sight at similar velocities, or colder outer layers of the same cloud. If most of the CO in the absorbing gas is in the ground state (i.e., the intervening cloud is very cold) the ($J = 2 \rightarrow 1$) transition will not suffer this effect, thereby artificially raising the ($J = 2 \rightarrow 1$)/($J = 1 \rightarrow 0$) integrated intensity ratio. In case 2

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**TABLE 2**

| Identifier | $T_{mb}$ | $V_{LSR}$ | FWHM | $I = \int T_{mb} dv$ | $I/I_{10}$ |
|------------|----------|-----------|-------|----------------|-----------|
|            | (K)      | (km s$^{-1}$) | (K km s$^{-1}$) |                      |           |
| $^{12}\text{CO}$ ($J = 1 \rightarrow 0$)* | | | | | |
| N159W ...... | 0.64 ± 0.01 | 235.1 ± 0.1 | 6.9 ± 0.1 | 4.67 ± 0.04 | 0.12 ± 0.02 |
| N159E ...... | 0.60 ± 0.01 | 235.6 ± 0.1 | 6.1 ± 0.1 | 2.13 ± 0.04 | 0.07 ± 0.01 |
| N159S ...... | 0.57 ± 0.01 | 235.6 ± 0.1 | 5.7 ± 0.1 | 3.37 ± 0.07 | 0.10 ± 0.01 |
| N160 ...... | 0.56 ± 0.01 | 237.7 ± 0.1 | 4.6 ± 0.2 | 1.59 ± 0.06 | 0.12 ± 0.02 |
| R1 ......... | ... ... | ... | ... | 0.01 ± 0.10 | ... |
| R2 ......... | ... ... | ... | ... | 0.09 ± 0.11 | ... |
| $^{12}\text{CO}$ ($J = 2 \rightarrow 1$)* | | | | | |
| N159W ...... | 4.80 ± 0.01 | 237.7 ± 0.1 | 7.8 ± 0.1 | 39.12 ± 0.06 | 1.01 ± 0.14 |
| N159E ...... | 3.60 ± 0.01 | 234.6 ± 0.1 | 7.3 ± 0.1 | 27.42 ± 0.06 | 0.89 ± 0.13 |
| N159S ...... | 3.22 ± 0.01 | 234.9 ± 0.1 | 8.1 ± 0.1 | 27.00 ± 0.08 | 0.78 ± 0.11 |
| N160 ...... | 3.46 ± 0.01 | 237.7 ± 0.1 | 5.0 ± 0.1 | 18.24 ± 0.10 | 1.59 ± 0.23 |
| R1 ......... | 0.16 ± 0.01 | 238.0 ± 0.7 | 10.8 ± 1.5 | 1.75 ± 0.20 | 3.57 ± 1.40 |
| R2 ......... | 0.25 ± 0.01 | 235.4 ± 0.2 | 7.6 ± 0.4 | 1.94 ± 0.10 | 2.81 ± 0.64 |

* Errors are statistical and ±1σ. Systematic calibration uncertainty is 1σ ~ ±10%.

* Values and errors derived from Gaussian fit.

* Ratio of transition intensity to that of $^{12}\text{CO}$ ($J = 1 \rightarrow 0$), convolved to the same beam, in K km s$^{-1}$.

* Errors are ±1σ, and include 10% 1σ calibration uncertainty in both lines.

* Measured in a HPBW = 1 beam.

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**Fig. 3.** Heating of the molecular cloud complex. The optical (left panel: blue band, SERC) and 60 μm FIR (right panel: IRAS HIRES, 40 iterations) emission are shown here with $^{12}\text{CO}$ ($J = 2 \rightarrow 1$) contours overlaid (alternate black and white, same levels as Fig. 1). This picture illustrates the detailed structure of the nebulae and the intimate and complex association between nebulosity, obscuration lanes, and molecular clumps. The southern cloud appears to have no UV or heating sources associated with it.
the $\tau = 1$ surface arises at different places along the line of sight for the two transitions. The observed line ratio will be the ratio of temperatures of the regions where the $\tau = 1$ surface occurs. If there are temperature gradients in the cloud, then this ratio can in principle take any value. In case 3, because the opacity grows faster with $N_{\text{CO}}$ in the $(J = 2 \rightarrow 1)$ than in the $(J = 1 \rightarrow 0)$ transition (eq. [A2]), it is possible for the clumps to appear larger in the higher transition and consequently fill more of the beam. For this effect to be considerable it requires small and warm CO clumps (see Appendix). In case 4 the ratio of both transitions will be in the range 0–4, depending on the temperature of the emit-

| Identifier | $T_{\text{mb}}$ | $V_{\text{LSR}}$ | FWHM | $I = \int T_{\text{mb}} \, dv$ | $I_{\text{CO}}/I_{\text{CO}}$ |
|------------|----------------|----------------|-------|----------------------|----------------------|
| N159W ...... | 0.95 ± 0.01 | 237.7 ± 0.1 | 8.6 ± 0.1 | 8.43 ± 0.08 | 0.48 ± 0.07 |
| N159E ...... | 0.42 ± 0.01 | 235.5 ± 0.1 | 7.7 ± 0.2 | 7.41 ± 0.08 | 0.27 ± 0.04 |
| N160 ...... | 0.39 ± 0.07 | 239.1 ± 0.1 | 9.4 ± 0.2 | 9.81 ± 0.08 | 1.16 ± 0.17 |
| N159W ...... | 0.13 ± 0.01 | 237.6 ± 0.1 | 1.18 ± 0.4 | 1.59 ± 0.05 | 0.11 ± 0.02 |
| N159E ...... | 0.14 ± 0.01 | 235.5 ± 0.1 | 6.1 ± 0.3 | 6.87 ± 0.03 | 0.09 ± 0.01 |
| N159S ...... | 0.17 ± 0.01 | 238.1 ± 0.1 | 10.1 ± 0.4 | 1.90 ± 0.06 | 0.15 ± 0.02 |
| N160 ...... | 0.14 ± 0.01 | 239.2 ± 0.1 | 2.4 ± 0.1 | 3.41 ± 0.02 | 0.10 ± 0.02 |
| R1 ...... | 0.06 ± 0.01 | 238.3 ± 0.3 | 9.1 ± 0.7 | 5.55 ± 0.04 | 0.14 ± 0.02 |
| R2 ...... | 0.09 ± 0.01 | 236.6 ± 0.2 | 7.7 ± 0.6 | 7.35 ± 0.05 | 0.12 ± 0.02 |

Errors are statistical and $\pm 1\sigma$. Systematic calibration uncertainty is $\pm 10\%$.

Values and errors derived from Gaussian fit.

Ratio of transition intensity to that of $^{12}\text{CO} (J = 1 \rightarrow 0)$, convolved to the same beam, in K km s$^{-1}$. To obtain ratios for intensities in ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$ multiply by $(v/\nu_{10})^3$.

Errors are $\pm 1\sigma$, and include $10\% 1\sigma$ calibration uncertainty in both lines.

$^{[C\text{II}]/\text{CO}} (J = 1 \rightarrow 0)$ line intensity ratio in a 4$^\prime$ beam, in ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$.

Measured in a HPBW = 4$^\prime$ beam.
ting CO gas (see Fig. 6). It can be shown that, in general, the ratio of integrated brightness temperatures for two consecutive rotational transitions in the optically thin, thermalized limit is

$$\frac{T(J+1) \rightarrow J}{T(J \rightarrow (J-1))} = \left(\frac{J+1}{J}\right)^2 e^{-\left(h\nu_{10}(J+1)/kT_{\text{ex}}\right)},$$

(1)

where $J$ is the rotational quantum number, $T_{\text{ex}}$ is the excitation temperature, and $h\nu_{10}/k \sim 5.5$ K for $^{12}$CO. For the transitions considered, a line ratio of $\approx 3$ implies excitation temperatures $T_{\text{ex}} \approx 40$ K.

Which one of these possibilities is occurring in regions R1 and R2? The ($J = 1 \rightarrow 0$) spectrum for R2 (Fig. 5) shows no clear evidence for self-absorption. Also, self-absorption tends to be a rather localized phenomenon: it is difficult to imagine it happening for two completely unrelated regions like R1 and R2. Thus, we think it is an unlikely explanation. To decide among the remaining possibilities it would be ideal to be able to estimate the CO column density. The $^{13}$CO observations, however, are not sufficiently sensitive to provide useful limits for the $^{12}$CO/$^{13}$CO ratio and subsequently determine if the emission is optically thick.

Because some of the possibilities we are discussing require warm gas, it is important to consider the sources of heating in these two regions. Region R1 is located between the N160 and N159 nebulae, and consequently its temperature can easily be higher than 40 K. Region R2 is found, however, in a quiescent region about 4' (~60 pc projected distance) away from the center of the N159 nebula. To raise the gas temperature of region R2 to the ~40 K needed to explain our ratios with optically thin CO emission, it is necessary to have heating sources. Surface temperature calculations of the PDR show that only a
modest radiation field, $\chi_{av}$, is required to produce that tem-
perature ($\chi_{av} \sim 10$, Kaufman et al. 1999). Eastward of
N159S there are a few very faint and inconspicuous H II
regions (DEM 272, 277, and 279, see Fig. 1; Davies et al.
1976), and traces of low-level 60 $\mu$m emission (Fig. 3). This
suggests that photons, possibly from these H II regions or
from their much brighter northern cousins, find their way
to heat the dust and elevate the temperature of the
diffuse gas. Calculations in § 3.2 show that the N159 nebula
is probably bright enough to provide the $\chi_{av} \sim 10$ field
needed to raise the temperature of the gas to 40 K. This
radiation is not, however, intense enough to heat the core of
N159S and make it a strong 60 $\mu$m or CO ($J = 4 \rightarrow 3$
emitter (Fig. 4). It is certainly not enough to produce any
measurable 158 $\mu$m [C II] emission, a transition that
requires $T \sim 92$ K to be excited (Fig. 7).

Given the fact that regions R1 and R2 are at the edges of
the molecular cloud complex, we find the case for optically
thin CO emission more compelling than the alternative
explanations. It is, however, difficult to choose among poss-
sibilities 2, 3, and 4 with the available data. Nevertheless, we
can make some specific predictions for the last two cases. In
case 3 (larger beam-filling fraction for the ($J = 2 \rightarrow 1$
transition), simple geometric arguments show that very
small CO clumps are required (Appendix). These clumps
are so small that they have only $\tau \sim 2$ in the ($J = 1 \rightarrow 0$
transition and fill less than 1% of the beam. Future mea-
surements of the ($J = 3 \rightarrow 2$) and ($J = 4 \rightarrow 3$
transitions in these regions may help distinguish between case 3 and opti-
cally thin emission (case 4). Because the ratio of opacities
between the ($J = 3 \rightarrow 2$) and ($J = 2 \rightarrow 1$) transitions of CO
is 2.25 for infinite temperature (eq. [1]), compared with 4 for
$\tau(J = 2 \rightarrow 1)/\tau(J = 1 \rightarrow 0)$, the increase in beam filling frac-
tion going from the ($J = 2 \rightarrow 1$) to the ($J = 3 \rightarrow 2$) transition
will be only modest. Thus, assuming uniform density clumps in LTE we expect peak intensities $T_{mb} \sim 0.18$ and
0.30 K in the $^{12}CO$ ($J = 3 \rightarrow 2$) transition for regions R1
and R2, respectively, only 20% brighter than the observed
($J = 2 \rightarrow 1$). For clumps with density increasing toward the
center the difference between the beam filling fraction for
both transitions, and consequently the increase in bright-
ness temperature, will be even smaller.

Concerning case 4, optically thin CO, the observed
($J = 2 \rightarrow 1$) intensities require CO column densities of $N_{CO} \sim 2 \times 10^{15}$ cm$^{-2}$ assuming optically thin LTE emis-
sion at $T_K = 40$ K. A prediction of this model is that $^{12}CO$
($J = 3 \rightarrow 2$) and ($J = 4 \rightarrow 3$) emission should be readily
observable with peak intensities in a $\sim 1'$ beam of $T_{mb} \sim
0.25$ and 0.45 K for regions R1 and R2, respectively. Because of the low angular resolution of our $^{12}CO$

![Fig. 7.—Distribution of the three dominant forms of gas phase carbon in N159/N160. The pseudo-color image shows the AST/RO [C I] observations at an angular resolution of $\sim 4.3$ (sensitivity $1 \sigma \sim 0.1$ K km s$^{-1}$). (Left) In black contours is the CO ($J = 2 \rightarrow 1$) map, at a resolution $\sim 33''$ (contours 2, 5, 15, 25, . . ., 55 K km s$^{-1}$). In white contours is the [C II] map by Israel et al. (1996), at a resolution $\sim 55''$ (contours start at $6.8 \times 10^{-5}$ in steps of $6.8 \times 10^{-5}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$). (Right) The three transitions have been smoothed to a common resolution of 4.3. We use here the CO ($J = 1 \rightarrow 0$) map by Johansson et al. (1994) to avoid edge effects when convolving the CO. The CO intensity contours start at 2 K km s$^{-1}$ in steps of 2 K km s$^{-1}$. The $I_{[Ca]}$ contours start at $1 \times 10^{-3}$ in steps of $2 \times 10^{-3}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$.](image-url)
(\(J = 4 \rightarrow 3\)) data, however, we are not able to cleanly separate these regions from the nearby peaks that dominate the emission and therefore cannot test these models. Nevertheless, the fact that these regions are relatively bright in [C I] (§3.2.2), together with the results of column density calculations (§3.3), strongly suggest that they are part of a translucent, mostly photodissociated envelope.

3.2. Carbon in the Gas Phase of the ISM

Here we analyze the AST/RO [C I] (\(3^2P_1 \rightarrow 3^2P_0\)) map in conjunction with the available [C II] and CO data (Israel et al. 1996; Johansson et al. 1998). Figure 7 reveals the distribution of the three dominant forms of carbon in the gas phase of the ISM. The striking features of this map are the complex interplay between CO, C\(^0\), and C\(^+\), and the fact that [C I] peaks in the southern cloud, a quiescent region entirely devoid of strong UV sources.

Throughout the map there is an overall anticorrelation between the distributions of [C II] and [C I]. Only in N159W do the three species peak at approximately the same place, while in all the other clouds only two of the species show intense emission. The northern regions, with abundant star formation activity, are bright in [C II] but very dim in [C I]. The opposite is true for N159S. This cloud, with no massive star formation activity, is the peak of [C I] in the whole complex. It is also the region with the largest [C I]/CO intensity ratio (see Table 3). The [C I] emission in N159E is relatively faint, and the CO, C\(^0\), and C\(^+\) there appear to occupy adjacent and partially overlapping regions. Finally, in N160 a [C I] hole is filled in by a bright lobe of [C II], with a very faint ridge of [C I] emission overlapping with the CO.

The distribution of the different forms of gas phase carbon in N159/N160 may be affected by peculiarities of the region. For example, the central [C II] peak (N159-M; Israel et al. 1996), which has no FIR counterpart, is very close to the position of LMC-X1. It may be associated with that X-ray source, which is located at offsets \([-1',+1']\) (Fig. 1). LMC-X1, one of the strongest X-ray sources in the LMC, is a black-hole candidate with an O7 III companion star (Cowley et al. 1995; Schmidtke, Ponder, & Cowley 1999). It has been suggested that X-ray radiation has considerable effect on the chemistry of the ISM (e.g., Lepp & Dalgarno 1996), and it is possibly a way to produce C\(^+\) and C\(^0\). Dissociation of CO in shocks may be another way of generating these species. Approximately 2' east of LMC-X1, Chu et al. (1997) have identified a supernova remnant, SNR 0540–697, based on optical spectra and X-ray data. This remnant is expanding at \(\sim 150 \text{ km s}^{-1}\) and overlaps with most of the nebulosity NW of N159E (Fig. 3). We see no evidence in our data for [C I] emission at these velocities, and the ratio maps (Fig. 8) show no peculiar enhancement of the \(I_{[\text{C I}]}/I_{\text{CO}}\) and \(I_{[\text{C II}]}/I_{\text{CO}}\) ratios at the position of the remnant. Thus, shock-induced dissociation of CO does not appear to be an important mechanism producing [C II] or [C I] in this area.
On the spatial scale of these observations ($1' \sim 15$ pc) we do not expect to be resolving the PDRs into their three separate $C^+$, $C^0$, and CO regions. This has been accomplished only in a few Galactic sources observable with much greater spatial resolution (e.g., the Orion bar). Accordingly, we expect to observe coextensive $[\text{C II}]$, $[\text{C I}]$, and CO emission for the molecular peaks. This is not necessarily the case for the translucent medium. In diffuse gas and in the presence of strong UV sources most carbon will be ionized. Thus, $C^+$ will dominate the emission, forming $[\text{C II}]$ regions akin to Stromgren spheres around the ionizing sources. This is apparently happening in the northern portion of the map where bright lobes of $[\text{C II}]$ emission east and west of N160 fill in holes in the $[\text{C I}]$ distribution. These $[\text{C II}]$ peaks and $[\text{C I}]$ holes are unequivocally associated with H II regions (Fig. 9). Most of their $[\text{C II}]$ emission may arise from $C^+$ mixed with H II inside the Stromgren sphere, collisionally excited by electrons.

In principle, over a small range of extinction ($A_V \sim 0.3$–1) we could have clouds where $C^+$ and $C^0$ are dominant, with little or no CO emission. That may be occurring between N160 and N159W, where bright $[\text{C II}]$ and $[\text{C I}]$ overlap in a region that shows little CO emission. One must be careful, however, when interpreting and combining data with very different (and, for the $[\text{C I}]$, low) angular resolutions. Figure 7b shows the three transitions convolved to a common resolution ($\sim 4.3$). In this map there are only two peaks in the $[\text{C II}]$ distribution (N160 and N159W), and the $[\text{C II}]$, $[\text{C I}]$, and CO maxima near N159W are displaced by about 1' from each other in a way that resembles a PDR $C^+/C^0$/CO transition. This structure, however, is not a PDR: if these clouds were moved to Orion (0.5 kpc away and perhaps the best example of a resolved PDR) the distance between the $[\text{C II}]$ and the CO peaks would span 2' in the sky. What we are observing are large scale excitation and chemical gradients. The extended $[\text{C II}]$ emission is heavily weighted in the convolved data and pulls the overall maximum northward, also diluting the peak coincident with N159W. In much the same manner, the $[J = 1 \rightarrow 0]$ peak is pulled southward by the extended CO emission. Notice that the CO maximum near N159S moves westward for the same reason.

### 3.2.1. The Neutral Carbon Emission from N159S

The fact that the peak of $[\text{C I}]$ emission for the entire complex is a quiescent region is unexpected if $C^0$ has, chiefly, a PDR origin and thus requires UV photons to be produced. To review the evidence: N159S is a dark cloud with weak CO ($J = 4 \rightarrow 3$) emission (hence at a low temperature), with no conspicuous heating sources apparent in the optical or the FIR (hence little or no star formation), and with very faint $[\text{C II}]$ emission (hence no UV sources). Nevertheless, according to the analysis by Heikkila et al. (1999) it is the cloud with the largest column density in the complex ($N_{\text{H}_2} \sim 1.7 \times 10^{22}$ cm$^{-2}$, $A_V \sim 4.5$ compared to $N_{\text{H}_2} \sim 1.1 \times 10^{22}$ cm$^{-2}$, $A_V \sim 2.9$ for N159W and N160), and it is also the brightest $[\text{C I}]$ emitter, possessing the largest $I_{\text{CO}}/I_{\text{CO}}$ ratio. This is certainly indirect evidence, but it suggests that most of the $C^0$ in this cloud originates not by UV photodissociation of CO in the PDR, but inside the CO cores.

Recent modeling results indicate, however, that the $I_{\text{CO}}/I_{\text{CO}}$ ratio is very insensitive to the radiation field (Kaufman et al. 1999). Therefore, only a small amount of UV radiation is necessary to explain the observed ratio in the context of a PDR. This can be understood in the following way: in $A_V$ space the extent of the $[\text{C I}]$ emitting region in a homogeneous one-dimensional calculation, and consequently the $C^0$ column density, is relatively insensitive to the input radiation field. The depth at which the $C^+$/CO transition occurs, however, increases for larger $A_V$. Because $^{12}\text{CO}$ becomes optically thick soon after this transition, neither the $[\text{C I}]$ nor the CO emerging intensities are a strong function of the radiation field at the surface of the cloud. All the molecular peaks in this region feature optically thick $^{12}\text{CO}$, based on the $^{13}\text{CO}/^{12}\text{CO}$ intensity ratios listed in Table 2 ($^{12}\text{C}/^{13}\text{C} \sim 50$ for the LMC, Johansson et al. 1994).

The previous reasoning applies to homogeneous clouds with plane-parallel (i.e., one-dimensional) geometry. If molecular clouds are in fact clumpy, they can be modeled as an ensemble of spherical clouds. In this scenario the UV field should have a dramatic effect on the $C^+$, $C^0$, and CO column densities and intensity ratios. In a clump subjected to an increasing UV field, the CO emitting region can be pushed toward the center only as far as the radius of the clump, after which the entire clump photodissociates. This
scenario has been modeled in detail by Bolatto et al. (1999). Following those calculations we expect an inverse dependence between $\chi_{\text{av}}$ and CO column density, and a modest increase in the $[\text{C}^\text{I}]/\text{CO}$ ratio for increasing $\chi_{\text{av}}$ (growing by $\approx 25\%$ per order of magnitude in $\chi_{\text{av}}$). This model, however, does not include an interclump medium. Modeling of clumpy PDRs as a collection of high-extinction $(A_V \approx 100)$, dense regions immersed in a diffuse interclump gas exposed to high UV (Meixner & Tielens 1993, 1995) suggests that dense regions immersed in a diffuse interclump gas exposed to high UV (Meixner & Tielens 1993, 1995) suggests that the N159/N160 complex, based on IRAS HIRES data, are given in Table 4. These estimates are generally lower than those based on the FIR, mostly because spectral types later than O6 are still very luminous (adding to the FIR luminosity) but contribute little to the radio continuum. Recent ISOCAm observations (Comerón & Claes 1998), for example, reveal three strong 15 $\mu$m peaks in N159 which feature very faint radio continuum and are thus attributed to ultracompact H II regions which are optically thick at 21 cm. These are examples of sources that would add to the FIR luminosity but be invisible at 1.42 GHz. Nevertheless, both the radio continuum and the FIR measurements agree within a factor of $\sim 2$ ($L_{\text{FIR}} \sim 2L_{\text{RC}}$), strongly suggesting that most UV is actually intercepted by the surrounding dust. Taking into account the various estimates and caveats discussed in the previous paragraph, we conclude that $\chi_{\text{av}}(\text{N159S}) \lesssim 10$. Such a low UV field is consistent with the faint [C II] emission from N159S, as well as its low $I_{(\text{CII})}/I_{\text{CO}}$ ratio.

Even orders of magnitude in $\chi_{\text{av}}$, however, have little impact on the value of the $I_{(\text{CII})}/I_{\text{CO}}$ ratio in standard PDR plane-parallel models. According to the calculations by Kaufman et al. (1999), the $[\text{C}^\text{I}]/\text{CO}$ intensity ratio observed in N159S can be attributed to gas with $n \approx 10^{5}$ cm$^{-3}$ at $\chi_{\text{av}} \sim 1-10^5$. Note that metallicity has only very small effects on plane-parallel model calculations, for reasons essentially similar to those discussed for $\chi_{\text{av}}$. Thus, although the aforementioned calculations were performed for Galac-

TABLE 4

FIR PARAMETERS FOR THE N159/N160 COMPLEX

| Identifier  | $S_{60}$ | $S_{100}$ | $S_{100}/S_{60}$ | $T_{\text{dust}}$ | $L_{\text{FIR}}$ | Equiv. Spectral Type $^a$ |
|-------------|---------|----------|-----------------|-----------------|-----------------|---------------------------|
| N159W ...... | 204.9   | 671.8    | 3.28            | 30              | 3.40            | 5 × O5 V                  |
| N159E ...... | 179.6   | 393.7    | 2.19            | 34              | 1.86            | 3 × O5 V                  |
| N159S ...... | 6.6     | 39.5     | 6.01            | 25              | <0.24           | <O6 V                     |
| N160 ......  | 393.1   | 580.1    | 1.48            | 40              | 2.74            | 4 × O5 V                  |
| N160E ...... | 48.5    | 76.1     | 1.57            | 39              | 0.36            | 0.55 V                    |

$^a$ Dust source flux density at 60 and 100 $\mu$m derived from IRAS HIRES data.
$^b$ Dust temperature derived from the ratio of $S_{100}$ to $S_{60}$, assuming the dust emits as a graybody with emissivity exponent $\beta = 1$.
$^c$ FIR luminosity computed according to Lonsdale et al. 1985, assuming a dust emissivity exponent $\beta = 1$ and $D = 52$ kpc.
$^d$ Equivalent spectral type and multiplicity (Panagia 1973), assuming all starlight is absorbed by dust and reemitted in the FIR.
$^*$ There is no infrared source associated with N159S, therefore the IRAS fluxes are upper limits.
tic sources, their results can be safely applied to the LMC. The coincidence between this density and that obtained by Heikkilä et al. (1999) for N159S appears satisfying, until we take into account the different scale of the measurements: the 4′ (60 pc) region over which $I_{\text{CO}}/I_{\text{CO}} \approx 0.15$ is $\approx 25$ times larger than the SEST $\sim 48''$ beam used to carry out the multiline excitation analysis. This is an extremely high density for such a large region. Invoking beam filling fraction arguments avoids this problem, by assuming that only small and dense regions within the beam are dominating the CO ($J = 1 \to 0$) and [C I] emission. Comparison of the measured [C I] intensity with the model results suggests $\sim 10\%$ beam filling fraction. Nevertheless, if such a high density is characteristic of the gas producing the [C I] emission, it rules out the interclump medium as the main reservoir of neutral carbon. Meixner & Tielens’ (1995) modeling of two-phase (clump + interclump) PDRs shows that $I_{\text{CO}}/I_{\text{CO}} \sim 10$ can be obtained for a mixture of $5 \times 10^{5}$ cm$^{-3}$ $A_V \sim 100$ clumps immersed in a $3 \times 10^3$ cm$^{-3}$ diffuse component, with 20% volume filling fraction for the clumps. These computations, however, were carried out for $\chi_{av} \sim 5 \times 10^4$, and no similar calculations are available for UV fields closer to that of N159S.

At the beginning of this section we pointed out a series of intriguing facts about N159S that may suggest a non-PDR origin for most of its neutral carbon. Despite them, however, we conclude that the observed [C II], [C I], and CO intensities in N159S are consistent with standard PDR theory assuming $n \approx 10^5$ cm$^{-3}$ and $\chi_{av} \sim 10$. These values of the density and UV field agree with previous excitation analysis and with the best estimates of $\chi_{av}$ in N159S, assuming it is illuminated by the northern complex of H II regions.

### 3.2.2. The $I_{\text{CO}}/I_{\text{CO}}$ Ratio in the Complex

How are the relative intensities of the different forms of carbon affected by the local conditions? In the previous sections we have seen that [C I] is dim in the northern portion of the map, where there is active massive star formation, and bright in N159S. In this section we will compare the $I_{\text{CO}}/I_{\text{CO}}$ and $I_{\text{CO}}/I_{\text{CO}}$ ratios throughout this region, and look for the effects of radiation fields and metallicity.

Figure 8 shows the $I_{\text{CO}}/I_{\text{CO}}$ and $I_{\text{CO}}/I_{\text{CO}}$ ratios mapped for the entire complex, with the data convolved to a common 4.3 resolution. Table 3 shows our $I_{\text{CO}}/I_{\text{CO}}$ results tabulated for the regions of interest. Notice that Table 3 uses a 4′ beam size. To convert from intensity ratios given in K km s$^{-1}$ to ratios in ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$ multiply by $\sim 78$ for $I_{\text{CO}}/I_{\text{CO}}$. Since N160 is such a weak [C I] source, its ratio is dominated by the surrounding extended [C I] emission and therefore the ratio increases noticeably when measured in a larger beam. For N159S the angular resolution of the measurement is unimportant, and the ratio remains mostly unchanged. Therefore, the high $I_{\text{CO}}/I_{\text{CO}}$ ratio at N159S is not an artifact caused by the nearby emission. The first measurement of the [C I]/CO intensity ratio in N159 was carried out by Stark et al. (1997a), who obtained $I_{\text{CO}}/I_{\text{CO}} \approx 0.26$ (intensities in K km s$^{-1}$). This determination was based on a single spectrum taken toward the nominal position of N159W and assumed an unresolved structure for the CO from this cloud. We find that, albeit in a larger beam, $I_{\text{CO}}/I_{\text{CO}} \approx 0.12$ for N159W. This difference is largely due to an underestimate of the CO intensity in the aforementioned paper.

Two regions of the map feature high [C I]/CO intensity ratios: the northern region, where there $I_{\text{CO}}/I_{\text{CO}}$ also peaks, and the southeast corner, where there is extended low-level CO ($J = 2 \to 1$) but little ($J = 1 \to 0$) emission and no detectable [C II] emission. We think that in both cases we are seeing translucent, mostly photodissociated gas, with the important difference that the abundant UV radiation in the northern region raises the temperature of the PDRs over the 91.3 K required to excite the 158 $\mu$m [C II] transition (see § 3.3). There is the possibility that the southeastern extension of the N159S cloud in [C I] is an artifact of the sampling, since the map is missing a few spectra there. Because of the heavy oversampling of the beam, however, we think that this extension is probably real. It appears also that there is a modest increase in the $I_{\text{CO}}/I_{\text{CO}}$ ratio at the edges of the complex, and perhaps in the immediate vicinity of LMC-X1. The lowest ratios are found south of N159W.

How does the $I_{\text{CO}}/I_{\text{CO}}$ ratio in this complex compare with the $I_{\text{CO}}/I_{\text{CO}}$ ratio? Since both C$^+$ and C$^0$ are produced by the action of UV photons in the PDR, the naive expectation is that [C II] and [C I] should have a similar distribution in unresolved PDRs. Excitation differences, important for very low radiation fields ($\chi_{av} < 10$), will become negligible for $\chi_{av} > 100$ as the PDR reaches temperatures well over 100 K (Kaufman et al. 1999). As discussed at the beginning of § 3.2 there are other reasons why we may not expect [C II] and [C I] to be coextensive in the diffuse translucent gas, namely the formation of C$^+$ “Strömgren spheres” near UV sources. In these regions carbon ionization and not dust absorption
is the dominant process that removes UV photons, and consequently all the carbon is in the form of C$^+$. In the molecular material, however, UV photons should be predominantly removed by dust grains, leaving a fraction of the carbon in the form of C$^0$. Consequently, if the structure of the ISM is clumpy and therefore allows the UV photons to penetrate deep into the clouds, the expectation is for [C I] and [C II] to be coextensive and in many ways behave similarly. In particular, modeling of clumpy PDRs suggest to penetrate deep into the clouds, the expectation is for the ISM is clumpy and therefore allows the UV photons consequently all the carbon is in the form of C$^+$. No. 1, 2000 CARBON IN LMC N159/N160 COMPLEX 247
dominantly removed by dust grains, leaving a fraction of we pointed out in § 1, Mochizuki et al. (1994) found a considerable enhancement of the global $I_{[\text{C} \text{II}]}/I_{\text{CO}}$ ratio of the LMC ($I_{[\text{C} \text{II}]}/I_{\text{CO}} \approx 23,000$) over that of the Milky Way. Average ratios for Galactic objects are $I_{[\text{C} \text{II}]}/I_{\text{CO}} \sim 1300$ for GMCs, and $\sim 4400$ for H II regions (Stacey et al. 1991). Observations by Israel et al. (1996) of N159/N160 (see Table 1) show that the three northern molecular peaks (N159E, N159W, and N160) have $I_{[\text{C} \text{II}]}/I_{\text{CO}}$ ratios 1–5 times larger than comparable Galactic regions while their $I_{[\text{C} \text{II}]}/I_{\text{CO}}$ ratios are 3–40 times lower, suggesting a much larger abundance of C$^+$. Measurements of the 30 Doradus region (Poglitsch et al. 1995) yielded a ratio $I_{[\text{C} \text{II}]}/I_{\text{CO}} \approx 65,000$ for its molecular peaks. Madden et al. (1997) studied the global [C II] emission from the low-metallicity dwarf galaxy IC 10 which has $Z_{\text{IC10}} \approx Z_{\text{MW}}/4$ (where we have used the oxygen abundance in Orion as representative of the Galaxy, 12 + log [O/H] $\approx 8.75$; Lequeux et al. 1979). They found ratios in the range $I_{[\text{C} \text{II}]}/I_{\text{CO}} \approx 14,000$–87,000 for various regions.

Unlike the widely varying $I_{[\text{C} \text{II}]}/I_{\text{CO}}$ ratio, the $I_{[\text{C} \text{I}]}/I_{\text{CO}}$ ratio for the molecular peaks of N159/N160 is surprisingly uniform. The values range only between $I_{[\text{C} \text{I}]}/I_{\text{CO}} \approx 7$ to $\sim 12$. These are very similar to the typical ratio in the Milky Way, where $I_{[\text{C} \text{I}]}/I_{\text{CO}} \sim 13$ (intensities in ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$). This is not an isolated result. Wilson (1997) observed the [C I] emission from several clouds at different galactocentric distances in M33, a spiral galaxy with a well-known metallicity gradient. She obtained ratios of $I_{[\text{C} \text{I}]}/I_{\text{CO}} \sim 3$–14 and found no obvious trend with inferred metallicity. Recently, Bolatto et al. (2000) studied the $I_{[\text{C} \text{I}]}/I_{\text{CO}}$ ratio in the molecular cloud complex associated with the brightest star-forming region of IC 10. They obtained an average ratio $I_{[\text{C} \text{I}]}/I_{\text{CO}} \sim 18$, only slightly larger than the average Galactic ratio. Finally, the recent study by Gerin & Phillips (2000) of atomic carbon in a variety of galaxies finds some dispersion in the $I_{[\text{C} \text{I}]}/I_{\text{CO}}$ intensity ratio, but no clear segregation with galaxy type. Their sample of galaxies has an average ratio $I_{[\text{C} \text{I}]}/I_{\text{CO}} \sim 16$, with most ratios found in the interval $I_{[\text{C} \text{I}]}/I_{\text{CO}} \approx 8$–32.

Overall, if there is a trend for $I_{[\text{C} \text{I}]}/I_{\text{CO}}$ with metallicity, it is certainly much weaker than the one observed for $I_{[\text{C} \text{II}]}/I_{\text{CO}}$. A plausible explanation for the constancy of the [C I]/[CO] intensity ratio is a non-PDR origin for a fraction of the C$^0$. While it seems unequivocal that in the diffuse gas most neutral carbon is associated with PDRs, it is possible that a different mechanism dominates its production inside molecular cloud cores. If C$^0$ is indeed produced in these cores by processes unrelated to photochemistry, it would simply explain the close observed association between the [C I] and CO line intensities.

### 3.3. The Column Density in the Extended Envelope

The entire molecular cloud complex appears to be surrounded by an extended envelope visible in CO ($J = 2 \rightarrow 1$), and possibly [C I] and [C II]. For example, the extended and relatively bright [C I] emission east of N159S and south of N159E correlates very well with the faint, extended CO ($J = 2 \rightarrow 1$) in the same region, as does the tongue of [C I] spreading north of the N159 nebula. Assuming, as was discussed in § 3.1.2, that the CO emission in this region is optically thin, then we appear to be seeing translucent gas emitting in [C I]. translucent clouds are clouds with visual extinction $A_V \lesssim 1$, where an important fraction of the carbon is in the form of C$^+$ and C$^0$ (e.g., Ingalls et al. 1997). While the regions surrounding R1 are strong [C II] emitters, region R2 and its environs are very faint in [C II]. Understated by Israel et al. (1996), the upper limit for the integrated intensity from R2 is $I_{[\text{C} \text{II}]} \lesssim 6.8 \times 10^{-5}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$. The limit for the corresponding C$^+$ column density, derived for the high-temperature, high-density case that is, the minimum column density corresponding to the intensity limit is $N_{\text{C}^+} \approx 4 \times 10^{16}$ cm$^{-2}$, about 20 times larger than the corresponding column density of CO derived in § 3.1.2. Singly ionized carbon could well be the dominant form of carbon in this region yet remain undetected.

Assuming that most of the carbon is in the form of C$^+$, we can estimate the hydrogen column density along these lines of sight. For R1, $I_{[\text{C} \text{II}]} \approx 1.4 \times 10^{-4}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$, therefore $N_{\text{C}^+} \approx 8 \times 10^{16}$ cm$^{-2}$. Assuming an LMC gas phase carbon abundance per H nucleus $x_C \approx 7 \times 10^{-5}$ (Dufour 1984), this yields $N_H \approx 1.2 \times 10^{21}$ cm$^{-2}$, or $A_V \approx 0.15$ (using the conversion factor $A_V \approx 8 \times 10^{21}$ cm$^{-2}$, which is 4 times that of the Galaxy). In the case of R2, where no [C II] is detected, Figure 7b shows that there is some very low-level emission that becomes statistically significant only after spatial smoothing. We will assume $I_{[\text{C} \text{II}]} \approx 3 \times 10^{-5}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$ (about half the sensitivity limit). In the high-temperature, high-density limit this would result in $N_{\text{C}^+} \approx 4 \times 10^{10}$ cm$^{-2}$, or $A_V \approx 0.05$. If we allow for a relatively low PDR temperature, $T_{\text{kin}} \approx 40$ K, consistent with a low $\chi_{\text{av}}$ and the optically thin CO analysis, we find $A_V \approx 0.15$. It is important to point out that these are line-of-sight extinctions and not necessarily equal to the $A_V$ that extends the UV field and enters the PDR calculation. For a completely edge-on PDR, for example, two of these extinctions would be measured along orthogonal directions and thus be unrelated. If this gas fills the beam and has a density near the critical density of [C II] ($n_{\text{II}} \approx 3 \times 10^3$ cm$^{-3}$), as we implicitly assumed in the calculations, then we are seeing a $\sim 0.1$ pc thick layer of gas. We find this sheetlike geometry, with a sheet thickness of only 1/100 of the extent in the plane of the sky, uncomfortable although not impossible.

**How do these results compare with column density predictions based on the H I data?** We assume a spin temperature of $T_{\text{spin}} \sim 110–180$ K based on the H I absorption observed toward the N159 continuum sources (Spitzer 1978). We can then compute atomic hydrogen column densities of $N_H \approx 4.2 \times 10^{21}$ cm$^{-2}$ and $N_H \approx 4.5 \times 10^{21}$ cm$^{-2}$ for regions R1 and R2, respectively. These column densities
are ~ 3 times larger than those derived from \( I_{\text{CII}} \). The gas is apparently hot enough to populate the upper fine structure level of \( C^+ \) and excite the 158 \( \mu m \) [C II] transition (recall \( h\nu/k = 91.3 \) K for [C II]), thus this discrepancy is probably not due to temperature effects.

This method, however, is not very precise since it heavily relies on similar excitation conditions for the H I seen in absorption and emission, and this assumption is compromised by the large scales involved in the map (recall \( 1^\circ \sim 15 \) pc). Other possible causes for the apparent discrepancy in \( N_H \) are (1) a deficiency of \( C^+ \) in the atomic gas (only 30% of the C is photoionized), (2) the volume density of the atomic gas is low, and consequently the excitation of [C II] is subthermal \( \left(n < n_{\text{crit}}(\text{[C II]})\right) \), or (3) there are density fluctuations within the beam, and the [C II] emission is dominated by the fraction of the C + column that is thermalized \( \left(n > n_{\text{crit}}(\text{[C II]})\right) \).

The first possibility appears to be very improbable, since unless the material is well shielded from the UV most of the carbon should be in the form of \( C^+ \) rather than \( C^0 \). Unfortunately, the large beam in our [C I] observations makes impossible to separate cleanly these regions from the molecular peaks, thus precluding us from obtaining a reliable estimate for the column density of \( C^0 \) in R1 and R2. Subthermal excitation of \( C^+ \) requires the density of H I to be below the critical density of the 158 \( \mu m \) transition, \( n_1 \approx 3000 \text{ cm}^{-3} \). The intensity \( I_{\text{CII}} \) of C II collisionally excited by H atoms can be computed using \( \text{e.g.} \), Madden et al. 1997)

\[
I_{\text{CII}} = 2.35 \times 10^{-21} N_C \times \left[ \frac{2 \exp \left(-h\nu/kT\right)}{1 + 2 \exp \left(-h\nu/kT\right) + n_e/n_1} \right],
\]

where \( h\nu/k = 91.3 \) K. Consequently, a discrepancy of a factor of 3 would require \( n \sim 500 \text{ cm}^{-3} \), well below the critical density of [C II]. Notice that this density would bring the physical thickness of the [C II] emitting layer to \( \sim 3 \) pc. The third possibility (density fluctuations within the beam, akin to clumping) would make the regions where \( n > n_{\text{crit}} \) dominate the [C II] emission (about 1/3 of the total column), while in most of the gas \( n \ll n_{\text{crit}} \) and the [C II] excitation is subthermal. This ought to be happening at some level, because CO \((J = 2 \rightarrow 1)\) is present throughout the region and its excitation requires \( n \sim 10^4 \text{ cm}^{-3} \). This density is probably too large to be the average volume density in the envelope, thus most of the CO and perhaps a large fraction of the [C II] emission is originating in clumps within the envelope.

4. SUMMARY AND CONCLUSIONS

We have discussed new \(^{13}\text{CO} \) \((J = 1 \rightarrow 0)\), \(^{12}\text{CO} \) \((J = 2 \rightarrow 1)\), \(^{12}\text{CO} \) \((J = 4 \rightarrow 3)\), and [C I] \((^3P_1 \rightarrow ^3P_0)\) emission line maps of the N159/N160 molecular cloud complex of the Large Magellanic Cloud.

The \(^{12}\text{CO} \) \((J = 2 \rightarrow 1)\) map shows extended faint emission previously undetected in the \((J = 1 \rightarrow 0)\) transition. Further analysis of the \((J = 2 \rightarrow 1)/(J = 1 \rightarrow 0)\) intensity ratio in two selected subregions (R1 and R2) shows that this ratio is \( \gtrsim 3 \) for the extended low-level emission. This high value indicates optically thin CO emission from warm gas \((T_{\text{kin}} \gtrsim 40 \text{ K})\). The \( I_{\text{CO}}/I_{\text{CO}} \) ratio for R1 and R2 appears modestly enhanced with respect to the molecular peaks (Fig. 8). The \( I_{\text{CII}}/I_{\text{CO}} \) ratio is large for the northern region (R1), but [C II] was not detected by Israel et al. (1996) toward region R2. Because of the low UV field heating the ISM in the southern region, this may be a temperature effect. The gas in the southern portion of the complex, far away from the massive star formation and bright H II regions, is too cold to excite the 158 \( \mu m \) transition \((T < 92 \text{ K})\). The faint CO envelope appears to be translucent \((A_v < 1)\), and column density calculations assuming that \( C^+ \) is the dominant form of carbon confirm this result. The column density derived from the neutral hydrogen 21 cm data appears to be \( \sim 3 \) times larger than \( N_H \) obtained from [C II]. This is probably caused by density enhancements (clumping) within the beam.

The \(^{12}\text{CO} \) \((J = 4 \rightarrow 3)/(J = 1 \rightarrow 0)\) intensity ratio is \( \sim 4 \) times larger in the northernmost cloud (N160) than in the southern cloud (N159S). This agrees very well with indicators of star formation activity \((I_{\text{FIR}}, I_{\text{CO}})\), radio continuum and is probably due to the much lower temperature of the quiescent southern cloud. Estimates of the radiation field incident on N159S suggest \( \chi_{\text{IR}} \lesssim 10 \), consistent with a low temperature. The ratio of 100/60 \( \mu m \) continuum also indicates a low temperature.

The [C I] \((^3P_1 \rightarrow ^3P_0)\) map shows the [C I] intensity and the \( I_{\text{CO}}/I_{\text{CO}} \) ratio for the molecular concentrations peaking in N159S. The observed values are consistent with the PDR computations available for homogeneous, plane-parallel models, at \( n \sim 10^5 \text{ cm}^{-3} \) and \( \chi_{\text{IR}} \sim 10 \). Because in those models \( I_{\text{CII}} \) is not sensitive to \( \chi_{\text{IR}} \), however, the presence of intense [C I] emission in N159S is not a good test for a possible non-PDR origin for \( C^0 \) inside GMCs. There is pervasive [C I] emission throughout the region between N159EW and N160. This region also emits strongly in [C II], and features some of the largest \( I_{\text{CII}}/I_{\text{CO}} \) and \( I_{\text{CII}}/I_{\text{CO}} \) ratios in the complex. The radio continuum sources embedded in this gas appear as holes in the [C I] distribution, while they are peaks in the [C II]. The [C II] in these peaks probably originates inside the H II regions, mostly excited by collisions with electrons.

The [C I]/CO intensity ratios measured in the molecular peaks of the complex range between \( I_{\text{CII}}/I_{\text{CO}} \sim 7-12 \) (intensities in ergs s\(^{-1}\) cm\(^{-2}\) sr\(^{-1}\)). This ratio is similar to the average ratio in the Milky Way \( I_{\text{CII}}/I_{\text{CO}} \sim 13 \) and to that measured in the low-metallicity dwarf IC 10 \( I_{\text{CII}}/I_{\text{CO}} \sim 18 \), Bolatto et al. 2000). The [C I]/CO intensity ratio for the translucent gas is somewhat larger, \( I_{\text{CII}}/I_{\text{CO}} \sim 20-30 \). While intense [C II] \((^3P_{1,2} \rightarrow ^3P_{1,2})\) emission and large \( I_{\text{CII}}/I_{\text{CO}} \) ratios appear to be unequivocally associated with massive star formation, [C I] \((^3P_1 \rightarrow ^3P_0)\) emission and the \( I_{\text{CII}}/I_{\text{CO}} \) ratio shows no such clear association and has a much more complex behavior. The \( I_{\text{CII}}/I_{\text{CO}} \) ratio is more uniform than the \( I_{\text{CII}}/I_{\text{CO}} \) ratio throughout the complex, which spans values of \( I_{\text{CII}}/I_{\text{CO}} \sim 5-25 \), whereas \( I_{\text{CII}}/I_{\text{CO}} \) ranges between \( \sim 500-25,000 \) (i.e., a factor of 5 vs. a factor of 50). This is partially due to the more stringent excitation conditions required by [C II].

We believe that our understanding of the ISM, especially the actively star-forming ISM, can be enormously advanced by further studies of the Magellanic Clouds. These galaxies, with their proximity, their active star formation, their low metallicities, and their unobscured lines of sight, present unique opportunities for detailed multiwavelength studies. Among the different regions in the Clouds, the N159/N160 complex is located at a privileged place, between the violent starburst of 30 Doradus and the quiescent southern CO ridge. Because of its location, its distinct environments, and
the wealth of phenomena taking place within its bounds, the N159/N160 complex is one of the most interesting places in the Magellanic Clouds. Unfortunately, these galaxies are out of the reach of the large radioastronomy facilities in the Northern Hemisphere. The advent of some of the observatories now being planned, such as the Atacama Large Millimeter Array or a large South Pole telescope, will change that. The study of the ISM in these objects will vastly benefit from large submillimeter telescopes, array receivers, and millimeter/submillimeter interferometers located south of the equator. Future studies of N159/N160 should include the detailed characterization of the translucent molecular envelope, the dust properties, and the heating and cooling balance of the ISM near and away from star formation sites. Other observational programs could address the creation of molecular clouds by ram pressure compression, and their disruption by star formation activity.

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APPENDIX

BEAM FILLING RATIO FOR TWO TRANSITIONS

For this calculation we will assume spherical clumps of radius \( R \), immersed in an isotropic UV field. A transition turns optically thick (i.e., its opacity, \( \tau \), is unity) at a distance \( x \) from the surface of the clump. Therefore, the radius of the clump at given transition (i.e., the distance from the center of the clump to the transition’s \( \tau = 1 \) surface) is \( r = R - x \). The ratio of beam filling fractions \( \Phi \) in two transitions will then be proportional to the ratio of the projected areas:

\[
\frac{\Phi_2}{\Phi_1} = \frac{(R - x_2)^2}{(R - x_1)^2}. \tag{A1}
\]

It can be shown easily that for gas in LTE the ratio of optical depths in the \( (J = 1 \rightarrow 0) \) and \( (J = 2 \rightarrow 1) \) transitions will be

\[
\frac{\tau_{21}}{\tau_{10}} = 2 \frac{1 - e^{-h\nu_{21}/kT_{ex}}}{e^{h\nu_{10}/kT_{ex}} - 1},
\]

where \( h \) and \( k \) are Planck’s and Boltzmann’s constants, respectively, and \( T_{ex} \) is the excitation temperature. For uniform density clumps the \( \tau = 1 \) surface occurs first for the transition with faster growing opacity, that is, \( x_2/x_1 = \tau_1/\tau_2 \). Equation (A1) thus has the solution

\[
R = x_1 \left( \sqrt{\frac{\Phi_2}{\Phi_1}} - \frac{\tau_1}{\tau_2} \right) \left/ \left( \sqrt{\frac{\Phi_2}{\Phi_1}} - 1 \right) \right. \tag{A3}
\]

In order to reproduce the CO \( (J = 2 \rightarrow 1)/(J = 1 \rightarrow 0) \) intensity ratios observed in regions R1 and R2, \( \Phi_2/\Phi_1 \approx 3 \). Using \( \tau_2/\tau_1 \approx 3 \) (i.e., \( T_{ex} \approx 40 \) K according to eq. [A2]) yields \( R \approx 1.9x_1 \). Thus, \( \tau(1 \rightarrow 0) \approx 2 \) at the center of the clump. The average over the whole projected spherical clump is \( \approx 30\% \) larger, or \( \tau(1 \rightarrow 0) \approx 2.5 \).

REFERENCES

Abgrall, H., Le Bourlot, J., Pineau des Forêts, G., Roueff, E., Flower, D. R., & Heck, L. 1992, A&A, 253, 525
Bolatto, A. D., Jackson, J. M., & Inglis, J. G. 1999, ApJ, 513, 275
Bolatto, A. D., Jackson, J. M., Wilson, C. D., & Moriarty-Schieven, G. 2000, ApJ, 532, 909
Bouchet, P., Lequeux, J., Maurice, E., Prévote-L, & Prévote-Burnichon, M. L. 1985, A&A, 149, 330
Chu, Y.-H., Kennicutt, R. C., Snowden, S. L., Smith, R. C., Williams, R. M., & Bomans, D. J. 1997, PASP, 109, 554
Cioni, M. R., Habing, H. J., & Israel, F. P. 2000, A&A, 358, L9
Cohen, R. S., Dame, T. M., Garay, G., Montani, J., Rubio, M., & Thaddeus, P. 1988, ApJ, 331, L35
Comerón, F., & Claes, P. 1998, A&A, 335, L13
Cowley, A. P., Schmidtke, P. C., Anderson, A. L., & McGrath, T. K. 1995, PASP, 107, 145
Davies, R. D., Elliot, K. H., & Meaburn, J. 1976, MmRAS, 81, 89
de Boer, K. S., Braun, J. M., Vallenari, A., & Mebold, U. 1998, A&A, 329, L49
Dufour, R. J. 1984, in Structure and Evolution of the Magellanic Clouds, ed. S. van der Bergh & K. S. de Boer (Dordrecht: Kluwer), 353
Franco, J., & Cox, D. P. 1986, PASP, 98, 1076
Gerin, M., & Phillips, T. G. 2000, ApJ, 537, 644
Habing, H. J. 1967, Bull. Astron. Inst. Netherlands, 9, 421
Heikinheimo, A., Johansson, L. E. B., & Olofsson, H. 1999, A&A, 344, 817
Henize, K. G. 1956, ApJS, 2, 315
Inglis, J. G., Chamberlin, R. A., Bania, T. M., Jackson, J. M., Lane, A. P., & Stark, A. A. 1997, ApJ, 479, 296
Israel, F. P. 1997, A&A, 328, 471
Israel, F. P., et al. 1993, A&A, 276, 25
Israel, F. P., Maloney, P. R., Geis, N., Hermann, F., Madden, S. C., Poglitisch, A., & Stacey, G. J. 1996, ApJ, 465, 738
Jackson, J. M., & Kraemer, K. E. 1999, ApJ, 512, 250
Johansson, L. E. B., Olofsson, H., Hjalmarson, Å., Grede, R., & Black, J. H. 1994, A&A, 292, 371
Johansson, L. E. B., et al. 1998, A&A, 331, 857
Kaufman, M. J., Wolffire, M. G., Hollenbach, D. J., & Luhman, M. L. 1999, ApJ, 527, 795
Kraemer, M. J., & Bomans, D. J. 1997, A&A, 328, 471
Kuchner, J. E. 1992, A&A, 253, 525
Kutner, M. L., et al. 1997, A&AS, 122, 255
Koornneef, J. 1982, A&A, 107, 247
Lefèvre, J., Peimbret, M., Rayo, J. F., Serrano, A., & Torres-Peimbert, S. 1979, A&A, 80, 155
Lepp, S., & Dalgarno, A. 1996, A&A, 306, L21
Staveley-Smith, L., Dopita, M., Freeman, K., Sault, R., Kesteven, M. J., & McDonald, D. 1998, ApJ, 503, 674
Koornneef, J. 1982, A&A, 107, 247
Kutner, M. L., et al. 1997, A&A, 122, 255
Lequeux, J., Peimbret, M., Rayo, J. F., Serrano, A., & Torres-Peimbert, S. 1979, A&A, 80, 155
Lepp, S., & Dalgarno, A. 1996, A&A, 306, L21
BOLATTO ET AL.

Lisenfeld, U., & Ferrara, A. 1998, ApJ, 496, 145
Lonsdale, G., Helou, G., Good, J. C., & Rice, W. 1985, Cataloged Galaxies and Quasars Observed in the IRAS Survey (Pasadena: JPL)
Madden, S. C., Poglitsch, A., Geis, N., Stacey, G. J., & Townes, C. H. 1997, ApJ, 483, 200
Mathewson, D. S., & Ford, V. L. 1984, in Structure and Evolution of the Magellanic Clouds, ed. S. van den Bergh & K. S. de Boer (Dordrecht: Reidel), 125
Meixner, M., & Tielens, A. G. G. M. 1993, ApJ, 405, 216
———. 1995, ApJ, 446, 907
Mochizuki, K., et al. 1994, ApJ, 430, L37
Pak, S., Jaffe, D. T., van Dishoeck, E. F., Johansson, L. E. B., & Booth, R. S. 1998, ApJ, 498, 735
Panagia, N. 1973, AJ, 78, 929
Panagia, N., Gilmozzi, R., & Kirshner, R. P. 2000, in ASP Conf. Ser., SN 1987A: Ten Years After, ed. M. Phillips & N. Suntzeff (San Francisco: ASP), in press
Poglitsch, A., Krabbe, A., Madden, S. C., Nikola, T., Geis, N., Johansson, L. E. B., Stacey, G. J., & Sternberg, A. 1995, ApJ, 454, 293
Rubio, M., Lequeux, J., & Boulanger, F. 1993, A&A, 271, 9
Schmidtke, P. C., Ponder, A. L., & Cowley, A. P. 1999, AJ, 117, 1292
Spitzer, L. 1978, Physical Processes in the Interstellar Medium (New York: Wiley), 47
Stacey, G. J., Geis, N., Genzel, R., Lugten, J. B., Poglitsch, A., Sternberg, A., & Townes, C. H. 1991, ApJ, 373, 423
Stark, A. A., Bolatto, A. D., Chamberlin, R. A., Lane, A. P., Bania, T. M., Jackson, J. M., & Lo, K.-Y. 1997a, ApJ, 480, L59
Stark, A. A., Chamberlin, R. A., Cheng, J., Ingalls, J. G., & Wright, G. 1997b, Rev. Sci. Instrum., 68, 2200
Warin, S., Benayoun, J. J., & Viala, Y. P. 1996, A&A, 308, 535
Wilson, C. D. 1997, ApJ, 487, L49