CO (J=4→3) and [C I] Observations of the Carina Molecular Cloud Complex

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Abstract

We present large area, fully-sampled maps of the Carina molecular cloud complex in the CO ($J = 4 \rightarrow 3$) and neutral carbon [C I] ${}^3P_1 \rightarrow {}^3P_0$ transitions. These data were obtained using the 1.7 meter diameter Antarctic Submillimeter Telescope and Remote Observatory (AST/RO). The maps cover an area of approximately 3 square degrees with a uniform $1'$ spatial sampling. Analysis of these data, in conjunction with CO ($J = 1 \rightarrow 0$) data from the Columbia CO survey and the IRAS HIRES continuum maps for the same region, suggests that the spiral density wave shock associated with the Carina spiral arm may be playing an important role in the formation and dissociation of the cloud complex, as well as in maintaining the internal energy balance of the clouds in this region. Massive stars form at the densest regions of the molecular cloud complex. The winds and outflows associated with these stars have a disrupting effect on the complex and inject mechanical energy into the parent clouds, while the UV radiation from the young stars also heat the parent clouds. The present set of data suggests, however, that massive stars alone may not account for the energetics of the clouds in the Carina region. The details of the data and the correlation among the various data sets hint at the possible role that the spiral density wave shock plays in feeding interstellar turbulence and in heating molecular clouds.

1 Introduction

1.1 Submillimeter-wave Studies of Molecular Clouds

Studies of the Interstellar Medium (ISM) on large scales are often pursued through radio surveys because the Galaxy is transparent at radio wavelengths and because interstellar gas in its various phases emits radio lines which can be observed in emission over large areas of sky. The line shapes are easily resolved by radio spectroscopic techniques and reflect the motion of the ISM on the galactic scale and the internal dynamics of clouds. The past half-century of progress in radio techniques have seen dramatic improvements in sensitivity (cf. Carlstrom & Zmuidzinas 1995) as well as a general trend towards higher frequencies and the application of those newly-available frequencies to the study of interstellar material.

This paper describes the study of a region of roughly 150×100 pc in size surrounding the bright southern peculiar star η Carinae, observed in the mid-submillimeter lines of CO ($J = 4 \rightarrow 3$ at 460 GHz) and neutral carbon ([C I] $^3P_1 \rightarrow ^3P_0$ at 492 GHz). The CO ($J = 4 \rightarrow 3$) line is a tracer of the warm ($T \sim 50\,\mathrm{K}$) and dense ($n \sim 10^5\,\mathrm{cm}^{-3}$) cores in molecular clouds (Viscuso & Chernoff 1988), whose average properties as seen in CO $J = 1 \rightarrow 0$ line studies are colder ($\sim 10\,\mathrm{K}$) and more diffuse ($n \sim 10^3\,\mathrm{cm}^{-3}$). The excitation of the CO ($J = 4 \rightarrow 3$) transition thus requires high densities, similar to those of common tracers of dense gas such as H_2CO (e.g., Magnani, La Rosa & Shore 1993) and CS $J = 2 \rightarrow 1$ (e.g., Lada, Bally & Stark 1991). Unlike these, however, it also requires warm temperatures.

The [C I] line, on the other hand, is expected to trace the photon-dominated regions (PDR) in the outer envelopes of molecular clouds (Tielens & Hollenbach 1985). In these regions neutral carbon is found in a thin layer between C^+ and CO, determined by the equilibrium between photoionization/recombination processes on the C^+/C^0 side, and photodissociation/molecule formation processes on the C^0/CO side. The [C I] $^3P_1 \rightarrow ^3P_0$ transition has a minimum excitation temperature of 24K and critical density $n \sim 10^3\,\mathrm{cm}^{-3}$ for collisions with H_2 (e.g. Schroder et al. 1991). Therefore, it is easily excited in dense interstellar gas. Observations show that the [C I] emission is surprisingly well-mixed and well-correlated with ^{12}CO and ^{13}CO emission in the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transitions (e.g., Plume 1995; Keene et al. 1997). Stutzki et al. (1988) suggest that this effect results from the clumpiness of molecular material, so that the "surface" layers are distributed throughout the volume of the cloud. Clumpy PDR models (Meixner & Tielens 1993, 1995; Spaans 1996) produce levels of [C I] emission similar to what is observed near star-forming regions in molecular cloud cores, but have not been entirely successful in explaining the surprising uniformity of [C I] in the bulk of molecular clouds (Keene et al. 1997).

1.2 Giant Molecular Cloud Complexes

It is a well known fact that the most massive molecular cloud complexes are concentrated in spiral arms (Stark 1979; Elmegreen 1979; Dame et al. 1986). Indeed, massive stars, H II regions, and dust lanes, which are the visual tracers of spiral arms, are all manifestations of concentrations of giant molecular clouds. The processes leading to the formation of these complexes are not completely understood, but the observational evidence suggests they are strongly linked to the passage of the gas through the spiral density wave shock. Indeed, the role of spiral density wave shock in the formation and evolution of the galactic giant molecular cloud complexes has been speculated upon and investigated since the advent of the density wave theory, and this effort has continued throughout the past decades (Roberts 1969; Elmegreen 1979; Balbus & Cowie 1985; Dame et al. 1986; Heyer 1998; Zhang 1998).

The problem of cloud complex formation and dissociation are closely related to two other issues:

1. The source of the supersonic turbulence energy injection into the clouds (see, e.g. Larson 1981; Myers 1983 and the references therein). Turbulence has a natural tendency to cascade downward and dissipate into heat and line radiation at the smallest scales. For the galactic molecular clouds, the time scale for this cascade is on the order of a free-fall time for the largest clouds (i.e., $\sim 10^6$ yr), much shorter than the lifetime of molecular clouds (Larson 1981). Therefore, turbulent energy must be constantly injected into the interstellar medium (ISM) to sustain the supersonic linewidths observed in galactic molecular clouds. The size-linewidth relation connects the physical size of a region with the observed linewidths, and it is observed to hold over four orders of magnitudes in cloud size (Larson 1981; Myers 1983). The small-scale energy injection mechanisms considered (e.g., stellar winds and outflows) usually fail to either generate sufficient energy injection or reproduce the correct form of the size-linewidth relation. Associated with the issue of the source of turbulence energy input is the issue of how and where the turbulence energy is dissipated.

2. The processes dominating the overall energy balance in the ISM. In recent years the theory of PDRs (believed to constitute more than 90% of the galactic ISM) has gradually confronted serious challenges as observational data accumulate. In a recent review article, Hollenbach and Tielens (1999) cite several instances of observations of Galactic and extragalactic star-forming regions where the current theory of the PDR often produces a much a lower temperature than that measured in the rotational quadrupole transitions of H_2, and a much higher ratio of [C II]/L_{FIR} than is seen in infrared luminous regions. These authors conclude that these regions must have additional sources of energy input in order to account for the energy balance of the PDR. These sources may include the dissipation of magnetohydrodynamic turbulence.

Recent work on the theory of the dynamics and evolution of spiral galaxies (Zhang 1996, 1998, 1999) indicates that there is significant energy and angular momentum exchange between a quasi-steady spiral density wave and the basic state of the galactic disk. This exchange process is of such a magnitude that it should significantly affect molecular cloud complex formation and dissociation. An important consequence of this process is that the orbiting disk matter, including both stars and gas, receives random-motion energy injection each time it crosses a spiral wave crest. The amount of this energy injection is found to be of the right magnitude to feed the interstellar turbulence and support the cascade of turbulent energy to the small scales and subsequent dissipation (Zhang 2000). Thus, the spiral density wave may play an important role in the internal energy balance and the turbulent motions of the galactic molecular clouds. A clear demonstration of the relation between the spiral density wave and molecular clouds, however, is yet to be established. It is in this context that we have selected the Carina molecular complex as the region of our study.

1.3 The Carina Molecular Cloud Complex

The Carina molecular complex is a segment of the Carina spiral arm surrounding the extraordinary Luminous Blue Variable (LBV) star η Carinae.

It is located between Galactic longitudes 284° and 289° and latitudes −2° and 1°. Figure 1 is a large area CO ($1 \rightarrow 0$) map from the Columbia CO survey of the southern Milky Way (Grabelsky et al. 1988) showing this complex.

Situated near the center of the Carina molecular complex is the Carina nebula, which contains an extremely bright and extended OB association (Car OB1) and a bright H II region, NGC 3372. In a region about 40 pc in diameter there are 64 O type stars (including 6 of the only 11 type O3 stars known in the Milky Way), η Carinae itself, and a Wolf-Rayet star (Walborn 1995). This high concentration of the earliest type stars is unique in the Galaxy. The nearest region of higher concentration surrounds 30 Doradus region in the Large Magellanic Cloud. Many spectroscopic and morphological studies of the Carina region have been made, covering the entire spectral range from centimeter to X-rays. A good overview of the physical conditions in this region can be obtained from the many contributions in the July 1995 issue of Revista Mexicana de Astronomia y Astrofisica, entitled "The η Carina Region: A Laboratory of Stellar Evolution".

Past study of the Carina region has focused mainly on the peculiar star η Carinae and on the H II region surrounding it. The larger molecular complex is mapped by the Columbia CO survey with a $8.8'$ beam, and by the IRAS satellite in its four spectral bands. These are large surveys which are not particularly focused on the Carina region. We have chosen to map the entire complex with the AST/RO telescope. We intended to use the AST/RO data, combined with the existing survey data, to study the large-scale physical conditions in this region, and investigate the role of spiral density wave in the formation and dissociation of molecular cloud complexes. AST/RO is very well-suited for this work, because it was designed as a Galactic survey instrument.

The Carina complex has a very clear line of sight, with a mean color excess $E_{B-V} = 0.5$ at a distance of 2.5 kpc (Feinstein 1995). The various clouds and sub-complexes are distributed along the Galactic plane in what appears to be a sequential order. Their kinematics suggest that locations of decreasing longitude correspond to advancement in the spiral-arm-crossing phase, as can be seen for those cloud clumps nearest to the Sun on the well-delineated Carina spiral arm in Figure 4a of Grabelsky et al. (1988). This correspondence is further supported by cloud morphology (see Figure 2): clumps near the nebula appear to be coherently shocked, while clouds to the north are more fragmented. Moreover, there is an age gradient in the various star clusters across the complex. The Tr 14 and Tr 16 clusters within the Carina nebula (NGC 3372) at $(l, b) = (287.6°, -0.65°)$ are the youngest (age $\sim 10^6\,$yr) and IC 2581/NGC 3293 at (284.7°, 0.1°) are the oldest (age $\sim 5 \times 10^6\,$yr). They are separated by a projected distance of $\sim$ 130pc. This sequential arrangement is advantageous to the study of the evolution of physical conditions in the clouds, as the different clouds stream across the spiral arm.

The Carina nebula itself contains an archetypical outflow (Duschl et al. 1995) centered on η Carinae at (287.6°, −0.64°), and the highest concentration of early type stars known in the Galaxy in the two ionizing clusters Tr 16 (which is centered on η Carinae, and which also includes a smaller cluster Cr 228 to the south) and Tr 14 (about $10'$ to the north of η Carinae). The region offers the opportunity to study and possibly disentangle the effects of energy input to the molecular clouds by massive stars and by spiral density wave shocks.

In §2 and 3, we describe the observational results and analysis of the Carina region. Sensitive receivers and the clear skies of the South Pole have permitted extensive mapping of the CO ($J = 4 \rightarrow 3$) and [C I] lines over a region including several molecular clouds and covering a segment of the Carina spiral arm. These maps are less biased to cloud cores and known heating sources than was previously possible, and therefore allow us to investigate the important question of the relation between molecular clouds and the environment where these clouds form and dissociate.

2 Observations and Data Reduction

The CO ($4 \rightarrow 3$) and [C I] data presented here were obtained during the Austral winter of 1998, using the 1.7 m telescope of the Antarctic Submillimeter Telescope and Remote Observatory (Stark et al. 1997; Lane & Stark 1996) located at the United States Amundsen-Scott South Pole Station.

The CO ($4 \rightarrow 3$) data were taken during the Austral fall and have system temperatures between 1500 K and 3000 K. The [C I] data set was acquired during the months of July through September, with the system temperature ranging from 1200K to 2200K. Both maps were obtained sampling on a $1'$ grid, with an integration time of 60 s per point at most locations. Half of the integration time was spent on source and half on the two reference positions, situated $\pm 90'$ away from the mapping center in RA (which is the same as in Az for a telescope located at the geographic South Pole). The reference positions are free of emission in the Columbia survey map. The entire data set was acquired in less than three weeks.

The line strength is calibrated using warm and cold loads, together with the sky measurement at a location near the source. Skydips are done roughly twice a day to assure the stability of the telescope efficiency and to check the consistency of the single-slab atmospheric model used to correct for atmospheric absorption. The beam size for the SIS quasi-optical receiver used for [C I] observations was $\sim 3.5'$, and the beam size for the SIS waveguide receiver used for CO ($4 \rightarrow 3$) observations was $\sim 3'$. These sizes are estimated by scanning the beam across the limb of the full Moon. The main beam telescope efficiency (η_{mb}) for both receivers is $\sim 70\%$, as estimated from the skydip measurements. The backend used was the 2048 channel acousto-optical spectrometer, with a spectral resolution of 0.4 $\mathrm{km\,s^{-1}}$ (Schieder, Tolls & Winnewisser 1989). AST/RO's pointing was carefully monitored using the source G291.28-0.72 (located at a declination similar to the Carina nebula), which was observed every 8 hours (Huang et al. 1999). The rms pointing accuracy for both data sets is estimated to be better than $30''$. The calibrated data is expressed as T_R^* (Kutner & Ulich 1978), which is essentially the same as T_A^* for AST/RO.

The raw data were corrected for atmospheric absorption and a linear baseline was removed using the software package COMB. The data cube thus generated has been further analyzed using the software packages IRAF and AIPS and plotted using the software packages PGPLOT and WIP.

3 Results

In the this section we will introduce the submillimeter data and discuss three of its properties:

1. the extent of the CO ($4 \rightarrow 3$) and [C I] emission,
2. the spatial and velocity correlation between both submillimeter transitions, and
3. their relation to the CO (J=$1 \rightarrow 0$) emission.

Figure 3 shows an overlay map of the AST/RO [C I] and CO ($4 \rightarrow 3$) observations. The maps were obtained by integrating the calibrated data cube over the entire velocity range of the Carina complex, that is, between $-50\,\mathrm{km\,s^{-1}}$ and $-9\,\mathrm{km\,s^{-1}}$. This velocity range is chosen to coincide with that used by Grabelsky et al. (1988) for the CO ($1 \rightarrow 0$) data, although there appears to be small amount of emission belonging to the complex at velocities as high as $0\,\mathrm{km\,s^{-1}}$. Each map is a composite of 3 individual, partially overlaping, submaps for each transition. While the southernmost and northernmost submaps have identical size in [C I] and CO ($4 \rightarrow 3$), the central submap in [C I] is significantly smaller than its CO ($4 \rightarrow 3$) counterpart, as shown by the color and contour boundaries in Figure 3.

From Figure 3, it is immediately evident that the CO ($4 \rightarrow 3$) and [C I] transitions are approximately coextensive throughout the whole Carina region. This is the first instance in which a higher transition of CO and the [C I] emission are found to be coextensive over such a large area, spanning approximately 150×100 parsecs. Previous studies have found a similar result for the lower transitions of CO as well as ^{13}CO with [C I] (e.g., Philipps & Huggins 1981; Keene et al. 1985, 1997; Plume 1995, and the references therein). This result is noteworthy, since CO ($4 \rightarrow 3$) requires warm, high density conditions to be excited.

The extent of the [C I] emission over the entire region is also remarkable. The theoretical expectation is that [C I] arises as a result of the photodissociation of CO in the PDR occurring at extinction $A_\mathrm{v} < 3$ (Keene et al. 1997).

Usually the coextensiveness of the [C I] and CO emission is attributed to the fact that the ISM is clumpy, and therefore porous to UV radiation. We see copious [C I] emission arising from clouds located far away from UV sources, for example those in Region 6 (Figure 2). Recent PDR modeling results by Kaufman et al. (1999) indicate that the intensity of the [C I] transition is insensitive to the radiation field. The nearby open clusters (NGC 3293 and NGC 3324) possess one type O star and several early type B stars (Clariá 1977; Feinstein & Marraco 1980), and may thus be capable of photodissociating CO several parsecs away.

The intensity peaks of the [C I] and CO ($4 \rightarrow 3$) distributions are approximately coincident, and are located near the infrared peak illuminated by the compact star cluster Tr 14 (Figure 12). Small differences in the morphology of the two transitions do exist, however. Most noticeable is the double peaked structure of Region 5 in [C I], which exhibits only one peak in CO ($4 \rightarrow 3$). The second peak of neutral carbon is probably associated with an embedded source that must have photodissociated most of the surrounding CO (Figure 10). Figures 4 and 5 show the CO ($4 \rightarrow 3$) data overlayed on the lower resolution Columbia CO ($J{=}1 \rightarrow 0$) map ($8.8'$ resolution, Grabelsky et al. 1988) and on the high-resolution MOPRA map ($1.4'$ resolution, Brooks et al. 1998).

A closer look at the velocity information reveals that both lines display identical kinematics. Figures 6 and 7 show velocity channel maps for the [C I] and CO ($4 \rightarrow 3$) transitions. These are essentially identical in both species, indicating that the [C I] and CO ($4 \rightarrow 3$) emitting gas are well mixed. A few clumps, most noticeably in Region 3, do not quite follow the general trend determined by Galactic rotation. This is perhaps an indication that they are perturbed by the activity (i.e., winds and outflows) surrounding the star η Carinae.

Figure 8 displays the composite spectra for Region 1 through 6, where the similarity of the line profiles can be appreciated. The strongest emission arises from Region 3, where there is a clearly non-gaussian line profile. This is the signature of the gas entrained in the bipolar outflow from η Carinae. The double peaks observed for region 2 are also likely to be produced by the interaction of the ambient gas with the winds and outflows originating in η Carinae.

4 Discussion

4.1 Physical Conditions in the Region

A comparison of the [C I] and CO ($4 \rightarrow 3$) distributions as shown in Figure 3 gives us some qualitative idea of the temperature and density distribution in the mapped region, after taking into account the excitation conditions for these two species. Estimates of the physical conditions of the gas independent of chemistry can be obtained by using two transitions of the same chemical species. The CO $(4 \rightarrow 3)/(1 \rightarrow 0)$ ratio is sensitive to a combination of density and temperature, but mostly to density when $T > 50$ K and, and mostly to temperature when $n > 10^5$ cm^{-3} and $T < 50$ K. While temperatures $T > 50$ K are very rare in molecular clouds over large spatial scales, densities $n \sim 10^5$ cm^{-3} necessary to thermalize the CO ($4 \rightarrow 3$) transition are more commonly found. Furthermore, in opaque cores radiative trapping easily reduces this density requirement to $n \sim 10^4$ cm^{-3}, which is a typical molecular cloud density over large spatial scales. Thus, although the CO $(4 \rightarrow 3)/(1 \rightarrow 0)$ intensity ratio is affected by both density and temperature, in the discussion following we will assume that the prevalent effects are due to temperature.

A quantitative estimate of the average excitation temperature for a region can be obtained assuming thermalized but optically thin emission. After convolving our CO ($4 \rightarrow 3$) data to the resolution of the Columbia CO ($1 \rightarrow 0$) survey for this region (generously provided by T. Dame), a rough estimate of the gas temperature is given by:

$$T_{\rm ex} \sim \frac{55\,{\rm K}}{\ln\left(\frac{16{\rm T}^{\rm peak}_{1\rightarrow 0}}{{\rm T}^{\rm peak}_{4\rightarrow 3}}\right)} \quad . \tag{1}$$

Note that use of this equation assumes both the local thermodynamic equilibrium (LTE) and optically thin conditions. While LTE is expected to hold in dense molecular clouds, the optically-thin emission certainly does not hold for CO. Here we assume that the clouds are composed of many smaller optically-thick cloudlets (i.e., the "mist model", Dickman et al. 1986; Solomon et al. 1987). We further assume that the fluxes we measured in the two transitions are proportional to that emitted by the optically-thin envelopes of the constituent cloudlets. Thus in taking the ratio of the fluxes in these two transitions, we are effectively using the optically thin sub-components of the original cloud to estimate its temperature. This procedure has been found to give consistent temperature estimates when using two pairs of adjacent CO transitions. For example, the excitation temperature obtained from the CO ($2 \rightarrow 1$) and CO ($1 \rightarrow 0$) ratios has been found to be very close to the excitation temperatures obtained from the CO ($3 \rightarrow 2$) and CO ($2 \rightarrow 1$) ratios for the same regions (Zhang 1992). Thus, we are confident that despite the caveats Eq. 1 can be used to obtain a rough estimate of the physical temperatures.

Figure 9 shows the excitation temperature map derived using Eq. 1 and the ratio of integrated intensities (i.e., implicitly assuming similar linewidths for both CO transitions). This method will produce spuriously high temperatures if the CO ($1 \rightarrow 0$) emission is self-absorbed, but fortunately there is little evidence for such problems in this map. Apart from the noise near the boundaries of the emitting regions, it is apparent that the highest average excitation temperature is obtained in the vicinity of η Carinae. There is also an excitation temperature gradient across the entire map, with higher temperatures in the southern regions. This is likely due to the combined effect of two energy inputs: 1) the southern region is situated near the ionizing star cluster, and 2) it is near the spiral density wave crest, experiencing energy injection during arm crossing. Naturally, these two sources of energy are difficult to separate. In the six regions marked in Figure 2, the average excitation temperatures are respectively, $T_{ex1} = 34\,K$, $T_{ex2} = 52\,K$, $T_{ex3} = 33\,K$, $T_{ex4} = 24\,K$, $T_{ex5} = 19\,K$, and $T_{ex6} = 10\,K$. By comparison, Ghosh et al. (1988) found a dust temperature ~ 40 K in the nebula region (our Region 2). The similarity of these two temperatures suggests that our estimates based on Eq. 1 are not unreasonable.

While these average excitation temperatures are lower than the nominal excitation threshold for the CO ($4 \rightarrow 3$) transition of 55 K, they presumably represent the mean excitation temperatures over an ensemble of clumps within each region. From the excitation temperatures obtained above, we see that these regions have a much hotter temperature than that expected for well-shielded, dark clouds (i.e., 8—10 K). This is true even for regions 4 and 5 located farther away from the Carina nebula and star clusters.

The far-infrared (FIR) maps of the Carina complex reveal the position of the heating sources, and their association with the molecular peaks. We obtained IRAS HIRES (resolution-enhanced) maps of this region in all 4 bands (12 μm, 25 μm, 60 μm, and 100 μm). Figures 11 and 12 show the overlay of the CO ($4 \rightarrow 3$) emission with the IRAS HIRES 12 μm and 100 μm maps, respectively. Figure 10 shows the overlay of our [C I] map with the IRAS HIRES 100 μm continuum. The FIR peaks are concentrated near the Carina nebula region, with the brightest emission peak at 100 μm closely associated with the main CO peak in Region 3. For shorter wavelengths, the FIR emission peak shifts gradually towards the ionizing cluster Tr 14, as discussed by Cox (1995). The region near the star η Carinae (the bright far-IR point source at $l = 287.6°$, $b = -0.64°$, between the two molecular clumps) appears free of submillimeter emission, possibly due to the cavity blown open by the outflow and winds from the star (Cox 1995). Away from the nebula region, there is a drastic decrease in the FIR luminosity accompanied by a diminishing number of 12 μm or 100 μm peaks. This suggests that these molecular clouds contain few embedded young stellar objects. It is unclear whether the star-formation activity near Regions 4 and 5 is enough to maintain their cloud temperatures ($T \sim 20$ K), or additional energy inputs are needed.

Is there evidence for unaccounted sources of energy input in this region? The total FIR luminosity of the nebula region can be estimated using (Lonsdale et al. 1985, Lee et al. 1996)

$$L_{FIR} = 0.394\,\mathrm{L}_{\odot} \cdot R(\overline{T_d}, \beta) \left[\frac{S_{100} + 2.58 S_{60}}{1\mathrm{MJy\,sr}^{-1}}\right] \left[\frac{D}{\mathrm{kpc}}\right]^2 \quad , \tag{2}$$

where D is distance, and the correction factor $R(\overline{T_d}, \beta)$ is given by

$$R(\overline{T_d}, \beta) = (\int_{x_1}^{x_2} \frac{x^{3+\beta}}{e^x - 1} dx) / (\int_{x_3}^{x_4} \frac{x^{3+\beta}}{e^x - 1} dx) \quad , \tag{3}$$

where $x_n \equiv hc/\lambda_n k\overline{T_d}$, $\lambda_1 = 1\mu$m, $\lambda_2 = 500\mu$m, $\lambda_3 = 42.5\mu$m, $\lambda_4 = 122.5\mu$m, and we assume $\beta = 1$. Using an average dust temperature of 40 K for the nebula region (Ghosh et al. 1988), we obtain a total FIR luminosity $L_{FIR} \sim 10^7$ $L_\odot$. This number is comparable to the total luminosity of all the OB stars in the nebula, $L_{stars} \sim 2 \times 10^7 L_\odot$ (Feinstein 1969; Walborn 1973). Since the nebula region is already a blown-open cavity, however, we expect that only a small part of the UV flux of the OB stars will be intercepted by the dust and gas. Even though the UV power from stars and the FIR luminosity are comparable, it seems likely that there is additional energy input to the region, for example in the form of mechanical energy from shocks. The extent of the CO ($4 \rightarrow 3$) emission in the broader surrounding area also reinforces the above evidence from analysing the far-IR emission near the nebula that the heating of the Carina molecular complex is likely to be contributed by energy sources in additional to stellar luminosity.

4.2 Origins of the [C I] Emission

A striking feature of this dataset is the large spatial extent of the [C I] emission, as well as the homogeneity of its intensity, both near and far from the UV sources.

We first estimate the column density of neutral carbon using the equation

$$N_{\mathrm{C}^0} = 1.7 \times 10^{16}\,\mathrm{cm}^{-2} \left[\frac{\int \mathrm{T_a^*[C\ I]dv}}{1\mathrm{K\,km\,s^{-1}}} \right] \tag{4}$$

(Plume 1995). From the observed integrated intensity of [C I] we obtain a peak C^0 column density $N(\mathrm{C}^0) \sim 1.4 \times 10^{17}\,\mathrm{cm}^{-2}$. This can be compared to $N(\mathrm{C}^0) \sim 1.2 \times 10^{17}\,\mathrm{cm}^{-2}$ measured for the bulk of the S 140 molecular cloud (Plume 1995), and $N(\mathrm{C}^0) \sim 2$–$3 \times 10^{17}\,\mathrm{cm}^{-2}$ as given by the PDR models (van Dishoeck & Black 1988; Hollenbach, Takahashi, & Tielens 1991). The brightness of [C I] emission in the Carina molecular complex is therefore unexceptional.

According to the 100μm and [C I] overlay in Figure 10, it appears that most of the [C I] emission in Regions 2 and 3 is likely to have originated from the photodissociated CO by the intense UV radiation near the core of the nebula. The connection of the [C I] emission in Region 3 to the UV sources is also manifested by the bar-like profile of the strongest [C I] emission peak bending towards the ionizing cluster Tr 14 and the peculiar star η Carinae.

In Regions 4 and 5, however, the [C I] emission reaches almost the same intensity as the peak of Region 3, near the nebula. In fact, the [C I] emission across the entire molecular complex ($\sim$ 150 pc) is extremely homogeneous and appears to have little correlation with the presence of FIR peaks or the location of nearby sources of ionizing radiation, aside from some localized examples. The UV flux G_0, however, varies by several orders of magnitudes as indicated by the FIR intensity. The average UV field in the 6 regions can be estimated using

$$G_0 \sim \frac{1}{1.6 \times 10^{-3}} \frac{L_{FIR}}{8\pi d^2} \quad , \tag{5}$$

where $G_0 = 1$ is the interstellar UV radiation field in the vicinity of the Sun ($1.6 \times 10^{-3} \mathrm{erg\,s^{-1}\,cm^{-2}}$; Habing 1967), d is the average radius of a region, and we are implicitly assuming that all the UV photons are collected by interstellar dust grains and reradiated in the FIR. The G_0 values for regions 1 through 6 are approximately 800, 1700, 1000, 170, 130, and ≤ 10 respectively. The UV field around the emission peaks can be several order of magnitude higher than the region average. The insensitivity of the [C I] emission to the radiation field incident on the clouds has been predicted by PDR models (Kaufman et al. 1999) and may provide the explanation for the observed homogeneities of [C I] emission, although we do not consider that a unique connection between the full content of [C I] in this region and a photodissociation process is firmly established.

What is the $I_{[C\ I]}/I_{CO(4\to3)}$ throughout the region, and what does it tell us about the density of the molecular gas according to the standard theories of PDR? In Figure 13 we present the scatter plots of the [C I] and CO ($4 \rightarrow 3$) integrated intensities (each represented in units of K km s^{-1}) for regions 1 through 6. The two transitions are well correlated within each region, whereas between the different regions the line intensity ratio changes: $I_{[C\ I]}/I_{CO(4\rightarrow3)}$=0.21, 0.17, 0.19, 0.32, 0.45, 0.34 for regions 1 through 6 respectively. This roughly corresponds to a monotonically increasing ratio of $I_{[C\ I]}/I_{CO(4\rightarrow3)}$ with decreasing Galactic longitude (i.e., advancing spiral arm crossing phase, see Fig. 2), due mostly to the decrease in CO ($4 \rightarrow 3$) intensity away from the nebula region in comparison with the relatively homogeneous [C I] (Figure 3). Figure 14 shows the $I_{[C\ I]}/I_{CO(4\rightarrow3)}$ ratio predicted by the standard PDR calculations (Kaufman et al. 1999). Using the values of G_0 found in the previous paragraph, and the $I_{[C\ I]}/I_{CO(4\rightarrow3)}$ ratio measured for the same regions, we can place them on this plot. We see that Regions 1, 2, and 3 have an average density $n \sim 10^5$ cm^{-3}, while for Regions 4 and 5 we predict somewhat lower densities $n \sim 3 \times 10^4$ cm^{-3}, and the density prediction is uncertain for Region 6 because the [C I] intensity there is below the noise level.

Although most physico-chemical models of molecular clouds find that neutral carbon is predominatly produced by photodissociation of CO and recombination of C^+, some models predict a large fraction of the gas phase carbon to be C^0 ($N(C^0)/N(CO) \sim$ 0.1 to 0.2) at densities below $\sim 5.5 \times 10^3\,\mathrm{cm}^{-3}$ (Pineau des Fôrets et al. 1992; Le Bourlot et al. 1993; Flower et al. 1994). The observed correlation between [C I] and CO ($4 \rightarrow 3$) together with the critical density of the CO transition ($> 10^5\,\mathrm{cm}^{-3}$) suggests, however, that this mechanism is not the source of a significant fraction of neutral carbon in this region.

4.3 Origins of the Size-Linewidth Relation

In Figure 15 we show the size-linewidth correlation plot for the molecular clumps derived from the CO ($4 \rightarrow 3$) data cube, using the clump-finding algorithm developed by one of the authors (Y. Lee). The boundary of the clumps is defined to be three times the rms noise level of the data cube pixels. The fitted size-linewidth relation has a slope of 0.6, similar to that found in other studies of the galactic molecular clouds (cf. Myers 1983 and the references therein). Other statistics of the clumps are given in Table 2.

The major trend of the correlation in Figure 15 is a single linear relation across the entire complex, regardless of whether a particular clump lies near or farther away from the η Carinae outflow. The role of this outflow appears to be mainly in perturbing the velocities of several clumps (such as the clump in region 2 seen in the velocity channel maps). The outflow also perturbs the size-linewidth relation from a perfect linear correlation—i.e., it adds noise into the relation. In fact, the two extreme outliers on Figure 15 are clumps from Regions 2 and 3, which are most affected by the outflow. In view of the basic uniformity of the correlation law across the whole complex, we conclude that the outflow is not the cause of the size-linewidth correlation, but is rather a cause for departure from a perfectly linear relation.

We are, therefore, still in need of a mechanism which is capable of injecting energy into the interstellar clouds on spatial scales of hundreds of parsecs. For the particular region of the Carina molecular complex at least, many of the proposed large scale processes, such as supernovae and superbubbles (Kornreich & Scalo 2000) do not appear to be applicable. Another proposed mechanism operating on the galactic level is the coupling of galactic rotational energy (von Weizsacker 1951; Fleck 1981). However, detailed numerical simulations have already shown that it is in fact rather difficult to couple this energy into the internal motion energy of the cloud (Das and Jog 1995).

An alternative candidate mechanism is the spiral density wave. It has been shown recently that spiral density waves constantly inject energy into the interstellar medium during spiral arm crossings, at size scales from 1 kpc down to a few parsecs (Zhang 2000). Since this energy is injected through the mediation of the gravitational potential, it happens simultaneously on large and small spatial scales. Using average Galactic spiral parameters, the orbit-averaged rate of energy injection per unit mass due to the interaction of a spiral density wave with the disk matter is calculated to be (Zhang 2000)

$$\frac{d\Delta E}{dt} = 3 \times 10^{-7} (\mathrm{km\,s^{-1}})^2\,\mathrm{yr}^{-1}. \tag{6}$$

Using an average line-width of $\Delta v = 2\ \mathrm{km\,s^{-1}}$ at size scale of 10 pc from Figure 15, the rate of the energy cascade can be found from the following equation

$$\frac{\Delta v^3}{L} = \frac{(2\,\mathrm{km\,s^{-1}})^3}{10\,\mathrm{pc}} = 8.1 \times 10^{-7} (\mathrm{km\,s^{-1}})^2\,\mathrm{yr}^{-1}. \tag{7}$$

These two numbers are quite comparable, especially considering that the energy injection rate during the period of spiral arm crossing is several times larger than its value averaged over the entire orbital period. Energy injection due to the spiral density wave is therefore a plausible source for maintaining the degree of turbulent motion and producing the basic trend of size-linewidth correlation observed in this region.

5 Conclusions

We have observed the Carina molecular cloud complex in the CO ($4 \rightarrow 3$) and [C I] $^3P_1 \rightarrow ^3P_0$ transitions using the AST/RO telescope. We find that throughout the mapped area ($\sim 150 \times 100$ pc in extent) the CO ($1 \rightarrow 0$), CO ($4 \rightarrow 3$) and [C I] emissions are ubiquitous and approximately coextensive. The extent and intensity of the [C I] emission is almost uncorrelated with the location and strength of of the UV sources. We also find that the clouds in this region appear to be warmer than typical dark molecular clouds.

We find that there is a unique size-linewidth correlation throughout the $\sim 150 \times 100$ pc region, which does not seem to be related to the spatially confined outflow originating in η Carinae. This suggests that the dominant energy injection mechanism responsible for turbulence in molecular clouds operates on very large spatial scales, and is different from localized stellar outflows.

We propose that the same large-scale mechanism could be the energy source for feeding the interstellar turbulence (thus producing the observed size-linewidth relation), and increasing the temperature of these clouds. We suggest that the spiral density wave shock may play an important role in the formation and evolution of the molecular cloud complexes as well as in the energy balance of the clouds. In particular, the energy injection from the spiral density wave is found to be of the correct order to produce the observed size-linewidth relation for molecular clouds, so it might also be responsible for a part of the heating of the clouds through the dissipation of turbulent energy.

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Table 1 Known OB associations within the mapping region

name	l (deg)	b (deg)	D (kpc)	V (km/s)	Ntot	Dl (pc)	Db (pc)	N_KM
CAR 1 B	285.98	0.40	2.14	-2.7	24	44.8	74.6	4
CAR 1 C	286.30	-0.16	2.59		8	22.6	31.7	1
CAR 1 E	287.61	-0.68	2.64	-11.0	77	83.0	60.0	3

name: Association name
l: Galactic longitude
b: Galactic latitude
D: Distance
V: Average radial velocity of the association relative to the Sun
Ntot: Total number of stars in the association
Dl: Size of association along longitude
Db: Size of association along latitude
N_KM: Number of K and M supergiants

source: Melnik A.M. & Efremov Yu.N. (1995)

Table 2. Cloud clump statistics from the CO 4-3 data set

l (degree)	b (degree)	v (km/s)	dv (km/s)	size (pc)	Tpk (K)	I_CO (Kkm/s)
287.68	-0.75	-24.38	0.80	1.89	3.06	148.2
287.74	-0.62	-23.24	1.10	2.56	3.20	281.2
287.38	-0.67	-22.10	1.08	1.37	3.01	73.5
286.36	-0.27	-20.50	0.67	1.62	2.80	66.4
287.32	-0.56	-16.43	1.40	5.43	5.32	1713.5
286.08	0.21	-18.63	1.25	2.53	4.13	390.3
288.06	-1.11	-17.43	1.71	7.52	4.05	1273.2
287.00	-0.36	-17.85	0.75	2.91	4.52	372.6
287.13	-0.54	-17.40	0.53	3.56	3.59	198.4
287.13	-0.85	-16.68	0.92	2.74	3.18	225.0
287.23	-0.22	-16.34	0.74	2.25	3.26	122.6
287.10	-0.72	-16.45	0.58	1.20	2.85	42.7
287.25	-0.91	-12.56	0.50	1.16	2.93	27.1
285.27	-0.01	3.53	0.62	1.47	3.69	79.7

Figure Captions

Figure 1. Columbia CO survey integrated intensity map (in units of $\mathrm{K\,km\,s^{-1}}$) of the fourth quardrant containing the Carina molecular complex region.

Figure 2. Carina molecular complex region, shown as a contour plot of CO ($1 \rightarrow 0$) of the Columbia data superimposed on the Digital Sky Survey image (obtained from the SkyView database of the Goddard Space Flight Center). The contour level are 10%-90% of 70 $\mathrm{K\,km\,s^{-1}}$. The three star symbols represent the known OB associations in this region, and their detailed properties are given in Table 1. The three concentrations of stars and nebulosities are respectively the Carina nebula/H II region (NGC 3372), NGC 3324 at (286.2°, −0.2°), as well as NGC 3293 and its companion H_α region G30 at (285.9°, 0.1°). The 6 dashed boxes mark regions identified for subsquent analysis.

Figure 3. AST/RO CO ($4 \rightarrow 3$) and [C I] maps. The contour levels for CO ($4 \rightarrow 3$) are 10% to 90% of 80 $\mathrm{K\,km\,s^{-1}}$. The half tone for [C I] is from 0 to 12 $\mathrm{K\,km\,s^{-1}}$. The extent of the mapping area for each transition is indicated by the boundaries of the contour or halftone images.

Figure 4. AST/RO CO ($4 \rightarrow 3$) map overlayed on the Columbia CO (1-0) map of the same region. Note that the AST/RO map only cover a limited area within that mapped by the Columbia Survey, as indicated in the previous figure.

Figure 5. AST/RO CO ($4 \rightarrow 3$) map overlayed on the high-resolution CO ($1 \rightarrow 0$) map taken by Brooks et al (1998) with the MOPRA telescope. The MOPRA map region is indicated by the boundaries of the halftone figure.

Figure 6. Velocity channel maps of the CO ($4 \rightarrow 3$) emission. Contour levels are 10%–90% of 40 $\mathrm{K\,km\,s^{-1}}$.

Figure 7. Velocity channel maps of the [C I] emission. Countour levels are 10%–90% of 12 $\mathrm{K\,km\,s^{-1}}$.

Figure 8. Composite spectra averaged for each region 1–6 as identified in Figure 3. CO ($4 \rightarrow 3$) spectra are plotted as solid lines; [C I] spectra are

plotted as dashed lines.

Figure 9. Excitation temperature (in degrees Kelvin) derived from the CO $(4 \rightarrow 3)$ and CO $(1 \rightarrow 0)$ integrated intensity map. The CO $(4 \rightarrow 3)$ emission is convolved to the same spatial and velocity resolutions as the CO $(1 \rightarrow 0)$ data.

Figure 10. [C I] integrated intensity overlayed on the IRAS 100 μm emission. The 100 μm emission is in units of $\mathrm{MJy\,sr^{-1}}$, and the CI contours are from 2 - 12 $\mathrm{K\,km\,s^{-1}}$ with a spacing of 2 $\mathrm{K\,km\,s^{-1}}$.

Figure 11. CO $(4 \rightarrow 3)$ integrated intensity overlayed on the IRAS 12 μm emission. The 12 μm emission is in units of $\mathrm{MJy\,sr^{-1}}$, and the CO $(4 \rightarrow 3)$ contours are from 10% - 90% of 80 $\mathrm{K\,km\,s^{-1}}$.

Figure 12. CO $(4 \rightarrow 3)$ integrated intensity overlayed on the IRAS 100 μm emission. The 100 μm emission is in units of $\mathrm{MJy\,sr^{-1}}$, and the CO $(4 \rightarrow 3)$ contours are from 10% - 90% of 80 $\mathrm{K\,km\,s^{-1}}$.

Figure 13. [C I] versus CO $(4 \rightarrow 3)$ integrated intensity scatter plot.

Figure 14. [C I] versus CO $(4 \rightarrow 3)$ ratio from the standard PDR theory calculation for different UV intensity and gas volumn density (courtesy Mark Wolfire).

Figure 15. Size-linewidth relation for the clumps in the Carina molecular cloud complex, derived from the CO $(4 \rightarrow 3)$ data cube.

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