FIRST DETECTION OF SUBMILLIMETER [C i] EMISSION IN THE SMALL MAGELLANIC CLOUD

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ABSTRACT

We report the first detection of [C i] (1P → 1P) emission at 609 µm in a region of the Small Magellanic Cloud (N27). Environments poor in heavy elements and dust such as the SMC are thought to be dominated by photodissociation regions (PDRs). This is the lowest metallicity source where submillimeter neutral carbon emission has been detected. Studying the I_Ci/I_CO ratio in several sources spanning more than an order of magnitude in metallicity Z, we find that the I_Ci/I_CO ratio increases for decreasing Z. The existence of such a trend points to a photodissociation origin for most of the neutral carbon in molecular clouds, in agreement with standard PDR models. We also report Infrared Space Observatory far-infrared (FIR) spectroscopic observations of N27 and use them to derive its physical properties. Comparison between the density and radiation field revealed by FIR diagnostics (n ~ 300–1000 cm⁻³, x_m ~ 30X_H~100X_H) and those derived from millimeter and submillimeter data (n ~ 10⁸ cm⁻³, x_m ~ 30X_H) suggests that the FIR lines originate in more diffuse gas and are perhaps dominated by the interclump medium. Regardless of the cause, analysis of the FIR and millimeter-submillimeter data produces a discrepancy of 2 orders of magnitude for the density of this source.

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

1 INTRODUCTION

Studies of the interstellar medium (ISM) in the Small Magellanic Cloud (SMC) allow us to investigate star-forming clouds that are poor in heavy elements. The SMC is indeed an excellent choice to study this phenomenon because it is nearby (D ~ 61 kpc; Lany & Stobie 1994), has an unobserved line of sight and very small internal obscuration, and possesses the lowest metallicity Z among the nearby members of the Local Group (Z ~ Z_G/10; Dufour 1984). Therefore, studies such as this will eventually allow us to draw conclusions about those much more elusive galaxies: the high-z primitive galaxies.

The depletion of heavy elements and the consequent low dust-to-gas ratio [(D/G)_SMC ~ 1/6(D/G)_MW; Bouchet et al. 1985] affects the ISM by enhancing photodissociation. Because of its high abundance (i.e., strong self-shielding) and cross-shielding with atomic hydrogen lines, molecular hydrogen is mostly unaffected by Z. The usual tracer molecules such as CO, however, are efficiently destroyed in dust-poor systems. A much larger fraction of the ISM in these systems is thus expected to be occupied by photodissociation regions (PDRs; e.g., Tielens & Hollenbach 1985; Sternberg & Dalgarno 1995). Consequently, we expect the intensities of the spectral lines associated with the PDR (e.g., [C ii], [C i]) to be enhanced when compared to molecular lines [e.g., 12CO (J = 1 → 0)], resulting in increasing I_Ci/I_CO and I_Ci/I_CO ratios (Bolatto, Jackson, & Ingalls 1999).

The immediate purpose of this work is twofold: (1) to test for the existence of an increasing I_Ci/I_CO ratio with decreasing metallicity Z (§ 3.1) and (2) to investigate the power of far-infrared (FIR) spectroscopic diagnostics and compare their results to those obtained using millimeter and submillimeter lines (§ 3.2). An I_Ci/I_CO dependence on Z could be useful for determining metallicities in high-z sources using only radio observations. The trend in I_Ci/I_CO with Z is also a test for the origin of neutral carbon inside molecular clouds. An increasing I_Ci/I_CO ratio for decreasing Z points to a PDR origin, while a flat I_Ci/I_CO ratio suggests that C0 is produced inside the CO cores by means other than UV photons.

Our SMC source, the N27 nebula, was first cataloged by Henize (1956). A later survey by Davies, Elliott, & Meaburn (1976) calls it DEM 40. Its associated IR peak is also known as LIRS 49 (Schwering & Israel 1989). This region was mapped by the Swedish-ESO Submillimeter Telescope (SEST) in the (J = 1 → 0) and (J = 2 → 1) transitions of CO (Rubio et al. 1993) and studied in detail in several molecular transitions by Heikilä, Johansson, & Olafsson (1999). Albeit a weak emitter when compared to Galactic sources, the molecular cloud associated with N27 features some of the strongest CO (J = 1 → 0) emission in the SMC (Israel et al. 1993).

2 OBSERVATIONS

2.1 Far-Infrared Data

We observed N27 using the long-wavelength spectrometer (LWS) on board the Infrared Space Observatory (ISO) satellite at R = λ/Δλ ~ 200. These LWS data are a 4160 s long full-grating scan obtained on 1997 December 20 as part of the LOMETPDR project. The instrumental characteristics are described by Clegg et al. (1996), and the calibration of the ISO LWS instrument is described by Swinyard et al. (1996). The data pipeline was version 8.7, and the observations were processed using ISAP version 2.0. We averaged the spectra across scans and scan direction, but not across detectors, with the default wavelength spacing of 0.135 µm. The averaging was necessary to account for the long full-grating scan and the small wavelength spacing.
done after 2.5σ clipping of outlying points. For the purposes of obtaining an $I_{\text{FIR}}$ estimate only, we joined the detectors together by offsetting them with the dark correction method in ISAP, using detector LW1 as the reference. Table 1 summarizes the spectroscopic results.

We can assess the calibration of the LWS data by comparing it with previous $[\text{C}\,\text{i}]$ measurements of N27 featuring a similar beam size (Israel & Maloney 1993). The intensity measured by the Far-Infrared Fabry-Perot Interferometer (FIFI) on board the Kuiper Airborne Observatory at the LWS pointing is $I_{[\text{C}\,\text{i}]} \approx 9 \times 10^{-4}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$. The LWS measured intensity after applying the recommended correction factors for beam size and extended source is $I_{[\text{C}\,\text{i}]} \approx 9.5 \times 10^{-4}$ ergs s$^{-1}$ cm$^{-2}$ sr$^{-1}$, in remarkable agreement with the FIFI observations. The measurements listed in Table 1 include both corrections.

### 2.2. Submillimeter Data

We observed the $[\text{C}\,\text{i}] (^{2}P_{1} \rightarrow ^{2}P_{0})$ transition of neutral atomic carbon at $\nu = 492.1607$ GHz (609 μm) using AST/RO, the Antarctic Submillimeter Telescope and Remote Observatory located at the Amundsen-Scott South Pole base (Stark et al. 1997). The observations were obtained on 1998 July 3–7 using the AST/RO SIS quasi-optical receiver, with a system temperature $T_{\text{sys}} \sim 1800$–2400 K. The back end was the 2048 channel low-resolution acousto-optical spectrometer. The spectra were observed in position switching mode, chopping 15′ in azimuth (same as right ascension at the pole). At 492 GHz the telescope beam had a half-power beamwidth $\sim 3.8′/0.3′$. The forward efficiency determined from sky dips was 70%, and it is assumed to be identical to $\eta_{\text{sky}}$. The pointing was better than 30′. A $6′ \times 6′$ region centered on this source was mapped on a $30″$ grid, considerably oversampling the beam. The data were calibrated using the standard procedure for AST/RO, which includes sky, hot, and cold load measurements every 30 minutes, and were processed using the COMB package. The total accumulated integration time, after rejecting bad spectra, was 63 hr. The spectrum obtained after averaging all the observations together is shown in Figure 1. A Gaussian fit to the data gives $\nu_{\text{cen}} = 115.2 \pm 1.4$ km s$^{-1}$, $\Delta\nu = 9.3 \pm 3.3$ km s$^{-1}$, and $T_{\text{max}} = 14 \pm 4$ mK (main-beam brightness). The location of the [C i] line agrees very well with the strongest CO component, for which $\nu_{\text{cen}} = 114.5$ km s$^{-1}$ (Rubio et al. 1993).

The relatively weak [C i] emission from N27, combined with its small size and consequent beam dilution, produced a low signal-to-noise ratio map. Thus, the analysis in § 3.1 will be focused on the averaged spectrum for the region.

### 3. RESULTS AND DISCUSSION

#### 3.1. Metallicity and the $I_{[\text{C}\,\text{i}]/I_{\text{CO}}}$ Ratio

The prime motivation for this study is to determine the $I_{[\text{C}\,\text{i}]/I_{\text{CO}}}$ intensity ratio in the SMC, an environment that because of its low metallicity and low dust-to-gas ratio should be dominated by PDRs (see § 1). To do this we compare our [C i] data with the $^{12}\text{CO} (J = 1 \rightarrow 0)$ map by Rubio et al. (1993). This map covers only a relatively small fraction of the area mapped in [C i], but it probably contains most of the CO emission; to obtain a $I_{[\text{C}\,\text{i}]/I_{\text{CO}}}$ ratio we assume that there is no CO emission outside this region. The CO emission associated with N27 has two components, at 114.5 and 126.9 km s$^{-1}$. For this analysis we have integrated the CO and [C i] data over the velocity range corresponding to the strongest component, at $\sim 114$ km s$^{-1}$. In order to compute a ratio we have convolved the CO ($J = 1 \rightarrow 0$) integrated intensity data to the angular resolution of the [C i] map. Subsequently, we sampled the convolved CO map at the positions observed in [C i], excluding those positions where [C i] spectra were discarded. These samples were averaged with the same weighting scheme used for [C i]. This procedure allows us to obtain a reliable average ratio for the N27 region, relatively insensitive to uncertainties in the [C i] beam size and pointing. The resulting intensities, integrated over the velocity interval 107–119 km s$^{-1}$, are $I_{[\text{C}\,\text{i}]} \approx 0.132 \pm 0.027$ and $I_{\text{CO}} \approx 0.517 \pm 0.052$ K km s$^{-1}$, yielding a ratio $I_{[\text{C}\,\text{i}]/I_{\text{CO}}} \approx 0.26 \pm 0.06$. The corresponding cooling ratio (the ratio of intensities in ergs per second per
square centimeter per steradian) is \( I_{\text{c}, \text{i}}/I_{\text{CO}} \approx 19.9 \pm 4.5 \). The uncertainties are 1 \( \sigma \) and include the statistical errors as well as a 10\% 1 \( \sigma \) calibration uncertainty in the intensities, added in quadrature.

Figure 2 compares the \( I_{\text{c}, \text{i}}/I_{\text{CO}} \) ratio in N27 to a sample of molecular clouds associated with star-forming regions in systems of different metallicities. This plot suggests that there is an increasing trend in the \( I_{\text{c}, \text{i}}/I_{\text{CO}} \) ratio with decreasing metallicity \( Z \), such that \( I_{\text{c}, \text{i}}/I_{\text{CO}} \propto Z^{-0.5} \). The scatter around this line is relatively large, as shown by the data for the Large Magellanic Cloud. Theoretical expectations notwithstanding, this scatter has made it difficult to identify a trend in past studies over a narrower range of metallicities (e.g., Bolatto et al. 2000b).

Shown also in Figure 2 is a model for carbon in unresolved PDRs (Bolatto et al. 1999). This model consists of intensity ratios computed over a distribution of clumps with uniform excitation, where each spherical clump is divided in three concentric regions of \( \text{C}^{\text{+}}, \text{C}^{\text{0}}, \) and \( \text{CO} \). The sizes of these regions depend on the metallicity (or the dust-to-gas ratio) of the ISM. While necessarily crude, this model incorporates the effects of clumping and the increase in the physical size of the PDR for decreasing metallicity. The growth of the PDR is mostly caused by the diminishing attenuation of the UV radiation, as the dust-to-gas ratio of the ISM decreases for smaller metallicities. In this scenario, the primary reason why the \( I_{\text{c}, \text{i}}/I_{\text{CO}} \) ratio increases for decreasing metallicity is the reduction and eventual disappearance of the CO cores in the clumps.

Are the models for the \( I_{\text{c}, \text{i}}/I_{\text{CO}} \) ratio as a function of Z quantitatively consistent with the measurements? Bolatto et al. (1999) explore two possibilities: \( \text{C}^{\text{0}} \) produced in the growing PDR (model A) and \( \text{C}^{\text{0}} \) restricted to a region whose size does not change with metallicity (model B). The latter model predicts an essentially flat \( I_{\text{c}, \text{i}}/I_{\text{CO}} \) ratio \( I_{\text{c}, \text{i}}/I_{\text{CO}} \propto Z^{0.5} \). A similar result (constant \( I_{\text{c}, \text{i}}/I_{\text{CO}} \)) would be obtained if \( \text{C}^{\text{0}} \) was produced inside the CO cores via unidentified chemical reactions. The slope predicted by model A in this metallicity range is slightly steeper than that suggested by the data, \( I_{\text{c}, \text{i}}/I_{\text{CO}} \propto Z^{-0.8} \). Whether this difference is actually significant is difficult to assess given the paucity of observations and the intrinsic scatter in the data. Nevertheless, several possibilities could explain this discrepancy: (1) an increase in CO excitation for decreasing metallicity (i.e., hotter molecular gas for diminishing \( Z \)); (2) clump-to-clump shielding preventing the efficient photodissociation of CO; (3) a dust-to-gas ratio not proportional to the oxygen abundance (but this would require the dust abundance to be a slower function of \( Z \), e.g., \( D(G) \propto Z^{0.5} \); when observations suggest \( D(G) \propto Z^{2} \); Lisenfeld & Ferrara 1998); and (4) some fraction (\( \sim 30\% \)) of the \( \text{C}^{\text{0}} \) produced inside the CO cores instead of the PDR. We conclude that, within the bounds imposed by the limitations of the models and the paucity of the measurements, the observed trend for the \( I_{\text{c}, \text{i}}/I_{\text{CO}} \) ratio with metallicity shown in Figure 2 agrees with theoretical expectations for mostly photodissociation-produced \( \text{C}^{\text{0}} \).

### 3.2. Physical Conditions

The FIR spectroscopic data can be used to determine the conditions prevalent in N27. Using Table 1 and the PDR models by Kaufman et al. (1999), we will find the UV field \( \chi_{\text{uv}} \) and the gas density \( n_{\text{H}_2} \). The important FIR ISM diagnostics computed by Kaufman et al. are (1) the \([\text{O} \, \text{i}] \,(^{1}P_{1} \rightarrow ^{3}P_{0})/(^{1}P_{1} \rightarrow ^{3}P_{1}) \) line ratio \( (I_{\text{a}5}/I_{\text{a}3}) \sim 0.051 \pm 0.006 \), according to our measurements; (2) the \([\text{O} \, \text{i}] \,(^{1}P_{1} \rightarrow ^{3}P_{0})-[	ext{C} \, \text{i}] \,(^{2}P_{3/2} \rightarrow ^{2}P_{1/2}) \) line ratio \( (I_{\text{a}3}/I_{\text{a}5}) \sim 0.42 \pm 0.01 \); (3) the ratio of \([\text{O} \, \text{i}] \,(^{1}P_{1} \rightarrow ^{3}P_{0}) + [\text{C} \, \text{i}] \,(^{2}P_{3/2} \rightarrow ^{2}P_{1/2}) \) to the FIR continuum (using the LWS spectrum we estimate \( I_{\text{BR}} \sim 1 \times 10^{-2} \) ergs \( \text{cm}^{-2} \text{sr}^{-1} \), yielding \( I_{\text{a}3}/I_{\text{BR}} \sim 0.012 \pm 0.002 \); and (4) the \([\text{C} \, \text{i}] \,(^{2}P_{3/2} \rightarrow ^{2}P_{1/2}) \) intensity itself. These joint four diagnostics agree very well, placing N27 in the low-density, \( n \sim 300-1000 \) cm\(^{-3} \), moderate-UV field, \( \chi_{\text{uv}} \sim 30 \chi_{\text{0}}=100 \chi_{\text{av}} \), region of the \( \chi_{\text{uv}} \)-\( \chi_{\text{av}} \) diagrams (\( \chi_{\text{av}} \) is the interstellar UV field in the vicinity of the Sun, \( \chi_{\text{av}} \approx 1.6 \times 10^{-6} \) ergs cm\(^{-2} \text{ s}^{-1} \); Habing 1968). The corresponding PDR temperature in these conditions is \( T_{\text{pdr}} \sim 200 \) K. The FIR continuum dust temperature, derived from the LWS spectrum, is \( T_{\text{d}} \sim 40 \) K.

The density and radiation field derived using millimeter and submillimeter lines, however, strongly disagree with the FIR results. This lack of agreement is not surprising, perhaps, since these lines probably originate in different regions of the ISM. A millimeter wavelength multiline excitation analysis using several molecular species was performed by Heikillé et al. (1999), yielding \( n \sim 10^{3} \) cm\(^{-3} \), \( T \approx 15 \) K, and visual extinction \( A_{\text{v}} \approx 1 \) for N27. The \( I_{\text{c}, \text{i}}/I_{\text{CO}} \) ratio determined in § 3.1 strongly constrains the density according to the calculations by Kaufman et al. (1999), also resulting in \( n \sim 10^{3-10^{4}} \) cm\(^{-3} \) (albeit over a much larger area). Finally, using the \(^{13}\text{CO} \,(J = 1 \rightarrow 0) \) observations by Rubio et al. (1993) convolved to the FIFI beam we compute an accurate \( I_{\text{c}, \text{i}}/I_{\text{CO}} \) ratio at the LWS pointing, yielding \( I_{\text{c}, \text{i}}/I_{\text{CO}} \approx 7000 \). This ratio alone does not constrain either parameter very well, but implies \( \chi_{\text{uv}} > 100 \chi_{\text{av}} \), and when used in combination with the measured \( I_{\text{c}, \text{i}}/I_{\text{CO}} \) ratio results in \( \chi_{\text{uv}} \sim 10^{4} \chi_{\text{av}} \). This is not a fair comparison, however, since both the \( I_{\text{c}, \text{i}}/I_{\text{CO}} \) and \( I_{\text{c}, \text{i}}/I_{\text{CO}} \) ratios will be affected by the low metallicity and extinction of this source. Fortunately, Kaufman et al. (1999) provide some calculations for small \( Z \) and \( A_{\text{v}} \). Using their model tracks for \( Z = 0.1 \) and \( A_{\text{v}} = 1 \) we find \( n \sim 10^{5} \) cm\(^{-3} \) and \( \chi_{\text{uv}} \sim 30 \chi_{\text{av}} \) for N27, based on \( I_{\text{c}, \text{i}}/I_{\text{BR}} \sim 10^{-2} \) and \( I_{\text{CO}}/I_{\text{BR}} \sim 10^{-4} \). These measurements are also consistent with \( n_{\text{CO}} > n_{\text{C}} \) at a lower radiation field if we
allow the model tracks to be shifted in the abscissa as described by the model authors.

At any rate, the diagnostics including [C i] or molecular line observations are inconsistent with the density \( n \sim 10^4 \text{ cm}^{-3} \) implied by the FIR transitions. Because in general the FIR lines are generated closer to the surface of the cloud, this discrepancy may indicate a real density gradient in the gas. Another possibility is that the millimeter-submillimeter and FIR lines originate in different regions of the cloud, with the latter dominated by material in a more diffuse interclump medium, or perhaps associated with the H ii region rather than the molecular cloud. A third possibility is that the FIR line ratios are significantly affected by \( A_v \) and \( A_n \), and using model results computed for Galactic metallicity and large \( A_v \) is inappropriate. If this is the cause of the density discrepancy, however, it is remarkable that all four FIR diagnostics agree on essentially the same value for the density and radiation field. Independent of which explanation is correct, we conclude that (1) the FIR and millimeter-submillimeter measurements roughly agree on the radiation field intensity, although it is extremely important to use models with the appropriate \( A_v \) and \( A_n \), and (2) the millimeter-submillimeter data systematically indicate a density about 2 orders of magnitude higher than that derived from FIR fine-structure data.

4. SUMMARY AND CONCLUSIONS

We report new FIR and submillimeter observations of the star-forming region N27 in the SMC. Using our measured intensities for the FIR continuum and [O i] and [C ii] fine-structure transitions and comparing with existing model calculations (Kaufman et al. 1999), we derive the density and radiation field in N27 to be \( n \sim 300-1000 \text{ cm}^{-3} \) and \( \chi_{av} \sim 30\chi_{0}=100\chi_{0} \). In contrast, the density derived using millimeter and submillimeter data is 2 orders of magnitude higher, \( n \sim 10^4 \text{ cm}^{-3} \), while the radiation field is similar or lower, \( \chi_{av} \leq 30\chi_{0} \). The cause for this discrepancy is not clear, but we suggest that the FIR and the millimeter-submillimeter lines arise in different parcels of gas, with the former perhaps dominated by the interclump medium or the H ii region.

We have detected [C i] \((2P_1 \rightarrow 2P_0)\) emission from the SMC for the first time. This is the lowest metallicity source in which submillimeter neutral carbon emission has been detected. Low-metallicity, dust-poor environments are thought to be dominated by PDRs. Despite the factor of \( \sim 5 \) in metallicity spanned by N27 and Orion, however, the \( I_{[C\,i]}/I_{[CO]} \) ratio in N27 is only modestly larger than the \( I_{[C\,i]}/I_{[CO]} \) ratio in Orion. Nevertheless, when we study the ratio in several sources spanning more than an order of magnitude in metallicity, we find a noisy but convincing increasing trend in the \( I_{[C\,i]}/I_{[CO]} \) ratio for decreasing metallicity (Fig. 2). This trend is somewhat flatter than, but in rough agreement with, the modeling results by Bolatto et al. (1999). The existence of an increasing trend points to a photodissociation origin for most neutral carbon inside molecular clouds, in agreement with standard PDR models.

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