THE ASTROPHYSICAL JOURNAL, 480:L59–L62, 1997 May 1

FIRST DETECTION OF 492 GHz [C I] EMISSION FROM THE LARGE MAGELLANIC CLOUD

ANTONY A. STARK,[1] ALBERTO D. BOLATTO,[2,3] RICHARD A. CHAMBERLIN,[2,4] ADAIR P. LANE,[1] T. M. BANIA,[2]
JAMES M. JACKSON,[2] AND K.-Y. LO[5]

Received 1996 November 25; accepted 1997 January 16

ABSTRACT

The $^3P_1 \rightarrow {}^3P_0$ fine-structure transition of neutral atomic carbon [C I] was observed with the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) toward two star-forming regions in the Large Magellanic Cloud: N159 and 30 Doradus. The [C I] line is weak in the vicinity of 30 Dor, a region with a uniquely hard and intense UV field. The $I_{[\rm C\,I]}/I_{\rm CO}$ ratio in N159 is enhanced by a factor $\gtrsim 2$ compared to the Milky Way Galaxy, a result attributable to the lower metallicity of the Large Magellanic Cloud.

Subject headings: galaxies: ISM — ISM: atoms — ISM: individual (N159, 30 Doradus) — Magellanic Clouds — radio lines: ISM

1. INTRODUCTION

The response of a metal-poor interstellar medium (ISM) to radiation fields differs from that of an ISM with galactic abundances (Israel 1988; Maloney 1990). If the abundances of heavy elements are small, the equilibrium concentrations of molecular species are disproportionately affected (e.g., van Dishoeck & Black 1988; Lequeux et al. 1994). At the same time, the paucity of dust that also characterizes the low-metallicity ISM reduces the effectiveness with which dust shields the molecules from the dissociating ultraviolet (UV) radiation. The molecular gas consequently suffers from the combined effects of diminished self-shielding and dwindling dust shielding, enhancing the photodissociation rate of most molecules as if the effective UV radiation field were much stronger than the actual UV intensity. While this argument applies to all the chemical tracers of molecular hydrogen, it does not apply to H_2 itself. Self-shielding of H_2 and cross shielding with atomic hydrogen are extremely effective for molecular hydrogen (Abgrall et al. 1992), and most hydrogen atoms combine to form H_2 even though the formation rate is reduced by the paucity of dust.

A decrement in trace molecules, CO in particular, is in fact observed in low-metallicity systems. Dwarf galaxies systematically display very low levels of CO emission (Tacconi & Young 1987; Israel, Tacconi, & Baas 1995). Observations of the nearest of those systems, the Magellanic Clouds, show that their molecular clouds are underluminous in CO by factors of a few when compared with Galactic clouds of similar mass (Cohen et al. 1988; Israel et al. 1993; Rubio, Lequeux, & Boulanger 1993). The $I_{\rm CO}$ to $N_{\rm H_2}$ conversion factor, $X_{\rm CO} = N_{\rm H_2}/I_{\rm CO}$, has been studied for several metal-poor environments by comparing the CO intensity with the virial mass derived from CO line widths (Cohen et al. 1988; Rubio et al. 1993; Wilson 1995; Verter & Hodge 1995). These studies show that the ratio of CO intensity to virial mass depends on the spatial scale of the observations. Observations performed with larger spatial beam sizes find bigger $X_{\rm CO}$ conversion factors than those carried out with smaller beams. This result can be understood if we consider that low metallicity both greatly enhances the photodissociation rate of the diffuse CO gas and also diminishes the size of the CO clumps (Maloney & Black 1988). Although the low-metallicity $X_{\rm CO}$ factor is in fact not very different from the Galactic $X_{\rm CO}$ on small scales (Wilson 1995), at larger spatial scales the CO emission becomes swiftly diluted in a metal-poor environment.

There is additional evidence for the lack of a diffuse CO component in the low-metallicity ISM, caused by the enhanced photodissociation. Recent observations of the 158 μm [C II] transition in the Large Magellanic Cloud (LMC) (Poglitsch et al. 1995; Israel et al. 1996) show extended and greatly enhanced [C II] emission. According to these observations, the [C II] luminosity in the LMC is about 1% of the total far-infrared (FIR) luminosity, much higher than in the Galaxy and most galactic nuclei where [C II] is 0.1%–0.3% of the FIR (Stacey et al. 1991).

Neutral carbon in the envelopes of molecular clouds results from an equilibrium between two competing processes: the photodissociation of CO, which creates C I, and the photoionization of C^0, which destroys it, creating C II. The neutral carbon fine-structure line $^3P_1 \rightarrow {}^3P_0$ [C I] at 492 GHz is thus a tracer of a transition zone of the ISM occurring at optical extinctions of a few ($A_V \sim 1$–3) where H_2 exists but it is not traced by CO. The above arguments indicate that the extent of these "photodissociation regions" is enhanced in metal-poor environments. Photodissociation regions (PDRs) dominate the interstellar medium in low-metallicity systems.

As a consequence of the increased size of the PDRs, the intensity of the [C I] emission could be augmented in these systems. We have investigated this effect in N159 and 30 Doradus, two of the brightest star-forming regions in the Large Magellanic Cloud, using the newly installed Antarctic Submillimeter Telescope and Remote Observatory (AST/RO).

2. OBSERVATIONS AND RESULTS

We observed the $^3P_1 \rightarrow {}^3P_0$ [C I] transition at 492.1607 GHz toward two positions in the LMC during the 1995 austral winter. AST/RO is a 1.7 m offset Gregorian telescope located at the US National Science Foundation Amundsen-Scott

---

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; aas@cfa.harvard.edu, adair@cfa.harvard.edu.

[2] Astronomy Department, Boston University, 725 Commonwealth Avenue, Boston, MA 02215; bolatto@bu.edu, bania@bu.edu, jackson@bu.edu.

[3] Departamento de Astronomía, Universidad de la República, Montevideo, Uruguay.

[4] Current address: Caltech Submillimeter Observatory, 111 Nowelo Street, Hilo, HI 96720; cham@ulu.submm.caltech.edu.

[5] Astronomy Department, University of Illinois, 1002 West Green Street, Urbana, IL 61801; kyl@sgr.astro.uiuc.edu.

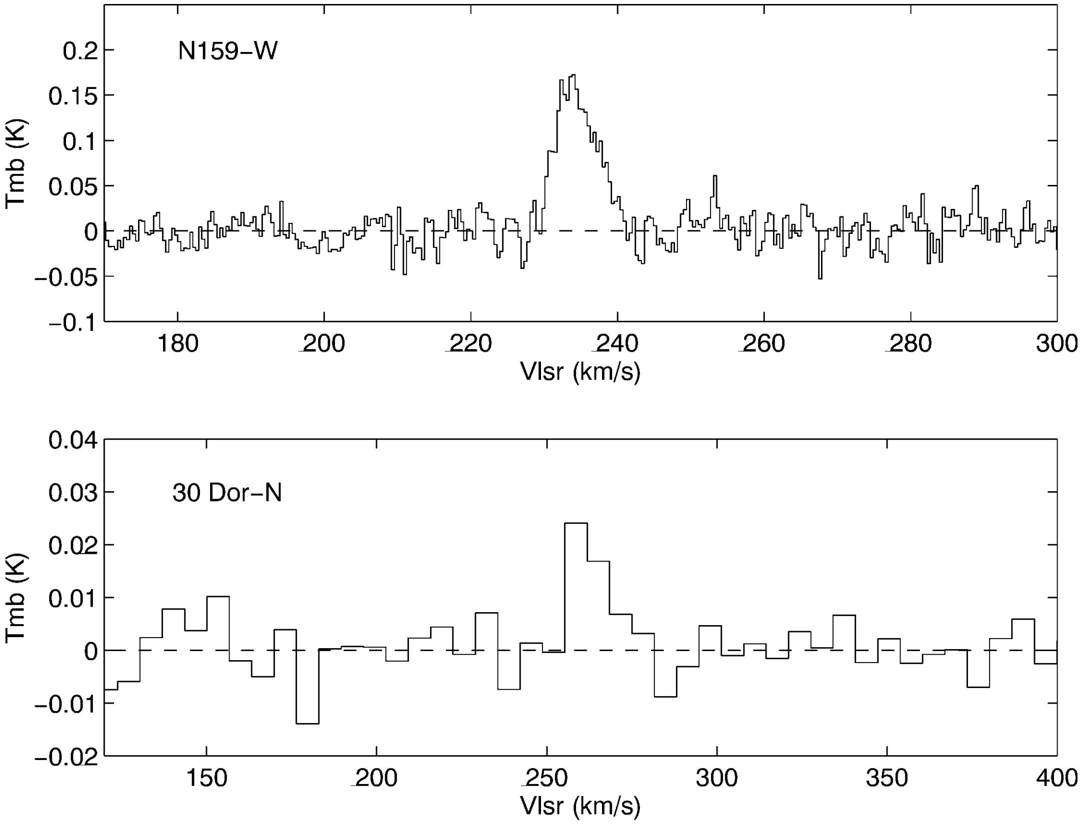

FIG. 1.—*Top:* [C I] spectrum of N159W. A linear baseline was subtracted from the data. The velocity resolution is 0.67 km s^{-1}, and the rms of the baseline is 18 mK. The total observing time (ON + OFF) was 6 hr. The asymmetric line profile bears a striking resemblance to other published transitions, particularly HCO^+ (Johansson et al. 1994). *Bottom:* Averaged [C I] spectrum of 30 DorN, with a second order baseline subtracted. The data were averaged to 6.56 km s^{-1} resolution. The total observing time was 5.5 hr, and the baseline rms is 5 mK. This spectrum is strikingly similar in shape to the CO spectrum of Garay et al. (1993).

South Pole Station and is a general-purpose instrument for astronomy and aeronomy at wavelengths between 3 mm and 200 μm (Stark et al. 1994, 1997; Lane & Stark 1996).

The observations were made with a 492 GHz quasi-optical SIS receiver (Zmuidzinas & Le Duc 1993; Engargiola, Zmuidzinas, & Lo 1994), which had a 165 K double sideband receiver noise temperature. The back end was a 1.1 GHz wide acousto-optical spectrometer with 1 MHz resolution (Schieder, Tolls, & Winnewisser 1989), yielding a velocity resolution of 0.67 km s^{-1}. During the observations the opacity-corrected system temperature was in the range 1200–1400 K. During the 1995 austral winter, the median zenith atmospheric opacity at 492 GHz was 0.70, with good stability over periods of many days (Chamberlin, Lane, & Stark 1997).

All observations were performed using double position switching with reference positions ±1° in azimuth (or right ascension, since both are the same at the South Pole). Intensity calibration was accomplished by measuring blackbody loads at 40 K, 90 K, and room temperature. Sky dips were interleaved with the observations. The calibration scheme used by AST/RO is described in Stark et al. (1997). The 492 GHz beam size of the instrument was measured to be 130″ ± 10″ (or ∼34 pc at the distance of the LMC) by scanning the limb of the Moon and making beam maps of Jupiter.

Pointing during the 1995 season was problematic, mostly because of stiffness problems in the telescope mounting tower, which have since been remedied. We conservatively estimate the pointing to be within the half-power point of the beam (∼60″). Inaccurate pointing will therefore decrease the observed line brightness no more than a factor of 2, since the regions of [C I] emission are larger than a point source.

Our [C I] spectra toward N159 West and 30 Dor are shown in Figure 1. Measured [C I] line parameters are given in Table 1. The 28 mK [C I] line detected by AST/RO toward 30 Dor is the faintest submillimeter line observed to date, but was obtained under average winter weather at Pole. This shows the excellence of the South Pole as a submillimeter site and implies that the limits of ground-based submillimeter-wave sensitivity have not yet been reached.

3. DISCUSSION

N159 and 30 Dor are part of a chain of massive star-forming cloud complexes. The 30 Dor region is more evolved and has less molecular gas than the southern complexes N160 and N159 (Israel et al. 1996). The N159 region (Henize 1955) exhibits some of the most intense CO lines in the Swedish-ESO Submillimeter Telescope (SEST) survey of the Magellanic Clouds (Israel et al. 1993). CO mapping of N159 (Johansson et al. 1994) shows that the cloud complex is resolved into three components: N159-W(the object of our study), N159 East, and N159 South. The first two regions show strong signs of ongoing star formation: intense radio continuum (Mills & Turtle 1984), *IRAS* 12 μm, and [C II] 158 μm emission (Mochizuki et al. 1994; Israel et al. 1996). N159-S seems to be passively illuminated by the two northern components. Modeling of the N159-W region (Bolatto et al. 1997)

TABLE 1

MEASURED LINE PARAMETERS OF [C I] AT TWO POSITIONS IN THE LMC

Name	R.A. (B1950)	Decl. (B1950)	$T_{\rm mb}$[a] (K)	$V_{\rm lsr}$ (km s^{-1})	Δv (km s^{-1})	$\int T_{\rm mb}$ dv[a] (K km^{-1} s^{-1})
N159-W	054003.0	−694703	0.162 ± 0.008	234.1 ± 0.2	6.52 ± 0.36	1.12 ± 0.11
30 Dor-N..........	053911.5	−690600	0.028 ± 0.007	258 ± 1	9.7 ± 2.9	0.29 ± 0.10

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] The calibration uncertainty is estimated to be ~15% (Stark et al. 1997). Pointing errors may cause the observed temperatures to be spuriously weak by as much as a factor of 2. Error values in this table result from system noise internal to our calibration system and do not include systematic calibration or pointing errors.

indicates a mean density of $\sim 8 \times 10^3$ cm^{-3} and an ambient UV field of 400 to 700 G_0, making this region comparable to the Orion Bar and S140.

3.1. *N159*

Extensive molecular line observations toward N159-W have been made by Johansson et al. (1994). Using the standard assumption of optically thick ^{12}CO lines, the measured intensity of the $J = 2 \rightarrow 1$ transition yields a kinetic temperature of ~15 K for the region. To evaluate the effect of geometrical beam dilution on the AST/RO observations, we will estimate the [C I] source size. The source is unresolved in the SEST map of CO ($J = 1 \rightarrow 0$). Assuming that both ^{12}CO transitions have the same excitation temperature, we can obtain a beam-filling factor and consequently an angular size for the N159W cloud of ~35″, consistent with the half-intensity contours of the ^{13}CO ($J = 1 \rightarrow 0$) map.

Large-scale [C I] observations of the molecular clouds S140 (Minchin, White, & Padman 1993; Plume, Jaffe, & Keene 1994), M17 (Genzel et al. 1988), and NGC 2024 (Plume 1995) have established that the CO and [C I] emissions are roughly coextensive. This can be explained by the clumpiness of the ISM, which permits the UV to penetrate deep into the cloud and generate C I. The [C I] emission arises in the PDR envelopes surrounding irregularly shaped molecular cores. Enlargement of the PDR in metal-poor environments will cause a thickening of the PDR layer, even as the large-scale [C I] and CO emission remains mixed. Assuming that the spatial extents of the CO and [C I] emission are similar, the intrinsic [C I] brightness temperature (that is, the observed brightness temperature corrected for the geometrical beam dilution) of the source would be ~2.2 K. Under the same assumption, the integrated line intensity ratio is independent of the source size (depending only on the ratio of beam sizes on both systems) and thus is more accurately determined. If the integrated intensity is expressed in K km s^{-1}, the ratio $I_{[\rm C\,I]}/I_{^{12}\rm CO(1\rightarrow 0)}$ is ~0.26. This is twice the average ratio for the Milky Way Galaxy, where $I_{[\rm C\,I]}/I_{^{12}\rm CO(1\rightarrow 0)} = 0.13$, as determined from COBE all-sky measurements (Wright et al. 1991). Observations of ^{13}CO and [C I] toward the Orion Bar region find a ratio $I_{[\rm C\,I]}/I_{^{13}\rm CO} \approx 0.8$ (Tauber et al. 1995). Comparing our [C I] observations to the ^{13}CO data of Johansson et al. (1994), $I_{[\rm C\,I]}/I_{^{13}\rm CO} \approx 1.5$ for N159-W, again a factor of ~2 larger than what is observed in the Galaxy. The presence of enlarged PDRs in metal-poor environments (Israel et al. 1996) leads us to conclude that the enhancement observed in the $I_{[\rm C\,I]}/I_{\rm CO}$ ratio for N159-W with respect to the typical Galactic ratio $I_{[\rm C\,I]}/I_{\rm CO} \approx 0.13$ may be a consequence of the low metallicity of the LMC. We note that the probable effect of our pointing error is to reduce the $I_{[\rm C\,I]}/I_{\rm CO}$ ratio we measure, perhaps by as much as a factor of 2.

3.2. *30 Doradus*

The 30 Dor Nebula is a site of intense massive star formation. Its UV field is equivalent to 230 stars of type O5 V (Kennicutt 1984), making it one of the strongest UV fields in any star-forming region (Israel & Koornneef 1979). CO and [C II] maps of 30 Dor (Werner et al. 1978; Poglitsch et al. 1995) both show a similar morphology: the central star cluster R136 illuminates two molecular condensations located northeast and southwest of it. Our observations were pointed toward the northern component, 30 Dor North. The integrated CO intensity in the AST/RO 492 GHz beam is ~3 K km s^{-1} (Poglitsch et al. 1995), which when combined with our observations yields an intensity ratio $I_{[\rm C\,I]}/I_{\rm CO} \sim 0.1$.

This ratio is similar to the intensity ratio for the Milky Way, but 30 Dor is a peculiar region subjected to an extreme UV field. The increased UV hardness will enhance photoionization of C^0 over photodissociation of CO, diminishing the size of the PDR and reducing the $I_{[\rm C\,I]}/I_{\rm CO}$ ratio. Under normal conditions, this ratio is not sensitive to the hardness of the radiation field because of the similarity of the photodissociation potential of CO (11.09 eV) and the photoionization potential of C^0 (11.3 eV). Under the extreme conditions of 30 Dor, however, this difference may be significant enough to affect the intensity ratio.

4. CONCLUSIONS

The intensity ratio for N159-W, $I_{[\rm C\,I]}/I_{\rm CO} \approx 0.26$, is higher than the average $I_{[\rm C\,I]}/I_{\rm CO} \approx 0.13$ in the Galaxy (Wright et al. 1991) by a factor ~2, suggesting that this ratio is indeed enhanced in metal-poor systems. Theoretical arguments support the idea of a higher-than-Galactic ratio for spatially unresolved observations of PDRs in low-metallicity environments, since the size of the region where [C I] is dominant is enlarged while the CO clump sizes are diminished.

For 30 Dor-N, we find $I_{[\rm C\,I]}/I_{\rm CO} \sim 0.1$, a typical Milky Way value. The 30 Dor region is unusual, however, with an extremely hard and intense UV field; it has no equivalent in our own Galaxy. Therefore, the lower ratio measured for 30 DorN cannot be taken as representative of the low-metallicity ISM in the Large Magellanic Cloud.

We thank J. Zmuidzinas and T. Phillips for the 492 GHz SIS mixer. We thank J. Ingalls and M. Huang for helpful discussions. We thank the 1995 winter-over crew at South Pole station and the Antarctic Support Associates team. This research was supported by the National Science Foundation under a cooperative agreement with the Center for Astrophysical Research in Antarctica (CARA), grant number NSF OPP 89-20223. CARA is a National Science Foundation Science and Technology Center.

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., et al. 1997, in preparation
Chamberlin, R. A., Lane, A. P., & Stark, A. A. 1997, ApJ, 476, 428
Cohen, R. S., Dame, T. M., Garay, G., Montani, J., Rubio, M., & Thaddeus, P. 1988, ApJ, 331, L95
Engargiola, G., Zmuidzinas, J., & Lo, K.-Y. 1994, Rev. Sci. Instrum., 65, 1833
Garay, G., Rubio, M., Johansson, L. E. B., & Thaddeus, P. 1993, A&A, 274, 743
Genzel, R., Harris, A. I., Jaffe, D. T., & Stutzki, J. 1988, ApJ, 332, 1049
Henize, K. G. 1955, ApJS, 2, 315
Israel, F. P. 1988, in Millimetre and Submillimetre Astronomy, ed. R. D. Wolstencroft & W. B. Burton (Dordrecht: Kluwer), 281
Israel, F. P., et al. 1993, A&A, 276, 25
Israel, F. P., & Koornneef, J. 1979, ApJ, 230, 390
Israel, F. P., Maloney, P. R., Geis, N., Hermann, F., Madden, S. C., Poglitsch, A., & Stacey, G. J. 1996, ApJ, 465, 738
Israel, F. P., Tacconi, L. J., & Baas, F. 1995, A&A, 295, 599
Johansson, L. E. B., Olofsson, H., Hjalmarson, Å., Gredel, R., & Black, J. H. 1994, A&A, 291, 89
Kennicutt, R. C. 1984, ApJ, 287, 116
Lane, A. P., & Stark, A. A. 1996, Antarctic J. U.S., 30 (5), 377
Lequeux, J., Le Bourlot, J., Pineau des Forêts, G., Roueff, E., Boulanger, F., & Rubio, M. 1994, A&A, 292, 371
Maloney, P. 1990, in The Interstellar Medium in Galaxies, ed. H. A. Thronson & J. M. Shull (Dordrecht: Kluwer), 493
Maloney, P., & Black, J. H. 1988, ApJ, 325, 389
Mills, B. Y., & Turtle, A. J. 1984, in IAU Symp. 108, Structure and Evolution of the Magellanic Clouds, ed. S. van den Bergh & K. S. de Boer (Dordrecht: Reidel), 283
Minchin, N. R., White, G. J., & Padman, R. 1993, A&A, 277, 595
Mochizuki, K., et al. 1994, ApJ, 430, L37
Plume, R. 1995, Ph. D. thesis, Univ. of Texas
Plume, R., Jaffe, D. T., & Keene, J. 1994, ApJ, 425, L49
Poglitsch, A., et al. 1995, ApJ, 454, 293
Rubio, M., Lequeux, J., & Boulanger, F. 1993, A&A, 271, 9
Schieder, R., Tolls, V., & Winnewisser, G. 1989, Exp. Astron., 1, 101
Stacey, G. J., Geis, N., Genzel, R., Lutgen, J. B., Poglitsch, A., Sternberg, A., & Townes, C. H. 1991, ApJ, 373, 423
Stark, A. A., et al. 1994, Antarctic J. U.S., 29, 344
———. 1997, in preparation
Stark, A. A., Chamberlin, R. A., Cheng, J., Ingalls, J. G., & Wright, G. 1997, Rev. Sci. Instrum., in press
Tacconi, L. J., & Young, J. S. 1987, ApJ, 322, 681
Tauber, J. A., Lis, D. C., Keene, J., Schilke, P., & Buttgenbach, T. H. 1995, A&A, 297, 567
van Dishoeck, E. F., & Black, J. H. 1988, ApJ, 334, 771
Verter, F., & Hodge, P. W. 1995, ApJ, 446, 616
Werner, M. W., Becklin, E. E., Gatley, I., Ellis, M. J., Hyland, A. R., Robinson, G., & Thomas, J. A. 1978, MNRAS, 184, 365
Wilson, C. D. 1995, ApJ, 448, L97
Wright, E. L., et al. 1991, ApJ, 381, 200
Zmuidzinas, J., & Le Duc, H. G. 1993, IEEE Trans. Microwave Theor. & Tech., 40, 1797