Atomic Carbon Emission from Individual Molecular Clouds in M33

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ABSTRACT

We present observations of the 492 GHz [CI] emission for four individual giant molecular clouds in the Local Group galaxy M33 obtained with the James Clerk Maxwell Telescope. The average [CI] to CO \( J=1-0 \) integrated intensity ratio of 0.10 ± 0.03 is similar to what is observed in Galactic molecular clouds but smaller than what is seen in starburst galaxies. Similarly, the column density ratio \( N(C)/N(CO) \) is similar to that observed in the Orion Bar, but smaller than values obtained for starburst galaxies. The [CI] line is found to be a more important coolant than the lowest three rotational transitions of CO for all the clouds in the sample. The [CI] luminosity does not appear to be enhanced significantly in two low-metallicity clouds, which may be due to the unusual ionization environment of the clouds.

Subject headings: HII regions – galaxies: individual (M33) – galaxies: ISM – galaxies: Local Group – ISM: individual (NGC 604) – ISM: molecules

1. Introduction

The amount and distribution of atomic and ionized carbon are important for understanding the physical and chemical structure of molecular clouds, as well as the effect of star formation in changing that structure. Since the energy required to ionize carbon (11.3 eV) is close to that required to photo-dissociate CO (11.09 eV), [CI] emission should exist over a fairly narrow range of column densities, sandwiched between regions where the carbon is predominantly ionized and regions where it is bound up in CO (Tielens & Hollenbach 1985). However, early results for the edge-on photo-dissociation region (PDR)

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in M17 revealed that the [CI] emission is quite extended (Keene et al. 1985), while a more recent $25 \times 25'$ map of S140 has confirmed that the atomic carbon emission can be very extended indeed (Plume, Jaffe, & Keene 1994). One interpretation for the large extent of the [CI] emission is that the internal structure of molecular clouds is clumpy, which allows ultraviolet radiation to reach deep into the cloud. High-resolution maps in [CI] of a small area near the PDR in M17 demonstrate that the [CI] emission occurs on the edges of high-density clumps (White & Padman 1991) and provide direct confirmation that the clumpy structure of the cloud is important to understanding the origin of the [CI] emission.

The large extent of the [CI] emission in molecular clouds raises the question of whether a PDR powered by nearby massive star formation is necessary to produce significant [CI] emission in a molecular cloud. Because the [CI] emission is relatively insensitive to the intensity of the ultraviolet radiation field (Hollenbach, Tielens, & Takahashi 1991), a substantial amount of atomic carbon could exist even in molecular clouds heated by the interstellar radiation field. Indeed, relatively large column densities of atomic carbon are observed towards high latitude clouds (Stark & van Dishoeck 1994). Thus, rather than being confined to a small region near the PDR, atomic carbon could be present on the entire surface of the cloud, or even throughout the cloud depending on the self-shielding of the clumps and the amount of attenuation provided by the interclump medium. In addition, chemical processes involving $\text{H}^+$ may be able to produce significant amounts of atomic carbon throughout the cloud (Pineau des Forêts, Roueff, & Flower 1992).

Observations of the total [CI] emission from individual clouds are the best way to determine just how widespread atomic carbon is in molecular clouds. Unfortunately, large-area maps of [CI] emission are very time consuming to obtain with the small beams of most submillimeter telescopes (see Plume et al. 1994 for an interesting counter-example). However, the beams of the largest submillimeter telescopes are sufficiently small that they can isolate individual molecular clouds in galaxies in the Local Group. Indeed, [CI] emission has been detected recently in the LMC using a beam subtending 34 pc (Stark et al. 1997). This paper presents the results of [CI] observations obtained for four individual molecular clouds in the Local Group spiral galaxy M33.

2. Observations and Data Reduction

Four giant molecular clouds in M33 were observed with the James Clerk Maxwell Telescope (JCMT) in the $^3P_1 - ^3P_0$ fine structure line of atomic carbon on 1995 October 29. The half-power beamwidth of the JCMT at 492 GHz is $11''$ or 45 pc at the distance of M33 (0.84 Mpc, Freedman, Wilson, & Madore 1991). The clouds were selected from the
interferometric samples of Wilson & Scoville (1990, 1992). The observations were obtained by position-switching with an offset of < 25′ to a point outside the HI disk of the galaxy. The total integration time per cloud was 50 to 70 minutes. The data were binned to a resolution of 2 MHz (1.22 km s\(^{-1}\)) and first order baselines (fifth for MC 20) were removed. All data were converted to the main beam temperature scale using the main beam efficiency at 492 GHz published in the JCMT User’s Guide (\(\eta_{MB} = 0.52\)). The absolute calibration was checked by observing the source W75N which had a peak temperature of 12.1 K and an integrated intensity of 58.1 K km s\(^{-1}\). This peak temperature is \(\sim\)20% smaller than the peak of 14 K found in standard JCMT reference spectra. The spectra are shown in Figure 1 and the measured [CI] properties are given in Table 1.

The integrated intensity for each cloud was measured by integrating over the full width of the [CI] line, which for all clouds except MC 20 was somewhat smaller than the width of the CO J=2-1 line observed with a 22″ beam at the JCMT (Wilson, Walker, & Thornley 1997). Assuming the [CI] emission is optically thin, the atomic carbon column density is given by

\[
N(C) = 2 \times 10^{15} \left( e^{23.6/T_{ex}} + 3 + 5 e^{-38/T_{ex}} \right) \int T_{MB} dv \text{ cm}^{-2}
\]

(Phillips & Huggins 1981), where \(T_{ex}\) is the excitation temperature of the [CI] line and \(\int T_{MB} dv\) is the integrated intensity of the [CI] line. The minimum column density is obtained for \(T_{ex} = 24\) K, while \(N(C)\) is a factor of two larger if \(T_{ex} = 10\) K and only 15% larger if \(T_{ex} = 100\) K. For the excitation temperature we have adopted the kinetic temperature derived from a large velocity gradient (LVG) analysis of the low-J CO lines (Wilson et al. 1997). For two clouds (MC 20 and NGC 604-2), the LVG analysis gives a range of kinetic temperature; we have adopted the minimum temperature, which minimizes both the atomic carbon and CO column densities. Finally, since the sizes of the clouds are known from the CO interferometer surveys, we have also corrected \(N(C)\) by the beam filling factor, \(f = (\bar{D}/11′′)^2\), where \(\bar{D}\) is the average full-width half-maximum diameter of the cloud (Wilson & Scoville 1990, 1992).

To calculate the [CI] to CO integrated intensity ratio, \(I_{[CI]}/I_{CO}\), we used the published interferometric measurements of the CO J=1-0 transition (Wilson & Scoville 1990, 1992). The data were converted from Jy to K using the conversion factor appropriate for each interferometric beam (\(\sim 0.6\) Jy/K). In addition, since the beam of the interferometer data is typically 8″ × 7″, smaller than the 11″ beam of the JCMT [CI] data, the CO data were scaled by the relative beam areas to obtain temperatures appropriate for an 11″ beam. The \(\text{H}_2\) masses were calculated from the CO integrated intensities using the calibration of Wilson (1995) to obtain a CO-to-\(\text{H}_2\) conversion factor appropriate for the metallicity of each cloud.
3. Atomic Carbon Content of the Molecular Clouds in M33

The average $[\text{CI}]$ to CO integrated intensity ratio for this sample of four clouds in M33 is $0.10 \pm 0.03$. This line ratio is similar to that observed in Galactic molecular clouds, where the $^{13}\text{CO} J=1-0$ and $[\text{CI}]$ line intensities are comparable (Tauber et al. 1995). This line ratio is lower than most values observed in other galaxies, which are typically in the range of 0.1-0.3 (Table 2). However, most measurements of $I_{[\text{CI}]}/I_{\text{CO}}$ have been of starburst galaxies, where the physical conditions are likely to be quite different. The observations of M33 and the Milky Way suggest that $I_{[\text{CI}]}/I_{\text{CO}}$ is likely to be somewhat smaller in normal galaxies than in starburst galaxies.

The $[\text{CI}]$ to CO integrated intensity ratio for the clouds in M33 ranges from 0.04 to 0.18 (Table 1). For example, the $[\text{CI}]$ emission is four times stronger in MC 20 than in MC 32 despite their very similar masses and metallicities. Thus, we are seeing a real and significant variation in the $[\text{CI}]$ luminosity per unit mass from one cloud to another in M33. Recent observations of the LMC reveal similar line ratio variations (Stark et al. 1997). The higher $[\text{CI}]$ luminosity of MC 20 is likely due to the presence of a nearby HII region (Wilson & Scoville 1991), which probably produces a face-on PDR on the surface of the cloud. The two clouds near NGC 604 show a similar trend, with NGC 604-2, which is closest to the giant HII region, having a larger $[\text{CI}]$ luminosity than NGC 604-4.

The column density ratio $N(C)/N(\text{CO})$ for three of the clouds is comparable to that observed in the Orion Bar, but somewhat smaller than that observed in S140 and in several starburst galaxies (Table 2). The column density ratio is substantially lower for NGC 604-2, which is subject to the most intense radiation field. Unlike 30 Doradus in the LMC, where the $[\text{CI}]$ emission is genuinely weak, the low $N(C)/N(\text{CO})$ ratio in NGC 604-2 is due to a large CO column density rather than a lack of $[\text{CI}]$ emission. This large value of $N(\text{CO})$ arises from the high kinetic temperature derived for NGC 604-2 (Wilson et al. 1997). Given the unusual location of NGC 604-2 near the ionizing star cluster of a giant HII region, it is quite likely that there is more than one kinetic temperature component in this cloud. If the strong CO $J=3-2$ emission in this cloud originates in a small amount of hot gas while the lower transitions arise in a cooler component (i.e. Wilson et al. 1997), the CO column density obtained from the LVG analysis could be significantly overestimated.

There are a few possible sources of systematic error in our column density analysis. First, although we have assumed the same beam-filling factors for the CO and $[\text{CI}]$ emission, the $[\text{CI}]$ emission could be confined to a small portion of the cloud, in which case $N(C)$ would be underestimated. This effect is likely to be most important for the two clouds in NGC 604, which are subject to edge-on heating by the giant HII region. Second, by adopting the lowest kinetic temperature solution for MC 20 and NGC 604-2, both $N(C)$ and
$N(CO)$ may be underestimated. Since $N(CO)$ is much more sensitive to temperature than $N(C)$, the net result would be an overestimate of $N(C)/N(CO)$. Third, recent observations of the $^3P_2 - ^3P_1$ 809 GHz line of $[\text{Cl}]$ in M82 suggest that the optical depth in both $[\text{Cl}]$ lines may be close to unity (Stutzki et al. 1997). If the optical depths toward the M33 clouds are significant, $N(C)$ would again be underestimated. However, these effects are unlikely to be large enough to bring the M33 line ratios into agreement with the starburst line ratios.

Since MC 32 is located $\sim 120$ pc from the nearest HII region, its atomic carbon is likely produced either by ionization by the interstellar radiation field (Hollenbach et al. 1991) or perhaps by low density equilibrium chemistry (Pineau des Forêts et al. 1992). The atomic carbon column density observed in MC 32 is $\sim 3$ times smaller than the column density predicted by models of low-intensity PDRs ($N(C) \sim 10^{17}$ cm$^{-2}$ for $G/G_0 = 1$ and $n = 10^4$ cm$^{-3}$, Hollenbach et al. 1991). However, these models assume a solar gas-phase carbon abundance i.e. there is no depletion of carbon onto dust grains. Models of translucent clouds ($1 < A_V < 5$) assuming some depletion onto dust grains give atomic carbon column densities similar to what is observed for MC 32 and NGC 604-4 (van Dishoeck & Black 1988, Spaans 1996). The atomic carbon column densities for MC 20 and NGC 604-2 agree quite well with dense PDR models with moderate gas-phase carbon depletion ($N(C) \sim 1 - 6 \times 10^{17}$ cm$^{-2}$, van Dishoeck & Black (1988), but are again somewhat smaller than undepleted models ($N(C) \sim 4 \times 10^{17} - 2 \times 10^{18}$ cm$^{-2}$, Tielens & Hollenbach 1985).

We have used our $[\text{Cl}]$ data to estimate the relative importance of the $[\text{Cl}]$ and CO lines to the cooling of molecular clouds. Since the CO J=2-1 and J=3-2 measurements of these clouds were made with larger beams (Wilson et al. 1997), we have chosen to scale the CO J=1-0 intensity in Table 1 by the average CO J=2-1/J=1-0 line ratio measured in M33 (0.67, Thornley & Wilson 1994) and by the CO J=3-2/J=2-1 line ratios appropriate for the individual clouds (Wilson et al. 1997). With all the data now referred to the same beam, the integrated intensity ratios can then be scaled by $(\nu_1/\nu_2)^3$ to convert from K km s$^{-1}$ to erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$. For all four clouds, the cooling in the $[\text{Cl}]$ line exceeds that of the CO lines, by a factor of 1.5 for MC 32, $\sim 3$ for the NGC 604 clouds, and 7 for MC 20. The variations in the relative importance of the $[\text{Cl}]$ cooling are primarily due to variations in the intensity of the $[\text{Cl}]$ line. As expected, $[\text{Cl}]$ cooling is most important for MC 20, the cloud with a face-on PDR. However, the case of MC 32 shows that the 492 GHz line of $[\text{Cl}]$ is an important coolant even for quiescent clouds without bright PDRs.

Since atomic carbon may be more closely associated with atomic than molecular hydrogen, it is important to consider the atomic hydrogen content of the clouds. For MC 20, the total mass of atomic hydrogen is $1.5 \times 10^4$ M$_\odot$, or about 5% of the H$_2$ mass, and is offset from the peak of the molecular gas by $\sim 70$ pc (Wilson & Scoville 1991). Since the atomic
carbon measurement was made towards the CO peak, it seems very likely that, for MC 20, substantial atomic carbon is located in regions that contain predominantly molecular rather than atomic hydrogen, as is predicted by the dense PDR models of Sternberg & Dalgarno (1995). This conclusion is similar to recent results for ionized carbon in the LMC (Poglitsch et al. 1995), which appears to be associated with molecular rather than atomic hydrogen.

The column density ratio $N(C)/N(H_2)$ is smaller by a factor of 2-3 in clouds with an oxygen abundance reduced by 2.5 (Table 1; compare MC 20 with NGC 604-2 and MC 32 with NGC 604-4). This good correlation of $N(C)/N(H_2)$ with oxygen abundance suggests that the [CI] emission is at least marginally optically thin and we are seeing the effect of the changing carbon abundance in the clouds. In this case, the trend of carbon with oxygen in M33 would be more consistent with Galactic measurements, which show a constant C/O ratio as the oxygen abundance decreases, than with measurements of dwarf galaxies, where the carbon abundance falls more quickly than the oxygen abundance (Garnett et al. 1995). The low metallicity of the two NGC 604 clouds could be responsible for some of the observed variation in the $I_{[CI]}/I_{CO}$ ratios in M33. Lowering the metallicity by a factor of 2.5 reduces the CO line strengths by a factor of $\sim 1.9$ (Wilson 1995). Assuming the [CI] intensity is linearly proportional to the metallicity, the net result would be to reduce $I_{[CI]}/I_{CO}$ for the NGC 604 clouds by a factor of 1.3 compared to MC 20.

It is often expected that the size of the PDR will be larger in low metallicity regions, due to reduced self-shielding and shielding by dust (i.e. Poglitsch et al. 1995). This effect is observed in the LMC, where the [CI] emission appears enhanced at most of the positions observed to date (Stark et al. 1997; Bania, private communication). However, note that $I_{[CI]}/I_{CO}$ is what is observed to be enhanced in the LMC; correcting for the lowered CO emission due to the metallicity of the LMC would bring this ratio in good agreement with the Milky Way value. One interesting result of our study is that the two low-metallicity clouds in NGC 604 have slightly smaller [CI] luminosities than the more metal rich cloud MC 20. The weak [CI] emission could be attributed to the intense ionization in the vicinity of the giant HII region, which may tend to convert the atomic carbon into ionized carbon (see the discussion of 30 Doradus in Stark et al. 1997). Other competing factors such as a drop in the absolute abundance of carbon may be complicating the picture as well.

4. Conclusions

We have detected [CI] emission from four individual giant molecular clouds in the Local Group spiral galaxy M33. The average [CI] to CO J=1-0 integrated intensity ratio is $0.10 \pm 0.03$, similar to what is observed in Galactic clouds but somewhat lower than
in starburst galaxies. The \([\text{CI}]\) emission is observed to be stronger for clouds associated with optical HII regions. The column density ratio \(N(C)/N(CO)\) for three of the clouds is similar to that observed in the Orion Bar, but smaller than in starburst galaxies. The cloud nearest the giant HII region NGC 604 has a value of \(N(C)/N(CO)\) that is five times smaller than the other clouds. This small column density ratio can be traced to a high CO column density rather than a low atomic carbon column density. The atomic carbon column densities for all clouds are in reasonable agreement with predictions from photo-dissociation region models. The cooling by the 492 GHz \([\text{CI}]\) line dominates the cooling in the lowest three rotational transitions of CO, and is important even for clouds without active star formation. Contrary to expectations, the \([\text{CI}]\) luminosity does not appear to be enhanced in two clouds with lower metallicities. The unusual ionization environment of the clouds or a drop in the absolute abundance of carbon may be complicating the analysis.

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REFERENCES

Fig. 1.— $^3P_1 -^3P_0$ [CI] spectra for individual molecular clouds in M33 are shown as the heavy line. The beam of the [CI] observations is 11′′. The $^{12}$CO J=2-1 spectra obtained with a 22″ beam are shown for comparison (thin line).
Table 1. Atomic Carbon Emission from Molecular Clouds in M33

<table>
<thead>
<tr>
<th>Cloud</th>
<th>MC 20</th>
<th>MC 32</th>
<th>NGC 604-2</th>
<th>NGC 604-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{[CI]}^a$ (K km s$^{-1}$)</td>
<td>6.0 ± 0.7</td>
<td>1.5 ± 0.4</td>
<td>2.8 ± 0.4</td>
<td>1.6 ± 0.3</td>
</tr>
<tr>
<td>$I_{[CI]}/I_{CO}^b$</td>
<td>0.18 ± 0.05</td>
<td>0.042 ± 0.014</td>
<td>0.10 ± 0.03</td>
<td>0.062 ± 0.017</td>
</tr>
<tr>
<td>$M_{H_2}$ (10$^5$ M$_\odot$)</td>
<td>3.8</td>
<td>3.8</td>
<td>6.3</td>
<td>5.5</td>
</tr>
<tr>
<td>12+log(O/H)$^c$</td>
<td>8.89</td>
<td>8.89</td>
<td>8.48</td>
<td>8.48</td>
</tr>
<tr>
<td>H$\alpha$ flux$^d$</td>
<td>≥ 1</td>
<td>0.05</td>
<td>4.8</td>
<td>0.95</td>
</tr>
<tr>
<td>$f^e$</td>
<td>0.78</td>
<td>1</td>
<td>0.56</td>
<td>0.93</td>
</tr>
<tr>
<td>$T_{ex}^f$ (K)</td>
<td>20</td>
<td>10</td>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>$N(CO)^f$ (10$^{17}$ cm$^{-2}$)</td>
<td>7</td>
<td>3</td>
<td>30</td>
<td>3</td>
</tr>
<tr>
<td>$N(C)$(10$^{16}$ cm$^{-2}$)</td>
<td>11</td>
<td>4.3</td>
<td>8.0</td>
<td>4.8</td>
</tr>
<tr>
<td>$N(C)/N(H_2)^g$ (10$^{-6}$)</td>
<td>11</td>
<td>6.5</td>
<td>3.5</td>
<td>3.4</td>
</tr>
<tr>
<td>$N(C)/N(CO)^h$</td>
<td>0.16</td>
<td>0.14</td>
<td>0.03</td>
<td>0.16</td>
</tr>
</tbody>
</table>

$^a$Uncertainties are the formal measurement uncertainties only; the 20% absolute calibration uncertainty is not included.

$^b$Ratio uses the CO J=1-0 line. The uncertainties are calculated assuming a 20% calibration uncertainty in each line.


$^d$Relative H$\alpha$ flux (erg s$^{-1}$ cm$^{-2}$) normalized to the flux of MC 20. Adopted H$\alpha$ luminosities and projected distances from the molecular clouds are: for MC 20, 1.1 × 10$^{38}$ erg s$^{-1}$ and 25 pc; for MC 32, 1.4 × 10$^{38}$ erg s$^{-1}$ (to MC 35 HII region) and 25 pc; for NGC 604-2, 5.6 × 10$^{39}$ erg s$^{-1}$ and 80 pc; for NGC 604-4, 5.6 × 10$^{39}$ erg s$^{-1}$ and 180 pc (Wilson & Scoville 1991, 1992).


$^f$Only the lowest possible excitation temperature and $N(CO)$ are given for MC 20 and NGC 604-2 (Wilson et al. 1997).

$^g$H$_2$ column densities are area-averaged values calculated from the H$_2$ mass and the area of the cloud.
Table 2. Comparison with Previous [CI] Observations

<table>
<thead>
<tr>
<th>Source</th>
<th>$I_{[CII]}/I_{CO}^a$</th>
<th>$N(C)/N(CO)$</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>M82</td>
<td>0.11</td>
<td>0.5</td>
<td>Schilke et al. 1993, Stutzki et al. 1997</td>
</tr>
<tr>
<td>IC 342</td>
<td>0.17</td>
<td>...</td>
<td>Büttgenbach et al. 1992</td>
</tr>
<tr>
<td>NGC 253</td>
<td>0.30</td>
<td>0.2-0.3</td>
<td>Israel et al. 1995</td>
</tr>
<tr>
<td>Cloverleaf</td>
<td>0.18$^b$</td>
<td>$\sim 1$</td>
<td>Barvainis et al. 1997</td>
</tr>
<tr>
<td>Milky Way</td>
<td>0.16$^c$</td>
<td>...</td>
<td>Wright et al. 1991</td>
</tr>
<tr>
<td>LMC</td>
<td>0.1,0.26</td>
<td>...</td>
<td>Stark et al. 1997</td>
</tr>
<tr>
<td>M33</td>
<td>0.04-0.18</td>
<td>0.03-0.16</td>
<td>this paper</td>
</tr>
<tr>
<td>Orion</td>
<td>...</td>
<td>0.17</td>
<td>Tauber et al. 1995</td>
</tr>
<tr>
<td>S140</td>
<td>...</td>
<td>0.5</td>
<td>Plume et al. 1994</td>
</tr>
</tbody>
</table>

$^a$CO J=1-0 line. Integrated intensities are in units of K km s$^{-1}$.

$^b$CO J=3-2 line.

$^c$Calculated from the CO J=2-1 line assuming a CO J=2-1/J=1-0 ratio of 0.7 (Sakamoto et al. 1994).