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ATOMIC CARBON IN M82

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ABSTRACT

We report observations of C I($^3P_1$–$^3P_0$) emission at 492 GHz toward the starburst galaxy M82. Both the C I/C II intensity ratio and the C/CO column density ratio are a factor of 2–5 higher than observed toward Galactic photodissociation regions (PDRs) or predicted by PDR models. We argue that current PDR models are insufficient to explain the observations, and propose that some of the emission is due to atomic carbon existing within molecular clouds. Employing new chemical models, which use a fast H_3^+ dissociative recombination rate, we find that enhanced cosmic-ray flux supplied by supernova remnants in the M82 starburst lead to an enhanced atomic carbon abundance and elevated temperatures deep within the molecular clouds, resulting in a higher C I emissivity than found in previous PDR models.

Subject headings: galaxies: abundances — galaxies: individual (M82) — galaxies: ISM — galaxies: starburst — radio lines: galaxies

1. INTRODUCTION

M82 has attracted attention as a nearby example of a starburst galaxy. Numerous studies of continuum and lines in the X-ray, optical, infrared, and radio wavelength ranges have been carried out (see reviews in Carlstrom & Kronberg 1991; Kronberg 1988; Sofue 1988; and Telesco 1988). The interstellar medium in the inner region has been investigated using single-dish millimeter and submillimeter telescopes (Sutton, Masson, & Phillips 1983; Olofsson & Rydbeck 1984; Baan et al. 1990; Nakai et al. 1987; Loiseau et al. 1990; Tilanus et al. 1991; Wild et al. 1992; Güsten et al. 1993; Harris et al. 1991) and millimeter interferometers (Lo et al. 1987; Carlstrom 1988a; Brouillet & Schilke 1993) to observe molecular gas, and the Kuiper Airborne Observatory (KAO) to observe fine-structure transitions of atoms and atomic ions (Watson et al. 1984a; Watson, Stanger, & Griffiths 1984; Lugten et al. 1986).

These studies revealed that the starburst has heavily influenced the interstellar medium of the inner part of M82 by producing high cosmic-ray and UV fluxes, thus creating a low-density ionized component filling a substantial fraction of the volume, as traced by H II. The molecular gas is found to be embedded in this component in the form of many small dense (a few times 10^5 cm^{-3}) and warm (50 K) cores, as traced by CO, CS, and HCN. At the interface of the molecular and ionized gas hot (200–400 K), moderately dense ($\approx 10^4$ cm^{-3}) atomic gas is found, as observed by the O I and C II fine-structure transitions. Emission from low-to moderate-density molecular gas, which dominates the molecular gas mass in our Galaxy, seems to be less important in M82.

An important cornerstone of this picture was missing: atomic carbon, which has previously been observed toward only one extragalactic object, IC 342 (Büttgenbach et al. 1992). It was thought to exist primarily in the transition zone between the ionized and molecular phases, according to current models of photodissociation regions (PDRs) (e.g., Tielens & Hollenbach 1985; Wolfire, Tielens, & Hollenbach 1990). However, new PDR models using a revised recombination rate for H_3^+ suggest large amounts of atomic carbon inside molecular gas even in the absence of adequate UV flux (Flower et al. 1993). Here we report the first observations of the C I($^3P_1$–$^3P_0$) line at 492 GHz toward the inner region of M82.

2. OBSERVATIONS

Atomic carbon at 492.2607 GHz has been observed on 1992 30 January and 1993 May 26–30 with the Caltech Submillimeter Observatory (CSO) at Mauna Kea, Hawaii. The beam size at this frequency is 15″. We used the 492 GHz facility receiver (Walker et al. 1992) and the CSO 1024 channel AOS with 584 MHz bandwidth (354 km s^{-1} at 492 GHz). The typical double-sideband (DSB) system temperatures were around 4200 K. As a center position we adopted the 2.2 μm peak of Dietz et al. (1989), $\alpha(1950) = 9^h51^m43^s.5$, $\delta(1950) = 69°55'01''$. The beam efficiency was 35% for the 1992 run, but 50% for the 1993 run due to improvements in the surface of the CSO. The bandwidth is insufficient to cover the velocity spread of emission at the central position, so for this position we centered the backend on two different velocities 300 km s^{-1} apart, to obtain a total bandwidth of 1 GHz (650 km s^{-1}). The 50 km s^{-1} overlap was sufficient to check the matching of the two parts of the spectrum after a zero-order baseline had been subtracted. For the other positions, a single velocity setting was sufficient.

3. RESULTS

We observed C I toward five positions in the center of M82: three located in the plane of the galaxy, where strong, bright CO and many other molecules have been observed, and two positions south of the plane, where weak diffuse emission in a variety of molecules has been detected [Sutton et al. 1983 in CO(2–1), Carlstrom 1988a in CO(1–0) and HCO$^+$(1–0), and Brouillet & Schilke 1993 in HCN(1–0)] (see Fig. 1). C I has been detected toward all positions. Table 1 lists the calculated intensities and column densities and the line parameters as calculated by Gaussian fits to the spectra. Intensities and

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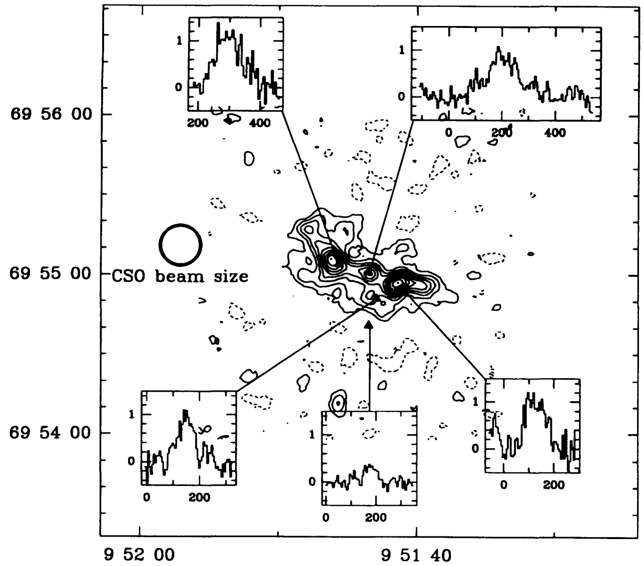

FIG. 1.—CO(1–0) map and C I spectra toward M82. The center position is the 2.2 μm peak of Dietz et al. (1989), $\alpha(1950) = 9^h51^m43^s.5$, $\delta(1950) = 69°55'01''$. The CO(1–0) map is the BIMA map of Carlstrom (1988b) with 5″ resolution. The CSO beam size is indicated.

column densities are derived from (Phillips & Huggins 1981)

$$I(\text{C I}) = 1.22 \times 10^{-7} \int T_{\text{MB}}\, dv \quad (\text{ergs cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1})\,, \quad (1)$$

$$N(\text{C I}) = 1.9 \times 10^{15} \int T_{\text{MB}}\, dv\, e^{E_1/kT_{\text{ex}}} Q \quad (\text{cm}^{-2}) \quad (2)$$

where the partition function is given by

$$Q = 1 + 3e^{-E_1 kT_{\text{ex}}} + 5e^{-E_2/kT_{\text{ex}}}\,, \quad (3)$$

E_1 is the energy of the $J = 1$ level (23.6 K), E_2 is the energy of the $J = 2$ level (62.5 K), the integrated intensity is in units of K km s^{-1}, and optically thin emission is assumed. The critical density for C I is 10^3 cm^{-3} (Nussbaumer & Rusca 1979; Schröder et al. 1991), hence we can safely assume thermalization. For the excitation temperature T_{ex} we have taken 24 K, since this gives a lower limit for the C I column density. For lower excitation temperatures the calculated column density increases (by 105% for $T_{\text{ex}} = 10$ K); for higher excitation temperatures the calculated column density increases insignificantly (by 4% for $T_{\text{ex}} = 50$ K). The column density is also a lower limit by virtue of the optically thin assumption.

We compare our C I column densities with CO column densities derived by Wild et al. (1992) in a 13″ beam. They calculate typical C^{18}O column densities of 10^{16} cm^{-2}, assuming an excitation temperature of 40 K, which leads to a ^{12}CO column density of 5×10^{18} cm^{-2} adopting ^{16}O/^{18}O = 500. This may be too high, since observations suggest that the ^{16}O/^{18}O ratio may be as low as 150–250 in galactic center regions (Henkel & Mauersberger 1993). Inspection of our table shows that a lower limit for the C/CO column density ratio lies in the range 0.1–0.3. The true value may exceed this lower limit by a factor of 2 or more, given the uncertainties of excitation temperature and optical depth of C I and the ^{16}O/^{18}O ratio.

To investigate the relative importance of C I and CO as coolants, we have to derive the total C I emission by estimating the contribution from the C I($^3P_2$–$^3P_1$) line at 809 GHz. The results of Zmuidzinas et al. (1988) suggest that line temperatures and line widths of this line are comparable to the C I($^3P_1$–$^3P_0$) line at 492 GHz. If this is the case, the total C I emission toward the center of M82 is about 8×10^{-5} ergs cm^{-2} s^{-1} sr^{-1}. A lower limit to the total CO intensity is obtained by adding up the intensities of all measured CO lines toward the center position (J = 1–0 through J = 6–5, with the exception of J = 5–4), giving 1.3×10^{-4} ergs cm^{-2} s^{-1} sr^{-1}. The J = 6–5 line shows the highest intensity of all observed CO lines, and therefore we expect a substantial contribution from the higher rotational transitions. Thus, in M82 CO is a more important coolant than C I, in contrast to our Galaxy, where the *COBE* results suggest that the integrated CO intensity is slightly less than the C I intensity (Wright et al. 1991). This is due to the fact that the temperature in M82 is higher than in our Galaxy, so that the higher CO levels can contribute significantly to the total cooling.

4. MODELS OF THE C I EMISSION

Wolfire et al. (1990) have modeled the C II, Si II, and O I emission toward M82 in terms of PDR models. They found a density of 10^5 cm^{-3} and a temperature of 370 ± 100 K for the dense ionized phase. To reproduce the observations, they needed a UV field enhanced by a factor of 10^4 relative to the standard Galactic field. They did not discuss atomic carbon, since no observational data were available at the time. The intensity of atomic carbon in the framework of the same models is discussed by Hollenbach, Takahashi, & Tielens (1991). Although their figures do not show exactly the values determined by Wolfire et al. (1990), inspection indicates a C I intensity [$\approx(1\text{–}2) \times 10^{-6}$ ergs cm^{-2} s^{-1} sr^{-1}] roughly one order of magnitude short of what we observed. As shown by the models of Hollenbach et al. (1991), the C I intensity is only weakly dependent on the UV field, because C I emits mostly in the very narrow transition zone between the ionized and the

TABLE 1

LINE AMPLITUDES, CENTER VELOCITIES, LINE WIDTHS, INTENSITIES, AND COLUMN DENSITIES FOR C I IN M82

Offset[a] (arcsec)	T_{MB} (K)	v_{LSR} (km s^{-1})	Δv (km s^{-1})	Intensity (10^{-6} ergs s^{-1} cm^{-2} sr^{-1})	N(C I) (10^{17} cm^{-2})
(−13, −6)[c]	1.1 ± 0.3	126 ± 3	84 ± 5	12.9 ± 1.1	14.8 ± 1.1
(0, −20)[c]	0.3 ± 0.1	178 ± 3	51 ± 6	2.3 ± 0.2	2.5 ± 0.3
(−3, −10)[d]	0.9 ± 0.3	149 ± 4	83 ± 11	9.2 ± 0.9	9.9 ± 0.9
(0, 0)[c]	0.8 ± 0.2	202 ± 3	146 ± 8	15.8 ± 0.7	17.2 ± 0.8
(11, 3)[d]	1.1 ± 0.3	297 ± 4	100 ± 8	14.6 ± 1.1	15.8 ± 1.2

[a] The offset is given in arcseconds relative to the 2.2 μm peak of Dietz et al. 1989 [$\alpha(1950) = 9^h51^m43^s.5$, $\delta(1950) = 69°55'01''$].

[b] The column densities were calculated using an excitation temperature of 24 K.

[c] Observed 1993.

[d] Observed 1992.

molecular gas. This means that some mechanism other than increased UV flux has to be evoked to enhance the column density of atomic carbon.

One possible explanation for the observed high C I intensities within the framework of the PDR models would be to have more than one PDR region along the line of sight. Given that we see M82 almost edge-on, this does not seem unlikely. However, although this may increase the absolute intensities, it should not alter the observed ratios of intensities and column densities for optically thin lines. The lines are likely to be optically thin, since the individual PDRs are shifted relative to one another in velocity space. Clumpy models (similar to those of Meixner & Tielens 1993) may be able to reproduce the observed intensity ratios using clump/interclump ratios and UV fields much more extreme than are present in M82. The fact that the C I/CO column density ratio and the C I/C II and C I/O I intensity ratios in M82 are higher than in regions in our Galaxy exposed to local UV fields of about the same strength as the global field in M82 remains to be explained by these PDR models and suggests an additional source of C I emission in M82.

Such a source of C I emission has been proposed recently by Pineau des Forêts, Roueff, & Flower (1992). Their model predicts, under certain circumstances, a high abundance of atomic carbon in molecular gas even in the absence of UV radiation. They predict two phases of the interstellar medium, one at low densities, where H^+ is the dominant ion and atomic carbon is abundant (C/CO ≈ 0.1), and a high-density phase where H_3^+ is the dominant ion and the atomic carbon abundance is much reduced (C/CO $< 10^{-3}$). The density at which the abrupt phase transition occurs is determined by the dissociative recombination of H_3^+, the rate of which is a matter of current debate. Using the fast recombination coefficient measured by Canosa et al. (1991), the transition takes place at a density of about $n_H = 5 \times 10^3$ cm^{-3} for Galactic interstellar conditions. In the low-density phase, H_3^+ is destroyed by electron recombination and the gas remains to some degree atomic, while in the high-density phase its main destruction paths are due to proton transfer, which initiates the standard ion-molecule chemistry. This transition point is a function of many physical parameters, including the cosmic-ray flux, oxygen and sulfur depletion, temperature, etc. In particular, an increased cosmic-ray flux shifts the transition density upward (Flower et al. 1993), resulting in a significant contribution by the cloud core to the C I column density.

It is evident that this may be a source of increased C I intensity in M82, since a high cosmic-ray rate is expected, based on strong synchrotron emission and high star formation and supernova rates (Rieke et al. 1980; Kronberg, Biermann, & Schwab 1985). By comparing star formation rates and synchrotron emissivities in M82 and in our Galaxy, Suchkov, Allen, & Heckman (1993) recently determined the cosmic-ray flux to be 170–500 times stronger in M82. The cosmic rays heat the dense gas, further contributing to the high C I intensity. High temperatures of the dense gas are consistent with observations; e.g., Güsten et al. (1993) found a component of the molecular phase with a temperature of 50 K and a density of 10^6 cm^{-3} on the basis of multilevel, multi-isotopomer observations of CO. Furthermore, M82 is the only galaxy in the sample of Nguyen-Q-Rieu et al. (1992) which shows a HCO^+/HCN ratio greater than 1. This has been interpreted by the authors as evidence for an enhanced cosmic-ray flux which increases the fractional ionization in general and the abundance of HCO^+ in particular. Quantitative estimates of the cosmic-ray flux just on the basis of the HCO^+ flux are difficult, since it is not the major ionic charge carrier. In the two-phase picture, the HCO^+ emission comes predominantly from the dense regions where ion-molecule chemistry dominates and the C/CO ratio is low.

To investigate the influence of an increased cosmic-ray flux and the H_3^+ dissociative recombination rate on the C I intensity, we ran a series of four models, based on the isochoric PDR models of Le Bourlot et al. (1992). Our first model, which we use as reference model, uses the parameters derived for M82 by Wolfire et al. (1990): $n = 10^5$ cm^{-3}, $G_0 = 10^4$, their elemental abundances, the standard Galactic cosmic-ray ionization rate $\zeta = 10^{-17}$ s^{-1}, and the slow H_3^+ dissociative recombination coefficient measured by Adams, Smith, & Alge (1984). We obtained a C I($^3P_1$–$^3P_0$) integrated intensity of $I(\text{C I}) = 5 \times 10^{-6}$ ergs cm^{-2} s^{-1} sr^{-1}, a factor of 3.5 below our highest observed value. We were able to reproduce the observed O I 63 μm and O I 145 μm fluxes within a factor of 2 (our calculated fluxes were higher by that amount) and the C II flux exactly (see Fig. 2, *top*). This demonstrates that the model

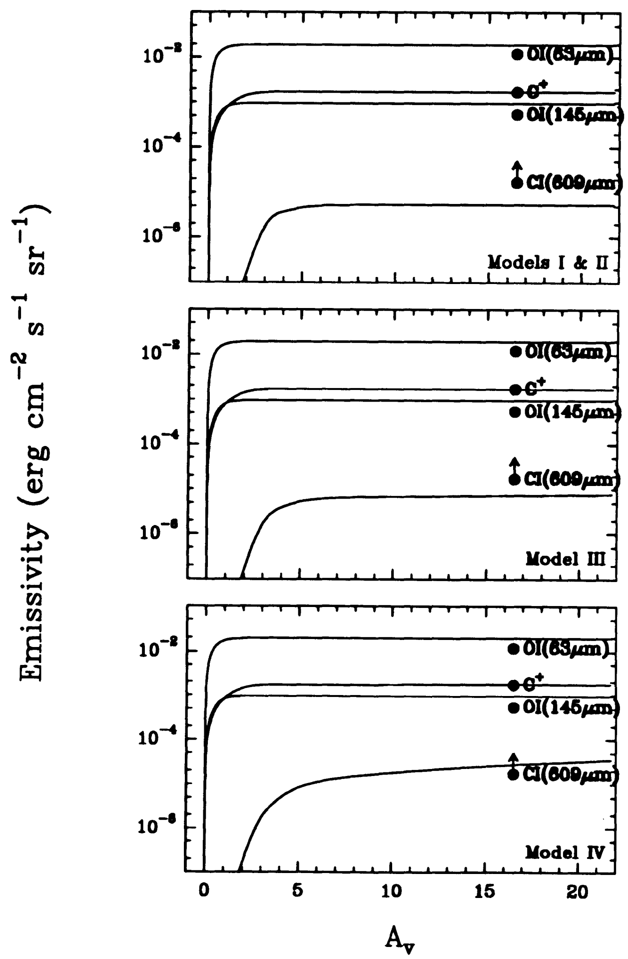

FIG. 2.—PDR models of integrated emissivity of O I 63 μm, O I 145 μm, C II 158 μm, and C I 609 μm as a function of visual extinction A_V. All models use a density of $n_H = 10^5$ cm^{-3} and an incident UV field of 10^4 times the standard Galactic field. Models I (*top*) and IV (*bottom*) use the fast H_3^+ recombination rate. Models I and II have a standard cosmic-ray flux, while models III and IV have the cosmic-ray flux enhanced by a factor of 300. The dots denote the observed values. Note that in the first three models emission in all considered lines comes exclusively from the PDR region, while in model IV C I in the molecular phase contributes to the emission, causing the C I emission to rise as a function of A_V.

we used agreed sufficiently well with the Wolfire et al. (1990) model. To match the observed values exactly, fine tuning of the density and UV field would be required. Furthermore, a realistic model would have to take the problem of elemental depletion into account. Wolfire et al. (1990) and Hollenbach et al. (1991) use only slightly depleted solar elemental abundances, as might be appropriate for diffuse clouds, while observations of the Galactic interstellar medium suggest that a depletion of 5–10 is more realistic in molecular clouds (cf. Graedel, Langer, & Frerking 1982 and references therein). However, since our goal is not a complete model of the interstellar medium in M82 but rather a qualitative explanation for the strong atomic carbon emission, we have chosen to employ their abundances for ease of comparison. In all four models, the C II and O I intensities remain unchanged, since they are determined by the density structure and incident UV flux, which are kept constant in the model. Thus, since these fluxes match the observed ones reasonably well, the comparison of the calculated with the observed absolute C I intensity is justified.

The C/CO column density ratio, which is the relevant number here, since we are comparing column densities determined by observations of optically thin $C^{18}O$ and optically thin C I, is 0.1–0.05, depending on the total column density of the clouds, since the C I emission comes only from the edge of the cloud in this reference model. The abundance ratio in the dense gas is only 0.01.

In our second model we used the same parameters, but the fast H_3^+ dissociative recombination coefficient (Canosa et al. 1991). It leads to exactly the same results as the first model, since with the employed parameters the model is in the high-density regime, where recombinations are unimportant. In our third model we increase the cosmic-ray flux by a factor of 300, as suggested by the results of Suchkov et al. (1993), and use again the slow H_3^+ dissociative recombination coefficient (Adams et al. 1984). The slow recombination coefficient keeps the phase transition at densities much lower than considered here, in spite of the enhanced cosmic-ray flux. The C I($^3P_1$–$^3P_0$) emissivity is raised to 8×10^{-6} ergs cm^{-2} s^{-1} sr^{-1} (Fig. 2, *center*). Here the C/CO ratio in the dense gas is also 0.01, and the C I emission again originates almost exclusively in the ionized gas/molecular gas transition zone. The C/CO column density ratio is, as before, 0.1–0.05. Hence, increased production of atomic carbon due to increased cosmic-ray dissociation of CO is insignificant.

In our fourth model we used the fast H_3^+ dissociative recombination coefficient and again a factor of 300 increased cosmic-ray flux. The phase transition is pushed to densities higher than 10^5 cm^{-3}, and hence we find a large C/CO abundance ratio of 0.4 deep inside the cloud and a column density ratio of about 0.5 through the cloud. The atomic carbon in the molecular gas contributes significantly to the total emission, and the integrated intensity is a few times 10^{-5} ergs cm^{-2} s^{-1} sr^{-1}, depending on which total A_V is assumed for the cloud (Fig. 2, *bottom*). The exact cosmic-ray enhancement factor is not crucial as long as it is above a critical rate of about 200. Heating by cosmic rays could explain the temperature 50 K determined by Güsten et al. (1993) for the dense phase in M82. Only the fourth model generates the observed high C/CO column density and C I/C II intensity ratios.

We conclude that the enhanced C I/C II intensity and C I/CO column density ratio is due to the enhanced cosmic-ray flux in M82. In the context of new chemical models using a fast H_3^+ recombination rate, the cosmic rays increase the critical density below which atomic carbon can exist in molecular clouds and hence increases the contribution of atomic carbon within molecular clouds to the total C I emission. The total C I emission increases proportionally to the H_2 column density of the cloud, while in previous PDR models, where the C I emission occurs only in the transition zone, the total C I emission is independent of the H_2 column density (see Fig. 2). The cosmic rays heat the molecular gas, further enhancing the emissivity.

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