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DETECTION OF CO^+ IN THE NUCLEUS OF M82

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ABSTRACT

We present the detection of the reactive ion CO^+ toward the prototypical starburst galaxy M82. This is the first secure detection of this short-lived ion in an external galaxy. Values of $[CO^+]/[HCO^+] > 0.04$ are measured across the inner 650 pc of the nuclear disk of M82. Such high values of $[CO^+]/[HCO^+]$ have previously only been measured toward the atomic peak in the reflection nebula NGC 7023. This detection corroborates the scenario in which the molecular gas reservoir in the M82 disk is heavily affected by the UV radiation from recently formed stars. Comparing the column densities measured in M82 with those found in prototypical Galactic photon-dominated regions (PDRs), we need ∼20 clouds along the line of sight to explain our observations. We have completed our model of the molecular gas chemistry in the M82 nucleus. Our PDR chemical model successfully explains the $[CO^+]/[HCO^+]$ ratios measured in the M82 nucleus but fails by an order of magnitude to explain the large measured CO^+ column densities [$\sim(1–4) \times 10^{13}$ cm^{-2}]. We explore possible routes to reconcile the chemical model and the observations.

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

1. INTRODUCTION

M82 is one of the nearest and brightest starburst galaxies. Located at a distance of 3.9 Mpc, and with a bolometric luminosity of 3.7×10^{10} $L_\odot$, it has been extensively studied in many molecules. Several studies reveal that the starburst has heavily influenced the interstellar medium in M82 by producing high UV and cosmic-ray fluxes. Recent interferometric observations at millimeter wavelengths (García-Burillo et al. 2001) show that while the chemistry of the molecular gas in the disk-halo interface is dominated by shocks, the chemistry of the molecular gas in the M82 disk seems to be dominated by the intense UV flux. García-Burillo et al. (2002) obtained a high angular resolution image showing widespread enhanced HCO abundances ($[HCO]/[H^{13}CO^+] \sim 3.6$) across the whole M82 disk, which was interpreted in terms of a giant photon-dominated region (PDR) of 650 pc size. We previously (Fuente et al. 2005, hereafter Paper I) observed a selected set of PDR tracers (CN, C_2H, HOC^+, and c-C_3H_2) in three positions across the M82 disk and measured $[CN]/[HCN] \sim 5$ in the inner 650 pc galaxy disk. Such a large value of [CN]/[HCN] is only reached in the layers of a PDR most heavily exposed to the UV radiation (Fuente et al. 1993; Fuente & Martín-Pintado 1997; Sternberg & Dalgarno 1995; Boger & Sternberg 2005). Furthermore, we detected the HOC^+ $1 \rightarrow 0$ line and obtained an $[HCO^+]/[HOC^+]$ ratio of ∼40. Such a low $[HCO^+]/[HOC^+]$ ratio is only expected in molecular gas that is highly ionized [$X(e^-) > 10^{-5}$], either by UV photons (PDRs) or X-rays (XDRs) (Fuente et al. 2003; Rizzo et al. 2003; Usero et al. 2004).

In this Letter, we report the detection of CO^+ in the nucleus of M82. This is the first secure CO^+ detection in an extragalactic object, as it previously has only been tentatively detected toward the active galactic nucleus Cyg A (Fuente et al. 2000). CO^+ is a reactive ion that can only survive in the highly ionized layers of PDRs and XDRs (see, e.g., Sternberg & Dalgarno 1995). In our Galaxy, CO^+ has only been detected in a handful of objects, which are well-known prototypical PDRs (NGC 7027 and M17 SW: Latter et al. 1993, Fuente et al. 2003; the Orion bar: Störzer et al. 1995, Fuente et al. 2003; NGC 7023: Fuente & Martín-Pintado 1997, Fuente et al. 2003; Mon R2 and G29.96−0.02: Rizzo et al. 2003; S140 and NGC 2023: Savage & Ziurys 2004). In fact, CO^+ may be the best molecular tracer of the outermost layers ($A_v > 2$ mag) of PDRs. In contrast to other molecular PDR tracers such as CN and HOC^+, CO^+ is exclusively formed in these layers by reactions of C^+ with OH. The formation of the chemically related ion HOC^+ is favored in this region, but it can also be formed at a lower rate in molecular clouds. In addition to the CO^+ detection, we present observations of the high-excitation HCO^+ $3 \rightarrow 2$, HOC^+ $3 \rightarrow 2$, and CH_3OH $5_{k,k'} \rightarrow 4_{k,k'}$ lines.

2. OBSERVATIONS AND RESULTS

The observations were carried out in 2004 June and November with the IRAM 30 m radio telescope at Pico de Veleta (Spain). We used two SIS receivers tuned in single-sideband mode in the 1 mm band. The observed transitions were HCO^+ $3 \rightarrow 2$, HOC^+ $3 \rightarrow 2$, CO^+ $N = 2 \rightarrow 1$ $J = 5/2 \rightarrow 3/2$ and $J = 3/2 \rightarrow 1/2$, and CH_3OH $5_2 \rightarrow 4_2$ and $5_{-2} \rightarrow 4_{-2}$ E. In Figure 1 we present the observed spectra, and Gaussian fits are shown in Table 1. The intensity scale is main-beam brightness temperature. The forward efficiency (η_{ff}), main-beam efficiency (η_{MB}), and half-power beamwidth (HPBW) of the telescope are 0.91, 0.52, and 11″ at 235 GHz and 0.88, 0.46, and 9″ at 260 GHz. Pointing was checked every 2 hr by observing a reference source. We observed three positions across the M82 disk in the CO^+ lines: the nucleus (R.A. = $09^h55^m51\overset{s}{.}9$, decl. = 69°04′47″.11; J2000) (hereafter referred to as “Center”) and the two peaks in the HCO emission [offsets (+14″, +5″) and (−14″, −5″), hereafter referred to as “E” and “W,” respectively]. Only E and Center were observed in the HCO^+ $3 \rightarrow 2$ and HOC^+ $3 \rightarrow 2$ lines. The HOC^+ $3 \rightarrow 2$ line has been detected toward E. This detection constitutes a further corroboration of the HOC^+ $1 \rightarrow 0$ detection reported in Paper I. The CH_3OH line was only observed toward Center.

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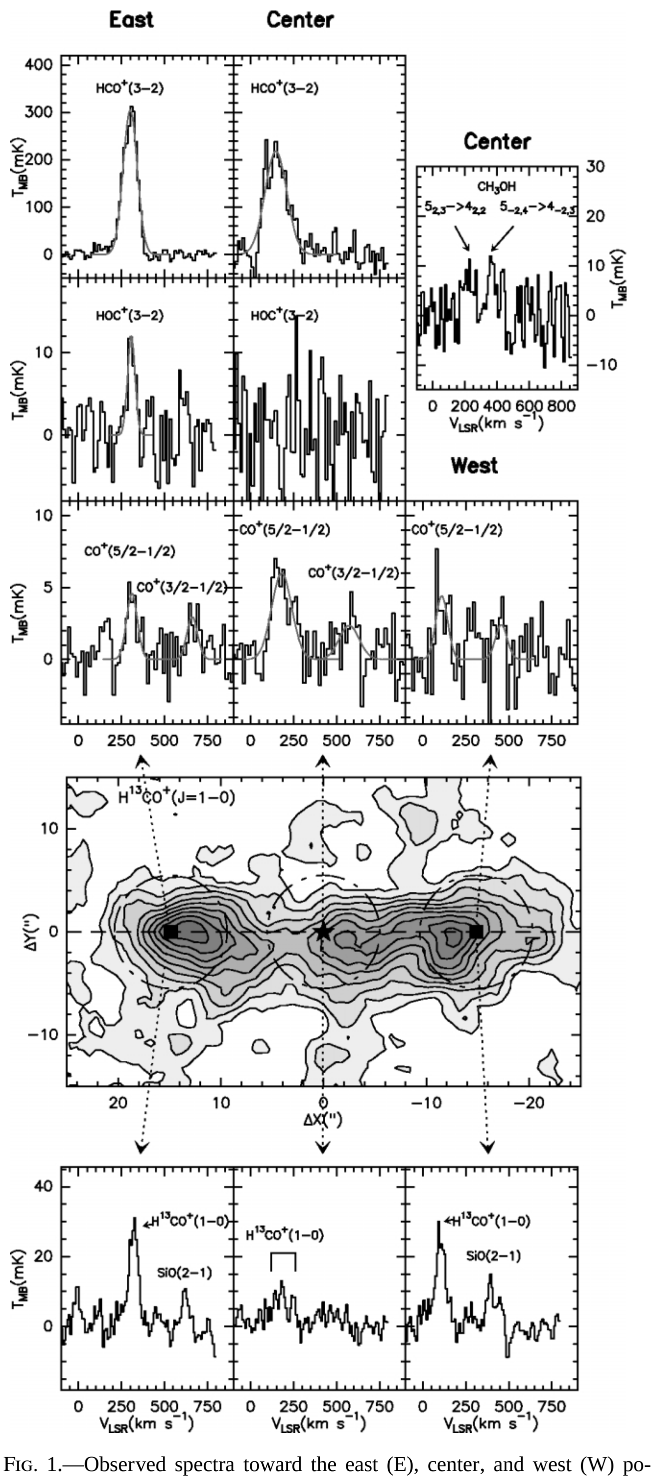

FIG. 1.—Observed spectra toward the east (E), center, and west (W) positions in M82. The 30 m beam at 236 GHz around the three observed positions is shown in the interferometric $H^{13}CO^+$ image (by García-Burillo et al. 2002).

2.1. CO^+ *Detection*

CO^+ has a $^2\Sigma$ ground electronic state in which each rotational level is split into two fine-structure levels with $J = N \pm \frac{1}{2}$. The $N = 1 \rightarrow 0$ rotational line is heavily obscured by the O_2 line at 118 GHz and cannot be observed from ground-based telescopes. The most intense transitions of the $N = 2 \rightarrow 1$ rotational spectrum are $J = 5/2 \rightarrow 3/2$ at 236.062 GHz and $J = 3/2 \rightarrow 1/2$ at 235.789 GHz. Since they are very close in frequency, the two lines can be observed simultaneously. In the optically thin limit, the intensity ratio $I(236.062)/I(235.789)$ is 1.8. The detection of the two lines with the expected intensity ratio provides supporting evidence of the reality of the CO^+ detection.

The CO^+ $N = 2 \rightarrow 1$, $J = 5/2 \rightarrow 3/2$ line has been detected toward E (>4 σ) and Center (>8 σ) and very tentatively (∼3 σ) toward W. Furthermore, we have a ∼3 σ detection of the weakest component toward Center. The 236.062 GHz CO^+ line is blended with the $5_{-2,4} \rightarrow 4_{-2,3}$ and $5_{2,3} \rightarrow 4_{2,2}$ E lines of $^{13}CH_3OH$ (at 236.062 and 236.063 GHz, respectively). To confirm the CO^+ detection and estimate the possible contamination of the 13-methanol lines, we observed toward Center the same transitions of the abundant isotope $^{12}CH_3OH$ and obtained $T_{MB} \sim 10$ mK. Assuming a $^{12}C/^{13}C$ ratio greater than 50 (Mao et al. 2000), the intensity of the CH_3OH line should be less than 0.2 mK toward Center, that is, at least a factor of 30 lower than the intensity observed in the CO^+ spectrum. Therefore, we can conclude that the detected emission at 236.062 GHz corresponds to the $J = 3/2 \rightarrow 1/2$ line of CO^+.

2.2. *Column Density Ratios*

The physical conditions of the molecular gas are estimated by fitting the intensities of the $H^{13}CO^+$ $1 \rightarrow 0$ and HCO^+ $3 \rightarrow 2$ lines using a large velocity gradient (LVG) code. For these calculations, we assume $T_k = 50$ K (Weiss et al. 2001) and $[HCO^+]/[H^{13}CO^+] = 89$. The $^{12}C/^{13}C$ ratio in the M82 nucleus is not well known. Mao et al. (2000) derived a $^{12}C/^{13}C$ ratio between 50 and 75 from multiline CO observations using an LVG code. However, they obtained a larger value of the $^{12}C/^{13}C$ ratio when applying a PDR model to the same data. For consistency with Paper I, we adopt the canonical value $[HCO^+]/[H^{13}CO^+] = 89$. The derived molecular hydrogen densities are $(3–8) \times 10^4$ cm^{-3}. These densities are in agreement with those derived from the CN and HCN lines in Paper I within the uncertainties inherent to this kind of calculation. Assuming these densities and an emission size of 6″ for E, W, and Center, we obtain the $H^{13}CO^+$ and HOC^+ column densities shown in Table 2. The size of the emission toward E, W, and Center has been derived from the interferometric HCO and $H^{13}CO^+$ images published by García-Burillo et al. (2002; see Fig. 1). To calculate the CO^+ column density, we assume optically thin emission and use the local thermodynamic equilibrium (LTE) approximation with $T_{rot} = 10$ K. This rotation temperature has been estimated using an LVG code applied to a linear molecule with the same dipole moment as CO^+ and $n(H_2) = 10^5$ cm^{-3}. Assuming a size of 6″ for the CO^+ emission, we derive CO^+ column densities of $\sim(1–4) \times 10^{13}$ cm^{-2} across the M82 disk.

We can calculate the $[HCO^+]/[HOC^+]$ ratio toward E by using the HCO^+ $3 \rightarrow 2$ and HOC^+ $3 \rightarrow 2$ lines. Since both lines lie at the same frequency and have similar dipole moments, $[HCO^+]/[HOC^+] \approx I(HCO^+\ 3 \rightarrow 2)/I(HOC^+\ 3 \rightarrow 2)$. We obtain $[HCO^+]/[HOC^+] \approx 48$, in excellent agreement with our previous estimates (Paper I). In Table 2, we compare the column density ratios in M82 with those measured in some prototypical Galactic PDRs. The $[CO^+]/[HCO^+]$ ratio is larger than 0.04 all across the M82 disk. This is one of the largest values of the $[CO^+]/[HCO^+]$ ratio measured thus far. Values of $[CO^+]/[HCO^+]$ larger than 0.01 are only found toward the atomic peaks in prototypical Galactic PDRs, and such a high value of the $[CO^+]/[HCO^+]$ ratio has only been measured in the most exposed layers of the PDR associated with the reflection nebula NGC 7023. This result is consistent with the values of the $[HCO^+]/[HOC^+]$ and [CN]/[HCN] ratios previously measured in the M82 disk (Paper I). We estimate $[HCO^+]/[HOC^+] \sim 40$ and [CN]/[HCN] > 5 across the M82 nucleus. These values are also similar to those measured in the PDR peak toward NGC 7023. The very favorable geometry of the PDR associated with this reflection nebula al-

TABLE 1
Observational Parameters and Results of Gaussian Fits

Region	Molecule	Rest Freq.[a] (MHz)	$\int T_{MB}\,dv$ (K km s^{-1})	v_{lsr} (km s^{-1})	Δv (km s^{-1})	T_{MB} (mK)	t_{int} (minutes)
E (+14″, +5″) ……	CO^+ $J = 5/2 \rightarrow 3/2$	236062.55	0.36 (0.08)	311 (8)	74 (19)	4.6	695
	HCO^+ $J = 3 \rightarrow 2$	267557.00	31.33 (0.45)	301 (1)	96 (2)	304.7	127
	HOC^+ $J = 3 \rightarrow 2$	268451.00	0.65 (0.13)	307 (5)	51 (12)	12.0	125
	$H^{13}CO^+$ $J = 1 \rightarrow 0$[a]	86754.33	2.05 (0.15)	320 (2)	66 (6)	29.0	…
Center (0″, 0″) ……	CO^+ $J = 5/2 \rightarrow 3/2$	236062.55	0.88 (0.11)	181 (9)	137 (19)	6.0	340
	CO^+ $J = 3/2 \rightarrow 1/2$	235789.64	0.34 (0.09)	…	137[b]	2.4	340
	HCO^+ $J = 3 \rightarrow 2$	267557.00	34.66 (1.52)	147 (4)	149 (7)	218.1	12
	HOC^+ $J = 3 \rightarrow 2$	268451.00	<0.34[c] K km s^{-1}				190
	$H^{13}CO^+$ $J = 1 \rightarrow 0$[a]	86754.33	1.21 (0.13)	171 (8)	140 (18)	8.1	…
	CH_3OH $J_k = 5_{2,3} \rightarrow 4_{2,2}$[d]	241904.63	0.92 (0.27)	222 (13)	85 (27)	10.0	70
W (−14″,−5″) ……	CO^+ $J = 5/2 \rightarrow 3/2$	236062.55	0.38 (0.10)	111 (8)	81 (21)	4.4	390
	$H^{13}CO^+$ $J = 1 \rightarrow 0$[a]	86754.33	1.94 (0.15)	103 (3)	73 (7)	24.8	…

[a] Spectra obtained from the interferometric $H^{13}CO^+$ image reported in García-Burillo et al. (2002) by convolving to a Gaussian resolution of HPBW = 11″.
[b] Gaussian fit obtained by fixing the velocity and line width.
[c] Value is a 3 σ limit with $\Delta v = 50$ km s^{-1}
[d] The $J_k = 5_{-2,4} \rightarrow 4_{-2,3}$ line at 241904.15 MHz overlaps this.

lowed us to detect the outermost layers of the PDR (Fuente et al. 1993, 1996a). Our observations suggest that the bulk of the dense molecular gas in M82 is surviving in a similar environment to that found in the H I–H_2 transition layer of this PDR.

We can also compare the CO^+, HOC^+, and CN column densities in M82 with those derived in Galactic PDRs, although the derived column densities are more uncertain than the column density ratios, since the former depend on the assumed beam filling factor. In Galactic PDRs, the CO^+ column densities are quite uniform, taking a value of $\sim10^{12}$ cm^{-2} in all star-forming regions regardless of the incident UV field over a range of 3 orders of magnitude. Furthermore, the $[CO^+]/[HOC^+]$ ratio is ~0.5–9 (Rizzo et al. 2003; Savage & Ziurys 2004). The $[CO^+]/[HOC^+]$ ratio measured in M82 is similar to those found in the PDRs associated with star-forming regions in our Galaxy (see Table 2). This suggests a similar CO^+-HCO^+-HOC^+ chemistry and a similar origin for the reactive ions. Since the CO^+ column density is a factor of 20–40 larger in M82 than in Galactic PDRs, we need about 20–40 PDRs along the line of sight to account for our observations. In the scenario of clouds immersed in a pervasive UV field, this implies about 10–20 clouds along the line of sight, which is a reasonable number for an edge-on galaxy.

3. CHEMICAL MODEL

To obtain deeper insight into the physics and chemistry of the molecular clouds in M82, we modeled their chemistry using Le Bourlot's semi-infinite plane-parallel PDR model (Le Bourlot et al. 1993) and the same physical conditions as in Paper I: $G_0 = 10^4$ in units of the Habing field, $n = n_H + 2n_{H_2} = 4 \times 10^5$ cm^{-3}, and a cosmic-ray flux of 4×10^{-15} s^{-1}. As discussed in Paper I, this model explains with reasonable success all the molecular abundances observed in M82 and should therefore account for our CO^+ detection.

The model results for CO^+ and HCO^+ are shown in Figure 2. The $N(CO^+)/N(HCO^+)$ ratio (hereafter r_{CO^+}) is very high (>0.1) for $A_v < 0.5$ mag. Then r_{CO^+} remains constant and equal to ~0.1 until $A_v < 5$ mag. This is because in this range of visual extinction, 0.5 mag $< A_v <$ 4.5 mag, r_{CO^+} is determined by the CO^+ and HCO^+ abundances in the most external layers ($A_v <$ 1 mag) of the PDR. For higher extinctions, r_{CO^+} decreases because of the rapid increase of the HCO^+ abundance. In our plane-parallel model, the values of r_{CO^+} observed across the M82 nucleus ($r_{CO^+} > 0.04$) are found only for $A_v < 6.5$ mag (see Fig. 2). In an external galaxy, one does not expect to have a single PDR but a population of clouds (or cloudlets) immersed in an intense UV field (Paper I; García-Burillo et al. 2002). In this scenario, our model results imply that the individual cloudlets have $N_{tot} \lesssim 1.3 \times 10^{22}$ cm^{-2}. Thus, our CO^+ observations corroborate the scenario for the M82 nucleus proposed in Paper I of a highly fragmented interstellar medium in which the dense cores ($n \sim 4 \times 10^5$ cm^{-3}, $N_{tot} \lesssim 1.3 \times 10^{22}$ cm^{-2}) are bathed in an intense UV field ($G_0 = 10^4$ Habing fields).

Thus far, we have only compared the observed and model-predicted molecular column density ratios. We can also compare

TABLE 2
Column Densities and Relative Fractional Abundances

Molecule	M82[a] E	M82[a] Center	M82[a] W	Orion Bar[b] IF	NGC 7023[c] PDR Peak	Mon R2[d] IF
N(CN) …………	6.3×10^{15}	8.8×10^{15}	1.1×10^{16}	2.4×10^{14}	2.4×10^{14}	…
$N(CO^+)$ …………	1.5×10^{13}	3.7×10^{13}	1.6×10^{13}	8.0×10^{11}	1.6×10^{12}	4.4×10^{12}
$N(HOC^+)$ ……….	2.5×10^{13}	4.3×10^{13}	2.5×10^{13}	4.0×10^{11}	1.3×10^{11}	1.4×10^{12}
CN/HCN ……….	6	8	7	3	4–8	…
HCO^+/HOC^+ ……	44	36	30	<166	50–120	460
CO^+/HCO^+ ……..	0.04	0.1	0.04	~0.01	0.01–0.11	0.005

[a] The molecular column densities are derived assuming a size of 6″ and data from Paper I and this Letter. The HCO^+/HOC^+ and CN/HCN ratios are averaged values in a beam of ~29″ (Paper I). The CO^+/HCO^+ ratio is derived in this Letter with a beam of 11″.
[b] Assuming that the bar fills half of the beam at the ionization front (IF) position and data from Fuente et al. (1993, 1996b).
[c] Assuming a filament of 6″ and data from Fuente et al. (1993, 2003).
[d] Assuming the size of the radio continuum emission at 6 cm (10″) and data from Rizzo et al. (2003).

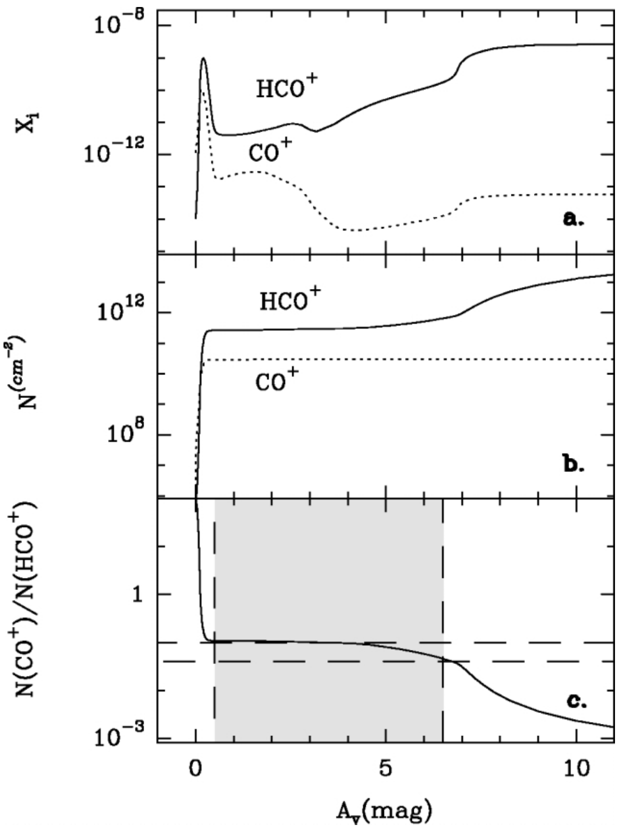

FIG. 2.—Model predictions for (*a*) the fractional abundances and (*b*) the cumulative column densities of CO^+ and HCO^+ derived using Le Bourlot et al.'s code for the physical conditions in the M82 nucleus ($G_0 = 10^4$ in units of the Habing field, $n = 10^5$ cm^{-3}, and $\zeta = 4 \times 10^{-15}$ s^{-1}). Note that the $N(CO^+)/N(HCO^+)$ ratios measured in the M82 nucleus (*dashed lines in* [*c*]) are well explained if the emission arises in PDRs with total visual extinction between 4.5 and 6.5 mag, in perfect agreement with our results in Paper I based on the CN/HCN ratio.

the molecular column densities. The predicted CO^+ column density is $\sim 3 \times 10^{10}$ cm^{-2} for $A_v = 6.5$ mag. This value is a factor of 20–40 lower than the CO^+ column densities observed in the prototypical Galactic PDRs. Furthermore, it is 3 orders of magnitude lower than the CO^+ column densities measured in M82, and an unrealistically large number of PDRs along the line of sight would be required in order to explain our CO^+ observations. For deeper insight into the cause of this discrepancy between theoretical predictions and the observations, we also compared the predicted CN column densities with the observed ones (see Table 1). Like CO^+, CN is a good tracer of PDRs and can be used to estimate the number of PDRs along the line of sight. Our model predicts $N(CN) \sim 1.5 \times 10^{14}$ cm^{-2} for $A_v \sim 6.5$ mag. This value agrees within a factor of 2 with those observed in prototypical Galactic PDRs such as the Orion bar and NGC 7023. Comparing with the CN column densities observed in the M82 nucleus, we need about 20–40 individual cloudlets along the line of sight to account for our observations (see also Boger & Sternberg 2005). This is a reasonable number of cloudlets for an edge-on galaxy. Thus, there is a reasonable agreement between model predictions and observations for CN in both Galactic and extragalactic PDRs. However, the chemical model falls short by more than an order of magnitude to account for the CO^+ column densities measured in Galactic PDRs and the M82 nucleus.

The failure of chemical models to account for the observed reactive ions' column densities is a long-standing problem (Black 1998; Fuente et al. 2000). The chemistry of reactive ions is very sensitive to the gas physical conditions in the H I–H_2 transition layer. In particular, CO^+ is mainly produced by means of the reaction $C^+ + OH \rightarrow CO^+ + H$. The production of OH is very dependent on the temperature, as $O + H_2$ may come into play at the H-H_2 transition region when H_2 is abundant and the temperature is still a few hundred kelvins. The corresponding endothermicity is about 3000 K. An increase in the gas kinetic temperature in the H I–H_2 interface could have a dramatic effect on CO^+ production.

There are several pieces of observational evidence that suggest that chemical models fail to predict the gas kinetic temperature in the H I–H_2 region. One of the best-studied PDRs is the Orion bar, which is the paradigm of a Galactic PDR associated with an H II region. Observations of the H_2 rotational lines in the Orion bar by Parmar et al. (1991) revealed unexpectedly large amounts of warm gas ($T \sim 400$–700 K). They proposed that clumpiness could help to reconcile the observations with chemical models. Recently, Allers et al. (2005) proposed that the dust far-UV attenuation cross sections should be reduced by a factor of 3 in order to explain the separation between the ionization front and the H_2 emission peak in the Orion bar. In order to explain the intensities of the H_2 rovibrational lines, they needed to readjust the photoelectric heating rate. A change in the size distribution of the grains or the photoelectric heating rate would produce large variations in the thermal balance of the PDR.

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