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PHOTON-DOMINATED CHEMISTRY IN THE NUCLEUS OF M82: WIDESPREAD HOC^+ EMISSION IN THE INNER 650 PARSEC DISK

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ABSTRACT

The nucleus of M82 has been mapped in several 3 and 1 mm lines of CN, HCN, C_2H, c-C_3H_2, CH_3C_2H, HC_3N, and HOC^+ using the IRAM 30 m telescope. These species have been purposely selected as good tracers of photon-dominated chemistry. We have measured [CN]/[HCN] ~ 5 in the inner 650 pc galaxy disk. Furthermore, we have detected the HOC^+ $1 \rightarrow 0$ line with an intensity similar to that of the $H^{13}CO^+$ $1 \rightarrow 0$ line. This implies an [HCO^+]/[HOC^+] ratio of ~40. These results corroborate the existence of a giant photodissociation region (PDR) in the nucleus of M82. In fact, the low [HCO^+]/[HOC^+] ratio can only be explained if the nucleus of M82 is formed by small ($r < 0.02$–0.2 pc) and dense ($n \sim$ a few times 10^4–10^5 cm^{-3}) clouds immersed in an intense UV field ($G_0 \sim 10^4$ in units of the Habing field). The detection of the hydrocarbons c-C_3H_2 and CH_3C_2H in the nucleus of M82 suggests that a complex carbon chemistry is developing in this giant PDR.

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 luminosity of $3.7 \times 10^{10}\ L_\odot$, it has been extensively studied in many molecules. Compared to other prototypical nearby starburst galaxies like NGC 253 and IC 342, M82 presents systematically low abundances of the molecules NH_3, CH_3OH, CH_3CN, HNCO, and SiO (Takano et al. 2003). Different explanations have been proposed to account for this peculiar chemistry. Since all these molecules are related to dust grain chemistry, Takano et al. (2003) proposed that the formation of molecules on dust and/or evaporation to the gas phase is not efficient in M82.

On the other hand, several studies have revealed that the starburst has heavily influenced the interstellar medium in M82 by producing high cosmic-ray and UV fluxes. A low-density ionized component is filling a substantial fraction of the volume in M82 (see, e.g., Seaquist et al. 1996). The molecular gas is embedded in this component in the form of warm ($T_k > 50$ K) and dense ($n > 10^4$ cm^{-3}) clouds (Mao et al. 2000). Dense photodissociation regions (PDRs) are expected to form in the borders of these clouds (Wolfire et al. 1990; Lord et al. 1996). Wolfire et al. (1990) have modeled the C II, Si II, and O I emission and estimated a UV field of $G_0 = 10^4$ in units of the Habing field and a density of $n \sim 10^5$ cm^{-3} for the atomic component. Schilke et al. (1993) reported observations of the C I ($^3P_1$–$^3P_0$) line, deriving a [C I]/CO column density ratio (~0.5) higher than that observed in nonstarburst galaxies (e.g., [C I]/CO ~ 0.15 in our Galaxy). They proposed that the enhanced cosmic-ray flux supplied by supernova remnants could produce the enhanced C I emission in M82. Recent results suggest that the strong UV flux dominates the chemistry of the molecular gas in M82. García-Burillo et al. (2002) obtained a high angular resolution image showing widespread HCO emission in this galaxy. The enhanced HCO abundance ([HCO]/[$H^{13}CO^+$] ~ 3.6) measured across the whole M82 disk was interpreted in terms of a giant PDR of 650 pc size.

In this Letter, we present observations of a selected set of radicals (CN, C_2H), reactive ions (CO^+, HOC^+), and small hydrocarbons (c-C_3H_2) that are excellent probes of the atomic-to-molecular transition in PDRs. In particular, the [CN]/[HCN] ratio has been successfully used as a PDR indicator in regions with very different physical conditions in our Galaxy (Fuente et al. 1993, 1995, 1996). The detection of the reactive ion HOC^+ is almost unambiguously associated to regions with a high ionizing flux (Fuente et al. 2003; Rizzo et al. 2003; Usero et al. 2004). Recent works have revealed that the abundances of some hydrocarbons are an order of magnitude larger in PDRs than those predicted by gas-phase models (Teyssier et al. 2004; Pety et al. 2004).

2. OBSERVATIONS AND ANALYSIS

The observations were carried out in 2004 June and November with the IRAM 30 m radio telescope at Pico de Veleta (Spain). We used 2 SIS receivers tuned in single-sideband mode in the 1 and 3 mm bands. The observed transitions are CN $1 \rightarrow 0$ (113.490 GHz), CN $2 \rightarrow 1$ (226.874 GHz), HCN $1 \rightarrow 0$ (88.631 GHz), C_2H $1 \rightarrow 0$ (87.317 and 87.402 GHz), c-C_3H_2 $2_{1,2} \rightarrow 1_{0,1}$ (85.339 GHz), c-C_3H_2 $6_{1,6} \rightarrow 5_{0,5}$ (217.822 GHz), CH_3C_2H $5_k \rightarrow 4_k$ (85.457 GHz), HC_3N $9 \rightarrow 8$ (81.881 GHz), and HOC^+ $1 \rightarrow 0$ (89.487 GHz). The line intensities have been scaled to the main-beam brightness temperature. The half-power beamwidth of the telescope is 29″ at 85 GHz, 22″ at 115 GHz, and 12″ at 230 GHz. We observed three positions across the M82 disk: the nucleus [R.A.(J2000.0) = $09^h55^m51^s.9$, decl.(J2000.0) = 69°4′47″.11] and the two peaks in the HCO emission [offsets (+14″, +5″) and (−14″, −5″), hereafter referred to as the east and west knots, respectively]. The observed spectra are shown in Figure 1. To compare the 1.3 and 3 mm CN and c-C_3H_2 lines and make excitation calculations, we have derived beam filling factors from the $H^{13}CO^+$ interferometric image of García-Burillo et al. (2002). This assumption is justified since $H^{13}CO^+$ is an optically thin

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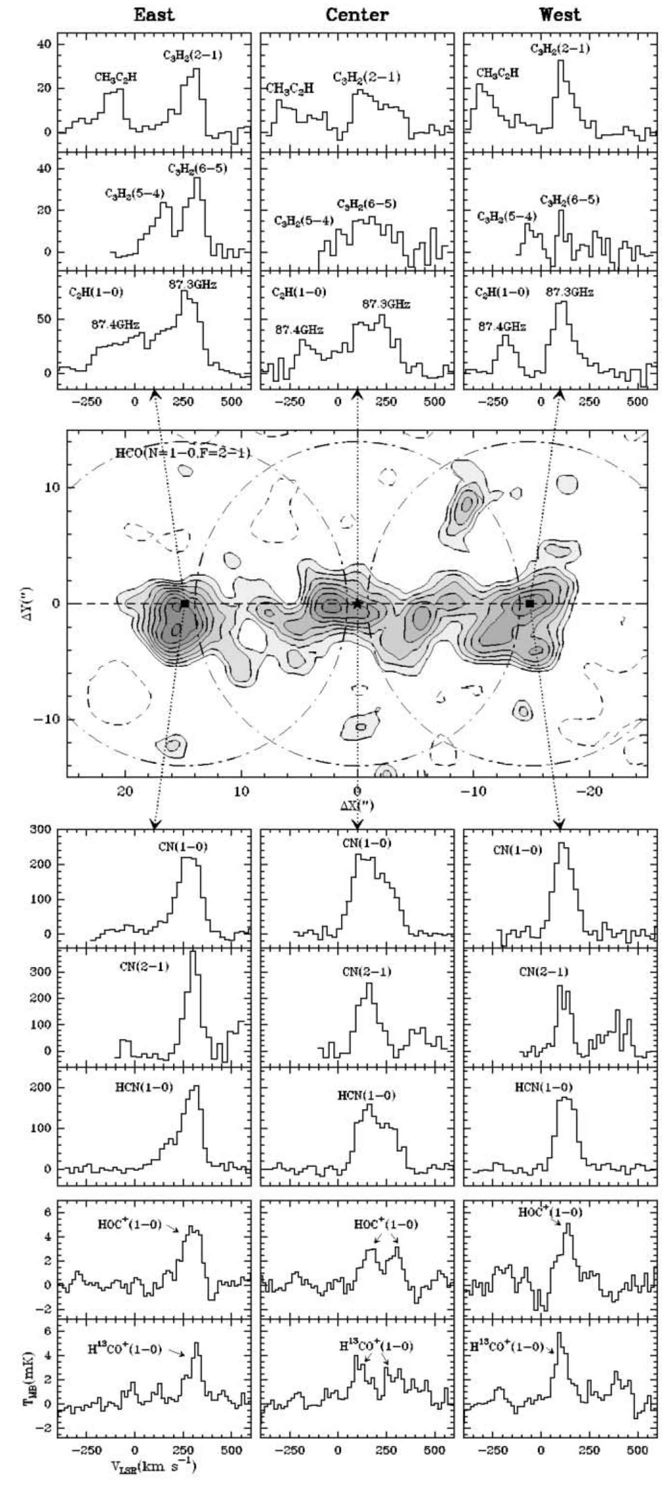

FIG. 1.—Observed spectra toward the east, center, and west positions in M82. The 30 m beam at 90 GHz around the three observed positions has been drawn in the interferometric HCO image by García-Burillo et al. (2002).

tracer of dense gas ($n > 10^4$ cm^{-3}) and presents a quite uniform abundance in a wide range of physical conditions.

The CH_3C_2H and C_2H column densities have been estimated using the LTE approximation. For C_2H, we have assumed the typical rotation temperature in Galactic PDRs, $T_{rot} = 10$ K (Fuente et al. 2003). In the case of CH_3C_2H, all the lines of the K-ladder are blended. In our estimates, we have assumed that 40% of the emission comes from the $K = 0$ line and $T_{rot} = 20$ K. These assumptions are based on the CH_3C_2H observations of Sgr B2 and Orion, which have similar physical conditions to M82 (Churchwell & Hollis 1983). A large velocity gradient (LVG) code has been used to derive densities and beam-averaged column densities for the other species. In these calculations, we have assumed $T_k = 60$ K, inferred from the NH_3 lines by Weiß et al. (2001).

3. RESULTS

We have estimated the hydrogen densities in the M82 disk by fitting with an LVG code the CN and C_3H_2 lines. Hydrogen densities between $n_{H_2} \sim 5 \times 10^4$ cm^{-3} and $n_{H_2} \sim 2 \times 10^5$ cm^{-3} are derived from both molecules. Assuming $n_{H_2} \sim 1 \times 10^5$ cm^{-3}, we have calculated the column densities averaged in a beam of 29″. The CN and HCN column densities are quite constant along the galaxy disk, with values N(CN) $= (2.0 \pm 0.5) \times 10^{14}$ cm^{-2} and N(HCN) $= (4.0 \pm 0.5) \times 10^{13}$ cm^{-2}. The [CN]/[HCN] ratio is similar to 5 in all positions (see Table 1). As discussed in § 4, this large value of the [CN]/[HCN] ratio is only reached in the most heavily UV exposed layers of a PDR. The derived c-C_3H_2 and CH_3C_2H column densities are also quite uniform along the disk with values $N(C_3H_2) \sim (1.7 \pm 0.4) \times 10^{13}$ cm^{-2} and $N(CH_3C_2H) \sim (1.0 \pm 0.6) \times 10^{14}$ cm^{-2}. These column densities are in agreement with previous estimates by Oike et al. (2004) and Mauersberger et al. (1991). Finally, we have not detected the HC_3N $9 \rightarrow 8$ line toward any position. As discussed in § 4, the nondetection of HC_3N and the derived lower limit to the [c-C_3H_2]/[HC_3N] ratio argue in favor of a PDR chemistry in M82.

We have detected the reactive ion HOC^+ in the three selected positions across the M82 disk. Furthermore, the intensities of the HOC^+ $1 \rightarrow 0$ lines are similar, even larger, than those of the $H^{13}CO^+$ $1 \rightarrow 0$ lines. Assuming the same physical conditions for $H^{13}CO^+$ and HOC^+, we derive an [HCO^+]/[HOC^+] ratio of ∼40 across the 650 pc inner disk, which is 2 orders of magnitude lower than that found in Galactic giant molecular clouds (GMCs; Apponi & Ziurys 1997). However, the $H^{13}CO^+$ spectra are derived from interferometric data. In order to assess the amount of missed flux (and hence the $H^{13}CO^+$ column density), we have compared our results to those of HCO^+ from Nguyen-Q-Rieu et al. (1992), which were obtained by single-dish observations. From our $H^{13}CO^+$ spectra, we obtain $N(H^{13}CO^+) \sim 5 \times 10^{11}$ cm^{-2} across the galaxy. If we assume a $^{12}C/^{13}C$ ratio of 89, this implies $N(HCO^+) \sim 4.5 \times 10^{13}$ cm^{-2}. This value is in agreement within a factor of 1.5 with the previous estimate by Nguyen-Q-Rieu et al. (1992). Thus, even in the most conservative case we can conclude that the [HCO^+]/[HOC^+] ratio is less than 80 in the M82 disk. Such low values of the [HCO^+]/[HOC^+] ratio have only been found in the galactic reflection nebula NGC 7023 (Fuente et al. 2003) and in the active nucleus of NGC 1068 (Usero et al. 2004) and put severe constraints to the ionization degree of the molecular gas in M82.

4. PHOTON-DOMINATED CHEMISTRY IN M82

Sternberg & Dalgarno (1995) found from detailed modeling that [CN]/[HCN] > 1 arises naturally in the surface layers ($A_v < 4$ mag) of dense PDRs. Values of the [CN]/[HCN] ratio between 1 and 3 have been found in prototypical dense galactic PDRs (Fuente et al. 1993, 1995, 1996). We have derived [CN]/[HCN] ratios of ∼5 in all positions across the M82 nucleus, suggesting that the molecular clouds in this galaxy are bathed in an intense UV field. To determine the averaged physical conditions of these clouds, we have carried out model calculations

TABLE 1
Relative Fractional Abundances

Molecule	M82 East	M82 (0, 0)	M82 West	Orion Bar Ionization Front	NGC 7023 PDR Peak	Horsehead IR Peak	TMC1 Cyanopolyyne Peak	L134N	References
C_2H (10^{13} cm^{-2}) ……	58	41	30	57	3.8	16	7.2	15	1, 2, 3, 4, 5
c-C_3H_2/C_2H ……….	0.02	0.04	0.02	0.02	0.03	0.06	0.8	0.33	2, 3, 5, 6
CH_3C_2H/C_2H ………	0.2	0.4	0.3	…	…	<0.07	1.4	0.07	3, 4, 5
c-C_3H_2/HC_3N ………	>6	>4	>3	>10	…	19	0.4	3	3, 5, 6, 7, 8, 9
CN/HCN ………….	4	6	4	3	4–8	…	0.07	0.07	1, 2, 4, 9
CN/HC_3N …………	>120	>58	>80	>180	…	…	0.05	0.9	1, 4, 8, 9
HCO^+/HOC^+ ………	35	49	50	<166	50–120	…	…	…	1, 6

References.—(1) Fuente et al. 1996; (2) Fuente et al. 1993; (3) Teyssier et al. 2004; (4) Pratap et al. 1997; (5) Fossé 2003; (6) Fuente et al. 2003; (7) Rodríguez-Franco et al. 1998; (8) Takano et al. 1998; (9) Dickens et al. 2000.

using the plane-parallel PDR model developed by Le Bourlot and collaborators (Le Bourlot et al. 1993). The model includes 135 species (HOC^+, CH_3C_2H, and HC_3N are not included) and standard gas-phase reactions. Adopting $G_0 \sim 10^4$ (Wolfire et al. 1990) and a total hydrogen nuclei density $n_H = n_{H\,I} + 2 \times n_{H_2} = 4 \times 10^5$ cm^{-3}, the model predicts that [CN]/[HCN] ratios $\gtrsim 5$ are only expected in regions at $A_v < 5$–6 mag (see left panels of Fig. 2). This implies an important limit to the cloud sizes in the nucleus of M82. Since the clouds are bathed in a pervasive UV field, the averaged column density of individual clouds should be $N_{H_2} \sim 10^{22}$ cm^{-2} in order to have averaged [CN]/[HCN] ratios of ∼5.

Strong constraints are also derived from the HOC^+ observations. We have measured an [HCO^+]/[HOC^+] ratio of ∼40 in the M82 disk. A simple calculation of the CO^+/HCO^+/HOC^+ chemical network shows that a high ionization degree, $X(e^-) > 10^{-5}$, is required to have [HCO^+]/[HOC^+] < 80 (Usero et al. 2004). Our PDR model shows that this high electron abundance is only found at $A_v < 4$ mag (see left panels of Fig. 2). This implies that the averaged column density of the clouds in the nucleus of M82 is $N(H_2) < 8 \times 10^{21}$ cm^{-2}. Thus, the M82 nucleus seems to be formed by small ($r \sim 0.02$–0.2 pc) and dense ($n \sim 10^4$–10^5 cm^{-3}) clouds immersed in a UV field of $G_0 \sim 10^4$. Mao et al. (2000) estimated similar column densities for

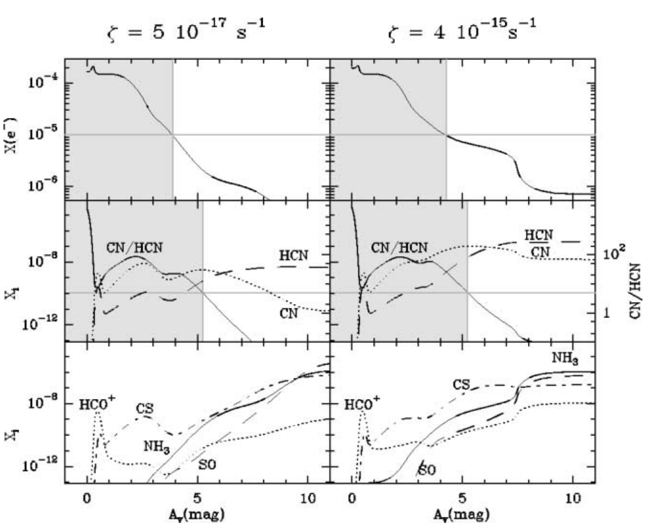

Fig. 2.—Predictions for the abundances of various species derived from the updated Le Bourlot et al. (1993) model. The calculations have been carried out for $n = 4 \times 10^5$ cm^{-3} and $G_0 = 1 \times 10^4$ in units of the Habing field. The cosmic-ray flux is set to $\zeta = 5 \times 10^{-17}$ s^{-1} (galactic value) in the left panels and $\zeta = 4 \times 10^{-15}$ s^{-1} (M82 value as derived by Suchkov et al. 1993) in the right panels. We have shadowed the region of the plot in agreement with the observational results in M82.

the clouds in the inner 400 pc disk of M82 by modeling the ^{12}CO, ^{13}CO, and C^{18}O lines. Low values of the [HCO^+]/[HOC^+] ratio are also found in X-ray–dominated regions with a high ionization degree, such as active galactic nuclei (AGNs; Usero et al. 2004). However, the polycyclic aromatic hydrocarbon (PAH) emission is very low in AGNs since the doubly ionized PAHs produced by X-rays are very unstable (Leach et al. 1989). The intense PAH emission observed in M82 (Normand et al. 1995; Förster Schreiber et al. 2003) indicates that X-rays are not the driving agent of the molecular gas chemistry in this galaxy.

5. HYDROCARBON CHEMISTRY

The hydrocarbon chemistry in PDRs has been a subject of increasing interest both from the theoretical and the observational point of view. Recent works have revealed that the c-C_3H_2 abundance in PDRs is similar to that in dark clouds. This is quite surprising if we take into account that this carbon cycle is easily photodissociated. In fact, PDR gas-phase models fall short of explaining the observed c-C_3H_2 and C_4H abundances by an order of magnitude (Teyssier et al. 2004; Pety et al. 2004). This is clearly seen when one compares the [c-C_3H_2]/[HC_3N] ratio in PDRs and dark clouds (see Table 1). While both species have similar abundances in dark clouds, the [c-C_3H_2]/[HC_3N] ratio is greater than 10 in PDRs. Since both molecules are easily destroyed by photodissociation, this suggests the existence of an additional c-C_3H_2 formation mechanism in PDRs. Several authors have proposed formation processes of small hydrocarbons linked to the PAH chemistry (Teyssier et al. 2004; Pety et al. 2004). We have detected widespread emission of C_2H and c-C_3H_2 in the M82 disk. However, we have not detected HC_3N toward any position. The derived upper limits to the HC_3N column density in M82 show that the [c-C_3H_2]/[HC_3N] ratio is at least a factor of 10 larger in this starburst galaxy than in the prototypical galactic dark cloud TMC 1 and is similar to that found in dense galactic PDRs (see Table 1). This result reinforces the scenario where the inner 650 pc region of M82 is a giant PDR.

In addition to C_2H and c-C_3H_2, we have detected CH_3C_2H in all the positions across the M82 disk. This detection is rather puzzling, since this molecule is easily photodissociated in regions exposed to intense UV fields and therefore its abundance is expected to be very low in these regions. Furthermore, this molecule is not detected in prototypical Galactic PDRs, like the Horsehead, which is known to be especially rich in carbon compounds (Teyssier et al. 2004; Pety et al. 2004). One possibility is that the CH_3C_2H emission arises in a population of clouds similar to the Galactic GMCs. The molecule CH_3C_2H is quite abundant in GMCs, presenting similar abundances to those of chemically related species like CH_3OH and CH_3CN.

The same behavior is observed in other prototypical starburst galaxies like NGC 253, where $[CH_3C_2H]/[CH_3OH] \sim 1$ and $[CH_3C_2H]/[CH_3CN] \sim 8$. However, $[CH_3C_2H]/[CH_3OH] > 8$ and $[CH_3C_2H]/[CH_3CN] > 25$ in M82 (Mauersberger et al. 1991; Huettemeister et al. 1997), i.e., a factor of 3–10 larger than in NGC 253. These abundance ratios show that the hydrocarbon chemistry in M82 is very different from that of GMCs. We think that the overabundance of CH_3C_2H could also be related to the enhanced UV flux in this galaxy. In fact, Cernicharo et al. (2001) found a similar behavior in the inner PDR of the proto–planetary nebula CRL 618.

6. A GLOBAL SCENARIO FOR THE CHEMISTRY IN M82

The observations presented in this Letter show that the strong UV flux drives the chemistry of the molecular gas in the M82 disk. In this Letter, we explore whether the PDR chemistry can solely account for all the molecular abundances measured in this galaxy so far. For this aim, we compare the molecular abundances in M82 to those of the prototypical starburst NGC 253. Molecules such as NH_3, CH_3OH, CH_3CN, SO, SiO, and HC_3N are clearly underabundant in M82 compared to NGC 253 (Weiß et al. 2001; Huettemeister et al. 1997; Mauersberger et al. 1991; Takano et al. 2003; García-Burillo et al. 2000, 2001). All these molecules are easily photodissociated and are not expected in a PDR. Other species such as CS, CN, HCN, and HCO^+ present fractional abundances of ∼a few times 10^{-9} in M82, which are very similar to those measured in NGC 253 (Mauersberger & Henkel 1989). These molecules belong to the reduced group of species that have significant abundances at $A_v < 5$ mag in our PDR model (see left panels of Fig. 2). However, our model predicts abundances a factor of 10 lower than those observed. Cosmic rays and/or shocks could contribute to enhance the abundances of these species.

To investigate the possible effect of the enhanced cosmic-ray flux on the chemistry, we have repeated the model calculations with a cosmic-ray flux of $\zeta = 4 \times 10^{-15}$ s^{-1}. This is the value estimated by Suchkov et al. (1993) to account for the physical conditions of the molecular gas in M82 and is, very likely, an upper limit to the actual cosmic-ray flux. The enhanced cosmic-ray flux does not change significantly the value of the [CN]/[HCN] ratio and the ionization degree at $A_v < 5$ mag (see right panels of Fig. 2). However, the fractional abundances of HCN, CN, and CS averaged over the region at $A_v < 5$ mag are a factor of 10 larger than those obtained with the standard value $\zeta = 5 \times 10^{-17}$ s^{-1}. Moreover, these values are in reasonable agreement with the observational results in M82. Thus, by including the enhanced cosmic-ray flux, we get a better fit of the model to the observational results. However, the HCO^+ abundance still remains a factor of 10 lower than the observed one.

Some of the underabundant species in M82 like SiO are well-known shock chemistry tracers. This suggests that shocks are not the dominant mechanism at work in the galaxy disk. This is consistent with the interpretation of M82 as an evolved starburst compared to NGC 253. While in NGC 253 the molecular chemistry is determined by the shocks associated with the early stages of star formation, in M82 it is determined by the UV radiation produced by evolved stars and the enhanced cosmic-ray flux (García-Burillo et al. 2002).

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