PHOTODISSOCIATION CHEMISTRY FOOTPRINTS IN THE STARBURST GALAXY NGC 253

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Received 2009 July 29; accepted 2009 October 15; published 2009 November 11

ABSTRACT

UV radiation from massive stars is thought to be the dominant heating mechanism of the nuclear interstellar medium (ISM) in the late stages of evolution of starburst galaxies, creating large photodissociation regions (PDRs) and driving a very specific chemistry. We report the first detection of PDR molecular tracers, namely HOC+ and CO+, and also confirm the detection of the PDR tracer HCO toward the starburst galaxy NGC 253, claimed to be mainly dominated by shock heating and in an earlier stage of evolution than M 82, the prototypical extragalactic PDR. Our CO+ detection suffers from significant blending to a group of transitions of $^{13}$CH_2OH, tentatively detected for the first time in the extragalactic ISM. These species are efficiently formed in the highly UV-irradiated outer layers of molecular clouds, as observed in the late stage nuclear starburst in M 82. The molecular abundance ratios we derive for these molecules are very similar to those found in M 82. This strongly supports the idea that these molecules are tracing the PDR component associated with the starburst in the nuclear region of NGC 253. The presence of large abundances of PDR molecules in the ISM of NGC 253, which is dominated by shock chemistry, clearly illustrates the potential of chemical complexity studies to establish the evolutionary state of starbursts in galaxies. A comparison with the predictions of chemical models for PDRs shows that the observed molecular ratios are tracing the outer layers of UV-illuminated clouds up to two magnitudes of visual extinction. We combine the column densities of PDR tracers reported in this paper with those of easily photodissociated species, such as HNCO, to derive the fraction of material in the well-shielded core relative to the UV-pervaded envelopes. Chemical models, which include grain formation and photodissociation of HNCO, support the scenario of a photo-dominated chemistry as an explanation to the abundances of the observed species. From this comparison, we conclude that the molecular clouds in NGC 253 are more massive and with larger column densities than those in M 82, as expected from the evolutionary stage of the starbursts in both galaxies.

Key words: galaxies: abundances – galaxies: individual (NGC 253) – galaxies: ISM – galaxies: starburst

1. INTRODUCTION

Intense UV radiation from massive stars is one of the main mechanisms responsible for the heating of the interstellar medium (ISM) in the nuclear region of starburst galaxies. This mechanism is particularly important in the latest stages of starburst (SB) galaxies where the newly formed massive star clusters are responsible for creating large photodissociation regions (PDRs). This is the case for the prototypical SB galaxy M 82, where the large observed abundances of molecular species such as HCO, HOC+, CO+, and H_2O^+ are claimed to be probes of the high ionization rates in large PDRs formed as a consequence of star clusters are responsible for creating large photodissociation regions (PDRs) and driving a very specific chemistry. We report the first detection of PDR molecular tracers, namely HOC+ and CO+, and also confirm the detection of the PDR tracer HCO toward the starburst galaxy NGC 253, claimed to be mainly dominated by shock heating and in an earlier stage of evolution than M 82, the prototypical extragalactic PDR. Our CO+ detection suffers from significant blending to a group of transitions of $^{13}$CH_2OH, tentatively detected for the first time in the extragalactic ISM. These species are efficiently formed in the highly UV-irradiated outer layers of molecular clouds, as observed in the late stage nuclear starburst in M 82. The molecular abundance ratios we derive for these molecules are very similar to those found in M 82. This strongly supports the idea that these molecules are tracing the PDR component associated with the starburst in the nuclear region of NGC 253. The presence of large abundances of PDR molecules in the ISM of NGC 253, which is dominated by shock chemistry, clearly illustrates the potential of chemical complexity studies to establish the evolutionary state of starbursts in galaxies. A comparison with the predictions of chemical models for PDRs shows that the observed molecular ratios are tracing the outer layers of UV-illuminated clouds up to two magnitudes of visual extinction. We combine the column densities of PDR tracers reported in this paper with those of easily photodissociated species, such as HNCO, to derive the fraction of material in the well-shielded core relative to the UV-pervaded envelopes. Chemical models, which include grain formation and photodissociation of HNCO, support the scenario of a photo-dominated chemistry as an explanation to the abundances of the observed species. From this comparison, we conclude that the molecular clouds in NGC 253 are more massive and with larger column densities than those in M 82, as expected from the evolutionary stage of the starbursts in both galaxies.

Key words: galaxies: abundances – galaxies: individual (NGC 253) – galaxies: ISM – galaxies: starburst

OBSERVATIONAL EVIDENCES POINT TO A SIGNIFICANT ENHANCEMENT IN THE ABUNDANCE OF HOC+ IN REGIONS WITH LARGE IONIZATION RATES. Low ratios of [HCO+]/[HCO] = 270 is found in the prototypical Galactic PDRs of the Orion Bar (Apponi et al. 1999). Similar or even lower abundance ratios are observed in the PDRs NGC 7023 (50–120, Fuente et al. 2003), Sgr B2(OH) and NGC 2024 (360–900; Ziurys & Apponi 1995; Apponi & Ziurys 1997), and the Horsehead (75–200; Goicoechea et al. 2009), as well as in diffuse clouds (70–120; Liszt et al. 2004). This is in contrast with the much larger ratios of ≳ 1000 found in dense molecular clouds well shielded from the UV radiation. However, these low HCO+/HOC+ ratios are not found in other galaxies. Large values of this ratio of ≳ 2000 are found in the PDRs M17–SW, S140, and NGC 2023 (Apponi et al. 1999; Savage & Ziurys 2004). The HCO molecule has also been observed to be a particularly good tracer of the PDR interfaces. Low ratios of [HCO+]/[HCO] = 2.5–30 are found in prototypical Galactic PDRs (Schenewerk et al. 1988; Schilke et al. 2001). The large HCO abundance (∼ 1010) altogether with the low ratio [HCO+]/[HCO] = 1 in the Horsehead PDR is claimed to be a diagnostic for an ongoing FUV-dominated photochemistry (Gerin et al. 2009). CO+ is also claimed to be a particularly prominent in the chemical modeling of PDRs, and high abundances of this molecule appear to be correlated to similar enhancements of HOC+ (Starmberg & Dalgarno 1995; Savage & Ziurys 2004). [CO+]/[HOC+] ratios in the range of 1–10 are observed in a number of PDRs (Savage & Ziurys 2004), but only of ≳ 0.1 toward the Horsehead PDR (Goicoechea et al. 2009).

As mentioned above, this set of PDR probes has been extensively studied toward M 82. However, no such complete studies have been carried out toward other prototypical galaxies, but for the detection of HCO and HOC+ toward NGC 1068 (Usset al. 2004) and H_2O+ in Arp 220 (van der Tak et al. 2008). M 82 and NGC 253 are the brightest prototypes of nearby SB galaxies, at a similar distance and showing very similar IR luminosities and star formation rates of 3 M_☉ yr⁻¹ (Ott et al. 2005; Minh et al. 2007). However, both galaxies show very different chemical composition. The chemistry and to a large extend the heating in the central region of NGC 253 are believed to be dominated by large-scale low-velocity shocks (Martín et al. 2006b). The similar chemical composition found in the nuclear region of NGC 253 to that in Galactic star-forming molecular complexes points to an earlier evolutionary stage of...
the starburst in this galaxy than that in M 82 (Martín et al. 2003, 2005, 2006b).

Furthermore, our recent observations of the PDR component as traced by the easily photodissociated HNCO molecule toward a sample of galaxies (Martín et al. 2008) showed the non-detection of HNCO in M 82, at a very low abundance limit. This low HNCO abundance supports the scenario that the PDR chemistry dominates the molecular composition of the ISM in this galaxy. However, from the HNCO measured abundance in NGC 253, it would be placed in an intermediate stage of evolution where photodissociation should be starting to play a significant role in driving a UV-dominated chemistry which has not yet been identified toward this galaxy. The presence of a significant PDR component in NGC 253 claimed from the HNCO measured abundance chemistry dominates the molecular composition of the ISM in both M 82 and NGC 253.

In this paper, we present the first detection of PDR molecular tracers HOC* and CO*, and confirm the detection HCO* (tentatively detected by Sage & Ziurys 1995) in the central region of NGC 253 which allows the evaluation of the influence of the photodissociation radiation in the nuclear ISM of this SB galaxy. The results presented here support the scenario of the presence of a significant PDR component and clearly show the potential of molecular complexity in estimating the contribution of the different heating mechanisms of the ISM in the nuclei of galaxies.

2. OBSERVATIONS AND RESULTS

The observations presented in this paper were carried out at the IRAM 30 m and JCMT telescopes on Pico Veleta, Spain, and Mauna Kea, USA, respectively.

2.1. IRAM 30 m

The IRAM 30 m observations were performed in a symmetrical wobbler switched mode with a frequency of 0.5 Hz and a beam throw of 4″ in azimuth. The 516 × 1 MHz filter banks were used as spectrometers.

We have observed the transitions of C18O J = 1 − 0 (109.782 GHz), HCO* J = 1 − 0 (89.188 GHz), HOC* J = 1 − 0 (89.487 GHz), and 3 − 2 (268.451 GHz), and the HCO 1,0,1 − 0,0,0 (86.670 GHz). Beam sizes at these frequencies were 22″, 28″, and 9″. The nominal position for the observation was α2000 = 00h47m33.3s, δ2000 = −25°17′23″ for HCO* and HOC*, matching up the position used for the 2 mm line survey (Martín et al. 2006b). The data on C18O and HCO were centered at α2000 = 00h47m33.5s, δ2000 = −25°17′27″. The two positions are separated by <5″ which, considering the 3 mm beam sizes, should have a negligible influence in the relative intensities. Double Gaussian profiles have been fitted to all observed transitions, and the corresponding derived fitting parameters are summarized in Table 1.

Figure 1 shows the simultaneously observed J = 1 − 0 features of HCO* and HOC* compared to the C18O J = 1 − 0 line profile. Although at this frequency the SIS receivers image band rejection is larger than 20 dB, we observed the HOC* line tuned to two different velocities (250 and 500 km s−1) in order to confirm that the observed profile was not line emission coming from the upper sideband. Figure 1 shows the average of both observations. The HCO* J = 1 − 0 was detected at the edge of the band covered in the 500 km s−1 tuning of HOC*. Although pointing accuracy was of the order of 3″, the different shapes observed for the HCO* and HOC* are attributed to a small change in the pointing position during the two observations. This effect accounts for an uncertainty in the integrated intensity of <10%. Even though the HCO* feature was not completely observed between the HCO+ and HOC+ are attributed to a small band rejection is larger than 20 dB, we observed the HOC+ line profile. Although at this frequency the SIS receivers image band rejection is larger than 20 dB, we observed the HOC+ line tuned to two different velocities (250 and 500 km s−1) in order to confirm that the observed profile was not line emission coming from the upper sideband. Figure 1 shows the average of both observations. The HCO* J = 1 − 0 was detected at the edge of the band covered in the 500 km s−1 tuning of HOC*. Although pointing accuracy was of the order of 3″, the different shapes observed for the HCO+ and HOC+ are attributed to a small change in the pointing position during the two observations. This effect accounts for an uncertainty in the integrated intensity of <10%. Even though the HCO+ feature was not completely

\[ \text{Table 1 Parameters Derived from the Observed Line Profiles} \]

| Transition | \( \frac{\Delta \nu}{\nu_{\text{LSR}}} \) (K km s\(^{-1}\)) | \( \Delta \nu_{1/2} \) (K km s\(^{-1}\)) | \( T_{MB} \) (mK) |
|------------|-----------------|-----------------|-----------------|
| C18O J = 1 − 0 | 3.1 ± 0.6 | 183 ± 13 | 100 ± 9 | 116.75 |
|            | 6.0 ± 0.8 | 283 ± 7 | 100 ± 9 | 223.48 |
| HCO* J = 1 − 0 | 21.98 ± 1.1 | 177.9 ± 0.4 | 118.1 ± 0.3 | 174.9 |
|            | 35.79 ± 1.4 | 289.0 ± 0.3 | 118.1 ± 0.3 | 284.8 |
| HOC* J = 1 − 0 | 0.8 ± 0.2 | 170 ± 10 | 100 ± 20 | 7.6 |
|            | 1.0 ± 0.2 | 282 ± 9 | 100 ± 20 | 9.2 |
| HOC* J = 3 − 2 | <0.8b | | | 13.9 |
| HCO 10,1 − 0,0,0 | 0.41 ± 0.08 | 183 ± 14 | 102 ± 4 | 3.8 |
|            | 0.43 ± 0.08 | 297 ± 13 | 102 ± 4 | 3.9 |
| H13CO+ J = 1 − 0 | 1.26 ± 0.09 | 176 ± 6 | 102 ± 4 | 11.6 |
|            | 1.36 ± 0.10 | 285 ± 5 | 102 ± 4 | 12.5 |
| SiO 2 − 1 | 1.52 ± 0.11 | 182 ± 5 | 102 ± 4 | 13.9 |
|            | 1.59 ± 0.11 | 292 ± 5 | 102 ± 4 | 14.6 |
| HCN J = 5 − 4 | 1.05 ± 0.15 | 191 ± 7 | 95 ± 18 | 10.5 |
| CO 3/2 − 3/2F = 2 − 1 | 0.30 ± 0.10 | 191c | 95c | 3.0 |
|            | 0.17 ± 0.10 | 191c | 95c | 1.6 |
| H3CCH J = 3/2 − 1/2 | 0.10 ± 0.07 | 191c | 95c | 1.0 |
|            | 0.16 ± 0.07 | 191c | 95c | 1.6 |

Notes:

a Line widths forced to have the same value in the Gaussian fit.

b 3σ upper limit assuming a 200 km s\(^{-1}\) line width.

c Parameters forced to equal those derived from HCN J = 5 − 4 Gaussian fit.
blended to the latter. With a significantly improved signal-to-noise ratio, we confirm the previous tentative detection of this HCO transition reported by Sage & Ziurys (1995) with the NRAO 12 m telescope. Moreover, using the main beam brightness temperature from Sage & Ziurys (1995) of \( \sim 1 \) mK with at 72'' beam and our observed \( \sim 4 \) mK with a 28'' beam, we can make an estimate of the emitting source extent of \( > 20'' \). The double Gaussian profiles fitted to each species were constrained to have similar line widths. The resulting fitted line positions agree within the errors to those expected from the rest frequencies of each line. Figure 2 shows the results of the fit superimposed on the observations as well as the position of the hyperfine structure lines of HCO. Only the brightest of the group \( (F = 2 - 1) \) has been taken into account for the fit. Assuming optically thin emission, the \( F = 2 - 1 \) and \( F = 1 - 1 \) transitions (at 86,708 and 86,777 GHz) are expected to show an intensity half of the main transition, but they are completely blended to the latter. With a significantly improved signal-to-noise ratio, we confirm the previous tentative detection of this HCO transition reported by Sage & Ziurys (1995) with the NRAO 12 m telescope. Moreover, using the main beam brightness temperature from Sage & Ziurys (1995) of \( \sim 1 \) mK with at 72'' beam and our observed \( \sim 4 \) mK with a 28'' beam, we can make an estimate of the emitting source extent of \( > 20'' \). The double Gaussian profiles fitted to each species were constrained to have similar line widths. The resulting fitted line positions agree within the errors to those expected from the rest frequencies of each line. Figure 2 shows the results of the fit superimposed on the observations as well as the position of the hyperfine structure lines of HCO. Only the brightest of the group \( (F = 2 - 1) \) has been taken into account for the fit. Assuming optically thin emission, the \( F = 2 - 1 \) and \( F = 1 - 1 \) transitions (at 86,708 and 86,777 GHz) are expected to show an intensity half of the main transition, but they are completely blended to the H\(^{13}\)CO\(^+\) emission. The \( F = 0 - 1 \) transition at 86.805 GHz is expected to be even fainter by a factor of 5, well below our detection limit. Figure 2 shows (in the dotted line) a synthetic spectrum of HCO, assuming one velocity component centered at 255 km s\(^{-1}\) with a line width of 192 km s\(^{-1}\) (as derived if only one component is fitted to the spectrum from the other lines) and a peak intensity of the HCO \( F = 2 - 1 \) line of 3.6 mK. This shows that the fainter HCO hyperfine transitions may account for up to a 10\%\textendash{}20\% of the H\(^{13}\)CO\(^+\) integrated intensity.

### 2.2. JCMT

JCMT observations were performed in a beam switched mode with a frequency of 1 Hz and beam throw of 2'' in azimuth. The ACSIS digital auto-correlator spectrometer was used with a bandwidth of 1600 MHz providing a resolution of \( \sim 1 \) MHz.

We have used the receiver A3 to observe the CO\(^+\) transition at 236.062 GHz. At this frequency, the beam size of the telescope is 21'' and the main beam efficiency 0.69. The observations were carried toward the nominal position \( \alpha_{J2000} = 00^h 47^m 33^s 1, \delta_{J2000} = -25^\circ 17' 18'' \) (radio continuum position; Douglas et al. 1996). As seen in the HCO\(^+\) \( J = 25 - 24 \) profile, most of the emission is observed from one of the velocity components at this position, which is due to the JCMT observed position being \( \sim 6'' \) and 10'' away from those observed with the IRAM 30 m, respectively. This position is half-beam away from the positions observed with the IRAM 30 m, so the abundance ratios derived from this observation might be affected by a larger uncertainty of up to a factor of 2. However, this effect might be attenuated by the emission being extended over scales of \( > 20'' \).

As shown in Figure 3, the CO\(^+\) \( 5\)-\( 3 \) transition is clearly detected above the noise level (\( \sim 1.5 \) mK in 30 km s\(^{-1}\) channels). However, we observe its profile significantly blended to that of the group of transitions of \( \sim 1m K \) is assumed. We have estimated the fractional abundances of the newly observed species in NGC 253 assuming optically thin emission, LTE conditions, and similar spatial distribution for all species. Under these assumptions, we have calculated the column densities of H\(^{13}\)CO\(^+\), HOC\(^+\), HCO, and CO\(^+\) for an excitation temperature \( T_ex = 15 \pm 5 \) K and an estimated source extent for each velocity component of 10''. The \( T_ex = 15 \pm 5 \) K is assumed based on the average rotational temperatures derived from most of the species detected toward NGC 253 (Martín et al. 2006b). Indeed the non-detection of HOC\(^+\) \( 3 \) implies low excitation.

### 3. MOLECULAR ABUNDANCES AND RATIOS

We have estimated the fractional abundances of the newly observed species in NGC 253 assuming optically thin emission, LTE conditions, and similar spatial distribution for all species. Under these assumptions, we have calculated the column densities of H\(^{13}\)CO\(^+\), HOC\(^+\), HCO, and CO\(^+\) for an excitation temperature \( T_ex = 15 \pm 5 \) K and an estimated source extent for each velocity component of 10''. The \( T_ex = 15 \pm 5 \) K is assumed based on the average rotational temperatures derived from most of the species detected toward NGC 253 (Martín et al. 2006b). Indeed the non-detection of HOC\(^+\) \( 3 \) implies low excitation.
temperatures of $T_{\text{ex}} \sim 10$ K. Both the excitation temperature and the emission extent have an important impact in the absolute derived column densities by up to a factor of 2; however, the fractional abundances and abundance ratios are mostly independent of these assumptions. We assume that the emission extent is similar for all observed species. Table 2 presents the column densities and fractional abundance ratios with respect to H$_2$ for all the species. The total H$_2$ column density has been derived from the C$^{18}$O column density for each velocity component assuming an isotopic ratio of $^{16}$O/$^{18}$O = 150 (Harrison et al. 1999) and a CO/H$_2$ = 10$^{-4}$.

The most abundant molecule in the nucleus of NGC 253 (Martín et al. 2006b).

4. DISCUSSION: THE PDR COMPONENT IN NGC 253

4.1. NGC 253 in Context

Table 3 shows the HCO$^+$/HOC$^+$, HCO$^+$/HCO, and HCO$^+$/CO$^+$ abundance ratios resulting from our measurements in NGC 253 compared to those of the similar SB galaxy M 82, and the Seyfert 2 with nuclear SBs, NGC 1068, and NGC 4945, together with prototypical galactic PDRs, where observations of these species have been reported. For the sake of consistency, the abundance ratios of the other galaxies have been calculated from the available line profiles obtained from the literature. As already explained before, for this comparison, we used H$^{13}$CO$^+$ to derive the HCO$^+$ column densities in order to avoid the opacity effects. We have assumed the isotopic ratio of $^{12}$C/$^{13}$C = 40 (Henkel et al. 1993) to derive the column densities of the main isotopologue. For M 82, the HCO$^+$/HOC$^+$ and HCO$^+$/CO$^+$ abundance ratio have been derived from the observations by Fuente et al. (2006) toward the Eastern molecular lobe. Our measured ratios are $\sim$59 and $\sim$0.8, which are $\gtrsim$30% larger that the ratios derived by Fuente et al. (2006). This difference is due to the significant missing flux of the H$^{13}$CO$^+$ interferometric maps (García-Burillo et al. 2000) they used for comparison, as well as the higher $^{12}$C/$^{13}$C ratio they used to compare with single dish HCO$^+$ observations. By comparing the convolved integrated intensity from the $^{13}$CO$^+$ interferometric maps by García-Burillo et al. (2000) toward the western lobe, Fuente et al. (2006) and the single dish data of by Mauersberger & Henkel (1991) toward a nearby position, we have estimated a $\gtrsim$50% missing flux. Thus, we used the H$^{13}$CO$^+$1 - 0 data
by Mauersberger & Henkel (1991) in our measured ratios. The ratios toward NGC 1068 were derived for the regions within the galaxy where line intensities were tabulated by Usero et al. (2004). The observations from Wang et al. (2004) were used to derive the HCO+/HCO ratio toward NGC 4945.

4.1.1. PDR Abundance Ratios in SB Galaxies

We find that the three derived HCO+/HOC+, HCO+/HCO, and HCO+/CO+ abundance ratios in the two starbursts, NGC 253 and M 82, are equivalent within the measurement errors. The ratios are also in reasonable good agreement to those found in galactic sources with similar FUV fluxes (see Table 3). Such high abundance ratios of HOC+, HCO, and CO+ relative to HCO+ have been claimed to be the evidence of M 82 being mostly dominated by photodissociation. We note that the average HCO+/HCO ratio in NGC 253 is even lower than that measured in M 82. In the case of HCO, the interferometric maps of M 82 clearly resolve the spatial variations in this ratio across the galaxy nuclear region. However, toward the region of peak HCO emission in the M 82 maps, we find a ratio of $\frac{\mathrm{HCO}}{\mathrm{HCO}} \sim 0.12 \pm 0.04$, equivalent to the average observed toward NGC 253. Our data show that the ISM in the nuclear region in NGC 253 must be significantly pervaded by a strong UV radiation flux from the massive star clusters formed in the starburst, as also suggested by the study of the abundances of the HNCO/CS ratio (Martín et al. 2009). Moreover, these new observations would imply that photodissociation plays a similar role in the ISM heating of both NGC 253 and M 82.

4.1.2. PDR Abundance Ratios in AGN Galaxies

Both HCO+/HCO and HCO+/HOC+ abundance ratios in NGC 1068 are different by a factor 2–3 from those of NGC 253 and M 82. Furthermore, HCO+/HCO is also found to be up to a factor of $\sim 2$ lower in the ring of star formation than toward the nuclear region. Like in NGC 253, these ratios are consistent with the decrease in the abundance of molecules such as HNCO from the nuclear region to the starburst ring (Martín et al. 2009). The tentative detection of HCO in the circumnuclear disk (CND) of NGC 1068 (Usero et al. 2004), suggests a rough $\frac{\mathrm{HCO}}{\mathrm{HCO}}$ to HCO line intensity ratio of $\sim 2$–3, which turns into an abundance ratio in the range of $\sim 0.09$–0.13, closer to the values derived in SB-dominated galaxies. This value at the CND can be significantly biased by the emission from the star-forming ring covered at half-power by the 28″ beam. Therefore, it is clear that this ratio does not significantly decrease toward the nuclear active galactic nucleus (AGN) in this galaxy with the typical angular resolution of 20″–30″. On the other hand, the ratio HCO+/HOC+ is only a factor of 2 lower in the SB galaxies than the nuclear AGNs in NGC 1068. From these observations, it is unclear whether photodissociation does play a major role in the AGN-dominated center of NGC 1068. Unfortunately, no observations of HOC+ are available toward the SF ring in this galaxy.

Similar to NGC 1068, the obscured Seyfert 2 nucleus in NGC 4945 is surrounded by a starburst ring more prominent than in NGC 1068 (Genzel et al. 1998). The HCO+/HCO ratio found in NGC 4945 is even lower than that found in the other galaxies. However, the fit to these lines was claimed to be very uncertain by Wang et al. (2004).

4.2. Comparison to PDR Chemical Models

We have compared our observed fractional abundances and abundance ratios with those predicted by the UCL_PDR model (Bell et al. 2006). The UCL_PDR code is a time- and depth-dependent one-dimensional PDR model that simultaneously solves the chemistry, thermal balance, and radiative transfer within a cloud (see Bell et al. 2006, for more details). We have adopted a hydrogen density of $10^5 \text{cm}^{-3}$, a radiation field $G_0 \sim 5000$ in units of the Habing field, and a cosmic radiation rate of $10^{-16}$. The high density of $10^5 \text{cm}^{-3}$ is derived from the multiline analysis of CS and HC$_3$N (Bayet et al. 2008, 2009; R. Aladro et al. 2010, in preparation). Our estimates of the cloud structure (see Section 4.3) depend on the averaged radiation field which might be different in both galaxies. The averaged radiation fields in both NGC 253 and M 82 have been inferred from the fine structure lines, and they are of 2 x $10^4$ and $10^3$, respectively, with large errors of a factor of 2 (Carral et al. 1994; Lord et al. 1996). This would imply that the PDR envelope should be larger in the clouds of NGC 253 than in M 82. Since we do not aim to quantitatively model the particular abundances measured in NGC 253 but to investigate the physical conditions that would give rise to the wealth of observed molecules in starburst, the value of $G_0 = 5 \times 10^4$ is used as a geometric mean value derived from the fine structure lines in both galaxies. Given that our estimates of the $A_\nu$ for the PDR are based on this geometric mean, the expected changes in $A_\nu$ for the two galaxies would be just a factor of 1.6.

We have run two different models: Model A is a standard time-dependent gas-phase PDR model where the initial composition is atomic, while Model B is computed using a coupled dense core-PDR model where the diffuse material, initially also purely atomic and gaseous, collapses to reach a final density of $10^4 \text{cm}^{-3}$. During the collapse, the gas depletes on the grains forming icy mantles which remain on the dust until irradiation from a UV field is switched on, evaporation occurs, and the typical PDR chemistry takes place. In both models, the temperature is calculated self-consistently at each depth and time step by thermal balance. Figure 4 shows the predicted abundances and abundance ratios as a function of visual extinction ($A_v$) for Models A (left panels) and B (right panels). HNCO and CH$_3$OH results are only shown for Model B in Figure 4.

Observed abundances of HCO+ and HOC+ toward NGC 253 (shown as horizontal lines in the key of Figure 4) are well reproduced by the models for very low extinction of $A_v \sim 1$–2. The HCO abundance observed is a factor 2–6 above the maximum predicted by the Model B. It is important to take into account that while we assumed a ratio CO/H$_2$ = $10^{-4}$ to calculate the fractional abundances, this ratio is not constant in the models and hardly ever reaches this value. On the other hand, the abundance ratios of the observed molecules, unaffected by the hydrogen determination uncertainty, agree well with the model predictions. The model shows that the abundances of CO+ follows the same pattern as HOC+. The correlation between these two molecules was also predicted by previous theoretical studies (Sternberg & Dalgarno 1995; Savage & Ziurys 2004). Thus, CO+ measurement allows us to confirm the effect of photodissociation suggested by the large abundance of HOC+.

The ions HOC+, CO+, and HOC+ are mostly formed at the edge of the cloud and while the two models predict similar abundances for these ions, it is worth noting that the observed abundances of other species such as HNCO, CH$_3$OH, or HOCO+ can only be explained with Model B. However, HNCO and CH$_3$OH only reach observable abundances for $A_v \sim 5$ mag. This implies that, while photodissociation does play an important role in the chemistry of NGC 253, the molecular clouds affected by the UV radiation must contain
Figure 4. Theoretical predictions for the fractional abundances relative to H$_2$ (upper panels) and abundance ratios (lower panels) for the observed species as derived from the two different PDR models: a pure gas-phase model A (left panels) and a coupled dense core-PDR model B (right panels). Details are given in Section 4.2. The vertical position of the key for each molecule and ratio shown only in the plots for Model A correspond to the actual derived parameters from the observations. Additionally, the fractional abundances of CH$_3$OH and HNCO are shown for Model B.

4.3. The Molecular Clouds in SB Galaxies

Martín et al. (2008) have used a comparison with the GC molecular clouds to propose another PDR diagnostic based on the relative abundance of HNCO to CS. The large variation of the HNCO/CS abundance ratio between UV radiated clouds to those well-shielded clouds only affected by shocks was interpreted as the fast photodissociation of the fragile molecule HNCO, efficiently produced on the icy mantles and delivered into gas phase by low-velocity shocks. Similarly, in a sample of nearby galaxies, Martín et al. (2009) found changes of nearly two orders of magnitude from the shock-dominated chemistry in M 83 and IC 342 to UV-dominated chemistry in M 82. The extremely low HNCO abundance in M 82 and the large abundances of HCO, HOC$^+$, and CO$^+$ support the idea that the HNCO/CS ratio is a measure of the relative importance of the UV heating to shock heating and the evolutionary state of the starburst in galaxies.

The detection of HCO, HOC$^+$, and CO$^+$ in NGC 253 with similar column densities and abundance to those in M 82 suggest that the PDR component is similar in both galaxies as suggested by the similar atomic line structure and CO emission lines in both galaxies. The results of Model B confirm the observational trends observed in NGC 253 and other PDR molecules in galaxies. For molecular clouds with $A_v \sim 1–2$ (i.e., column densities of $(1–2) \times 10^{21}$ cm$^{-2}$) illuminated by a strong UV radiation field like in the galaxies in our sample, HNCO, and CH$_3$OH are largely photodissociated and only HCO, HOC$^+$, and CO$^+$ should be observed like in M 82 (Martín et al. 2006a, 2009). Then, not very massive molecular clouds and widely translucent to the UV radiation should dominate in M 82. On the other hand, for galaxies with massive molecular clouds (large visual extinction) or low UV radiation fields, HNCO, and CH$_3$OH are well shielded and the abundance ratio of HNCO/CS will reach its maximum value. Considering that M 83 and IC 342 represent the stage of galaxies with an extremely low PDR component, the lower HNCO/CS ratios measured for NGC 253, NGC 4945, and NGC 1068 indicate that the PDR component must be substantial, as observed in other PDR tracers.

For NGC 253, we find that the PDR component is similar to that in M 82, but the total column density of dense gas is a factor of 2–3 larger in NGC 253 than in M 82 from the low HNCO and CH$_3$OH abundance in the latter. Considering the PDR column densities in both galaxies are similar, this component should represent about 1/3–1/2 of the total molecular column density in NGC 253. This is roughly consistent with the decrease by a factor of 2–3 of the HNCO/CS ratio as compared with that of M 83 or IC 342 (Martín et al. 2009). This suggests that the molecular cloud’s properties in M 82 and NGC 253 must be quite different in terms of the total molecular column density, which implies that the sizes or the densities are different, or a combination of both. Using the atomic fine structure and CO emission lines, Carral et al. (1994) and Lord et al. (1996) have also proposed that the clouds in M 82 and NGC 253 are quite different. The clouds in NGC 253 are slightly smaller than those...
in M 82, but with masses a factor of 15 larger than for M 82. The NGC 253 average cloud column densities are therefore a factor of 20 larger than in M 82. Though the total column densities of the M 82 clouds inferred from the atomic fine structure lines are a factor of 5 larger than those predicted from the PDRs tracers and the HNCO abundance in this galaxy, similar constraints are derived from both the molecular and the atomic tracers. Therefore, the clouds in NGC 253 are more massive than in M 82.

We can even make a very rough estimate of the average properties and structure of the molecular clouds in NGC 253 and M 82 by combining the complementary information obtained from the PDR tracers presented in this paper and the HNCO column densities from Martín et al. (2009). While HCO, HOC+, and CO+ mainly trace the PDR region up to $A_v = 4-5$ (i.e., $H_2$ column densities of $5 \times 10^{21}$ cm$^{-2}$), the HNCO emission only arises from the well-shielded core ($A_v > 7$) of the molecular clouds. The HCO, HOC+, and CO+ column densities in NGC 253 and M 82 indicate similar averaged column densities in the PDR envelopes of the molecular clouds in both galaxies. The big difference in the molecular cloud structure in both galaxies is in the size ($H_2$ column density) of the well-shielded cores of the molecular clouds. In the case of M 82, where HNCO has not been detected, we can set an upper limit to the HNCO column density of $7 \times 10^{22}$ cm$^{-2}$. This translates to a upper limit to the core $H_2$ column density of $\lesssim 3 \times 10^{20}$ cm$^{-2}$ for the HNCO fractional abundance of 2 \times 10^{-8} derived for the well-shielded clouds in the galactic center (Martín et al. 2008). The averaged shielded cloud cores in M 82 are smaller by more than one order of magnitude than the PDR envelope. In the case of NGC 253, the $H_2$ column densities of the shielded cloud cores are $10^{22}$ cm$^{-2}$, a factor of 2 larger than the PDR envelope. Assuming a similar averaged density distribution in the molecular clouds in both galaxies, the clouds in NGC 253 would be a factor 2–3 larger than in M 82.

4.4. The Contribution X-ray Induced Chemistry

The PDR model presented by Fuente et al. (2006) failed to reproduce the large CO+ column density of a few $10^{13}$ cm$^{-2}$ observed toward M 82. This led Spaans & Meijerink (2007) to explore the possibility of an enhanced X-ray induced chemistry in this galaxy. Spaans & Meijerink (2007) concluded that such high formation of CO+ can only be explained by X-ray-irradiated molecular gas with densities of $10^3$–$10^5$ cm$^{-3}$. Although the X-ray luminosity of NGC 253 is a factor of 2–4 below that of M 82, both galaxies have a significant X-ray emission in the range of $\sim 10^{40}$ erg s$^{-1}$ (Cappi et al. 1999). Similar to M 82, the NGC 253 total CO+ column density is $(3.6 \pm 1.1) \times 10^{13}$ cm$^{-2}$. Moreover, both show a similar HCO+/CO+ ratio of $\sim 30$–40.

The models presented in this paper are able to produce such column densities for visual extinctions of $A_v \sim 3$–5 for Model A, and $A_v \sim 0.5$–1 for Model B. These models have been calculated with a radiation field, a cosmic ray flux, and a $H_2$ density smaller by a factor of 2, 40, and 4, respectively, with respect to those assumed in the models of Fuente et al. (2006). Furthermore, we are able to reproduce the abundances and abundance ratios measured for all the other observed species presented in this paper. van der Tak et al. (2008) showed how the measured abundance of $H_2$O+ in M 82 can be both produced by the PDR with a high cosmic-ray ionization or by an X-ray dominated region (XDR). Indeed, an increase of cosmic-ray ionization rate in PDR models may be qualitatively used to simulate XDR-like environments. Our models, however, do not use particularly high cosmic-ray fluxes (a factor of 5 higher than standard). Thus, though the X-ray irradiation is substantial in SB galaxies, the PDR models presented in this paper can reproduce the molecular abundances observed toward the brightest prototypes, M 82 and NGC 253. Moreover, no significant changes in the abundances of HOC+ and HCO are found toward the nuclear AGN of NGC 1068, where X-ray radiation is significantly more important than in SB nuclei, as shown in Section 4.1.2. Unfortunately, no CO+ observation has been reported toward this Seyfert 2 nucleus.

5. CONCLUSIONS: THE PERVERSING UV FIELD IN EVOLVED STARBURST

The comparison of model predictions with the observations presented shows that the abundance of the species observed in this work toward NGC 253, namely HCO+, CO+, and HCO, are most efficiently formed in the outer region of the molecular clouds where the gas is highly irradiated by the incident UV photons from massive stars. The high molecular abundances derived for these species in NGC 253 suggest that the PDR component in this galaxy is similar to that found in M 82, and claimed to be the prototype of the extragalactic PDR. The abundance ratios found for this limited sample of galaxies are of the same order as those observed toward galactic PDRs, which stress the importance of photo-dominated chemistry in galaxy nuclei. Large amounts of molecular material are affected by photodissociation not only in NGC 253, but also toward the star-forming regions around the Seyfert 2 nuclei in NGC 4945 and NGC 1068. This is consistent with the HNCO/CS ratio in these galaxies which suggest that a fraction of HNCO have been photodissociated in PDRs. The combination of the observations of HCO, HOC+, and CO+ with that of HNCO seems to confirm that their abundances reflect the evolutionary stage of the starbursts in these galaxies. Although photodissociation is the most likely scenario for the enhancement of the observed reactive ion in starburst environments, X-ray-dominated chemistry has been claimed to be responsible for the high abundances observed around AGNs in the CND of NGC 1068 (HOC+; Usero et al. 2004) and toward the ultraluminous infrared galaxy Arp 220 (H$_2$O+; van der Tak et al. 2008).

Therefore, M 82 is still outstanding not only as a PDR-dominated galaxy, but also by the underabundance of complex molecules such as CH$_3$OH, HNCO, or SiO (Mauersberger & Henkel 1993; Martín et al. 2006a, 2006b), evidence for the lack of large amounts of dense molecular material which would potentially fuel its nuclear starburst as compared to other starburst galaxies like NGC 253 (Martín et al. 2009). Our data in combination with the HNCO abundances (Martín et al. 2009) indicate that the molecular clouds in M 82 are different from those in NGC 253. Although having a similar overall PDR component, the clouds in NGC 253 have to be more massive and have larger column densities than those in M 82.

This work has been partially supported by the Spanish Ministerio de Ciencia e Innovación under project ESP2007-65812-C02-01 and by the “Comunidad de Madrid” Government under PRICIT project S-0505/ESP-0237 (ASTROCAM). Facilities: IRAM 30 m, JCMT.

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