WIDESPREAD HCO EMISSION IN THE NUCLEAR STARBURST OF M82

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ABSTRACT

We present a high-resolution (~5") image of the nucleus of M82 showing the presence of widespread emission of the formyl radical (HCO). The HCO map, the first obtained in an external galaxy, reveals the existence of a structured disk of ~650 pc full diameter. The HCO distribution in the plane mimics the ring morphology displayed by other molecular/ionized gas tracers in M82. More precisely, rings traced by HCO, CO, and H II regions are nested, with the HCO ring lying in the outer edge of the molecular torus. Observations of HCO in Galactic clouds indicate that the abundance of HCO is strongly enhanced in the interfaces between the ionized and molecular gas. The surprisingly high overall abundance of HCO measured in M82 [X(HCO) ~ 4 × 10^{-10}] indicates that its nuclear disk can be viewed as a giant photon-dominated region (PDR) of ~650 pc size. The existence of various nested gas rings, with the highest HCO abundance occurring at the outer ring [X(HCO) ~ 0.8 × 10^{-9}], suggests that PDR chemistry is propagating in the disk. We discuss the inferred large abundances of HCO in M82 in the context of a starburst evolutionary scenario, picturing the M82 nucleus as an evolved starburst.

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

1. INTRODUCTION

M82 is the closest galaxy experiencing a massive star formation episode (Rieke et al. 1980; Wills et al. 1999). Its nuclear starburst, located in the central 1 kpc, has been the subject of continuum and line observations made in virtually all wavelengths from X-rays to the radio domain. These studies indicate that the high rate of supernova explosions and the strong UV radiation fields have heavily influenced the physical properties and kinematics of the interstellar medium in M82. The high supernova rate has created a biconical outflow of hot gas (Bregman, Schulman, & Tomisaka 1995; Shopbell & Bland-Hawthorn 1998) also observed in the cold gas and dust (Alton, Davies, & Bianchi 1999; Seaquist & Clark 2001). The discovery of a ~500 pc molecular gas chimney and a giant super-shell in M82, detected in SiO, indicates the occurrence of large-scale shocks in the disk-halo interface of the starburst (García-Burillo et al. 2001). Furthermore, there is evidence that the strong UV fields have created a particular physical environment in the molecular gas reservoir of M82 (Stutzki et al. 1997; Mao et al. 2000; Weiss et al. 2001). The common picture emerging from these studies is that the bulk of CO emission in the nuclear disk of M82 comes from moderately dense (with n(H_2) ~ 10^3–10^4 cm^{-3}) photon-dominated regions (PDRs). However, these conclusions are model dependent and not free from internal inconsistencies (Mao et al. 2000).

Observational evidence supports that the emission of the formyl radical (HCO) mainly arises from PDR at the interfaces between the ionized and molecular gas in our Galaxy. Since the first detection of HCO by Snyder, Hollis, & Ulich (1976), ulterior searches have confirmed that this radical is associated with regions where chemistry is driven by an enhanced UV radiation field (Hollis & Churchwell 1983; Snyder, Schenewerk, & Hollis 1985; Schenewerk et al. 1988; Schilke et al. 2001). On the theoretical side, several chemical models have been put forward to account for the observed abundances of HCO in PDRs (de Jong, Boland, & Dalgaro 1980; Leung, Herbst, & Huebner 1984; Schilke et al. 2001).

We have chosen HCO, a privileged tracer of PDR chemistry, to investigate the influence of the M82 starburst on its molecular gas reservoir. Sage & Zirurys (1995) tentatively detected the emission of HCO at 3 mm in M82, using single-dish observations. However, the HCO lines appear blended with SiO and H^{13}CO^+ lines in their spectrum. Furthermore, the low spatial resolution (50") of their single-pointed map did not allow to infer the spatial distribution of HCO. In this Letter we present a high-resolution (~5") image of the emission of HCO in the nucleus of M82.

The interferometer HCO map of M82, the first obtained in an external galaxy, shows unambiguous evidence that the whole nuclear disk has become a giant PDR of ~650 pc size with a total HCO abundance of ~4 × 10^{-10}. The enhancement of HCO presents spatial variations that depend on the distance to the most prominent H II regions of the M82's starburst.

2. OBSERVATIONS

The HCO observations of M82 were carried out with the Institut de RadioAstronomie Millimétrique array at Plateau de Bure, France, during 1999 June, using the four-antenna CD set of configurations. We observed four of the strongest N_{K,K'} = 1_{01}–0_{00} hyperfine lines of HCO. These transitions form a 3 mm quartet: J = 3/2–1/2, F = 2–1 (86.671 GHz), and J = 1–0 (86.708 GHz); J = 1/2–1/2, F = 1–1 (86.777 GHz), and F = 0–1 (86.806 GHz). We observed simultaneously the J = 2–1 line of SiO (86.847 GHz) and the J = 1–0 line of H^{13}CO^+.
covering the eastern and western lobes are as shown. Hyperfine components of marked by the central filled square. (∼eastward and northward. The major axis has to run parallel to the galaxy major and minor axes, respectively, /H11034 P.A. and H13CO equally affected by this bias. If they were to be corrected, HCO discussion is based on the study of the ratios of lines that are primary beam attenuation. Note however that the bulk of the subtraction of the continuum emission, is 1 mJy beam−1, which corresponds to the 2.2 μm peak. We assume a distance to M82 of Mpc (Sakai & Madore 1999); the latter implies pc. We define the region of M82 (contour levels: 0.024 Jy beam−1). The synthesized beam is almost circular (5′.9 × 5′.6, P.A. = 105°). The rms noise level in 2.5 MHz wide-channel maps, derived from subtraction of the continuum emission, is 1 mJy beam−1 (5 mK). We assume a distance to M82 of D = 3.9 Mpc (Sakai & Madore 1999); the latter implies 1″ ~ 20 pc. We define the x- and y-axes to run parallel to the galaxy major and minor axes, respectively, where x ≥ 0 eastward and y > 0 northward. The major axis has P.A. = 70°, (x, y) offsets are referred to the 2.2 μm peak. Throughout the Letter, line intensities are not corrected from primary beam attenuation. Note however that the bulk of the discussion is based on the study of the ratios of lines that are equally affected by this bias. If they were to be corrected, HCO and H13CO+ intensities should both be multiplied by a factor ~1.3 at the edge of the M82’s nuclear disk (at a ~17″ radius).

3. THE HCO MAP

Figure 1a represents the velocity-integrated intensity map obtained for the strongest hyperfine component (F = 2–1) of the J = 3/2–1/2 line of HCO. This image shows that the emission of HCO is widespread in the nuclear starburst of M82. The bulk of the emission comes from a highly structured disk of ~650 pc full diameter and barely resolved vertical thickness. The HCO distribution in the plane mimics the ring morphology displayed by other molecular gas tracers in M82 (Mao et al. 2000). Two emission peaks at (x, y) = (+16″, −2″) and (−15″, 0″) locate the eastern and western lobes of the HCO ring viewed edge-on. A central clump at (+2″, 0″) is close to the 2.2 μm peak identified as the dynamical center (García-Burillo et al. 2001). With lower statistical significance, we detect out-of-plane emission in a clump at (~9″, 8″). However, the full size of this structure is smaller than the beam, and therefore its reality is doubtful.

Figure 1b shows the spectra of HCO, SiO, and H13CO+ integrated in the regions of the two ring maxima (see Fig. 1a). Gaussian profiles are fitted for the identified lines. Together with the strongest F = 2–1 line, emission of the F = 1–0 component is detected at the 4 α level in the two ring lobes. We have also detected the F = 1–1 and 0–1 transitions in the western and eastern lobes, respectively. We estimate an average F = 2–1/1–0 line ratio of ~3 ± 1 (~1.5 ± 0.5) for the western (eastern) lobe. Within the errors, these ratios are close to the theoretical line ratio of ~1.7, expected for optically thin emission.

Figures 2a and 2b show the HCO-integrated (F = 2–1) intensity contours overlaid with the zero-moment maps of H13CO+ (1–0) (García-Burillo et al. 2001) and 12CO (2–1) (Weiss et al. 2001). Although all images reveal a ringlike distribution of molecular gas in the nucleus of M82, the separation between the east and west lobes differs significantly between HCO (~32″) and both 12CO and H13CO+ (~25″). The HCO emission extends farther out in the disk, especially in the eastern lobe. The HCO torus encircles the molecular torus traced by
H$^{13}$CO$^+$ and CO. Most remarkably, the ring of H II regions (of 10′−15′ size) identified by Brγ (Larkin et al. 1994), Ne II (Achtermann & Lacy 1995), and radio recombination lines (e.g., the H41α map of Seaquist et al. 1996) lies just inside the CO molecular ring. The HCO, CO, and H II rings are nested with HCO lying in the outer edge of the disk. The central HCO maximum is also displaced from the $^{13}$CO/H$^{13}$CO$^+$ hot spot at ($−3′$, $0′$). At smaller scales also, the peaks of HCO appear to avoid the brightest H II regions (see § 4). To interpret the described morphology, we first estimate the spatial distribution of the abundance of HCO in M82 and discuss different scenarios accounting for it. Kinematics of HCO gas in M82’s disk show no significant departures from the general rotation pattern typically displayed by other molecular gas tracers in this galaxy.

4. THE HCO ABUNDANCE MAP IN M82

Figure 3 represents in gray scale the HCO ($F = 2–1$)/$^{13}$HCO$^+$ ($1–0$) intensity ratio map in the nucleus of M82, derived using a 6 σ clipping for $^{13}$HCO$^+$ ($1–0$) and a 4 σ clipping for HCO ($F = 2–1$). The inferred ratio, accurate to 30%, varies between $−0.50 ± 0.15$ (at the outer edges of the ring and in the central peak) and $−0.15 ± 0.04$ (in the region between the HCO maxima), with an average ratio of $−0.25 ± 0.07$ for the whole disk. In order to derive the HCO-to-$^{13}$HCO$^+$ column density ratio, we need to make several assumptions about both the optical thickness and excitation temperature of the lines. Based on studies of HCO emission in Galactic PDR (Schenewerk, Snyder, & Hjalmarson 1980; Schenewerk et al. 1988), it is plausible to suppose that the HCO lines should be optically thin also in M82. The hyperfine line ratios measured in M82 seem to confirm these expectations. As the excitation temperature for HCO we assume $T_{ex} = 10$ K; this value was derived from a multitransition analysis made by Snyder et al. (1985) on NGC 2024.

For $^{13}$HCO$^+$ we also consider optically thin emission (García-Burillo et al. 2000) and the same excitation temperature as that assumed for HCO. These are reasonable guesses, especially for $T_{ex}$, as the two molecules have similar critical densities for the examined transitions. In this case, the calculation of HCO-to-$^{13}$HCO$^+$ column density ratio is straightforward using the expression (Schenewerk et al. 1988)

$$\frac{N(\text{HCO})}{N(13\text{HCO}^+)} \approx 12 \frac{I_{\text{HCO}} A_{\text{HCO}}^{13}}{g_\nu I_{13\text{HCO}^+} A_{13\text{HCO}^+}^{13}}$$

where $N$ is the total column density, $g_\nu$ is the degeneracy of the upper hyperfine level ($g_\nu = 5$ for $F = 2$), $I$ is the integrated intensity, and $A$ is the Einstein coefficient of the transition. We derive values for $N(\text{HCO})/N(13\text{HCO}^+)$ that range from 2 to 8, with an average value of 3.6 for the whole disk. Adopting an average fractional abundance for $13$HCO$^+$ of $\sim 10^{-10}$ (García-Burillo et al. 2000, 2001), we derive $X(\text{HCO}) \sim 4 \times 10^{-10}$ in M82.

Schenewerk et al. (1988) measured a value of $N(\text{HCO})/N(13\text{HCO}^+) \sim 9.7$ in the H II region NGC 204. On the contrary, values of $N(\text{HCO})/N(13\text{HCO}^+)$ significantly lower than 1, i.e., an order magnitude below those found in NGC 204, have been reported by Schenewerk et al. (1988) in Galactic clouds without developed H II regions or having no indication of star formation. More recently, Schilke et al. (2001) have searched for HCO in a reduced sample of prototy whole PDR. The estimated $N(\text{HCO})/N(13\text{HCO}^+)$ abundance ratios range from $\sim 30$ (in the Orion bar) to $\sim 3$ (in NGC 7023). The largest HCO abundances are found in the Orion bar: the paradigm of interaction between an H II region (M42) and its parent molecular cloud. Comparing our global estimates of $N(\text{HCO})/N(13\text{HCO}^+) \sim 3.6$ in M82 with the values measured for the prototypical PDR in our Galaxy, we conclude that the nuclear disk of M82 can be viewed as a giant PDR. Further analysis of the spatial variation of the $N(\text{HCO})/N(13\text{HCO}^+)$ ratio shows that the chemistry driven by the strong UV fields has produced the highest HCO enhancement in the outer edges of the starburst ring; the central clump also shows a similar HCO enrichment [$N(\text{HCO})/N(13\text{HCO}^+) \sim 7–8$]. These regions, with HCO abundances approaching those of NGC 2024, lie close to the loci of H II regions in M82 but do not quite coincide spatially with them. A mere inspection of Figure 3 indicates that the HCO-enriched molecular clouds surround the ionized gas as shown by the strongest [Ne III] emission: $X(\text{HCO})/\text{[Ne III]}$ peaks avoid each other and are shifted by offsets of $\sim 50–150$ pc. This might seem paradoxical as a close correlation between H II regions and PDR could be expected at these scales. As discussed below, this distribution could be explained, however, as the final result of the propagation of PDR chemistry in M82.

5. DISCUSSION

The enhancement of HCO in PDRs is mostly an observational fact, reproduced with uneven success by models. PDR models published so far have tried to account for the derived abundance of HCO either using gas-phase schemes (de Jong et al. 1980; Leung et al. 1984) or incorporating dust grains to the chemistry (Schilke et al. 2001). According to de Jong et al. (1980), the C$^+$ ion, highly abundant in UV-processed cloud envelopes, would start the chain of reactions leading to CH$_2$ and, finally, to HCO. Confirming these expectations, Hollis & Churchwell (1983) found an empirical correlation between HCO and C$^+$ radio recombination line emission in two Galactic clouds. Schilke et al. (2001) have proposed a model where HCO is the final byproduct of the photodesorption or evaporation of solid formaldehyde on dust grain mantles (Westley et al. 1995). Although the values of $X(\text{HCO})$ predicted by Schilke et al. (2001) are still 1 order of magnitude below what is typically found in PDRs, these results are encouraging. Based on a one-dimensional model made for the Orion molecular cloud, Schilke et al. (2001) predict that the large photodissociation rate of HCO (van Dishoeck 1988) could be counterbalanced only for extinctions $A_v > 5–6$. For a population of clouds uniformly bathed in the pervasive UV field of a starburst galaxy,
the $A_e$ limit should be increased by a factor of approximately a few, making the equivalent condition on column density close to $N(H_2) > 10^{22}$ cm$^{-2}$.

The HCO map of M82 provides direct evidence that the starburst event has heavily processed the bulk of molecular gas in this galaxy. The global fractional abundance of HCO ($\sim 4 \times 10^{-10}$, averaged over $\sim 650$ pc) can be accounted for within a PDR scenario. Paradoxically, the spatial correlation between HCO-enriched clouds and H II regions is poor. This is noticeable at large scales (HCO/CO/H$^+$ ratio) but also at small scales (peaks of HCO/H$^+$ emission avoid each other). The poor correlation suggests that UV fields coming from the strongest H II regions of M82, lying in the inner $\sim 400$ pc, have photodissociated the bulk of HCO in nearby molecular cloud envelopes. Previous observational evidence pointed to a disrupted physical environment for the dense interstellar medium in M82. Observations of the atomic carbon [C II] $3P_1 \rightarrow 3P_0$ and $3P_1 \rightarrow 3P_2$ lines (Schilke et al. 1993; Stutzki et al. 1997) confirmed that the M82 [C II]/CO abundance ratio ($\sim 0.5$) is higher than observed in non-starburst disks (it is $\sim 0.15$ in our Galaxy). Moreover, the measured $J = 2$–$1$–$1$–$0$ ratio can only be reconciled with clouds being small (with sizes of $\sim 1$ pc), only moderately dense (with densities of $\sim 10^3$–$10^4$ cm$^{-3}$) and hot (with temperatures of $\sim 100$ K; Stutzki et al. 1997). Similar conclusions, based on large velocity gradient and PDR modeling of $^{12}$CO, $^{13}$CO, and $^{15}$O line ratios, have been reported by Mao et al. (2000) and Weiss et al. (2001). The bulk of molecular clouds in the inner $\sim 400$ pc of M82 might have low densities (at some places in the disk as low as $\sim 10^2$ cm$^{-3}$) and small sizes ($\sim 1$ pc). Assuming this scenario, the survival of HCO against photodissociation, requiring column densities $N(H_2) > 10^{22}$ cm$^{-2}$, might be difficult. Most remarkably, the location of HCO-enriched clouds in our map, identified by their largest $N$(HCO)/$N$(H$^{13}$CO$^+$) ratio (the outer ring and the central clump), coincides with Weiss et al.’s model predictions on where individual molecular clouds may have the largest column densities (where volume densities reach a few times $\sim 10^4$ cm$^{-3}$). Furthermore, the intensity of UV fields is there comparatively lower (see Fig. 3).

The reported differences between HCO and H$^{13}$CO$^+$ maps in M82 cannot be easily explained with the present PDR models however, as both species are expected to be closely associated in the PDR. Other unexplored scenarios cannot be excluded as plausible explanations for the enhancement of HCO: X-ray– or cosmic-ray–dominated region chemistries might account for it in the case of M82 (Suchkov, Allen, & Heckman 1993). Moreover, we cannot exclude the presence of dense molecular gas (with $n(H_2) > 10^9$ cm$^{-3}$) in the central 1 kpc of M82 as already pointed out by Mao et al. (2000) and Weiss et al. (2001) or shown by the detection of tracers of dense molecular gas (see HCN map of Brouillet & Schilke 1993). However, our results suggest that evaporation/destruction of molecular clouds by UV fields is highly efficient in the inner $\sim 400$ pc of the galaxy. This efficiency shows spatial trends within the disk of M82, but the reasons behind these variations remain to be understood.

M82 is the only galaxy where emission of HCO has been detected so far. HCO emission was also searched for in the starburst galaxy NGC 253 by García-Burillo et al. (2000). Their data, giving no detection, allowed to set a 3 $\sigma$ upper limit for the HCO/H$^{13}$CO$^+$ ratio of $\lesssim 0.12$, i.e., a factor of 4–5 smaller than the value measured in the M82’s ring. HCO is the only complex molecule showing a larger fractional abundance in M82 than in NGC 253 (Mauersberger & Henkel 1993). Furthermore, the remarkably different abundances and spatial distributions of SiO gas in NGC 253 and M82 are suggestive of an evolutionary link between these starbursts (García-Burillo et al. 2000, 2001). The large HCO abundance in M82 may fit this scenario, which considers the M82 starburst episode as more evolved than that in NGC 253. The chemistry of molecular gas in NGC 253 is heavily influenced by the large-scale shocks and heating induced by a burst of pre-main-sequence massive stars. This explains the high abundance of SiO and the significantly low abundance of HCO. The chemistry of molecular gas in M82 is dominated by the action of UV fields produced by more evolved massive stars giving rise to H II regions. The remnant of the starburst presents a PDR-like chemistry favoring the presence of HCO but forcing a low abundance for other complex molecules.

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