CO\(^+\) IN M82: A CONSEQUENCE OF IRRADIATION BY X-RAYS

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ABSTRACT

Based on its strong CO\(^+\) emission, it is argued that the M82 starburst galaxy is exposed to a combination of FUV and X-ray radiation. The latter is likely to be the result of the starburst superwind, which leads to diffuse thermal emission, and a compact hard source (but not an AGN). Although a photon-dominated region (FUV) component is clearly present in the nucleus of M82, and capable of forming CO\(^+\), only X-ray irradiated gas of density \(10^4-10^5\) \(\text{cm}^{-3}\) can reproduce the large, \((1-4) \times 10^{13}\) \(\text{cm}^{-2}\), columns of CO\(^+\) that are observed toward the prototypical starburst M82. The total X-ray luminosity produced by M82 is weak, \(~10^{41}\) \(\text{ergs s}^{-1}\), but this is sufficient to drive the formation of CO\(^+\).

Subject headings: galaxies: starburst — ISM: molecules — X-rays: galaxies — X-rays: ISM

1. INTRODUCTION

M82 is a starburst galaxy located at 3.9 Mpc (Sakai & Madore 1999). It has a bolometric luminosity of \(~4 \times 10^{10}\) \(L_{\odot}\), and a large body of observational data exists for this system. The observed X-ray luminosity of M82 is modest at \(~4 \times 10^{40}\) \(\text{ergs s}^{-1}\), and Röntgensatellit and Advanced Satellite for Cosmology and Astrophysics data indicate that it has a hard, strongly absorbed \((N_H \approx 10^{22} \text{ cm}^{-2})\) power-law component and thermal contributions at \(kT \approx 0.6\) and 0.3 keV (Moran & Lehnert 1997). The thermal contributions result from the starburst superwind and the star formation itself (supernova heating of the interstellar medium), while ubiquitously present infrared photons scatter the supernova-generated relativistic electrons and generate a hard X-ray component that is absorbed with a photon index of 1.7 in the nucleus of M82 (Moran & Lehnert 1997). The latter authors further argue that the intrinsic luminosity of M82 in the 0.1–10 keV band is about 4 times larger when absorption is properly taken into account, yielding about \(10^{41}\) \(\text{ergs s}^{-1}\) in total. There is a compact hard (2–10 keV) X-ray component that is absorbed with a photon index of 1.7 in the nucleus of M82, and that on a 62 day period (Kaaret et al. 2006a, 2006b). There is no clear evidence of an active galactic nucleus (i.e., a buried Seyfert nucleus) in M82. The X-ray luminosity is about \(~0.2\)% of the total far-ultraviolet (FUV) energy budget as measured by the far-infrared luminosity (Pak et al. 2004).

In the center of the late-type galaxy M82, bright (and optically thin) CO\(^+\) \(N = 2\rightarrow 1, J = 5/2\rightarrow 3/2\) (236.06 GHz), and \(J = 3/2\rightarrow 1/2\) (235.79 GHz) rotational emission has been observed by Fuente et al. (2006). On the basis of combined CN and HCO\(^+\) measurements (their Fig. 2 and Table 2), the latter authors argue for a clumpy photon-dominated region (PDR) model where \(~4 \times 10^5\) \(\text{cm}^{-3}\) clumps are embedded in an interclump medium and are exposed to an enhancement in the FUV radiation field of \(G_0 \approx 10^5\). This enhancement is with respect to the average FUV (6–13.6 eV) interstellar radiation field in the Milky Way, which enjoys a typical FUV flux of \(1.6 \times 10^{-3}\) \(\text{ergs s}^{-1}\text{ cm}^{-2}\). It is certainly established that FUV photons produced by the vigorous star formation in M82 dominate the state of the molecular gas in its center (e.g., Pak et al. 2004 and references therein for rovibrational \(\text{H}_2\) as well as \([\text{C}\ II]\) and \([\text{O}\ I]\) fine-structure emission), and observations of CO, HCO\(^+\), and CN can be explained as well by a PDR interpretation. However, CO\(^+\) is underabundant by at least an order of magnitude in such PDR models, compared to the observed CO\(^+\) columns of \((1-4) \times 10^{13}\) \(\text{cm}^{-2}\) (Fuente et al. 2006).

In this Letter, we investigate whether the large CO\(^+\) columns measured toward M82 by Fuente et al. (2006) can be explained by the irradiation of molecular gas by the modest X-ray component that M82 exhibits, without violating the clear merits of PDR physics.

2. PDR AND XDR MODELS

We have constructed a set of PDR and X-ray–dominated region (XDR) models from the codes described by Meijerink & Spaans (2005) and Meijerink et al. (2006, 2007), in which we vary the incident radiation field, density, and cosmic-ray ionization rate. The thermal balance (with line transfer) is calculated self-consistently with the chemical balance through iteration. Absorption cross sections for X-rays are smaller, \(~1/\text{E}^2\), than for FUV photons. Therefore, PDRs show a stratified structure while the changes in the chemical and thermal structure in XDRs are very gradual. In XDRs, additional reactions for fast electrons that ionize, excite, and heat the gas are included. The heating efficiency in XDRs is much higher. Since we focus on galaxy centers, we have assumed the metallicity to be twice solar. We take the abundance of carbon to be equal to that of oxygen, since the carbon abundance increases faster than oxygen for larger metallicity. The precise C : O ratio does not affect our general results, with the exception of \(\text{O}_2\) and \(\text{H}_2\text{O}\) abundances (Bergin et al. 2000; Spaans & van Dishoeck 2001). Because the metallicity, even for a system like M82, is generally poorly known in the central regions of active star formation, we have also run models with solar metallicity. We come back to these in \(\S\) 4.

Our models (Meijerink et al. 2007) have \(n = 10^2-10^6\) \(\text{cm}^{-3}\) and \(G_0 = 10^{-10}\) \((\text{F}_X = 0.01-160\) \(\text{ergs s}^{-1}\text{ cm}^{-2}\)). We adopt a standard size for our model clouds of 1 or 10 pc. Our X-ray spectrum follows the spectral characteristics observed for M82, corrected for extinction by the observed hydrogen column density \((~10^{22}\) \(\text{cm}^{-2}\)). This attenuation is important (factor of \(~4\)) and is the reason why the total X-ray luminosity is about \(10^{41}\)
ergs s$^{-1}$ (see § 1). The X-ray spectral shape matters a lot for the penetration of photons in particular energy bands. Still, for the case of M82, molecular ion formation is not very sensitive to the exact spectrum. Overall, most X-ray energy is emitted below a few keV. Now, a purely soft spectrum would be absorbed quickly in the outer layers of the XDR, while a purely hard spectrum would penetrate all the way through. But to first order it is the total energy deposition rate, basically the integral of the absorbed flux, that drives the chemistry (Meijerink & Spaans 2005). Our model clouds, with $N_{\text{HI}} \sim 10^{22}$ cm$^{-2}$ per cloud, are chosen such that they absorb the bulk of the X-ray flux of M82, consistent with the significant absorption that the observations indicate, and thus the dependence on the exact X-ray spectral shape is modest as far as the produced column densities are concerned.

The considered densities and fluxes are representative of the conditions in M82 in terms of PDRs, but only the models with $F_x \leq 10$ ergs s$^{-1}$ cm$^{-2}$ should be typical of the X-ray background in M82. That is, a total X-ray luminosity of $10^{41}$ ergs s$^{-1}$ yields $F_x = 0.4$ ergs s$^{-1}$ cm$^{-2}$ for a point source at 50 pc from a molecular cloud. We also consider larger values for $F_x$ because the thermal X-ray emission is diffuse and molecular gas will enjoy a range of distances to ambient X-ray sources. For example, Fuente et al. (2006) adopt an emission size of 6 arcmin for CO, corresponding to a linear scale of about 100 pc at the distance to M82. Imagine then that the interstellar medium of M82 consists of a large number of $\sim 1$–10 pc clouds. If some of these clouds are at distances of about 1 pc to individual sources of X-ray radiation, then only about 1% of the total X-ray luminosity per source would already yield $F_x \sim 10$ ergs s$^{-1}$ cm$^{-2}$ impinging on these clouds. At the same time, the covering factor of about a hundred of these clouds on the sky can approach 5%–50% and thus contribute significantly to the XDR signal.

3. RESULTS

Figure 1 shows the CO$^+$ column densities for an $n = 10^2$–$10^3$ cm$^{-3}$ (10 pc cloud) and an $n = 10^3$–$10^4$ cm$^{-3}$ (1 pc cloud) density range. When comparing the model results with the observations, one should realize that the observed CO$^+$ column densities are actually determined for gas densities around $10^2$ cm$^{-3}$ and a rotational excitation temperature of about 10 K (Fuente et al. 2003). We also show lower density models in Figure 1 because the excitation of CO$^+$ is quite complicated (Black 1998; St"{a}uber et al. 2007). We come back to this point in § 4. In Table 1, an overview is given of all the relevant chemical species and their ratios.

It is obvious that XDRs allow columns of CO$^+$ that are comparable to the observed range of $\sim (1–4) \times 10^{10}$ cm$^{-2}$ for modest densities, while $10^3$ cm$^{-3}$ gas requires a few clouds to be superposed along the line of sight, which seems very reasonable. From the abundances shown in Figure 2, where a comparison is made between a typical XDR and PDR model, it is evident that the CO$^+$ abundance is more than an order of magnitude enhanced for the same total impinging flux by energy. This is a direct consequence of the more significant

| Table 1 |
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| **COLUMN DENSITIES AND COLUMN DENSITY RATIOS** |
| | $N_{\text{CO}}$ | $N_{\text{HOC}}$ | $N_{\text{HOCO}}$ | $N_{\text{CN}}$ | $N_{\text{HCN}}$ | $N_{\text{CO}}/N_{\text{HOC}}$ | $N_{\text{HOCO}}/N_{\text{HOC}}$ | $N_{\text{HCN}}/N_{\text{CN}}$ |
| XDR: $n = 10^2$ cm$^{-3}$ and $F_x = 5.1$ ergs s$^{-1}$ cm$^{-2}$ |
| 1.0E22 \ldots \ldots | 3.0E12 | 3.3E12 | 4.3E13 | 1.1E15 | 6.0E12 | 0.07 | 13.2 | 181 |
| 2.0E22 \ldots \ldots | 4.8E12 | 5.0E12 | 1.6E14 | 2.7E15 | 2.8E13 | 0.03 | 31.5 | 95.4 |
| 3.0E22 \ldots \ldots | 5.7E12 | 5.9E12 | 2.7E14 | 4.7E15 | 5.9E13 | 0.02 | 46.4 | 78.9 |
| XDR: $n = 10^3$ cm$^{-3}$ and $F_x = 1.6$ ergs s$^{-1}$ cm$^{-2}$ |
| 3.0E22 \ldots \ldots | 1.2E12 | 5.7E11 | 1.5E12 | 5.2E13 | 3.2E10 | 0.8 | 2.6 | 1.6E3 |
| 6.0E22 \ldots \ldots | 8.3E12 | 6.9E12 | 3.7E13 | 5.1E14 | 9.4E11 | 0.2 | 5.4 | 543 |
| 9.1E22 \ldots \ldots | 1.8E13 | 1.5E13 | 1.3E14 | 1.5E15 | 3.8E12 | 0.14 | 8.5 | 400 |
| PDR: $n = 10^4$ cm$^{-3}$, $G_n = 10^{10}$, and $\xi = 5 \times 10^5$ s$^{-1}$ |
| 1.0E22 \ldots \ldots | 1.6E10 | 1.0E10 | 2.8E14 | 2.3E15 | 3.5E14 | 5.6E–5 | 2.8E4 | 6.6 |
| 2.0E22 \ldots \ldots | 1.7E10 | 1.5E10 | 7.8E14 | 4.5E15 | 9.5E14 | 2.2E–5 | 5.2E4 | 4.7 |
| 3.0E22 \ldots \ldots | 1.9E10 | 2.0E10 | 1.3E15 | 6.7E15 | 1.6E15 | 1.4E–5 | 6.5E4 | 4.3 |
C\textsuperscript{+} + OH \rightarrow \text{CO}\textsuperscript{+} + H pathway in XDRs, where large amounts of C\textsuperscript{+} and OH coexist to large depths (Meijerink \& Spaans 2005). Note in this that the endothermic O + H\textsubscript{2} \rightarrow OH + H reaction is driven efficiently at the high (\geq 100 K) gas temperatures that pertain in XDRs even at large columns (Meijerink \& Spaans 2005), augmented by the vibrational excitation of H\textsubscript{2}. The XDR HOC\textsuperscript{+} abundances are also much larger than in PDRs, and the model column densities are comparable to those of CO\textsuperscript{+}, consistent with observations. The XDR HCO\textsuperscript{+}/HOC\textsuperscript{+} column density ratios are on the order of 20–40 when the total hydrogen column density is \leq 10\textsuperscript{23} cm\textsuperscript{-2}, also consistent with observations (Fuente et al. 2006, their Table 2).

Similarly, Figure 2 and Table 1 show that for column densities exceeding 10\textsuperscript{21.5} cm\textsuperscript{-2} the CO\textsuperscript{+}/HCO\textsuperscript{+} column density ratio reaches values of 0.01–0.1 in XDRs and is boosted relative to PDRs for the same ambient density and total impinging flux by energy. Values of 0.01–0.1 can be reached for PDRs as well, but only if the columns are modest, \leq 10\textsuperscript{21.5} cm\textsuperscript{-2}. All this compares well with the 4.5–6.5 mag range for individual clumps in the Fuente et al. model. Our adopted cosmic-ray ionization rate is 5 \times 10\textsuperscript{-15}, comparable to the Fuente et al. value. We find (see also Meijerink et al. 2006) that a boost in the formation of CO\textsuperscript{+} through an enhanced cosmic-ray ionization rate does not occur because direct ionization of CO is negligible and the C\textsuperscript{+} abundance is simply too small beyond the radical region in PDRs to react with OH.

Finally, in their model Fuente et al. (2006) require about 20–40 PDR clumps of 4 \times 10\textsuperscript{3} cm\textsuperscript{-3} density and 7 mag extinction in order to reproduce the observed CN column of \sim 10\textsuperscript{16} cm\textsuperscript{-2}. Figure 2 shows that XDRs with low impinging X-ray fluxes do not exhibit strongly enhanced CN abundances (with large F\textsubscript{X} they would) but have abundances similar to or somewhat smaller than PDRs. Table 1 shows that our PDR model with G\textsubscript{0} = 10\textsuperscript{15} and n = 10\textsuperscript{4} cm\textsuperscript{-3} produces a CN column of a few times 10\textsuperscript{16} cm\textsuperscript{-2} and requires several clumps along the line of sight, consistent with the CO\textsuperscript{+} requirement at that density.

The impinging FUV flux of this PDR model is a factor of 10 below the best-fit model of Fuente et al. (2005). The PDR CN/HCN column density ratios of about 4–7 are also consistent with observations (Fuente et al. 2006, their Table 2). The XDR CN/HCN column density ratios are about 80–180. However, the HCN abundance in an XDR is not strongly boosted at all for low F\textsubscript{X} (see also Lepp \& Dalgarno 1996, their Fig. 3). Consequently, the PDR contribution will dominate the observed HCN (as well as CN) signal, and no inconsistency arises.

Our models do not experience the bistability effect, where a low- and a high-ionization phase coexist through the interplay of H\textsuperscript{2}, S\textsuperscript{+}, and O\textsubscript{3} (e.g., Boger \& Sternberg 2006), because gas-grain neutralization is rapid.

4. DISCUSSION

The CO\textsuperscript{+} abundance in X-ray irradiated interstellar gas is boosted, relative to the FUV irradiation case. The starburst galaxy M82 appears to need only a modest flux of X-rays, consistent with observations, in order to reproduce the observed CO\textsuperscript{+} column across its nuclear disk at a density of 10\textsuperscript{13}–10\textsuperscript{14} cm\textsuperscript{-3}. We conjecture that other starburst galaxies may experience similar effects.

The metallicity in the central regions of M82 is poorly known. For comparison, we have run models with solar metallicity and the same density and irradiation conditions. It turns out that solar metallicity lowers the abundance of CO\textsuperscript{+} by about a factor of 2–3 for columns less than a few times 10\textsuperscript{22} cm\textsuperscript{-2}, while the difference is no more than \sim 50\% for columns larger than a few times 10\textsuperscript{22} cm\textsuperscript{-2}. This is a direct consequence of the fact that a lower metallicity causes a lower absorption rate of X-rays and thus a larger total column of material is needed to build up the same column of ionization-driven species like CO\textsuperscript{+}. Since the bulk of the M82 X-rays is absorbed in our model, i.e., we have total hydrogen columns of more than 3 \times 10\textsuperscript{22} cm\textsuperscript{-2} (a few clumps), the impact of metallicity variations is modest. Specifically, for solar metallicity and a total hydrogen column density of 2.5 \times 10\textsuperscript{22} cm\textsuperscript{-2} (about two clumps) or 5 \times 10\textsuperscript{22} cm\textsuperscript{-2} (about four clumps), we find CO\textsuperscript{+} columns of 2 \times 10\textsuperscript{12} cm\textsuperscript{-2} (a factor of 2.7 lower) or 5 \times 10\textsuperscript{12} cm\textsuperscript{-2} (a factor of 1.5 lower), respectively.

It would be quite useful to have H, H\textsubscript{2}, and electron collisional rate coefficients for CO\textsuperscript{+}. Still, the situation for CO\textsuperscript{+} is quite special in that it is a “transient” molecule (Black 1998), for which the destruction time is shorter than the time to reach collisional equilibrium. As a consequence, the excited state that the formation process leaves the CO\textsuperscript{+} molecule in should be an integral part of the excitation analysis because inelastic collisions with H\textsubscript{2} may not be able to thermalize the CO\textsuperscript{+} levels. Indeed, if CO\textsuperscript{+} is formed in an excited state, then a low-density, n = 10\textsuperscript{14}–10\textsuperscript{15} cm\textsuperscript{-3}, gas component as shown in Figure 1 and Table 1 can already lead to large CO\textsuperscript{+} emissivities because CO\textsuperscript{+} column densities increase with F\textsubscript{X}/n.
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