CO, C I and C II observations of NGC 7023

Maryvonne Gerin, Thomas G. Phillips, Jocelyn Keene, A.L. Betz, and R.T. Boreiko

Received ______________; accepted ______________

1Radioastronomie millimétrique, Laboratoire de Physique de l’ENS, 24 Rue Lhomond, 75231 Paris cedex 05, France
2Caltech Submillimeter Observatory, Caltech 320-47, Pasadena, CA 91125
3Center for Astrophysics & Space Astronomy, Campus Box 593, University of Colorado, Boulder, CO 80309-0593
ABSTRACT

We present new data on the photodissociation regions associated with the reflection nebula NGC 7023, particularly the three bright rims to the north, south and east of the illuminating star HD 200775. $^{13}$CO(3–2) emission, mapped at 20″ resolution at the Caltech Submillimeter Observatory (CSO), delineates a molecular cloud containing a cavity largely devoid of molecular gas around this star. Neutral carbon is closely associated with the $^{13}$CO emission while ionized carbon is found inside and at the edges of the cavity. The ionized carbon appears to be, at least in part, associated with HI. We have mapped the northern and southern rims in $^{12}$CO(6–5) emission and found a good association with the H$_2$ rovibrational emission, though the warm CO gas permeates a larger fraction of the molecular cloud than the vibrationally excited H$_2$.

The column density contrast between the bright rims and the diffuse region inside and in front of the cavity is about 10. Despite the fact that the edges of the cavity are viewed edge-on, the carbon emission extends much further into the molecular gas than does the photodissociation region, as defined by the H$_2$ emission region. Geometrically, NGC 7023 consists of a sheet of dense molecular gas in which the star was born, subsequently blowing away much of the surrounding gas. The three bright rims are located at the edges of the remaining molecular cloud, and are viewed approximately edge-on.

The results are compared with PDR models, invoking direct illumination from the star, which are largely successful, except in explaining the presence of neutral carbon deep in the molecular cloud. We suggest that, in the particular case of NGC 7023, a second PDR has been created at the surface of the molecular cloud by the scattered radiation from HD 200775. This second PDR produces a layer of atomic carbon at the surface of the sheet, which increases
the predicted [C]/[CO] abundance ratio to 10%, close to the observed value. Further tests for the applicability of PDR models in such regions are suggested.
1. Introduction

Reflection nebulae are produced when a massive star illuminates a molecular cloud. Due to the enhanced radiation field, the gas surrounding the star is heated and its chemistry is modified. Reflection nebulae belong to the generic class of sources known as PDRs (Photon-Dominated Regions). These are typically located at the transition layer between warm, ionized gas produced by an intense radiation field and a cold neutral atomic or molecular cloud. If this definition is extended to low values of the radiation fields, down to the average intensity of the interstellar radiation field (ISRF), $I = G_0 \times \text{ISRF}$ with $G_0 = 1$ at the solar radius, PDRs comprise a very significant fraction of the mass of the neutral gas in our Galaxy (Hollenbach & Tielens 1995). Furthermore, due to their high efficiency in producing intense emission (line and continuum), PDRs produce a significant fraction of the dust and gas emission of external galaxies including the CO rotational lines and C I & C II fine structure lines (Bennett et al. 1994, Hollenbach & Tielens 1995).

In PDRs at the surface of molecular clouds illuminated by a strong radiation field, $G_0 \approx 1000$ or more, the gas temperature is high and, in general, atomic and molecular lines are intense. For some reflection nebulae, the geometry of the cloud is visually revealed. Such sources are thus suitable places to study basic physical processes of the interstellar medium. In particular the processes leading to the thermal balance of interstellar gas can be investigated in detail due to the knowledge of the radiation field and the overall geometry of the source.

Carbon plays a key role in PDR models because it is expected to be dominantly in three different species throughout the PDR. There is a layer of almost totally ionized carbon at the outer edge, an intermediate region where carbon is neutral and then the cold molecular interior where carbon should
be locked into CO. Because oxygen and nitrogen remain neutral in the outer edge, no equivalent structure can be seen in the main repositories of these other abundant species so carbon plays a unique role in testing PDR models. The possibility of observations of $\text{C}^+$, C and CO at the same spatial locations in the same source therefore provides a unique diagnostic of predictions: the depth and width of the CI emission zone can test the accuracy of the chemistry and radiative transfer, and the excitation of C and CO are sensitive to the thermal balance. Previous observations of interstellar clouds reveal that atomic carbon is generally both overabundant and more widely distributed than simple models predict (Phillips & Huggins 1981, Keene et al. 1985). This has led to questions concerning the homogeneity of the cloud resulting in proposals for porous clouds with greater than expected UV penetration (Phillips & Huggins 1981, Stutzki et al. 1988). In that case a PDR structure is expected at the surface of each substructure in the porous cloud as long as a significant UV field is present ($G_0 \geq 1$ to produce C I (Spaans 1996)).

A widely used test for models of the surface of the PDR is the H$_2$ rovibrational emission in the near infrared. H$_2$ reveals details of the external zone of the PDR, but because the emission is very sensitive to both the UV field intensity and the gas density, the extent of the H$_2$ emission is much reduced compared to that of the three carbon species, even in the case of a porous cloud.

The combination of data from both the H$_2$ rovibrational emission and the carbon budget therefore represents a powerful tool for investigating PDRs, particularly at high spectral resolution when the velocity structure can be resolved. We present in this paper a new $^{13}$CO (3–2) map of the reflection nebula NGC 7023 together with selected data of C$^{18}$O(3–2), $^{12}$CO(6–5), neutral (C I) and ionized (C I) carbon emission. A $^{12}$CO(3–2) map has been taken but
is not shown, because the structure of the cavity region is obscured by the lower column density foreground material. Though the NGC 7023 reflection nebula has been extensively investigated in the past, this is the first observation of neutral carbon and the first study of C II at high spectral resolution.

NGC 7023 is illuminated by the young B3Ve star HD 200775 ($\alpha(1950) = 21^h00^m59^s7, \delta(1950) = 67^\circ57'55''.5$), at a distance of 600 pc (Rogers, Heyer, & Dewdney 1995). The radiation field is enhanced by a factor of a few thousand over the average value in the solar vicinity (Chokshi et al. 1988). Due to this enhanced radiation field, the very small dust grains experience large excursions in temperature and produce continuum emission in the near IR, as first observed by Sellgren (1984) for this and other reflection nebulae. The scattering properties of dust grains have also been investigated in NGC 7023 (Murthy et al. 1993, Witt et al. 1993). Maps of the dust continuum emission in the far infrared (Whitcomb et al. 1981, Casey 1991) have been taken at a spatial resolution of about 1′. The dust temperature varies from 50 K in the vicinity of HD 200775 to 20K in the molecular cloud. The decrease in dust temperature is accompanied by an increase of the dust opacity at 250 $\mu$m, indicating a rise of column density in the molecular cloud surrounding HD 200775.

The structure of the molecular gas has been determined at low spatial resolution (1′ − 2′) by Watt et al. (1984), Fuente et al. (1992) and Rogers et al. (1995) by mapping in $^{12}$CO, $^{13}$CO and C$^{18}$O. The $^{13}$CO emission is found at the border of the bright nebula, and delineates a cavity with an hourglass shape roughly centered on HD 200775, in which the $^{13}$CO and C$^{18}$O emission is extremely weak or not detectable. This is seen in Figure 1, which is our new high spatial resolution ($\sim 20''$) $^{13}$CO($3$–$2$) map of most of the region. At this resolution the bright inner edge of the $^{13}$CO emission traces the nebulosity
seen on the POSS plate. Rogers et al. (1995) were also able to isolate the H I emission from the nebula from the general, widespread H I emission. They found H I emission from the cavity, mostly north of the star, and conclude that there is global pressure equilibrium between the warm gas around the star and the gas in the molecular cloud. H I is slightly redshifted compared to the molecular gas, by about 2 km s$^{-1}$. Fuente et al. (1996) obtained an H I map with 10$''$ resolution which showed that the neutral gas does not completely fill the interior of the cavity, but accumulates on the inner edges, at the surface of the molecular gas, as expected for a stratified PDR. The absence of significant H I emission in the largest lobe of the cavity, west of the star, and the presence of background stars indicates that we are dealing with a sheet of material in which the star HD 200775 has created a nearly complete hole (Rogers et al. 1995).

Fuente et al. (1993) have investigated, at high spatial resolution ($\sim 12''$), the northern part of the nebula, 1$'$ north-west of the star. They found a sharp ridge in $^{13}$CO and C$^{18}$O emission, which we here call the north rim. They have shown that the gas chemistry is affected by the UV radiation and that abundance ratios such as [CN]/[HCN] and [HCN]/[HNC] are enhanced in the gas affected by the UV. As deduced from HCN measurements, the density in the gas is fairly high, about $10^5$ cm$^{-3}$ in the ridge. Somewhat lower densities ($0.3 - 2 \times 10^4$ cm$^{-3}$) are obtained from the excitation of CO and its isotopes.

Ionized carbon and atomic oxygen have been detected at low spectral resolution by Chokshi et al. (1988) in the nebula, and they presented the first PDR model for NGC 7023. The PDR model has been refined by Lemaire et al. (1996), who obtained images of the rovibrational lines of molecular hydrogen with 1$''$ resolution. The H$_2$ emission is concentrated in narrow and long filaments, located mostly north of the star. These filaments have also been
detected in HCO$^+$ (Fuente et al. 1996). Lemaire et al. (1996) show that the H$_2$ emission is not uniform in the filaments but shows variations down to the 1″ scale. Both the high brightness and spatial structure of the H$_2$ emission are evidence that the illuminated gas is fairly dense, $n_H \simeq 10^5$ cm$^{-3}$ (Lemaire et al. 1996, Martini, Sellgren, & Hora 1997). There is a second H$_2$ front south of the star, fainter than the northern front by a factor 2–3. Similar filaments are found in R and V-R pictures (Watkin, Gledhill, & Scarrott 1991) as sources of Extended Red Emission (ERE). H$_2$ emission and ERE are coincident in both fronts (50″ NW and 70″ S) but have different small scale structure (Lemaire et al. 1996). It is clear from Figure 1 that a third powerful PDR exists on the east rim of the cavity. We have initiated some studies here, but in total there is little data available on this. It should be investigated further in the future.

Because high $J$ CO lines and the carbon fine structure lines are predicted to be strong by these PDR models, we have observed the $J = 3–2$ lines of $^{12}$CO, $^{13}$CO and C$^{18}$O, the $J = 6–5$ line of $^{12}$CO and the 1–0 line of C I in NGC 7023 with the Caltech Submillimeter Observatory (CSO). We also present Kuiper Airborne Observatory (KAO) spectra of the C II emission at high spectral resolution. We describe the observations in the next section, then present the results and compare the line maps with the H$_2$ images in order to obtain a more precise understanding of the geometry of the nebula. Finally we discuss the validity of the PDR models for this source.

2. Observations

The CO and C I observations were performed at the CSO in July & October 1995, and July & October 1996. The telescope is equipped with SIS receivers operated in double-sideband (DSB) mode. The observations were performed by
position switching, with the reference position (devoid of emission) located 30′ north of the star HD 200775, which was used as the map center. For the C I observations, we also used the position (−40″, 0″) as a reference position, since previous data had shown it to be devoid of emission. The $^{12}$CO and $^{13}$CO maps were made in the “on the fly” (OTF) mode, where the telescope continuously sweeps across the sky and data are binned in a series of positions. A reference position is taken at the beginning and the end of each row, and is used to subtract the sky emission. We selected a sweep rate of 1″/sec and a map step of 10″, resulting in 10 sec on source integration time per point. The spectra were analyzed with a 1024 channels acousto-optic spectrometer (AOS) with a total bandwidth of 50 MHz and an effective spectral resolution of about 100 kHz. The main beam efficiencies of the telescope were 0.65, 0.53 and 0.45 at 345, 492 and 691 GHz respectively. The angular resolution at the CSO is 20″ at CO(3–2), 15″ at C I(1–0) and 10″ at CO(6–5).

The C II 158 μm line was observed using the KAO during two flights in August and November 1991, using a far-infrared heterodyne receiver described in detail by Betz & Boreiko (1993). The local oscillator was an optically pumped CH$_2$F$_2$ laser and the mixer was a liquid nitrogen-cooled GaAs Schottky diode in a corner-reflector mount. The back-end consisted of an AOS with 400 independent channels each with 0.5 km s$^{-1}$ resolution. The system noise temperature was 15,000 K SSB in August and 12,000 K SSB in November. The diffraction-limited beam size on the KAO at 158 μm is 43″ FWHM, and pointing accuracy is estimated to be 15″. Calibration is performed relative to the Moon, for which a physical temperature of 395 K and emissivity of 0.98 are assumed. Overall, the C II antenna temperature should be accurate to within approximately 25%, comparable to the uncertainty in the CO and C I
3. Overall geometry of NGC 7023

3.1. $^{13}$CO and $^{12}$CO data

Figure 1 presents a map of the integrated intensity in the $^{13}$CO(3–2) line; the contours represent the H$_2$ v = 1–0 S(1) emission from Lemaire et al. (1996). The $^{13}$CO map reveals a cavity of hourglass shape around the star. Moreover, the emission is not constant at the edges of this cavity but presents three maxima located north-west, south and east of HD 200775, with peak antenna temperatures of about 15 K.

The three bright rims are located at the outer edge of H I maxima, and represent examples of PDRs with radiation fields relative to the average radiation field proposed by Mathis, Mezger, & Panagia (1983, MMP) of $G_0 = 5000$ (north rim), 2000 (south rim) and 250 (east rim). These numbers are computed for a B3 star with an effective temperature of 17000 K (Chokshi et al. 1988, Casey 1991, Draine and Bertoldi 1996), assuming that the distances are the projected ones. Many slightly different values and color temperatures for the average interstellar radiation field at 1000 Å have been proposed in the literature. These have been summarized by Draine and Bertoldi (1996). Among these, the MMP radiation field is most appropriate because it has the same color temperature in the UV as HD 200775 (17000 K). The calculated fields are in reasonable agreement with the fields deduced from H$_2$ near infrared emission seen from the north and south rims. There is no report of a search for H$_2$ emission from the east rim.

It appears that no large scale velocity gradient is present in this cloud. There is however a gradual velocity shift along the north rim.
Figures 2 and 3 present representative spectra in $^{12}\text{CO}(3–2)$, $^{12}\text{CO}(6–5)$, $^{13}\text{CO}(3–2)$ and C I(1–0). The selected spectra were taken near the star position ($-10''$, $20''$), in the cavity ($90''$, $10''$), in the bright rims: south ($-40''$, $-80''$), north ($-40''$, $30''$) ($-40'', 40''$) and ($-50'', 60''$), and east ($210'', 10''$) and in the molecular cloud ($-40'', 90''$). The $^{13}$CO line profiles are nearly Gaussian with most of the emission centered at the $V_{LSR} = 2.5$ km s$^{-1}$ whereas the $^{12}$CO(3–2) profiles have complicated shapes with multiple peaks or flat tops, mostly in the northern region of the map. Towards the southern and northern rims, the $^{12}$CO(6–5) profiles are nearly Gaussian with peak intensity of $30 - 40$ K. Whereas the $^{12}$CO(6–5) line profile closely follows the the $^{12}$CO(3–2) profile in the southern rim, it is considerably stronger than $^{12}$CO(3–2) in the northern rim (compare position ($-40'', -80''$) in the south rim with positions ($-40'', -40''$) and ($-50'', 60''$) in the north rim). This difference between the $^{12}$CO(3–2) and (6–5) profiles is seen for most of the observed positions located north of HD 200775, and even in the molecular cloud away from the north rim. For example, towards the position ($-40'', 90''$), the two lines do not peak at the same velocity. A likely explanation for this behavior is the effect of self absorption by cold foreground gas, which would affect mostly the low J profiles. The $^{13}$CO lines towards the eastern edge are double peaked or somewhat broader than those towards the northern and southern edges of the cavity. At the position ($210'', 10''$) the two components visible in $^{13}$CO(3–2) line profile are merged in the $^{12}$CO(3–2) profile. The $^{12}$CO(6–5) line is somewhat narrower than the (3–2) line.

The main difference between the $^{13}$CO and the $^{12}$CO maps is that $^{13}$CO shows the structure of the bright rims more clearly, but is barely detected in the cavity, whereas the main isotope reveals the presence of some diffuse molecular
gas in the cavity and of foreground material.

3.2. The cavity

In Figure 1, the $^{13}$CO emission is found at the outer border of the H$_2$ emission, which itself is found further away from the star than the K-band continuum radiation. This continuum radiation arises both from stellar reflected light and from stochastically heated small dust grains. The overall absence of $^{13}$CO, and even H I and C I (see below) around the star supports the hypothesis that it has created a cavity of warm ionized gas around it, possibly by the mechanical action of a past outflow as suggested by the opening angle and straight edges. The rather low reddening of HD 200775, 1.5 mag (Finkenzeller & Mundt 1984), the presence of background stars in the western lobe of the cavity and the absence of strong $^{13}$CO emission from the back side suggest that the cavity was created in a sheet of molecular gas, which has been essentially destroyed close to the star. In the following we deduce more information about this cavity and its edges from the analysis of the $^{13}$CO and $^{12}$CO data and their comparison with the H I and near infrared H$_2$ maps.

3.3. The region around HD 200775

The star HD 200775 has a color excess E(B-V) = 0.45, and a reddening of 1.5 mag (Finkenzeller and Mundt 1984, Buss et al. 1994). It also presents a CH absorption line in its visible spectrum, with a CH column density of $3.2 \times 10^{13}$ cm$^{-2}$ (Federman et al. 1994; 1997). The column densities of atomic and molecular hydrogen have been measured by Buss et al. (1994) from UV absorption lines to be $N$(H) $\sim 1.3 \times 10^{21}$ cm$^{-2}$ and $N$(H$_2$) $\sim 3.5 \times 10^{20}$ cm$^{-2}$.
The value of the color excess would indicate a somewhat higher value of the total column hydrogen column density, namely $N(H) + 2N(H_2) = 2.6 \times 10^{21}$ cm$^{-2}$. However, this atomic hydrogen is probably not totally associated with the nebula, but is partly distributed along the line of sight since the interferometrically measured H I column density at the position of HD 200775 in velocities associated with the nebula is only about $5 \times 10^{20}$ cm$^{-2}$ (Fuente et al. 1996). We adopt a value for the total hydrogen column density to the star of $2.0 \times 10^{21}$ cm$^{-2}$. Federman et al. (1997) have measured a velocity difference between the atomic absorption lines and the molecular absorption lines: the former appear blueshifted relative to the latter, which are seen at $V_{LSR} = 1 - 2$ km s$^{-1}$. The sole exception is the absorption due to the molecular ion CH$^+$ which has the same velocity as the atomic lines ($-2$ km s$^{-1}$).

We could not detect C I and were barely able to detect $^{13}$CO in the cavity, but $^{12}$CO(3–2) lines were seen everywhere. In the cavity as well as towards the north rim, the $^{12}$CO(3–2) profiles are broad and complex with two or three maxima. This complex shape is also seen in lower resolution (1–0) data (Rogers et al. 1995) and probably results from the combination of velocity structure and self absorption. Around the star, the $^{12}$CO(3–2) profiles get smoother and the central velocity shifts from $\sim 2.5$ km s$^{-1}$ to $\sim 1.5$ km s$^{-1}$. The antenna temperature is about 6 K, whereas the $^{13}$CO(3–2) peak intensity is about 0.8 K. This $^{12}$CO emission is probably associated with the material which causes the CH and C$_2$ visible absorptions. Indeed, the $^{12}$CO(3–2) spectra toward the north rim present a wing at low velocities (0–1 km s$^{-1}$), which is not seen in the $^{12}$CO(6–5) line nor in the $^{13}$CO(3–2) or C I lines. This material at low velocity may be the continuation of the molecular gas seen in absorption along the line of sight to HD 200775.
To find the physical conditions of the gas along the line of sight to the star, we used an LVG model and adopted a kinetic temperature of 30 K, deduced from the peak intensity of $^{12}$CO lines, (3–2) and (1–0), in the south part of the molecular cloud where the lines have Gaussian shapes. This assumes that all the molecular gas lies at about the same distance from the star and that the kinetic temperature of the molecular gas is fairly homogeneous. The $^{12}$CO data around the star (at positions (0$''$, 0$''$) and (−10$''$, 20$''$)) are well fitted with a gas density of $\simeq 3,000$ cm$^{-3}$ and a column density $N$(CO) = $3.0 \times 10^{16}$ cm$^{-2}$. The excitation temperature of the 3–2 transition is 13 K, and the opacity is of the order 2.5. This column density must be viewed as a lower limit since the $^{12}$CO lines may still suffer from self absorption. Using the same density and temperature, the weak $^{13}$CO emission observed at these positions corresponds to a column density of about $1.5 \times 10^{15}$ cm$^{-2}$, a value consistent with previous determinations by Rogers et al. (1995). The measured isotopic ratio $[^{12}$CO]/$[^{13}$CO] is then larger than 20, well within the expected range for diffuse illuminated gas where carbon fractionation is thought to take place (see below, §5). Using the hydrogen column density of $2.0 \times 10^{21}$ cm$^{-2}$ derived from the star reddening and the CH absorption, the CO relative abundance to H is $1.5 \times 10^{-5}$ in the gas along the line of sight to the star. The $^{13}$CO abundance relative to H is $7.5 \times 10^{-7}$. This is smaller than the CO abundance relative to hydrogen in dark clouds, $4 \times 10^{-5}$ (Irvine, Goldsmith, & Hjalmarson 1987), but is consistent with the presence of a thin sheet of molecular material illuminated by the intense UV radiation of HD 200775 and located in front of the nebula.
3.4. Secondary maximum inside the cavity

Inside the cavity at about 100″ east of the star, a faint maximum appears in the $^{13}$CO integrated intensity map (Fig. 1). We present in Figures 2 and 3 the spectra obtained towards the position (90″, 10″). The line is centered at $V_{LSR} = 3.3$ km s$^{-1}$, clearly different from the bulk velocity of the molecular gas, 2.5 km s$^{-1}$. Thus in this case the emission is clearly real and not merely due to the error pattern of the telescope, which is a common source of illusory features when looking at a low emissivity region surrounded by high intensity emission. The $^{12}$CO(3–2) line profile is complex with multiple peaks. The correspondence of the $^{13}$CO(3–2) peak at 3.3 km s$^{-1}$ with a dip in the $^{12}$CO spectrum is a clear indication of self absorption. A second dip in the $^{12}$CO spectrum at 4.5 km s$^{-1}$ might be associated with a weak $^{13}$CO signal. The $^{12}$CO velocity component at 0 km s$^{-1}$, with $T_A^* = 2.5$ K has no counterpart in $^{13}$CO.

Assuming again a kinetic temperature of 30 K, with a density of $1 \times 10^4$ cm$^{-3}$, the column density of the secondary maximum at the position (90″, 10″) is $N(^{13}$CO) = $2 \times 10^{15}$ cm$^{-2}$. From the map published by Rogers et al. (1995), the $^{13}$CO(1–0) peak temperature lies in the 3–4 K range, consistent with the density and column density derived above. Due to the self absorption in $^{12}$CO(3–2), which shows up in the $^{12}$CO(1–0) spectra as well, it is not possible to derive a $^{12}$CO column density for the 3.3 km s$^{-1}$ velocity component. However, assuming a $^{13}$CO abundance relative to H$_2$ of $2 \times 10^{-6}$ at most, we can obtain a lower limit of the H$_2$ column density of $N(H_2) \geq 1 \times 10^{21}$ cm$^{-2}$. An upper limit is obtained by assuming the same abundance of $^{13}$CO relative to hydrogen as towards the star where the gas is diffuse, $[^{13}$CO] = $7.5 \times 10^{-7}$, hence $N(H + 2H_2) \leq 3 \times 10^{21}$ cm$^{-2}$. A likely value is $N(H_2) = 1.5 \times 10^{21}$ cm$^{-2}$. At this position the H I column density is about $4 \times 10^{20}$ cm$^{-2}$, thus most of
the gas along this line of sight is molecular. This gas could be either a remnant of a dense clump, located inside the cavity and currently evaporating, or be a remnant of the now disrupted cavity edge which used to extend in front of or behind the cavity.

3.5. The three bright rims

We have observed $^{12}$CO(6–5) toward the bright rims. Figure 4 presents the contours of the $^{12}$CO(6–5) emission overlaid on the H$_2$ picture from Lemaire et al. (1996) and spectra are displayed in Figure 2. As observed for the $^{12}$CO(7-6) transition in other reflection nebulae (Jaffe et al. 1990), the $^{12}$CO(6–5) lines are extremely bright in NGC 7023 with peak intensities of 38 K in the north rim. The profiles are Gaussian in the north, south, and east rims (see the spectra at the positions ($-50''$, 60'') ($-40''$, $-80''$), & (210'', 10'') displayed in Fig 2.).

Overall, the $^{12}$CO(3–2) and (6–5) profiles are similar except toward the north rim because of self absorption in the (3–2) line. These intense CO lines must be produced in a warm medium, with kinetic temperatures in excess of 30 K over most of the mapped region and larger than 40 K at the $^{12}$CO(6–5) emission peaks. For both the northern and southern rims, the $^{12}$CO(6–5) emission presents a sharp edge on the side closer to the star, a maximum associated with the H$_2$ rovibrational emission, and a shallow decrease going deeper into the cloud. Because $^{12}$CO(6–5) emission is also detected towards the east rim, it is interesting to ask whether H$_2$ emission will also be observable at this rim, even though the value of $G_0$ should be much lower.

The $^{13}$CO(3–2) maximum temperatures vary from 6 to 17 K along the edges of the cloud. With a kinetic temperature of 45 K, and densities around $10^4 \text{cm}^{-3}$ as inferred by Fuente et al. (1993) and confirmed by us (see below), this
corresponds to column densities in the range $0.3 - 1.3 \times 10^{16}$ cm$^{-2}$. Towards the south rim, for example at position $(-40'', -80'')$, we measured $N(^{13}\text{CO}) = 6.5 \times 10^{15}$ cm$^{-2}$ for $T_K = 45$ K and $n(\text{H}_2) = 10^4$ cm$^{-3}$, using the (1–0) data from Rogers et al. (1995) to constrain the excitation. In the northern and eastern rims, the peak $^{13}\text{CO}(3–2)$ temperature reaches 17 K. The column density is then $N(^{13}\text{CO}) = 1.3 \times 10^{16}$ cm$^{-2}$ at the position $(-40'', 50'')$ in the northern rim and $N(^{13}\text{CO}) = 1.1 \times 10^{16}$ cm$^{-2}$ at the position $(210'', 10'')$ in the eastern rim. In these dense ridges, the gas is totally molecular (apart from the carbon atom content) and the $^{13}\text{CO}$ fractional abundance should be the same as in dark clouds, $1 - 2 \times 10^{-6}$ (Irvine et al. 1987, Wilson & Rood 1994). The total molecular gas column density is therefore $\approx 10^{22}$ cm$^{-2}$. Using the relationships between extinction and molecular column densities established by Frerking, Langer, & Wilson (1982), Duvert, Cernicharo, & Baudry (1986) and Lada et al. (1994), the total extinction through the northern and eastern rims is 6 – 10 magnitudes. The higher value is preferred since, using the C$^{18}$O(3–2) data, we obtain a column density of $N(\text{C}^{18}\text{O}) = 2.7 \times 10^{15}$ cm$^{-2}$ at the position $(-40'', 50'')$ in the northern rim, which indicates a visual extinction of about 10 magnitudes using the same relationships as above. Comparing to the gas in the cavity, the column density contrast is about a factor 10. A summary of the physical parameters for these various positions is given in Table 1.

In an edge-on view of a PDR, the H$_2$ rovibrational emission is forced to lie at the edge of the C$^+$/C/CO region, although it does not have to extend along the full length of the interface, because it arises from regions of high density and requires a large UV intensity. While the H$_2$ rovibrational emission closely follows the edge of the molecular cloud on the north front, there is a clear discrepancy on the south front. The CO(6–5) map (Fig. 4) follows more closely the H$_2$
feature than either the CO(3–2) or the $^{13}$CO maps. A likely explanation is that
the H$_2$ emission in the south comes from some high density surviving clump in
the cavity, at about the same distance from the star as in the northern rim.
The bulk of the molecular gas in the southern rim itself is slightly farther from
the star and so may not achieve the necessary conditions for H$_2$ rovibrational
emission.

4. Carbon budget in the northern and southern fronts

4.1. C and C$^{18}$O

We have observed the $^3P_1 - ^3P_0$, 492 GHz fine structure line of carbon along
two cuts, at RA = $-40''$ and Dec = $+60''$, together with a few other points
either observed by Fuente et al. (1993) or presenting strong H$_2$ v = 1–0 S(1)
emission. Some C I spectra overlaid on $^{13}$CO(3–2) are shown in Figure 3. The
C I emission clearly peaks at the interfaces between the cavity and the molecular
cloud with no line detected inside the cavity, but with a strong extension into
the molecular cloud. By contrast with $^{13}$CO and C I which start to emit at the
peak of the H$_2$ emission, at RA = $-40''$, Dec = $+30''$ in the north rim, C$^{18}$O
is found to start its emission deeper in the cloud at RA = $-40''$, Dec = $+50''$.
C$^{18}$O was marginally detected towards the southern rim. We present in Figure
5a a comparison of the C I(1–0), $^{13}$CO(3–2), C$^{18}$O(3–2) and H$_2$ S(1) intensities
along the two cuts, and show in Figure 5b the intensity ratios C I/$^{13}$CO and
C$^{18}$O/$^{13}$CO. The H$_2$ data have been smoothed to 15'', the spatial resolution of
the C I data.

The C I/$^{13}$CO(3–2) antenna temperature ratio is about 0.6 for the northern
rim, with a sharp increase to 1.7 at the position of the H$_2$ rovibrational emission.
C I is fainter compared to $^{13}$CO(3–2) towards the south, with a C I/$^{13}$CO(3–2)
antenna temperature ratio only reaching 0.4. Apart from this sharp maximum at
the cloud edge, C I and $^{13}$CO behave in the same way inside the cloud. As seen
in previous studies of a variety of clouds (e.g. Phillips & Huggins 1981; Keene et
al. 1985), the line profiles are also very similar for both species (Fig. 3). The line
ratios have a somewhat larger scatter in the horizontal cut, with C I/$^{13}$CO(3–2)
ranging between 0.5 and 1.3. The lower value, 0.5, is found at offset -50" along
the cut, a position deep in the cloud with a large column density, because
it shows both the maximum $^{18}$O(3–2) emission and $^{18}$O(3–2)/$^{13}$CO(3–2)
intensity ratio. Indeed, at this position, $^{18}$O/$^{13}$CO reaches 0.2, the expected
isotopic ratio indicating that the gas is well shielded from the UV radiation and
consequent photodissociation. Along this horizontal cut, the C I/$^{13}$CO intensity
ratio follows a pattern anticorrelated with the $^{18}$O/$^{13}$CO ratio, with largest
value when isotopic fractionation should be taking place. Thus the carbon
line is seen both at the edge of the PDR, as predicted by the models, but also
throughout the cloud as previously noted for S140 and M17 (Keene et al. 1985).
The only place where carbon is not detected is in the cavity around the star.

We have calculated the carbon column densities using the LTE formula:

$$N(C) (\text{cm}^{-2}) = 1.9 \times 10^{15} \int T_{MB}dv \times Q e^{E_1/kT},$$

where $Q$ is the partition function:

$$Q = 1 + 3e^{-E_1/kT} + 5e^{-E_2/kT},$$

and $E_1 = 23.6$ K and $E_2 = 62.5$ K are the energies of the fine structure levels of carbon. Because both upper levels of the
C I ground triplet are easily excited, LTE conditions are usually reached. At a
kinetic temperature of 30 K, this gives:

$$N(C) (\text{cm}^{-2}) = 1.25 \times 10^{16} \int T_{MB}dv \ (\text{K km s}^{-1}).$$

Therefore the column density of carbon is $4.2 \times 10^{16}$ cm$^{-2}$ for the south rim
($-40'', -80''$), and $8.1 \times 10^{16}$ cm$^{-2}$ for the north rim ($-40'', 30''$). At the
same positions, the $^{13}$CO column densities are respectively $6.5 \times 10^{15}$ cm$^{-2}$ and
1.6 \times 10^{15}\text{ cm}^{-2}. \text{ With a } ^{12}\text{CO}/^{13}\text{CO abundance ratio variable between 20 and 70 to take into account possible fractionation effects, the possible range of } ^{12}\text{CO column density at these positions is } 1.3 - 4.6 \times 10^{17} \text{ and } 0.32 - 1.1 \times 10^{17}\text{ cm}^{-2}. \text{ Though much of the carbon is locked into CO, the abundance of neutral carbon relative to CO is still high, from at least 15% up to 70%.

As shown above, the C I/^{13}\text{CO}(3-2) intensity ratio decreases further inside the cloud and reaches a value of about 0.5. We have looked at the positions \((-40'', 90'')\) and \((-50'', 60'')\) where \(^{13}\text{CO}, \text{C}^{18}\text{O}\) and C I have been detected. The observed intensity ratio corresponds to a column density ratio \(N(\text{C I})/N(\text{^{13}CO}) = 9\) and 6 respectively, and a C/CO abundance ratio of 12% and 9%, estimating the CO column density from the \(^{13}\text{CO}\) and C\(^{18}\text{O}\) data with isotopic ratios \([^{12}\text{CO}]/[\text{C}^{18}\text{O}] = 500\) and \([^{12}\text{CO}]/[^{13}\text{CO}] = 70\). For those positions, the C\(^{18}\text{O}\) column densities are \(1.6 \times 10^{15}\) cm\(^{-2}\) and \(2.0 \times 10^{15}\) cm\(^{-2}\) respectively with \([^{13}\text{CO}]/[\text{C}^{18}\text{O}]\) column density ratios of 6.0 and 6.5. Thus even towards positions where most of the gas does not experience heavy illumination, as evidenced by the low value of the \([^{13}\text{CO}]/[\text{C}^{18}\text{O}]\) column density ratio, neutral carbon still represents about 10% of the available gas phase carbon. As discussed above, this is a common finding in illuminated clouds (Keene 1995).

### 4.2. C\(^{+}\)

C II observations have been taken with the KAO with a 45'' beam using a heterodyne receiver (Betz & Boreiko 1993). We present in Figure 6 a comparison of the C II spectra with \(^{12}\text{CO} \text{ and } ^{13}\text{CO points averaged to represent the same beam on the sky. Apparently, the C II emission occurs with two separate distributions. It has a component similar to } ^{13}\text{CO with similar centroid velocity for the positions covering the northern rim. For positions centered in the cavity}}
where we could barely detect $^{13}$CO, C II emission occurs at a more positive velocity. This second component has clearly broader lines. Both the positive velocity and the broader lines suggest that this emission may be associated with the neutral hydrogen, which also appears at positive velocities relative to the molecular gas (Rogers et al. 1995, Fuente et al. 1996). The antenna temperature of the C II line is about 10 K in the cavity and rises to 20 K for the position closest to the H$_2$ edge. For a gas density larger than $10^4$ cm$^3$ and a temperature of about 80 K, this corresponds to a column density of $1 - 3 \times 10^{17}$ cm$^{-2}$ (Jansen et al. 1996). However the emission may not be uniform in the beam, since it is predicted from PDR models to rise steeply at the H$_2$ front. It is clear that C II emission is associated with both the cavity and the PDR, in contrast to C I which is only seen in the PDR and the molecular cloud.

The $^{12}$CO spectra in the cavity are centered at $V_{LSR} = 1$ km s$^{-1}$ while the C II line appears at a more positive velocity, 3.5 km s$^{-1}$. It is likely that the observed C II emission is associated with the H I region inside the cavity, while the $^{12}$CO and $^{13}$CO lines towards the cavity are produced in the layer of molecular gas associated with the CH absorption and located in front of the cavity.

5. Comparison with PDR Models and Discussion

PDR models are well established as capable of explaining the molecular and atomic emission lines seen on the boundaries of molecular clouds when illuminated by starlight (Hollenbach & Tielens 1995). These models have recently been modified to incorporate new data on reaction rates and molecular excitation processes. We have used the PDR model based on the code of Abgrall et al. (1992) and Le Bourlot, Pineau des Forêts, & Roueff (1993a), with different
geometric configurations, in order to check the validity of actual parameters and
to investigate the marked difference between the northern and the southern rims
in NGC 7023, in both the H$_2$ and C I intensities relative to $^{13}$CO. In part these
differences could be due to geometrical effects. Since this PDR model starts
with a semi-infinite H$_2$ slab on the surface of which the UV impinges, it cannot
address the structure of the cavity, the region between the PDR and the star.

¿From Figure 5, it is clear that the north rim is viewed almost edge-on:
the large variation of the column density of molecular hydrogen as traced by
$^{13}$CO(3–2) emission, the position of the molecular hydrogen emission at the edge
of the molecular cloud, and the coincidence of the peak in the C I/$^{13}$CO ratio
with the zone of H$_2$ emission result naturally from the edge-on geometry. It is
quite likely that the actual geometry is that of a sheet with a sharp cut-off edge,
which is the surface illuminated by the star. The sections of these edges closest
to HD 200775 are the north and south rims, where bright H$_2$ emission has been
detected.

In order to investigate the role of the viewing geometry in a PDR model,
we have calculated abundances as a function of depth within a bright rim.
These abundances are naturally interpreted as corresponding to a “face-on”
viewing geometry, and from them we approximated the emergent intensities
for a PDR viewed “edge-on” by summing the local emissivities at each
depth inside the cloud along a path length of 3 × 10$^{16}$ cm (0.01 pc). This
approximation is valid only for optically thin lines for which the emissivities
may be enhanced significantly by limb brightening. The model we have used is
an isochoric model, with a UV enhancement factor $G_0$ of $10^4$ and a density of
$n(H + 2H_2) = 2 \times 10^5$ cm$^{-3}$. We have used as gas phase elemental abundances
the values found towards ζ Oph listed in Table 2. We have also tried a model
with oxygen, carbon and nitrogen depleted by a factor of three from these values. From Lemaire et al. (1996), it is known that the hydrogen density has to be larger than about $10^5$ cm$^{-3}$ to reproduce the observed intensities of the H$_2$ rovibrational lines. An analysis of the molecular emission lines (CS and HCN) also suggest high densities, in the $10^5$ cm$^{-3}$ range (Fuente et al. 1993).

The results are illustrated in Figure 7 where we show the variation of the local abundances $n(X)/(n(H) + 2n(H_2))$ of $^{12}$CO, $^{13}$CO, C and C$^+$ with the depth into the cloud expressed in arcsec at the distance of NGC 7023 (600 pc) (top panel) and the predicted emissivities for the edge-on view (bottom panel). For the optically thick $^{12}$CO($3–2$) line, little or no limb brightening is expected and we show only the face-on emissivity. In this plane-parallel structure, the model predicts a layered structure with C$^+$ at the outer boundary of the cloud, then C and CO. For this isochoric model, in the outer region where C and C$^+$ dominate over $^{12}$CO, the high density and temperature cause efficient excitation of $^{12}$CO and therefore produces strong high $J$ $^{12}$CO emission.

We discuss below the different layers in the photo dissociation region:

1) C II emission is found in the warm ionized and partially dissociated medium which lies at the surface on which the UV impinges. It is also present in the next layer where H$_2$ is able to resist photodissociation and is strongly excited. This is qualitatively consistent with the observed C$^+$ data which show two different components depending on the actual observed positions. The emission from the C II region in the models would be clearly diluted in the 45$''$ KAO beam. With a dilution factor of about 5, i.e. assuming that the C II emission comes from a structure of width 10$''$ and longer than 60$''$, the observed peak antenna temperature of the C II emission from this region corresponds to an absolute antenna temperature of 75 K, close to the predicted values.
2) The next layer is the atomic carbon region and the main problem for the models is the fit of the carbon data: whereas the model predicts no C I emission at distances larger than 20" from the PDR, C I has been observed throughout the molecular cloud (Fig. 5). The distribution of neutral carbon is therefore much more extended than expected for a simple PDR. Because reflected starlight is seen in this nebula, and neutral carbon is produced in even low radiation field environments, it is possible that some neutral carbon emission we observe comes from the externally illuminated visible surface of the sheet.

We have evaluated the UV intensity due to scattered light from HD 200775 using the observations with UIT (Witt et al. 1992). We found an enhancement factor of $G_0 \sim 20$ at 100" from HD 200775. This scattered radiation forms another PDR at the surface of the molecular cloud. To evaluate the role of this second PDR in producing neutral and ionized carbon at large distances from the north rim, we have run a PDR model with the same abundances, the same high density, $n = 2 \times 10^5$ cm$^{-3}$, but a low radiation field $G_0 = 50$. The variation of the abundances of C$^+$, C and CO as a function of the depth into the cloud $A_V$ are displayed in Figure 8. For $A_V$ of a few magnitudes, this second PDR is an important source of neutral carbon in the molecular gas, so that the predicted [C]/[CO] abundance ratio is larger than 10%. Indeed, even in a low UV field, the PDR is associated with ionized and neutral carbon layers at the surface of the molecular cloud. When viewed “face-on” the layered structure results in significant cumulative column densities of neutral and ionized carbon for all values of $A_V$ hence significant abundances of C$^+$ and C appear, even though most of the neutral and ionized carbon reside at the outer surface. With this low UV flux, the model does not predict any H$_2$ or warm dust emission, as observed.

In further studies this proposal could be tested by determining if a substantial
amount of C$^+$ is also present in the mixed C/CO regime, which could indicate a UV origin to the effect. This would require a platform such as SOFIA or FIRST with heterodyne receivers. PDR models predict the existence of a zone where carbon isotopic fractionation takes place at the edge of the molecular cloud close to the UV source. In that zone, the [$^{12}\text{CO}]/[^{13}\text{CO}]$ abundance ratio drops to 30 (Kopp et al. 1996). Carbon fractionation takes place as soon as the formation of molecules enhances the cooling and the temperature drops. It stops deeper into the cloud because of the lack of C$^+$. If the PDR model is appropriate for these regions far from the star, $^{13}\text{CO}/^{12}\text{CO}$ fractionation should exist in such a regime and could be observed with ground based techniques. If carbon deeper into the cloud is due to non-UV processes, such as turbulent mixing (Xie, Allen, & Langer 1995) or high ionization phase chemistry (Le Bourlot et al. 1993b; Le Bourlot, Pineau des Forêts, & Roueff 1995; Flower et al. 1994), there will be much less C$^+$ and fractionation.

The assumed values for elemental abundances are important parameters for PDR models. The models with depleted elements exhibit the same brightness for the $^{12}\text{CO}$ and $^{13}\text{CO}$ lines essentially due to the high optical depths, but reduced emissivities of ionized and neutral carbon by a factor roughly equal to the input depletion. The strength of both the observed C I and C II lines favor the models with rather high gas phase abundances of carbon and oxygen, i.e. the models using the $\zeta$ Oph abundances. Because the cooling is slightly reduced in the models with lowered elemental abundances, the $^{13}\text{CO}$ edge is not as sharp as in the case of $\zeta$ Oph abundances. In any case, the edge is likely to be unresolved because the emission rises over $3 \times 10^{16}$ cm. At the distance of NGC 7023, 450 – 600 pc, this corresponds to at most 4″, which is below the resolution of these observations but could be resolved by millimeter interferometers.
We thank J. Le Bourlot, G. Pineau des Forêts and E. Roueff for the use of their PDR model. The CSO is funded by NSF contract AST96-15025. Work on the NASA Kuiper Airborne Observatory was carried out under NASA grant NAG 2-605 to JBK.
REFERENCES

Abgrall, H., Le Bourlot, J., Pineau des Forêts, G., Roueff, E., Flower, D.R., & Heck, L. 1992, A&A, 253, 525

Bennett, C.L., Fixsen, D.J., Hinshaw, G., Mather, J.C., Moseley, S.H., Wright, E.L., Eplee, R.E., Gales, J. Hewagama, T. et al. 1994, ApJ, 434, 587

Betz, A.L., & Boreiko, R.T. 1993, Astronomical Infrared Spectroscopy, Astron. Soc. of Pacific Conf. Series Vol. 41, S. Kwok, 349

Buss, R.H., Allen, M., McCandliss, S., Kruk, J., Liu, J., & Brown, T. 1994, ApJ, 430, 630

Cardelli, J.A., Mathis J.S., Ebbets, D.C., & Savage, B.D. 1993, ApJ, 402, L17

Casey, S.C. 1991, ApJ, 371, 183

Chokshi, A., Tielens, A.C.G.M., Werner, M.W., & Castelaz, M.W. 1988, ApJ, 334, 803

Draine, B.T., & Bertoldi, F. 1996, ApJ, 468, 269

Duvert, G., Cernicharo, J., & Baudry, A. 1986, A&A, 164, 349

Federman, S.R., Knauth, D.C., Lambert, D.L., & Andersson, B.G., 1997, ApJ, 489, 758

Federman, S.R., Strom, C.J., Lambert, D.L., Cardelli, J.A., Smith, V.V., & Joseph, C.L. 1994, ApJ, 424, 772

Finkenzeller, U., & Mundt, R. 1984, A&A,S 57, 285

Flower, D.R., Le Bourlot, J., Pineau des Forêts, G., & Roueff, E. 1994, A&A, 282, 225

Frerking, M.A., Langer, W.D., & Wilson, R.W. 1982, ApJ, 262, 590
Fuente, A., Martin-Pintado, J., Cernicharo, J., & Bachiller, R. 1993, A&A, 276, 43

Fuente, A., Martin-Pintado, J., Cernicharo, J., & Bachiller, R. 1996, A&A, 310, 286

Fuente, A., Martin-Pintado, J., Cernicharo, J., Brouillet, N., & Duvert, G. 1992, A&A, 260, 341

Hollenbach, D.J., & Tielens, A.G.G.M. 1995, The Physics and Chemistry of Interstellar Molecular Clouds, G. Winnewisser & G. Pelz, Springer-Verlag: Berlin, 164

Irvine, W.M., Goldsmith, P.F., & Hjalmarson, Å. 1987, Interstellar Processes, D. J. Hollenbach & H. A. Thronson, Dordrecht: Reidel, 561

Jaffe, D.T., Genzel, R., Harris, A.I., Howe, J.E., Stacey, G.J., & Stutzki, J. 1990, ApJ, 353, 193

Jansen, D.J., van Dishoeck, E.F., Keene, J., Boreiko, R.T., & Betz, A. 1996, A&A, 309, 899

Keene, J. 1995, The Physics and Chemistry of Interstellar Molecular Clouds, G. Winnewisser & G. Pelz, Springer-Verlag: Berlin, 186

Keene, J., Blake, G.A., Phillips, T.G., Huggins, P.J., & Beichman, C.A. 1985, ApJ, 299, 967

Lada, C.J., Lada, E.A., Clemens, D.P., & Bally, J. 1994, ApJ, 429, 694

Le Bourlot, J., Pineau des Forêts, G., & Roueff, E., 1993a, A&A, 267, 233

Le Bourlot, J., Pineau des Forêts, G., Roueff, E., & Schilke, P. 1993b, ApJ, 416, L87

Le Bourlot, J., Pineau des Forêts, G., & Roueff, E., 1995, A&A, 297, 251
Lemaire, J.L., Field, D., Gerin, M., Leach, S., Pineau des Forêts, G., Rostas, F., & Rouan, D. 1996, A&A, 308, 895

Martini, P., Sellgren, K., & Hora, J.L. 1997, ApJ, 484, 296

Mathis, J.S., Mezger, P.G., & Panagia, N. 1983, A&A, 128, 212

Murthy, J., Dring, A., Henry, R.C., Kruk, J.W., Blair, W.P., Kimble, R.A., & Durrance, S.T. 1993, ApJ, 408, L97

Phillips, T.G., & Huggins, P.J. 1981, ApJ, 251, 533

Rogers, C., Heyer, M.H., & Dewdney, P.E. 1995, ApJ, 442, 694

Savage, B.D., Cardelli, J.A., & Sofia, U.J. 1992, ApJ, 401, 706

Sellgren, K. 1984, ApJ, 277, 623

Snow, T.P., & Witt, A.N. 1996, ApJ, 468, L65

Spaans, M. 1996, A&A, 307, 271

Stutzki, J., Stacey, G.J., Genzel, R., Harris, A.I., Jaffe, D.T., & Lugden, J.B. 1988, ApJ, 332, 379

Watkin, S., Gledhill, T.M., & Scarrott, S.M. 1991, MNRAS, 252, 229

Watt, G.D., Burton, W.B., Choe, S.U., & Liszt, H.S. 1986, A&A, 163, 194

Whitcomb, S.E., Gatley, I., Hildebrand, R.H., Keene, J., Sellgren, K., & Werner, M.W. 1981, ApJ, 246, 416

Wilson, T.L., & Rood, R.T. 1994, ARAA, 32, 191

Witt, A.N., Petersohn, J.K., Bohlin, R.C., O’Connel, R.W., Roberts, M.S., Smith, A.M., & Stecher, T.P. 1992, ApJ, 395, L5

Witt, A.N., Petersohn, J.K., Holberg, J.B., Murthy, J., Dring, A., & Henry, R.C. 1993, ApJ, 410, 714
Xie, T., Allen, M., & Langer, W.D. 1995, ApJ, 440, 674

This manuscript was prepared with the AAS \LaTeX\ macros v4.0.
Table 1. Physical parameters at representative positions

| Position | $T_K$ (K) | $n(H_2)$ (cm$^{-3}$) | $N(^{13}CO)$ (cm$^{-2}$) | $N(C^{18}O)$ (cm$^{-2}$) | $N(C)$ | $[^{13}CO]/[C^{18}O]$ | $[^{12}C]/[CO]$ |
|----------|-----------|---------------------|-------------------------|------------------------|--------|---------------------|----------------|
| (0,0)    | 30        | $2 \times 10^3$    | $1.1 \times 10^{15}$    |                        |        |                     |                |
| (-10,20) | 30        | $10^4$              | $1.8 \times 10^{15}$    | $\leq 4.0 \times 10^{16}$ | $\leq 0.3$ |                     |                |
| (-40,-90)| 45        | $10^4$              | $5.4 \times 10^{15}$    | $13 \times 10^{14}$    | $4.7 \times 10^{16}$ | $4.0$     | $0.12$            |
| (-40,-80)| 45        | $10^4$              | $6.5 \times 10^{15}$    | $13 \times 10^{14}$    | $4.2 \times 10^{16}$ | $5.0$     | $0.09$            |
| (-40,-70)| 45        | $7 \times 10^3$    | $3.7 \times 10^{15}$    | $6.0 \times 10^{14}$    | $4.0 \times 10^{16}$ | $6.2$     | $0.15$            |
| (-40,30) | 45        | $7 \times 10^3$    | $1.6 \times 10^{15}$    | $\leq 7.0 \times 10^{14}$ | $8.1 \times 10^{16}$ | $\geq 2$  | $0.70$            |
| (-40,40) | 45        | $10^4$              | $7.7 \times 10^{15}$    | $14 \times 10^{14}$    | $14 \times 10^{16}$ | $5.5$     | $0.26$            |
| (-40,50) | 55        | $10^4$              | $13 \times 10^{15}$    | $27 \times 10^{14}$    | $16 \times 10^{16}$ | $4.8$     | $0.17$            |
| (-40,90) | 30        | $10^4$              | $9.6 \times 10^{15}$    | $16 \times 10^{14}$    | $7.8 \times 10^{16}$ | $6.0$     | $0.12$            |
| (-50,60) | 40        | $10^4$              | $13 \times 10^{15}$    | $20 \times 10^{14}$    | $7.9 \times 10^{16}$ | $6.5$     | $0.09$            |
| (90,10)  | 30        | $10^4$              | $2.2 \times 10^{15}$    |                        |        |                     |                |
| (210,10) | 35        | $10^4$              | $11 \times 10^{15}$    |                        |        |                     |                |

Note. — The column densities have been calculated with $[^{12}CO]/[^{13}CO] = 70$ and $[^{12}CO]/[C^{18}O] = 500$. 
Table 2. Elemental abundances used in the PDR model

| Parameter | Value          | Reference          |
|-----------|----------------|--------------------|
| [O]/n\text{H} | $2.93 \times 10^{-4}$ | Savage et al. 1992  |
| [C]/n\text{H} | $1.32 \times 10^{-4}$ | Cardelli et al. 1993 |
| [N]/n\text{H} | $7.76 \times 10^{-5}$ | Snow & Witt 1996   |
| $[^{12}\text{C}]/[^{13}\text{C}]$ | 70              |                    |
| $[^{16}\text{O}]/[^{18}\text{O}]$ | 500             |                    |
Fig. 1.— Map of the $^{13}$CO(3–2) integrated area between 0 and 4.5 km s$^{-1}$. The grey scale ranges from 1 to 12 K km s$^{-1}$. Two contours of the H$_2$ v=1–0 S(1) (Lemaire et al. 1996) emission are overlaid (the circles around the star and the straight line features are artifacts of the IR data).

Fig. 2.— Spectra observed in $^{12}$CO(3–2) (black line) and $^{12}$CO(6–5) (grey line) at representative positions in NGC 7023. Velocities are given relative to the LSR; positional offsets are in arc seconds relative to HD 200775, at $\alpha(1950) = 21^h00^m59^s.7$, $\delta(1950) = 67^\circ57'55''.5$.

Fig. 3.— Spectra observed in $^{13}$CO(3–2) (black line) and CI (grey line) at representative positions in NGC 7023. Velocities are given relative to the LSR.

Fig. 4.— Map of the $^{12}$CO(6–5) integrated intensity overlaid on the near infrared image of the H$_2$ v = 1–0 S(1) emission in NGC 7023 (Lemaire et al. 1996). The first contour is drawn at 14 K km s$^{-1}$, and the level spacing is 7 K km s$^{-1}$. Black dots show the positions observed in CO(6–5).

Fig. 5.— a) Comparison of the $^{13}$CO(3–2) (full line), CI (dashed line), C$^{18}$O(3–2) (bold line) and H$_2$ v = 1–0 S(1) (dotted line) emission along the two cuts at RA = $-40''$ (top panel) and Dec = $+60''$ (bottom panel). The H$_2$ data have been smoothed to a resolution of 15'' to match the CI data. b) Intensity ratios along the same cuts.

Fig. 6.— Map of the CII spectra observed with the KAO with a 45'' beam. The spectral resolution is 0.5 km s$^{-1}$. CO(3–2) spectra obtained by convolving the CSO data to the resolution of the KAO observations are shown with a dotted line. $^{13}$CO(3–2) spectra obtained by convolving the CSO data to the resolution of the KAO observations are shown at high spectral resolution with a thin black
The unit for all spectra is $T_A^*$ in (K). Velocities are given relative to the LSR.

Fig. 7.— a) Local abundances, $n(X)/(n(H) + 2n(H_2))$, as a function of the distance from the cloud edge for a PDR model with a total hydrogen density $n_H = 2 \times 10^5$ cm$^{-3}$, a UV field $G_0 = 10^4$ and elemental abundances from Table 2. We have used a distance of 600 pc to convert linear distances to angular scales. 
b) Predicted emissivities (erg cm$^{-2}$s$^{-1}$) of the PDR model for CI, CII, $^{12}$CO(6–5), $^{13}$CO(3–2), and H$_2$ for an edge-on view. A depth of the slab along the line of sight of $3 \times 10^{16}$ cm (0.01 pc) is assumed. The emissivity of the optically thick $^{12}$CO(3–2) line is shown for a face-on view. The observed emissivities at the position ($-40''$, $50''$) in the north rim are: $6.3 \times 10^{-7}$ erg cm$^{-2}$s$^{-1}$ for $^{13}$CO(3–2) and $1.5 \times 10^{-6}$ erg cm$^{-2}$s$^{-1}$ for CI. For position ($-40''$, $-70''$) in the south rim, we found: $2.1 \times 10^{-7}$ erg cm$^{-2}$s$^{-1}$ for $^{13}$CO(3–2), $3.7 \times 10^{-7}$ erg cm$^{-2}$s$^{-1}$ for CI and $1.5 \times 10^{-6}$ erg cm$^{-2}$s$^{-1}$ for $^{12}$CO(3–2).

Fig. 8.— Column density ratios $N(X)/(N(H) + 2N(H_2))$ as a function of $A_V$ for a PDR model with the same density as Fig. 7, $n_H = 2 \times 10^5$ cm$^{-3}$, and a lower UV field $G_0 = 50$. 
