Photon dominated regions in NGC 3603

[CI] and mid-J CO line emission


1. Introduction

Understanding the feedback between star formation and the interstellar medium (ISM) is important in order to understand the process of star formation (see Zinnecker & Yorke 2007, and references therein). The physical and chemical properties of stars are the heritage of their parental clouds. Stars are born from interstellar gas and release metal-enriched material to the ISM when they die. Radiation from the stars is the prime heating source for gas and dust in nearby molecular clouds and may trigger velocity and density fluctuations, that stimulate further star formation. To understand the formation of these next generation stars, it is important to understand how the previous generation interacts with its parental clouds (Dale et al. 2005).

The energy incident on the clouds in the form of stellar far-ultraviolet (FUV: 6 eV ≤ hν ≤ 13.6 eV) radiation is coun-
tered by cooling continuum radiation plus emission of atomic fine-structure lines ([CII] 158 μm, [CI] 370 μm, 610 μm, and [OI] 63 μm, 145 μm) and by molecular rotational lines (CO, H2O, OH, etc.). The cooling emission carries the imprint of the local physical and chemical conditions and can be used to infer

ABSTRACT

Aims. We aim at deriving the excitation conditions of the interstellar gas as well as the local FUV intensities in the molecular cloud surrounding NGC 3603 to get a coherent picture of how the gas is energized by the central stars.

Methods. The NANTEN2-4 m submillimeter antenna is used to map the [CI] 1–0, 2–1 and CO 4–3, 7–6 lines in a 2′ × 2′ region around the young OB cluster NGC 3603 YC. These data are combined with C18O 2–1 data, HIRES-processed IRAS 60 μm maps of the FIR continuum, and Spitzer/IRAC maps.

Results. The NANTEN2 observations show the presence of two molecular clumps located south-east and south-west of the cluster and confirm the overall structure already found by previous CS and C18O observations. We find a slight position offset of the peak intensity of CO and [CI], and the atomic carbon appears to be further extended compared to the molecular material. We used the HIRES far-infrared dust data to derive a FUV field heating the dust. We constrain the FUV field to values of χ = 3–6 × 10^3 in units of the Draine field across the clouds. Approximately 0.2 to 0.3% of the total FUV energy is re-emitted in the [CII] 158 μm cooling line observed by ISO. Applying LTE and escape probability calculations, we derive temperatures (T_{m1} = 43 K, T_{m2} = 47 K), column densities (N_{m1} = 0.9 × 10^{20} cm^-2, N_{m2} = 2.5 × 10^{20} cm^-2) and densities (n_{m1} = 3 × 10^3 cm^-3, n_{m2} = 10^{-10}–10^{-9} cm^-3) for the two observed molecular clumps MM1 and MM2.

Conclusions. The cluster is strongly interacting with the ambient molecular cloud, governing its structure and physical conditions. A stability analysis shows the existence of gravitationally collapsing gas clumps which should lead to star formation. Embedded IR sources have already been observed in the outskirts of the molecular cloud and seem to support our conclusions.

Key words. ISM: clouds – ISM: structure – ISM: molecules – submillimeter: ISM
the type of environment conducive to maintaining star formation. On their way into a molecular cloud FUV photons are absorbed, and a depth-dependant chemical balance is established. Models of these so-called photon dominated regions (PDRs; see references in Hollenbach & Tielens 1999; Röllig et al. 2007) typically predict a stratification of species like \( \text{H}_2, \text{C}^+, \text{C}^2/\text{CO}, \) and others. This stratification is found to be independent of the shape of the PDR (Gorti & Hollenbach 2002). However, observations often reveal \([\text{CII}]\) emission coincident with that of \( \text{CO} \) (Tatematsu et al. 1999; Ikeda et al. 2002; Mookerjea et al. 2006; Sakai et al. 2006; Kramer et al. 2008; Sun et al. 2008). Plan-parallel models cannot explain this behavior unless full face-on orientation is assumed. Spherical models under isotropic illumination show well-correlated \([\text{CII}]\) and \( \text{CO} \) emission for low density clouds \( (n < 10^4 \text{ cm}^{-3}) \) but predict a limb brightening of the \([\text{CII}]\) emission (Röllig et al. 2006). In this work we analyze the distribution of atomic carbon and warm CO in the NCG 3603 star forming region and use LTE approximations and an escape probability model (Stutzki & Winnewisser 1985) to derive the excitation conditions of the gas as well as gas abundances. We refrain from applying more detailed models like the KOSMA-\( \tau \) PDR model (Störzer et al. 1996; Röllig et al. 2006; Cubick et al. 2008). Recent Herschel/HIFI observations of massive star forming regions provide additional strict constraints on the PDR modeling of these regions, resulting in significantly altered predictions of the local physical and structural conditions (Ossenkopf et al. 2010; Dedes et al. 2010). Hence, we postpone all attempts of PDR modeling in NCG 3603 until the region has been observed with Herschel in the framework of the Herschel Guaranteed Time Key Project Warm And Dense ISM.

2. The NCG 3603 star forming region

NGC 3603 is located in the Carina spiral arm \( (l \approx 291.6^\circ, b \approx -0.5^\circ) \) at a distance of approximately 7–8 kpc (see discussion in Melena et al. 2008). It is one of the most luminous \((L_\odot > 10^5 L_\odot)\), optically visible HII regions in the Galaxy, with the massive OB cluster NGC 3603 YC (Young Cluster) as a power source (Goss & Radhakrishnan 1969). The compact core of the cluster was designated HD 57950 due to its star-like appearance. As a comparison, NGC 3603 is 100 times more luminous than the Trapezium cluster in Orion. This young cluster can be considered one of the few Galactic starburst clusters, which are essential for the understanding of extragalactic star bursts. With a dynamic stellar cluster mass of \( 17 600 \pm 10^2 M_\odot \) (Rochau et al. 2010) residing in a cloud of total gas mass of \( 4 \times 10^5 M_\odot \) (Grabelsky et al. 1988), it is the most compact Galactic star-forming complex outside the Galactic center region (Stolte et al. 2004). In a number of recent studies, the stellar cluster and the surrounding HII region has been investigated thoroughly (Pandey et al. 2000; Sung & Bessell 2004; Stolte et al. 2006; Lebouteiller et al. 2007, 2008; Harayama et al. 2008; Nünberger 2008; Crowther et al. 2010). To the south of the cluster we find a giant molecular cloud (see Fig. 1). The intensive radiation and stellar winds from the cluster shape large gaseous pillars at the edge of the cloud (Brandner et al. 2000). CS observations by Nünberger et al. (2002) show that the molecular gas also extends much further to the north \((>10')\) and to the south, hosting numerous massive molecular clumps which may be future sites of star formation. A number of prominent IR sources have been found so far (Frogel et al. 1977; Nünberger 2008; Nünberger et al. 2010) as well as propylid like objects (Mücke et al. 2002). Recent AKARI observations of NGC 3603 have been presented by Okada et al. (2010) showing that the \([\text{CII}]\) 158 \( \mu \)m emission is widely distributed and that the \([\text{OIII}]\) 88 \( \mu \)m emission follows the MIR, FIR, and radio continuum emission.

3. Observations

We used the NANTEN2-4m antenna at 4865 m altitude in Pampa la Bola in northern Chile to map the central \( 2' \times 2' \) region of NGC 3603. Our reference position is RA(J2000.0) = \( 11^{1}15^{m}08^{s}.85 \), Dec(J2000.0) = \( -61^\circ 16'50''0'\). We observed the rotational transitions of \( ^{12}\text{CO} \) \( J = 4–3 \) (461.0408 GHz) and \( J = 7–6 \) (806.6517 GHz) and the two fine-structure transitions of atomic carbon \( [\text{CII}] \) \( 3P_1–3P_0 \) (492.1607 GHz) and \( 3P_1–3P_2 \) (809.3446 GHz) (henceforth \( 1–0 \) and \( 2–1 \)), between September and November 2006 with a dual-channel 460/810 GHz receiver. The exact line frequencies were taken from the Cologne Database for Molecular Spectroscopy (CDS (Müller et al. 2005, 2001)). Double sideband (DSB) receiver temperatures were \( \approx 250 \text{ K} \) in the lower frequency channel and \( \approx 750 \text{ K} \) in the upper channel. The intermediate frequencies (IF) are 4 GHz and 1.5 GHz, respectively. The latter IF allows simultaneous observations of the CO \( 7–6 \) line in the lower sideband and the \([\text{CII}] \) \( 2–1 \) line in the upper sideband. These two lines were observed simultaneously with one of the two lower lines in the 460 GHz channel. As backends, we used two acousto optical spectrometers (AOS) with bandwidths of 1 GHz. The channel spacing was 0.37 km \( s^{-1} \) at 460 GHz and 0.21 km \( s^{-1} \) at 806 GHz. The pointing accuracy was checked regularly on Jupiter, IRC+10216, and IRC2 in Orion A. The applied corrections were always <20" and usually <10". To determine the atmospheric transmission, we measured the atmospheric emission at the reference position. Spectra of the two frequency bands were calibrated separately, and sideband imbalances were corrected using the atmospheric model atm (Atmospheric Transmission at Microwaves, cf. Pardo et al. 2001). Observations were taken on-the-fly (OTF), scanning in
right ascension at a speed of 2.5″/s and sampling every 10″. The reference position was observed at the beginning of each OTF scanning line.

The half power beam widths (HPBW) deconvolved from the observed full widths at half maximum (FWHM) are 38.0″ and 26.5″ in the lower and upper receiver bands, respectively. Beam efficiencies $B_{\text{eff}}$ are 50% and 45%, respectively (Simon et al. 2007; Kramer et al. 2008). The median rms across the map is 1.74, 1.53, 0.70, and 1.25 K for CO 4–3, 7–6, [CI] 1–0, and 2–1 respectively. The forward efficiency, $F_{\text{eff}} = 86\%$ in both bands, was determined from sky-dips. The raw data were calibrated to antenna temperatures $T_A^*$ and scaled to main beam temperatures $T_{\text{mb}}$ with the factor $F_{\text{eff}}/B_{\text{eff}}$. We present all data in units of $T_{\text{mb}}$.

Fifth order polynomial baselines were subtracted from all spectra. Observations of the atomic carbon lines are very challenging and require many OTF coverages to achieve a signal to noise (S/N) ratio above 3σ.

4. Data

4.1. Dust and PAHs

In Fig. 1, we show a map of integrated CO 4–3 intensities from NANTEN2 overlayed to an 8 μm image taken with the Infrared Array Camera (IRAC) on board the Spitzer space telescope. The position of the OB cluster is marked by a star. The image shows prominent molecular clumps southwest and southeast of the cluster position. Following Nünberger et al. (2002), we refer to them as MM1 and MM2, respectively. The IRAC image shows the sharp PDR interfaces between the HII region and the molecular cloud. The positions of these interfaces match the pillar-like structures visible in HST and VLT images (Brandner et al. 2000). Note that these pillars are much smaller than the molecular clouds from which they protrude. We also note a dusty filament, which connects MM1 and MM2 in a large arc 1.5′ to 2′ south of the western pillar head. This filament is not visible in CO or [CI] emission. The strong 8 μm emission (>10$^3$ MJy/sr) includes strong PAH emission (7.6, 7.8, and 8.6 μm). The 8 μm band is an excellent tracer of the PDR interface. For a detailed analysis of the emission by PAH’s and very small grains see Lebouteiller et al. (2007).

4.2. NANTEN2 observations

4.2.1. Maps of integrated intensity

Figure 2 shows maps of integrated CO 4–3, 7–6, [CI] 1–0, and 2–1 emission integrated over a velocity range from 4 to 26 km s$^{-1}$. The two molecular clumps MM1 and MM2 are visible: MM1 to the southwest of the OB cluster and MM2 to the southeast. The peak intensities are 267 K km s$^{-1}$ for CO 4–3, 121 K km s$^{-1}$ for CO 7–6, 28 K km s$^{-1}$ for [CI] 1–0, and 30 K km s$^{-1}$ for [CI] 2–1. The position of the compact OB cluster is marked by a white star. The position of the pillars, as seen in the HST images, are marked by white squares. Dashed lines and small crosses spaced by 22″ mark two cut from the OB cluster to the peak positions of the two clumps MM1 (short cut) and MM2 (long cut). The circle marks the resolution and the two white crosses mark the position of the CS(2–1) peaks (Nünberger et al. 2002) in MM1 and MM2. The position (0, 0) corresponds to RA(J2000.0) = 11h15m08s85, Dec(J2000.0) = −61°16′50″.

Fig. 2. Velocity integrated maps (200″ × 200″) of CO 4–3, 7–6, [CI] 1–0, and 2–1 smoothed to a common angular resolution of 38″ (1.3–1.5 pc at 7–8 kpc), and integrated over a velocity range from 4 to 26 km s$^{-1}$. Color scale and contours show the same data. Contours range between 10 and 90% of the peak intensities which are 267 K km s$^{-1}$ for CO 4–3, 121 K km s$^{-1}$ for CO 7–6, 28 K km s$^{-1}$ for [CI] 1–0, and 30 K km s$^{-1}$ for [CI] 2–1. The position of the compact OB cluster is marked by a white star. The position of the the pillars, as seen in the HST images, are marked by white squares. Dashed lines and small crosses spaced by 22″ mark two cut from the OB cluster to the peak positions of the two clumps MM1 (short cut) and MM2 (long cut). The circle marks the resolution and the two white crosses mark the position of the CS(2–1) peaks (Nünberger et al. 2002) in MM1 and MM2. The position (0, 0) corresponds to RA(J2000.0) = 11h15m08s85, Dec(J2000.0) = −61°16′50″.

The observed intensity distributions of the CO rotational line transitions. The peak positions of [CI] are slightly shifted away from the cluster compared to CO. However, the S/N of both [CI] transitions is too low to allow further conclusions. MM1 can be identified in both CO maps. In [CI] a diffuse emission is visible without a clear distinction between clump center and its more diffuse environment. The MM2 peak positions of both CO maps match within the pointing accuracy. The same is true for both [CI] maps. Both [CI] peaks are shifted away from the OB cluster with respect to CO. However, we note a good spatial correlation between the CO and [CI] emission as all peaks coincide within a beam radius. We do not see any C-CO layering as expected from simple edge-on, plane-parallel PDR scenarios. It is possible to explain coincident [CI] and CO emission with a face-on configuration, but the visible pillar structures in the HST observations and the very sharp interface visible in the IRAC image in Fig. 1 clearly show a prominent, edge-on PDR interface.

The velocity structure of the observed field is shown in the CO 4–3 velocity channel maps (Fig. 3). From the channel maps, it is evident that the emission towards MM1 shows a smaller kinematic range than in MM2. MM1 is not observable at velocities higher than 16 km s$^{-1}$, while the emission in MM2 extends up to 21 km s$^{-1}$. At larger velocities, the emission gradually shifts to the southwest. A similar kinematic behavior is also visible from CS (3–2) observations by Nünberger et al. (2002). Their results also show a velocity drift for MM1 with distance.
Table 1. Observed integrated intensities $I = \int T_{\text{mb}} \, dv$ in units of K km s$^{-1}$, $\nu_{\text{LSR}}$ in units of km s$^{-1}$, and the line widths $FWHM$ in units of km s$^{-1}$ computed as $0^\circ$, $1^\circ$, and $2^\circ$ moment of the spectra between $v = 8...22$ km s$^{-1}$.

<table>
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<tr>
<th>$\Delta v / \Delta \delta$</th>
<th>$I_{43}$</th>
<th>$\Delta v_{43}$</th>
<th>$\nu_{\text{LSR}}$</th>
<th>$I_{76}$</th>
<th>$\Delta v_{76}$</th>
<th>$\nu_{\text{LSR}}$</th>
<th>$I_{10}$</th>
<th>$\Delta v_{10}$</th>
<th>$\nu_{\text{LSR}}$</th>
<th>$I_{21}$</th>
<th>$\Delta v_{21}$</th>
<th>$\nu_{\text{LSR}}$</th>
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<td>29</td>
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<td>13.9</td>
<td>0</td>
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<td>14.5</td>
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<tr>
<td>20/10</td>
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<td>6.7</td>
<td>14.2</td>
<td>71</td>
<td>7.4</td>
<td>13.5</td>
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<td>7.8</td>
<td>14.9</td>
<td>119</td>
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<td>13.6</td>
<td>27</td>
<td>7.1</td>
<td>14.6</td>
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<tr>
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<td>121</td>
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<td>13.7</td>
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<td>84</td>
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<td>20</td>
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<td>6.9</td>
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Notes. The positions lie along a line starting from the OB cluster. The cluster position has been omitted. Rotational transitions of CO are denoted $3(12CO \, 4–3)$ and $76 (12CO \, 7–6)$. The atomic carbon fine-structure transitions are denoted $10 (3A^8, P_{1/2})$, and $21 (3A^8, P_{3/2})$. In MM1 we find ratios between 0.8 and 0.9, and in MM2 the ratios range from 0.7 to 0.8. In both clouds the $I_{21}/I_{43}$ ratio is remarkably constant across both clouds. We find an excitation temperature slightly above 50 K for both clouds. First, we don’t find significant emission to derive significant values.

Fig. 3. Velocity structure of the observed field: CO 4–3 intensity in velocity channels of 1 km s$^{-1}$ width. Contours range between 5 and 45 K in steps of 5 K. The position (0,0) corresponds to RA(J2000.0) = 11$^h$15$^m$08$^s$, Dec(J2000.0) = –61$^\circ$16′50″.

Fig. 4. Spectra along two cuts connecting the OB cluster and the centre of MM1 (bottom) and MM2 (top). The CI spectra appear to show sinusoidal standing waves, however a detailed analysis shows no consistent standing wave pattern. These baseline variations are thus attributed to instabilities of the system and/or the atmosphere during the measurements. All data are at a common resolution of 38″ and on the main beam temperature scale.

4.3. Analysis

4.3.1. LTE – Column densities and temperatures

In Table 2 we give the velocity integrated line ratios $R_{21}$ ($I_{21}/I_{10}$), $R_{21}$ ($I_{21}/I_{10}$) and $R_{21}$ ($I_{21}/I_{10}$) for all positions along the two cuts. We compute the LTE temperatures using the optically thick CO 4–3 emission assuming a beam filling of 1 and obtain temperatures of 42 K for the peak position in MM2 and 24 K for MM1. This is roughly consistent with estimates from the [CI] line ratio. $R_{21}$ is a sensitive function of the [CI] excitation temperature. In the optically thin limit and assuming LTE, $T_{\text{ex}}$ is remarkably constant across both clouds. We find an excitation temperature slightly above 50 K for both clouds. First, this confirms that both clouds have comparable excitation conditions despite their different appearance. Second, they seem not to be composed of hot, unresolved clumps which would result in
a much higher excitation temperature derived from $R_{24}$. Instead the gas appears to be more smoothly distributed and excited.

The atomic carbon column density was derived under the assumption of LTE and optically thin [C I] emission. To derive the total H$_2$ column densities we used the integrated intensity of C$^{18}$O 2–1 as presented in Nürnberger et al. (2002). Assuming optically thin emission, an isotope ratio of 500 and CO:H$_2$ = 8×10$^{-3}$ (Ferking et al. 1982), i.e., an assumed ratio of C$^{18}$O:H$_2$ = 2×10$^{-3}$, we compute the column densities along the two cuts. The results are summarized in Table 2. For MM1, we find a total column density of 1.5×10$^{22}$ cm$^{-2}$; for MM2, $N = 2.5×10^{22}$ cm$^{-2}$. We find that the relative abundance of atomic carbon $N_{C}/N_{H_2}$ drops towards the peak positions with values of 10$^{-5}$ (MM1) and 8–19×10$^{-6}$ (MM2), and increases at positions towards as well as away from the OB cluster. Even though the spatial resolution of our maps is rather coarse, this could be an indication for a C/CO stratification, because in this case we would expect limb brightened [C I] emission. The gas pressure within MM1 and MM2 (assuming a density of 10$^{3}$ cm$^{-3}$) is about 10–30% of the pressure in the HII region (Shaver & Goss 1970). Hence, the interface region is compressed and driven against the molecular cloud, visible, e.g., in the pillars protruding from MM1 and MM2. From the total column density we can estimate the total mass per beam. The results are given in Table 2. We also derived virial mass estimates across the cuts assuming a density of 10$^{3}$ cm$^{-3}$ and kinetic temperatures of 50 K (the densities are in agreement with the calculations from Sect. 4.3.3). The virial masses agree very well with the LTE masses and are much larger than the Jeans mass of the material of 87 $M_\odot$. This means, the gas is gravitationally bound and not transient. We expect that the strong HII pressure and the gravitational instability causes strong fragmentation and cloud collapse. Nürnberger et al. (2002) derived a star formation efficiency of $\gtrsim$30% and a mean star formation rate of $1.3 \times 10^{-3}$ $M_\odot$ yr$^{-1}$. Embedded IR sources have already been identified (Frogel et al. 1977) along the outskirts of the molecular clouds and particularly at the base of the pillar like structures at the edge of MM2 (Nürnberger 2008; Nürnberger et al. 2010).

### 4.3.2. Dust temperatures and FUV intensities

To estimate the total FUV flux, we consider the total luminosities of the most massive O stars in the central OB cluster. Recently, Melena et al. (2008) published an updated census of the massive star content of NGC 3603. The most massive members of the OB cluster are 3 WNL stars, 14 O3 (and 3.5) stars (III+V) and at least 20 late O-type stars. They produce the FUV flux that dominates the heating of the PDRs and the molecular clouds.

At an effective temperature of 24 000 K, the ratio of the FUV energy density to the total energy density emitted by the star $\Phi_{FUV}/\Phi_{eff} \approx 0.7$ is maximal if we assume pure black body emission. At higher temperature, relatively more energy is emitted in the EUV range (13.6 eV < $h\nu < 130$ eV$^2$).

Applying effective temperatures and luminosities as given by Martins et al. (2005) for the O stars, Panagia (1973) for the B stars and Crowther (2007) for the WR stars, we calculated a total FUV luminosity of 1.1×10$^{43}$ erg s$^{-1}$ from the contribution of each cluster member. This is a lower limit since the spectral classes for more than 10 cluster members remains unknown. Depending on the distance from the cluster center $d$, in units of pc, the FUV flux is $\chi = 9.4 \times 10^{-1}d^2$ in units of the Draine field. At a distance of 7–8 kpc, one parsec corresponds to angular distances of 26–29$''$, i.e., somewhat smaller than the projected distance between the cluster center and the edge of MM2 as seen for example in Fig. 1 ($\approx 46''$). If we assume that the cluster and the molecular cloud are situated in the same plane, the FUV field at the peak position in MM2 drops to $\chi = 5000$–6600. This is of the same order as the flux at the MM2-peak derived from the IRAS data. If the clumps are displaced from the plane of the OB cluster, or if the distance to the complex is different, the derived $\chi$ changes. Uncertainties in the in-plane displacement of $\pm 4$ pc and in the distance (7–8 kpc) lead to $\chi = 2400$–6600.

We use IRAS data to derive dust temperatures and the FUV continuum in the observed region. Enhanced resolution images of $\sim 1''$ resolution were created using the maximum correlation method (Aumann et al. 1990). We estimate dust temperatures from the ratio of HIRES 60$\mu$m and 100$\mu$m data, assuming a dust spectral index of emissivity of 1.5. We obtained high resolution (HIRES) 60 and 100$\mu$m images ($2'' \times 2''$) from the IPAC data center$^3$. Along the two cuts, we find almost constant dust temperatures of 35 K. This value is very close to the dust temperature of 37 K derived from MSX data by Wang & Chen (2010). Again, comparison with the higher resolution Spitzer maps shows that the warm dust is not distributed homogeneously. We conclude that the HIRES data are, therefore, affected by beam filling.

Following Nakagawa et al. (1998), we combined 60 and 100$\mu$m data to create a map of far-infrared intensities between 42.5$\mu$m and 122.5$\mu$m (Helou et al. 1988). Under the assumption

### Notes

The LTE excitation temperature $T_{C\alpha,\lambda}$ is derived from the optically thick $I_{C\alpha}$ emission. $T_{C\alpha,74}$ is derived from $R_{24}$. The C I column densities are derived assuming LTE and optically thin [C I] emission. Values of the integrated intensities of C$^{18}$O 2–1 are given as presented in Nürnberger et al. (2002) along the two cuts, the LTE excitation temperature is derived from $I_{C\alpha}$.

The LTE column densities of C$^{18}$O, and the total gas column density assume an isotope ratio of 500 and CO:H$_2$ = 8×10$^{-3}$ (Ferking et al. 1982), i.e., a ratio of C$^{18}$O/H$_2$ = 2×10$^{-7}$.

### Table 2

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<th>$\Delta \alpha/\Delta \delta$</th>
<th>$R_{24}$</th>
<th>$R_{25}$</th>
<th>$R_{24}$</th>
<th>$T_{ex,\lambda}$</th>
<th>$N_{C}$</th>
<th>$J_{T_{ex}C^{18}O}$</th>
<th>$N_{C^{18}O}$</th>
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<td>33</td>
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<td>1.9</td>
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<td>40/–30</td>
<td>0.45</td>
<td>1.09</td>
<td>0.10</td>
<td>42</td>
<td>52</td>
<td>$4.1 \times 10^2$</td>
<td>4.3</td>
<td>9.87</td>
<td>49.36</td>
<td>8.2×10$^{-6}$</td>
<td>1028</td>
</tr>
<tr>
<td>50/–50</td>
<td>0.47</td>
<td>0.79</td>
<td>0.15</td>
<td>34</td>
<td>54</td>
<td>$3.7 \times 10^2$</td>
<td>2.1</td>
<td>4.04</td>
<td>20.20</td>
<td>1.9×10$^{-5}$</td>
<td>421</td>
</tr>
<tr>
<td>–30/60</td>
<td>0.43</td>
<td>8.89</td>
<td>0.01</td>
<td>21</td>
<td>51</td>
<td>$1.0 \times 10^3$</td>
<td>1.3</td>
<td>1.73</td>
<td>8.64</td>
<td>1.2×10$^{-5}$</td>
<td>180</td>
</tr>
<tr>
<td>–50/50</td>
<td>0.44</td>
<td>0.84</td>
<td>0.12</td>
<td>24</td>
<td>51</td>
<td>$1.5 \times 10^3$</td>
<td>2.1</td>
<td>3.07</td>
<td>15.37</td>
<td>1.0×10$^{-5}$</td>
<td>320</td>
</tr>
</tbody>
</table>

Notes: The LTE excitation temperature $T_{ex,\lambda}$ is derived from the optically thick $I_{C\alpha}$ emission. $T_{C\alpha,74}$ is derived from $R_{24}$. The C I column densities are derived assuming LTE and optically thin [C I] emission. Values of the integrated intensities of C$^{18}$O 2–1 are given as presented in Nürnberger et al. (2002) along the two cuts, the LTE excitation temperature is derived from $I_{C\alpha}$.

The LTE column densities of C$^{18}$O, and the total gas column density assume an isotope ratio of 500 and CO:H$_2$ = 8×10$^{-3}$ (Ferking et al. 1982), i.e., a ratio of C$^{18}$O/H$_2$ = 2×10$^{-7}$.
that all FUV energy absorbed by the grains is re-radiated in the far-infrared (FIR), we compute the FUV fluxes ($\chi$) from the emergent FIR intensities (cf. Kramer et al. 2005) $I_{\text{FIR}}$, using $\chi/\chi_0 = 4\pi I_{\text{FIR}}$, with $\chi_0 = 2.7 \times 10^{-3}$ erg s$^{-1}$ cm$^{-2}$ (Draine 1978). The resulting map of the FIR continuum is shown in the left panel of Fig. 5. Overlayed as thin contours is the NANTEN2 CO 4–3 map. At the peak position of MM1, we find FUV fields of $\chi = 3460$. Along the cut in MM2, we find that $\chi$ gradually increases from 3350 at the position of the OB cluster to 5230 at the peak position. Due to the low spatial resolution of the HIRES data, these values are lower limits since beam dilution effects are not negligible.

One would expect a decrease of FUV with growing distance from the cluster. However, such a decrease is not seen, Fig. 5 shows the opposite. This is because the method of deriving FUV intensities from IRAS data is not working for too small dust column densities because then UV radiation can not be effectively transformed to IR. Consequently, it would be best to exclude these parts from the further analysis. In our case, this is impossible due to the large beam. HIRES beam sizes vary from $\sim 35''$ to over 120'' across the maps, hence the FUV values in Fig. 5 are considerably beam diluted. In the right panel in Fig. 5, we overlayed the FUV fields derived from the NANTEN2 CO 4–3 map. The central OB cluster is marked by a star. The two pillar heads are denoted by the squares, White.

The derived FUV fluxes can be used to estimate the ratio $I_{\text{CII}}/I_{\text{FUV}}$, i.e. the fraction of FUV energy that is re-emitted in the [CII] 158 $\mu$m cooling line. We retrieved the [CII] spectrum from the ISO data archive and compute an integrated intensity of $2 \times 10^{-3}$ erg s$^{-1}$ cm$^{-2}$. Most of the FUV energy that irradiates the cloud is re-radiated in the continuum, but a small fraction is re-emitted in cooling lines, such as the [CII] 158 $\mu$m line. Applying the FUV flux derived from the NANTEN2 CO data, we estimate $I_{\text{CII}}/I_{\text{FUV}} \approx 0.2 \pm 0.3\%$. This is consistent with similar results for regions of active star formation, e.g., nuclear regions of galaxies, where approximately 0.1 to 1% of the total FUV input is re-radiated in the [CII] line (Stacey et al. 1991). However, this remains a rough estimate because of the large beam sizes involved.

Considering the similar FUV estimates from stellar luminosities and from the FIR data, we conclude that the FUV flux illuminating the molecular clumps MM1 and MM2 is $3000$–$6000$ in units of the Draine field. Approximately 0.2 to 0.3% of the total FUV energy is re-emitted in the [CII] 158 $\mu$m cooling line. We retrieved the [CII] spectrum from the ISO data archive and compute an integrated intensity of $2 \times 10^{-3}$ erg s$^{-1}$ cm$^{-2}$.

4.3.3. Escape probability – density and temperatures

We performed escape probability (EP) calculations (Stutzki & Winnewisser 1985) to derive local gas densities, column densities, and gas temperatures from the observed line ratios ($R_{21}, R_{21}, R_{12}$, and $I_{\text{CII}}/I_{\text{FUV}}$). The model assumes a finite, spherical cloud geometry. We fitted the column densities of $^{12}$CO

4 Taken at RA(J2000.0) = $11^h15^m08.3^s$, Dec(J2000.0) = $61^\circ16'50.5''$, FITS file name: lsan20100302.fits

5 http://isowww.estec.esa.nl/ida/
The derived temperatures for MM1 and MM2 are about 104 cm−3. We present fully sampled 200" × 200" maps integrated over the full velocity range as well as velocity channel maps. The observed field includes the central OB cluster, as well as the two adjacent molecular clumps MM1 and MM2, hosting two pillars observed by the HST and similar in appearance to the famous pillar structures in the M16 nebula. We selected two cuts from the OB cluster position to the peak emission in MM1 and MM2 for detailed analysis. The spectra along the two cuts show a rich kinematic structure, especially towards MM2. The observed maps show a strong correlation between the spatial distribution of C and CO. This implies either a face-on configuration of the clouds, i.e., both clouds being not in the same plane as the OB cluster and thus being illuminated face-on, or a more complex configuration, for instance a composition of many small clumps. The overall good C-CO correlation may indicate an unresolved, clumpy structure, but the increase of NC towards a cloud edge could hint towards relatively well shielded inner parts.

Using escape probability model calculations we derived temperatures, densities, and column densities for both clouds from the observed line ratios. The temperatures are 43 K and 47 K for the peak positions of MM1 and MM2, respectively. We find gas densities of n = 103–104 cm−3 in MM1 and MM2. From the best fit CO column densities we derive total H2 column densities (filling corrected) of 0.187 × 1022 cm−2 and 2.38 × 1022 cm−2 for MM1 and MM2 and a ratio of NC/NH2 of 1.5 × 10−5.

The cluster is strongly interacting with the ambient molecular cloud and governing its structure and physical conditions. The stability analysis shows the existence of gravitationally bound gas which should lead to star formation. Embedded IR sources have already been observed in the outskirts of the molecular cloud and support our conclusions.

We used HIRES/IRAS far-infrared data to narrow down the value of the FUV field at the positions of the two molecular clouds. Consistent with estimates from spectral type approximations and with [CII] observations by ISO we find χ ≈ 3–6 × 105 in units of the Draine field.

However, many issues remain unresolved. For example, the analysis results are not conclusive regarding the clumpiness of the gas. NGC 3603 will be observed within the Herschel Guaranteed Time Key project Warm and Dense ISM – WADI. These data will allow us to perform a much more detailed study of the local gas conditions. Cooling lines like [O I] and [C II] as well as high-J CO lines can be used to study the clumpiness and the energy balance of the gas.

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Appendix A: Velocity channel maps

Here we present the velocity channel maps of all observed transitions. Each map is shown at its original spatial resolution, i.e. 38" for CO 4–3 and CI 1–0 as well as 26.5" for CO 7–6 and CI 2–1.
Fig. A.1. Velocity structure of the observed field: CO 4–3 intensity in velocity channels of 1 km s\(^{-1}\) width. Contours range between 5 and 45 K in steps of 5 K. The position (0, 0) corresponds to RA(J2000.0) = 11h15m08.85, Dec(J2000.0) = −61°16′50.0″.
Fig. A.2. Velocity structure of the observed field: CO 7–6 intensity in velocity channels of 1 km s$^{-1}$ width. Contours range between 2 and 20 K in steps of 2 K. The position (0, 0) corresponds to RA(J2000.0) = 11h15m08.85, Dec(J2000.0) = −61°16′50.0′′.
Fig. A.3. Velocity structure of the observed field: [CI] 1–0 intensity in velocity channels of 1 km s\(^{-1}\) width. Contours range between 1 and 10 K in steps of 1 K. The position (0, 0) corresponds to RA(J2000.0) = 11\(^{h}\)15\(^{m}\)08.85, Dec(J2000.0) = −61°16′50.0″.
Fig. A.4. Velocity structure of the observed field: [CI] 2–1 intensity in velocity channels of 1 km s$^{-1}$ width. Contours range between 1 and 10 K in steps of 1 K. The position (0, 0) corresponds to RA(J2000.0) = 11h15m08.s85, Dec(J2000.0) = −61°16′50″.0.
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