Molecular gas and star formation toward the IR dust bubble S 24 and its environs

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ABSTRACT

Aims. We present a multiwavelength analysis of the infrared dust bubble S 24 and the extended IR sources G341.220-0.213 and G341.217-0.237 located in its environs. We aim to investigate the characteristics of the molecular gas and the interstellar dust linked to them and analyze the evolutionary state of the young stellar objects identified there and the relation of the bubble to S 24 and the IR sources.

Methods. Using the APEX telescope, we mapped the molecular emission in the CO(2−1), 13CO(2−1), C18O(2−1), and 13CO(3−2) lines in a region of about 5′ × 5′ in size around the bubble. The cold dust distribution was analyzed using submillimeter continuum images from ATLASGAL and Herschel. Complementary IR and radio data at different wavelengths were used to complete the study of the interstellar medium in the region.

Results. The molecular gas distribution shows that gas linked to the S 24 bubble and to G341.220-0.213 and G341.217-0.237 has velocities of between ~48.0 km s⁻¹ and ~40.0 km s⁻¹, compatible with the kinematical distance of 3.7 kpc that is generally adopted for the region. The gas distribution reveals a shell-like molecular structure of ~0.8 pc in radius bordering the S 24 bubble. A cold dust counterpart of the shell is detected in the LABOCA and Herschel-SPIRE images. The weak extended emission at 24 μm from warm dust and radio continuum emission projected inside the bubble indicates exciting sources and that the bubble is a compact H II region. Part of the molecular gas bordering the S 24 H II region coincides with the extended infrared dust cloud SDC341.194-0.221. A molecular and cold dust clump is present at the interface between the S 24 H II region and G341.217-0.237, shaping the eastern border of the IR bubble. The arc-like molecular structure encircling the northern and eastern sections of the IR source G341.220-0.213 indicates that the source is interacting with the molecular gas. The analysis of the available IR point source catalogs reveals some young stellar object candidates linked to the IR-extended sources, thus confirming their nature as active star-forming regions. Gas and dust masses were estimated for the different features. The total gas mass in the region and the H₂ ambient density amount to 10³³ M₀ and 5900 cm⁻³, indicating that G341.220-0.213, G341.217-0.237, and the S 24 H II region are evolving in a high-density medium. A triggering star formation scenario for the H II region is investigated.

Key words. molecular data – H II regions – submillimeter: ISM – ISM: molecules

1. Introduction

Churchwell et al. (2006, 2007) identified more than 600 infrared (IR) dust bubbles in the Spitzer 8.0 μm-images of the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE, Benjamin et al. 2003) between longitudes of −60° to +60°. These IR dust bubbles are bright at 8.0 μm, showing the emission of polycyclic aromatic hydrocarbons (PAHs) typical of photodissociation regions (PDRs) and enclose 24 μm emission, indicating the existence of warm dust inside (Watson et al. 2008). These characteristics indicate excitation sources (O- and/or B-type stars) that dissociate the molecular gas in the border of the PDRs and heat the dust through their UV photons. The dense shells surrounding many IR dust bubbles are believed to favor the formation of new generations of stars through the radiatively driven implosion (RDI) or the collect-and-collapse (CC) processes (Pomarès et al. 2009; Deharveng et al. 2009, 2012; Samal et al. 2014). Indeed, detailed studies of these bubbles have shown young stellar objects (YSOs) in their environs, although in some cases triggered star formation could not be proved (see, for example, Alexander et al. 2013; Dewangan & Ojha 2013).

We selected the complex of IR dust bubbles S 21-S 24 identified by Churchwell et al. (2006) in the GLIMPSE images to perform a multiwavelength study of the interaction with their environs and search for YSOs in their vicinity. Here we report on the study of S 24. This bubble is centered at RA, Dec(J2000) = (16°52′20″, −44′28′40″) or (l, b) = (341°203, −0°23) and coincides with the IR source IRAS 16487-4423, which has colors typical of ultracompact H II regions (Wood & Churchwell 1989).

A composite image of S 24 and its environs at 3.6, 4.5, and 8.0 μm is displayed in Fig. 1. At 3.6 μm the emission arises in a faint PAH feature at 3.3 μm and in dispersed stellar light,
while at 8.0 \( \mu \)m most of the emission originates in strong features from PAHs. The 4.5 \( \mu \)m band shows emission from Br\( \alpha \) and Pf\( \beta \), and vibrational H\( _2 \) lines and ro-vibrational CO lines, typical of shocked gas (see Watson et al. 2008). At 8 \( \mu \)m the bubble presents a full filamentary shell of about 28\( ^\circ \) in radius, brighter toward the north and east, and displays a sharp eastern border. Two small and bright regions of extended emission can be identified at 8 \( \mu \)m in the image, named G341.220-0.213 at RA, Dec(J2000) = (16\(^{h}\)52\(^{m}\)18.25\(^{s}\), -44\(^{\circ}\)26’54’’), of about 10\( ^\circ \) in radius, and G341.217-0.237 at RA, Dec(J2000) = (16\(^{h}\)52\(^{m}\)23.74\(^{s}\), -44\(^{\circ}\)27’53’’), of about 5\( ^\circ \) in radius, placed to the north and east of S 24, respectively. At this wavelength, the shape of G341.220-0.213 resembles a horseshoe opened toward the east. The infrared dark cloud (IRDC) identified by Peretto & Fuller (2009) as SDC341.194-0.221 is evident to the west of the bubble where the emission at 8 \( \mu \)m is lacking. It is centered at RA, Dec(J2000) = (16\(^{h}\)52\(^{m}\)15.5\(^{s}\), -44\(^{\circ}\)28’19.4’’), and extends almost 2\( ^\circ \) in declination. Two IRDCs were also identified by Peretto & Fuller (2009): one at RA, Dec(J2000) = (16\(^{h}\)52\(^{m}\)15.4\(^{s}\), -44\(^{\circ}\)30’6.9’’)(SDC 341.171-0.241), to the south of the bubble, and the other one at RA, Dec(J2000) = (16\(^{h}\)52\(^{m}\)35.7\(^{s}\), -44\(^{\circ}\)28’21.8’’)(IRDC SDC 341.232-0.268). Finally, fainter emission can be detected in the whole region, encircling S 24, G341.22-0.213, and G341.217-0.237. An almost circular structure of about 16\( ^\circ \) in radius that we call G341.210-0.252, is also detected in the 8 \( \mu \)m image at RA, Dec(J2000) = (16\(^{h}\)52\(^{m}\)26.5\(^{s}\), -44\(^{\circ}\)28’50’’), to the southeast of S 24. These features are indicated in Fig. 1. The figure also shows that G341.220-0.213, G341.217-0.237, and part of the S 24 bubble coincide with sources at 4.5 \( \mu \)m.

Henning et al. (2001) observed the region at 1.2 mm using the SEST telescope with an angular resolution of 23\( ^\circ \). They detected cold dust emission from G341.220-0.213 and G341.217-0.237 and an extended halo linked to S 24, and estimated that the total mass in the region amounts to almost 5000 \( M_\odot \) (adopting a gas-to-dust ratio of 100 and a distance of 3.7 kpc).

Previous studies toward the region of S 24 have shown that star formation is active. Two spots of maser emission were detected. The first spot is a methanol and water maser emitter (Bayandin et al. 2012; Urquhart et al. 2013; Walsh et al. 2014) with peak velocities of between \(-30\) km s\(^{-1}\) and \(-38\) km s\(^{-1}\) (Pestalozzi et al. 2005; Caswell et al. 2010; Voronkov et al. 2014; Walsh et al. 2014), coincident with G341.220-0.213. The second spot is also a methanol maser emitter (Vassilev et al. 2008; Bayandin et al. 2012) with peak velocities of between \(-70\) km s\(^{-1}\) and \(-16\) km s\(^{-1}\) (Larionov & Val’tts 2008; Voronkov et al. 2014) located at RA, Dec(J2000) = (16\(^{h}\)52\(^{m}\)15.9\(^{s}\), -44\(^{\circ}\)28’36’’7’’), coincident with the IRDC SDC341.194-0.221. Although a number of EGO candidates have been identified in the S21-S24 complex (Cyganowski et al. 2008), none of them appear projected in the close environs of the IR bubble.

S 24 is detected as a radio continuum source in the Molonglo Galactic Plane Survey at 843 MHz (MGPSS165220-442802, Murphy et al. 2007; synthesized beam = 65’’ \times 45’’), with an integrated flux density \( S_{0.843} = 0.92 \pm 0.04 \) Jy.

Bronfman et al. (1996) performed CS(2–1) line observations with an angular resolution of 50’’ using the SEST telescope. They observed the molecular line in one position toward IRAS16487-4423 (RA, Dec(J2000) = (16\(^{h}\)52\(^{m}\)21.24\(^{s}\), -44\(^{\circ}\)28’27.5’’)) detecting CS emission with a velocity of \(43.4\) km s\(^{-1}\), which indicates dense gas toward the IR source. Russell & Castets (2004) observed the CO(1–0) and CO(2–1) lines with an angular resolution of 42’’ and 21’’, respectively, toward a position located 4.7 toward the southeast of the S 24 bubble, detecting molecular gas with velocities in the range \(-40\) km s\(^{-1}\)
to $-37$ km s$^{-1}$. All velocities in this paper are given with reference to the LSR.

Circular galactic rotation models predict that gas with velocities of $-43.4$ km s$^{-1}$ lies at near and far kinematical distances of 3.6 kpc and 12–13 kpc (see, for example, Brand & Blitz 1993). Similar distances can be derived from maser velocities. Following Henning et al. (2001), we adopt a distance of 3.7 kpc for the S 24 region and its environment. Taking into account a velocity dispersion of 6 km s$^{-1}$ for the interstellar gas, we adopt a distance uncertainty of 0.5 kpc.

Here, we present the very first molecular line and dust continuum study toward S 24 and its environs aimed at determining the distribution of the molecular gas and the dust linked to the bubble and the correlation between them, analyzing their physical conditions, masses, and ambient densities, and investigating the status of star formation in the region. The dense gas linked to this region makes it particularly interesting to investigate the physics and kinematics of HII regions and bubbles in dense media, allowing a better understanding of the evolution and star formation processes around these objects. Preliminary results were published in Cappa et al. (2013).

2. Data sets

2.1. Molecular line observations

The molecular gas characteristics were investigated by performing $^{13}$CO(3$\rightarrow$2) line observations (at 330.58797 GHz) of a region of 3/2 $\times$ 3/2 during August 2009, and $^{12}$CO(2$\rightarrow$1), $^{13}$CO(2$\rightarrow$1), and C$^{18}$O(2$\rightarrow$1) line observations of a region of 5$\times$5$'$ obtained in October 2010, with the APEX telescope using the APEX-1 and APEX-2 receivers, whose system temperatures are 150 K and 300 K, respectively.

The half-power beam-widths of the telescope are 30$'$ (for the (2$\rightarrow$1) lines) and 21$'$ (for the (3$\rightarrow$2) lines). The data were acquired with a FFT spectrometer, consisting of 4096 channels, with a total bandwidth of 1000 km s$^{-1}$ and a velocity resolution of 0.33 km s$^{-1}$. The region was observed in position-switching mode using the OTF technique with a space between jumps in the scanning direction of 9$'$ for the (2$\rightarrow$1) transition, and in position-switching mode in the (3$\rightarrow$2) transition. The off-source position free of CO emission was located at RA, Dec(J2000) = (13$^h$33$^m$10.3$^s$, $-$62$^o$2$'$41$''$).

Calibration was performed using Mars and X-TrA sources. Pointing was made twice during observations using X-TrA, o-Ceti, and VY-CMa. The intensity calibration has an uncertainty of 10%.

The spectra were reduced using the Continuum and Line Analysis Single-dish Software (CLASS) of the Grenoble Image and Line Data Analysis Software (GILDAS) working group. A linear baseline fitting was applied to the data. The rms noise of the profiles after baseline subtraction and calibration is 0.35 K for the (2$\rightarrow$1) and (3$\rightarrow$2) transitions. The observed line intensities are expressed as main-beam brightness temperatures $T_{mb}$, by dividing the antenna temperature $T_A$ by the main-beam efficiency $\eta_{mb}$, equal to 0.72 for APEX-1 and 0.82 for APEX-2 (Vassilev et al. 2008). The Astronomical Image Processing System (AIPS) package and CLASS software were used to perform the analysis.

2.2. Dust continuum data

To trace cold dust emission we used far-infrared (FIR) images from the Herschel Space Observatory and from the APEX Telescope Large Area Survey of the Galaxy (ATLASGAL, Schuller et al. 2009).

2.2.1. Herschel data

The archival data correspond to the Hi-GAL key program (HiGAL:Herschel Infrared GALactic plane survey, Molinari et al. 2010, OBSIDs: 1342204094 and 1342204095).

The data have been taken in parallel mode with the instruments PACS (Poglitsch et al. 2010) at 70 and 160 $\mu$m, and SPIRE (Griffin et al. 2010) at 250, 350, and 500 $\mu$m. The chosen tile covers a field of 2.2 sq. deg and is approximately centered at (l, b) = (340$^o$, 0$'$). The angular resolutions for the five photometric bands spans from 8$''$ to 35$''$ for 70 $\mu$m to 500 $\mu$m. Herschel interactive processing environment (HIPE v12, Ott 2010) was used to reduce the data, with reduction scripts from standard processing. To combine the two obsids (scan and cross-scan) of PACS archive data, we used the HIPE implementation script of the map merger called Scanmorphs. This script starts from Level1 frames and creates a map from the data. The obtained pixel sizes are 2$''$/px to blue and 3$''$/px to red.

The zero-level of the PACS and SPIRE archive data is unknown, which may cause problems, for example, to derive dust temperatures. The zero-level offsets of the SPIRE maps were corrected as described in Bernard et al. (2010). A proper zero-level was set bearing in mind that Planck includes the same fraction of the sky as Hi-GAL data and taking into account that the two common photometric channels of Planck and SPIRE (857 GHz $\sim$ 350 $\mu$m and 545 GHz $\sim$ 550 $\mu$m) are calibrated with respect to FIRAS (Piat et al. 2002). We used the HIPE implementation script to run destriper gain corrections and to recalculate the absolute offset via cross-calibration with Planck-HFI data (HIPE v12, updated version by L. Conversi 2013).

To estimate fluxes, a Gaussian smoothing was applied to convolve all images at a low resolution of 500 $\mu$m (a FWHM of 35$''$/2).

Assuming that an extended source has a spectral index $\alpha = 4$ (2 for the blackbody emission plus 2 for the opacity of the dust), the obtained fluxes of each source were multiplied by 0.98755, 0.98741, and 0.96787 for 250, 350, and 500 $\mu$m, respectively, to convert from monochromatic intensities of point sources to monochromatic extended sources.

2.2.2. ATLASGAL data

This survey was performed at 870 $\mu$m (345 GHz) with an angular resolution of 19$''$2 (HPBW), using the Large Apex Bolometer Camera (LABOCA; Siringo et al. 2009). The camera operates with 295 pixels at the APEX 12-m submillimeter telescope.

$^1$ http://www.iram.fr/IRAMFR/PDB/class/class.html

$^2$ Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

$^3$ HIPE is a joint development by the Herschel Science Ground Segment Consortium, consisting of ESA, the NASA Herschel Science Center, and the HIFI, PACS and SPIRE consortia members, see http://herschel.esac.esa.int/HerschelPeople.shtml
To search for YSO candidates in the 2MASS catalog, we have constructed an \([H - K_s, J - H]\) diagram using only sources with photometric quality A or B. Six candidates were identified. The two upper panels of Fig. 3 show the 2MASS color–color (CC) and color-magnitude (CM) diagrams with the YSO candidates represented by red asterisks. We have performed a search for candidates in the Spitzer database adopting the criteria by Allen et al. (2004), which allow distinguishing IR sources according to a class scheme: Class I are protostars surrounded by dusty infalling envelopes, and Class II are objects whose emission is dominated by accretion disks. Considering only sources detected in the four Spitzer-IRAC bands, we investigated their evolutionary stage by analyzing their location in a color–color diagram (middle panel of Fig. 3) following the color criteria determined empirically by Allen et al. (2004). Class II candidates lie in the region \(0 \leq [3.6] - [4.5] \leq 0.8\) and \(0.4 \leq [5.8] - [8.0] \leq 1.1\), and their IR excess might be produced by accretion disks around the stellar objects. Sources outside the domain of Class II objects are identified as Class I candidate objects, and their IR excess might be due to circumstellar envelopes around the star. We identified 14 Class I candidates, 5 Class I/II candidates, and one Class II. The middle panel of Fig. 3 shows the position of the 20 Spitzer sources in the color–color \([3.6] - [4.5]\) vs. \([5.8] - [8.0]\) diagram. In this panel, the area delineated by thin lines corresponds to the locus of Class I objects, while the area within thick dashed lines corresponds to class II objects.

Finally, with the aim of identifying candidate YSOs using photometric data from the Wide-field Infrared Survey Explorer survey, which maps the whole sky in four bands centered at 3.4, 4.6, 12, and 22 \(\mu\)m, we used the criteria of Koenig et al. (2012), using \([3.4] - [4.6]\) vs. \([4.6] - [12]\) diagrams as follows: after removing contamination arising from background objects such as galaxies (very red in \([4.6] - [12]\)'), broad-line active galactic nuclei (of similar colors as YSOs, but distinctly fainter), and resolved PAH emission regions (redder than the majority of YSOs), we identified infrared excess sources by requiring that

\[
[3.4] - [4.6] - \sigma_1 > 0.25 \quad [4.6] - [12.0] - \sigma_2 > 1.0,
\]

where \([3.4], [4.6],\) and \([12.0]\) are the WISE bands 1, 2, and 3, respectively, and \(\sigma_1 = \sigma([3.4] - [4.6])\) and \(\sigma_2 = \sigma([4.6] - [12.0])\) indicate the combined errors of \([3.4] - [4.6]\) and \([4.6] - [12.0]\) colors, added in quadrature. Class I sources are a subsample of this defined by

\[
[3.4] - [4.6] > 1.0 \quad [4.6] - [12.0] > 2.0.
\]

The remaining sources are then Class II objects. Identified Class I and Class II candidates are shown in the bottom panel of Fig. 3. In this panel, the separation between the location of Class I and Class II sources is indicated by the dashed lines.

As can be seen from Fig. 2, four candidates (one MYSO, one 2MASS source, one Spitzer Class I, and one WISE Class I) appear projected onto G341.220-0.213. This fact along with the presence of maser emission towards the region confirms that this is an active star-forming region. Three candidates coincide in position with the S 24 bubble, while only one WISE Class II candidate is projected onto G341.217-0.237. Most of the candidates appear to the east of the IRDC SDC341.193-0.221 and are projected onto emission at 8 \(\mu\)m. Finally, two Spitzer candidates coincide with the IRDC SDC341.194-0.221, and another three candidates appear projected onto the borders of G341.210-0.252.
It is clear from Table 1 that there is little correspondence among 2MASS, Spitzer, and WISE candidate YSOs (coincidences: #24 with #52; and #2 with #15 and #34). In spite of the similar wavelengths of two of the bands and in the different angular resolution of the Spitzer and WISE catalogs, an analysis of the coincidence of Spitzer and WISE YSOs identified in Table 1 shows that 33% of the WISE and Spitzer candidates project onto S 24 and its environs. For the remaining 67%, the Spitzer and WISE sources, respectively, which are undetected in at least one band and cannot be properly classified. For the remaining 17%, the Spitzer and WISE sources coincide, but their counterparts are not classified as Class I or II.

| Spitzer candidates | # | h m s | δ( ′ ′ ′ ) | 2MASS name | J [mag] | H [mag] | K [mag] | Class |
|--------------------|---|-------|-----------|-------------|--------|--------|--------|-------|
| 16 52 20 54.2 | 16 52 20 54.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 |
| 16 52 20 54.2 | 16 52 20 54.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 |
| 16 52 20 54.2 | 16 52 20 54.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 |
| 16 52 20 54.2 | 16 52 20 54.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 |
| 16 52 20 54.2 | 16 52 20 54.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 |
| 16 52 20 54.2 | 16 52 20 54.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 | 16522054.2 |

Table 1. YSO candidates projected onto S 24 and its environs.
**Fig. 3.** Upper panels: \([H - K_s, J - H]\) and \([H - K_s, K_s]\) diagrams of the 2MASS YSO candidates indicated by red crosses. Green asterisks correspond to main sequence stars projected onto the S 24 bubble (see Sect. 7.2). The dashed lines show the reddening vectors corresponding to M0 III and B2 V stars in the CC-diagram, and to B2 V stars in the CM-diagram. The squares are placed at intervals of ten magnitudes of visual extinction. Middle panel: location of YSO candidates from the Spitzer database. Crosses represent Class I and II sources. Bottom panel: YSO candidates from the WISE database. Class I and II sources are indicated in red and green, respectively.

**Fig. 4.** Composite image of the IRAC emission at 4.5 (in green) and 8.0 \(\mu m\) (in red), and the Herschel emission at 250 \(\mu m\) (in blue). Contours show the emission at 870 \(\mu m\) and correspond to 0.5 MJy sr\(^{-1}\) to 4.0 MJy sr\(^{-1}\) in steps of 0.5 MJy sr\(^{-1}\).

A more detailed analysis is performed in connection to the molecular dust and cold dust in the next sections.

**4. Distribution of the interstellar dust**

The distribution of the interstellar dust was investigated using data at different wavelengths in the IR.

Figure 2 shows a superposition of the IRAC 8 \(\mu m\) (in red) and 3.6 \(\mu m\) (in green) emissions, and the ATLASGAL 870 \(\mu m\) emission (in blue). Emission at 870 \(\mu m\) reveals the presence of cold dust. This emission approximately encircles the S24 bubble. The dust clumps identified at this wavelength by Contreras et al. (2013) are indicated. AGAL SDC341.216-00.236 and AGAL SDC341.17-00.212 are bright, coincide with G341.217-0.237 and G341.220-0.213, respectively, and correlate with the emission at 1.2 mm detected by Henning et al. (2001). Weaker emission at 870 \(\mu m\) (AGAL SDC341.196-00.221) coincides in position with the IRDC SDC341.194-0.221 placed to the west of the bubble following its sharp eastern border, and is evident from the 8 \(\mu m\) emission in Fig. 2. Additionally, two cold dust clumps are located to the south and southeast of S 24, at RA, Dec(J2000) = (16h52m19.6s, −44°30’38”00), AGAL SDC341.219-00.259, located at RA, Dec(J2000) = (16h52m32’37”1, −44°29’26”1) (AGAL SDC341.211=00.271). AGAL SDC341.219-00.259, located at RA, Dec(J2000) = (16h52m32’32”, −44°28’30”), coincides with a section of the IRDC SDC341.232-0.268 and is being analyzed by Vasquez et al. (in prep.). G341.210-0.252 does not coincide with emission at 870 \(\mu m\).

Figure 4 displays an overlay of the emission at 870 \(\mu m\) (in contours) and the emissions at 4.5 (in green) and 8.0 \(\mu m\) (in red) from Spitzer and 250 \(\mu m\) (in blue) from Herschel. Dust clumps identified at 870 \(\mu m\) have counterparts at 250 \(\mu m\), although the emission at 250 \(\mu m\), which also shows the distribution of cold dust, appears more extended. The brightest dust
clumps at 250 \( \mu m \) coincide with G341.220-0.213 and G341.217-0.237 and are also detected at 350 and 500 \( \mu m \) (the images are not shown here). The S 24 bubble appears clearly surrounded to the east and north by SPIRE emission. *Herschel* emission at these wavelengths is also projected onto the IRDC identified to the west of S 24, which can be defined as a *Herschel* bright IRDC (Peretto et al. 2010). Faint extended emission at 250 \( \mu m \) also coincides with the IRDC SDC341.171-0.241, bordering the weak halo of 8 \( \mu m \) emission, and near RA, Dec(J2000) = (16\(^{h}\)52\(^{m}\)28\(^{s}\), -44\(^{\circ}\)29\('\)30\(')\), in coincidence with a *Spitzer* point source identified at 4.5 \( \mu m \). In summary, the correlation between 250 and 870 \( \mu m \) is excellent.

The PACS emission at 70 and 160 \( \mu m \) differs significantly from the emission at longer wavelengths (Fig. 5). The brightest source at these wavelengths coincides with G341.220-0.213. G341.217-0.237 also emits at 70 and 160 \( \mu m \), while a bright source is also detected to the east of G341.217-0.237. Faint emission correlates with the S 24 bubble, mainly at 70 \( \mu m \). This emission delineates the sharp western border of the bubble. The IRDC SDC 341.194-0.221 cannot be identified at either 70 \( \mu m \) or 160 \( \mu m \). Emission at 70 \( \mu m \) is also projected onto G341.210-0.252, located at 16\(^{h}\)52\(^{m}\)26.5\(^{s}\), -44\(^{\circ}\)28\('\)50\(')\), but is lacking at 160 \( \mu m \) and higher wavelengths. The presence of emission at 70 \( \mu m \) and its absence at 160 \( \mu m \) suggests the existence of dust at a higher temperature.

Dust temperatures \( T_{\text{dust}} \) for the region using the PACS images at 70 \( \mu m \) and 160 \( \mu m \) were estimated by convolving the image at 70 \( \mu m \) down to the angular resolution at 160 \( \mu m \) by applying color corrections, subtracting a background local to the S 24 bubble, and assuming that the emission is optically thin.

The color-temperature map was constructed as the inverse function of the ratio map of *Herschel* 70 \( \mu m \) and 160 \( \mu m \) color-and-background-corrected maps, that is, \( T_{\text{dust}} = f(T)^{-1} \) (see details in Preibisch et al. 2012; Ohlendorf et al. 2013). In the optically thin thermal dust emission regime \( f(T) \) has the following parametric form:

\[
 f(T) = \frac{S_\nu(\nu = 70 \mu m)}{S_\nu(\nu = 160 \mu m)} = \frac{B_\nu(70 \mu m, T)}{B_\nu(160 \mu m, T)} \left( \frac{70}{160} \right)^{\beta_\nu},
\]

where \( B_\nu(y, T) \) is the blackbody Planck function and \( \beta_\nu \) corresponds to the spectral index of the thermal dust emission. The pixel-to-pixel temperature was calculated assuming \( \beta_\nu = 2 \). This is a typical value adopted for irradiated regions (see Preibisch et al. 2012).

The obtained dust temperature map is shown in Fig. 6. We were able to estimate dust temperatures for G341.220-0.213, G341.217-0.237, G341.210-0.252, and for the S 24 bubble. Dust temperatures using this method were almost impossible to obtain for the IRDCs due to their low emission at 70 \( \mu m \). Values for G341.220-0.213 are in the range 26–30 K, while for G341.217-0.237 temperatures are about 29 K. The image reveals a clear gradient in dust temperatures (from 26 to 60 K) for the S24 bubble: the higher the temperature, the closer to the center of the bubble. This is compatible with ionizing sources that are linked to S 24. Dust temperatures for S 24 are compatible with values derived by Watson et al. (2010) for the interior of IR dust bubbles based on images at 24 and 70 \( \mu m \) from MIPS and by

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**Fig. 5. Upper panel:** overlay of the PACS emission at 70 \( \mu m \) (contours) and the IRAC 8 \( \mu m \) emission (colorscale). Contours are 0.3 to 0.9 Jy px\(^{-1} \) in steps of 0.2 Jy px\(^{-1} \); 2 to 7 Jy px\(^{-1} \) in steps of 1 Jy px\(^{-1} \); and 9, 11, 13 to 33 Jy px\(^{-1} \) in steps of 4 Jy px\(^{-1} \). **Bottom panel:** overlay of the PACS emission at 160 \( \mu m \) (contours) and the IRAC 8 \( \mu m \) emission (colorscale). Contours are 2 to 7 Jy px\(^{-1} \) in steps of 1 Jy px\(^{-1} \); 10 to 25 Jy px\(^{-1} \) in steps of 3 Jy px\(^{-1} \); and 30 to 65 Jy px\(^{-1} \) in steps of 5 Jy px\(^{-1} \).

**Fig. 6.** Dust temperature map derived from the *Herschel* emission at 70 and 160 \( \mu m \). The grayscale extends from 20 to 50 K. Contour levels correspond to 20 to 32 K in steps of 3 K, 35, 40, 50, and 60 K. The darkest regions indicate the highest dust temperatures.
Anderson et al. (2012) for HII regions using Herschel data. Dust temperatures for G341.217-0.237 are about 28 K.

We also estimated T$_{\text{dust}}$ for G341.220-0.213 from the whole set of Herschel data and the LABOCA image by fitting a Planck function. Fluxes at 70, 160, 250, 350, and 500 $\mu$m were calculated with HIPE using rectangular sky aperture photometry and convolving all images down to the angular resolution at 500 $\mu$m. For each aperture we measured the average surface brightness with an uncertainty derived from the standard deviation of the surface brightness within each aperture and the flux calibration uncertainty. Derived values are 776.0, 1047.2, 499.5, 213.3, and 69.3 Jy at 70, 160, 250, 350, and 500 $\mu$m, respectively. Figure 7 shows the spectral energy distribution (SED), which also includes the flux density at 870 $\mu$m obtained by Contreras et al. (2013; 14.63 ± 2.47 Jy), and the best fit (obtained using a gray-body), which corresponds to T$_{\text{dust}}$ = 28 ± 1 K. Dust temperature for G341.217-0.237 from an SED is difficult to determine. As a result of the poor angular resolution of the Herschel images at 350 and 500 $\mu$m, fluxes estimated from these data include part of S 24, which can give a false impression of the dust temperature.

Dust masses can be estimated from the expression (Hildebrand 1983)

$$M_{\text{dust}} = \frac{S_{870} d^2}{\kappa_{870} B_{870}(T_{\text{dust}})}$$

where $S_{870}$ is the flux density at 870 $\mu$m, $d = 3.7 ± 0.5$ kpc, $\kappa_{870} = 1.0$ cm$^2$/gr is the dust opacity per unit mass (Ossenkopf & Henning 1994), and $B_{870}(T_{\text{dust}})$ is the Planck function for a temperature T$_{\text{dust}}$.

Two processes may contribute to the emission at this wavelength in addition to the thermal emission from cold dust: molecular emission from the CO(3$\rightarrow$2) line and free-free emission from ionized gas. The continuum emission contribution at 345 GHz due to ionized gas was estimated from the radio continuum image at 1.4 GHz considering that the radio emission is thermal (see Sect. 5) using the expression $S_{345} = (345/1.4)^{-0.1}S_{1.4}$. Adopting $S_{1.4} = 1.2$ Jy (see Sect. 5), this contribution amounts to about 1% of the emission at 870 $\mu$m. To estimate the contribution from CO(3$\rightarrow$2), we took into account the intensity in the $^{13}$CO(3$\rightarrow$2) line. This mechanism contributes less than 1%. Thus, the contribution by both mechanisms is within calibration uncertainties.

Adopting $T_{\text{dust}} = 28 ± 1$ K for G341.220-0.213, and a flux $S_{870} = 14.63 ± 2.47$ Jy derived by Contreras et al. (2013) for AGAL341.217-00.212, a dust mass $M_{\text{dust}} = 12.9 ± 6.3$ $M_\odot$ can be estimated for G341.220-0.213. Assuming the same dust temperature for G341.217-0.237 and a flux $S_{870} = 25.55 ± 4.11$ Jy (for AGAL341.216-00.236), we estimate $M_{\text{dust}1} = 22.4 ± 11.0$ $M_\odot$. Finally, for the IRDC to the west of the bubble, we adopt temperatures in the range 10–20 K (see Peretto et al. 2010), which, along with a flux $S_{870} = 12.43 ± 2.14$ Jy for AGAL341.196-00.221, results in $M_{\text{dust}2} = 17 ± 57$ $M_\odot$. Uncertainties in these values are about 50%. Adopting a gas-to-dust ratio of 100, gas masses are 1300 $M_\odot$ for G341.220-0.213, 2300 $M_\odot$ for G341.217-0.237, and 1700–5700 $M_\odot$ for the IRDC.

5. Ionized gas

Figure 8 displays an overlay of the radio continuum image at 843 MHz (contours) and the emissions at 8 $\mu$m and 24 $\mu$m (in colorscale). The image at 843 MHz reveals radio emission coincident with the sources, and in particular with the S 24 bubble. The emission at 1.4 GHz (not shown here) correlates with that at the lower frequency. We derived a flux density $S_{1.4} = 1.2$ Jy. Taking into account a flux density $S_{0.843} = 0.92$ Jy, a spectral index $\alpha = 0.5$ ($S_\nu \propto \nu^\alpha$) can be estimated from the emission at both frequencies. The $\alpha$-value indicates that at least 843 MHz, the radio emission is optically thick, and that the source is thermal in nature.

Figure 8 also shows that S 24, as well as G341.220-0.213, G341.217-0.237, and G341.210-0.252 emit at 24 $\mu$m, indicating the presence of warm dust linked to the sources, and consequently, the existence of excitation sources inside them. Emission at this wavelength also coincides with the PDR, as revealed by the emission at 8 $\mu$m. In fact, the emission at 24 $\mu$m from HII regions has two components: emission from very small grains out of thermal equilibrium, detected inside the HII region,
Fig. 9. Dec vs. RA map showing $^{12}\text{CO}(2-1)$ (in red) and $^{13}\text{CO}(2-1)$ (in black) profiles observed in a $5' \times 5'$ region centered in the S 24 bubble. Each profile shows $T_{\text{mb}}$ in the interval from $-1$ K to 20 K vs. LSR velocity in the range from $-80$ km s$^{-1}$ to 0 km s$^{-1}$. The (0, 0) position corresponds to RA, Dec(J2000) = (16h52m20s, $-44^\circ 27' 30''$). Note that RA increases towards the right.

and thermal emission from the PDR from grains in thermal equilibrium (Anderson et al. 2012).

Lower limits for the electron density $n_e$ and the ionized mass $M_i$ can be derived from the image at 843 MHz. For an estimated flux density of 0.92 Jy, using the classical expressions by (Mezger & Henderson 1967), a typical electron temperature of $10^4$ K, and bearing in mind a He abundance of 10% by particle number and that He is single ionized, we derived $n_e > 200$ cm$^{-3}$, and $M_i > 22 M_\odot$. We note that similar results can be obtained using the emission at 1.4 GHz. Clearly, the fact that the emission at 1.4 GHz is optically thick also cannot be ruled out. Bearing in mind that the emission at 8 $\mu$m due to PAH in the photodisociation region marks the boundary of the ionized region, we measured a radius of 0.33 pc for the H$^\text{ii}$ region.

Although these results cannot be used to determine either the ionized mass or the electron density, they reveal the existence of an H$^\text{ii}$ region.

6. Distribution of the molecular gas

Figure 9 displays the CO(2−1) and $^{13}$CO(2−1) spectra obtained for the region under study. The spatial separation between these profiles is 30'' . Relative coordinates are expressed in arcseconds, referred to RA, Dec(J2000) = (16h52m20s, $-44^\circ 27' 30''$). The individual spectra show that the molecular emission appears concentrated between $\sim -55$ km s$^{-1}$ and $-20$ km s$^{-1}$, where a number of velocity components are present, and an isolated component near $-10$ km s$^{-1}$ (which is not going to be taken into account). The CO(2−1)/$^{13}$CO(2−1) line ratios are close to 1−1.5 in the central and northeastern parts of the figure, suggesting that the gas is optically thick at $^{13}$CO(2−1) where S 24, G341.220-0.213, and G341.217-0.237 are located.

The CO spectra of Fig. 10 illustrate the general behaviour of the molecular gas towards the entire region. There, we show the CO(2−1), $^{13}$CO(2−1), and C$^{18}$O(2−1) spectra averaged within the observed region. At least three velocity components can be identified in the line of sight within the velocity interval from $-55$ km s$^{-1}$ to $-20$ km s$^{-1}$. The bulk of the molecular emission is detected in the three molecular lines and peaks at $\sim -45$ km s$^{-1}$, while fainter gas components are present at $\sim -38$ km s$^{-1}$ and $-30$ km s$^{-1}$. The faintest component is present near $-10$ km s$^{-1}$ in the $^{13}$CO(2−1) line only. The velocity components peaking at $-38$ km s$^{-1}$ and $-30$ km s$^{-1}$ can be barely identified in the $^{13}$CO(2−1) spectrum and are absent in the C$^{18}$O(2−1) profile. Gas components having the same velocity can be also identified in the averaged $J = 3−2$ profile (not shown here).

Circular galactic rotation models (e.g. Brand & Blitz 1993) predict near and far kinematical distances in the range 3.2−3.9 kpc and 12−13 kpc, respectively, for the gas component at $-45$ km s$^{-1}$, while near and far kinematical distances in the range 2.4−3.5 and 12−14 kpc, respectively, were obtained for gas in the components at $-38$ km s$^{-1}$ and $-30$ km s$^{-1}$. Particularly for the component at $-45$ km s$^{-1}$, near kinematical
Intensity is expressed as main-beam brightness-temperature.

Fig. 10. CO(2–1) (in black), 13CO(2–1) (in red), and C18O(2–1) (in blue) spectra obtained by averaging the observed spectra in the region of S 24. Intensity is expressed as main-beam brightness-temperature.

Figure 10.

7. Joining the details

In this section we investigate the gas distribution in S 24 in more detail and study the different features in its environment and its relation to the warm and cold dust and the YSO candidates.

7.1. G341.220-0.213

Panel A of Fig. 12 displays the 13CO(3–2) emission with velocities in the range −43.8 km s\(^{-1}\) and −42.0 km s\(^{-1}\) superimposed onto the emission at 8 μm for comparison. The emission distribution at these velocities reveals a molecular arc-like structure closely encircling the bright northern and western borders of G341.220-0.213. At 8 μm, G341.220-0.213, which resembles a horseshoe, is open opposite to the molecular emission. The IR source clearly interacts with the surrounding molecular gas and evolves in a medium with a density gradient. The coincidence of G341.220-0.213 with emission at 24 μm (see Sect. 5) suggests excitation sources inside. Bearing in mind the morphology of the source at 8 μm and in molecular lines, a champagne flow (Garay & Lizano 1999) cannot be discarded.

A number of YSO candidates appear inside the horseshoe: one MSX source classified as MYSO (#2 in Table 1); one Spitzer and one WISE source coincident in position, both classified as Class I (#15 and #34). We inspected the SED of sources #2, #15, and #34, which are assumed to be only one source, using the online\(^4\) tool developed by Robitaille et al. (2007), which can help to distinguish between evolved stars and reliable candidate YSOs. This tool fits radiation transfer models to observational data according to a χ\(^2\) minimization algorithm. Models that accomplished the following condition were selected:

\[
\chi^2 - \chi_{\text{min}}^2 < 3n,
\]

where \(\chi_{\text{min}}^2\) is the minimum \(\chi^2\) value from all models, and \(n\) is the number of input data fluxes.

To perform the fitting, we used the photometric data listed in Table 1 along with fluxes derived from Herschel and ATLASGAL images, visual absorption values in the range 30–40 mag, and distances in the range from 3.2 to 4.2 kpc. The result is shown in the left panel of Fig. 13. Fluxes obtained from Herschel and ATLASGAL were considered upper limits. The best fit suggests a massive central source of about 10 \(M_\odot\), a disk mass of 5 × 10^{-4}\ M_\odot, an envelope mass of 21 \(M_\odot\), a total luminosity of 5300 \(L_\odot\), and an age of 1 × 10^6 yr. With these characteristics, the evolutionary stage of the central source according to Robitaille et al. (2007) would correspond to Stage II (objects with optically thick disks). These results point to a massive central object.

We propose that this source has started modifying its environment by dissociating and then ionizing the nearby material, generating a PDR detected by its emission at 8 μm at the interface between the ionized and molecular material. It may have contributed to the heating of the dust as revealed by the emission at 24 μm. In addition, the detection of maser emission toward G341.220-0.213 (see Sect. 1) indicates that star formation is active.

A low-emission region is located at RA, Dec(J2000) = (16\(^{h}\)52\(^{m}\)22.5\(^{s}\), −44°26′40″), probably linked to a weak IR arc seen slightly to the north of that position.

Panels B and C of Fig. 12 show the emission distribution in the 13CO(2–1) and C18O(2–1) lines for the same velocity interval as panel A, while in panel D the emission corresponds to the CO(2–1) line in a slightly different velocity interval. The emission distribution reveals a molecular clump coincident with the G341.220-0.213. No signs of the arc-like structure are present in the (2–1) transitions, probably due to the lower angular resolution of these lines (30″) in comparison with the one of the 13CO(3–2) (20″).

The molecular clump detected in the interval [−44.0, −42.0] km s\(^{-1}\) coincides with the emission of cold dust as imaged in the far-IR by LABOCA (AGAL 341.217-00.212) and Herschel (see Fig. 4), indicating that gas and dust are well mixed in the region.

The analysis of the data cubes allows us to identify molecular gas associated with G341.220-0.213 in the velocity interval from −46.5 km s\(^{-1}\) to −40.2 km s\(^{-1}\).

\(^4\) http://caravan.astro.wisc.edu/protostars/
7.2. H II S24

The upper left panel of Fig. 14 shows the $^{13}$CO(3–2) emission distribution at $-43.2 \text{ km s}^{-1}$ in grayscale and contours, while the upper right panel displays an overlay of the same CO contours and the emission at $8 \mu\text{m}$. The middle and bottom panels show the emission at the same velocity for the $^{13}$CO(2–1) and C$^{18}$O(2–1) lines, respectively.

The emission at this velocity reveals a U-shaped, almost complete molecular shell encircling the S24 bubble. The strongest emission regions of this molecular shell encircle the brightest sections of S 24 as seen at $8 \mu\text{m}$. The shell appears open toward RA, Dec(J2000) $= (16^h52^m19^s, -44^\circ28'30'')$. The emission in the western part of the shell coincides with the IRDC SDC341.194-0.221, which borders this section of the bubble. The molecular shell is extends throughout the interval from $-46 \text{ km s}^{-1}$ to $-41.5 \text{ km s}^{-1}$.

As shown in Fig. 11, in the velocity interval from $-46.5 \text{ km s}^{-1}$ to $-43.5 \text{ km s}^{-1}$ the molecular gas borders the eastern, northern, and western sections of S 24. Molecular gas at these velocities coincides with cold dust detected in the far IR at $\lambda > 160 \mu\text{m}$, as shown in Figs. 2 and 4. Molecular shells have been found around many IR dust bubbles, in particular those identified as HII regions (e.g., Petriella et al. 2010; Pomarès et al. 2009; Deharveng et al. 2010). The presence of CO in the HII region interior suggests that the shell corresponds to a three-dimensional structure. The appearance of the shell indicates that it is inhomogeneous, with the molecular gas distributed unisotropically (e.g., Anderson et al. 2015).
The molecular shell might be expanding at 2–3 km s$^{-1}$ due to the difference in pressure between the ionized gas inside the bubble and the neutral gas outside, although no signs of expansion are detected in position-velocity diagrams. We note, however, that low expansion velocities such as those expected in this case are difficult to detect. In the case of expansion, the emission detected toward the interior of the region would correspond to the approaching and receding sections of the shell.

Three YSO candidates are projected onto the S 24 bubble: one MYSO (#1 in Table 1) and two WISE sources identified as Class II (#35 and #36).

A number of YSOs also coincide in position with the molecular shell, suggesting that star formation is active in the environs of the bubble.

Two YSOs appear projected onto the IRDC SDC341.194-0.221. They do not coincide with the spot of maser emission described in Sect. 1 projected onto this IRDC.

In addition to these YSO candidates, three stars could be identified in the 2MASS catalog in the region under study. These stars are indicated with green asterisks in the [$H - K_s$, $J - H$] and [$H - K_s$, $K_s$] diagrams of Fig. 3. In particular, 2MASS J17502070-4428012 is projected inside the bubble at RA, Dec(J2000) = (16$^\circ$.5220.7$^\prime$, $-44^\circ$.2814$^\prime$). Its locus in the CC and CM diagrams ($H - K_s$) = 1.19 mag, ($J - H$) = 2.18 mag, and $K_s = 10.94$ mag) is indicative of a massive star with an optical absorption $A_V \approx 30$ mag. Although more studies are necessary, this star might be responsible for dissociating and ionizing the gas, creating the observed PDR at 8 μm.

7.3. Interface between S 24 and G341.217-0.237

As described in Sect. 6, a bright molecular clump appears projected onto the interface between G341.217-0.237 and S 24 at RA, Dec(J2000) = (16$^\circ$.5220.23$^\prime$, $-44^\circ$.28$^\prime$). Figure 15 displays an enlargement of the region of the clump showing the emission in the $^{13}$CO(3–2) line at $-47.4$ km s$^{-1}$ (in contours) and the 8 μm image in grayscale. The peak CO emission is coincident with the interface between the two sources. The anticorrelation between the CO and IR emissions strongly suggests that the molecular clump has modeled the eastern border of the PDR in the HII region.

These facts suggest that S 24 and G341.217-0.237 are interacting with the molecular clump. The molecular clump coincides with emission at 870 μm and in the $Herschel$ bands at 250 and 350 μm.

The YSO candidate #43, classified as Class I, coincides with G341.217-0.237. The SED corresponding to this source is shown in the right panel of Fig. 13. To perform the fitting we used the
photometric data listed in Table 1 and the flux derived from the image at 70 μm. Herschel fluxes at longer wavelengths include a significant part of the S 24 bubble and were not used for the SED. Visual absorption is in the range 30–50 mag, and distances are from 3.2 to 4.2 kpc. The best fit corresponds to a central SED. Visual absorption is in the range $30 \pm 5$ for the S 24 region and the whole region the spectra were averaged in a region of $30 \pm 5$ g, and the molecular mass in the whole region were estimated from the emission in the CO(2−1) line using

$$T_{F - 12CO} = T_{12CO} \left[ \left( \frac{T_{\nu}}{T_{\nu}} \right) - 1 \right] \left[ \left( \frac{T_{\nu}}{T_{\nu}} \right) - 1 \right]^{-1}$$,

where $T_{12} = \frac{h\nu_{12}}{k}$, $v_{12}$ is the frequency of the $^{12}$CO(2−1) line, and $T_{bg}$ = 2.7 K. To obtain the peak main beam temperature in the CO(2−1) line ($T_{\nu}$) we took into account the averaged spectrum within regions of about 30′′ in diameter for the cases of G341.220-0.213 and the S 24 region and the whole region the spectra were averaged in a region of 2′′ and 3′′ in diameter, respectively.

The optical depth $\tau_{13}$ was obtained from the $^{13}$CO(2−1) line by assuming that the excitation temperature is the same for CO(2−1) and $^{13}$CO(2−1) emission lines using the expression

$$\tau_{13} = -\ln \left[ 1 - \frac{T_{F - 12CO}}{T_{13}} \right] \left[ \frac{T_{\nu}}{T_{\nu}} - 1 \right] \left[ \frac{T_{\nu}}{T_{\nu}} - 1 \right]^{-1}$$,

$$h = \frac{e^{T_{\nu}/T_{\nu}} - 1}{1 - e^{-T_{\nu}/T_{\nu}}}$$,

$$T_{\nu} = \int e^{T_{\nu}/T_{\nu}} d\nu$$,

where $T_{F - 12CO}$ is the line radiation temperature of a molecular transition as a function of the kinetic temperature ($T_{k}$) and the volume density ($n_{H}$).

8. Parameters of the molecular gas

The molecular mass linked to G341.220-0.213, the clump at the interface between G341.217-0.237 and S 24 and the S 24 HII region, and the molecular mass in the whole region were estimated from the emission in the J = 2 → 1 line. The derived parameters are listed in Table 2.

Assuming local thermodynamic equilibrium (LTE) conditions and that the emission in the CO(2−1) line is optically thick, we derived the excitation temperature $T_{exc}$ from the emission in the CO(2−1) line using

$$T_{12CO} = T_{12CO} \left[ \left( \frac{T_{\nu}}{T_{\nu}} \right) - 1 \right] \left[ \frac{T_{\nu}}{T_{\nu}} - 1 \right]^{-1}$$,

where $T_{12} = \frac{h\nu_{12}}{k}$, $v_{12}$ is the frequency of the $^{12}$CO(2−1) line, and $T_{bg}$ = 2.7 K. To obtain the peak main beam temperature in the CO(2−1) line ($T_{\nu}$) we took into account the averaged spectrum within regions of about 30′′ in diameter for the cases of G341.220-0.213 and the interface between G341.217-0.237 and S 24, while for the S 24 region and the whole region the spectra were averaged in a region of 2′′ and 3′′ in diameter, respectively.

The optical depth $\tau_{13}$ was obtained from the $^{13}$CO(2−1) line by assuming that the excitation temperature is the same for CO(2−1) and $^{13}$CO(2−1) emission lines using the expression

$$\tau_{13} = -\ln \left[ 1 - \frac{T_{F - 12CO}}{T_{13}} \right] \left[ \frac{T_{\nu}}{T_{\nu}} - 1 \right] \left[ \frac{T_{\nu}}{T_{\nu}} - 1 \right]^{-1}$$,

where $T_{F - 12CO}$ is the line radiation temperature of a molecular transition as a function of the kinetic temperature ($T_{k}$) and the volume density ($n_{H}$).

Assuming LTE, the $^{13}$CO column density, $N_{col}(^{13}$CO), can be estimated from the $^{13}$CO(2−1) line data following

$$N_{col}(^{13}$CO) = 3.2 \times 10^{14} \left[ \frac{e^{T_{\nu}/T_{\nu}} - 1}{1 - e^{-T_{\nu}/T_{\nu}}} \right] \int \tau_{13} \, d\nu \left(cm^{-2}\right)$$.

The integral of Eq. (6) can be approximated by

$$T_{exc} \int \tau_{13} \, d\nu \approx \frac{\tau_{13}}{1 - e^{-\tau_{13}}} \int T_{mb} \, d\nu$$.

This approximation helps to eliminate some extended optical depth effects and is good within 15% for $\tau < 2$ (Rohlfs & Wilson 2004). Bearing in mind the $\tau_{13}$-values listed in Table 2, it is appropriate for our region. Then, the molecular mass was calculated using

$$M(H_2) = \left( m_{\text{mass}} \right) \mu m_\text{H} A N(H_2) \alpha^2 \left(M_\odot \right)$$,

where $m_{\text{mass}}$ is the solar mass ($\sim 2 \times 10^{13}$ g), $\mu$ is the mean molecular weight, which is assumed to be equal to 2.76 after allowing for a relative helium abundance of 5% by mass (Yamaguchi et al. 1999), $m_\text{H}$ is the hydrogen atom mass ($\sim 1.67 \times 10^{-24}$ g), $A$ is the solid angle of the CO emission, $d$ is the adopted distance expressed in cm, and $N(H_2)$ is the H$_2$ column density, obtained using an abundance $N(H_2) / N(^{13}$CO) = $5 \times 10^5$ (Dickman 1978). Uncertainties in molecular masses and ambient densities are about 50% and 70%, respectively, and originate mainly in distance uncertainties and optically thick emission in the $^{13}$CO(2−1) line.

To explore the questions of temperature and density on G341.220-0.213 and G341.217-0.237 in depth, we performed a large velocity gradient (LVG) analysis (Scoville & Solomon 1973; Goldreich & Kwan 1974) for radiative transfer of molecular emission lines. We used the img task implemented as part of the MIRIAD package of SMA. For a given column density (normalized by the line width), this program estimates the line radiation temperature of a molecular transition as a function of the kinetic temperature ($T_k$) and the H$_2$ volume density ($n_{H_2}$). We generated 50 × 50 model grids for the $^{13}$CO(3−2),

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http://www.cfa.harvard.edu/sma/miriad/packages/
$^{13}$CO(2−1) lines with $T_k$ in the range 1−300 K and $n_{H_2}$ with the range $1 \times 10^5$ to $1 \times 10^6$ cm$^{-3}$. In all cases we convolved the $^{13}$CO(3−2) data with a Gaussian of FWHM 30″ to smooth the cubes down to the angular resolution of the $^{13}$CO(2−1) data. We then derived peak main beam temperatures and line widths for the studied components by fitting Gaussian functions to the line profiles. We then calculated two ratios, $R_{3−2}/(2−1) = T_{mb}^{^{13}CO(3−2)}/CO(2−1)$ and $R_{12}/13 = T_{mb}^{^{13}CO(2−1)}/CO(2−1)$. The input column densities of CO and $^{13}$CO were estimated from the dust-derived column density measured from the 870 μm emission in each region, and assuming relative abundances $N$(CO)/$N$(H$_2$) = $1 \times 10^{-4}$ and $N$(^{13}CO)/N(H$_2$) = $2 \times 10^{-6}$ (Dickman 1978). The same procedure was applied to the IRDC SDC341.194-0.221, for which we did not derive molecular mass and ambient density since its molecular emission is included in the S 24 molecular shell.

Figure 16 shows the solutions for G341.220-0.213, G341.217-0.237, and the IRDC. They indicate that kinetic temperatures in the IRDC are about 20 K, not different than derived in other IRDCs (Egan et al. 1998), and not much higher than typical temperatures of molecular gas without an extra heat source other than interstellar radiation field. The volume density of the IRDC is about 10$^4$ cm$^{-3}$. The temperatures for G341.220-0.213, G341.217-0.237 are slightly higher ($\sim 30$–40 K), as expected, because they are active star-forming regions (see Sect. 7). Their volume densities are less well constrained, but values higher than $4 \times 10^5$ cm$^{-3}$ are inferred from the plots.
Table 2 shows that molecular gas densities are in the range 10^5–10^6 for particular regions including the shell around the S 24 HII region. Masses derived from molecular data are compatible, within errors, with those obtained from the emission at 870 μm, assuming a gas-to-dust ratio equal to 100. Additionally, molecular ambient densities are compatible with values derived from LVG analysis. The large difference for G341.217-0.237 arises because the mass estimate from molecular emission only corresponds to the emission at the interface between G341.217-0.237 and the S 24 HII region. The ambient density obtained by distributing the total molecular mass in the whole observed region is high (5900 cm^{-3}), indicating that G341.220-0.213, G341.217-0.237 and S 24 are evolving in a high-density ambient medium.

The high opacity estimated for G341.220-0.213 is expected considering the high column density of this source.

9. Triggered star formation scenario in S 24?

We have found evidence for ongoing star formation in the dense molecular envelope encircling the S 24 HII region. Were these YSOs triggered by the collect-and-collapse (CC) mechanism? To answer this question, we can apply the analytical model by Whitworth et al. (1994). For the HII regions, the model predicts the age of the HII region at which the fragmentation occurs (the fragmentation timescale), \( t_{\text{frag}} \), the size of the HII region at that moment, \( R_{\text{frag}} \), the mass of the fragments, \( M_{\text{frag}} \), and their separation along the compressed layer, \( r_{\text{frag}} \). The parameters required to derive these quantities are the UV photon flux of the exciting star, \( N_{\alpha} \), the ambient density of the surrounding medium into which the HII region is evolving, \( n_0 \), and the isothermal sound speed in the shocked gas, \( c_s \).

Since the exciting star is unknown, we took into account a wide range of spectral types, that is, from O5V to O9V stars, with UV fluxes in the range \( N_{\alpha} = (18–0.8) \times 10^{48} \text{ s}^{-1} \) (Martins et al. 2002). Using the mean H2 ambient density \( n_{\text{H2}} = 5900 \text{ cm}^{-3} \) (see Table 2), and \( c_s = 0.2–0.6 \text{ km s}^{-1} \), we obtained \( t_{\text{frag}} = (6.6–8.8) \times 10^3 \text{ yr} \), \( R_{\text{frag}} = 1.8–2.3 \text{ pc} \), \( M_{\text{frag}} = 22–29 \ M_\odot \), and, \( r_{\text{frag}} = 0.5–0.4 \text{ pc} \).

The dynamical age of the HII region can be estimated using the equation (Dyson & Williams 1997)

\[
t_{\text{dyn}} = \frac{4R_S}{7c_s} \left( \frac{R}{R_S} \right)^{7/4} - 1
\]

where \( R_S \) is the original Strömgren radius, equal to 0.09–0.25 pc for the adopted spectral types, and \( c_s \) is the sound velocity in the ionized gas. Derived dynamical ages span the range (9–43) \times 10^3 \text{ yr}.

We find that the dynamical age is younger than the fragmentation timescale \( t_{\text{frag}} \) for the adopted ambient density. The comparison of these two quantities does not support a collect-and-collapse process, which is a relatively slow process, for the triggering of star formation in the envelope. An RDI scenario could be investigated, but evidence of this process (such as pillars) appear to be absent. Very probably, the compact HII region is too young for triggering to have begun.

10. Conclusions

Based on the molecular emission in the CO(2–1), 13CO(2–1), C18O(2–1), and 13CO(3–2) lines that were obtained with the APEX telescope and images in the near-, mid-, and far-IR from IRAC-Glimpse, Herschel, and ATLASGAL, we performed a multiwavelength analysis of the infrared dust bubble S 24 and two extended IR sources (G341.220-0.213 and G341.217-0.237) located in its environs. The region coincides with the IRAS point source 16487-4423, which is classified as UCHII. We also investigated the presence of YSO candidates in the region using the MSX, 2MASS, Spitzer, and WISE catalogs.

The molecular emission distribution shows that gas linked to the S 24 bubble, G341.220-0.213, and G341.217-0.237 has velocities between ~48.0 km s^{-1} and ~40.0 km s^{-1}, compatible with the kinematical distance of 3.7 kpc previously adopted for the region.

The gas distribution reveals a shell-like molecular structure of ~0.8 pc in radius detected in the velocity interval of ~46 km s^{-1} to ~41.5 km s^{-1}, encircling the S 24 bubble. A cold dust counterpart of this shell is detected at wavelengths longer than 160 μm, that is, in the LABOCA and SPIRE images. In contrast, PACS emission at 70 μm and MIPS emission at 24 μm from warm dust appears to be projected inside the bubble. Dust temperatures derived from the emission at 70 and 160 μm are in the range 26 to 60 K, with the higher values closer to the center of the bubble. The detection of radio continuum emission and the warm dust indicate exciting sources and that the bubble is a compact HII region. We estimated a molecular gas and H2 ambient density in the shell of 3100 M_\odot and 2.5 \times 10^4 cm^{-3}. A search for excitation sources allowed identifying a massive star candidate projected onto the HII region, which would provide the ultraviolet photons to heat the gas and dissociate and ionize the gas. A number of YSO candidates appear to be projected onto the molecular shell.

Part of the molecular gas bordering the S 24 bubble coincides with the extended IRDC SDC341.194-0.221, for which we derived a kinetic temperature of about 20 K and a volume density of 10^4 cm^{-3}, based on LVG analysis.

For the source G341.220-0.213, which resembles a horse-shoe open toward the east, the 13CO(3–2) line emission allowed detecting an arc-like structure with velocities in the range ~43.8 km s^{-1} to ~42.0 km s^{-1}, encircling the brightest sections of the IR source. The morphology indicates that the molecular gas interacts with the IR source. A dust counterpart is detected in the Herschel (SPIRE and PACS) and LABOCA images.
The spectral energy distribution constructed using Herschel and ATLASGAL fluxes allowed deriving a dust temperature of 28 ± 1 K. A molecular mass of 1550 $M_\odot$ is linked to this source, compatible with the mass derived from ATLASGAL. The $H_2$ ambient density amounts to $6.6 \times 10^4$ cm$^{-3}$, in agreement with the ambient density value estimated from the LVG analysis. A number of IR point sources with characteristics of YSOs coincide with this region, which along with the maser emission indicates that star formation is active. The SED for the derived fluxes suggests a massive central source of 10 $M_\odot$, which would be responsible for heating the dust and dissociating the molecular gas.

The source G341.217-0.237 also coincides with molecular gas and cold dust. The line emission allowed detecting a molecular clump at the interface between the S 24 H$\text{II}$ region and G341.217-0.237, shaping the eastern border of the IR bubble. A high ambient density ($4.2 \times 10^5$ cm$^{-3}$) was estimated for the clump.

The total mass of molecular gas in the region and the $H_2$ ambient density amount to 10 300 $M_\odot$ and $5900$ cm$^{-3}$, indicating that G341.220-0.213, G341.217-0.237, and the S 24 H$\text{II}$ region are evolving into a high-density region.

Finally, we investigated whether a collect-and-collapse scenario can explain the YSOs in the dense envelope around the S2 4 H$\text{II}$ region. We conclude that neither this mechanism nor the RDI process seem to occur in this region. Very probably, the H$\text{II}$ region is too young for triggering to have begun.

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