CO OBSERVATIONS AND INVESTIGATION OF TRIGGERED STAR FORMATION TOWARD THE N10 INFRARED BUBBLE AND SURROUNDINGS

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ABSTRACT

We studied the environment of the dust bubble N10 in molecular emission. Infrared bubbles, first detected by the GLIMPSE survey at 8.0 μm, are ideal regions to investigate the effect of the expansion of the H II region on its surroundings and the eventual triggering of star formation at its borders. In this work, we present a multi-wavelength study of N10. This bubble is especially interesting because infrared studies of the young stellar content suggest a scenario of ongoing star formation, possibly triggered on the edge of the H II region. We carried out observations of 12CO(1-0) and 13CO(1-0) emission at PMO 13.7 m toward N10. We also analyzed the IR and sub-millimeter emission on this region and compare those different tracers to obtain a detailed view of the interaction between the expanding H II region and the molecular gas. We also estimated the parameters of the denser cold dust condensation and the ionized gas inside the shell. Bright CO emission was detected and two molecular clumps were identified from which we have derived physical parameters. We also estimate the parameters for the denser cold dust condensation and for the ionized gas inside the shell. The comparison between the dynamical age of this region and the fragmentation timescale favors the “Radiation-Driven Implosion” mechanism of star formation. N10 is a case of particular interest with gas structures in a narrow frontier between the H II region and surrounding molecular material, and with a range of ages of YSOs situated in the region, indicating triggered star formation.

Key words: H II regions – ISM: bubbles – ISM: molecules – stars: formation

Supporting material: machine-readable table

1. INTRODUCTION

In the last decade, studies of massive star-forming regions have gained considerable attention. Questions regarding whether or not the interaction between massive stars and their surrounding molecular clouds triggers the star formation have been amply discussed. The discovery of the “infrared bubbles,” a new type of object first cataloged through GLIMPSE⁴ (Benjamin et al. 2003; Churchwell et al. 2009) at 8.0 μm, offers a new powerful tool to investigate the star formation process. Those objects present a bright border at 8.0 μm, caused by the emission of polycyclic aromatic hydrocarbons (PAHs), excited by ultraviolet radiation (UV), which surrounds a region of ionized gas (Churchwell et al. 2006, 2007).

The bubbles were detected in observations performed by the Spitzer satellite, in a survey that revealed about 600 bright objects at mid-infrared wavelengths (Churchwell et al. 2006). Shortly afterward, the Churchwell catalog was complemented by the Milky Way Project (MWP) catalog by Simpson et al. (2012). This is the most recent scientific citizen-generated catalog, where the bubbles were identified by thousands of volunteers and therefore their classification is more reliable. Deharveng et al. (2010) have identified and studied a large sample of bubbles and concluded that the shell of each one, detected at 8.0 μm, is evidence of an H II region produced by the ionizing massive stars. Thompson et al. (2012) suggested that the expansion of the bubbles triggers the formation of young stellar objects (YSOs), which is a non-negligible process in Galactic scales. Kendrew et al. (2012, 2016) have also observed this behavior and, although evidence of triggering via bubble expansion was missing, these authors found populations of YSOs near the borders of expanding bubbles, which could offer us important clues regarding the star formation process and the expansion of infrared bubbles.

We can interpret these bubbles as basically ionized gas surrounded by cold dust. A photon-dominated region (PDR) in the inner regions of the shell, can be identified and described at mid-infrared wavelengths (Lefloch et al. 2005). The PDRs can be the result of the H II region expansion. They can be seen as regions where the ionization front is still progressing in the densest medium of the original cloud, generating an interface between ionized and neutral gases. The larger density in the PDR is possibly due to material collected by the expansion of the H II region. In this region, the UV flux decreases sharply, allowing the existence of molecular and grain species. The massive stars interact with the original molecular cloud and, by their UV radiation, generate the interface between ionized gas and neutral gas.

In principle, the structure of the objects, should it be spherical shells or rings, allows us to understand correctly the kinematics of the gas and the chronology of the newly formed stars. Several works claimed that there was evidence for star formation triggered by the expansion of the H II region (Zavagno et al. 2010; Beuther et al. 2011; Dewangan et al. 2012). Yuan et al. (2014) found velocity differences of the order of 30 km s⁻¹ between distinct parts of the ring in the bubble N6, which would indicate a larger expansion velocity than those considered by other authors, of a few km s⁻¹ (e.g., Beaumont & Williams 2010). Dale et al. (2005) and Dale & Bonnell (2008) carried out simulations to study the effects of stellar feedback in molecular clouds. They suggested that it is not possible to determine if the formation of a YSO was...
triggered or not by the expansion of the H II region and, as a consequence, studies of triggered star formation should be done statistically.

Therefore, it is important to gather a number of well studied bubbles to establish if they have similar formation histories, if they have similar morphology and if they give similar answers to the process about triggered star formation. In this work, we present a detailed study of N10, a remarkable bubble that has molecular clumps and YSOs associated with its surrounding shell. We present our CO observations and we analyze them together with the relevant data at different wavelengths: 8.0 μm, PAH emission; 24 μm, hot grains from the ionized region; 870 μm, dust emission; and 20 cm free–free emission from hot gas.

This paper is organized as follows. Our target object is introduced in Section 2. In Section 3, we describe the CO observations and the archival data used in this paper. We dedicate Section 4 to present our results and the Section 5 to discuss these results. Finally, we summarized our main conclusions in Section 6.

2. THE BUBBLE N10

N10 is situated in the direction l = 13°188, b = 0°039 (Churchwell et al. 2006). This object is also identified as MWP1G013189+000428 by Simpson et al. (2012). It appears in the Spitzer-GLIMPSE 8.0 μm image as a bright ring-like structure (Figure 1). The 8.0 μm emission in the border of bubbles is attributed to PDRs containing PAHs; the gas density in the PDR can be much larger (up to a factor of 10) than that of the surrounding medium (Churchwell et al. 2006; Deharveng et al. 2010). In Figure 1, we show an ellipse to mark the boundaries of the bubble, for later reference in images at different wavelengths. Churchwell et al. (2006) consider N10 to be a bipolar (or double) bubble, since a small bubble (N11) seems to be connected to the north of N10. However, Deharveng et al. (2015) recently showed that N10/N11 is not a bipolar bubble, as Churchwell et al. (2006) misidentified it. In this work, we deal only with the case of N10.

The distance of N10 was estimated as 4.9 kpc by Churchwell et al. (2006), 4.1 kpc by Beaumont & Williams (2010), 4.6 kpc by Pandian et al. (2008), and 4.9 kpc by Watson et al. (2008). These are kinematic distances estimated using different rotation curves, which explain the discrepancies.

A methanol (CH₃OH) maser in the N10 region was first reported by Szymczak et al. (2000), detected toward the IRAS 18111-1729 source. It is accepted that the methanol masers (as is the case of the present one) are associated with the earliest stages of massive star formation (Minier & Booth 2002). Figure 2 shows this methanol maser source located on the border of one of the two bright 870 μm condensations adjacent to the bubble. The second CH₃OH maser reported by Pandian et al. (2008) seems to be associated with an SVSS5 source.

### Table 1

| ID | A.R. (J2000) | Decl. (J2000) | Spectral Type | AV |
|----|-------------|-------------|--------------|----|
| IN10-1 | 18 14 06.343 | −17 28 33.86 | O7.5 V | 7 |
| IN10-2 | 18 14 04.771 | −17 27 58.74 | O6.5 V | 7 |
| IN10-3 | 18 14 07.104 | −17 29 21.27 | O6 V | 5 |
| IN10-4 | 18 14 06.666 | −17 29 21.34 | O7 V | 8 |

**Note.**

1 Identification by Watson et al. (2008).
In their study of the central region, Watson et al. (2008) identified four stars as possible ionizing stars in N10 (see Table 1), based on their spectral energy distributions (SEDs), which are well-fitted by a stellar photosphere. The position of stars are also plotted in Figure 2. Assuming a radius of 1.61 pc for the densest dark cloud, Ma et al. (2013) estimated a dynamical age $t_{\text{dyn}} = 9.17 \times 10^4$ year for N10. Nevertheless, they argue that this value could be larger since the density of the true ambient where the stars originally were formed could be larger that they considered.

Hereafter, we will adopt the position of N10 and the ellipse in Figure 2 as reference: top of the bubble (higher galactic latitude with the center as reference), bottom (lower galactic latitude), right (lower galactic longitude), and left (higher galactic longitude).

3. OBSERVATIONS AND DATA

3.1. CO Observations

The observations were carried out with the PMO (Purple Mountain Observatory) 13.7 m radio telescope in 2012 June. We observed the $J = 1 - 0$ transition of $^{12}\text{CO}$ (115.27 GHz), $^{13}\text{CO}$ (110.20 GHz), and $^{18}\text{O}$ (109.78 GHz). The On-The-Fly (OTF) observing mode was applied to map a 21' × 25' region centered at $\alpha_{2000} = 18^h14^m01\fs361$ and $\delta_{2000} = -17\degr28\arcmin23\arcsec14$. For the 13.7 m PMO antenna, we have considered a half-power beam width (HPBW) around 52'.

We used a nine-beam array of SIS receivers at the front end (Shan et al. 2012). The main beam efficiency at the center of the 3 × 3 array is about 0.44 at 115 GHz and 0.48 at 110 GHz. Our spectral resolution was about 61 kHz, corresponding to velocity resolution of 0.16 km s$^{-1}$ (at 115 GHz) and 0.17 km s$^{-1}$ (at 110 and 109 GHz).

The cloudy weather condition during our observations led to system temperatures reaching 550 K and 350 K at 115 GHz and 110 GHz, respectively. This resulted in rms noises of 1.7 and 1.2 K in the brightness temperature for $^{12}\text{CO} J = 1 - 0$ and $^{13}\text{CO} J = 1 - 0$, respectively. Such large noise would make relatively weak signals undetectable. However, regions with strong line emission can be validly probed. The velocity information provided by these data convincingly reveal the kinematics of the bubble and molecular conditions in some subregions.

3.2. Other Observations

Public data from infrared to centimeter surveys was used to analyze the bubble N10 at other wavelengths. The GLIMPSE survey (Benjamin et al. 2003) mapped parts of the inner Galactic plane, with the Infrared Array Camera (IRAC; Fazio et al. 2004) on the Spitzer Space Telescope. We obtained images of 4.5, 5.8, and 8.0 μm IRAC bands (see Figure 3). The 24 μm image (100 μm) was obtained from another survey of the inner Galactic plane, MIPS GAL, using the MIPS instrument (Multiband Imaging Photometer for the Spitzer; Rieke et al. 2004). In the panel at 24 μm of Figure 3, we can see that this emission fills the whole area indicated by the red ellipse. This emission, typical of galactic bubbles, is caused by warm dust present in the region of ionized gas.

N10 was mapped at sub-millimeter wavelengths with the APEX telescope (Miettinen 2012). The images at 870 μm wavelength were obtained with ATLASGAL (APEX Telescope Large Area Survey of the Galaxy), an observing program using the LABOCA (Large Apex BOlometer CAmera instrument Schuller et al. 2009). The 870 μm cold dust emission is useful to reveal the presence of dense dark clouds. Two of these clouds, reported by Wienen et al. (2012), are seen bordering the bubble, along the upper and left borders of the bubble. The H II region, which is probably expanding, seems to be interacting with these clouds. We used the MAGPIS website to obtain the images presented Figure 3.

We also used the all-sky Wide-field Infrared Survey Explorer satellite (WISE; Wright et al. 2010) data to analyze the content of YSOs in N10, in order to reveal the regions where star formation took place recently and possible gradients of the evolutionary stage.

4. RESULTS

4.1. Molecular Emission

The emission of $^{12}\text{CO}$, $^{13}\text{CO}$, and $^{18}\text{O}$ $J = 1 - 0$ was observed at the same time. Strong emission of $^{12}\text{CO}$ and $^{13}\text{CO}$ was observed; the emission of $^{18}\text{O}$ is weak and we do not analyze in this work. Figure 4 presents the observed spectral lines.

Detected $^{12}\text{CO}$ and $^{13}\text{CO}$ emission allows us to identify three peaks of velocity: at 20, 37, and 52 km s$^{-1}$, approximately. The central velocities and line widths were determined by Gaussian fits using the CLASS package (GILDAS software). In this paper, velocities are referred to the local standard of rest ($V_{\text{LSR}}$). The upper panel in Figure 5 displays a channel map of $^{12}\text{CO}$ emission and the bottom panel shows the channel map of $^{13}\text{CO}$ emission. The background in both figures shows 8.0 μm emission. We have fitted the channels by increasing the velocity from 45 to 62 km s$^{-1}$. There is an strong correlation between $^{12}\text{CO}$ and $^{13}\text{CO}$ emission, especially in the range of 48–53 km s$^{-1}$.

The broad CO component centered at 20 km s$^{-1}$ has the lower intensity of the three peaks. The component centered at 37 km s$^{-1}$ presents a narrower profile than the former and lower intensity if compared with the component centered at 52 km s$^{-1}$.

The velocities found in the literature for different emission lines associated with N10 range from 48.5 to 54.1 km s$^{-1}$, as shown in Table 2. This leads us to adopt the component with peak at 52.6 km s$^{-1}$ as the one related to the source.

In our observation, velocities along the emission with peaks at 52.6 km s$^{-1}$ range from 48 to 53 km s$^{-1}$. In order to verify the correspondence between the physical distribution of molecular gas and the bubble seen in infrared, $^{12}\text{CO}$ and $^{13}\text{CO}$ contours of narrow-velocity emission were superposed over a Spitzer 8.0 μm image in Figure 6. The spatial distribution of $^{12}\text{CO}$ shows two main structures that seem to be related to the 8.0 μm emission, and $^{13}\text{CO}$ presents two denser clumps in the border of the ring morphology of N10, at the same position of $^{12}\text{CO}$ structures.

4.2. Distribution of Gas and Dust

We have studied the bubble N10 through the emission of the CO and the cold dust, which is useful to reveal the densest and coldest regions of N10. However, it is necessary to explore other tracers.

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[6] http://third.ucllnl.org/gps
[7] http://www.iram.fr/IRAMFR/GILDAS
Figure 3. Multi-wavelength images of the N10 region. The panels show 4.5, 5.8, 8.0, 24, 870 μm, and 20 cm emission toward the target region, from Spitzer-GLIMPSE, Spitzer-MIPSGAL, LABOCA-ATLASGAL, and GPS-VLA, respectively. All the images show the same region in the sky; in the first panel the white cross marks the center of the H II region; in all images the red ellipse is for reference, as shown in Figure 1.

Figure 4. Spectral lines. The left column shows the average spectra of $J = 1 - 0$ transition of $^{12}$CO in the upper panel and $^{13}$CO in the lower panel of the observed region ($Δl = 0′′002, Δb = 0′′304$). The right column presents spectra of these two lines in the peak position, at $l = 13°21, b = 0°307$. 
4.2.1. Ionized Gas

Ionized gas associated with N10 can be traced by VLA 20 cm emission. The presence of emission at $\nu = 1.5$ GHz implies that the HII region in the inner part of the bubble is created by UV photons. Using the Greg/GILDAS software, we estimated the 20 cm total flux $F_{20\, \text{cm}} = 1.17$ Jy inside the bubble and we calculated the electron density ($n_e$) according to Panagia & Walmsley (1978):

$$n_e \text{cm}^{-3} = 3.113 \times 10^2 \left( \frac{T_e}{10^4 \text{ K}} \right)^{0.25} \left( \frac{S_\nu}{\text{ Jy}} \right)^{0.5} \left( \frac{D}{\text{kpc}} \right)^{-0.5} \times b(\nu, T)^{-0.5} \times \theta_R^{-1.5},$$

(1)

where $T_e$ in K is the electron temperature, $S_\nu$ is the measured total flux density in Jy, $D$ is the distance in kpc, and $\theta_R$ is the angular radius in arcmin. The function $b(\nu, T)$ is defined as

$$b(\nu, T) = 1 + 0.3195 \log\left( \frac{T_e}{10^4 \text{ K}} \right) - 0.2130 \log\left( \frac{\nu}{10^4 \text{ GHz}} \right)$$

(2)

Assuming $T_e = 10^4$ K for the free–free emission region, the electron density is $n_e = 129.71$ cm$^{-3}$.

Figure 7 displays two peaks of radio continuum emission in grayscale and black contours in the left panel. In the same figure, the right panel shows one of the peaks coinciding with an O-type star.

Table 2

| Velocity (km s$^{-1}$) | Method | References |
|-----------------------|--------|------------|
| 54.1                  | H II region, radio recombination line | 1          |
| 48.5                  | 6.7 GHz methanol maser emission | 2          |
| 54.1                  | H I absorption line | 3          |
| 50.2                  | CO line emission | 4          |
| 48.5                  | NH$_3$ inversion line (from 870 $\mu$m data) | 5          |
| 54.1                  | mid-infrared from \textit{WISE} H II region | 6          |

References. (1) Lockman (1989), (2) Szymczak et al. (2000), (3) Pandian et al. (2008), (4) Beaumont & Williams (2010), (5) Wienen et al. (2012), (6) Anderson et al. (2014).

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Figure 6. Upper panels show contours of $^{12}$CO emission distribution centered at 20 km s$^{-1}$ from 6 to 13 K in steps of 1 K (left); at 37 km s$^{-1}$ in steps of 1 K, from 8 to 14 K (middle); at 52 km s$^{-1}$ from 5 to 12 K, in steps of 1 K (right). The lower panels display contours of $^{13}$CO emission distribution centered at 20 km s$^{-1}$ from 1 to 3 K in steps of 0.5 K (left); at 37 km s$^{-1}$ in steps of 1 K, from 5 to 10 K (middle); at 52 km s$^{-1}$ from 10 to 21 K, in steps of 1 K (right). All panels exhibit 8.0 $\mu$m image in background.

Figure 7. Left panel: VLA 20 cm (1.4 GHz) intensity in grayscale, from 0 to 20 mJy beam$^{-1}$, with contours starting from $2\sigma$ with steps of $2\sigma$ ($1\sigma = 2.8$ mJy beam$^{-1}$). Right panel: RGB Spitzer image in the background (3.6 $\mu$m in blue, 4.5 $\mu$m in green, and 8.0 $\mu$m in red). Yellow stars mark the position of the candidate’s ionizing stars.
The number of Lyman continuum photons that are absorbed by the gas in the region H II was calculated using the radio continuum map, following the relation given by Matsakis et al. (1976):

\[ N_{\nu} = 7.5 \times 10^{46} \left( \frac{\nu}{\text{GHz}} \right)^{0.1} \left( \frac{T_e}{10^{4} \text{ K}} \right)^{-0.45} \left( \frac{S_{\nu}}{\text{Jy}} \right) \left( \frac{D}{\text{kpc}} \right)^{2}. \]  

We estimate \( N_{\nu} = 1.86 \times 10^{49} \) ionizing photons s\(^{-1}\) in the Lyman continuum, equivalent to a single star type O (Watson et al. 2008). Considering a model of the H II region in expansion, the neutral material accumulates between the ionization front and the shock front (Deharveng et al. 2010) and the ionized gas is surrounded by a shell of dense, neutral material hosting PAHs, the main material responsible for 8.0 \( \mu \text{m} \) emission in infrared wavelengths. Therefore, ionized gas appears to be confined by the bubble shell exhibited by 8.0 \( \mu \text{m} \) emission in red color.

### 4.2.2. Cold and Warm Dust

In Figure 3, the set of emission maps at 4.5, 5.8, 8.0, and 24 \( \mu \text{m} \) has been displayed. These emissions, corresponding to warm dust, allow us to identify clearly the expanding H II region around the bubble N10. The upper panels, maps at 4.5, 5.8, and 8.0 \( \mu \text{m} \), reveal the arc-shaped boarder of N10.

The thermal emission from cold dust is mainly responsible for the continuum 870 \( \mu \text{m} \) distribution toward N10, while the emission at 8.0 \( \mu \text{m} \) originates from polycyclic aromatic hydrocarbons (PAHs) excited by UV photons. Figure 8 displays the emission at 870 \( \mu \text{m} \) in grayscale and contours for N10 (left panel), and the same contours of the cold dust emission are superimposed on a Spitzer 8.0 \( \mu \text{m} \) image (right panel).

The two 870 \( \mu \text{m} \) clumps coincide with \(^{13}\)CO molecular condensations detected at the peak velocity of 52 km s\(^{-1}\) shown in the upper right panel of Figure 6. According to Dewangan et al. (2015), the coincidence of distribution of the molecular gas, PAH and cold dust emission are evidence of star-forming material around the bubble. Following the example of Duronea et al. (2015) we calculated the physical parameters for the denser condensation in the right panel of Figure 8. We consider that the 870 \( \mu \text{m} \) radiation originates from the thermal radiation from dust grains. The total mass (dust and gas) in grams can be estimated following the relation by Hildebrand (1983):

\[ M_{\text{tot}} = 100 \frac{S_{870 \mu m} D^2}{N_{870 \mu m} B_{870 \mu m}(T_{\text{dust}})}, \]  

where \( S_{870 \mu m} \) is the flux density of 870 \( \mu \text{m} \) emission in Jy, \( N_{870 \mu m} \) is the dust opacity per unity mass at 870 \( \mu \text{m} \), and \( B_{870 \mu m} \) is the Planck function for a given dust temperature \( T_{\text{dust}} \) in Jy. We assumed \( T_{\text{dust}} = 20 \text{ K} \) and \( \kappa_{870 \mu m} = 1.8 \text{ cm}^2 \text{ g}^{-1} \). We assumed a gas-to-dust ratio of 100 (Mathis et al. 1977; Draine & Anderson 1985).

The H\(_2\) column density \( N(\text{H}_2) \) can be estimated using the following formula, by Deharveng et al. (2010):

\[ N(\text{H}_2) = \frac{100 F_{870 \mu m}}{N_{870 \mu m} B_{870 \mu m}(T_{\text{dust}}) 2.8 m_\text{H} \Omega_{\text{beam}}}, \]  

where \( N(\text{H}_2) \) is in cm\(^{-2}\), the surface brightness \( F_{870 \mu m} \) is in Jy beam\(^{-1}\), the beam solid angle \( \Omega_{\text{beam}} \) is in steradians and the hydrogen mass \( m_\text{H} \) is in grams. We estimated a column density of \( N(\text{H}_2) = 6.3 \times 10^{22} \text{ cm}^{-2} \).

We calculate the effective radius of the clumps as

\[ R_D = (R_{\text{maj,D}} \times R_{\text{min,D}})^{0.5} = \left( \frac{\theta_{\text{maj,D}}}{2} \times \frac{\theta_{\text{min,D}}}{2} \right)^{0.5}, \]
shown in our results too. From Figure 3, we can see that in the saturated region both the IRAC and 20 cm emissions are strong.

In resume, the map at 8.0 μm is very useful, since it traces the expanding arc in the upper left part of N10, this region is associated with ionized gas, excited PAHs, and warm dust.

On the other hand, the emission map at 20 cm exposes the central part of the H II region, which is surrounded by the N10 boarder, as would be expected, this region contains dust warmer than the expanding arcs. Furthermore, Figure 7 shows clearly the central part of the H II region.

4.3. Distance

Adopting a distance of 4.6 kpc from Pandian et al. (2008; see also Deharveng et al. 2010), the physical size of the ring is about 4.7 × 2.5 pc. Using this distance, N10 is found to be close to the near extremity of the Galactic bar, a region of intensive star formation (see, e.g., the maps of the Galactic arms structure by Hou & Han 2014).

For this work, using circular Galactic rotation models (e.g., Brand & Blitz 1993) is possible to compute near and far kinematic distances of the source; we have analyzed the kinematic distance ambiguity and the results show that the near kinematic one may be more reasonable.

Churchwell et al. (2006) argued that infrared bubbles are more likely located at their near kinematic distances, since objects on the far side of the Galactic disk would be obscured by interstellar extinction and contamination of other structures.

Based on our CO observations and using the velocity of 52.6 km s⁻¹ (see Section 4.4), we obtained near and far kinematic distances of 4.7 kpc and 11.3 kpc, respectively. This value is compatible with the near distance estimated by Szymczak et al. (2000) d = 4.4 kpc, using the methanol maser emission (see Table 2). Since N10 is located in the inner disk of the Galaxy, we adopt a 10% uncertainty for the kinematic distance (Yuan et al. 2014), resulting in a value of 4.7 ± 0.5 kpc for N10.

4.4. Observed and Derived Parameters

In the following discussion, we adopt the labels given in Figure 10 to refer to identified condensations. Due to the poor spatial resolution of PMO (the beam size is ~0.9 pc in our observations), the sizes of these molecular condensations could be smaller than 0.9 pc.

We used CLASS to calculate the parameters performing Gaussian fits to the average spectra obtained for the whole observed region. We obtained the centroid velocity (V_{LSR}), the antenna temperature (T_A^*) , and the full width at half maximum (ΔV_{FWHM}). These observed parameters are shown in Table 3.

In order to understand the evolutionary status of molecular clumps, we derived the physical properties for the two clumps we identified in our CO observations. The masses of the clumps were estimated by using the Miriad software package (Sault et al. 1995).

The mass of the molecular gas in a clump is calculated from the intensity of the emission line, under the local thermal equilibrium (LTE) assumption. With the radiation transfer equation Garden et al. (1991), we derived the mass of the
the electric dipole of the molecule. $T_{\text{ex}}$ is the excitation temperature and $\tau$ is the optical depth from 48 to 53 km s$^{-1}$.

Since the excitation temperature ($T_{\text{ex}}$) is measured as a function of brightness temperature ($T_r$), we estimate (Garden et al. 1991)

$$T_r = \frac{h \nu}{k} \times \left[ \frac{1}{\exp(h\nu/kT_{\text{ex}}) - 1} - \frac{1}{\exp(h\nu/kT_r) - 1} \right] \left[ 1 - \exp(-\tau) \right] f,$$

where $T_r$ is the brightness temperature and the temperature of the cosmic background radiation $T_{\text{br}} = 2.73$ K. Here we assume a filling factor of $f = 1$.

Assuming that $T_{\text{ex}}$ is the same for $^{12}$CO and for $^{13}$CO, the optical depth for both lines can be obtained directly comparing the measure of its brightness temperatures $T_r$ (Garden et al. 1991): 

$$\frac{T_r(^{12}\text{CO})}{T_r(^{13}\text{CO})} \approx \frac{1 - \exp(-\tau_3)}{1 - \exp(-\tau_3)}.$$

We adopted an isotope ratio of $[^{12}\text{CO}] / [^{13}\text{CO}] = 60$ (Wilson & Rood 1994; Deharveng et al. 2008), implying $\tau_2/\tau_3 = 60$, and the canonical $[^{12}\text{CO}]/[^{13}\text{CO}]$ abundance ratio of $10^{-4}$.

Thus we can estimate the optical depth from Equation (12), and then, using it in Equation (11), and knowing the brightness temperature, we can estimate $T_{\text{ex}}$.

Using the estimated value of $T_{\text{ex}}$ for the line $^{13}$CO, we can finally obtain the hydrogen column density ($N_{\text{H}_2}$) using Equation (10). Thus, the intensity of the $^{13}$CO line traces the column density of the clumps #1 and #2, as listed in Table 4.

Obtaining the velocity dispersion and the mass under the LTE assumption, we can estimate the virial condition, by comparing the gas mass ($M_{\text{LTE}}$) with the virial mass ($M_{\text{virial}}$). In a cloud in which the temporal average kinetic energy is equal to half of the temporal average of the potential energy, the system is considered in virial equilibrium. The assumption that a gravitationally bound system is in virial equilibrium is widely used in astrophysics to estimate its mass (Huang 1954). The virial mass $M_{\text{virial}}$ is given by Ungerechts et al. (2000) by the expression

$$\frac{M_{\text{virial}}}{M_\odot} = 2.10 \times 10^4 \left( \frac{R}{\text{pc}} \right) \left( \frac{\Delta V_{\text{FWHM}}}{\text{km s}^{-1}} \right)^2,$$

where $R$ is the mean radius of the clump and $\Delta V_{\text{FWHM}}$ is the line width of $^{13}$CO line.

The Jeans mass $M_J$ is the mass above which a gas cloud will collapse, for a given density and temperature, when the gravitational attraction overcomes the pressure of the gas. It can be calculated according to Stahler & Palla (2005):

$$\frac{M_{\text{Jeans}}}{M_\odot} = \left( \frac{T}{10 \text{ K}} \right)^{3/2} \left( \frac{n_{\text{H}_2}}{10^8 \text{cm}^{-3}} \right)^{-1/2}.$$

The results are presented in Table 4, where columns 2–7 list the following clump parameters: mean radius ($R$), excitation temperature ($T_{\text{ex}}$), column density ($N_{\text{H}_2}$), volume density ($n_{\text{H}_2}$), gas mass calculated under LTE assumption ($M_{\text{LTE}}$), virial mass ($M_{\text{virial}}$), and Jeans mass ($M_{\text{Jeans}}$). We discuss the clump status in Section 5.1.

### Table 3

|       | $V_{\text{lsr}}$ (km s$^{-1}$) | $T_r^*$ (K) | $\Delta V_{\text{FWHM}}$ (km s$^{-1}$) |
|-------|-------------------------------|-------------|-------------------------------------|
| $^{12}$CO | 52.6                          | 8.3         | 9.2                                 |
| $^{13}$CO | 52.6                          | 2.9         | 6.1                                 |

Figure 10. Region of the clumps identified in the $^{13}$CO intensity centered at 52 km s$^{-1}$, in grayscale. Clump #1 and clump #2 seem to be physically associated with bubble N10. Black contours also show the gas, and $b_{\text{maj}}$ and $b_{\text{min}}$ are the sizes of the ellipse, respectively, obtained using the Miriad software.

We first estimated the value of the column density $N_{\text{H}_2}$ through the CO column density. According to Garden et al. (1991), the column density $N$ of a rigid, asymmetric linear molecule, under LTE condition, can be expressed by

$$N = \frac{3k}{8\pi^3 \mu^2 B J} \times \exp[h B J (J + 1)/k T_{\text{ex}}] \times \left( \frac{T_{\text{ex}} + hB/3k}{1 - \exp(-h\nu/kT_{\text{ex}})} \right) \times \int r \, dr \, d\nu$$

where $B$ is the rotational constant, $J$ is the rotational quantum number of the lower state of the observed transition, and $\mu$ is the mean atomic weight of the gas, and $n_{\text{H}_2} = n/2R$ is the volume density. The mean radius of the clump is obtained by the relation $R = b_{\text{maj}} \times b_{\text{min}}/2$, where $b_{\text{maj}}$ and $b_{\text{min}}$ are the sizes of the minor and major axes of the ellipse, respectively, obtained using the Miriad software.

### Table 4

| Clump | $R$ (pc) | $T_{\text{ex}}$ (K) | $n_{\text{H}_2}$ ($10^8$ cm$^{-3}$) | $M_{\text{LTE}}$ ($M_\odot$) | $M_{\text{virial}}$ ($M_\odot$) | $M_{\text{Jeans}}$ ($M_\odot$) |
|-------|---------|------------------|--------------------------------|----------------------------|-------------------------------|-------------------------------|
|       |         |                  |                               |                            |                               |                               |

The clumps under LTE condition, as follows.

$$M_{\text{LTE}} = \frac{4}{3} \pi R^3 \mu^2 n_{\text{H}_2}$$ (9)
4.5. Identification of YSOs in the Field of N10

The distribution of YSOs plays a major role in the interpretation of the dynamics of star-forming region. To identify the YSOs present in the field of N10, we adopted the method described by Koenig & Leisawitz (2014; hereafter KL), based on the data of the WISE (see Wright et al. 2010). In particular, we used the AllWISE release (Cutri et al. 2011, 2013), which combined the data from the cryogenic and postcryogenic phases of the survey, resulting in a catalog with enhanced sensitivity.

The catalog was accessed through the VIZIER facility of the Strasbourg Data Center. The catalog contains infrared photometric data at 3.6, 4.9, 5.8 and 22 μm wavelengths, hereafter designated as w1, w2, w3, and w4 bands, respectively. In a first step, we selected all the objects situated in the area around N10 that we explored, in the range of Galactic coordinates 13°711 < l < 13°727 and −0°04 < b < 0°12.

We found 565 WISE sources in this area. We next filtered this list of sources by applying a series of quality criteria defined by KL, which they call the uncertainty/signal-to-noise/chi-squared criteria. The purpose of this is to avoid regions in the space of these parameters with relatively high probabilities of spurious catalog entry. Accordingly, the Class I YSOs are classified as such if their color matches with all the following criteria:

\[w1 - w3 > 2.0;\]
\[w1 - w2 > -0.42 \times (w2 - w3) + 2.2;\]
\[w1 - w2 > 0.46 \times (w1 - w3) - 0.9;\]
\[w2 - w3 < 4.5.\]

These conditions reflect the divisions in the SED slope \(\alpha = d \log (\lambda F_\lambda)/d \log \lambda\).

The Class II objects were also classified according to KL, whose criteria are

\[w1 - w2 > 0.25;\]
\[w1 - w2 < -0.9 \times (w2 - w3) + 0.25;\]
\[w1 - w2 > 0.46 \times (w2 - w3) - 0.9;\]
\[w2 - w3 < 4.5.\]

Similarly, also on the criteria by KL, transition disks were classified as follows:

\[w3 - w4 > 1.5;\]
\[0.15 < w1 - w2 < 0.8;\]
\[w1 - w2 > 0.46 \times (w2 - w3) - 0.9;\]
\[w1 \leq 13.0.\]

For w3, we kept only the condition of S/N larger than five. It is considered that if a source satisfies the criteria of being a true source in any one of the bands, it has little probability of being a fake one and will be included in the final list. After this filtering, the list of sources was reduced to 407 entries.

The next step was to separate the sources into Class I, Class II, Transition Disks, and remaining objects. Following KL, the Class I and Class II YSOs are classified as such, based on the \(w1 - w2\) versus \(w2 - w3\) color–color diagram only. The regions of the diagram that are used to classify the YSOs are defined by a number of frontier lines, shown in Figure 12. The equations of the lines are given by KL (their Equations (12) to (20)). We found 12 Class I stars and 91 Class II sources. The transition disk stars are selected separately by means of the \(w1 - w2\) versus \(w2 - w3\) color–color diagram as shown in Figure 13. We found 131 transition disk stars. Note that the selection criteria follow an order of priority: a Class I object will remain Class I even if it also satisfies the criterion for Class II, and next the Class II selection prevails over the following selection. This is why we find many Class II objects in the box defining transition disk stars in Figure 13: they were classified Class II in the previous step, on the basis of the different color–color plot.

This selection of Class I objects is robust, since these objects are well separated from the other classes in the color diagrams. Furthermore, we made experiments with another classification scheme available in the literature (using Spitzer data, e.g., Gutermuth et al. 2009) and the same Class I objects were retrieved. On the other hand, the distinction between Class II and the transition disk is a little arbitrary, as we can see some overlap in Figures 12 and 13. In the samples of objects previously known to belong to given classes, used by KL to decide the position of the frontier lines in Figures 12 and 13, one can see a number of transition disk sources in the locus of Class II and vice versa. So, one must consider that the decision to attribute sources to one or the other classes is only valid in a statistical sense, being correct in about 70% of the cases.

4.6. SED Fitting

We have compared the position of Class I YSOs, the most embedded young stellar sources, with the molecular distribution and the objects identified from #1 to #9 (see Table 6) are more likely to be physically related to N10 molecular structure. We have fitted their SED by using the online tool developed by Robitaille et al. (2007). Radiation transfer models were fitted to observational data extracted from the WISE catalog based on a \(\chi^2\) test. We selected models for which \(\chi^2 - \chi^2_{\text{min}} < 3n\), where \(\chi^2_{\text{min}}\) is the minimum value and \(n\) is the number of input data.

The fitting was performed using fluxes from WISE data, distance ranges from 4.23 to 5.17 kpc. Interstellar extinction in the direction of N10 was predict to be approximately 10.7 mag according to model S of Amôres & Lépine (2005), values adopted were from 9.7 to 11.7 mag. The best fit is shown in Figure 11. Resulting values for model parameters are given in Table 5. We found that Class I YSOs have stellar masses ranging from \(\sim 1\) to \(\sim 13 M_\odot\), stellar temperatures from \(\sim 4000\) to \(20,000\) K, total luminosities from \(\sim 3 \times 10^3 - 1 \times 10^3 L_\odot\),
envelope accretion rates from $\sim 9 \times 10^{-8} - 3 \times 10^{-3} \, M_\odot$ yr$^{-1}$, disk masses from $\sim 7 \times 10^{-3} - 6 \times 10^{-1} \, M_\odot$, and stellar ages from $\sim 2 \times 10^3$ to $\sim 1 \times 10^6$ years.

5. DISCUSSION

In this section, we discuss the distribution of molecular material around the bubble N10 and its connection with the star formation history.
Table 5
Physical Parameters Derived from Robitaille et al. (2007) Model, for Associated Class I Object Candidates

| Parameters                  | 1       | 2       | 3       | 4       | 5       | 6       | 7       | 8       | 9       |
|-----------------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Stellar Mass ($M_\odot$)    | 1.42    | 6.53    | 7.07    | 6.08    | 7.42    | 9.86    | 12.94   | 12.89   | 6.43    |
| Stellar Temperature (K)     | 4173    | 10107   | 4293    | 4148    | 20167   | 4260    | 12262   | 7471    | 19400   |
| Total Luminosity ($L_\odot$) | $3.11 \times 10^1$ | $1.02 \times 10^3$ | $5.45 \times 10^2$ | $5.96 \times 10^2$ | $2.33 \times 10^3$ | $2.47 \times 10^3$ | $1.13 \times 10^4$ | $7.31 \times 10^3$ | $1.19 \times 10^3$ |
| $M_{env}$ ($M_\odot$ yr$^{-1}$) | $2.49 \times 10^{-5}$ | $1.20 \times 10^{-5}$ | $4.70 \times 10^{-5}$ | $1.19 \times 10^{-5}$ | $7.60 \times 10^{-5}$ | $1.12 \times 10^{-5}$ | $3.61 \times 10^{-3}$ | $2.25 \times 10^{-4}$ | $8.62 \times 10^{-8}$ |
| Disk Mass ($M_\odot$)       | $1.01 \times 10^{-2}$ | $3.05 \times 10^{-2}$ | $3.38 \times 10^{-2}$ | $4.45 \times 10^{-3}$ | $1.46 \times 10^{-3}$ | $7.1 \times 10^{-3}$ | $1.49 \times 10^{-1}$ | $6.09 \times 10^{-1}$ | $5.25 \times 10^{-5}$ |
| Stellar Age (year)          | $1.24 \times 10^4$ | $2.77 \times 10^5$ | $7.07 \times 10^3$ | $1.84 \times 10^4$ | $2.97 \times 10^5$ | $2.41 \times 10^4$ | $2.88 \times 10^4$ | $1.60 \times 10^4$ | $1.02 \times 10^6$ |

Notes.

* Identification from Table 6.
* Total system luminosity.
* Envelope and ambient density mass, in solar mass.
5.1. Surrounding Gas of N10

Channel maps are presented in Figure 5; since $^{12}$CO is optically thick, it appears to be spread over a large area, whereas $^{13}$CO traces the denser regions, once it is optically thinner. Figure 10 displays two peaks of molecular emission, i.e., two $^{13}$CO condensations. Clump #1 is centered at $l = 13^\circ.218$, $b = 0^\circ.043$ and Clump #2 is located at $l = 13^\circ.169$, $b = 0^\circ.072$. The two clumps are located precisely on the edge of the ring structure revealed by the 8.0 $\mu$m emission and highlighted by an ellipse in Figure 2.

5.2. Other Components of CO Emission

As highlighted in Section 4.1, CO components at 20 and 37 km s$^{-1}$ do not seem to be physically related with bubble N10. What could be the origin of this contribution? It is known that CO emission in galaxies is concentrated in spiral arms (Nieten et al. 2006; Schinnerer et al. 2013). The line of sight toward N10 crosses two spiral arms before reaching the distance of 4.7 kpc (see, e.g., Figure 10 of Hou & Han 2014). The velocities of peaks 20 and 37 km s$^{-1}$ correspond near kinematic distances of 2.4 and 3.7 kpc, respectively, representing roughly the distance of those arms.

It is therefore reasonable to suppose that these two velocity peaks are associated with foreground gas situated in distinct spiral arms. Furthermore, emission at these two velocities does not seem to be correlated with the geometry of N10; emission appears to be irregularly spread over a studied field. If one examines Figure 4 of the $^{12}$CO (1-0) survey of the Galaxy by Lee et al. (2001), selecting the panel corresponding to $b = 0^\circ.05$, one can see at longitude 13°2 the presence of $^{13}$CO at about 50, 35, and 20 km s$^{-1}$. The last two are part of the elongated structures in the longitude-velocity diagram (extending to higher and lower longitudes), which are usually interpreted as spiral arms. In this region of the diagram, lower velocities correspond to the closest arms.

Note that kinematic distances are uncertain at longitudes close to the Galactic center. We have to make use of a $^{13}$CO survey because in $^{12}$CO longitude-velocity diagrams, the spiral arms are wider in velocity and are not seen separated.

5.3. Situation of Star Formation

The densest clump in the 870 $\mu$m emission seems to be a candidate region to form stellar clusters, since it has a total mass of $M_{\text{tot}} = 240 M_\odot$ and a mean radius of $R = 0.36$ pc. In accordance with Motte et al. (2003), fragments in the range between 0.09 and 0.56 pc and masses covering a range from 20 to 3600 $M_\odot$ have characteristics of protoclusters.

Elmegreen & Lada (1977) were the first to propose the scenario of “Collect and Collapse,” where the radiation of the massive stars of an H II region creates an ionization front at the interface with the molecular cloud that drives the propagation of a shock front into the neutral material and that accumulates mass and eventually becomes gravitationally unstable. Other scenarios of triggered star formation have been proposed, such as, e.g., the “Radiation-Driven Implosion” model, based on the over pressure exerted by the ionized gas, suggested by Lefloch & Lazareff (1994). While the “Collect and Collapse” model takes place in a large spatial size (~10 pc) with a longer timescale (a few million years), “Radiation-Driven Implosion” takes place in ~1 pc with a timescale of 0.5 Myr.

![Figure 14. Distribution of the identified YSOs. The background is the Spitzer 8.0 $\mu$m image. Red crosses are Class I sources; green circles are class II sources; and blue diamonds are “transition disk” sources. Black contours show the $^{13}$CO emission around the bubble.](image)

Although we found evidence for active star formation in N10, we are not sure that the formation of these YSOs was triggered by the “Collect and Collapse” mechanism around the infrared bubble. In order to verify if this process is viable, we can apply the analytical model proposed by Whitworth et al. (1994) and compare the fragmentation timescale $t_{\text{frag}}$ with the dynamical age $t_{\text{dyn}}$ of the region. The Whitworth et al. (1994) model describes the fragmentation time as

$$t_{\text{frag}} = 1.56 c_s^{7/11} N_{\text{av}}^{-1/11} n_o^{-5/11},$$

where $c_s$ is the isothermal sound speed in the ionized gas in the shocked layer in units of 0.2 km s$^{-1}$, $N_{\text{av}}$ is the ionizing photon flux in units of $10^{49}$ photons s$^{-1}$, and $n_o$ is the initial particle number density of the ambient neutral gas in units of $10^3$ cm$^{-3}$. Considering $c_s = 0.2$ km s$^{-1}$ (Liu et al. 2012), $N_{\text{av}} = 1.86 \times 10^{49}$ photons s$^{-1}$ and $n_o = 10^3$ cm$^{-3}$ (Ma et al. 2013), we estimated $t_{\text{frag}} \sim 1.5 \times 10^6$ years for the region. From Ma et al. (2013), $t_{\text{dyn}} = 9.17 \times 10^4$ years, i.e., the dynamical age is smaller than the fragmentation timescale, which indicates that the region does not support the “Collect and Collapse” mechanism. In this case, the “Radiation-Driven Implosion” could be considered and further investigated.

The position of YSOs compared with CO distribution indicates that stars are forming inside the molecular clumps. Figure 14 shows the spatial distribution of identified YSOs from Table 6. In fact, the Class I YSO candidates to be associated with N10 presented in Table 5 have ages smaller than the fragmentation timescale, suggesting the possibility of triggered star formation by pre-existing condensations compressed by the pressure of the ionized gas, as the “Radiation-Driven Implosion” scenario proposes.

5.4. The Bubble N11

Infrared images show N11, a bubble that seems to be physically connected with N10 and extends about 3 pc in the
up-right direction. Conversely the molecular distribution of N11 does not suggest a physical connection with N10, since the emission of $^{13}$CO (1-0) between 47 and 53 km s$^{-1}$ is not coincident with 8.0 µm emission.

It is probable that this object is a remnant of an H II region, where the lack of 20 cm emission lead us to consider that there is no more ionized gas inside. It is likely that another energy source has triggered the formation of these YSOs, such as the explosion of an SN II.

Class I YSOs do not seem to be superimposed on the bubble N11 and many Class II YSOs can be found toward N11, as we can see in Figure 14. There is a remarkable concentration of transition disk sources surrounding the top frontier of N11. We consider, in this interpretation, that the concentration of Class II YSOs near the upper frontier of N11 is possibly the result of a past star formation activity related to that bubble.

5.5. A Small Bubble to the Right of N10: MWP1G013134+000580

The bubble MWP1G013134+000580, at coordinates $l = 13^h 13^m$ and $b = 0^\circ 058$, has a size smaller than 2 pc. Interestingly, this small bubble should have about the same distance as N10, since its CO emission is contained in the same main velocity peak, clearly seen in channel maps with velocities between 51 and 53 km s$^{-1}$ in Figure 5.

We found three Class I YSOs in the region covered by 8.0 µm emission of MWP1G013134+000580. The age of the small bubble seems to have the same order of N10, as we can infer from the evolutionary stages of the YSOs.

6. CONCLUSIONS

We have performed a comprehensive study of the infrared bubble N10 using the molecular line emissions of $^{12}$CO ($J = 1 - 0$) and $^{13}$CO ($J = 1 - 0$), mid-infrared Spitzer/GLIMPSE and MIPSagal images, VLA data of the 20 cm emission, APEX observations of the continuum 870 µm emission and WISE catalog of mid-infrared point sources. The key results are summarized as follows.

1. We observed the $J = 1 - 0$ transition of CO isotopologues at the PMO 13.7 m radio telescope. The distribution of the CO emission showed that the molecular gas around the bubble N10 has a velocity of $V_{lsr} = 52.6$ km s$^{-1}$, from which we estimated a distance of $D = 4.7 \pm 0.5$ kpc. This observation revealed two $^{13}$CO clumps with $M_{\text{clumps}} \sim 2 \times 10^3 M_\odot$, $M_{\text{total}} \sim 8.5 \times 10^3 M_\odot$, and $M_{\text{total}} \sim 6 \times 10^3 M_\odot$, which implies that the clumps are currently gravitationally unbound.

2. The emission of the radio continuum and the presence of 24 µm emission suggest ionizing sources inside the bubble. We estimated a total flux of 20 cm of $F_{20\text{cm}} = 1.17$ Jy and an electron density of $n_e \sim 130$ cm$^{-3}$, with a Lyman continuum photon flux of $N_{\text{LyC}} \sim 1.86 \times 10^{49}$ ionizing photons s$^{-1}$, equivalent to an $\sim$O7 V star (or stars) keeping the gas ionized.

3. Two cold dust clumps were identified toward N10 in LABOCA/APEX images. For the densest clump, we estimated the emission at 870 µm a total mass of $M_{\text{tot}} = 240 M_\odot$, a mean radius of $R \sim 0.72$ pc; a column density of $N(H_2) = 6.3 \times 10^{22}$ cm$^{-2}$, and an average volume density of $n(H_2) = 1.17 \times 10^4$ cm$^{-3}$; physical characteristics indicate that this condensation is a good candidate for a protocluster.

4. We identified 234 YSOs in the whole region: 12 of them were classified as Class I, 91 Class II, and 131 Transition Disks. We fitted the SED for Class I YSO candidates identified from #1 to #9 and we derived their physical parameters. From the models, we found stellar ages ranging from $\sim$10$^3$ to $10^6$ years. By comparing the estimated dynamical age ($t_{\text{dyn}} = 9.17 \times 10^4$ year) and the fragmentation timescale ($t_{\text{frag}} \sim 1.5 \times 10^6$ year), we infer that star formation can be triggered as a consequence of the “Radiation-Driven Implosion” process. Likewise, the age range for the Class I YSOs is below that found for the fragmentation timescale, indicating they were formed before the collect molecular cloud became gravitationally unstable to fragment and form stars.

5. In the Spitzer 8.0 µm image, the infrared bubble N11 can be seen in the direction of the N10; however, one is not physically connected with the other. Class II YSOs appear toward N11, suggesting that this could be a remnant of the H II region. A third infrared bubble, the small MWP1G013134+000580, appears in the observed field and, interestingly, has CO emission in the same main velocity as N10 and seems to shelter some evolved YSOs.
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