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Date: 2024-05-10T00:00:00+00:00

Abstract

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Full Text

Preamble

Research in Astronomy and Astrophysics, 24:045023 (9pp), 2024 April

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<https://doi.org/10.1088/1674-4527/ad3618>

Multiwavelength Observations of the Infrared Dust Bubble N75 and its Surroundings

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Received 2024 January 8; revised 2024 March 9; accepted 2024 March 18; published 2024 April 24

Abstract

Infrared dust bubbles play an important role in the study of star formation and the evolution of the interstellar medium. In this work, we investigate the infrared dust bubble N75 and the infrared dark cloud G38.93 primarily using tracers $C^{18}O$, HCO^+ , HNC, and N_2H^+ observed with the IRAM 30 m telescope. We also analyze the targets using data from large-scale surveys: GLIMPSE, MIPS GAL, GRS, NRAO VLA Sky Survey, and Bolocam Galactic Plane Survey. We find that the $C^{18}O$ emission is morphologically similar to the Spitzer IRAC 8.0 μm emission. The 1.1 mm cold dust emission of G38.93 shows an elongated structure from southwest to northeast. The ionized gas from G38.93 is surrounded by polycyclic aromatic hydrocarbon emission, which may be excited by radiation from G38.93. We find that the identified young stellar objects tend to cluster around G38.93 and are mostly Class II, with several Class I cases distributed around N75, but no Class II examples. We also find evidence of expanding feedback, which could have triggered star formation.

Key words: ISM: bubbles -infrared: ISM -galaxies: star formation

1. Introduction

Churchwell et al. (2006) detected and cataloged approximately 600 mid-infrared dust bubbles between longitudes -60° and $+60^\circ$. Ionizing O- and/or B-type stars may play an important role in the formation of infrared (IR) dust bubbles (e.g., Zhang & Wang 2012, 2013; Zhang et al. 2013, 2016; Xu et al. 2014). These bubbles provide an important opportunity to study the interplay between H II regions and molecular clouds (e.g., Zhang & Wang 2012, 2013). Simpson et al. (2012) presented a catalog of 5,106 IR bubbles created by visual classification via the online citizen science website “The Milky Way Project.” Ultraviolet (UV) radiation from ionizing stars can heat dust and ionize gas, resulting in the formation of an expanding bubble shell (Watson et al. 2008). Massive star formation can be triggered by this process in the vicinity of shell clumps.

Some bubbles are associated with infrared dark clouds (IRDCs). IRDCs harbor various evolutionary stages, provide excellent targets to study the initial conditions of massive star formation prior to cloud collapse, and are important for understanding the early evolution of massive star-forming clumps (Rathborne et al. 2006; Beuther et al. 2007; Henning et al. 2010). Therefore, IRDCs play

an important role in the study of star formation and the evolution of the interstellar medium (ISM) (e.g., Rathborne et al. 2005; Pillai et al. 2006; Beuther & Sridharan 2007; Zhang et al. 2017a). Additionally, bubbles associated with IRDCs provide an important sample to study both triggered star formation and the early stages of high-mass star formation. The dense and cold nature of IRDCs may be more conducive to special chemical reactions than in other star formation regions (e.g., Zhang et al. 2017b, 2019, 2020). For example, CO, a commonly used tracer of dynamics in cold and dense clouds (Hernandez & Tan 2011), can be affected by depletion of the gas-phase abundance due to freezing on dust grains (Hernandez et al. 2011). Due to the freeze-resistance of some N- or D-containing molecules, N- and D-bearing molecules such as N_2H^+ are more suitable for tracing dense and cold cores (e.g., Zhang et al. 2020).

G38.93–0.355 (hereafter G38.93) is an IRDC associated with the IR dust bubble N75 (Churchwell et al. 2006). The distance to G38.93 was measured to be 2.7 kpc (Zhang et al. 2014). Bubble N75 and IRDC G38.93 are excellent targets for studying triggered star formation and high-mass star formation. Masers, including H_2O masers (Forster & Caswell 1989, 1999), OH masers (Forster & Caswell 1989, 1999; Błazzkiewicz & Kus 2004; Szymczak & Gérard 2004), and Class II CH_3OH masers (Błazzkiewicz & Kus 2004; Szymczak & Gérard 2004), were detected in G38.93, suggesting massive star formation there. Xu et al. (2013) studied N75, N74, and their surrounding regions; however, they only used optically thick CO as tracers. In this paper, we use new molecular spectra to perform a more detailed study of G38.93 to verify and complement the results of Xu et al. (2013).

In this paper, we present a multiwavelength study of bubble N75, primarily probing the ISM around N75 and searching for evidence of star formation. The observations and data reduction are described in Section 2; the results and data analysis are presented in Section 3; the discussion of the corresponding star formation is presented in Section 4; and Section 5 provides the conclusions.

2. Observation and Data

The adopted spectral data, covering bubble N75 and clump G38.93, are primarily from the IRAM 30 m and FCRAO 15 m telescopes. These data are used to study the dense and cold structure. In addition, dust and continuum data from Spitzer and the NRAO VLA Sky Survey (NVSS) archival data are used to study the IR and H II background. Details about the observations and data are presented in the following sections.

2.1. IRAM 30 m Observations

The HCO^+ (1-0), HNC (1-0), N_2H^+ (1-0), and C^{18}O observations were made in December 2018 with the IRAM 30 m telescope on Pico Veleta, Spain. The half-power beamwidth was between 29 and 23', the main beam efficiency (B_{eff}) was between 81% and 78%, and the forward efficiency (F_{eff}) of the IRAM 30

m telescope was between 95% and 94%. The relation between the main beam temperature (T_{MB}) and the antenna temperature (T_{A}) is $T_{\text{MB}} = (F_{\text{eff}}/B_{\text{eff}}) \times T_{\text{A}}$. The on-the-fly mapping mode was used to scan each source in two orthogonal directions to reduce striping on the maps. The data reduction software is GILDAS.

2.2. ^{13}CO Data

The ^{13}CO ($J = 1 \rightarrow 0$) data are from the Boston University-Five College Radio Astronomy Observatory Galactic Ring Survey (GRS; Jackson et al. 2002). The data have a full width at half maximum (FWHM) of 46" and a velocity resolution of 0.21 km s^{-1} at 110.2 GHz. The ^{13}CO data are used to map our target and calculate physical parameters.

2.3. Dust and Continuum Data

The IR data are from the Spitzer GLIMPSE survey (Benjamin et al. 2003) and the MIPS GAL survey (Rieke et al. 2004). The NVSS is a 1.4 GHz continuum survey covering the entire sky north of -40° declination. NVSS was used to trace the ionizing gas (Condon et al. 1998) with a noise level of approximately $0.45 \text{ mJy beam}^{-1}$. We also used the 1.1 mm continuum data from the Bolocam Galactic Plane Survey (BGPS) and the Bolocam 1.1 mm source catalog (Ginsburg et al. 2013) to trace the dense part of our target source. The effective FWHM of the 1.1 mm map is 33".

3. Results and Analysis

3.1. Dust Emission

Figure 1 [Figure 1: see original paper] displays the ^{13}CO emission (white), 1.1 mm emission (cyan), and 1.4 GHz continuum emission (red) contours superimposed on a three-color image of 4.5" (blue), 8.0" (green), and 24" (red). The Spitzer IRAC 8" emission may originate from polycyclic aromatic hydrocarbons (PAHs), which are excited by the photodissociated region surrounding the H II region (Pomarès et al. 2009; Petriella et al. 2010). The 8" emission is extended at G38.93. The H II region N74, located to the southeast of N75, shows a ring-like shape. The 24" emission, originating from hot dust, appears inside the bubbles of N75 and N74. The 4.5" emission indicates the location of the brightest stars.

The 1.1 mm continuum emission traces cold dust. The cold dust emission of G38.93 shows an elongated structure from southwest to northeast. The structure of G38.93 is outlined by the 1.1 mm emission, which is comparable to the shape of the molecular emission contours in Figure 2 [Figure 2: see original paper]. We used the NVSS 1.4 GHz continuum emission overlaid on the three-color map to trace the ionized gas in the H II region.

3.2. Integrated Intensity Maps

We present the integrated intensity maps of G38.93 and N75 in Figure 2 [Figure 2: see original paper]. The $^{13}\text{CO}(J = 1-0)$ line can be used to trace the structure of the clump associated with the H II region. We find that the CO velocity component, ranging from 35 to 42 km s⁻¹, is related to these H II regions. The integrated intensity map of $^{13}\text{CO}(J = 1-0)$ in Figure 1 clearly shows two dense clumps, labeled G38.93 and G38.95. Additionally, G38.93 is located to the northwest of N75 and exhibits a compressed structure as seen from the CO distribution in Figure 1, suggesting a likely interaction between N75 and G38.93.

We also find that the HCO^+ , N_2H^+ , and HNC emissions have similar morphologies to the 1.1 mm emission, while the C^{18}O emission is more extended. The C^{18}O emission and the 8.0 m emission are very similar in morphology. In Figure 2, we see that the C^{18}O emission is weaker in the center of N75, which may indicate that the C^{18}O emission is optically thick under such conditions.

3.3. Spectral Analysis

From the BGPS 1.1 mm peak position of G38.93, we extracted individual C^{18}O , HCO^+ , HNC, and N_2H^+ spectra. The average spectra are displayed in Figure 3 [Figure 3: see original paper]. These spectra show that the velocity components are in the range of 33–45 km s⁻¹. We applied Gaussian fits to the spectra of C^{18}O , HCO^+ , HNC, and N_2H^+ , with the fitted results summarized in Table 1. We derive a system velocity of 38.98 km s⁻¹ using the C^{18}O line for clump G38.93.

3.4. Velocity Distribution

In Figure 4 [Figure 4: see original paper], we show the channel maps of $\text{C}^{18}\text{O}(1-0)$ to examine the detailed velocity distribution in the clump. We find that the bubble N75 has a velocity of 40.5 km s⁻¹. Figure 5 [Figure 5: see original paper] presents the channel maps of the HCO^+ line. The 8.0 m grayscale shows the position and size of N74, N75, and G38.93. The HCO^+ emission extends over a velocity range of $34 < V_{\text{LSR}} < 42$ km s⁻¹, while C^{18}O emission extends over $37.5 < V_{\text{LSR}} < 41.5$ km s⁻¹. Based on this velocity range, we constructed the position-velocity (PV) diagram of HCO^+ as displayed in Figure 8 [Figure 8: see original paper]. Using the PV diagram, we created the integrated intensity maps of G38.93 as depicted in Figure 6 [Figure 6: see original paper]. The blue contours indicate the blueshifted velocity components and the red contours correspond to the redshifted velocity components, suggesting the existence of an outflow.

3.5. Dust Temperature and Density

To study the effects of the H II regions on G38.93, it is crucial to calculate the temperature and density. Herschel observations covering wavelengths from

70–500 m can be used to construct the H_2 column density (N_{H_2}) and dust temperature maps at 160, 250, 350, and 500 m. We exclude 70 m because this emission traces hotter components heated by UV radiation. Using the Getsources algorithm (Men’ shchikov et al. 2010, 2012; Men’ shchikov 2013), we created the column density and dust temperature maps of G38.93 by fitting the spectral energy distributions (SEDs) on a pixel-by-pixel basis (Palmeirim et al. 2013).

Figure 7 [Figure 7: see original paper] shows the T_{dust} and N_{H_2} maps. We find that the dust temperature distribution ranges from 10 to 30 K, and the column density is about 10^{22} cm^{-2} with a maximum column density of about $9.73 \times 10^{22} \text{ cm}^{-2}$. The temperature reaches a minimum at the column density peak position of G38.93. Furthermore, the mean dust temperature is about 15.6 K, suggesting relatively cold conditions in this star formation region.

3.6. Excitation Temperature, Column Density, and Mass for G38.93

Using the molecular lines, we calculate the physical parameters T_{ex} , N_{H_2} , $n(H_2)$, and M_{LTE} for G38.93 assuming a kinematic distance of 2.70 kpc (Roman-Duval et al. 2009). Assuming local thermodynamic equilibrium (LTE), we use the relatively optically thin $^{13}\text{CO}(J = 1-0)$ emission to determine the column densities and mass of the G38.93 clump by applying the following equation (Garden et al. 1991):

$$N(^{13}\text{CO}) = 3.0 \times 10^{14} \frac{T_{\text{ex}} + 0.88}{\exp(-5.29/T_{\text{ex}})} \int T_{\text{mb}} dv$$

where T_{mb} is the corrected main-beam temperature of ^{13}CO , and T_{ex} is the excitation temperature in K. T_{ex} can be calculated by the following equation (Garden et al. 1991):

$$T_{\text{ex}} = \frac{5.53}{\ln \left[1 + \frac{5.53}{T_{\text{mb}}(^{13}\text{CO}) + 0.82} \right]}$$

The H_2 column density is calculated with the following equation (Frerking et al. 1982):

$$N(H_2) = \frac{N(^{13}\text{CO})}{X(^{13}\text{CO})}$$

where $X(^{13}\text{CO}) = 1.0 \times 10^{-6}$ is the abundance ratio of ^{13}CO relative to H_2 . The mean volume densities of the H_2 molecule are:

$$n(H_2) = \frac{N(H_2)}{R}$$

where m_{H} is the mass of a hydrogen atom and $\mu = 2.8$ is the mean molecular weight considering the contributions of He and other heavy elements to the total mass. Based on the assumption of LTE and spherical geometry, the masses of the clouds are calculated as:

$$M_{\text{LTE}} = \mu m_{\text{H}} N(\text{H}_2) \pi R^2$$

Finally, we derived the column density of the clump G38.93 as $N(\text{H}_2) = 5.34 \times 10^{21} \text{ cm}^{-2}$. Other corresponding parameters are $n(\text{H}_2) = 1.16 \times 10^3 \text{ cm}^{-3}$, $R = 3.055 \text{ pc}$, $D = 2.5 \text{ kpc}$, $T_{\text{ex}} = 6.953 \text{ K}$, $N(^{13}\text{CO}) = 1.068 \times 10^{16} \text{ cm}^{-2}$, and $M_{\text{LTE}} = 8 \times 10^4 M_{\odot}$.

3.7. Expansion Age of the Bubble N75

The PV diagram for G38.93 is shown in Figure 8 [Figure 8: see original paper]. The cutting direction passing through the selected dense core positions is indicated by the yellow line in the HCO^+ subfigure of Figure 2 [Figure 2: see original paper]. The dense cores form the backbone of the G38.93 clump and allow us to study its dynamical state. The PV plot shows a clear velocity gradient relative to the system velocity of 39 km s^{-1} . The broad and extended line wings of HCO^+ in Figure 3 [Figure 3: see original paper] represent the blueshifted and redshifted velocity components, respectively. The PV diagram in Figure 8 [Figure 8: see original paper] provides additional evidence for an outflow (Smith et al. 1997; Beuther et al. 2004).

We selected the integrated area of the wings and determined the outflow intensities of the red and blue lobes according to the PV plots and channel maps. The contours of the integrated intensities of the HCO^+ line wing identified a molecular outflow (Figure 6 [Figure 6: see original paper]). The dynamic timescale of the outflow is calculated using the equation $t_{\text{out}} = 9.78 \times 10^5 R/V \text{ (yr)}$, where R in pc is the outflow size and V in km s^{-1} is the maximum flow velocity relative to the cloud system velocity. The mean dynamic timescale of the outflow is $5.1 \times 10^5 \text{ yr}$.

Using the 1.4 GHz radio continuum emission, the ionizing luminosity N_{Ly} was computed via Mezger et al. (1974):

$$N_{\text{Ly}} = 7.5 \times 10^{46} \left(\frac{S_{\nu}}{\text{Jy}} \right) \left(\frac{D}{\text{kpc}} \right)^2 \left(\frac{T_e}{10^4 \text{K}} \right)^{-0.45} \left(\frac{\nu}{\text{GHz}} \right)^{0.1} \text{ s}^{-1}$$

Here we adopted an effective electron temperature of 10^4 K , a distance of 2.7 kpc , and $S_{\nu} = 23.7 \text{ mJy}$. We derived $N_{\text{Ly}} = 2.14 \times 10^{46} \text{ s}^{-1}$. Assuming the H II region is expanding into a homogeneous medium, the dynamical age was estimated by the method of Dyson & Williams (1980):

$$t_{\text{dyn}} = 1.56 \times 10^6 \left(\frac{R_{\text{HII}}}{20\text{pc}} \right)^{4/7} \left(\frac{n_0}{10^3\text{cm}^{-3}} \right)^{-3/7} \left(\frac{N_{\text{Ly}}}{10^{49}\text{s}^{-1}} \right)^{-1/7} \text{ yr}$$

The age of the H II region G38.93 is 1.38×10^6 yr.

4. Discussion

4.1. Star Formation Activity

The molecular outflows (see Figure 6 [Figure 6: see original paper]) and masers such as H₂O, OH, and Class II CH₃OH (Caswell et al. 1995) detected surrounding bubble N75 and G38.93 indicate that this star formation system is an active star formation region. Furthermore, we found many young stellar objects (YSOs) associated with this formation system, allowing us to derive their spatial distribution, ages, and masses. Based on the criteria of Allen et al. (2004), we selected near-infrared sources with 3.6, 4.5, 5.8, and 8.0 μm emission in our survey region from the GLIMPSE point source catalog. Figure 9 [Figure 9: see original paper] shows the [5.8]-[8.0] versus [3.6]-[4.5] color-color diagram. Only sources detectable in all four Spitzer IRAC bands were considered. In this diagram, Class I YSOs are protostars with circumstellar envelopes, Class II YSOs are disk-dominated objects, and Class III cases are main-sequence or giant stars.

From Figure 10 [Figure 10: see original paper], we see that YSOs tend to cluster around G38.93 and are mostly Class II, with several Class I instances distributed around N75, but no Class II cases. The ages of Class I YSOs are 10^5 yr, while the lifetimes of Class II YSOs are 10^6 yr (Andre & Montmerle 1994).

4.2. Triggered Star Formation

Figure 10 [Figure 10: see original paper] shows an RGB image with 4.5 μm , 8 μm , and 24 μm in blue, green, and red, respectively. The positions of candidate YSOs are shown, where Class I and II YSOs are indicated by black and red dots, respectively. The YSOs are mainly located in the compressed regions between bubble N75 and G38.93, suggesting that expanding feedback could have triggered star formation.

Four Class I stars are located on the compact shell of bubble N75, which may indicate triggered star formation. The age of N75 is greater than that of these Class I stars, suggesting sufficient time for this triggering process. Class II stars are concentrated to the east of G38.93 with strong 8 μm emission. The 8 μm emission distribution has a cocoon-like structure, which could be a compact H II region ionized by massive star formation. It is probable that the expansion of such a compact H II region has triggered the formation of Class II stars, the masers, and the outflows. We note that only a few YSOs are consistent with the bright bubble edges. It is possible that some YSOs are simply hidden in the high IR background, and the YSOs are mainly located in the compressed regions

between bubble N75 and G38.93. This may suggest that expanding feedback could have triggered star formation.

5. Conclusions

In this work, we studied bubble N75 with $C^{18}O$, HCO^+ , HNC , and N_2H^+ , and performed a multiwavelength study of the region around G38.93. We found that the $C^{18}O$ emission correlates well morphologically with the Spitzer IRAC 8.0 μm emission. The eastern part of G38.93 shows an arc-like shape, with a small area of higher PAH emission in the center. The 1.1 mm emission, tracing cold dust, outlines the shape of G38.93, which is similar to the shape of the molecular emission. The cold dust emission of G38.93 exhibits an elongated structure from southwest to northeast. The 1.4 GHz continuum emission shows the ionized gas in G38.93. The ionized gas from G38.93 is surrounded by PAH emission, which may be excited by radiation from G38.93. We found that the identified YSOs tend to cluster around G38.93 and are mostly Class II, with several Class I cases distributed around N75, but no Class II examples. We also found evidence of expanding feedback, which could have triggered star formation.

Acknowledgments

This work is supported by the National Key R&D Program of China (No. 2022YFA1602901), the local Science and Technology innovation projects of the central government (No. XZ202301YD0037C), and the National Natural Science Foundation of China (No. 11933011). We also wish to thank the anonymous referee for comments that improved the clarity of the paper.

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