New Insights in the Mid-infrared Bubble N49 Site: A Clue of Collision of Filamentary Molecular Clouds

L. K. Dewangan1, D. K. Ojha2, and I. Zinchenko3

1 Physical Research Laboratory, Navrangpura, Ahmedabad—380 009, India; lokeshd@prl.res.in
2 Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India
3 Institute of Applied Physics of the Russian Academy of Sciences, 46 Ulyanov Street, Nizhny Novgorod 603950, Russia

Received 2017 September 28; revised 2017 November 1; accepted 2017 November 16; published 2017 December 21

Abstract

We investigate the star formation processes operating in a mid-infrared bubble N49 site that harbors an O-type star in its interior, an ultracompact H II region, and a 6.7 GHz methanol maser at its edges. The 13CO line data reveal two velocity components (at velocity peaks ~88 and ~95 km s⁻¹) in the direction of the bubble. An elongated filamentary feature (length >15 pc) is investigated in each molecular cloud component, and the bubble is found at the interface of these two filamentary molecular clouds. The Herschel temperature map traces all these structures in a temperature range of ~16–24 K. In the velocity space of 13CO, the two molecular clouds are separated by ~7 km s⁻¹, and are interconnected by a lower-intensity intermediate velocity emission (i.e., a broad bridge feature). A possible complementary molecular pair at [87, 88] km s⁻¹ and [95, 96] km s⁻¹ is also observed in the velocity channel maps. These observational signatures are in agreement with the outcomes of simulations of the cloud–cloud collision process. There are also noticeable embedded protostars and Herschel clumps distributed toward the filamentary features including the intersection zone of the two molecular clouds. In the bubble site, different early evolutionary stages of massive star formation are also present. Together, these observational results suggest that in the bubble N49 site, the collision of the filamentary molecular clouds appears to be operated about 0.7 Myr ago, and may have triggered the formation of embedded protostars and massive stars.

Key words: dust, extinction – H II regions – ISM: clouds – ISM: individual objects (N49) – stars: formation

1. Introduction

Massive stars (>8 M⊙) can inject large amounts of energy to the neighboring interstellar medium, hence these stars can trigger the birth of a new generation of stars including young massive star(s) (Deharveng et al. 2010). However, the formation mechanisms of massive stars and their feedback processes are still being debated (Zinnecker & Yorke 2007; Tan et al. 2014). In recent years, the theoretical and observational studies of the cloud–cloud collision (CCC) process have drawn considerable attention, which can produce massive OB stars and young stellar clusters at the junction of molecular clouds (e.g., Habe & Ohta 1992; Furukawa et al. 2009; Ananthpindika 2010; Ohama et al. 2010; Inoue & Fukui 2013; Fukui et al. 2014, 2016; Takahira et al. 2014; Haworth et al. 2015a, 2015b; Torii et al. 2015, 2017; Dewangan 2017; Dewangan & Ojha 2017). Torii et al. (2017) suggested that the onset of the CCC process in a given star-forming region could be observationally inferred through the detection of a bridge feature connecting the two clouds in velocity space, the broad CO line wing in the intersection of the two clouds, and the complementary distribution of the two colliding clouds. However, such observational investigation is still limited in the literature (e.g., Torii et al. 2017).

The mid-infrared (MIR) bubble, N49 ([l 028°287; b = −00°229; Churchwell et al. 2006]) is a very well-studied star-forming site containing an H II region (Watson et al. 2008; Anderson & Bania 2009; Deharveng et al. 2010; Everett & Churchwell 2010; Zavagno et al. 2010; Diriengo et al. 2012). The N49 H II region is ionized by an O-type star (Watson et al. 2008; Deharveng et al. 2010; Diriengo et al. 2012) and is situated at a distance of 5.07 kpc (Dirienzo et al. 2012). We have also adopted a distance of 5.07 kpc to the bubble N49 throughout the present work. The bubble N49 is classified as a complete or closed ring with an average radius and thickness of 132 (or 1.95 pc) and 032 (or 0.45 pc), respectively (Churchwell et al. 2006). Diriengo et al. (2012) examined the 13CO line data and suggested the presence of two velocity components (at ~87 and ~95 km s⁻¹) in the direction of the bubble. Based on the radio recombination line observations, the velocity of the ionized gas in the N49 H II region was reported to be ~90.6 km s⁻¹ (Anderson & Bania 2009). Using the APEX 870 μm dust continuum data, Deharveng et al. (2010) reported the detection of at least four massive clumps (Mcum ~190–2300 M⊙) toward the infrared rim of the bubble (see Figure 18 in Deharveng et al. (2010) and also Figure 1 in Zavagno et al. 2010). An ultracompact (UC) H II region and a 6.7 GHz methanol maser emission (MME) (velocity range ~79.4–97.3 km s⁻¹; Walsh et al. 1998; Szyszczak et al. 2012) are also detected toward the dust condensations, which are seen at the edges of the bubble (e.g., Deharveng et al. 2010; Zavagno et al. 2010; Diriengo et al. 2012). The bubble N49 has also been considered as a candidate of a wind-blown bubble (Everett & Churchwell 2010). Using the multi-wavelength data, previous studies suggested that the N49 H II region is interacting with its surrounding molecular cloud, and has been cited as a possible site of triggered star formation (Watson et al. 2008; Anderson & Bania 2009; Deharveng et al. 2010; Zavagno et al. 2010; Diriengo et al. 2012).

Despite the availability of several observational data sets, the knowledge of the physical environments over larger spatial scale around the bubble is still unknown. Furthermore, the study of an interaction between molecular cloud components is yet to be performed in the bubble N49 site. To study the physical environment and star formation processes around the
bubble N49, we revisit the bubble using multi-wavelength data covering from the radio to near-infrared (NIR) wavelengths. Such an analysis offers an opportunity to examine the distribution of dust temperature, column density, extinction, ionized emission, kinematics of molecular gas, and young stellar objects (YSOs).

The paper is arranged as follows. The details of the adopted data sets are described in Section 2. Section 3 gives the outcomes concerning to the physical environment and point-like sources. In Section 4, we present the possible star formation processes ongoing in our selected target region. Finally, Section 5 summarizes the main results.

2. Data Sets and Analysis

In this paper, we have chosen a field of ~0°:42 × 0°:42 (~37.2 pc × 37.2 pc; centered at l = 28°:844; b = −0°:220) around the MIR bubble N49 site. In the following, we provide a brief description of the adopted multi-wavelength data.

2.1. Radio Centimeter Continuum Map

Radio continuum map at 20 cm was obtained from the VLA Multi-Array Galactic Plane Imaging Survey (MAGPIS; Helfand et al. 2006). The MAGPIS 20 cm map has a 6″ × 6″ beam size and a pixel scale of 2″/pixel.

2.2. $^{13}$CO ($J = 1–0$) Line Data

To examine the molecular gas associated with the selected target, the Galactic Ring Survey (GRS; Jackson et al. 2006) $^{13}$CO ($J = 1–0$) line data were adopted. The GRS line data have a velocity resolution of 0.21 km s$^{-1}$, an angular resolution of 45″ with 22″ sampling, a main beam efficiency ($\eta_{mb}$) of ~0.48, a velocity coverage of −5 to 135 km s$^{-1}$, and a typical rms sensitivity ($1\sigma$) of ~0.13 K (Jackson et al. 2006).

2.3. Far-infrared and Sub-millimeter Data

We examined the far-infrared (FIR) and sub-millimeter (mm) images downloaded from the Herschel Space Observatory (de Graauw et al. 2010; Griffin et al. 2010; Pilbratt et al. 2010; Poglitsch et al. 2010) data archives. Level2.5 processed 160–500 μm images were retrieved through the Herschel Interactive Processing Environment (HIPE; Ott 2010). The beam sizes of the Herschel images are 5″/8, 12″, 18″, 25″, and 37″ for 70, 160, 250, 350, and 500 μm, respectively (Griffin et al. 2010; Poglitsch et al. 2010). The plate scales of 70, 160, 250, 350, and 500 μm images are 3″/2, 3″/2, 6″, 10″, and 14″ pixel$^{-1}$, respectively. The Herschel images at 250–500 μm are calibrated in units of surface brightness, MJy sr$^{-1}$, while the units of images at 70–160 μm are Jy pixel$^{-1}$.

The sub-mm continuum map at 870 μm (beam size ~19″/2) was also retrieved from the APEX Telescope Large Area Survey of the Galaxy (ATLASGAL; Schuller et al. 2009).

2.4. Spitzer and Wide-field Infrared Survey Explorer (WISE) Data

The photometric images and magnitudes of point sources at 3.6–8.0 μm were downloaded from the Spitzer Galactic Legacy Infrared Mid-plane Survey Extraordinary (GLIMPSE; Benjamin et al. 2003) survey (resolution ~2″). In this work, we used the GLIMPSE-I Spring ’07 highly reliable photometric catalog.

We also utilized the WISE$^4$ (Wright et al. 2010) image at 12 μm (spatial resolution ~6″) and the Spitzer MIPS Inner Galactic Plane Survey (MIPSGAL; Carey et al. 2005) 24 μm image (spatial resolution ~6″). Furthermore, the photometric magnitudes of point sources at MIPSGAL 24 μm (from Gutermuth & Heyer 2015) were also collected.

\[^4\] WISE is a joint project of the University of California and the JPL, Caltech, funded by NASA.
3. Results

3.1. MIR Bubble N49 and Filamentary Features

In this section, we present multi-wavelength data to explore the physical environments over larger spatial scale around the bubble N49. Figure 1(a) shows a color-composite map obtained using the Herschel images (i.e., 250 µm (red), 160 µm (green), and 70 µm (blue)). The MIR bubble N49 is prominently seen in the composite map within a spatial area of 6.5 pc × 6.5 pc, and the Herschel images also reveal embedded filamentary features (i.e., fl-1, fl-2, and fl-3) in our selected field (see the arrows in Figure 1(a)). We also find that the bubble appears at the junction of filamentary features. However, one cannot confirm the physical association between the bubble and filamentary features without knowledge of velocities of molecular gas. In Figure 1(b), we present the observed $^{13}$CO ($J = 1–0$) profile in the direction of “zone I” (see the highlighted box in Figure 1(a)), which encompasses spatially some parts of the bubble and the filamentary features. The spectrum is obtained by averaging the “zone I” area, and reveals the presence of at least three velocity components (at peaks around 88, 95, and 100 km s$^{-1}$) along the line of sight. Based on the $^{13}$CO spectrum, in Figures 2(a) and (b), we present the overlay of the $^{13}$CO emissions on the Herschel 350 µm image. In Figure 2(a),
The $^{13}$CO gas is integrated over a velocity range of 83–91 km s$^{-1}$, and a majority of molecular gas are found toward the bubble and the filamentary feature “fl-1.” The distribution of molecular gases linked with two other molecular cloud components is presented in Figure 2(b). The molecular cloud linked with the filamentary feature “fl-2” is traced in a velocity range of 92–98.8 km s$^{-1}$, while the molecular cloud associated with the filamentary feature “fl-3” is depicted in a velocity range of 99–104 km s$^{-1}$.

Figure 2(c) displays the Herschel 350 µm image overlaid with the MAGPIS 20 cm emission. The ionized emission traced in the MAGPIS map is exclusively seen toward the bubble N49. In Figure 2(d), the ATLASGAL 870 µm continuum map is also superimposed with the 870 µm emission contour, indicating the presence of several condensations toward the filamentary features and the edges of the bubble. In Figures 2(c) and (d), despite the difference in spatial resolution, one can infer that the emission traced in the Herschel 350 µm is found to be more prominent compared to the emission detected in the 870 µm continuum map. It has also been reported that space-based Herschel observations could be considered as almost no loss of large-scale emission with respect to the ground-based APEX dust continuum observations (e.g., Liu et al. 2017). In our selected target field, based on the distribution of molecular gas, Figure 3 spatially delineates different elongated filamentary molecular clouds (lengths ~10–19 pc; average widths ~2 pc).

Figure 4 shows a zoomed-in view of the bubble N49 using multi-wavelength images (e.g., Spitzer 8–24 µm, WISE 12 µm, Herschel 70–500 µm, ATLASGAL 870 µm, GRS $^{13}$CO, and MAGPIS 20 cm). These images reveal a complete or closed ring morphology, containing the ionized emission in the bubble interior (e.g., Watson et al. 2008; Zavagno et al. 2010). As mentioned before, the N49 H ii region is powered by an O-type star (Watson et al. 2008; Deharveng et al. 2010; Dirienzo et al. 2012). Furthermore, a double shell-like structure is also observed in the 12–70 µm and 20 cm maps (e.g., Watson et al. 2008). The 6.7 GHz MME and the UCH ii region are seen at the edges of the bubble. The UCH ii region was reported to be ionized by a B0V star (e.g., Deharveng et al. 2010). In the panels “j” and “k,” one can also find the presence of two molecular cloud components in the direction of the bubble (e.g., Dirienzo et al. 2012). In Figure 5(a), we present a color-composite map produced using the MIR and FIR images (i.e., 70 µm (red), 24 µm (green), and 12 µm (blue)). The composite map is also overlaid with the MAGPIS 20 cm continuum emission, depicting the double shell-like structure. In the composite map, we have also highlighted the previously known UCH ii region and two embedded YSOs (i.e., YSO #1 and YSO #3; see Figure 1 in Zavagno et al. 2010). Interestingly, the position of the 6.7 GHz MME spatially coincides with the position of the YSO #3 that can be considered as an infrared counterpart (IRC) of the 6.7 GHz MME. No radio cm emission is detected toward the YSO #3. Considering the 6.7 GHz MME as a reliable tracer of a massive YSO (MYSO) (e.g., Walsh et al. 1998; Urquhart et al. 2013), the YSO #3 could be a MYSO candidate at its early formation stage prior to the UCH ii phase. Based on the high-resolution 6.7 GHz MME observations, Cyganowski et al. (2009) proposed the presence of a rotating disk associated with YSO #3.

Together, the bubble N49 is a very promising site, where different early evolutionary stages of massive star formation are present.

### 3.2 Kinematics of Molecular Gas

In this section, we present a kinematic analysis of the molecular gas in our selected field. In Figure 5(b), we show the observed $^{13}$CO ($J = 1–0$) spectrum in the direction of Reg 1 (see the solid box in Figure 5(a)). The spectrum is computed by averaging the area Reg 1 marked in Figure 5(a). In the spectrum, an almost flattened profile is observed between two velocity peaks (or molecular cloud components), which can be referred to as a bridge feature at the intermediate velocity range. This particular outcome indicates a signature of collisions between molecular clouds (Takahira et al. 2014; Haworth et al. 2015a, 2015b; Bisbas et al. 2017; Torii et al. 2017). In other words, it also suggests a mutual interaction of clouds (e.g., Bisbas et al. 2017).

In Figure 6, we display the integrated GRS $^{13}$CO ($J = 1–0$) velocity channel maps (starting from 81 km s$^{-1}$ at intervals of 1 km s$^{-1}$), tracing three molecular components along the line of sight (also see Figure 3). To further examine the molecular gas distribution in the direction of our selected target field, in Figure 7, we show the integrated $^{13}$CO intensity map and the position–velocity maps. The integrated GRS $^{13}$CO intensity map is shown in Figure 7(a), where the molecular emission is integrated over 83–104 km s$^{-1}$. The Galactic position–velocity diagrams of the $^{13}$CO emission also reveal three velocity...
components and the noticeable velocity spread (see Figures 7(b) and (d)). In the velocity space, we find a redshifted peak (at $\sim$95 km s$^{-1}$) and a blueshifted peak (at $\sim$88 km s$^{-1}$) that are interconnected by a lower-intensity intermediate velocity emission, suggesting the presence of a broad bridge feature (also see Figure 5(b)). Figure 7(c) shows the spatial distribution of three molecular components, similar to those shown in Figures 2(a) and (b).

Figure 4. Multi-wavelength view of the bubble N49. The images are shown at different wavelengths, which are highlighted in the panels. In panels j) and k) the $^{13}$CO emissions are superimposed on the Herschel 250 $\mu$m image. The $^{13}$CO integrated velocity ranges are also shown in these panels. In panel j), the $^{13}$CO contours are 40.847 K km s$^{-1}$ × (0.35, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.98). In panel k), the $^{13}$CO contours are 38.357 K km s$^{-1}$ × (0.6, 0.7, 0.8, 0.9, 0.98). In panel l), the MAGPIS 20 cm emission is superimposed on the Spitzer 24 $\mu$m image. The MAGPIS contours (in red) are shown with levels of 0.0018, 0.0035, 0.0045, and 0.005 Jy beam$^{-1}$. In each panel, a position of the Class II 6.7 GHz methanol maser is shown by a star.
3.3. Herschel Temperature and Column Density Maps

In this section, we present Herschel temperature and column density maps of the bubble N49. Following the methods described in Mallick et al. (2015), these maps are produced from a pixel-by-pixel spectral energy distribution (SED) fit with a modified blackbody to the cold dust emission at Herschel 160–500 μm (also see Dewangan et al. 2015). In the following, a brief step-by-step explanation of the adopted procedures is provided.

Before the SED fitting process, using the task “Convert Image Unit” available in the HIPE software, we converted the surface brightness unit of 250–500 μm images to Jy pixel$^{-1}$, same as the unit of 160 μm image. Next, using the plug-in “Photometric Convolution” available in the HIPE software, the 160–350 μm images were convolved to the angular resolution of the 500 μm image (≃37″), and then regrided on a 14″ raster. We then computed a background flux level. The sky background flux level was estimated to be 0.255, 0.708, 1.395, and −0.234 Jy pixel$^{-1}$ for the 500, 350, 250, and 160 μm images (size of the selected featureless dark region 10′/2 × 9′/8; centered at: l = 27°7′35″; b = −0°681″), respectively. The negative flux value at 160 μm is found due to the arbitrary scaling of the Herschel 160 μm image.

Finally, to obtain the temperature and column density maps, a modified blackbody was fitted to the observed fluxes on a pixel-by-pixel basis (see Equations (8) and (9) in Mallick et al. 2015). The fitting was performed using the four data points for each pixel, maintaining the column density (N(H$_2$)) and the dust temperature (T$_d$) as free parameters. In the calculations, we adopted a mean molecular weight per hydrogen molecule ($\mu_{m}$) of 2.8 (Kauffmann et al. 2008) and an absorption coefficient ($\kappa_{\nu}$) of 0.1 (ν/1000 GHz)$^3$ cm$^{-2}$ g$^{-1}$, including a gas-to-dust ratio ($R$) of 100, with a dust spectral index (β) of 2 (see Hildebrand 1983). The temperature and column density maps are shown in Figures 8(a) and (b), respectively.

The Herschel temperature map traces the filamentary features in a temperature range of about 16–20 K, while the N49 H II region is seen with considerably warmer gas (T$_d$ ~ 21–24 K). The filamentary features and the edges of the bubble N49 are traced in the column density map, where several condensations are observed (see Figure 8(b)). One can also compute extinction (A$_V$ = 1.07 × 10$^{-31}$ N(H$_2$); Bohlin et al. 1978) using the Herschel column density map, which can also be used to identify clumps. In the Herschel column density map, the “clumpfind” (Williams et al. 1994) IDL program helps us to find clumps and to estimate their total column densities. Thirty-five clumps are found in our selected target field, and are highlighted in Figures 9(a), (b), and (c). Several column density contour levels were used as an input parameter for the “clumpfind,” and the lowest contour level was considered at 3.5σ. Furthermore, the boundary of each clump is also shown in Figure 9(a). The knowledge of the total column density of each clump also enables to determine the mass of each Herschel clump using the following equation:

$$M_{\text{clump}} = \mu_{H_2} m_{H_2} A_{\text{pix}} \Sigma N(H_2),$$

(1)

where $\mu_{H_2}$ is assumed to be 2.8, $A_{\text{pix}}$ is the area subtended by one pixel, and $\Sigma N(H_2)$ is the total column density. The mass and the effective radius of each Herschel clump are listed in Table 1. The clump masses vary between 1076 $M_\odot$ and 20970 $M_\odot$. Three
Figure 6. $^{13}$CO$(J = 1-0)$ velocity channel contour maps. The molecular emission is integrated over a velocity interval, which is given in each panel (in km s$^{-1}$). The contour levels are 10%, 20%, 30%, 40%, 55%, 70%, 80%, 90%, and 99% of the peak value (in K km s$^{-1}$), which is also given in each panel. In each panel, a contour at 20 cm (in red) represents the location of the bubble N49, and the contour level is 0.0024 Jy beam$^{-1}$. 

| Channel | Contour |
|---------|---------|
| 5.642 K km s$^{-1}$ | N49 |
| 5.679 K km s$^{-1}$ | N49 |
| 3.644 K km s$^{-1}$ | N49 |
| 3.793 K km s$^{-1}$ | N49 |
| 61, 82 km s$^{-1}$ | N49 |
| 83, 84 km s$^{-1}$ | N49 |
| 9.554 K km s$^{-1}$ | N49 |
| 85, 86 km s$^{-1}$ | N49 |
| 11.244 K km s$^{-1}$ | N49 |
| 86, 87 km s$^{-1}$ | N49 |
| 10.857 K km s$^{-1}$ | N49 |
| 88, 89 km s$^{-1}$ | N49 |
| 12.284 K km s$^{-1}$ | N49 |
| 7.992 K km s$^{-1}$ | N49 |
| 4.123 K km s$^{-1}$ | N49 |
| 5.966 K km s$^{-1}$ | N49 |
| 5.856 K km s$^{-1}$ | N49 |
| 89, 90 km s$^{-1}$ | N49 |
| 90, 91 km s$^{-1}$ | N49 |
| 91, 92 km s$^{-1}$ | N49 |
| 92, 93 km s$^{-1}$ | N49 |
| 8.390 K km s$^{-1}$ | N49 |
| 8.660 K km s$^{-1}$ | N49 |
| 11.190 K km s$^{-1}$ | N49 |
| 11.380 K km s$^{-1}$ | N49 |
| 93, 94 km s$^{-1}$ | N49 |
| 94, 95 km s$^{-1}$ | N49 |
| 95, 96 km s$^{-1}$ | N49 |
| 96, 97 km s$^{-1}$ | N49 |
| 6.197 K km s$^{-1}$ | N49 |
| 5.911 K km s$^{-1}$ | N49 |
| 5.748 K km s$^{-1}$ | N49 |
| 5.462 K km s$^{-1}$ | N49 |
| 97, 98 km s$^{-1}$ | N49 |
| 98, 99 km s$^{-1}$ | N49 |
| 99, 100 km s$^{-1}$ | N49 |
| 100, 101 km s$^{-1}$ | N49 |
| 7.078 K km s$^{-1}$ | N49 |
| 5.152 K km s$^{-1}$ | N49 |
| 4.816 K km s$^{-1}$ | N49 |
| 3.097 K km s$^{-1}$ | N49 |
| 101, 102 km s$^{-1}$ | N49 |
| 102, 103 km s$^{-1}$ | N49 |
| 103, 104 km s$^{-1}$ | N49 |
| 104, 105 km s$^{-1}$ | N49 |
massive clumps (nos. 12, 13, and 14) are also seen in the intersection zone of two molecular clouds (see Figures 9(a) and (b)). Furthermore, the clumps (nos. 7, 8, 9, 10, and 11). These Herschel clump sizes are larger than the ones used by Deharveng et al. (2010). are found toward the filamentary feature, “fl-1,” while the filamentary feature, “fl-2” contains clumps (nos. 15, 16, and 17). The clumps (nos. 1, 4, 5, and 6) are also identified toward the filamentary feature, “fl-3.”

Previously, using the APEX 870 μm dust continuum data, Deharveng et al. (2010) computed the masses of four clumps varying between 190 and 2300 $M_\odot$, which are distributed toward the infrared rim of the bubble. In this paper, we identify two clumps (nos. 12 and 13; $M_{\text{clump}} \sim 8480–11538 M_\odot$) around the bubble in the Herschel column density map (see Figure 9(c)), and the masses of these clumps are much higher than the ones reported by Deharveng et al. (2010) (i.e., $M_{\text{Herschel}} > M_{\text{APEX}}$). More recently, Liu et al. (2017) studied a star-forming region RCW 79 using the Herschel data and also compared the masses of clumps derived using the Herschel data and the APEX 870 μm continuum map. They also found $M_{\text{Herschel}} > M_{\text{APEX}}$, and suggested that there are mass losses in ground-based observations due to the drawback in the data reduction (see Liu et al. 2017 for more details).

3.4. Young Stellar Populations

In this section, we identify embedded YSOs using the Spitzer photometric data at 3.6–24 μm. A brief description of the selection of YSOs is as follows.

1. A color–magnitude plot ([3.6]–[24]/[3.6]) has been utilized to separate the different stages of YSOs (Guieu et al. 2010;
Rebull et al. 2011; Dewangan et al. 2015). The plot also enables to distinguish the boundary of possible contaminants (i.e., galaxies and disk-less stars) against YSOs (see Figure 10 in Rebull et al. 2011). The color–magnitude plot of sources having detections in the 3.6 and 24 μm bands is shown in Figure 10(a). Adopting the conditions given in Guieu et al. (2010) and Rebull et al. (2011), the boundaries of different stages of YSOs and possible contaminants are highlighted in Figure 10(a). In Figure 10(a), we have plotted a total of 329 sources in the color–magnitude plot. We find 74 YSOs (15 Class I; 18 Flat-spectrum; 41 Class II) and 255 Class III sources. One can also infer from Figure 10(a) that the selected YSOs are free from the contaminants. In Figure 10(a), the Class I, Flat-spectrum, and Class II YSOs are represented by red circles, red diamonds, and blue triangles, respectively.

2. Based on the Spitzer 3.6–8.0 μm photometric data, Gutermuth et al. (2009) proposed different schemes to identify YSOs and also various possible contaminants (e.g., broadline active galactic nuclei (AGNs), PAH-emitting galaxies, shocked emission blobs/knots, and PAH-emission-contaminated apertures). One can also classify these selected YSOs into different evolutionary stages based on their slopes of the SED (\(\alpha_{3.6-8.0}\)) estimated from 3.6 to 8.0 μm (i.e., Class I (\(\alpha_{3.6-8.0} < -0.3\)), Class II (\(-0.3 > \alpha_{3.6-8.0} > -1.6\)), and Class III (\(-1.6 > \alpha_{3.6-8.0} > -2.56\)) (e.g., Lada et al. 2006; Dewangan & Anandarao 2011). Following the schemes and conditions listed in Gutermuth et al. (2009) and Lada et al. (2006), we have also identified YSOs and various possible contaminants in our selected target field. The color–color plot (\([3.6]-[4.5]\) versus \([5.8]-[8.0]\)) is presented in Figure 10(b). We select 38 YSOs (8 Class I; 30 Class II), and 1 Class III, which are plotted in Figure 10(b). In Figure 10(b), Class I and Class II YSOs are represented by red circles and blue triangles, respectively.

3. Based on the Spitzer 3.6, 4.5 and 5.8 μm photometric data, Hartmann et al. (2005) and Getman et al. (2007) utilized a color–color plot ([4.5]–[5.8] versus [3.6]–[4.5]) to select embedded YSOs. They proposed color conditions, [4.5]–[5.8] ≥ 0.7 and [3.6]–[4.5] ≥ 0.7, to find protostars. The color–color plot ([4.5]–[5.8] versus [3.6]–[4.5]) is presented in Figure 10(c). This scheme yields 8 protostars in our selected region.

Taken together, we have obtained a total of 120 YSOs in our selected target field. To examine the spatial distribution of these selected YSOs, in Figure 11(a), these YSOs are shown on the Herschel column density map. We find noticeable YSOs toward the filamentary features and the edges of the bubble N49. It shows signs of an ongoing star formation in the clumps linked with the filamentary features (see clump nos. 6–17 in Figure 11(a)). Previously, using the Spitzer photometric data, Dirienzo et al. (2012) carried out the SED fitting of sources in the bubble N49 site to identify YSOs. The previous results concerning the selection of YSOs are in a good agreement with our presented results. Hence, we have taken the physical parameters (e.g., stellar mass (\(M_{\ast}\)) and stellar luminosity (\(L_{\ast}\))) of some selected YSOs from Dirienzo et al. (2012), which are listed in Table 2. One can find more details about the SED fitting procedures of YSOs in Dirienzo et al. (2012). In Table 2, we have listed the physical parameters of the selected thirteen YSOs, and their positions are marked in Figure 11(b). In the direction of filamentary feature fl-1, at least three YSOs (i.e., s1, s2, and s3; \(M_{\ast} \sim 3.5–5.0\) \(M_{\odot}\)) appear to be found toward the Herschel clumps (nos. 7, 8, and 9; \(M_{\text{clump}} \sim 3760–5570\) \(M_{\odot}\)) at least three YSOs (i.e., s11, s12, and s13; \(M_{\ast} \sim 0.1–1.6\) \(M_{\odot}\)) are embedded within the Herschel clumps (nos. 14 and 15; \(M_{\text{clump}} \sim 5480–5800\) \(M_{\odot}\)) in the direction of filamentary feature fl-2, while the filamentary feature fl-3 harboring the Herschel clumps (nos. 4 and 6; \(M_{\text{clump}} \sim 1400–3160\) \(M_{\odot}\)) contains at least two YSOs (i.e., s5 and s7;
Furthermore, at least five YSOs (i.e., s4, s6, s8, s9, and s10; $M_\star \sim 1.6$–6.2 $M_\odot$) are found toward the edges of the bubble N49, where two Herschel clumps (nos. 12 and 13; $M_{\text{clump}} \sim 8480$–11540 $M_\odot$) are traced. Furthermore, the Herschel clump 12 also contains a MYSO candidate (i.e., an IRc of the 6.7 GHz MME without any ionized emission) at its early formation stage prior to the UCH II phase (see Section 3.1).

Together, low- and intermediate-mass stars are seen toward the filamentary features, and various early evolutionary stages of massive star formation (O-type star, UCH II region, and an IRc of the 6.7 GHz MME without any ionized emission) are also investigated in the bubble site.

4. Discussion

Previously, the bubble N49 has been extensively studied to assess the star formation process triggered by the expansion of an H II region (see Dirienzo et al. 2012, and references therein). However, the present work provides new insights into the physical processes in the MIR bubble N49 site. A careful...
The Astrophysical Journal, 851:140 (14pp), 2017 December 20

Dewangan, Ojha, & Zinchenko

Table 1

| ID | \(l\) (degree) | \(b\) (degree) | \(R_{\text{clump}}\) (pc) | \(M_{\text{clump}}\) (M\(_{\odot}\)) |
|----|--------------|---------------|----------------|----------------|
| 1  | 28.842       | -0.415        | 1.0             | 1076           |
| 2  | 28.897       | -0.411        | 1.4             | 1821           |
| 3  | 28.877       | -0.392        | 1.4             | 1954           |
| 4  | 28.834       | -0.368        | 1.2             | 1397           |
| 5  | 28.830       | -0.337        | 1.3             | 1836           |
| 6  | 28.830       | -0.318        | 1.7             | 3161           |
| 7  | 28.683       | -0.283        | 1.8             | 5317           |
| 8  | 28.710       | -0.298        | 1.6             | 3761           |
| 9  | 28.725       | -0.302        | 2.0             | 5569           |
| 10 | 28.768       | -0.294        | 1.5             | 2638           |
| 11 | 28.780       | -0.267        | 2.4             | 6177           |
| 12 | 28.830       | -0.255        | 2.7             | 11538          |
| 13 | 28.838       | -0.213        | 2.5             | 8480           |
| 14 | 28.877       | -0.228        | 2.4             | 5800           |
| 15 | 28.924       | -0.232        | 2.1             | 5483           |
| 16 | 28.959       | -0.209        | 1.2             | 1599           |
| 17 | 29.017       | -0.182        | 1.6             | 2876           |
| 18 | 29.052       | -0.139        | 1.0             | 948            |
| 19 | 28.729       | -0.244        | 2.7             | 9451           |
| 20 | 28.687       | -0.232        | 2.1             | 5114           |
| 21 | 28.675       | -0.178        | 2.1             | 4741           |
| 22 | 28.722       | -0.185        | 2.8             | 9734           |
| 23 | 28.768       | -0.189        | 2.7             | 8807           |
| 24 | 28.780       | -0.154        | 2.9             | 10093          |
| 25 | 28.830       | -0.182        | 2.6             | 7418           |
| 26 | 28.873       | -0.150        | 2.7             | 7671           |
| 27 | 28.893       | -0.143        | 1.5             | 2464           |
| 28 | 28.893       | -0.119        | 2.3             | 5761           |
| 29 | 28.889       | -0.088        | 3.4             | 13112          |
| 30 | 28.963       | -0.053        | 4.2             | 20970          |
| 31 | 28.881       | -0.026        | 3.2             | 12381          |
| 32 | 28.803       | -0.026        | 3.3             | 12885          |
| 33 | 28.702       | -0.065        | 2.2             | 5134           |
| 34 | 28.690       | -0.100        | 2.5             | 6592           |
| 35 | 28.764       | -0.104        | 3.5             | 12804          |

Note. Column 1 gives the IDs assigned to the clump. The table also lists galactic coordinates (\(l\), \(b\)), deconvolved effective radius (\(R_{\text{clump}}\)), and clump mass (\(M_{\text{clump}}\)). The clumps (nos. 12, 13, and 14) are highlighted by daggers, and are found in the intersection zone of two filamentary molecular clouds (see Figure 9(b)).

The Astrophysical Journal, 851:140 (14pp), 2017 December 20

Dewangan, Ojha, & Zinchenko

5. Summary and Conclusions

In this paper, to study the physical environment and star formation processes, we carried out an observational study of the bubble N49 site using multi-wavelength data. The major results of the present work are the following.

1. *Herschel* images reveal the bubble N49 and three filamentary features (“fl-1,” “fl-2,” and “fl-3”) in our selected target field. In the *Herschel* temperature map, the filamentary features are seen in a temperature range of about 16–20 K, while the considerably warmer gas (\(T_d \sim 21–24\) K) is found toward the N49 HII region. The filamentary features and the edges of the bubble N49 are traced in the column density map, where several condensations are investigated.

2. Using the \(^13\)CO line data, a majority of molecular gas, integrated over a velocity range of 83–91 km s\(^{-1}\), is distributed toward the bubble and the filamentary

The Astrophysical Journal, 851:140 (14pp), 2017 December 20

Dewangan, Ojha, & Zinchenko

5. Summary and Conclusions

In this paper, to study the physical environment and star formation processes, we carried out an observational study of the bubble N49 site using multi-wavelength data. The major results of the present work are the following.

1. *Herschel* images reveal the bubble N49 and three filamentary features (“fl-1,” “fl-2,” and “fl-3”) in our selected target field. In the *Herschel* temperature map, the filamentary features are seen in a temperature range of about 16–20 K, while the considerably warmer gas (\(T_d \sim 21–24\) K) is found toward the N49 HII region. The filamentary features and the edges of the bubble N49 are traced in the column density map, where several condensations are investigated.

2. Using the \(^13\)CO line data, a majority of molecular gas, integrated over a velocity range of 83–91 km s\(^{-1}\), is distributed toward the bubble and the filamentary
feature “fl-1.” The molecular cloud linked with the filamentary feature “fl-2” is traced in a velocity range of 92–98.8 km s\(^{-1}\), while the molecular cloud associated with the filamentary feature “fl-3” is depicted in a velocity range of 99–104 km s\(^{-1}\).

3. The \(^{13}\)CO line data analysis indicates the presence of two velocity cloud components (having velocity peaks at \(\sim 88\) and \(\sim 95\) km s\(^{-1}\)) in the direction of the bubble, which are separated by \(\sim 7\) km s\(^{-1}\) in the velocity space and are interconnected by a broad bridge feature.

4. In the velocity channel maps of \(^{13}\)CO, a possible complementary molecular pair at [87, 88] km s\(^{-1}\) and [95, 96] km s\(^{-1}\) is also traced.

5. The bubble N49 is found in the spatially overlapped zone of two filamentary molecular clouds.

6. The photometric analysis of point-like sources reveals noticeable YSOs toward the filamentary features including the intersection zone of two molecular clouds. Different early evolutionary stages of massive star formation (O-type star, UCH II region, and an IRc of

Figure 10. Selection of YSOs in our selected field around the MIR bubble N49 (see Figure 1(a)). (a) Color–magnitude plot ([3.6]–[24] vs. [3.6]) of sources. The plot enables to identify YSOs belonging to different evolutionary stages (see dashed lines). The boundary of YSOs against contaminated candidates (galaxies and disk-less stars) is shown by dotted–dashed lines (in red) (see Rebull et al. (2011) for more details). Flat-spectrum and Class III sources are represented by “o” and “★” symbols, respectively. (b) Color–color plot ([3.6]–[4.5] vs. [5.8]–[8.0]) of sources. The PAH-emitting galaxies and the PAH-emission-contaminated apertures are marked by “●” and “×” symbols, respectively (see the text). A Class III source is represented by a black square in the plot. (c) Color–color plot ([3.6]–[4.5] vs. [4.5]–[5.8]) of sources. In panels a), b), and c), we show Class I (circles) and Class II (open triangles) YSOs. In the first three panels, an extinction vector is shown and is obtained using the average extinction laws from Flaherty et al. (2007). In panels b) and c), the dot symbols show the stars with only photospheric emissions. Due to large numbers of stars with photospheric emissions, only some of these stars are randomly marked in panels b) and c).
the 6.7 GHz MME (without any ionized emission) are also present in the bubble site.

7. A typical collision timescale in the bubble site is computed to be $\sim 0.7$ Myr.

### Table 2

| ID    | YSO designation (lb) | $\chi^2_{\text{best}$/\chi_{\text{data}}}$ | $M_\star$ ($M_\odot$) | $L_\star$ ($L_\odot$) |
|-------|----------------------|---------------------------------------------|------------------------|------------------------|
| s1** | 028.6788-00.2786     | 0.05                                        | 3.8 $\pm$ 1.1          | 10$^{2.3}$ $\pm$ 2.6   |
| s2** | 028.6879-00.2739     | 0.31                                        | 3.6 $\pm$ 1.3          | 10$^{2.0}$ $\pm$ 1.1   |
| s3** | 028.6962-00.2913     | 0.47                                        | 5.0 $\pm$ 1.6          | 10$^{2.9}$ $\pm$ 1.1   |
| s4** | 028.8299-00.2532     | 0.39                                        | 6.2 $\pm$ 2.0          | 10$^{3.1}$ $\pm$ 1.2   |
| s5** | 028.8315-00.3123     | 0.49                                        | 2.4 $\pm$ 1.5          | 10$^{2.0}$ $\pm$ 1.2   |
| s6** | 028.8352-00.2354     | 0.04                                        | 4.1 $\pm$ 1.4          | 10$^{2.5}$ $\pm$ 1.2   |
| s7** | 028.8365-00.3594     | 0.17                                        | 4.0 $\pm$ 1.3          | 10$^{2.5}$ $\pm$ 1.2   |
| s8** | 028.8382-00.2051     | 0.15                                        | 3.5 $\pm$ 1.0          | 10$^{2.2}$ $\pm$ 1.2   |
| s9** | 028.8547-00.2192     | 1.80                                        | 2.8 $\pm$ 1.8          | 10$^{2.1}$ $\pm$ 1.2   |
| s10**| 028.8573-00.2184     | 0.54                                        | 1.6 $\pm$ 1.3          | 10$^{1.8}$ $\pm$ 1.2   |
| s11**| 028.9145-00.2258     | 1.60                                        | 3.1 $\pm$ 0.8          | 10$^{2.0}$ $\pm$ 1.2   |
| s12**| 028.9191-00.2304     | 0.10                                        | 1.1 $\pm$ 1.0          | 10$^{2.0}$ $\pm$ 1.2   |
| s13**| 028.9198-00.2283     | 1.39                                        | 5.0 $\pm$ 1.7          | 10$^{2.9}$ $\pm$ 1.1   |

**Note.** Column 1 gives the IDs assigned to the YSO. Table also lists YSO designation, $\chi^2_{\text{best}}$/\chi_{\text{data}}, stellar mass ($M_\star$), and stellar luminosity ($L_\star$) (see Diriendo et al. (2012) for more details). The YSOs distributed toward the edges of the bubble, filaments fl-1, fl-2, and fl-3 are highlighted with labels “bub,” fl1, fl2, and fl3, respectively (see Figure 11(b)).

Considering the observational outcomes presented in this paper, the bubble N49 is an promising site to explore the formation of massive star(s). We conclude that in the bubble site, the collision of the filamentary molecular clouds may have influenced the formation of massive stars and embedded protostars about 0.7 Myr ago.

We thank the anonymous reviewer for several useful comments. The research work at Physical Research Laboratory is funded by the Department of Space, Government of India. The Infrared Processing and Analysis Center/California Institute of Technology (funded by NASA and NSF), archival data obtained with the *Spitzer Space Telescope* (operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA). This publication makes use of molecular line data from the Boston University-FCRAO Galactic Ring Survey (GRS). The GRS is a joint project of Boston University and Five College Radio Astronomy Observatory, funded by the National Science Foundation (NSF) under grants AST-9800334, AST-0098562, and AST-0100793. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. I.Z. is supported by the Russian Foundation for Basic Research (RFBR) No. 17-52-45020 and by the IAP RAS state program 0035-2014-0030.

**ORCID iDs**

L. K. Dewangan https://orcid.org/0000-0001-6725-0483
D. K. Ojha https://orcid.org/0000-0001-9312-3816
I. Zinchenko https://orcid.org/0000-0003-2793-8229

**References**

Anathpindika, S. V. 2010, MNRAS, 405, 1431
Anderson, L. D., & Bania, T. M. 2009, ApJ, 690, 706
Benjamin, R. A., Churchwell, E., Babler, B. L., et al. 2003, PASP, 115, 953
Bisbas, T. G., Tanaka, K. E. I., Tan, J. C., Wu, B., & Nakamura, F. 2017, ApJ, 850, 23
