Star Formation in the Infrared Dust Bubble N109: Postprint

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Abstract

Infrared dust bubbles associated with HII regions serve as ideal astrophysical laboratories for investigating star formation, particularly triggered star formation. Employing multi-wavelength data, we have conducted a study of N109, one of the largest dust bubbles in the Milky Way, analyzing its impact on the surrounding medium and the star formation activity therein. Our research reveals the presence of 56 dense clumps around N109, predominantly distributed in the northern and western regions. All of these clumps are potential star-forming sites, with five likely to form massive stars and the remainder likely to form low-mass stars. Additionally, five compact HII regions are found in these two areas, signifying the formation of a new generation of massive stars. Moreover, observational evidence indicates that the expansion of the HII region associated with N109 is compressing the interstellar medium in the north and west. These findings collectively suggest that the infrared dust bubble N109 is influencing its surrounding medium through HII region expansion, re-accumulating material via compression, and thereby providing venues for new-generation star formation, which may offer a necessary condition for triggered star formation.

Full Text

Preamble

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Star Formation in the Infrared Dust Bubble N109

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Abstract

Infrared dust bubbles associated with H II regions are ideal astrophysical laboratories for studying star formation, particularly triggered star formation. Using multi-wavelength data, we have investigated one of the largest dust bubbles in the Milky Way, N109, analyzing its impact on the surrounding medium and star formation activity within it. We find 56 dense clumps around N109, predominantly distributed in the north and west. All of these clumps are likely to form stars, with five likely to form massive stars and the remainder likely to form low-mass stars. Five compact H II regions are also present in these two areas, indicating a new generation of massive star formation. Additionally, we observe signatures of the associated H II region' s expansion compressing the interstellar medium in the north and west. These results collectively demonstrate that the infrared dust bubble N109 is acting on its surroundings through H II region expansion, re-collecting material via compression to provide sites for a new generation of star formation. This may provide a necessary condition for triggered star formation.

Keywords: massive star formation; interstellar medium; H II regions; molecular clouds; infrared dust bubbles
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1 Introduction

Massive stars (M > 8 M) are typically born in clusters within dense molecular clouds. During their early formation and evolution, massive stars produce violent feedback in their parental molecular clouds, including outflows, stellar winds, expanding H II regions, and supernova explosions. On one hand, this feedback can accelerate surrounding dense molecular clouds to escape velocity, dissipating them into diffuse gas and thereby inhibiting new star formation. On the other hand, such feedback can compress the surrounding interstellar medium, causing it to become gravitationally unstable molecular clouds again, which then collapse to trigger a new generation of star formation—a process known as triggered star formation.

Over the past few decades, numerous studies on triggered star formation, particularly that associated with H II regions, have been conducted both theoretically and observationally [1-14]. Theoretically, two main models remain widely discussed: the collect-and-collapse model [1] and the radiation-driven implosion model [2, 3]. Briefly, the collect-and-collapse model describes a process where material around an H II region is re-collected at the ionization front and shock front, forming a molecular cloud with a shell (or ring) structure that eventually collapses due to gravitational instability to form a new generation of stars. This model can satisfactorily explain observed star formation activities around morphologically regular H II regions, such as Sh 104 [15], RCW 79 [16], RCW 120 [6], and N4 [17]. The radiation-driven implosion model refers to a process where a shock front driven by an ionization front triggers the implosion of a pre-existing, sub-critical molecular cloud clump, causing it to collapse and form a new generation of stars. Compared to collect-and-collapse, the radiation-driven implosion model lacks a material re-collection process. Observationally, possible signatures of radiation-driven implosion have been found in some bright-rim cloud star formation activities [18, 19].

Observationally, H II regions have been confirmed to be widespread throughout the Milky Way. Thanks to two survey projects by the Spitzer mid-infrared space telescope—GLIMPSE and MIPSGAL [20, 21]—a new class of objects has been discovered to be widely present in the Galaxy: infrared dust bubbles. Their main observational characteristic is a bright ring-like structure in mid-infrared dust continuum images. Using this feature, Churchwell et al. [22] identified and first cataloged a sample of about 600 bubbles. Based on the same survey data, a larger sample catalog containing over 5,000 infrared dust bubbles was identified by citizen scientists recruited online and compiled by Simpson et al. [23]. In fact, Deharveng et al. [24] used 20 cm data from MAGPIS [25] (The Multi-Array Galactic Plane Imaging Survey), which can trace H II regions, to conduct a detailed study of 102 selected infrared dust bubbles, finding that about 86% of infrared dust bubbles are associated with H II regions driven by OB-type stars. This indicates a close connection between infrared dust bubbles and H II regions.

Statistically, triggered star formation caused by the expansion of H II regions in the Milky Way is an important physical process, particularly for massive star formation. For example, Thompson et al. [26] searched for associations between massive young stellar objects (MYSOs) and 322 infrared dust bubbles from the Churchwell catalog, finding that about 14%–30% of massive star formation in the Milky Way may have been triggered by H II region or infrared dust bubble expansion. Subsequently, Kendrew et al. [10] used a similar method with a larger sample (1,018 infrared dust bubbles from the Simpson catalog) and found that about 22% ± 2% of MYSO formation may be related to triggered star formation. These statistical results consistently indicate that about 14%–30% of MYSO formation in the Milky Way may have experienced triggered star formation processes.

From these large-sample studies of infrared dust bubbles, we recognize that triggered star formation may be an important star formation mechanism in the Milky Way. Furthermore, independent and detailed studies of individual infrared dust bubble samples are also crucial for revealing how H II regions interact with their surrounding medium and the triggered star formation process. Previous studies have typically been limited to physically small infrared dust bubbles with scales less than 20 pc, such as S51 [27] (1.47 pc), N4 [17] (1.9 pc), N6 [28] (11 pc), N131 [29] (14 pc), and N68 [30] (25.5 pc). However, larger-scale infrared dust bubbles have longer evolutionary timescales, which helps us study how bubbles affect interstellar medium evolution and new generation star formation activities [31]. Therefore, this paper presents a systematic multi-wavelength study of N109, one of the largest bubbles in the Churchwell catalog. N109 is located at Galactic longitude 51.892° and latitude 0.562°. It is actually associated with a large-scale H II region G52L [32]. Assuming a line-of-sight velocity of v_{LSR} = 4.2 km s^{-1} (see Section 3) and using an online kinematic distance calculator, we determine that N109 is at a distance of (9.63 ± 0.38) kpc from the Sun. N109 has an equivalent geometric angular radius of 14.8 , corresponding to a physical scale of 41.5 pc.

This paper aims to use multi-wavelength data to study N109' s impact on the surrounding medium and star formation activity. Section 2 introduces the data sources used in this study; Section 3 describes in detail the identification process of dense clumps and YSOs; Section 4 discusses the properties of dense clumps and star formation activity; and Section 5 summarizes the entire paper.

2 Observational Data

To systematically study N109 using multi-wavelength physical information, we employ Spitzer-GLIMPSE and MIPS-GAL mid-infrared images, Herschel Hi-GAL [33] far-infrared images, GRS [34] ^{13}CO(J=1-0) millimeter molecular line, and VGPS [35] 21 cm continuum survey data, which are described in detail below.

GLIMPSE is a survey of the entire Galactic plane using the IRAC (Infrared Array Camera) instrument on the Spitzer Space Telescope at four bands: 3.6, 4.5, 5.8, and 8.0 m. MIPSGAL is an inner Galactic plane survey (Galactic longitude $|l| \leq 65°$, latitude $|b| \leq 1°$) using the MIPS (Multiband Imaging Photometer for Spitzer) instrument on the same telescope at 24 m and 70 m. The GLIMPSE four-band data have the same angular resolution of about 2 ; the MIPSGAL two-band data have angular resolutions of 6 and 18 , respectively.

GRS is the Galactic Ring Survey of the ^{13}CO(J=1-0) molecular line conducted with the 13.7 m millimeter-wave telescope at the Five College Radio Astronomy Observatory. The survey covers $18° \leq l \leq 55.7°$, $|b| \leq 1°$, with a total observed area of 75.4 square degrees. For $l \leq 40°$, the velocity distribution range of ^{13}CO(J=1-0) is -5 to 135 km s^{-1}, while for other regions it is -5 to 85 km s^{-1}. The entire survey has a velocity resolution of 0.21 km s^{-1}, with a typical noise of 0.13 K per velocity channel.

Hi-GAL is a Herschel Space Telescope survey mapping the entire Galactic plane at five far-infrared bands. The project uses PACS [36] (Photodetector Array Camera and Spectrometer) at 70 and 160 m and SPIRE [37] (Spectral and

Photometric Imaging Receiver) at 250, 350, and 500 m in parallel photometry mode with a scan speed of 60 s^{-1} [38]. The final measured angular resolutions at the five wavelengths are 8.4 , 13.5 , 18.2 , 24.9 , and 36.3 [39], corresponding to physical sizes of 0.4, 0.6, 0.8, 1.2, and 1.7 pc at the distance of N109. This paper uses both Hi-GAL images and its source catalog. The Hi-GAL team used the CuTEx algorithm to identify compact sources in the five-band images and compiled corresponding catalogs. This algorithm optimizes the identification of compact sources against the complex infrared background of the Galactic plane. The catalogs contain information on source positions, peak fluxes, integrated fluxes, and sizes [40].

VGPS is a VLA survey dedicated to HI line and 21 cm continuum observations, covering $18^\circ \leq l \leq 67^\circ$ and $|b| \leq 1.3^\circ$ with an angular resolution of about 1 . In this work, we only use the 21 cm continuum data to reveal the interaction between the H II region and the surrounding medium.

3 Results and Analysis

A three-color composite image of N109 is shown in Figure 1 [Figure 1: see original paper], where red, green, and blue represent 21 cm, 24 m, and 8 m continuum emission, respectively. The 21 cm continuum emission primarily originates from ionized gas. The 8 m emission mainly comes from polycyclic aromatic hydrocarbons (PAHs) at 7.7 and 8.6 m, indicating the presence of photodissociation regions (PDRs). As shown in Figure 1, the 8 m emission tightly surrounds the 21 cm radiation and forms a good ring structure, indicating that the ionized gas produced by the H II region is strongly acting on the surrounding interstellar medium. Additionally, the 24 m radiation is distributed both at the center of the H II region and on the ring structure (i.e., the edge of the infrared dust bubble). This distribution is closely related to the origin of the 24 m radiation, which is believed to come from very hot dust heated to high temperatures by absorbing high-energy UV photons from ionizing stars (i.e., the exciting stars of the H II region). Another possibility is that it is heated to high temperatures by radiation from massive young stars, which typically appear as locally bright features. In the far north of N109, two locally bright bubble-like structures in the 24 m radiation can be seen, indicating that a new generation of star formation activity already exists here and even throughout the entire infrared dust bubble.

Figure 2a [Figure 2: see original paper] shows the dust emission at 250 m (color background) and ^{13}CO(J=1-0) molecular line emission (contours) of N109. The velocity integration range for the ^{13}CO intensity map is -2.5 to 10.0 km s^{-1}, corresponding to a line center velocity of 4.2 km s^{-1}. It can be seen that the CO emission at this velocity component coincides with the 250 m cold dust emission, both distributed at the edge of the infrared dust bubble, suggesting that the medium around the dust bubble is likely being re-collected under the compression of the expanding H II region (see Section 4). Additionally, especially from the CO emission, some prominent small-scale molecular cloud clumps can be seen, which could be cradles for the next generation of star formation. Through careful examination of the CO velocity channel maps (such as region A in Figure 2b), we find that on large scales there are two velocity components with a continuous velocity gradient from north (redshifted component at 6.16-7.84 km s^{-1}) to south (blueshifted component at -1.8-1.12 km s^{-1}), and the gas at corresponding velocities appears to be approaching the main shell structure of N109. This indicates that the gas of the two velocity components has a close physical connection with the dust bubble. We speculate that the H II region associated with the dust bubble has caused the originally single-velocity shell structure to separate into two velocity components due to expansion, or that the H II region originally formed at the junction of two filamentary structures with different velocities, which persist even after the H II region formed. Both speculations require more detailed dynamical analysis for verification and are not discussed further in this paper.

3.1 Identification and Parameter Extraction of Dense Clumps

Dense molecular cloud clumps provide the material supply for star formation and determine the final mass of stars. To study the physical properties (such as mass, density, and scale) of dense clumps in N109, we identify all dense clumps that may form stars. We obtain the positions, sizes, and fluxes of dense clumps from the publicly available Hi-GAL 250 m source catalog.

To obtain reliable dense clumps, strict data screening was performed. First, the ratio of the major to minor axis of each clump must be less than 3, which helps filter out elongated structures such as filamentary or diffuse large-scale molecular cloud structures. Second, only sources with a signal-to-noise ratio (the ratio of peak to local background level) greater than 3 were selected. Additionally, the ^{13}CO(J=1-0) integrated intensity map within the velocity range -2.5 to 10.0 km s^{-1} was used to further constrain dense clumps associated with N109, requiring that the CO molecular emission intensity of dense clumps be at least greater than 5σ ($1\sigma = 0.33$ K km s^{-1}) to exclude background contamination sources as much as possible. We initially selected 199 dense clump candidates.

To obtain the dust temperature of each clump, we performed pixel-by-pixel spectral energy distribution (SED) fitting across the entire N109 region to obtain dust temperature and column density distribution maps (see Figures 2b and 2c). The specific fitting formula is a modified graybody spectrum, expressed as:

$$I_v = \kappa_{v0}(v/v_0)^{\beta} B(T_d) \mu m_H N(H_2)$$

where I_v is the surface brightness, $B(T_d)$ is the blackbody radiation brightness at temperature T_d, the mean molecular weight μ is assumed to be 2.8 [41, 42], and m_H is the hydrogen atom mass. The opacity per unit mass of gas and dust is defined as $\kappa_{v0}(v/v_0)^{\beta}$, with $\kappa_{v0} = 0.1$ cm^2 g^{-1} at $v_0 = 1$ THz assuming a gas-to-dust mass ratio of 100 [43]. Additionally, based on large-sample statistical results for H II regions, the dust emissivity index β is 2 [44]. Except for 70 m, the other four Herschel bands were used in the SED fitting [13, 45]. The 70 m dust radiation may also trace hotter components, such as very small hot dust grains and material heated by protostars, and therefore cannot be well fitted by a single-temperature graybody spectrum. Before fitting, the images from these four bands were first smoothed to the same resolution (36) and then regridded to the same pixel size (11.5). Notably, since it is difficult to estimate the actual contribution of background contamination radiation along the line of sight to N109, the surface brightness of each band was not background-subtracted before fitting. In fact, the effect of background contamination on the dust temperature of the N109 region is much smaller than on the column density, which highly depends on surface brightness variations (see equation (1)). Figure 2 shows the column density and temperature distribution maps obtained from pixel-by-pixel SED fitting. We can see that the temperature distribution map clearly shows the large-scale shell structure of N109, with temperatures on the shell significantly higher than in the surrounding medium. Similarly, the shell structure of N109 can also be seen in the column density distribution, though less prominently than in the temperature map. In particular, the small dust bubble located directly south shows an obvious ring structure in the temperature distribution but a blurred structure in column density, qualitatively indicating that background contamination affects column density much more than temperature.

In principle, dense clumps in N109 could be identified from the column density map, but this is actually difficult. On one hand, due to N109' s large distance, background contamination along the line of sight is severe, and the impact varies across different bands, making some dense clumps difficult to detect in the column density map (see Figure 2a). On the other hand, the obtained column density map has a resolution of 36.3 (about 1.7 pc), which is relatively large compared to the typical scale of dense clumps (about 0.1-1 pc) and therefore not conducive to identifying compact small-scale clump structures. Given these two factors, and since 250 m can trace dense cold dust material with relatively high resolution (about 0.8 pc), we directly used the Hi-GAL 250 m public source catalog to obtain observational parameters of dense clumps. Simultaneously, we extracted the average temperature of dense clumps from the dust temperature map. Given the temperature and flux at 250 m, the clump mass can be obtained through:

$$M_{clump} = F_v D^2 / (\kappa_v B_v(T_d))$$

where F_v is the clump flux at frequency v, D is the bubble distance, and M_{clump} is the dense clump mass. If the clump is simply approximated as a sphere, its number density $n(H_2)$ can be obtained:

$$n(H_2) = M_{clump} / (4/3 \pi R^3 \mu m_H)$$

where R is the clump' s equivalent radius. Correspondingly, the clump' s column density can be approximated as $N(H_2) = n(H_2) \times 2R$.

Through observational studies of the Aquila molecular cloud complex, André et al. [46] found that the column density threshold for prestellar cores is $N(H_2) > 7 \times 10^{21}$ cm^{-2}. Prestellar cores are gravitationally bound, starless cores with the potential for star formation. In this work, we mainly study the impact of H II regions on star formation in the surrounding medium. Therefore, we only consider dense clumps that may eventually form stars, meaning clumps with column densities of at least 7×10^{21} cm^{-2}. Using this criterion for screening, we finally obtained 56 dense clumps that may have the potential for star formation. Their relevant parameters are listed in Table 1 , including source ID, J2000 coordinates, major axis length, minor axis length, beam-deconvolved equivalent radius, 250 m flux, temperature, column density, and mass.

3.2 Dynamical Age of the Infrared Dust Bubble

Given a typical electron temperature of the H II region $T_e \approx 10^4$ K, sound speed $C_s \approx 10$ km s^{-1}, initial density of the surrounding medium $n_0 \approx 10^3$ cm^{-3}, and radius $R = 41.5$ pc, we can use the classical H II region evolution model to estimate its dynamical age and the properties of its exciting star [13, 17, 29, 47, 48]. For example, substituting our measured 21 cm radiation flux density within the H II region, $S_v = 11.5$ Jy, into the formula [29, 48]:

$$N_{LyC} \approx 4.761 \times 10^{48} \nu_{0.1} T_e^{-0.45} S_v D^2$$

where ν is the frequency corresponding to 21 cm and D is the bubble distance. Using equation (4), we obtain the number of Lyman photons ionized by the exciting star per second as $N_{Lyc} = 5 \times 10^{49}$ s^{-1}, corresponding to an O3V-type star [49]. Additionally, the dynamical age of the H II region is expressed as:

$$t_{dyn} = (4/7)(R_s/a_s)[(R/R_s)^{7/4} - 1]$$

where $R_s = (3N_{Lyc}/4\pi n^2 \alpha_B)^{1/3}$ is the Strömgren radius, and $\alpha_B = 2.6 \times 10^{-13}(10^4 K/T_e)^{0.7}$ cm^3 s^{-1} is the electron-ion recombination rate coefficient for hydrogen [50]. Using equation (5), we estimate $t_{dyn} \approx 40$ Myr. This result surprises us because massive stars with O-type spectra generally have main-sequence lifetimes not exceeding 5-6 Myr [51, 52]. Therefore, the dynamical age calculated by equation (5) is certainly severely overestimated. There may be two reasons for this overestimation: (1) the calculated distance to N109 is inaccurate; or (2) the classical dynamical evolution model is no longer applicable to super-large H II regions like N109. Regarding distance, we currently use the kinematic distance provided by the distance calculator developed by the BeSSeL project team, and there is only one result, namely 9.6 kpc; therefore, there is no near-far distance ambiguity for N109. The limitations of classical models in explaining the evolution of super-large H II regions were found by Tremblin et al. [53]: the larger the exciting star mass (e.g., $N_{Lyc} > 10^{49}$ s^{-1}), the more random the distribution of H II region dynamical ages becomes, unlike the characteristic distribution seen for H II regions driven by less massive exciting stars. This suggests that the evolution of H II regions like N109, driven by an O3V-type exciting star, may not be well described by existing dynamical models. Additionally, existing theoretical models assume that the entire evolution of H II regions occurs in a uniform medium [47, 53], but this assumption does not match the observed non-uniform medium environment around N109. For example, CO emission shows that the medium around N109 is currently mainly distributed in a shell structure in the northwest direction, while being sparse in other directions. In summary, we roughly consider that the dynamical age of the infrared dust bubble is similar to the main-sequence lifetime of the H II region' s exciting star, about a few million years, but not exceeding 5-6 Myr.

3.3 Classification of YSOs

Young stellar objects (YSOs) include protostars and pre-main-sequence stars. Protostars are accompanied by circumstellar disks that can absorb photons from the protostar and re-emit bright infrared radiation. As material in the circumstellar disk dissipates, infrared radiation rapidly decreases. Using the infrared spectral energy distribution (SED) characteristics of YSOs from 2.2 to 10 m, Lada [54] and Greene et al. [55] defined a spectral index α ($\alpha = d\log(\lambda F_{\lambda})/d\log(\lambda)$, where F_{λ} is the flux at wavelength λ) and classified YSOs into three categories based on this: Class I, Class II, and Class III. Class I are deeply embedded protostars with circumstellar disks; Class II have infrared-bright accretion disks and are also known as T Tauri stars or FU Orionis objects; Class III are classical pre-main-sequence stars with almost completely dispersed envelopes. The spectral index classification method is essentially similar to the SED classification method for young stars [56, 57], which can more accurately constrain YSO categories if their distances are known. Based on spectral index or SED classification, people later developed a fast and effective YSO identification and classification tool: color-color diagrams. For example, Gutermuth et al. proposed a practical set of color criteria for rapid YSO identification and classification using Spitzer mid-infrared data, and also discovered a transitional stage between Class II and Class III, namely transition disk (TD) objects [58, 59]. The first two YSO identification and classification methods are more accurate than color-color diagrams but require a large dynamic range and multi-band photometric flux information, from near-infrared to far-infrared and even millimeter wavelengths. Given N109' s large distance, it is difficult to obtain near-infrared photometric flux for associated YSOs due to survey sensitivity limitations. Therefore, we only use mid-infrared data and adopt the third, rapid color-color diagram method to identify and classify YSOs associated with N109.

To identify YSO candidates associated with N109, we first extracted 94,566 point source photometric data from the GLIMPSE Spring' 07 archive point source catalog within a 0.45-degree radius centered on the dust bubble (RA = 219.290°, Dec = 17.154°). To ensure data quality, we required photometric flux errors in each band (3.6, 4.5, 5.8, and 24 m) to be less than 0.2 mag. We then used the YSO infrared color criteria given by Gutermuth et al. [59]: (1) Class I: [4.5] - [5.8] > 0.7 and [3.6] - [4.5] > 0.7; (2) Class II: [4.5] - [8.0] - *σ{24} > 0.5 and [3.6] - [5.8] - σ*{13} > 0.35; [3.6] - [5.8] + *σ{13} > [([4.5] - [8.0] - σ_{24}) - 0.5] + 0.5; [3.6] - [4.5] - σ*{12} > 0.35; (3) TDs: [24] < 7; [5.8] - [24] > 2.5 or [4.5] - [24] > 2.5; [3.6] < 14. Here, [3.6], [4.5], [5.8], and [24] represent the fluxes in the corresponding bands, and *σ{12}, σ*{13}, σ_{24} represent the photometric uncertainties for the [3.6] and [4.5], [3.6] and [5.8], and [4.5] and [24] bands, respectively. Using these criteria, we obtained a total of 61 Class I, 110 Class II, and 47 TD candidates. Figures 3 and 4 show the identification results. It is worth noting that the young star candidates selected by this method may contain contamination sources along the line of sight to N109, but statistically this will not seriously affect the further analysis below [13, 60].

4 Discussion

Figure 2a shows the spatial distribution of dense clumps. As can be seen, dense clumps are mainly distributed in the north and west of the N109 shell structure. The average column density of these clumps is 1.38×10^{22} cm^{-2}, meeting the density conditions for star formation. That is, if these dense clumps can form stars in the future, star formation activity in the N109 shell structure will be concentrated in the north and west. This result in fact also coincides with the region of new generation massive star formation activity. From the 21 cm continuum emission, five compact continuum emission clumps can be seen in the north and west of N109 (Figure 5 [Figure 5: see original paper]), with two in the north (A and B) and three in the west (C–E). These 21 cm compact emission clumps reveal the existence of H II regions, and their scale (about 5 pc) indicates that they belong to classical small-scale H II regions rather than ultra-compact H II regions [63] (diameter < 0.5 pc). Therefore, we hereafter refer to these 21 cm compact emission clumps as pocket H II regions. On one hand, since they are still embedded in molecular cloud clumps, they are in the very early stages of evolution with timescales certainly shorter than that of N109. On the other hand, using the relationship between H II region size and age given by Tremblin et al. [53] for simple comparison, we can conclude that the timescale of pocket H II regions is shorter than that of N109. Therefore, we consider them to be indicators of a new generation of massive star formation activity near N109.

Furthermore, the mass-radius relationship for molecular cloud cores or clumps proposed by Kauffmann and Pillai [64] is often used to predict whether they will form low- or high-mass stars in the future: $m(r) > 870 M_{\odot} (r/pc)^{1.33}$.

Figure 6 [Figure 6: see original paper] shows the distribution of the 56 clumps in N109 in the mass-radius diagram, where the dashed line represents the Kauffmann and Pillai mass-radius relationship. Four clumps (15, 26, 42, 43) in the diagram lie above the threshold (dashed line), indicating they are likely to form high-mass stars. The other clumps below the threshold may tend to form low-mass stars. We note that clumps 15 and 43 are associated with detected Class II methanol masers in both space and velocity (3-7.5 km s^{-1}) [65]. Class II methanol masers are generally considered powerful probes for studying ongoing massive star formation activity. In contrast, no corresponding observations have been conducted at clumps 26 and 42. Additionally, clump 52, which lies below the threshold, was also found to be associated with Class II methanol masers [65]. Therefore, there may be at least five clumps in the N109 shell capable of forming high-mass stars. This further demonstrates that the distribution of dense clumps in N109 has good spatial correlation with new generation massive star formation activity.

Figure 5 shows the spatial distribution of 218 YSO candidates. The background is 8 m emission, and the contours are 21 cm continuum. As can be seen, the identified YSO candidates show an almost uniform spatial distribution throughout the entire studied infrared dust bubble region. Additionally, there is a phenomenon of missing YSO candidates in the shell structure of the infrared dust bubble. Moreover, although dense clumps are relatively concentrated in the north and west of N109, the spatial distribution of YSO candidates does not show obvious clustering in these two locations. On one hand, these results may be due to incompleteness in our young star sample. The background radiation at mid-infrared bands on the shell of N109 is very bright (e.g., 8 m, see Figure 5), making it difficult to identify young stars (if any) there. On the other hand, the number of young stars may be inherently small in places where molecular gas is diffuse in the shell, while deeply embedded young stars in the dense north and west may be too heavily extincted by dust to be detected.

Although the spatial distribution of young stars identified by us cannot represent possible ongoing star formation activity in the shell, the existence of a new generation of pocket H II regions indicates that the shell of N109 provides sites for the next generation of star formation. Additionally, as seen in Figure 5, there is a bow-shaped 21 cm continuum emission structure in the northwest of the dust bubble, indicating that the ionization front produced by the ionizing radiation of massive stars is adjacent to its relatively cold neighboring medium (i.e., 8 m). This shows that the ionized gas is interacting with the surrounding medium through the ionization front, either compressing it to make it denser or destroying it to make it more diffuse. To more qualitatively study these interactions, following the work of Zhang et al. [66], we present the radial distributions of flux densities at 250 m and 500 m, column density, and temperature for three regions (regions A, B, and C in Figure 2) (see Figure 7 [Figure 7: see original paper]). The radial distance starts from the center of the dust bubble, and the three regions can all be considered as sectors, so the radial distribution of each physical quantity in each region can overall represent the radial distribution along a specific direction.

As can be seen from Figure 7, in region A the flux densities at 250 m and 500 m show steep changes at the inner and outer radii. This steep trend becomes particularly obvious in the temperature radial profile but is not obvious in the column density radial distribution, mainly because the effect of background pollution on temperature calculation is much smaller than on column density (see Section 3.1). The steep trend of flux density and temperature at the inner and outer radii in region A implies that the shell structure of the dust bubble is compressed by the ionization front of the ionized gas at the inner radius and by the supersonic shock front at the outer radius, causing material to accumulate here. Since the shell is located ahead of the ionization front and behind the shock front, its temperature becomes higher than in the uncompressed external region. Compared with region A, the flux density and temperature in regions B and C change smoothly at the inner and outer radii, which may be related to the interstellar medium in these regions being destroyed by feedback from the H II region. Therefore, ongoing or upcoming low- or high-mass star formation activity in the north and west of N109 is being influenced by the H II region, mainly through the ionization front compressing the neighboring medium to re-collect material to gravitational instability and collapse to form a new generation of stars. Although this process is similar to the "collect-and-collapse" theoretical model (see Section 1), further research is needed to constrain the star formation process around N109.

5 Summary

We have conducted a comprehensive multi-wavelength study of the large infrared dust bubble N109 (diameter about 83 pc) driven by an H II region in the Milky Way. The multi-wavelength data include Spitzer-GLIMPSE and MIPSGAL mid-infrared, Herschel Hi-GAL far-infrared, GRS ^{13}CO(J=1-0) millimeter molecular line, and VGPS 21 cm continuum survey data. We mainly studied the impact of N109 on the surrounding medium and star formation activity within it. We found 56 dense clumps associated with the shell structure of N109, of which five are likely to eventually form high-mass stars and the others likely to form low-mass stars. Additionally, five pocket H II regions are also located on the shell structure. Finally, we found that the expanding H II region (ionization front) is interacting with the surrounding medium. In the north and west of N109, the ionization front is likely compressing the surrounding medium to re-collect material to gravitational instability and collapse to form a new generation of stars. This is actually consistent with the results of the five associated pocket H II regions in these two locations. These results collectively indicate that the infrared dust bubble N109 is acting on the surrounding medium through H II region expansion, re-collecting material through compression to provide sites for a new generation of star formation. This may provide a necessary condition for triggered star formation, and we therefore suggest that N109 is a potential site of triggered star formation.

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