New insights in giant molecular cloud hosting S147/S153 complex: signatures of interacting clouds

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Abstract

In order to understand the formation of massive OB stars, we report a multi-wavelength observational study of a giant molecular cloud hosting the S147/S153 complex (size ~90 pc × 50 pc). The selected complex is located in the Perseus arm, and contains at least five H II regions (S147, S148, S149, S152, and S153) powered by massive OB stars having dynamical ages of ~0.2 – 0.6 Myr. The Canadian Galactic Plane Survey ¹²CO line data (beam size ~100''.4) trace the complex in a velocity range of [-59, -43] km s⁻¹, and also reveal the presence of two molecular cloud components around -54 and -49 km s⁻¹ in the direction of the complex. Signatures of the interaction/collision between these extended cloud components are investigated through their spatial and velocity connections. These outcomes suggest the collision of these molecular cloud components about 1.6 Myr ago. Based on the observed overlapping zones of the two clouds, the collision axis appears to be parallel to the line-of-sight. Deep near-infrared photometric analysis of point-like sources shows the distribution of infrared-excess sources in the direction of the overlapping zones of the molecular cloud components, where all the H II regions are also spatially located. All elements put together, the birth of massive OB stars and embedded infrared-excess sources seems to be triggered by
two colliding molecular clouds in the selected site. High resolution observations of dense gas tracer will be required to further confirm the proposed scenario.

Key words: ISM: clouds — Stars:formation — HII regions

1 Introduction

H\(\text{II}\) regions are considered as the first observable manifestations of massive OB stars (\(\gtrsim 8 \, M_\odot\)). Such stars inject a great amount of radiative and mechanical energy in their host galaxies during their entire lifespan, and significantly affect their surrounding environments (e.g., Deharveng et al. 2010). However, understanding the birth mechanism of massive OB stars is a long-standing issue in star formation research, which is still being debated (Zinnecker & Yorke 2007; Tan et al. 2014). There are three major theories of massive star formation available in the literature, which are “Turbulent core accretion”, “Competitive accretion”, and “Cloud-Cloud Collision (CCC)”. Over the last decade, to explain the formation of massive OB stars, the CCC process has gained significant attention against the other ones (e.g., Zinnecker et al. 2007; Tan et al. 2014; Fukui et al. 2018). Because, this particular process provides appropriate initial conditions for the formation of massive stars at the intersection of two molecular clouds (e.g., Habe & Ohta 1992; Anathpindika 2010; Inoue & Fukui 2013; Takahira et al. 2014, 2018; Haworth et al. 2015a,b; Wu et al. 2015, 2017a,b; Torii et al. 2017; Balfour et al. 2017; Bisbas et al. 2017, and references therein).

In this paper, we have selected an extended star-forming S147/S153 complex or a system of Galactic H\(\text{II}\) regions, which is embedded in a giant molecular cloud (GMC; \(M_{\text{cloud}} \sim 6.1 \times 10^4 \, M_\odot\); Tatematsu et al. 1985) located in the Perseus arm (see also Kahane et al. 1985). The GMC hosts two small groups of H\(\text{II}\) regions, which are powered by late O or early B types stars (Crampton et al. 1978). One group consists of the S152 and S153 H\(\text{II}\) regions, while the other one contains S147, S148, and S149 H\(\text{II}\) regions (Tatematsu et al. 1985). Using the \(^{12}\text{CO}\) line data (beam size \(\sim 2.7\) ), they found two distinct cloud components at \(-50\) and \(-54\) km s\(^{-1}\) in the direction of the GMC. The cloud at \(-50\) km s\(^{-1}\) (\(M_{\text{cloud}} \sim 1.9 \times 10^4 \, M_\odot\); see Table 1 in Tatematsu et al. 1985) hosts the S152 and S153 H\(\text{II}\) regions, while the S147, S148, and S149 H\(\text{II}\) regions are associated with the cloud at \(-54\) km s\(^{-1}\) (\(M_{\text{cloud}} \sim 4 \times 10^3 \, M_\odot\); see Table 1 in Tatematsu et al. 1985). Using the JCMT \(^{12}\text{CO}(J=2-1)\) line data (beam size \(\sim 21''\)), Azimlu et al. (2011) also investigated two groups of molecular clumps toward the GMC. These
authors found the molecular gas at $[-51.8, -49.3]$ km s$^{-1}$ in the direction of the one group of molecular clumps, which are distributed toward the S152 and S153 H$\text{II}$ regions. The other group of molecular clumps at $[-55.1, -51.7]$ km s$^{-1}$ is seen toward the S147, S148, and S149 H$\text{II}$ regions. However, there is no study available in the literature to examine the interaction of these two cloud components, which can enable us to infer the exact operational star-formation process in the S147/S153 complex. In the eastern side of the GMC, a supernova remnant SNR G109.1$-$1.0 (CTB 109) has been reported (see Figure 2a in Tatematsu et al. 1985 and also Gregory et al. 1980), and has a semi-circular shell morphology detected both in radio and X-ray data. Sofue et al. (1983) reported the distance and age of the SNR G109.1$-$1.0 to be 4.1 kpc and $1.5 \times 10^4$ yr, respectively (see also Tatematsu et al. 1985). Tatematsu et al. (1985) compared the age of SNR G109.1$-$1.0 with the ages of S152 and S153, which are much older in the order of $10^6$ yr (see also their paper). Considering these observational facts, these authors ruled out the impact of the SNR on the surroundings of the selected complex, which is not explored in this paper. Earlier, Crampton et al. (1978) and Tatematsu et al. (1985) adopted a distance of $\sim$4 kpc to the star-forming S147/S153 complex. In this paper, we have used the distance of 4.0 kpc for the S147/S153 complex. In the star-forming S147/S153 complex, the formation process of the powering OB stars of H$\text{II}$ regions is unknown in the literature. To observationally explore the interaction of two cloud components present in the GMC and the birth process of massive OB stars, the Canadian Galactic Plane Survey (CGPS) $^{12}$CO $(J=1-0)$ line data ($1\sigma \sim 0.3$ K km s$^{-1}$; Taylor et al. 2003) and the deep UKIDSS near-infrared (NIR) photometric data have been analyzed in the S147/S153 complex.

The present paper is arranged as follows. The data sets used in this work are described in Section 2. Section 3 presents new results obtained through a multi-wavelength approach. A discussion on the observational findings is given in Section 4. Finally, we conclude in Section 5.

2 Data sets

Multi-wavelength data sets are adopted in this paper, and were retrieved from different existing surveys (see Table 1). In the selected large-scale area toward the complex (size $\sim$90 pc $\times$ $\sim$50 pc; central coordinates: $l = 108^\circ.515$, $b = -1^\circ.074$), these data sets are utilized to explore the ionized gas, molecular gas, dust continuum emission, mid-infrared (MIR) emission, and infrared excess sources.
Table 1. A list of multi-wavelength surveys utilized in the present work.

| Survey                                      | Wavelength/Frequency(s) | Resolution | Reference                  |
|---------------------------------------------|-------------------------|------------|----------------------------|
| NRAO VLA Sky Survey (NVSS)                  | 1.4 GHz                 | ∼45″       | Condon et al. (1998)       |
| Planck Survey                               | 100 GHz, 353 GHz, 857 GHz | ∼9′.7, 4′.9, 4′.6 | Planck Collaboration IX (2014) |
| Canadian Galactic Plane Survey (CGPS)       | 2.6 mm                  | ∼100″.4    | Taylor et al. (2003)       |
| BOLOCAM Galactic Plane Survey (BGPS)        | 1.1 mm                  | ∼33″       | Aguirre et al. (2011)      |
| Wide-field Infrared Survey Explorer (WISE)  | 12 μm                   | ∼6″.5      | Wright et al. (2010)       |
| UKIRT Near-Infrared Galactic Plane Survey (GPS) | 1.25 – 2.2 μm          | ∼0.8″      | Lawrence et al. (2007)     |
| Two Micron All Sky Survey (2MASS)           | 1.25 – 2.2 μm           | ∼2″.5      | Skrutskie et al. (2006)    |

3 Results

3.1 Physical environment of the S147/S153 complex

In this section, we present new observational outcomes derived using the analysis of the multi-wavelength data.

3.1.1 Multi-wavelength view of the S147/S153 complex

Figure 1a shows a color-composite map of a large scale view of the selected S147/S153 complex, which is made using three Planck images (857 GHz (red), 353 GHz (green), and 100 GHz (blue)). An area of the selected target complex is highlighted by a dashed box in Figure 1a. In Figure 1a, the positions of previously known five H ii regions and SNR G109.1−1.0 (CTB 109) are also marked and labeled. One can also find two groups of H ii regions in Figure 1a (i.e., S152–S153, and S147–S148–S149). Note that the Planck images do not provide more insights into the H ii regions due to their coarse resolutions (see Table 1). Using the MIR image at WISE 12 μm, a zoomed-in view of the area containing five H ii regions is displayed in Figure 1b. The WISE image is also overlaid with the NVSS radio continuum emission contours at 1.4 GHz (where 1σ = 0.45 mJy/beam; Condon et al. 1998), indicating the locations of the ionized regions in the complex. Some of the radio continuum emission peaks are associated with the extended MIR emission traced in the image at 12 μm.

Figure 2a shows an integrated intensity map of CGPS $^{12}$CO (J = 1−0) from −59 to −43 km s$^{-1}$, tracing the molecular cloud associated with the S147/S153 complex. The positions of five H ii regions, 22 GHz water masers ($V_{lsr} \sim -45 - -52$ km s$^{-1}$; Sunada et al. 2007), SNR G109.1−1.0, and 6.7 GHz methanol maser ($V_{lsr} \sim -45.7$ km s$^{-1}$; Xu et al. 2003) are

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1 Planck (http://www.esa.int/Planck) is a project of the European Space Agency - ESA - with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.
also highlighted in Figure 2a. In general, the 6.7 GHz methanol maser is known as a good tracer of massive star formation (Walsh et al. 1998; Urquhart et al. 2013), and the water maser emission has been reported as an important signpost of star formation activity (Litvak 1969; Genzel & Downes 1977; Greenhill et al. 1998). Figure 2b displays the overlay of the NVSS radio continuum emission contours at 1.4 GHz on the molecular map. Several ionized clumps are seen within the molecular cloud associated with the selected complex (see Section 3.1.2 for quantitative estimates). In Figure 2c, we have superimposed the BOLOCAM dust continuum emission contours at 1.1 mm on the molecular map. Using the BOLOCAM dust continuum data, we have qualitative found the locations of dense clumps in the direction of the molecular cloud associated with the selected complex (see Figure 2c). Using the JCMT $^{12}$CO(J=2-1) line data (beam size 21$''$), Azimlu et al. (2011) reported the positions of several molecular clumps in the direction of our target field, which are also marked in Figure 2c (see diamonds and triangles).

Together, Figure 2 provides the locations of the H\textsc{ii} regions, dust clumps, and signposts of star formation in the direction of the selected GMC.

3.1.2 Ionized clumps in the S147/S153 complex

Based on the NVSS radio continuum map, we have identified the ionized clumps in the selected complex. In the NVSS map at 1.4 GHz, we employed the clumpfind IDL program (Williams et al. 1994) to depict the ionized clumps and to estimate their integrated flux densities. Several radio continuum contour levels were given as an input parameter for the clumpfind, and the value of the lowest contour level was about 5$\sigma$ (where 1$\sigma$ = 0.45 mJy/beam; Condon et al. 1998; see NVSS contours in Figure 1b). Eighteen ionized clumps (i.e., c1–c18) are obtained in the complex, and are highlighted and labeled in Figure 2b. In Figure 2b, the radio clumps c1–c9 are seen in the direction of the boundary of the GMC hosting the S147/S153 complex, while other radio clumps (i.e., c10–c18) are away from the molecular cloud boundary. Among the radio clumps c1–c9, we find that the clumps (c1, c2, c7, and c9) are associated with the previously known H\textsc{ii} regions. We have estimated the number of Lyman continuum photons ($N_{uv}$) for each ionized clump using the following equation (Matsakis et al. 1976):

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

where $S_\nu$ is the measured total flux density in Jy, D is the distance in kpc, $T_e$ is the electron temperature, and $\nu$ is the frequency in GHz. The calculation uses the electron temperature of 10000 K and a distance of 4.0±0.5 kpc. The spectral type of the powering source of each ionized
clump is derived by comparing the observed Lyman continuum flux against the theoretical value given in Panagia (1973). Table 2 contains the positions, radius ($R_{\text{HII}}$), integrated flux, Lyman continuum photons, and spectral type of each ionized clump. We find the presence of massive OB stars in our selected complex (see Table 2). Using the values of $N_{\text{uv}}$ and $R_{\text{HII}}$, one can also compute the dynamical age ($t_{\text{dyn}}$) of each ionized clump using the following expression (Dyson & Williams 1980):

$$t_{\text{dyn}} = \left(\frac{4R_s}{7c_s}\right) \left[\left(\frac{R_{\text{HII}}}{R_s}\right)^{7/4} - 1\right]$$

where $c_s$ is the isothermal sound velocity in the ionized gas ($c_s = 11$ km s$^{-1}$; Bisbas et al. (2009)), $R_{\text{HII}}$ (with 20% uncertainty) is previously defined, and $R_s$ is the radius of the Strömgren sphere (= $(3N_{\text{uv}}/4\pi n_0^2 \alpha_B)^{1/3}$, where the radiative recombination coefficient $\alpha_B = 2.6 \times 10^{-13}$ ($10^4$ K/T)$^{0.7}$ cm$^3$ s$^{-1}$ (Kwan 1997), “$n_0$” is the initial particle number density of the ambient neutral gas, and $N_{\text{uv}}$ is defined earlier. Taking into account a typical value of $n_0$ (= $10^3$ cm$^{-3}$), dynamical ages of the ionized clumps vary between $\sim$0.2 and $\sim$0.6 Myr. The values of the dynamical ages with estimated uncertainties are tabulated in Table 2. Note that the calculation assumes that the H II region is homogeneous as well as spherically symmetric. Based on the analysis of the radio continuum data, one can also notice that many of the ionized clumps/H II regions have similar ages, which are distributed over $\sim$50 pc. It may indicate the onset of some triggering events for the star formation.

### 3.2 Molecular cloud components in the S147/S153 complex

In Figure 2c, the boundary of the GMC hosting the S147/S153 complex is shown, where the locations of the previously observed molecular clumps (from Azimlu et al. 2011) are also indicated (see diamonds and triangles). Blue triangles show the molecular clumps at $[-51.8, -49.3]$ km s$^{-1}$ (having effective radius range $\sim$0.25–0.42 pc) toward the S152 and S153 H II regions, while blue diamonds indicate the molecular clumps at $[-55.1, -51.7]$ km s$^{-1}$ (having effective radius range $\sim$0.51–1.07 pc) in the direction of the S147, S148, and S149 H II regions. We also examined the distribution of radial velocities of all these molecular clumps against their Galactic latitude positions, and found a velocity connection of these two groups of the molecular clumps (or molecular cloud components) in the GMC (not shown here). In order to further examine this result, we have produced the $^{12}$CO profiles, first moment map, second moment map, velocity channel maps, and position-velocity maps of the CGPS $^{12}$CO gas.

In Figure 3a, we have marked five positions (i.e., p1–p5; see red ellipses) in the direction of the boundary of the GMC hosting the S147/S153 complex. Figures 3b–3f show the observed
$^{12}$CO profiles for different positions (i.e., p1–p5) marked in Figure 3a, revealing two velocity peaks (around $-54$ and $-49$ km s$^{-1}$; see broken lines in each panel). The spectra are obtained by averaging the region highlighted by an ellipse in Figure 3a. In Figure 4a, we present the first moment map of $^{12}$CO, depicting the intensity-weighted mean velocity of the emitting gas. Considering the radial velocity observed toward the S152 H$\text{II}$ region against the S148 H$\text{II}$ region (see radial velocity bar in Figure 4a), velocity gradient is clearly seen in the first moment map, suggesting the presence of two velocity components (see also position-velocity maps in this paper). Figure 4b displays the second moment map (or intensity-weighted dispersion map), tracing a high velocity dispersion value (> 1.6 km s$^{-1}$) toward the GMC hosting the S147/S153 complex. In the first and second moment maps, we have also highlighted the positions, where double velocity peaks are observed (see open circles in Figures 3a and 3b).

Figure 5 displays the integrated CGPS $^{12}$CO velocity channel maps at intervals of 1 km s$^{-1}$. The gas distribution in the channel maps suggests the presence of two clouds, and their spatial association (see panels at $[-55, -54]$, $[-53, -52]$, and $[-49, -48]$ km s$^{-1}$ in Figure 5). Figures 6a and 6b show the latitude-velocity and longitude-velocity maps, respectively. In Figure 6b, we have also drawn a scale bar referring to 0.4 km s$^{-1}$ pc$^{-1}$, which can be used to examine the velocity gradient. The position-velocity maps of $^{12}$CO reveal two cloud components (around $-54$ and $-49$ km s$^{-1}$; see two broken vertical lines) in the direction of the complex. In the position-velocity maps, green horizontal lines show the five positions (i.e., p1–p5; see Figure 3a). Here, we again mention that the double peaks are found in the $^{12}$CO spectra toward these five positions (see Figure 3a). In Figures 6a and 6b, two arrows (in brown) indicate a lower intensity intermediate velocity emission between two velocity peaks, showing a velocity connection of two cloud components.

Figure 7a shows the spatial distribution of molecular gas associated with the cloud at $[-51.8, -43.5]$ km s$^{-1}$ (or around $-49$ km s$^{-1}$). On the basis of visual inspection, at least three parts of this cloud component (i.e., “rc1”, “rc2”, and “rc3”) are marked in Figure 7a, which appear to be spatially aligned (see a broken line in Figure 7a). Another cloud component at $[-59.2, -53.4]$ km s$^{-1}$ (or around $-54$ km s$^{-1}$) is presented in Figure 7b. In Figure 7b, based on visual inspection, we have also highlighted at least three parts of this cloud component (i.e., “bs1”, “bs2”, and “bs3”). No molecular emission is seen toward the central area of the part “bs1” (see an arrow in Figure 7b), which may indicate the ionizing impact of massive stars associated with the S147, S148, and S149 H$\text{II}$ regions. The part “bs1” is also spatially aligned with the other two parts “bs2” and “bs3” (see a broken line in Figure 7b). In Figure 7c, we present the spatial distribution of these two molecular cloud components around $-54$ and $-49$
We find that the parts “bs1”, “bs2”, and “bs3” are spatially overlapped with the cloud part “rc1”. Additionally, the cloud parts “rc2” and “rc3” are also spatially overlapped with the cloud part “bs1”. The five positions (i.e., p1–p5) are also indicated in Figure 7c. Interestingly, these positions are seen toward the overlapping areas of these two cloud components. At least four \( \text{H} \text{ii} \) regions associated with the sites S148, S149, S152, and S153 are also located toward the overlapping zones of the cloud components. Figure 7d shows the contour map of \( ^{12}\text{CO} \) at \(-52.6 \text{ km s}^{-1}\), which is an intermediate velocity value between two velocity components around \(-54\) and \(-49 \text{ km s}^{-1}\). The map at \(-52.6 \text{ km s}^{-1}\) also traces compact molecular distribution toward the five positions.

Altogether, the analysis of the CGPS \( ^{12}\text{CO} \) line data (beam size \( \sim 100'' \)) favours the spatial and velocity connections of two cloud components in the direction of the selected GMC. A detailed discussion on these findings is performed in Section 4.

### 3.3 Selection of infrared excess sources

To investigate the star formation activities in the S147/S153 complex, the knowledge of the infrared excess sources/young stellar objects (YSOs) in the selected area is needed. Hence, in this paper, the NIR color-magnitude scheme has been employed to identify a population of infrared excess sources. The excess emission of sources is expected due to the presence of circumstellar materials around them. Hence, these sources appear much redder in the NIR color-magnitude plot. In this work, the UKIDSS-GPS NIR data have been used for depicting more deeply embedded and faint young stellar populations, and are three magnitudes deeper than 2MASS. A reliable NIR photometric catalog of point-like sources was obtained from the UKIDSS GPS archival data release (see Dewangan et al. 2015 for more details, and also Lucas et al. 2008). Figure 8a shows the NIR color-magnitude plot (H–K vs K) of sources that have detections in the H and K-bands. In Figure 8a, the infrared excess sources with H–K \( \gtrsim 2.1 \) mag are highlighted by squares. The color H–K cut-off (i.e., H–K \( \sim 2.1 \) mag) is estimated by constructing the color-magnitude plot of sources detected in a nearby control-field region (central coordinates: \( l = 107^\circ.846, b = -1^\circ.88 \)), which has the same size as that of the selected complex. The color-magnitude scheme yields a total of 105 infrared excess sources in our selected target field. In Figure 8b, the positions of the infrared excess sources are overlaid on the two molecular maps around \(-54\) and \(-49 \text{ km s}^{-1}\) (see also Figure 7c). The NVSS radio continuum emission contours at 1.4 GHz are also shown in Figure 8b. Three radio clumps (i.e., c1–c3) are found toward the overlapping zones of the two clouds. The infrared excess
sources are distributed toward the radio clumps c1 (i.e., S152 H\textsc{ii} region) and c2 (i.e., S148 H\textsc{ii} region). The radio clump c1 is also associated with the 6.7-GHz methanol maser. In the direction of the molecular cloud associated with the complex, Figure 8c shows the positions of the infrared excess sources against the dust continuum clumps at 1.1 mm. Figures 8b and 8c together suggest the association of star formation activities with the dust clumps and/or the H\textsc{ii} regions, which are distributed toward the overlapping zones of the two clouds around −54 and −49 km s\textsuperscript{−1} (see also arrows in Figures 8b and 8c). Furthermore, in the direction of the overlapping zones of the two clouds, the $^{12}$CO spectra show double peaks as well as broad profiles (see Figures 3b–3f). We find the absence of the wing features in the profiles, suggesting that the observed broad velocity widths in these regions may not be attributed to the outflows (see panels related to p1, p2, and p3 in Figure 3). Hence, the broad profiles appear to be observed due to the overlapping of the two velocity components along the line-of-sight.

4 Discussion

The selected GMC ($M_{\text{cloud}} \sim 6.1 \times 10^{4} M_\odot$; Tatematsu et al. 1985) in this paper has been known to host two groups of H\textsc{ii} regions (Tatematsu et al. 1985; Kahane et al. 1985). In the direction of this molecular cloud, two velocity components-clouds ($M_{\text{cloud}} \sim 0.4–1.9 \times 10^{4} M_\odot$; Tatematsu et al. 1985) have also been reported in the literature (see also Azimlu et al. 2011). In the selected GMC, one group of molecular clumps at $[−51.8, −49.3]$ km s\textsuperscript{−1} is found toward the S152 and S153 H\textsc{ii} regions, while the other group of molecular clumps at $[−55.1, −51.7]$ km s\textsuperscript{−1} is seen in the direction of the S147, S148, and S149 H\textsc{ii} regions (see Azimlu et al. 2011 and also Figure 2c in this paper). We have revisited the work of Azimlu et al. (2011), and have found a connection of the two cloud components in the velocity (see Section 3.2). This particular result indicates the possibility of the interaction or collision of these two cloud components, which is yet to be examined in the selected GMC. In this connection, we have carefully analyzed the tracers of the molecular gas, ionized gas, dust clumps, and embedded young stellar population toward our selected GMC.

As mentioned in the Introduction, the CCC process can produce massive stars at the junction of molecular clouds or the shock-compressed interface layer. In order to study the CCC process, Habe & Ohta (1992) carried out numerical simulations of head-on collisions of two non-identical clouds. They found gravitationally unstable cores/clumps at the interface of the clouds due to the effect of their compression, where massive stars can be triggered (e.g., Inoue & Fukui 2013; Torii et al. 2017; Fukui et al. 2018). A spatial and velocity connection of
two clouds is considered as one of the observational signposts of the CCC process (e.g., Torii et al. 2017; Dewangan 2017; Dewangan & Ojha 2017; Dewangan et al. 2017, 2018a,b, 2019). The velocity connection of two clouds can be obtained via a lower intensity intermediate velocity emission (i.e., bridge feature) between them in the velocity space. The presence of the bridge feature might indicate the existence of a compressed layer of gas due to the collision of the clouds, which is also attributed to the turbulent layer created at the interface of the collision (e.g., Haworth et al. 2015a,b; Torii et al. 2017). Furthermore, the existence of a complementary spatial distribution of two clouds has been adopted as an another important signature of the CCC process (e.g., Torii et al. 2017; Fukui et al. 2018; Dewangan et al. 2018b, 2019). In this context, one expects the spatial fit of “Cavity/Keyhole/intensity-depression” and “Key/intensity-enhancement” features. In general, in the collision site, it is always not necessary to directly obtain the spatial fit of “Key” and “Key-hole” features. In such collision site, it is possible that one of these features could be displaced with respect to the other one (see Fukui et al. 2018, for more details). However, in a colliding system, a displacement may not be seen if the collision axis is parallel to the line-of-sight.

Considering these highlighted observational signatures of the CCC process, we have carefully examined the CGPS $^{12}$CO line data in our selected target GMC. The position-velocity maps of $^{12}$CO reveal the presence of two molecular clouds at [−59.2, −53.4] km s$^{-1}$ (or around −54 km s$^{-1}$) and [−51.8, −43.5] km s$^{-1}$ (or around −49 km s$^{-1}$), which are also found to be linked by an intermediate velocity emission or a broad-bridge feature (see Section 3.2). It implies the velocity connection of these two clouds. In Figure 7c, we have displayed a spatial connection of the two cloud components toward our selected target GMC (see Section 3.2 for more details). The observed bridge feature in the velocity space may show spatially compact molecular distribution (see position-velocity maps), which seems to be consistent with the overlapping zones found in the selected GMC. These findings together favour a collision between the two cloud components in the past. Considering the observed overlapping zones of the two clouds (see Figure 7c), the collision axis seems to be parallel to the line-of-sight. In this case, a displacement of one cloud with respect to other one may not be observed (e.g., Fukui et al. 2018). In the direction of the common zones of these two cloud components, the observed H$\text{II}$ regions, a majority of infrared excess sources, the 6.7-GHz methanol maser, and dust clumps have been investigated (see Sections 3.2 and 3.3). Hence, it may possible that the CCC process might have influenced the star formation history in the selected GMC. Therefore, we need to compute the collision timescale in the complex. The star formation activities are distributed upto about 20 pc (i.e., $l_{cc}$) toward the overlapping zone of the clouds (see the area around
S152/S153 in Figures 8b and 8c). With the help of the observed velocity separation range of the clouds (i.e., $V_{\text{rel}} = 5$–12 km s$^{-1}$), the cloud collision timescale ($\tau_{\text{cc}}/V_{\text{rel}}$) is estimated to be $\sim$3.9–1.6 Myr. In Section 3.2, the dynamical ages of the H II regions in the complex have been found to be $\sim$0.2–0.6 Myr. It indicates that the collision timescale (i.e., $\sim$3.9–1.6 Myr) is older than the dynamical ages of the H II regions. However, the collision timescale (i.e. $\sim$1.6 Myr) corresponding to 12 km s$^{-1}$ appears more consistent with the dynamical ages of the H II regions and the ages of sites S152–S153 (i.e., about the order of $10^6$ yr; Tatematsu et al. 1985). Additionally, a mean age of YSOs is reported to be $\sim$0.44–2 Myr (Evans et al. 2009). The 6.7-GHz methanol maser is also traced toward the S152 H II region, and suggests the existence of early stage of massive star formation ($<0.1$ Myr). In the simulations, Inoue & Fukui (2013) found that massive O stars can be produced within a few times of $10^5$ yr. Considering these various age estimations and the observational signatures, it seems that the CCC process might have influenced the birth of massive OB stars and embedded YSOs in our selected GMC, which hosts the star-forming S147/S153 complex. This interpretation is still valid even if we assume about 10–20% errors in the calculation of the collision timescale.

5 Summary and Conclusions

To study the formation process of massive OB stars in the GMC hosting the S147/S153 complex, an analysis of the multi-wavelength data has been performed in this paper. The major outcomes of the paper are given below:

- Using the CGPS $^{12}$CO line data, the GMC (extension $\sim$90 pc) associated with the S147, S148, S149, S152, and S153 H II regions is studied in a velocity range of $[-59, -43]$ km s$^{-1}$. These H II regions are excited by massive OB stars. The dynamical ages of these H II regions vary between $\sim$0.2 and $\sim$0.6 Myr for an ambient density of $10^3$ cm$^{-3}$.
- The CGPS $^{12}$CO line data reveal two molecular cloud components around $-54$ and $-49$ km s$^{-1}$ in the direction of the selected GMC. In the position-velocity space, these cloud components are connected through a broad-bridge feature at the intermediate velocity range. Spatial overlapping zones of these cloud components are investigated in the selected GMC.
- Using the deep UKIDSS and 2MASS NIR data sets, a total of 105 infrared-excess sources are selected in the target field.
- Signatures of the interaction between the cloud components are inferred through their spatial and velocity connections, which happened about 1.6 Myr ago. With the help of the observed overlapping zones of the two clouds, the collision axis is likely to be parallel to the line-of-sight.
The powering massive OB stars of the H\textsc{ii} regions, the 6.7-GHz methanol maser, and the embedded infrared excess sources are found at the overlapping zones of the two cloud components, where the dust continuum clumps at 1.1 mm are also observed.

Taking into account all the derived results in this paper, the formation of massive OB stars and embedded infrared excess sources seems to be triggered by two colliding molecular clouds in the S147/S153 complex. High resolution observations of dense gas tracer will be helpful to further confirm our interpretation.

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Fig. 1. a) The Planck 3-color composite map of a large scale area containing the S147/S153 complex (size $\sim 2.0 \times 2.0$; central coordinates: $l = 108^\circ.66, b = -0^\circ.68$). The color-composite map (in log scale) is made using the Planck images at 857 GHz (red), 353 GHz (green), and 100 GHz (blue). A broken box (in white) indicates the area (size $\sim 90$ pc $\times \sim 50$ pc; central coordinates: $l = 108^\circ.515, b = -1^\circ.074$), which is the target region of this paper. The position of SNR G109.1-1.0 is marked with an orange asterisk. b) The WISE 12 $\mu$m image of an area highlighted by a solid box (in cyan) in Figure 1a. The image at 12 $\mu$m is also overlaid with the NVSS radio continuum emission contours at 1.4 GHz, which are shown with the levels of 2.18, 2.62, 4.37, 7.0, 26.20, 61.12, 87.32, 436.60, 611.24, 698.56, and 855.74 mJy/beam (where $1\sigma = 0.45$ mJy/beam; Condon et al. 1998). Multiplication symbols (in yellow) represent the locations of the 22 GHz water masers, while the position of the 6.7 GHz methanol maser is marked by a plus sign (in blue). In each panel, black stars indicate the positions of previously known S147, S148, S149, S152, and S153 H$^\text{II}$ regions. The scale bar corresponding to 20 pc (at a distance of 4.0 kpc) is shown in both the panels.
Fig. 2. a) The CGPS $^{12}$CO intensity contour map integrated over the velocity range of $[-59, -43]$ km s$^{-1}$. The molecular emission contours are shown with the levels of 5.4, 7.9, 11.8, 17.8, 29.6, 39.5, 49.3, 59.2, 69.1, 78.9, 88.8, and 97.7 K km s$^{-1}$ (where 1σ $\sim$0.43 K km s$^{-1}$). The positions of SNR G109.1-1.0, S147, S148, S149, S152, S153, and masers are marked by the same symbols as shown in Figures 1a and 1b. Multiplication symbols (in yellow) represent the locations of the 22 GHz water masers, while the position of the 6.7 GHz methanol maser is marked by a plus sign (in white). b) Overlay of the NVSS 1.4 GHz radio continuum contours (in red) on the $^{12}$CO filled contour map. The molecular cloud boundary is highlighted by the $^{12}$CO contour with a level of 5.4 K km s$^{-1}$. The NVSS 1.4 GHz contours are plotted with the same levels of as shown in Figures 1b. Eighteen ionized clumps are marked by black circles along with corresponding IDs (see also Table 2). c) Overlay of the BOLOCAM 1.1 mm dust continuum contours (in black) on the $^{12}$CO filled contour map. The molecular cloud boundary is marked by the $^{12}$CO contour with a level of 5.4 K km s$^{-1}$. The BOLOCAM 1.1 mm contours are shown with the levels of 3.26 Jy/beam $\times$ (0.014, 0.019, 0.035, 0.11, 0.15, 0.25, 0.8, 0.9), where 1σ $\sim$11 mJy/beam (Aguirre et al. 2011). The positions of the $^{12}$CO molecular clumps (from Azimlu et al. 2011) are also marked in the panel (see diamonds and triangles).
Fig. 3. a) The molecular cloud boundary is highlighted by the $^{12}$CO contour with a level of 5.4 K km s$^{-1}$. Stars (in blue) indicate the positions of previously known S147, S148, S149, S152, and S153 H II regions. Additionally, five positions (i.e., p1 to p5) are also indicated by small ellipses in the figure. b–f) The $^{12}$CO profiles in the direction of five positions (i.e., p1 to p5; see corresponding positions in Figure 3a). Two velocities at $-54$ and $-49$ km s$^{-1}$ are indicated by two vertical broken lines.
Fig. 4. a) Intensity-weighted mean velocity map (or the first moment map) of the CGPS $^{12}$CO. The color bar indicates the mean $V_{lsr}$ (in km s$^{-1}$). b) Intensity-weighted dispersion map (or the second moment map) of the CGPS $^{12}$CO. The color bar indicates the velocity dispersion (in km s$^{-1}$). In each panel, stars indicate the positions of the S147, S148, S149, S152, and S153 H II regions. In all the panels, open circles show the positions, where two velocity peaks are seen (see Figure 3).
Fig. 5. Velocity channel maps of $^{12}$CO toward the selected GMC. The molecular emission is integrated with an interval of 1 km s$^{-1}$. The contour levels are (0.16, 0.2, 0.3, 0.5, 0.7, 0.8, 0.9) times of the peak value given in each panel in the unit of K km s$^{-1}$, where 1σ $\sim$ 0.3 K km s$^{-1}$. Five H ii regions (S147, S148, S149, S152, and S153) are also highlighted in all the panels.
Fig. 6. a) Latitude-velocity map of $^{12}$CO. The molecular emission is integrated over the longitude range from 107°.82 to 109°.19. The contour levels are 30, 50, 65, 80, 100, 115, 130, 150, 170, 190, 205, 230, 250, 280, 300, 350, 400, 450, 500, 550, 600, 650, and 700 deg K, where 1σ ∼5 deg K. b) Longitude-velocity map of $^{12}$CO. The molecular emission is integrated over the latitude range from -1°.46 to -0°.68. The contour levels are 50, 65, 80, 90, 105, 130, 160, 180, 200, 230, 260, 300, 320, 360, 400, 430, 500, 540, and 580 deg K, where 1σ ∼3.7 deg K. A scale bar referring to 0.4 km s$^{-1}$ pc$^{-1}$ is shown in the panel. In both the panels, green horizontal lines indicate the five positions (i.e., p1–p5; see Figure 3a), and two broken vertical lines indicate two cloud components (around −54 and −49 km s$^{-1}$). In each panel, two arrows (in brown) indicate an intermediate velocity emission.

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Fig. 7. a) Spatial distribution of molecular gas associated with the cloud at $[-51.8, -43.5]$ km s$^{-1}$ in the direction of the S147/S153 complex. The contour levels are 2.27, 4.16, 6.05, 9.07, 13.61, 18.90, 22.68, 30.25, 37.81, 45.37, 52.93, 60.49, 68.05, and 74.86 K km s$^{-1}$, where $1\sigma \sim 0.42$ K km s$^{-1}$. Based on visual inspection, three parts of the cloud (i.e., “rc1”, “rc2”, and “rc3”) are labeled in the figure. An arrow indicates the central part of the cloud part “rc1”. b) Spatial distribution of molecular gas associated with the cloud at $[-59.2, -53.4]$ km s$^{-1}$. The broken contours (in blue) are shown with the levels of 1.95, 2.84, 4.26, 6.39, 8.88, 10.66, 14.21, 17.76, 21.31, 24.86, 28.41, 31.97, and 35.16 K km s$^{-1}$, where $1\sigma \sim 0.35$ K km s$^{-1}$. On the basis of visual inspection, three parts of the cloud (i.e., “bs1”, “bs2”, and “bs3”) are labeled in the figure. An arrow highlights the central part of the cloud part “bs1”. c) Spatial distribution of molecular gas associated with the two clouds at $[-59.2, -53.4]$ and $[-51.8, -43.5]$ km s$^{-1}$ (see Figures 7a and 7b). d) Contour map of $^{12}$CO at $-52.6$ km s$^{-1}$ in the direction of the selected complex. The contour levels of the map are 0.72, 1.05, 1.58, 2.37, 3.29, 3.95, 5.27, 6.59, 7.9, 9.22, 10.54, 11.85, 13.04 K km s$^{-1}$, where $1\sigma \sim 0.3$ K km s$^{-1}$. In the panels “a” and “b”, an arbitrary broken line is marked, where selected cloud parts are almost aligned. In the panels “c” and “d”, five circles show the positions, where the $^{12}$CO profiles are extracted (see Figure 3a). In each panel, the velocity information of the map is given, and the positions of S147, S148, S149, S152, and S153 H II regions are also highlighted by stars.

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Fig. 8. a) NIR color-magnitude diagram (H−K vs K) of sources detected in the H and K bands. These photometric magnitudes were obtained from the UKIDSS and 2MASS catalogs. The selected infrared excess sources are highlighted by open red squares. Black dots show stars with photospheric emission. Due to large numbers of these photospheric emission stars detected in the region, only some of them are displayed. The blue dashed line separates the selected infrared excess sources against other stars. b) Distribution of the selected infrared excess sources (see red squares) in the direction of two molecular cloud components (around −54 and −49 km s\(^{-1}\)). The \(^{12}\)CO maps are the same as shown in Figure 7c. The NVSS 1.4 GHz radio continuum contours (in cyan) are also overlaid on the \(^{12}\)CO contour map (see also Figures 2b). c) Overlay of the selected infrared excess sources (see red squares) on the integrated molecular map and the dust emission contours (see Figure 2c). In the panels “b” and “c”, arrows indicate the association of star formation activities with the dust clumps and/or the H\(_{II}\) regions.
Table 2. Properties of the radio clumps derived using the NVSS 1.4 GHz radio continuum data (see Figure 2b). The radio clumps c1–c9 are seen toward the boundary of the molecular cloud (see dagger symbols), and other radio clumps c10–c18 are located away from the cloud boundary (see Figure 2b).

| ID | l (Deg) | b (Deg) | R_{HII} (pc) | S_{ν} (Jy) | LogN_{uv} (s^{-1}) | t_{dyn} (Myr) | Spectral Type | Remarks |
|----|---------|---------|-------------|-----------|-------------------|--------------|--------------|---------|
| c1† | 108.75  | -0.95   | 0.37        | 1.35      | 48.23             | 0.21±0.01   | O9–O9.5     | S152    |
| c2† | 108.36  | -1.05   | 0.28        | 0.58      | 47.86             | 0.30±0.02   | O9.5–B0     | S148/S149 |
| c3† | 108.39  | -0.86   | 0.14        | 0.06      | 46.91             | 0.23±0.01   | B0–B0.5    | -       |
| c4† | 108.54  | -0.97   | 0.12        | 0.04      | 46.72             | 0.21±0.01   | B0–B0.5    | -       |
| c5† | 108.79  | -1.14   | 0.11        | 0.03      | 46.62             | 0.22±0.01   | B0–B0.5    | -       |
| c6† | 108.66  | -1.13   | 0.10        | 0.01      | 46.48             | 0.33±0.01   | B0.5       | -       |
| c7† | 108.26  | -1.07   | 0.11        | 0.03      | 46.65             | 0.51±0.01   | B0–B0.5    | S147    |
| c8† | 108.02  | -1.25   | 0.07        | 0.02      | 46.09             | 0.28±0.01   | B0.5–B1    | -       |
| c9† | 108.80  | -1.0    | 0.08        | 0.01      | 46.26             | 0.42±0.01   | B0.5–B1    | S153    |
| c10 | 108.60  | -1.45   | 0.14        | 0.08      | 47.01             | 0.21±0.01   | B0–B0.5    | -       |
| c11 | 108.94  | -1.21   | 0.22        | 0.28      | 47.55             | 0.57±0.01   | B0–B0.5    | -       |
| c12 | 108.74  | -1.30   | 0.11        | 0.04      | 46.69             | 0.21±0.01   | B0–B0.5    | -       |
| c13 | 108.14  | -0.91   | 0.11        | 0.03      | 46.60             | 0.23±0.01   | B0–B0.5    | -       |
| c14 | 108.07  | -1.33   | 0.10        | 0.03      | 46.52             | 0.27±0.01   | B0.5       | -       |
| c15 | 107.85  | -0.92   | 0.09        | 0.02      | 46.37             | 0.22±0.01   | B0.5–B1    | -       |
| c16 | 109.05  | -0.99   | 0.08        | 0.01      | 46.26             | 0.23±0.01   | B0.5–B1    | -       |
| c17 | 108.02  | -0.81   | 0.08        | 0.01      | 46.20             | 0.21±0.01   | B0.5–B1    | -       |
| c18 | 109.11  | -1.14   | 0.11        | 0.02      | 46.59             | 0.47±0.02   | B0–B0.5    | -       |

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