Filamentary Structures and Star Formation Activity in the Sites S234, V582, and IRAS 05231+3512

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Received 2018 May 31; revised 2018 July 17; accepted 2018 July 17; published 2018 August 30

Abstract

To investigate ongoing physical processes, we present the results of observations of the sites S234, V582, and IRAS 05231+3512 situated toward $l = 171^\circ.7$–$174^\circ.1$. Based on the CO line data, we find that these sites are not physically connected, and contain at least one filament (with length $>7$ pc). The observed line masses ($M_{\text{line,obs}}$) of the filaments associated with V582 and IRAS 05231+3512 are $\sim 37$ and $\sim 28 M_\odot$ pc$^{-1}$, respectively. These filaments are characterized as thermally supercritical, and harbor several clumps. Groups of infrared-excess sources and massive B-type stars are observed toward the filament containing V582, while very little star formation (SF) activity is found around IRAS 05231+3512. Our results favor a radial collapse scenario in the filaments harboring V582 and IRAS 05231+3512. In the site S234, two filaments (i.e., ns1 ($M_{\text{line,obs}} \sim 130 M_\odot$ pc$^{-1}$) and ns2 ($M_{\text{line,obs}} \sim 45 M_\odot$ pc$^{-1}$)) are identified as thermally supercritical. An extended temperature structure at $27$–$30$ K surrounds the relatively cold ($\sim 19$ K) $\sim 8.9$ pc long filament ns1. At least four condensations ($M_{\text{clump}} \sim 70$–$300 M_\odot$) are seen in ns1, and are devoid of 610 MHz radio emission as observed by the Giant Metrewave Radio Telescope. The filament ns2 hosting clumps is devoid of ongoing SF, and could be at an early stage of fragmentation. Intense SF activity, with an SF efficiency $\sim 3.3\%$ and SF rate $\sim 40$–$20 M_\odot$ Myr$^{-1}$ (for $t_c \sim 1$–$2$ Myr), is observed in ns1. The feedback of massive stars in S234 seems to explain the observed SF in the filament ns1.

Key words: dust, extinction – ISM: H II regions – ISM: clouds – ISM: individual objects (S234) – stars: formation – stars: pre-main sequence

1 Introduction

In recent years, infrared and submillimeter data have revealed a wealth of bubbles and filamentary structures in star-forming regions (e.g., Churchwell et al. 2006; Myers 2009; André et al. 2010), which are often associated with star-forming clumps, clusters of young stellar objects (YSOs), and massive OB stars ($\geq 8 M_\odot$). Understanding the role of filaments in the formation of dense star-forming clumps and the feedback of OB stars in their vicinity is still an open research topic in the area of star formation (SF) (e.g., Zinnecker & Yorke 2007; Myers 2009; André et al. 2010; Deharveng et al. 2010; Schneider et al. 2012; Tan et al. 2014; Baug et al. 2015; Dewangan et al. 2015, 2016a, 2016b, 2017a, 2017b, 2017c, 2017d, 2017e). Furthermore, the processes concerning filament fragmentation are not well understood.

In this paper, we have chosen promising star-forming sites located toward $l = 171^\circ.7$–$174^\circ.1$, $b = -0^\circ.6$–$0^\circ.52$ (see Figure 1(a)), which include some of the major sites such as Sh 2-234 (hereafter S234), V582 Aur (hereafter V582), and Sh 2-237 (hereafter S237). The submillimeter map at 250 $\mu$m shows extended structures in these sites (see Figure 1(a)). The sites S234, V582, and S237 are situated at distances of 2.8 kpc (Marco & Negueruela 2016; Kun et al. 2017), 1.3 kpc (Kun et al. 2017; Ábrahám et al. 2018), and 2.3 kpc (Pandey et al. 2013; Dewangan et al. 2017e), respectively. The CO radial velocities of the sites S234, V582, and S237 were reported to be $-13.4$ km s$^{-1}$ (e.g., Blitz et al. 1982), $-10.5$ km s$^{-1}$ (e.g., Ábrahám et al. 2018), and $-4.5$ km s$^{-1}$ (e.g., Dewangan et al. 2017e).

V582 is characterized as an FU Ori-type young eruptive star (see Kun et al. 2017; Ábrahám et al. 2018, and references therein), and the progenitor of the V582 outburst is proposed to be a low-mass T Tauri star (Ábrahám et al. 2018). Kun et al. (2017) studied optical, near-infrared (NIR), and mid-infrared (MIR) data for a wide-field environment of V582, and suggested that V582 might be associated with the dark cloud LDN 1516. They further suggested that SF in the vicinity of V582 could be triggered by the radiation field of a few hot members of the Aur OB1 association.

The site S237 has an almost spherical shell morphology, and is powered by a star of radio spectral type B0.5V (Dewangan et al. 2017e). In the site S237, Dewangan et al. (2017e) investigated a cluster of YSOs and a massive clump at the intersection of filamentary features, and explained the SF through collisions of the filamentary features (see Figure 14 in Dewangan et al. 2017e).

The site S234 (IC 417) harbors a nebulosum stream (or filamentary structure) and a young cluster “Stock 8” (Jose et al. 2008; Marco & Negueruela 2016). Previous works also reported the presence of a dust shell lying between the nebulosum stream and Stock 8 (see Figures 1 and 9 in Marco & Negueruela 2016), which was also found to be associated with the ionized emission (e.g., Jose et al. 2008). Marco & Negueruela (2016) pointed out that the nebulosum stream is not directly linked with Stock 8. They identified about 15 early-type massive stars (>B2V) around Stock 8 based on photometric and spectroscopic observations. These authors also suggested that the site S234 is powered by the star LSR V+34°23 (HD 35633), with a spectral type of O8 II(f). Jose
et al. (2008) and Marco & Negueruela (2016) reported a stream of embedded sources and an obscured cluster (i.e., CC 14) toward the nebulous stream, and suggested ongoing SF activity in the site S234. It was pointed out that the YSOs associated with the nebulous stream (timescale $\sim$ 1 Myr; Jose et al. 2008) are younger than Stock 8 (timescale $\sim$ 4–6 Myr; Marco &
Negueruela 2016). It has also been discussed that the SF activity in the nebulosity and that in Stock 8 may be independent (e.g., Jose et al. 2008). Hence, these earlier studies together indicate that the site S234 contains several OB stars, a nebulosity stream/filamentary feature, a dust shell, and clusters of YSOs. However, the molecular velocity structures in these different features have not been investigated yet.

Taken together, the interesting extended features reported toward \( l = 171^\circ7–174^\circ1 \), \( b = -0^\circ6–0^\circ52 \) are very suitable for investigating the role of filaments in SF and the feedback of OB stars, which are yet to be carried out. To our knowledge, there is still no detailed study of the molecular gas, embedded clumps, and ionized gas toward the sites in the direction of \( l = 171^\circ7–174^\circ1 \). Therefore, new and unexplored submillimeter images, radio continuum maps, and molecular line data are analyzed in this paper to understand the ongoing physical processes in the star-forming sites.

We give our observations and data analysis procedures in Section 2. The results are presented in Section 3 and a discussion in Section 4. Finally, the conclusions are drawn in Section 5, which also includes a short summary of results.

### 2 Data and Analysis

#### 2.1 New Observations

We obtained new radio continuum observations at 610 MHz of the site S234. The data were observed with the Giant Metrewave Radio Telescope (GMRT) facility on 2016 December 8 (Proposal Code: 3D_025; PI: L.K. Dewangan). The radio data reduction was carried out using the AIPS software, in a similar manner to that given in Mallick et al. (2012, 2013). The synthesized beam size and the rms noise of the final 610 MHz continuum map are \( 5^\prime6 \times 4^\prime6 \) and 120 \( \mu Jy/\text{beam} \), respectively.

It is expected, specifically at low frequencies, that a sufficient amount of background emission will increase the antenna temperature while observing the source. Hence, we corrected the final GMRT map at 610 MHz for system temperature (see Omar et al. 2002; Mallick et al. 2012, 2013; Baug et al. 2015). More details about the procedure adopted for correction of system temperature can be found in Mallick et al. (2012, 2013).

#### 2.2 Archival Data Sets

The multi-wavelength data sets are also retrieved from different surveys (e.g., the NRAO VLA Sky Survey (NVSS; \( \lambda = 21 \, \text{cm}; \text{resolution} = 45^\prime \)); Condon et al. 1998), the Five College Radio Astronomy Observatory (FCRAO) \(^{12}\text{CO} \) (1–0) and \(^{13}\text{CO} \) (1–0) line data (\( \lambda = 2.6, 2.7 \, \text{mm}; \text{resolution} \sim 45^\prime \)); Heyer et al. 1998; Brun 2004), the Herschel Infrared Galactic Plane Survey (Hi-GAL; \( \lambda = 70, 160, 250, 350, 500 \, \mu m \); resolutions = \( 5^\prime8, 12^\prime, 18^\prime, 25^\prime, 37^\prime \)); Molinari et al. 2010), the Wide Field Infrared Survey Explorer (WISE; \( \lambda = 3.4, 4.6, 12, 22 \, \mu m \); resolutions = \( 6^\prime1, 6^\prime4, 6^\prime5, 12^\prime \)); Wright et al. 2010), the Warm-Spitzer IRAC 3.6 and 4.5 \( \mu m \) photometric data (GLIMPSE360; \( \lambda = 3.6, 4.5 \, \mu m \); resolution = \( 2^\prime \)); Whitney et al. 2011), the UKIRT NIR Galactic Plane Survey (GPS; \( \lambda = 1.25, 1.65, 2.2 \, \mu m \); resolution \( \sim 0.8^\prime \)); Lawrence et al. 2007), the Two Micron All Sky Survey (2MASS; \( \lambda = 1.25, 1.65, 2.2 \, \mu m \); resolution = \( 2^\prime5 \)); Skrutskie et al. 2006), and the Isaac Newton Telescope (INT) Photometric H\( \alpha \) Survey of the Northern Galactic Plane (IPHAS; \( \lambda = 0.653 \mu m; \text{resolution} \sim 1^\prime \)); Drew et al. 2005)). One can learn more details of these data sets and their analysis procedures in Dewangan et al. (2017a).

### 3 Results

#### 3.1 Extended Features in the Direction of \( l = 171^\circ7–174^\circ1 \)

To explore the extended and embedded features toward \( l = 171^\circ7–174^\circ1 \), we have employed the submillimeter image at 250 \( \mu m \), a radio continuum map at 1.4 GHz (having an rms sensitivity of \( \sim 0.45 \, \text{mJy/beam} \); Condon et al. 1998), and \(^{12}\text{CO} \) (\( J = 1–0 \)) line data (having a velocity resolution of 0.25 \( \text{km s}^{-1} \) and an rms sensitivity of 0.25 K; Heyer et al. 1996, 1998). These data enable us to depict cold dust, ionized gas, and molecular gas in the sites. Figure 1(a) displays the submillimeter image at 250 \( \mu m \) overlaid with the 1.4 GHz continuum emission contours. Figure 1(b) shows the \(^{12}\text{CO} \) emission contour map at \( [-17.75, -1.0] \, \text{km s}^{-1} \). We have labeled at least six objects (i.e., S237, S234, IRAS 05253+3504, IRAS 05231+3512, IRAS 05220+3455, and V582) in Figures 1(a) and (b). The submillimeter image traces a spherical shell morphology of the site S237 and noticeable filamentary structures in the direction of S234, IRAS 05231+3512, IRAS 05220+3455, and V582. Extended ionized emission is observed toward the sites S237, S234, and V582 (see Figure 1(a)). The filamentary morphologies of the molecular clouds associated with the sites S234, IRAS 05231+3512, IRAS 05220+3455, and V582 are revealed in Figure 1(b). To explore the molecular velocity structures, Figures 1(c) and (d) present latitude–velocity and longitude–velocity plots of \(^{12}\text{CO} \), respectively. Molecular gas in the sites S237, S234, IRAS 05231+3512, and V582 is traced in the velocity ranges \( [-7, -2] \, \text{km s}^{-1} \), \( [-17.75, -10] \, \text{km s}^{-1} \), \( [-8.5, -1] \, \text{km s}^{-1} \), and \( [-12.5, -7.5] \, \text{km s}^{-1} \), respectively. These velocity ranges differ, indicating that these three sites do not belong to a single system and are found at different distances (see Section 1). The sites IRAS 05220+3455 and V582 are physically linked and embedded in the same filamentary feature, whereas the site IRAS 05231+3512 is embedded in another filamentary feature that has no physical association with the sites IRAS 05220+3455 and V582. Note that no observational study of the site IRAS 05231+3512 is available in the literature. This paper does not include the results of the site S237, which have been reported by Dewangan et al. (2017a). A detailed study of the embedded filamentary features observed in the sites S234, IRAS 05231+3512, IRAS 05220+3455, and V582 is not available in the literature, and is presented in Sections 3.2 and 3.3.

#### 3.2 Physical Environment and Star Formation in the Sites V582 and IRAS 05231+3512

Maps of the temperature and column density (resolutions \( \sim 37^\prime \)) of the sites V582 and IRAS 05231+3512 are presented in Figures 2(a) and (b), respectively (see the dashed boxes in Figures 1(a) and (b)). Following the same analysis described in Mallick et al. (2015), these maps are produced using the Herschel 160–500 \( \mu m \) images. The NVSS 1.4 GHz emission contours are overlaid on the Herschel temperature map, tracing the ionized emission toward V582. A column density (\( N(\text{H}_2) \)) contour with a level of \( 4.5 \times 10^{20} \, \text{cm}^{-2} \) is also drawn in the Herschel column density map, allowing one to infer filamentary features. At least three filamentary features are identified in
the column density map, and they are designated as ff1 (length \( \sim \) 9.5 pc at a distance of 1.3 kpc), ff2 (length \( \sim \) 12.7 pc at a distance of 1.3 kpc), and ff3 (length \( \sim \) 6.9 pc at a distance of 1.3 kpc) (see Figure 2(b)). The feature ff1 contains IRAS 05231+3512, while the sites IRAS 05220+3455 and V582 are associated with the feature ff2. The features ff1, ff2, and ff3 are well traced at temperatures of 14–18 K (see Figure 2(a)). Figure 2(c) shows a first-moment map of \(^{12}\text{CO}\), revealing the distribution of mean velocities toward ff1, ff2, and ff3. The features ff2 and ff3 are traced in the velocity range \([-12.5, -7.5]\) km s\(^{-1}\), while ff1 is depicted in velocities of \([-8.5, -1]\) km s\(^{-1}\).

We have computed the total masses of ff1, ff2, and ff3 to be \( \sim 355, \sim 362, \) and \( \sim 182 M_\odot \), respectively. Here, the same procedures are adopted for computing the masses of Herschel features/clumps as given in Mallick et al. (2015). The line masses, or masses per unit length (i.e., \(M_{\text{line,obs}}\)), of ff1, ff2, and ff3 are computed to be \( \sim 37, \sim 28, \) and \( \sim 26 M_\odot \) pc\(^{-1}\), respectively. The inclination angles of the filamentary features are unknown, so the observed line masses are upper limits. A critical line mass \(M_{\text{line,crit}}\) is calculated to be 16–24 \( M_\odot \) pc\(^{-1}\) at \( T = 10–15 \) K. Here, the conversion relation is equal to \( \sim 16 M_\odot \) pc\(^{-1}\) \times \((T_{\text{gas}}/10 \) K\) for a gas filament, assuming that the filament is an infinitely extended, self-gravitating, isothermal cylinder without magnetic support (e.g., Ostriker 1964; Inutsuka & Miyama 1997; André et al. 2014). If the condition \(M_{\text{line,obs}} > M_{\text{line,crit}}\) is valid for a filament then it is a thermally supercritical filament, while a thermally subcritical filament is characterized by the condition \(M_{\text{line,obs}} < M_{\text{line,crit}}\). Our analysis suggests that the features ff1, ff2, and ff3 are thermally supercritical filaments. Such filaments should be unstable to radial gravitational collapse and fragmentation (e.g., André et al. 2010). In the direction of these filamentary features, several condensations, traced by peaks in column density, are seen in the column density map (see Figure 2(b)). In Figure 3(a), we display the integrated \(^{12}\text{CO}\) intensity map (with a velocity resolution of 0.25 km s\(^{-1}\) and an rms sensitivity of 0.2 K; Heyer et al. 1996, 1998), where the molecular emission is integrated over the velocity interval \([-12.5, -1]\) km s\(^{-1}\). Molecular \(^{13}\text{CO}\) gas is observed only toward the features ff1 and ff2 in the molecular intensity map. One should keep in mind that the optical depth in \(^{12}\text{CO}\) is much higher than that in \(^{13}\text{CO}\). Hence, the \(^{13}\text{CO}\) emission can trace relatively denser parts of a star-forming region than the \(^{12}\text{CO}\) emission. Figures 3(b) and (c) show the longitude–velocity and longitude–velocity plots of \(^{12}\text{CO}\), respectively. These position–velocity maps also indicate the molecular gas in the features ff1 and ff2 at different velocity intervals as highlighted earlier.

Based on the Spitzer-GLIMPSE360, UKIDSS-GPS, and 2MASS photometric data, the dereddened color–color scheme (i.e., \([K-3.6]_0\) and \([3.6]-[4.5]\)_0; see Figure 4(a)) and the NIR color–magnitude scheme (i.e., \(H-K\) versus \(K\); see Figure 4(b)) are utilized to identify the infrared-excess YSOs. More detailed descriptions of these schemes are given in Dewangan et al. (2017c) (see also Gutermuth et al. 2009). In the direction of our selected area around V582, color–color and color–magnitude schemes yield 243 YSOs (28 Class I and 215 Class II) and 76 YSOs, respectively. Figure 4(c) shows the spatial distribution of these YSOs overlaid on the column density map. Most of the Class I YSOs (mean lifetime \(\sim 0.44\) Myr; Evans et al. 2009) and Class II YSOs (mean lifetime \(\sim 1–3\) Myr; Evans et al. 2009) are seen along the feature ff2 (hosting IRAS 05220+3455 and V582), revealing noticeable SF activity. However, very little SF activity is found in the features ff1 and ff3 (see Figure 4(c)).
Figure 5(a) displays the integrated $^{12}$CO intensity map in the direction of the feature ff1 containing IRAS 05231+3512 at [-8.5, -1] km s$^{-1}$ overlaid with the NVSS contours. No radio continuum emission is observed toward IRAS 05231+3512. The selected YSOs are also overlaid on the molecular intensity map, where two distinct subcomponents (i.e., ff1a and ff1b) are highlighted. Figure 5(b) shows the longitude–velocity plot of $^{12}$CO toward the feature ff1, where the subcomponents ff1a and ff1b are indicated by broken curves. Molecular gas in the subcomponents is physically connected in velocity space, confirming the feature ff1 as a single elongated structure. Furthermore, a noticeable velocity gradient along each subcomponent is revealed in the position–velocity plot (see Figure 5(b)). Our analysis suggests the existence of starless clumps/condensations in the supercritical filament ff1.

Using the Spitzer 4.5 μm image, Figure 6(a) shows a zoomed-in view of the feature ff2 (hosting IRAS 05220+3455 and V582), and reveals bright rims and cometary globules in the local environment of V582. V582 is seen around one of the corners of the feature ff2. The image is overlaid with the NVSS 1.4 GHz continuum emission contours. The ionized emission is mainly seen toward the bright rims and the tips of the cometary globules. The NVSS 1.4 GHz map also shows at least five radio peaks (see arrows in Figure 6(a)). Based on the flux value of...
Each radio peak, we find that each of the radio peaks is powered by a B3–B2 type star, indicating the presence of massive stars in the local vicinity of V582. However, the observed position of V582 does not coincide with any of the radio continuum peaks. To estimate the Lyman continuum photons and spectral type of each radio peak, we have utilized the equation and procedures given in Dewangan et al. (2017e). In the calculations, we considered a distance of 1.3 kpc and an electron temperature of $10^4$ K. Here, we used the models of Panagia (1973) to infer the spectral classes from the observed

**Figure 4.** (a) Dereddened color–color ($[K - [3.6]]_b$ vs. $[[3.6] - [4.5]]_b$) plot of point-like objects toward the selected area around V582 Aur (see Figure 2(a)). The extinction vector is also shown in the panel (e.g., Flaherty et al. 2007). (b) Color–magnitude ($H - K$ vs. $K$) plot of point-like objects. (c) Overlay of selected YSOs on the Herschel column density map. In panels (a) and (b), circles and triangles indicate Class I and Class II YSOs, respectively. Also in panels (a) and (b), the dots (in gray) present the stars with only photospheric emissions. We have randomly plotted only some of these stars in the top two panels. In panel (c), the YSOs highlighted with red circles and white triangles are selected based on the dereddened color–color scheme (see Figure 4(a)), while green triangles refer to the YSOs identified using the color–magnitude plot (see Figure 4(b)).
Figure 5. A zoomed-in view of the feature ff1 (see the dotted–dashed box in Figure 4(c)). (a) Integrated $^{12}$CO intensity map overlaid with the selected YSOs (see Figure 4(c)). The $^{12}$CO emission is integrated over the velocity range from $-8.5$ to $-1$ km s$^{-1}$, and the contour levels are 50.3 K km s$^{-1} \times$ (0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.98). A big circle highlights the position of IRAS 05231+3512. The NVSS contours (in cyan), with levels of 0.45 mJy/beam $\times$ (3, 8, 10), are overlaid on the molecular map. (b) Longitude–velocity plot of $^{12}$CO. The $^{12}$CO emission is integrated over latitude from $-0\degree.23$ to $-0\degree.14$. A solid line (in blue) indicates the position of IRAS 05231+3512. Two broken curves highlight two subcomponents (i.e., ff1a and ff1b) in the feature ff1.
Figure 6. A zoomed-in view of V582 Aur (see the solid box in Figure 4(c)). (a) Overlay of the NVSS 1.4 GHz emission contours on the Spitzer 4.5 μm image. The contours are drawn with levels of 0.45 mJy/beam × (3, 4, 5, 6, 7, 8, 9, 10). At least five radio peaks are indicated by arrows on the map. (b) Integrated 12CO intensity map toward the field shown in panel (a). The 12CO emission is integrated over the velocity range from ~12.5 to ~7.5 km s⁻¹, and the contour levels are 77.5 K km s⁻¹ × (0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.98). The map is overlaid with the NVSS contours (see panel (a)) and the YSOs (see Figure 4(c)). (c) Overlay of the NVSS 1.4 GHz contours on the Spitzer ratio map of 4.5 μm / 3.6 μm emission. The ratio map is exposed to a Gaussian smoothing function with a width of 3 pixels. The dotted–dashed box (in cyan) encompasses the area shown in panel (d). (d) Overlay of the NVSS 1.4 GHz contours on the IPHAS Hα inverted grayscale image. (e) Latitude–velocity plot of 12CO. The 12CO emission is integrated over longitude from 172°58 to 172°88. (f) Longitude–velocity plot of 12CO. The 12CO emission is integrated over latitude from ~0.5° to ~0.2°. In panels (a) and (b), big circles highlight the positions of V582 Aur and IRAS 05220+3455. In the position–velocity plots, solid and broken lines (in blue) indicate the positions of V582 Aur and IRAS 05220+3455, respectively.
Lyman photons. Figure 6(b) displays the integrated $^{12}$CO intensity map overlaid with the NVSS contours. The $^{12}$CO emission is integrated over a velocity interval of $[-12.5, -7.5]$ km s$^{-1}$. The selected YSOs are also marked on the molecular intensity map. In Figure 6(b), SF is evident toward the bright rims and cometary globules. A group of YSOs is also found around IRAS 05220+3455, where the NVSS 1.4 GHz emission is absent. In Figures 6(c) and (d), we display the overlay of the NVSS 1.4 GHz continuum emission on the Spitzer-IRAC ratio map of 4.5 μm/3.6 μm emission and the IPHAS H$_{2}$O inverted grayscale image. The details of the ratio map can be found in Dewangan et al. (2016a). Figure 6(d) displays the spatial association between the H$_{2}$O extended features and the radio continuum emission. The ratio map shows the extended black or dark gray regions due to the excess of 3.6 μm emission. Note that the Spitzer 3.6 μm band contains emission from polycyclic aromatic hydrocarbons at 3.3 μm. Hence, the ratio map traces photodissociation regions (or photon-dominated regions) around the bright rims. This implies that the origin of the bright rims and the cometary globules appears to be influenced by the feedback process (such as radiation pressure, pressure-driven H II region, and stellar wind) of massive B-type stars.

Figures 6(e) and (f) show the latitude–velocity and longitude–velocity plots of $^{12}$CO, respectively. In the velocity space, a velocity spread is found in the direction of V582 toward the condensation dc1, dc2, and dc3, are also seen in the 350 μm image. The NVSS contour levels are 1, 1.7, 2, 2.8, 6, 13, and ∼20 mJy/beam. In each panel, the location of the star BD +34°1054 is marked by a blue dot. In both panels, the scale bar corresponding to 5 pc (at a distance of 2.8 kpc) is shown in the bottom left corner.

3.3 Physical Environment and Star Formation in the Site S234

3.3.1 Multi-wavelength Continuum Images of S234

Figure 7(a) shows a color-composite map (red: 350 μm; green: 22 μm, and blue: 12 μm) of a 0.7 × 0.7 area of the site (see the dotted–dashed box in Figures 1(a) and (b)). The positions of several OB stars (from Marco & Negueruela 2016) are also marked in the composite map. At least two nebulous stream features, designated as ns1 and ns2, are prominently seen in the 350 μm image, while Stock 8 is brighter in the 12–22 μm images. The composite map also reveals a spherical shell structure (see the highlighted circle in Figure 7(a)). The positions of the star LS V +34°23 (spectral type: O8 II(f); Marco & Negueruela 2016) and the star BD +34°1054 (LS V +34°29; spectral type: O9.7 IV; Marco & Negueruela 2016) are also highlighted in the composite map. The massive OB stars distributed around Stock 8 (see squares and upside down triangles in Figure 7(a)) may explain the observed spherical shell structure through their feedback mechanism. A false-color image at 160 μm of the site S234 is shown in Figure 7(b), and the map is overlaid with the NVSS 1.4 GHz emission contours. A dust shell, where the ionized emission is observed, is remarkably seen in the MIR and submillimeter images (see Figures 7(a) and (b)). Additionally, at least three dust condensations, designated as dc1, dc2, and dc3, are also indicated in Figure 7(a). The massive OB stars are also seen toward the condensation dc1 (see squares and upside down triangles in Figure 7(a)).

Using the Spitzer 4.5 μm image, a zoomed-in view of the dust shell is shown in Figure 8(a). The 4.5 μm image is overlaid with the NVSS 1.4 GHz continuum emission. In Figure 8(b), we present a new high-resolution map of GMRT radio continuum contours at 610 MHz (resolution ∼5°6 × 4°6; rms ∼120 μJy/beam). The GMRT radio contours are also overlaid on the Spitzer 4.5 μm image (see Figure 8(c), where the radio map is smoothed using a Gaussian function. Note that the GMRT map has better resolution and sensitivity than...
the NVSS data. Hence, the GMRT map provides more insight into the ionized features. The radio map at 610 MHz shows the distribution of the ionized gas toward the dust shell, Stock 8, and two dust condensations (i.e., dc2 and dc3). Furthermore, the ionized emission appears to be extended toward the nebulous stream ns1 in the GMRT map (see an arrow in Figures 8(b)–(d)). The GMRT data are smoothened using a Gaussian function with a radius of 7 pixels. The contours (in red) are shown with levels of 0.28 and 0.39 mJy/beam, while other contours (in black) are drawn with levels of 0.45, 0.65, 0.85, 1.2, and 1.5 mJy/beam. (d) Clumpfind decomposition of the GMRT continuum emission. The extent of each identified ionized clump in the GMRT map is shown along with its corresponding ID and position (see also Table 1).

Table 1. Ionized Clumps Detected in the GMRT 610 MHz Continuum Map toward the Site S234 (see Figure 8(d))

| ID   | (deg)   | (deg)   | \(R_{H II}\) (pc) | \(S_{\nu}\) (Jy) | \(\log N_{uv}\) (s\(^{-1}\)) | Spectral Type |
|------|---------|---------|-------------------|-----------------|----------------------------|---------------|
| 1    | 173.389 | −0.155  | 5.30              | 1.613           | 47.96                     | B0V–O9.5V     |
| 2    | 173.339 | −0.209  | 0.65              | 0.129           | 46.86                     | B0.5V–B0V     |
| 3    | 173.440 | −0.192  | 0.35              | 0.035           | 46.30                     | B1V–B0.5V     |
| 4    | 173.451 | −0.126  | 0.30              | 0.026           | 46.15                     | B1V–B0.5V     |
| 5    | 173.385 | −0.030  | 0.20              | 0.056           | 46.50                     | B0.5V         |

Note. The table lists ionized clump ID, position \((l, b)\), deconvolved effective radius of the ionized clump \(R_{H II}\), total flux \(S_{\nu}\), Lyman continuum photons \(\log N_{uv}\), and radio spectral type.
of the ionized clumps, the models of Panagia (1973) are employed.

3.3.2 Molecular Maps of S234

Figure 9 displays the integrated FCRAO $^{12}$CO ($J = 1–0$) velocity channel maps (at intervals of 1 km s$^{-1}$). Based on the gas distribution at different velocities, the maps confirm the existence of two nebulous streams in the site S234. Figures 10(a) and (b) show integrated $^{12}$CO and $^{13}$CO emission contours overlaid on the Herschel 250 μm map, respectively. The CO emission is integrated over the velocity interval $[-17.75, -10]$ km s$^{-1}$. Molecular gas is not observed toward Stock 8. The $^{12}$CO emission is detected toward the nebulous streams, dust shell, and dust condensations, as highlighted in Figure 7(a), while the $^{13}$CO emission is prominently seen toward the features ns1 and dc1. This implies that the features ns1 and dc1 seem to be denser regions in the site S234. Figure 10(c) displays the average $^{12}$CO profiles toward four small fields (i.e., sf1, sf2, sf3, and sf4). The fields sf1, sf2, sf3, and sf4 are selected in the direction of the features ns2, ns1, dust shell, and dust condensation, respectively. In the profiles, the peaks in molecular velocity toward the fields sf1, sf3, and sf4 are almost same (i.e., around $-15$ km s$^{-1}$), while that in the direction of the field sf2 is seen around $-13$ km s$^{-1}$.

To further study the molecular velocity structures, Figure 11 presents the position–velocity maps in the direction of the site S234. Figures 11(a) and (c) show the latitude–velocity plots of $^{12}$CO and $^{13}$CO, respectively. Figures 11(b) and (d) present the
longitude–velocity plots of $^{12}$CO and $^{13}$CO, respectively. The nebulous streams ns1 and ns2 are depicted at different velocity peaks, but they are linked by noticeable intermediate diffuse emission. These maps confirm the physical association of different features (i.e., ns2, ns1, dust shell, and dust condensation) in the site S234, and the velocity spread is observed toward all these different features. Using the $^{13}$CO line data, a zoomed-in view of the nebulous streams is displayed in Figures 12(a) and (b). The integrated $^{12}$CO emission at $[-17.75,-10]$ km s$^{-1}$ is shown in Figure 12(a), while the first-moment map of $^{12}$CO is presented in Figure 12(b). The first-moment map clearly displays the boundary of the two nebulous streams. In the direction of these streams, Figures 12(c)–(f) show the position–velocity plots of $^{12}$CO and $^{13}$CO. The filaments ns1 and ns2 are interconnected in the velocity space of $^{12}$CO and $^{13}$CO (see broken boxes in Figure 12(a)). In the velocity space, a velocity spread is noticeably seen in the direction of ns1.

3.3.3 Maps of Herschel Column Density and Temperature of S234

Figures 13(a) and (b) display the maps of temperature and column density (resolutions $\sim 37''$) of the site S234. In Figure 13(a), the filamentary features are seen with temperatures ($T_d$) of around 19 K, while Stock 8 and the dust shell are depicted in the temperature range 27–30 K (see the big circle in Figure 13(a)). The column density map reveals the embedded morphology of the S234 complex. The map clearly depicts several condensations (having peak $N$(H$_2$) $\sim (6-10) \times 10^{21}$ cm$^{-2}$) in a single $\sim 8.9$ pc long filamentary feature (or nebulous stream ns1), which is indicated by the column density contour of
The nebulous stream ns2, having length \(\sim 8.7\) pc, is also traced in the column density map. Interestingly, in the temperature map, the nebulous stream ns1 (around 19 K) appears to be surrounded by an extended structure with a temperature of 27–30 K (see Figure 13(a)). We have identified a total of 32 clumps in the column density map, which are labeled in Figure 13(c). Table 2 summarizes the properties (i.e., mass and effective radius) of the identified Herschel clumps. Among these clumps, we find that 25 clumps are distributed toward the spherical shell structure (including the dust condensations), nebulous streams, and dust shell (see ID nos. 1–25 in Table 2). The masses of these clumps vary between 10 and 593 \(M_\odot\). Figure 13(c) also displays the extent of each clump. Twelve clumps (IDs 12–20 and 23–25) are seen toward the spherical shell, while the dust shell contains five clumps (IDs 7–11). The condensation dc1 (see clump ID 23) is found to be more massive than other condensations (i.e., dc2 (see clump ID 21) and dc3 (see clump ID 22)). Three clumps (IDs 1–3) are associated with the filament ns2 (length \(\sim 8.7\) pc, temperature \(\sim 19\) K), and the total mass of these clumps is 392 \(M_\odot\). The filament ns1 (length \(\sim 8.9\) pc, temperature \(\sim 19\) K) contains three clumps (IDs 4–6), and the total mass of these clumps is \(\sim 1154\) \(M_\odot\), which we also consider to be the mass of the filament ns1 (i.e., \(M_{\text{ns1}}\)). Note that at least four peaks (or condensations) in column density are found within these three clumps.

The values of \(M_{\text{line,obs}}\) for the filaments ns1 and ns2 are also computed to be \(\sim 130\) and \(\sim 45\) \(M_\odot\) pc\(^{-1}\), respectively. These values are much higher than \(M_{\text{line,crit}} \sim 32\) \(M_\odot\) pc\(^{-1}\) (at \(T = 20\) K). Hence, there are two thermally supercritical filaments in the site S234.

Figure 11. Position–velocity plots toward the site S234. (a) Latitude–velocity plot of \(^{12}\)CO. (b) Longitude–velocity plot of \(^{12}\)CO. (c) Latitude–velocity plot of \(^{13}\)CO. (d) Longitude–velocity plot of \(^{13}\)CO. In both the left panels, the CO emission is integrated over longitude from 173:13 to 173:83. In both the right panels, the CO emission is integrated over latitude from \(-0.442\) to 0:259. In each plot, a solid line (in blue) indicates the position of the star BD+34\(^{\circ}\)1054 (see also Figure 10(a)).
Figure 12. (a) A zoomed-in map of integrated $^{12}$CO ($J = 1$–$0$) emission toward the elongated features (see the dotted–dashed box in Figure 10(a)). The $^{12}$CO emission is integrated over the velocity range from $-17.75$ to $-10$ km s$^{-1}$. (b) The $^{13}$CO first-order moment map. The bar at the top indicates $V_{lsr}$ (in km s$^{-1}$). (c) Latitude–velocity plot of $^{12}$CO. (d) Longitude–velocity plot of $^{12}$CO. (e) Latitude–velocity plot of $^{13}$CO. (f) Longitude–velocity plot of $^{13}$CO. In panels (c) and (e), the CO emission is integrated over longitude from $173^\circ.44$ to $173^\circ.72$. In panels (d) and (f), the CO emission is integrated over latitude from $-0^\circ.21$ to $0^\circ.25$. 

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3.3.4 Embedded Young Stellar Objects in S234

Figures 14(a) and (b) display the dereddened color–color plot (i.e., \(K - [3.6]_0\) and \([3.6] - [4.5]_0\)) and the NIR color–magnitude plot (i.e., \(H - K\) versus \(K\)) of point-like objects in the site S234, respectively. Color–color and color–magnitude schemes give 251 YSOs (27 Class I and 224 Class II) and 122 YSOs, respectively. Figure 15(a) shows the spatial distribution of the YSOs overlaid on the column density map. Figure 15(b) presents the overlay of the surface density contours of YSOs on the column density map. The YSO density contour levels are 3, 5, 10, and 25 YSOs pc\(^{-2}\). More detailed descriptions for obtaining the surface density map are given in Dewangan et al. (2017e). The clusters of YSOs are seen toward the filaments ns1, Stock 8, and dust condensations (i.e., dc1, dc2, and dc3), revealing ongoing SF activity toward them. The condensation dc2 contains both Class I and Class II YSOs, while only Class II YSOs are found toward dc1 and dc3.

3.3.5 Embedded Condensations in the Filament ns1

Figures 16(a) and (b) display the column density and first-moment maps of the filaments ns1 and ns2. The surface density

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**Table 2. Herschel Clumps Detected toward the Site S234 and Their Physical Properties**

(see Figures 13(b) and (c))

| ID | \(l\) (deg) | \(b\) (deg) | \(R_e\) (pc) | \(M_{clump}\) (\(M_\odot\)) |
|----|-------------|-------------|--------------|-------------------|
| 1  | 173.635     | 0.142       | 1.1          | 60                |
| 2  | 173.623     | 0.088       | 1.6          | 178               |
| 3  | 173.604     | 0.002       | 1.5          | 154               |
| 4  | 173.542     | -0.025      | 1.7          | 365               |
| 5  | 173.507     | -0.068      | 1.8          | 593               |
| 6  | 173.460     | -0.114      | 1.3          | 196               |
| 7  | 173.410     | -0.110      | 1.0          | 85                |
| 8  | 173.375     | -0.118      | 0.9          | 42                |
| 9  | 173.394     | -0.145      | 1.3          | 119               |
| 10 | 173.445     | -0.196      | 0.9          | 39                |
| 11 | 173.464     | -0.161      | 1.2          | 83                |
| 12 | 173.390     | -0.013      | 1.8          | 154               |
| 13 | 173.316     | -0.025      | 1.1          | 63                |
| 14 | 173.273     | -0.064      | 0.5          | 10                |
| 15 | 173.273     | -0.110      | 1.0          | 48                |
| 16 | 173.246     | -0.126      | 0.9          | 38                |
| 17 | 173.266     | -0.173      | 1.2          | 85                |
| 18 | 173.223     | -0.208      | 0.5          | 13                |
| 19 | 173.262     | -0.204      | 1.3          | 100               |
| 20 | 173.312     | -0.254      | 1.5          | 100               |
| 21 | 173.332     | -0.215      | 1.0          | 72                |
| 22 | 173.367     | -0.219      | 0.8          | 40                |
| 23 | 173.336     | -0.313      | 1.9          | 323               |
| 24 | 173.386     | -0.336      | 1.9          | 185               |
| 25 | 173.472     | -0.309      | 1.7          | 142               |
| 26 | 173.690     | -0.227      | 0.5          | 13                |
| 27 | 173.701     | -0.266      | 0.7          | 20                |
| 28 | 173.725     | -0.266      | 1.1          | 58                |
| 29 | 173.690     | -0.359      | 1.1          | 73                |
| 30 | 173.662     | -0.383      | 0.7          | 24                |
| 31 | 173.305     | 0.033       | 0.9          | 35                |
| 32 | 173.410     | 0.166       | 0.6          | 15                |

**Note.** Table lists Herschel clump ID, position \((l, b)\), deconvolved effective radius of the clump \((R_e)\), and clump mass \((M_{clump})\).
The extinction vector is also drawn in the panel (e.g., Flaherty et al. 2007). (b) Color–magnitude ($H - K$ vs. $K$) plot of point-like objects. In each panel, circles and triangles indicate Class I and Class II YSOs, respectively. In both panels, the dots (in gray) present the stars with only photospheric emissions. We have randomly plotted only some of these stars in both panels.

Contours of YSOs are also overlaid on the first-moment map. The supercritical filament ns2 is associated with three clumps (nos. 1–3), where YSOs are not found. No radio continuum emission is observed toward the filament ns2. This indicates that the filament ns2 seems to be at an early stage of fragmentation.

On the other hand, the supercritical filament ns1 hosting three clumps (nos. 4–6) is seen with a large number of YSOs. In the column density map (resolution $\sim 37\arcsec$, or 0.5 pc at a distance of 2.8 kpc), we find at least four distinct condensations, designated as c1–c4, within three clumps in the direction of the filament ns1. The boundary of each condensation is traced with the column density contour of $28.3 \times 10^{20} \text{cm}^{-2}$ (see Figure 16(a)). The peak column densities of c1, c2, c3, and c4 are found to be $\sim 8.6 \times 10^{21} \text{cm}^{-2}$ ($A_V = 9.2 \text{mag}$), $\sim 10 \times 10^{21} \text {cm}^{-2}$ ($A_V = 10.7 \text{mag}$), $\sim 6 \times 10^{21} \text{cm}^{-2}$ ($A_V = 10.7 \text{mag}$), and $\sim 6 \times 10^{21} \text{cm}^{-2}$ ($A_V = 6.4 \text{mag}$), respectively. Here, we use a conversion relation, i.e., $A_V = 1.07 \times 10^{-21} N(\text{H}_2)$ (Bohlin et al. 1978). The masses (radius) of c1, c2, c3, and c4 are computed to be $\sim 130 M_\odot$ ($\sim 0.6 \text{pc}$), $\sim 170 M_\odot$ ($\sim 0.75 \text{pc}$), $\sim 300 M_\odot$ ($\sim 0.9 \text{pc}$), and $\sim 70 M_\odot$ ($\sim 0.5 \text{pc}$), respectively.

Based on the $^{13}$CO line data, Mach numbers are derived for the condensations c1, c2, c3, and c4 to be 2.4, 3.1, 2.7, and 2.2, respectively, indicating that all the condensations are supersonic. Mach number is defined by the ratio of non-thermal velocity dispersion ($\sigma_{\text{NT}}$) to sound speed ($a_s$). We have also computed the ratio of thermal to non-thermal pressure ($P_{\text{NT}} = a_s^2/\sigma_{NT}^2$; Lada et al. 2003). The values of $P_{\text{NT}}$ for c1, c2, c3, and c4 are estimated to be 0.17, 0.11, 0.14, and 0.20, respectively. This suggests that the non-thermal pressure is higher than the thermal pressure in all the condensations. One can estimate the sound speed $a_s = (kT_{\text{kin}}/\mu m_H)^{1/2}$ using the value of gas kinetic temperature ($T_{\text{kin}}$) and mean molecular weight ($\mu = 2.37$; approximately 70% H and 28% He by mass). The non-thermal velocity dispersion is given by

$$\sigma_{\text{NT}} = \sqrt{\frac{\Delta V^2}{8 \ln 2} - \frac{kT_{\text{kin}}}{29 m_H}} = \sqrt{\frac{\Delta V^2}{8 \ln 2} - \sigma_T^2},$$

where $\Delta V$ is the measured FWHM linewidth of the observed $^{13}$CO spectra, $\sigma_T = (kT_{\text{kin}}/29 m_H)^{1/2}$ is the thermal broadening for $^{13}$CO at $T_{\text{kin}}$, and $m_H$ is the mass of a hydrogen atom. The measured $\Delta V$ values for c1, c2, c3, and c4 are 1.5, 1.8, 1.6, and 1.4 km s$^{-1}$, respectively. In the calculation, we have taken the $T_{\text{kin}}$ to be $\sim 19 \text{ K}$ (see Section 3.3.3). The estimated values of $\sigma_{\text{NT}}$ for c1, c2, c3, and c4 are 0.62, 0.78, 0.69, and 0.57 km s$^{-1}$, respectively. The ratio of $\sigma_{\text{NT}}/a_s$ (i.e., Mach number) is also calculated for the filament ns1 to be $\sim 3$, indicating that the thermally supercritical filament ns1 is supersonic. One can also consider the contribution of the non-thermal gas motions in the estimate of the critical line mass ($M_{\text{line, crit}}$), which is known as the virial line mass (i.e., $M_{\text{line, vir}}$; André et al. 2014; Kainulainen et al. 2016). One can write the expression $M_{\text{line, vir}} = [1 + (\sigma_{\text{NT}}/a_s)^2] \times [16 M_\odot \text{pc}^{-1} \times (T_{\text{gas}}/10 \text{ K})]$. In the case of the filament ns1, the value of $M_{\text{line, vir}}$ ($\sim 320 M_\odot \text{pc}^{-1}$) is more than 10 times higher than $M_{\text{line, crit}}$ ($\sim 32 M_\odot \text{pc}^{-1}$ at $T = 20 \text{ K}$), and is also larger than $M_{\text{line,obs}}$ ($\sim 130 M_\odot \text{pc}^{-1}$). The significance of these estimates is discussed in Section 4.4.

Using the Spitzer 4.5 $\mu$m image, a zoomed-in view of ns1 is shown in Figure 16(c). The image is also overlaid with the YSO surface density contours, the positions of 88 YSOs (9 Class I and 79 Class II), and the GMRT radio contours. The radio continuum emission is absent toward all the four condensations. Considering the detections of both Class I and
Class II YSOs, we take the SF timescale to be 1–2 Myr in the filament ns1 (e.g., Jose et al. 2008; Evans et al. 2009). We have also determined the star formation efficiency (SFE) and the star formation rate (SFR) in the filament ns1. In general, the low-mass star-forming regions follow a log-normal initial mass function with a characteristic mass of 0.5 $M_\odot$ (e.g., Chabrier 2003). Hence, we assume a mean mass of 0.5 $M_\odot$ for each YSO in the filament ns1. About five Class II YSOs appear away from the condensations or surface density contours (see Figure 16(c)). Hence, we compute a total mass of 80 YSOs in the filament ns1 (i.e., $M_{\text{ysos}} = 80 \times 0.5 M_\odot = 40 M_\odot$). Adopting the values of $M_{\text{ysos}}$ and the total mass of the filament ns1 (i.e., $M_{\text{ns1}} = 1154 M_\odot$), we have obtained the SFE (i.e., $M_{\text{ysos}}/(M_{\text{ysos}} + M_{\text{ns1}})$) to be $\sim$0.033 (or $\sim$3.3%). Following the work of Evans et al. (2009), the SFR (i.e., $M_{\text{ysos}}/t_d$) is estimated to be $\sim$40–20 $M_\odot$ Myr$^{-1}$, where $t_d$ is the SF timescale (i.e., $\sim$1–2 Myr). This quantitative analysis indicates the intense SF activity in the thermally supercritical filament ns1.

4 Discussion

4.1 Large-scale Structure in the Direction of $l = 172^\circ 8$, $b = 1^\circ 5$

In Figure 17(a), we present an integrated $^{12}$CO emission map toward $l = 172^\circ 8$, $b = 1^\circ 5$, and the molecular emission is integrated over the velocity interval $[-26, 0]$ km s$^{-1}$. An extended structure is seen in the molecular intensity map (see the dotted–dashed ellipse in Figure 17(a)). Earlier, Kang et al. (2012) and Kirsanova et al. (2017) also reported a similar extended shell-like structure/bubble-shaped nebula in the same longitude direction (see Figure 5 in Kang et al. 2012, and Figure 1 in Kirsanova et al. 2017). In Figure 17(b), the Galactic southern side of the extended structure is also presented using the Herschel 500 $\mu$m image, where our selected star-forming regions (i.e., S234 ($V_{\text{lsr}} \sim -13.4$ km s$^{-1}$; $d = 2.8$ kpc), IRAS 05220+3455 ($V_{\text{lsr}} \sim -10$ km s$^{-1}$; $d = 1.3$ kpc), IRAS 05231+3512 ($V_{\text{lsr}} \sim -6$ km s$^{-1}$), and S237 ($V_{\text{lsr}} \sim -4.5$ km s$^{-1}$; $d = 2.3$ kpc) are located (see the solid box in Figure 17(b)). The active star-forming complex G173+1.5 is located on the Galactic northern side of the extended structure (at $d \sim 1.8$ kpc and $V_{\text{lsr}} \sim -20$ km s$^{-1}$), where five Sharpless H II regions S231–S235 are distributed. These star-forming regions appear to be distributed toward the edges of the extended molecular structure. However, in the direction of the extended structure, different velocity components/star-forming sites are traced in the velocity range $[-26, 0]$ km s$^{-1}$, and are situated at different distances. This implies that the extended molecular structure cannot be considered as a single physical system.

Previously, Kang et al. (2012) reported the existence of an old supernova remnant (SNR) FVW 172.8+1.5 (age $\sim$0.3 Myr) in the direction of $l = 172^\circ 8$, $b = 1^\circ 5$, and suggested that the SNR is responsible for the extended shell-like structure/bubble-shaped nebula observed in the same longitude direction (see Figure 5 in their paper). They adopted a systemic velocity ($V_{\text{sys}}$) and the distance to FVW 172.8+1.5 to be $\sim$20 km s$^{-1}$ and $\sim$1.8 kpc, respectively, which are very similar to those for the H II complex G173+1.5. Hence, these authors pointed out that the SNR originates inside the H II complex G173+1.5. They proposed that the energetics of the SNR (with a kinetic energy $\sim 2.5 \times 10^{50}$ erg) may have affected the SF activity in the H II complex G173+1.5 and our selected star-forming sites. However, the SNR with an age of $\sim$0.3 Myr is too young to be a triggering agent. This is supported by the fact that the average ages of YSOs are computed to be $\sim$0.4–3 Myr (e.g., Evans et al. 2009), and YSOs are utilized as an excellent tracer for inferring SF activity in a given star-forming site. Kang et al. (2012) further proposed that the parent stellar association of the SNR could have influenced the birth of the massive OB stars seen near the edges of the extended structure. However, Kirsanova et al. (2014)
Figure 16. (a) A zoomed-in view of the Herschel column density map toward the elongated features (see the dotted–dashed box in Figure 15(b)). The column density contours with levels of $10^{20}$ cm$^{-2}$ $(13.3, 28.3, 38.5)$ are also drawn in the map. The peaks of four condensations, designated as c1–c4, are also highlighted in the map. (b) Velocity-field (moment 1) map of $^{12}$CO overlaid with the surface density contours of YSOs (in black), which are the same as in Figure 15 (see also Figure 12(b)). (c) Overlay of YSO surface density and contours of GMRT 610 MHz radio continuum emission on the Spitzer 4.5 μm image (see the dotted–dashed box in Figure 16(a)).
discussed that shock waves from the SNR could not trigger the formation of S235. Based on a photometric and spectroscopic study, Marco & Negueruela (2016) also rejected any influence of large-scale shocks on the SF in the site S234. Considering the observed distances and molecular velocity ranges, we do not find any physical association of our selected sites with the SNR or its parent stellar association (see also Marco & Negueruela 2016). Together, the proposed scenario of Kang et al. (2012) is unlikely to be applicable in our selected star-forming sites (i.e., S234, V582, IRAS 05220+3455, and S237).

Figure 17. (a) Large-scale map of integrated $^{12}$CO ($J = 1 \rightarrow 0$) emission in the direction of $l = 171^\circ 7-174^\circ 1$. The plus symbol is the same as in panel (a).

4.2 Supercritical Filaments in the Direction of $l = 171^\circ 7-174^\circ 1$

In the direction of our selected longitude range, the sites S234, V582, IRAS 05220+3455, and IRAS 05231+3512 are spatially seen in the infrared images. Based on the existing distance estimates (e.g., Marco & Negueruela 2016) and our analysis of molecular line data, we find that these sites are not part of the same physical system (see also Section 4.1). Using the Herschel submillimeter continuum images, we have identified at least five filamentary features (ff1, ff2, ff3, ns1, and ns2) toward $l = 171^\circ 7-174^\circ 1$. The site IRAS 05231+3512 is found to be embedded in the filament ff1, while the filament ff2 contains the sites V582 and IRAS 05220+3455. In the site S234, two embedded filaments (i.e., ns1 and ns2) are investigated in the direction of a previously known nebulous stream feature. One can note that there is no estimate of the distance to the site IRAS 05231+3512 in the literature, but we have used 1.3 kpc in this work. As highlighted earlier, the sites IRAS 05231+3512 ($V_{lsr} \sim -6$ km s$^{-1}$) and IRAS 05220+3455 ($V_{lsr} \sim -10$ km s$^{-1}$; $d = 1.3$ kpc) do not belong to a single system (see Section 3.1). Hence, it is possible that the site IRAS 05231+3512 could be located at a distance ranging from 1.3 to 2.0 kpc. This distance range can be supported by the fact that there is another nearby open cluster NGC 1907 ($l = 172^\circ 6, b = +0^\circ 3; V_{lsr} \sim 0.1$) located at a distance of $\sim 1.8$ kpc (e.g., Marco & Negueruela 2016).

In order to study the filaments, their observed line masses are computed and then compared with a critical line mass in an equilibrium state. As discussed in Section 3.2, the line mass of an infinite and isolated cylinder in equilibrium between thermal and gravitational pressures can be determined using a given temperature value (e.g., Ostriker 1964). The thermally supercritical filaments follow the condition $M_{line,obs} > M_{line, crit}$, whereas thermally subcritical filaments satisfy the condition $M_{line,obs} < M_{line, crit}$. The supercritical filaments can collapse radially perpendicular to their main long axis. In this context, gravitational fragmentation is an important physical processes in explaining the observed clumps in filaments (e.g., Ostriker 1964; Inutsuka & Miyama 1997; Hartmann 2002; Arzoumanian et al. 2013; André et al. 2014; Kainulainen et al. 2016; Williams et al. 2018). With the help of the Herschel maps of column density and temperature, the features ff1, ff2, ff3, ns1, and ns2 are consistent with the condition of thermally supercritical filaments. In recent years, researchers have also tried to explore embedded filaments at an early stage of fragmentation, where SF activity is not yet started or there is very little sign of ongoing SF (e.g., Kainulainen et al. 2016). Such filaments may preserve the initial conditions of gravitational fragmentation. A comparison study of YSOs against clumps in filaments can provide an important clue to assess different evolutionary stages of filaments. More detailed discussion concerning SF in the thermally supercritical filaments is presented in Sections 4.3 and 4.4.

4.3 Star Formation Scenario in the Sites V582, IRAS 05220+3455, and IRAS 05231+3512

In the $\sim 1^\circ 17 \times 0^\circ 81$ area of V582, three filaments are identified—ff1, ff2, and ff3—and they are classified as thermally supercritical. The column density map has shown the existence of condensations/clumps in these filaments.
Hence, the radial collapse scenario appears to operate in these filaments. We have found fewer infrared-excess sources in the two filaments fl1 and fl3, where the radio continuum emission is also not detected. This implies that the filament fl1 harboring IRAS 05231+3512 may be very young, and it seems to be located toward the Galactic southern edge of the extended molecular structure (see Figures 17(a) and (b)). Hence, considering the distance uncertainty of this IRAS site (see Section 4.2) and the age of the young SNR (see Section 4.1), the formation of the filament fl1 could be influenced by the SNR shock. In Figure 5(b), the observed velocity gradients along the filament fl1 appear to indicate accretion in the filamentary cloud (e.g., Vázquez-Semadeni et al. 2009; Arzoumanian et al. 2013); however, protostellar feedback cannot be completely ignored for the velocity gradient in the filament fl1.

In the thermally supercritical filament fl2, a group of YSOs is seen around IRAS 05220+3455, and a cluster of YSOs and at least five radio continuum peaks are also observed toward the site V582. The cometary globules and bright-rimmed clouds associated with the site V582 are seen at one end of fl2. Recently, Kun et al. (2017) suggested that SF in the nearby environment of V582 might be triggered by the radiation field of a few hot members of Aur OB1 (i.e., HD 35633 or LS V +34°23). However, Marco & Negueruela (2016) found the object HD 35633 to be the main source powering the site S234. Hence, SF in the site V582 cannot be affected by the object HD 35633. Considering the feedback of massive stars, the presence of massive B-type stars may be responsible for the bright-rimmed clouds and cometary globules in the site V582.

Based on the number of YSOs detected in the three filaments (see Section 3.2), we suggest that the filaments fl1–fl3 and fl2 represent two different evolutionary stages. The filament fl2 appears more evolved than the other two. Taking into account the existence of the supercritical filaments, our results favor the onset of the radial collapse process in the filaments fl1, fl2, and fl3.

4.4 Star Formation Scenario in the Site S234

In Section 3.3, we studied the molecular cloud associated with the site S234 at velocities of [−17.75, −10] km s⁻¹. This cloud hosts the nebulous stream, dust shell, young open cluster Stock 8, and dust condensations. Several OB stars were reported in the cluster Stock 8 by Marco & Negueruela (2016). Marco & Negueruela (2016) found the object LS V +34°23/HD 35633 to be the main source exciting S234 (see the position of this object in Figure 18). The GMRT radio continuum emission at 610 MHz is detected toward the dust shell, Stock 8, and dust condensations.

Earlier works suggested an age of 4–6 Myr for the open cluster Stock 8 (e.g., Marco & Negueruela 2016), and the lifetime of SF in the nebulous stream was reported to be ~1 Myr (e.g., Jose et al. 2008). Jose et al. (2008) argued that stars in Stock 8 represent second-generation SF activity, which was triggered by the first-generation stars in the site S234. The nebulous stream was classified as an active region of recent SF, where the small obscured cluster CC 14 and a significant number of YSOs were identified (e.g., Jose et al. 2008; Marco & Negueruela 2016). It was suggested that the ionizing feedback of OB stars in Stock 8 (and the first-generation stars) has not reached the nebulous stream. Hence, these OB stars may not influence the SF in the nebulous stream (e.g., Jose et al. 2008). The nebulous stream was characterized as a bright rim or an ionization front, and was excited by a massive O-type star (i.e., BD +34°1058) in the site S234 (e.g., Jose et al. 2008). They suggested that this source was not part of Stock 8 and the first-generation stars (see the position of this source in Figure 18).

In this work, we have identified two thermally supercritical filaments ns1 and ns2 toward the nebulous stream (see Section 3.3.3). The ~8.9 pc long filament ns1 (at $T_d$ ~ 19 K) is identified as the most interesting feature in the site S234, and is surrounded by an extended temperature structure at $T_d$ = 27–30 K. The observed temperature structure can be explained by heating from the massive OB stars in the site S234. We find that molecular gas in the filament ns1 (around −13 km s⁻¹) is redshifted with respect to the molecular gas in other features in the site S234 (around −15 km s⁻¹). This implies that the filament ns1 appears away from the other features in the site S234. Additionally, the filament ns1 is a relatively denser region in the molecular cloud associated with the site S234. For these reasons, the pre-existing molecular gas in the filament ns1 is not destroyed by the feedback of massive OB stars in the site S234. But at the same, the filament also seems to be influenced by these massive stars (see Figure 18). In Figure 18, we present the Spitzer-IRAC ratio map of 4.5 µm/3.6 µm emission in the direction of the site S234. As discussed in Section 3.2, the dark or gray regions in the ratio map help us to trace the photon-dominated regions in the site S234, suggesting the impact of massive stars in their surroundings.

The supercritical filament ns1 contains three clumps, which further host at least four condensations. These condensations are distributed along the filament. The intense SF activity (having SFE ~3.3% and SFR ~40–20 $M_\odot$ Myr⁻¹) is traced in the filament ns1. Furthermore, the thermally supercritical filament ns1 is also supersonic. In Section 3.3.5, we find $M_{\text{line, vir}} > M_{\text{line, obs}}$ for the filament ns1. This indicates that the feedback of massive stars as an external agent may provide the
necessary support to the filament ns1 against turbulence, and may be responsible for the intense SF activity in the filament. It is also favored by the presence of the observed age gradient in the site S234. More recently, Xu et al. (2018) also found similar results in the filamentary molecular cloud G47.06+0.26. Our interpretation is in agreement with the process of radiation-driven implosion (RDI; see Bertoldi 1989; Lefloch & Lazareff 1994), where the expanding ionized region initiates the instability and helps to collapse the pre-existing dense regions in a given molecular cloud.

On the other hand, no SF is seen in the thermally supercritical filament ns2 containing three Herschel clumps. Hence, the filament ns2 seems to be at an early stage of fragmentation. To obtain more insight into the physical conditions of the filaments, our multi-wavelength data analysis demands a high-density tracer and high-resolution molecular line observations for the site S234.

5 Summary and Conclusions

Using a multi-wavelength approach, we present an extensive study of the star-forming sites IRAS 05231+3512, IRAS 05220+3455, V582, and S234 located toward \( l = 171^\circ 7−174^\circ 1, b = −0^\circ 6−0^\circ 52 \). The goal of the present work is to understand the ongoing physical processes in these sites. The major results of this paper are as follows.

1. The molecular clouds associated with the sites S234, IRAS 05231+3512, and V582 are traced in the velocity ranges \([-17.75, -10]\) km s\(^{-1}\), \([-8.5, -1]\) km s\(^{-1}\), and \([-12.5, -7.5]\) km s\(^{-1}\), respectively. Based on the observed radial velocities and available distance estimates, we find that these three sites do not belong to a single physical system.

2. Based on the Herschel data of the \( \sim1^\circ 17 \times 0^\circ 81 \) area of V582, at least three filamentary features (i.e., ff1 (length \( \sim9.5\) pc; mass \( \sim355 M_\odot \)), ff2 (length \( \sim12.7\) pc; mass \( \sim362 M_\odot \)), and ff3 (length \( \sim6.9\) pc; mass \( \sim182 M_\odot \))) are identified with temperatures of \( \sim14−18\) K.

3. The feature ff1 hosts IRAS 05231+3512, while other two sites IRAS 05220+3455 and V582 are embedded in the feature ff2. With the help of the CO line data, the sites IRAS 05220+3455 and V582 are found to be physically linked, and are not associated with the site IRAS 05231+3512.

4. The observed line masses of the filaments ff1, ff2, and ff3 are derived to be \( \sim37, \sim28, \) and \( \sim26 M_\odot \) pc\(^{-1}\), respectively, which exceed the expected critical line mass at \( T = 10−15\) K (i.e., \( M_{\text{crit}} = 16−24 M_\odot \) pc\(^{-1}\)). Hence, the features ff1, ff2, and ff3 can be characterized as thermally supercritical filaments.

5. The NVSS radio continuum emission at 1.4 GHz is not observed toward the filaments ff1 and ff3, where very little SF activity is found.

6. In the filament ff2, a group of YSOs and massive B-type stars are depicted toward the site V582, and a cluster of YSOs is also seen around IRAS 05220+3455.

7. The cometary globules and bright-rimmed clouds linked with the site V582 are found at one corner of the filament ff2, and can be explained by the feedback of massive B-type stars.

8. In the site S234, using the molecular line data, the features ns1, ns2, dust shell, and dust condensation are physically connected in the velocity range \([-17.75, -10]\) km s\(^{-1}\). However, the molecular gas in the filament ns1 is redshifted (peaking around \( -13\) km s\(^{-1}\)) with respect to other molecular features (peaking around \( -15\) km s\(^{-1}\)) in the site.

9. In the site S234, two features (i.e., ns1 (length \( \sim8.9\) pc; mass \( \sim1154 M_\odot \); dust temperature \( \sim19\) K; \( M_{\text{line,obs}} \sim 130 M_\odot \) pc\(^{-1}\)) and ns2 (length \( \sim8.7\) pc; mass \( \sim392 M_\odot \); dust temperature \( \sim19\) K; \( M_{\text{line,obs}} \sim 45 M_\odot \) pc\(^{-1}\)) are investigated as thermally supercritical filaments, and they host several dust clumps.

10. The Herschel temperature map reveals the filament ns1 around \( T_d \sim 19\) K surrounded by an extended temperature structure at 27–30 K. The ratio \( \sigma_{\text{SF}}/a_{\text{f}} \) (i.e., Mach number) for the filament ns1 is computed to be \( \sim3 \), indicating that the thermally supercritical filament ns1 is supersonic. Taking turbulence into account, our analysis reveals \( M_{\text{line,vir}} \sim 320 M_\odot \) pc\(^{-1}\) for the filament ns1.

11. At least four condensations (\( M_{\text{clump}} \sim 70−300 M_\odot \)) are observed in the filament ns1 and are not associated with the GMRT 610 MHz continuum emission.

12. The filament ns2 displays almost no SF activity, indicating that it is at an early stage of fragmentation.

13. Intense SF activity is observed in the filament ns1, where both Class I and Class II YSOs are identified. In the filament ns1, the SF efficiency and the SFR are estimated to be \( \sim3.3\% \) and \( \sim40−20 M_\odot \) Myr\(^{-1}\) (for a 1–2 Myr timescale), respectively.

Considering the existence of the thermally supercritical filaments in our selected longitude range \( l = 171^\circ 7−174^\circ 1 \), our results suggest the onset of the radial collapse process in the filaments ns2, ff1, ff2, and ff3. At least three filaments—ff1, ff3, and ns2—appear to be at an early stage of fragmentation, while the filaments ff2 and ns1 are associated with ongoing SF activity. In the site S234, our observational outcomes favor the triggered SF in the filament ns1. Together, different evolutionary stages of the filaments are investigated toward \( l = 171^\circ 7−174^\circ 1 \).

We thank the anonymous reviewer for constructive comments and suggestions. The research work at Physical Research Laboratory is funded by the Department of Space, Government of India. This work is based on data obtained as part of the UKIRT Infrared Deep Sky Survey. This publication made use of data products from the Two Micron All Sky Survey (a joint project of the University of Massachusetts and 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). The Canadian Galactic Plane Survey (CGPS) is a Canadian project with international partners. The Dominion Radio Astrophysical Observatory is operated as a national facility by the National Research Council of Canada. The Five College Radio Astronomy Observatory CO Survey of the Outer Galaxy was supported by NSF grant AST 94-20159. The CGPS is supported by a grant from the Natural Sciences and Engineering Research Council of Canada.
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