The Molecular Cloud S242: Physical Environment and Star-formation Activities

L. K. Dewangan1, T. Baug2, D. K. Ojha2, P. Janardhan1, R. Devaraj3, and A. Luna3

1 Physical Research Laboratory, Navrangpura, Ahmedabad-380 009, India; lokeshd@prl.res.in
2 Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India
3 Instituto Nacional de Astrofísica, Óptica y Electrónica, Luis Enrique Erro #1, Tonantzintla, Puebla, C.P. 72840, México

Abstract

We present a multi-wavelength study to probe the star-formation (SF) processes on a larger scale (∼1.05 × 0.56 pc) around the S242 site. The S242 molecular cloud is depicted in a velocity range from −3.25 to 4.55 km s⁻¹ and has a spatially elongated appearance. Based on the virial analysis, the cloud is prone to gravitational collapse. The cloud harbors an elongated filamentary structure (EFS; length ∼25 pc), which is evident in the Herschel column density map, and the EFS has an observed mass per unit length of ∼200 M☉ pc⁻¹, exceeding the critical value of ∼16 M☉ pc⁻¹ (at T = 10 K). The EFS contains a chain of Herschel clumps (Mclump ∼ 150–1020 M☉), revealing the evidence of fragmentation along its length. The most massive clumps are observed at both the EFS ends, while the S242 HII region is located at one EFS end. Based on the radio continuum maps at 1.28 and 1.4 GHz, the S242 HII region is ionized by a B0.5V–B0V type star and has a dynamical age of ∼0.5 Myr. The photometric 1–5 μm data analysis of point-like sources traces young stellar objects (YSOs) toward the EFS and the clusters of YSOs are exclusively found at both the EFS ends, revealing the SF activities. Considering the spatial presence of massive clumps and YSO clusters at both the EFS ends, the observed results are consistent with the prediction of an SF scenario of the end-dominated collapse driven by the higher acceleration of gas.

Key words: dust, extinction – H II regions – ISM: clouds – ISM: individual objects (Sh 2-242) – stars: formation – stars: pre-main sequence

1. Introduction

The Herschel continuum observations demonstrated clearly that the filaments are common features seen in the star-forming regions (e.g., André et al. 2010). The dust continuum maps have been utilized as a very useful tool to investigate the filaments and to infer the underlying structure(s) within the filaments. These filaments are observed at various scales and often contain the star-forming clumps and cores along their lengths (e.g., Schneider et al. 2012; Ragan et al. 2014; Contreras et al. 2016; Li & Urquhart 2016, and references therein). However, the physical mechanisms concerning their formation and their link to the star-formation (SF) processes are not well understood. The role of filaments in the formation of dense massive star-forming clumps and clusters is also unknown (e.g., Myers 2009; Schneider et al. 2012; Nakamura et al. 2014; Tan et al. 2014; André et al. 2016; Kainulainen et al. 2016). In star-forming regions, the knowledge of physical conditions, kinematics of the molecular gas, and masses per unit length of filamentary features can help us to understand the ongoing physical processes.

The star-forming region, LBN 182.30+00.07 or Sh 2-242 (hereafter S242) is situated at a distance of 2.1 kpc (Blitz et al. 1982). The H II region linked to the S242 site (hereafter S242 H II region) is ionized by a star BD+26 980 of spectral type B0V (Hunter & Massey 1990). In the S242 HII region, Fich et al. (1990) reported the radial velocity of Hα emission to be about −0.6 km s⁻¹. Using the CO line data, Blitz et al. (1982) estimated the radial velocity of molecular gas to be 0.0 ± 0.5 km s⁻¹ toward S242. Kawamura et al. (1998) also studied the molecular gas content of molecular clouds in Gemini and Auriga, including the S242 site using 13CO (1-0) emission (see S242 region around l = 182.40; b = 0°27 in Figures 1, 2, and 9(j) in Kawamura et al. 1998). They referred to the molecular cloud associated with S242 as the “182.4 +0.3” cloud (Vlsr ∼ 0.7 km s⁻¹; line width (∆V) = 2.1 km s⁻¹) and estimated the mass of the cloud (Mcloud) to be ∼7000 M☉ (radius ∼7 pc; see source ID #73 in Table 1 in Kawamura et al. 1998). The cloud appears to be spatially elongated in the 12CO (1-0) map (see Figures 1 and 9(j) in Kawamura et al. 1998). However, the identification of filaments and their role in SF processes are yet to be probed within the molecular cloud 182.4+0.3/S242. Snell et al. (1990) investigated a CO outflow toward IRAS 05490+2658 and found that this IRAS source is located ∼5′ east of the S242 H II region. Beuther et al. (2002) investigated two 1.2 mm peaks toward IRAS 05490+2658 with the IRAM 30 m telescope (spatial resolution ∼11″). The H2 emission at 2.12 μm is also traced near the IRAS 05490+2658 (see Figure A9 in Varricatt et al. 2010) and they also mentioned the presence of two clusters of infrared excess sources near the IRAS 05490+2658. Together, these previous studies indicate that the S242 is an active site of SF and also contains a massive star. However, the impact of the massive star in its vicinity has yet to be examined in this star-forming site. On a larger scale, the physical conditions around the S242 site have yet to be investigated. In this paper, we present a detailed multi-wavelength study of observations from optical, near-infrared (NIR), mid-infrared (MIR), far-infrared (FIR), sub-millimeter (sub-mm), millimeter (mm) to centimeter (cm) wavelengths, including the Giant Metre-wave Radio Telescope (GMRT) radio continuum map at 1.28 GHz and United Kingdom Infra-Red Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS) NIR data.

In Section 2, we give the description of the multi-band data sets utilized in the present work. In Section 3, the results concerning the physical environment and point-like sources are summarized. The possible SF processes are discussed in...
Section 4. Finally, the main results are summarized and concluded in Section 5.

2. Data and Analysis

In this work, we have selected a region of $\sim1^\circ.05 \times 0^\circ.56$ ($\sim38.5$ pc $\times 20.5$ pc at a distance of 2.1 kpc; central coordinates: $l = 182^\circ.217; b = 0^\circ.239$) around the S242 site. The target area is selected in such a way that it contains the previously known molecular cloud, "182.4+00.3." In the following, we provide a brief description of the adopted multi-wavelength data sets.

2.1. H$\alpha$ Image

We retrieved a narrow-band H$\alpha$ image at 0.6563 $\mu$m from the Isaac Newton Telescope (INT) Photometric H$\alpha$ Survey of the Northern Galactic Plane (IPHAS; Drew et al. 2005) survey database. The IPHAS imaging survey was carried out using the Wide-Field Camera (WFC) at the 2.5 m INT, located at La Palma. The WFC contains four 4k $\times$ 2k CCDs, in an L-shape configuration. The pixel scale is 0$^\prime$.33 (see Drew et al. 2005 for more details).

2.2. NIR (1–5 $\mu$m) Data

We utilized the NIR photometric magnitudes of point-like sources extracted from the UKIDSS DR10PLUS Galactic Plane Survey (GPS; Lawrence et al. 2007) and the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006; hereafter GPS-2MASS). The UKIDSS observations (resolution $\sim0^\prime.8$) were made with the WFCAM mounted on UKIRT. The 2MASS photometric data were utilized to calibrate the UKIDSS fluxes. In this work, we extracted only a reliable NIR photometric catalog. More information about the selection procedures of the GPS photometry can be obtained in Dewangan et al. (2015). To obtain more details

2.3. Mid-infrared (12–22 $\mu$m) Data

MIR images at 12 $\mu$m (spatial resolution $\sim6^\prime$) and 22 $\mu$m (spatial resolution $\sim12^\prime$) were obtained from the publicly available archival WISE$^5$ (Wright et al. 2010) database.

2.4. Far-infrared and Sub-millimeter Data

We utilized the Herschel Space Observatory data archives to obtain FIR and sub-mm continuum images. The processed level2.5 images at 70, 160, 250, 350, and 500 $\mu$m were downloaded using the Herschel Interactive Processing Environment (HIPE; Ott 2010). The beam sizes of the Herschel images at 70, 160, 250, 350, and 500 $\mu$m are 5$''$.8, 12$''$, 18$''$, 25$''$, and 37$''$, respectively (Griffin et al. 2010; Poglitsch et al. 2010). In this work, Herschel temperature and column density maps are produced using the Herschel continuum images, following the methods described in Mallick et al. (2015). The Herschel temperature and column density maps are obtained from a pixel-by-pixel spectral energy distribution (SED) fit with a modified blackbody to the cold dust emission at Herschel 160–500 $\mu$m (also see Dewangan et al. 2015). The Herschel 70 $\mu$m data are not included in the analysis, because the 70 $\mu$m emission is dominated by the ultraviolet (UV) heated warm dust. Here we provide a brief step-by-step explanation of the procedures.

The Herschel 160 $\mu$m image is in units of Jy pixel$^{-1}$, while the images at 250–500 $\mu$m are in units of surface brightness, MJy sr$^{-1}$. The plate scales of 160, 250, 350, and 500 $\mu$m images are 3$''$.2, 6$''$.1, 10$''$.9, and 14$''$.7 pixel$^{-1}$, respectively. Prior to the SED fit, the 160–350 $\mu$m images were convolved to the lowest angular resolution of the 500 $\mu$m image ($\sim37''$) and were converted into the same flux unit (i.e., Jy pixel$^{-1}$). Furthermore, we regrided these images to the pixel size of the 500 $\mu$m image ($\sim14''$). These steps were performed using the convolution kernels available in the HIPE software. Next, the sky background flux level was estimated to be 0.060, 0.133, 0.198, and −0.095 Jy pixel$^{-1}$ for the 500, 350, 250, and 160 $\mu$m images (size of the selected region $\sim13''4 \times 14''8$; centered at $l = 183^\circ.181; b = -0^\circ.354$), respectively. The negative flux value at 160 $\mu$m is obtained due to the arbitrary scaling of the Herschel 160 $\mu$m image. To avoid diffuse emission linked with the S242 site, the featureless dark field away from the selected target was carefully chosen for the background estimation.

Finally, to generate the temperature and column density maps, a modified blackbody was fitted to the observed fluxes on a pixel-by-pixel basis (see Equations (8) and (9) in Mallick et al. 2015). The fitting was performed using the four data points for each pixel, maintaining the dust temperature ($T_d$) and the column density ($N(H_2)$) as free parameters. In the analysis, we used a mean molecular weight per hydrogen molecule ($\mu_{H_2}$) of 2.8 (Kauffmann et al. 2008) and an absorption coefficient ($\kappa_\nu$) of 0.1 (v/1000 GHz)$^{2}$ cm$^{-2}$ g$^{-1}$, including a gas-to-dust ratio ($R_g$) of 100, with a dust spectral index ($\beta$) of 2 (see Hildebrand 1983). We considered flux uncertainties of the order of $\sim15\%$ in all Herschel images, based on the previously reported work by Launhardt et al. (2013). We describe the Herschel temperature and column density maps in Section 3.1.1.

2.5. Dust Continuum 1.1 mm Data

We also obtained Bolocam dust continuum sources at 1.1 mm ($\nu$2.1; Ginsburg et al. 2013) from Bolocam Galactic Plane Survey (BGPS). The effective full width at half maximum (FWHM) of the 1.1 mm map (Aguirre et al. 2011) is $\sim35''$.

2.6. Molecular 12$^{12}$CO Line Data

To trace the molecular cloud associated with the S242 site, the 2.6 mm 12$^{12}$CO data (beam size $\sim8''$) were obtained from the 1.2 m CFA telescope (Dame et al. 2001). The line data have a velocity resolution of 0.65 km s$^{-1}$ and a typical rms value of

---

2 http://www.astro.wisc.edu/sirf/glimpse360/
5 Wide Field Infrared Survey Explorer, which is a joint project of the University of California and the JPL, Caltech, funded by the NASA.
Based on the distribution of molecular emission, we selected a component (brightness 12CO emission, indicating the presence of a single velocity component) from the integrated 12CO intensity map presented in Figure 2, a velocity range from −3.25 to 4.55 km s\(^{-1}\) and is shown by a gray-scale contour map. The 12CO emission contours are shown with levels of 43%, 45%, 48%, 50%, 55%, 60%, 65%, 70%, 80%, 85%, 90%, 94%, and 98% of the peak value (i.e., 10.478 K km s\(^{-1}\)). The positions of two IRAS sources (IRAS 05488+2657 and IRAS 05483+2728) in our selected region are also marked by stars. The scale bar corresponding to 10 pc (at a distance of 2.1 kpc) is shown in the left corner. The dotted–dashed red box encompasses the area shown in Figures 2, 3(a), and 3(b). The map is smoothed with a Gaussian function with a radius of three.

### 3. Results

#### 3.1. Large-Scale Physical Environment around S242

In this section, we study the distribution of dense materials, molecular gas, and ionized emission toward S242, enabling us to probe the physical environment around the target region. The study of molecular line data is very essential to trace the physical association of different subregions seen in the large-scale map of a given star-forming region. Based on the CTA150 continuum map, the molecular cloud linked with the S242 site is depicted in Figure 1. The S242 molecular cloud is elongated to the direction of the EFS and is prominently observed in the Herschel sub-mm images at 250–500 \(\mu\)m. Note that the Bolocam 1.1 mm dust emission map does not trace the entire EFS as seen in the Herschel sub-mm images; however, the Bolocam clumps are detected toward the EFS (see Figure 2(c)). Figure 1, with the help of the CTA150 continuum data, we find a continuous velocity structure in the direction of S242 and the EFS is embedded within the S242 molecular cloud (see Figures 3(a) and (b)). In the velocity space, there is only one velocity component observed in the direction of the EFS (see Figures 2(b) and (d)). This implies the existence of a single EFS. The peak positions of 10 dust continuum sources at 1.1 mm are also shown in Figures 3(a) and (b) and are mainly distributed toward the EFS (also see Figure 1). Distribution of molecular gas in the direction of our selected field reveals an elongated molecular cloud. The S242 molecular cloud is depicted in a velocity range from −3.25 to 4.55 km s\(^{-1}\) and is shown by a gray-scale contour map. The 12CO emission contours are shown with levels of 43%, 45%, 48%, 50%, 55%, 60%, 65%, 70%, 80%, 85%, 90%, 94%, and 98% of the peak value (i.e., 10.478 K km s\(^{-1}\)). The positions of two IRAS sources (IRAS 05488+2657 and IRAS 05483+2728) in our selected region are also marked by stars. The scale bar corresponding to 10 pc (at a distance of 2.1 kpc) is shown in the left corner. The dotted–dashed red box encompasses the area shown in Figures 2, 3(a), and 3(b). The map is smoothed with a Gaussian function with a radius of three.

Figure 3(a) shows a three-color composite map made using the Herschel 250 \(\mu\)m in red, WISE 22 \(\mu\)m in green, and WISE 12 \(\mu\)m in blue. The images at wavelengths longer than 150 \(\mu\)m trace the cold dust emission, while the 12–70 \(\mu\)m emission is sensitive for the warm dust components. Figure 3(b) shows the Herschel sub-mm images overlaid with the NVSS 1.4 GHz continuum emission. The NVSS map allows us to infer the spatial distribution of ionized emission, which is only found toward the S242 site. In Figures 3(a) and (b), an extended filamentary structure (EFS; extension ∼25 pc; average width ∼1.3 pc), containing the S242 site, is revealed and is prominently observed in the Herschel sub-mm images at 250–500 \(\mu\)m. Note that the Bolocam 1.1 mm dust emission map does not trace the entire EFS as seen in the Herschel sub-mm images; however, the Bolocam clumps are detected toward the EFS (see Figure 2(c)). Figure 1, with the help of the CTA150 continuum data, we find a continuous velocity structure in the direction of S242 and the EFS is embedded within the S242 molecular cloud (see Figures 3(a) and (b)). In the velocity space, there is only one velocity component observed in the direction of the EFS (see Figures 2(b) and (d)). This implies the existence of a single EFS. The peak positions of 10 dust continuum sources at 1.1 mm are also shown in Figures 3(a) and (b) and are mainly distributed toward the EFS (also see Figure 1). Distribution of molecular gas in the direction of our selected field reveals an elongated molecular cloud. The S242 molecular cloud is depicted in a velocity range from −3.25 to 4.55 km s\(^{-1}\) and is shown by a gray-scale contour map. The 12CO emission contours are shown with levels of 43%, 45%, 48%, 50%, 55%, 60%, 65%, 70%, 80%, 85%, 90%, 94%, and 98% of the peak value (i.e., 10.478 K km s\(^{-1}\)). The positions of two IRAS sources (IRAS 05488+2657 and IRAS 05483+2728) in our selected region are also marked by stars. The scale bar corresponding to 10 pc (at a distance of 2.1 kpc) is shown in the left corner. The dotted–dashed red box encompasses the area shown in Figures 2, 3(a), and 3(b). The map is smoothed with a Gaussian function with a radius of three.

Figure 1. Distribution of molecular gas in the direction of our selected field reveals an elongated molecular cloud. The S242 molecular cloud is depicted in a velocity range from −3.25 to 4.55 km s\(^{-1}\) and is shown by a gray-scale contour map. The 12CO emission contours are shown with levels of 43%, 45%, 48%, 50%, 55%, 60%, 65%, 70%, 80%, 85%, 90%, 94%, and 98% of the peak value (i.e., 10.478 K km s\(^{-1}\)). The positions of two IRAS sources (IRAS 05488+2657 and IRAS 05483+2728) are also marked by stars. The scale bar corresponding to 10 pc (at a distance of 2.1 kpc) is shown in the left corner. The dotted–dashed red box encompasses the area shown in Figures 2, 3(a), and 3(b). The map is smoothed with a Gaussian function with a radius of three.
Section 3.1.1 for a quantitative estimate. This particular result gives a hint about the fragmentation of the filamentary cloud. To further infer this signature, we estimated the virial mass ($M_{\text{vir}}$) and the virial parameter ($M_{\text{vir}}/M_{\text{cloud}}$) of the S242 molecular cloud using the observed physical parameters. Using the NANTEN $^{12}$CO (1-0) line data (beam size $\sim 2\prime\prime$), Kawamura et al. (1998) reported $M_{\text{cloud}}$ ($\sim 7000 M_\odot$), radius ($R_c \sim 7$ pc), and line width ($\Delta V = 2.1$ km s$^{-1}$) for the S242 molecular cloud. The virial mass of a cloud of radius $R_c$ (in pc) and line-width $\Delta V$ (in km s$^{-1}$) is defined as $M_{\text{vir}}(M_\odot) = k R_c^2 \Delta V^2$ (MacLaren et al. 1988), where the geometrical parameter, $k = 126$, for a density profile $\rho \propto 1/r^2$. A virial parameter less than 1 indicates that the cloud is prone to collapse, and a parameter greater than 1 indicates that it is resistant to collapse.

In the present case, we obtain $M_{\text{vir}} \sim 3890 M_\odot$, which is less than $M_{\text{cloud}}$. This implies that the virial parameter is less than 1, suggesting that the cloud is unstable against gravitational collapse.

In Figures 3(a) and (b), we find that the S242 site has a shell-like appearance, where noticeable warm dust emission at MIR is seen. In general, the ionized gas and the warm dust emissions are seen systematically correlated within H II regions (e.g., Deharveng et al. 2010). With the knowledge of the presence and absence of the radio continuum emission, we find two distinct ends of the EFS. One EFS end contains the S242 H II region, while the other EFS end is seen without noticeable ionized emission (see Figure 3(b)). Note that the majority of the dust continuum sources at 1.1 mm are seen at both ends of the EFS.
H$_2$ is assumed to be 2.8, Areapix is the area subtended
N
m
182.217; 0.239
lb
H II region in our selected site probed in this paper.
molecular cloud, EFS, dust continuum sources at 1.1 mm, and
Large-scale view of the region around S242
The Astrophysical Journal, 845:34 (14pp), 2017 August 10
Dewangan et al.

Together, Figures 1 and 3 allow us to probe the S242 molecular cloud, EFS, dust continuum sources at 1.1 mm, and H II region in our selected site probed in this paper.

3.1.1. Herschel Temperature and Column Density Maps

In this section, the temperature and column density maps derived using the Herschel continuum images are discussed. The final temperature and column density maps (resolution ~37") are shown in Figures 4(a) and (b), respectively.

In the Herschel temperature map, the S242 H II region is associated with the considerably warmer gas ($T_d \sim 22–32$ K; see Figure 4(a)). The map clearly traces the spatial extent of warm dust emission linked with the S242 site, where the ionized emission is observed. The temperature map reveals temperature variations toward the EFS (see areas near both the EFS ends). The EFS is traced in a temperature range of about 10–12 K away from the S242 H II region. In Figures 4(b), 5(a), and 5(b), the EFS (length ~25 pc) is evident in the Herschel column density map at a contour level of $1.5 \times 10^{21}$ cm$^{-2}$ and several condensations are also seen toward this feature (also see Figure 5(c)). The S242 site is located in the highest column density region (peak $N$(H$_2$) $\sim 2.7 \times 10^{22}$ cm$^{-2}$; $A_V \sim 29$ mag).

Here, we used a relation ($A_V = 1.07 \times 10^{-21} N$(H$_2$); Bohlin et al. 1978) between optical extinction and hydrogen column density. In the column density map (see Figure 5(a)), the "clumpfind" IDL program (Williams et al. 1994) is employed to trace the clumps and to find their total column densities. We used several column density contour levels as an input parameter for the "clumpfind" and the lowest contour level was assigned at 3$\sigma$. Eighteen clumps are identified in the map and are labeled in Figure 5(c). Furthermore, the boundary of each clump is also shown in Figure 5(c). Eleven out of eighteen clumps (e.g., 1–11) are found toward the EFS. We have also determined the mass of each clump using its total column density. The mass of a single Herschel clump is estimated using the following formula:

$$M_{clump} = \mu_{H_2} m_p \text{Area}_{\text{pix}} \Sigma N(H_2),$$

where $\mu_{H_2}$ is assumed to be 2.8, Area$_{\text{pix}}$ is the area subtended by one pixel, and $\Sigma N(H_2)$ is the total column density. The mass of each Herschel clump is tabulated in Table 1. The table also lists the effective radius, the peak column density, the peak temperature, and the mean central number density ($n_c$) of each clump. The clump masses vary between 25 $M_\odot$ and 1020 $M_\odot$. We also find peak temperatures, mean central number densities, and peak column densities (corresponding extinction) of

Figure 3. Large-scale view of the region around S242 (size of the selected region $\sim 1.05 \times 0.56$ ($\sim 38.5$ pc $\times$ 20.5 pc at a distance of 2.1 kpc); centered at $l = 182.217; b = 0.239$). (a) The color composite map is the result of the combination of three bands (in logarithmic scale): 250 $\mu$m in red (Herschel), 22 $\mu$m in green (WISE), and 12 $\mu$m in blue (WISE). (b) The distribution of the sub-mm emission toward the region around S242. The color composite map is the result of the combination of three Herschel bands (500 $\mu$m (red), 350 $\mu$m (green), and 250 $\mu$m (blue)) and is overlaid with the NVSS 1.4 GHz contours. The 1.4 GHz contours (in red) are superimposed with levels of 0.55%, 1%, 2%, 3%, 4%, 5%, 6%, 30%, 60%, and 90% of the peak value (i.e., 0.377 Jy/beam). In both of the panels, the positions of dust clumps at 1.1 mm are marked by square symbols and other marked symbols are similar to those shown in Figure 1.
the clumps ranging from 10–26 K, 505–2575 cm$^{-3}$, and $(1.9–27) \times 10^{21}$ cm$^{-2}$ ($A_V = 2–29$ mag), respectively. The mean central number density of each clump refers to the average number density along the line of sight and is obtained from the peak column density divided by the size of each clump. Eleven clumps, which are distributed toward the EFS, have masses varying between 150 and 1020 $M_\odot$. Interestingly, massive clumps ($M_{\text{clump}} \sim 260, 700, 700, \text{and } 1020$ $M_\odot$) are spatially seen at both the EFS ends (also see Table 1). The virial mass analysis of these clumps is not performed in this paper, due to the non-availability of optically thin line data (such as NH$_3$ and CS).

We have also obtained a total column density inside the contour of $N$(H$_2$) = $1.5 \times 10^{21}$ cm$^{-2}$ and have computed a total mass of the EFS ($M_{\text{EFS}}$) to be ~5000 $M_\odot$. Adopting a value of $M_{\text{EFS}}$ and length of EFS (~25 pc), the mass per unit length is calculated to be ~200 $M_\odot$ pc$^{-1}$. Note that there is no knowledge of the inclination angle, $i$, of the EFS, and we have adopted $i = 0$ here for reference. Due to the inclination, the line mass can be affected by a factor of cos $i$ (e.g., Kainulainen et al. 2016). Hence, the observed mass per unit length value can be considered as an upper limit.

3.2. SF Activities in and around S242

The infrared excess emission displayed by sources is an extremely powerful utility to probe the embedded young stellar populations. In a given star-forming region, the knowledge of spatial distribution of these young stellar populations helps us to infer the SF activities. In this section, we describe the identification and classification schemes of young stellar objects (YSOs) using the GPS-2MASS and GLIMPSE360 photometric data from 1 to 5 $\mu$m. Furthermore, to investigate the young stellar clusters, the distribution of YSOs is also presented in and around S242.
The dereddened color–color space \((K-[3.6])_0 \text{ and } ([3.6]-[4.5])_0\) is a very promising tool to identify infrared-excess sources (e.g., Gutermuth et al. 2009). We computed the dereddened color–color plot \((K-[3.6])_0 \text{ and } ([3.6]-[4.5])_0\) using the GLIMPSE360 and 2MASS photometric data at 1–5 μm. The dereddened colors were obtained using the color excess ratios listed in Flaherty et al. (2007). Using the dereddened color conditions presented in Gutermuth et al. (2009), we obtain 192 (39 Class I and 153 Class II) YSOs in our selected region probed in this paper. One can also infer possible dim extragalactic contaminants from the selected YSOs with additional conditions (i.e., \([3.6]_0 < 15\) mag for Class I and \([3.6]_0 < 14.5\) mag for Class II) (e.g., Gutermuth et al. 2009). The dereddened 3.6 μm magnitudes were obtained using the observed color and the reddening laws (from Flaherty et al. 2007). In Figure 6(a), we show the \([K-[3.6]]_0 \text{ versus...
Table 1

| ID | l   | b   | R_c | M_{clump} | peak N(H_2) × 10^{21} | peak T_d | n_{_r} |
|----|-----|-----|-----|-----------|----------------------|---------|-------|
|    | deg | deg | pc  | (M_\odot) | (cm^{-2})             | (K)     | (cm^{-3}) |
| 1a | 182.453 | 0.197 | 1.2 | 260 | 6.9 | 16 | 930 |
| 2a | 182.403 | 0.247 | 1.7 | 1020 | 27 | 26 | 2575 |
| 3  | 182.341 | 0.247 | 1.4 | 420 | 13 | 18 | 1505 |
| 4  | 182.177 | 0.239 | 1.6 | 480 | 8.3 | 14 | 840 |
| 5  | 182.068 | 0.263 | 1.5 | 380 | 4.7 | 14 | 505 |
| 6  | 181.987 | 0.290 | 1.6 | 405 | 5.6 | 13 | 565 |
| 7  | 181.971 | 0.302 | 0.8 | 150 | 9 | 13 | 1820 |
| 8  | 181.928 | 0.325 | 1.2 | 350 | 7.2 | 13 | 970 |
| 9a | 181.917 | 0.364 | 1.5 | 700 | 15.8 | 16 | 1705 |
| 10 | 181.851 | 0.309 | 1.5 | 700 | 12.7 | 16 | 1370 |
| 11 | 181.777 | 0.329 | 1.0 | 150 | 3.6 | 13 | 580 |
| 12 | 182.030 | 0.364 | 0.9 | 100 | 2.8 | 12 | 505 |
| 13 | 182.006 | 0.368 | 0.8 | 125 | 5.1 | 16 | 1030 |
| 14 | 182.057 | 0.399 | 1.1 | 250 | 6.8 | 10 | 1000 |
| 15 | 182.037 | 0.414 | 1.1 | 265 | 6.7 | 10 | 985 |
| 16 | 181.870 | 0.453 | 0.5 | 25 | 1.9 | 18 | 615 |
| 17 | 181.127 | 0.119 | 0.5 | 35 | 2.1 | 17 | 680 |
| 18 | 182.193 | -0.021 | 0.5 | 45 | 3.3 | 15 | 1070 |

Note. Column 1 gives the IDs assigned to the clump. The table also lists positions, deconvolved effective radius (R_c), clump mass (M_{clump}), peak column density (N(H_2)), peak temperature (T_d), and mean central number density (n_{_r} = peak N(H_2)/(2 \pi R_c^2)). The column density value can also be used to obtain the extinction using the relation \epsilon_K = 1.07 × 10^{-21} N(H_2). The clump IDs 1–11 are distributed toward the EFS containing the S242 site (see Figure 5(c)).

a It is found at the EFS end.

The Astrophysical Journal, 845:34 (14pp), 2017 August 10

In this section, we study the individual groups or clusters of YSOs based on their spatial distribution and the statistical surface density utility. In Figures 7(a) and (b), we superimpose the surface density contours of YSOs on the Herschel column density and temperature maps. The surface density map of YSOs is produced using the nearest-neighbor (NN) technique (e.g., Gutermuth et al. 2009; Bressert et al. 2010; Dewangan et al. 2015). Using a 5″ grid and 6 NN at a distance of 2.1 kpc, the surface density map of 293 YSOs is computed in a manner similar to that described in Dewangan et al. (2015). The clusters of YSOs are mainly seen at both the EFS ends (see Figures 7(a) and 7(b)); however, there is a noticeable presence of young stellar populations toward the EFS without any clustering away from both of its ends (i.e., its center; see Figure 6(c)). Furthermore, a cluster of YSOs is also evident toward the Herschel clumps, nos. 14 and 15, which are spatially distributed away from the EFS (see Figure 7(a)).

Together, the SF activities have been found toward the clumps linked with the EFS and other Herschel clumps.

3.3.1. S242 H II Region

In Figure 8, we present a zoomed-in view of the S242 site using the Spitzer-IRAC ratio map and the radio continuum maps. In Figures 8(a) and (b), the area around the S242 site is chosen based on the spatial extent of the warm dust emission (see Figure 7(b)). In combination with the radio continuum map, the Spitzer-IRAC ratio map of 4.5 μm/3.6 μm emission is used here to infer the signatures of molecular outflows and the impact of a massive star on its surroundings (e.g., Dewangan et al. 2016, 2017). The IRAC 3.6 μm band harbors polycyclic aromatic hydrocarbon (PAH) emission at 3.3 μm as well as a prominent molecular hydrogen feature at 3.234 μm (ν = 1−0 O (5)). The IRAC 4.5 μm band contains a hydrogen recombination line Brα (4.05 μm) and a prominent molecular hydrogen line emission (ν = 0−0 S(9); 4.693 μm), which is produced by outflow shocks. It is known that IRAC 3.6 μm and 4.5 μm images have almost identical point response functions; therefore, the ratio of 4.5 to 3.6 μm images can be used to directly produce a ratio map of 4.5 μm/3.6 μm emission (see Figure 8; e.g., Dewangan et al. 2016). In Figure 8(a), we infer the bright and dark/black regions in the ratio map of 4.5 μm/3.6 μm emission. In the ratio 4.5 μm/3.6 μm map, the bright emission regions trace the excess of 4.5 μm emission, while the black or dark gray regions depict the excess of 3.6 μm emission. In Figures 8(a) and (b), the ionized emissions at 1.28 and 1.4 GHz are distributed within a shell-like morphology. Due to the presence of the 3.3 μm PAH feature in the 3.6 μm band, the dark/black regions surrounding the ionized emission appear to trace photodissociation regions (or photon-dominated regions, or PDRs). Furthermore, the bright emission regions at one end of the EFS containing the S242 site, where the radio continuum emission is absent and three clusters of YSOs are found, appear to trace the outflow activities (see Figure 8(b)). This interpretation can be supported by the presence of the CO and H_2 outflow signatures in the embedded clusters near IRAS 05490+268 (e.g., Snell et al. 1990; Varricatt et al. 2010).

In Figure 9(a), we present an Hα image overlaid with the NVSS 1.4 GHz emission, showing the spatial match between the radio continuum emission and the Hα emission. The position of a previously characterized BOV star (BD+26 980) appears near the peak of radio continuum emission. The surface density contours of the identified YSOs are also highlighted in Figure 9(a). In Figure 9(b), we show a three-color composite map made using the Herschel 70 μm in red, Spitzer 4.5 μm in green, and IPHAS Hα in blue. The color composite map is superimposed with the GMRT 1.28 GHz emission and...
positions of two 1.2 mm dust continuum peaks (from Beuther et al. 2002). In order to compare the spatial distribution of dust temperature and column density with the ionized emission, the Herschel temperature and column density maps of the S242 site are shown in Figures 9(c) and (d), respectively. We find the YSO clusters toward the high column density materials. Additionally, there is a lack of column density material within the S242 H II region. Earlier in Section 3.1.1, we mentioned the spatial correlation between the warm dust emission and the ionized emission (also see Figures 9(b) and (c)). In Figure 9, one can infer the zoomed-in view of the S242 site, tracing the spatial location of the ionized emission, warm dust emission, high column density material, and the embedded stellar populations.

Using the radio continuum maps, we also compute the Lyman continuum photons and the dynamical age (t_{dyn}) of the S242 H II region. Using the NVSS 1.4 GHz map and the clumpyfind algorithm, the integrated flux density (S_{ν}) and the radius (R_{H II}) of the H II region are determined to be 437 mJy and 1.84 pc, respectively. Following the equation given in Matsakis et al. (1976), the number of Lyman continuum photons (N_{UV}) is computed to be \sim 1.5 \times 10^{47} s^{-1} (log N_{UV} \sim 47.18) for the S242 H II region (see Dewangan et al. 2016, for more details). In this analysis, we used the integrated flux density value, a distance of 2.1 kpc, and the electron temperature of 10,000 K. The value of N_{UV} is found to be consistent with a single ionizing star of spectral type B0.5–B0V (see Table 2 in Panagia 1973 and also Smith et al. 2002). The estimate of N_{UV} at GMRT 1.28 GHz frequency also corresponds to a single ionizing star of B0.5–B0V spectral type. These calculations are also in agreement with the previously reported spectral type of the ionizing source of the S242 site (Hunter & Massey 1990).
The equation of the dynamical age of the HII region is given below at a radius $R_{\text{H II}}$ (e.g., Dyson & Williams 1980):

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

where $c_s$ is the isothermal sound velocity in the ionized gas ($c_s = 11 \text{ km s}^{-1}$; Bisbas et al. 2009), $R_{\text{H II}}$ is mentioned above, and $R_s$ is the radius of the Strömgren sphere $= (3 N_{\text{av}}/4\pi n_0^2 \alpha_B)^{1/3}$, where the radiative recombination coefficient $\alpha_B = 2.6 \times 10^{-13} \left( 10^4 \text{ K}/T \right)^{0.7} \text{ cm s}^{-1}$ (Kwan 1997). $N_{\text{av}}$ is mentioned above, and “$n_0$” is the initial particle number density of the ambient neutral gas). Considering a typical value of $n_0$ ($=10^3 \text{ cm}^{-3}$), we determined the dynamical age of the S242 HII region to be $\sim 0.5 \text{ Myr}$.

We have also utilized 21 cm H I line data toward the S242 site. Figure 10 shows 21 cm H I velocity channel maps of the S242 site. We find the black or dark gray regions in the H I channel maps, which trace the H I self-absorption (HISA) features (e.g., Kerton 2005). In a velocity range of 3.48–5.95 km s$^{-1}$, the shell-like HISA feature is evident in the channel maps. The existence of the HISA features can be explained by the presence of the residual amounts of very cold HI gas in molecular clouds (Burton et al. 1978; Baker & Burton 1979; Burton & Liszt 1981; Liszt et al. 1981; Dewangan et al. 2017).

4. Discussion

The cold dust continuum emission traced in the 160–1100 $\mu$m images has been used to probe the elongated filaments and the distribution of clumps in these filaments (e.g., Schneider et al. 2012; Ragan et al. 2014; Contreras et al. 2016; Li & Urquhart 2016, and references therein). It has been observed that the large-scale filaments are found to be unstable to radial collapse and fragmentation. One of the key questions in SF research is how the filaments fragment into dense clumps/cores that form a star. The gravitational fragmentation process can be employed to explain the presence of “dense clumps/cores” in filaments and can be inferred with a
knowledge of the line mass of the filament \( (M_{\text{line}}; \text{e.g., André et al. 2010}) \). It has been suggested that thermally supercritical filaments are associated with the prestellar clumps/cores and SF activity, where the mass per unit length is greater than the critical value \( (M_{\text{line,crit}}; \text{i.e., } M_{\text{line}} > M_{\text{line,crit}}) \). On the other hand, thermally subcritical filaments \( (M_{\text{line}} < M_{\text{line,crit}}) \) often lack \textit{Herschel} prestellar clumps/cores and embedded protostars \( \text{(André et al. 2010)} \). The critical mass per unit length \( (M_{\text{line,crit}} = 2c_s^2/G; \text{where } c_s \text{ is the isothermal sound speed—i.e.,} \sim 0.2 \text{ km s}^{-1} \text{ at } T = 10 \text{ K—and } G \text{ is the gravitational constant)} \) is needed for a filament to be gravitationally unstable to radial contraction and fragmentation along its length \( \text{(Inutsuka & Miyama 1997)} \). A critical line mass \( M_{\text{line,crit}} \) is equal to \( \sim 16 M_\odot \text{ pc}^{-1} \times (T_{\text{gas}}/10 \text{ K}) \) for gas filaments \( \text{(André et al. 2014)} \), hence one can find \( M_{\text{line,crit}} \sim 16 M_\odot \text{ pc}^{-1} \) at \( T = 10 \text{ K} \) \( \text{(e.g., Ostriker 1964; Kainulainen et al. 2016)} \).

Using the \(^{13}\text{CO} \) line data analysis, the elongated S242 molecular cloud is unstable against gravitational collapse. The EFS embedded within the S242 molecular cloud is the most prominent feature observed in the \textit{Herschel} column density map. The \textit{Herschel} temperature map traces \( \sim 10–12 \text{ K} \) toward the EFS (except close to the S242 \text{H II} region). The observed mass per unit length of EFS is computed to be \( \sim 200 M_\odot \text{ pc}^{-1} \), which is much higher than the critical masses per unit length \( (16–48 M_\odot \text{ pc}^{-1}) \) at \( T = 10–30 \text{ K} \). For the purpose of comparison, André et al. \( \text{(2016)} \) presented a table \( \text{(their Table 1)} \) containing the physical parameters of some well-documented filaments \( (M_{\text{line}} \sim 4500 M_\odot \text{ pc}^{-1} \text{ (DR21)}, \sim 290 M_\odot \text{ pc}^{-1} \text{ (Serpens South)}, \sim 50 M_\odot \text{ pc}^{-1} \text{ (Taurus B211/B213)}, \text{ and} \sim 20 M_\odot \text{ pc}^{-1} \text{ (Musca)}) \). The EFS also contains a chain of \textit{Herschel} clumps \( (M_{\text{clump}} \sim 150 \text{ to } 1020 M_\odot) \), depicting the evidence of fragmentation along its length. The most massive clumps are seen at both the EFS ends and the S242 \text{H II} region is traced at one of the EFS ends. The young stellar populations are also spatially found toward the EFS, indicating convincing evidence of ongoing SF activities \( \text{(see Section 3.2)} \). However, the clusters of YSOs are only observed at both the EFS ends \( \text{(see Section 3.3)} \). Most recently, Kainulainen et al. \( \text{(2016)} \) also found the fragmentation strongly at the ends of the Musca cloud. In the long \( \text{(but finite-sized)} \) filaments, numerical and analytical studies showed that the acceleration of gas is a function of the relative position along the filament and is the greatest at both ends \( \text{(Bastien 1983; Pon et al. 2011, 2012; Clarke & Whitworth 2015; see also Burkert & Hartmann 2004 for a study of shell geometry)} \). These higher accelerations indicate shorter local collapse timescales, suggesting the formation of fragments at the ends of the filament prior to its center \( \text{(Pon et al. 2011, 2012)} \). Pon et al. \( \text{(2011)} \) reported that the local collapse may act a factor of two-to-three faster at the ends of the filament than at its center \( \text{(see Figures 5 and 6 in Pon et al. 2011)} \). Additionally, Heitsch et al. \( \text{(2008)} \) presented three-dimensional models of molecular cloud formation in large-scale colliding flows, including self-gravity, and found that global collapse of a molecular cloud produces centrally located large-scale filaments, while local gravitational collapse can cause massive cores to form far away from the centers of molecular clouds on much shorter timescales than the global dynamical collapse time. Taking into account the existence of YSO clusters and massive clumps at both the EFS ends, the observed results are in agreement with the outcome of a model of the end-dominated collapse caused by the higher accelerations of gas. Presently, we do not have optically thin line data \( \text{(such as NH}_3 \text{ and CS)} \) for the EFS, hence, the high-resolution molecular line data will be required to further explore the EFS and its velocity structure.

It has been observationally evident that numerous complex processes involved in SF operate in a given star-forming complex \( \text{(e.g., Kang et al. 2010; Dewangan et al. 2016)} \). At least three YSO clusters are found at one EFS end and also appear to be found near the edges of the shell-like morphology.
linked to the S242 HII region (see Figures 7(a), 8(b), and 9(a)). Hence, the detection of YSO clusters surrounding the S242 HII region also indicates the applicability of the triggered SF scenario (via an expanding HII region) in the S242 site. The dynamical or expansion age of the HII region is computed to be \( \sim 0.5 \) Myr (for \( n_0 = 10^3 \text{ cm}^{-3} \), see Section 3.3.1). The average lifetimes of Class I and Class II YSOs are estimated to be \( \sim 0.44 \) Myr and \( \sim 1-3 \) Myr, respectively (Evans et al. 2009). Considering these typical ages of YSOs and the dynamical age of the S242 HII region, it appears that the S242 HII region is too young to trigger further SF. Hence, the SF in the S242 site is unlikely influenced by the S242 HII region.

5. Summary and Conclusions

In the present work, we have studied the physical environment, molecular gas distribution, and stellar population in and around the S242 site, using the multi-wavelength data.
We have chosen a field of \(1.05 \times 0.56\) containing the sources, S242, IRAS 05490+2658, IRAS 05488+2657, and IRAS 05483+2728. The aim of this study is to investigate the physical environment and SF processes in and around the selected target. The major results of our multi-wavelength analysis are the following.

1. The molecular cloud associated with the S242 site (and three IRAS sources: IRAS 05490+2658, IRAS 05488+2657, and IRAS 05483+2728) is depicted in a velocity range from –3.25 to 4.55 km s\(^{-1}\) and has a spatially elongated appearance.

2. The distribution of ionized emission toward the S242 site detected in the NVSS 1.4 GHz and GMRT 1.28 GHz continuum maps and H\(\alpha\) image is almost spherical. The ionizing photon flux value computed at 1.4 GHz corresponds to a single ionizing star of B0.5V–B0V spectral type. The dynamical age of the S242 H\(\Pi\) region is computed to be \(\sim 0.5\) Myr (for \(n_0 = 10^3\) cm\(^{-3}\)). In the Herschel column density map, the S242 site is located in the highest column density region (peak \(N(H_2) \sim 2.7 \times 10^{22}\) cm\(^{-2}\); \(A_V \sim 29\) mag).

3. An elongated filamentary structure (EFS) is observed in the Herschel column density map and is embedded within...
the S242 molecular cloud. The S242 H II region is located at one of the EFS ends. The highest temperature (~32 K) is found toward the S242 H II region. In the temperature map, the EFS is depicted in a temperature range of about 10–12 K (except near the S242 H II region). The temperature map traces temperature variations toward the EFS (see areas near both ends of the EFS).

4. The EFS has an observed mass per unit length of ~200 \( M_\odot \) pc\(^{-1}\) larger than the critical value of ~16 \( M_\odot \) pc\(^{-1}\). Eleven Herschel clumps are found toward the EFS and their masses vary between 150 \( M_\odot \) and 1020 \( M_\odot \). This implies that the fragmentation has occurred along the EFS’s length. The most massive clumps are observed at both the EFS ends, and the S242 H II region is located at one of the EFS ends.

5. In our selected field, 293 YSOs are identified and the majority of these are spatially traced toward the EFS. The clusters of YSOs are exclusively found at both of the EFS ends, revealing the SF activities.

Taking into account the observational outcomes presented in this paper, the results favor an SF model of the end-dominated collapse, which originated from the higher acceleration of gas.

We thank the anonymous reviewer for constructive comments and suggestions. The research carried out at the 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). This paper makes use of data obtained as part of the INT Photometric H2 Survey of the Northern Galactic Plane (IPHAS, www.iphas.org) carried out at the Isaac Newton Telescope (INT). INT is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. The IPHAS data are processed by the Cambridge Astronomical Survey Unit, at the Institute of Astronomy in Cambridge. R.D. acknowledges CONACyT (México) for the PhD grant 370405. A.L. acknowledges the CONACyT(México) grant CB-2012-01-1828-41.