Star Formation in the Sh 2-53 Region Influenced by Accreting Molecular Filaments

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Abstract

We present a multiwavelength analysis of a ∼30′ × 30′ area around the Sh 2-53 region (hereafter S53 complex), which is associated with at least three H II regions, two mid-infrared bubbles (N21 and N22), and infrared dark clouds. The 13CO line data trace the molecular content of the S53 complex in a velocity range of 36–60 km s⁻¹ and show the presence of at least three molecular components within the selected area along this direction. Using the observed radio continuum flux of the H II regions, the derived spectral types of the ionizing sources agree well with the previously reported results. The S53 complex harbors clusters of young stellar objects (YSOs) that are identified using the photometric 2–24 μm magnitudes. It also hosts several massive condensations (3000–30,000 M☉) that are traced in the Herschel column density map. The complex is found at the junction of at least five molecular filaments, and the flow of gas toward the junction is evident in the velocity space of the 13CO data. Together, the S53 complex is embedded in a very similar “hub–filament” system to those reported in Myers, and the active star formation is evident toward the central “hub” inferred by the presence of the clustering of YSOs.

Key words: dust, extinction – H II regions – ISM: clouds – ISM: individual objects (N21, N22, Sh 2-53) – stars: formation

1. Introduction

The formation mechanism of massive stars (>8 M☉) is an unresolved problem in astrophysics in spite of the fact that they have significant influence to determine the fate of their host galaxies through strong stellar wind, energetic ultraviolet (UV) radiation, and supernova explosion. Several theoretical models have been proposed for describing the formation of massive stars (see Tan et al. 2014; Motte et al. 2018, for more details), but none of these theories are yet very well accepted. After the availability of the Herschel observations, filamentary structures are frequently identified toward the star-forming regions, and they are often considered to play an important role in the star formation processes (Myers 2009; Dale & Bonnell 2011; Schneider et al. 2012). There is increasing evidence for these filaments to channel the molecular gas toward the central junction, where the active star formation (including the formation of massive stars) is occurring (see Nakamura et al. 2014; Baug et al. 2015; Dewangan 2017, and references therein). It is also often found that filaments themselves harbor H II regions and methanol masers, which are obvious signatures of massive star formation (see Schneider et al. 2012; Dewangan et al. 2016b; Dewangan 2017).

It is also known that the energetics from massive Wolf–Rayet and O stars have the ability to influence the surrounding molecular environment to form next-generation stars (e.g., Samal et al. 2010; Dewangan et al. 2016a). However, it is not yet well established observationally how exactly a massive star triggers the formation of a new generation of stars. A detailed discussion about the various processes of triggered star formation can be found in the review article by Elmegreen (1998). Detailed observational studies are also performed showing the influence of massive stars on their surroundings inferring triggered star formation, but only for a handful of regions (see Pomarès et al. 2009; Samal et al. 2010; Zavagno et al. 2010a, 2010b, and references therein). Hence, in parallel to study of the formation mechanism, understanding the influence of massive stars on their surroundings is also equally important. If not identified directly, presence of a massive star can always be inferred by the existence of H II regions or 6.7 GHz Class II methanol masers in a given star-forming cloud. They are also often linked with the Galactic mid-infrared (MIR) bubbles, which have been widely identified in the Spitzer 8 μm images (Churchwell et al. 2006, 2007; Simpson et al. 2012).

In this paper, we have selected a ∼30′ × 30′ area centered on l = 18°140, b = −0°230 toward the Sh 2-53 region to probe the ongoing star formation scenario. The selected region is associated with at least three H II regions, two MIR Galactic bubbles (N21 and N22; Churchwell et al. 2006), and infrared dark clouds (IRDCs; hereafter S53 complex). The paper is organized in the following manner. We describe the multiwavelength data and their analyses in Section 2. More details on the past studies, morphology, and the open questions on this region are described in Section 3. The main results of this study are presented in Section 4. A detailed discussion on the possible star formation scenario operating in the S53 complex and its surrounding region is elaborated in Section 5, and a conclusion of the study is presented in Section 6.
2. Observations and Data Reduction

To understand the ongoing star formation processes in the S53 complex, we have utilized the available multiwavelength data starting from the near-infrared (NIR) to radio frequency. The details of these multiwavelength data are briefly described in the following subsections.

2.1. Near-infrared Imaging Data

In order to identify and classify young stellar objects (YSOs) toward the S53 complex, the NIR photometric magnitudes of point-like sources are obtained from the 3.8 m United Kingdom Infrared Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS) Galactic Plane Survey archive (GPS release 6.0; Lawrence et al. 2007). The UKIDSS images have a spatial resolution of ~0.9″. The sources with good photometric magnitudes, having accuracy better than 10%, are only considered for the analysis of YSOs. The reliable sources are selected for the complex using the SQL criteria given in Lucas et al. (2008) and Dewangan et al. (2015). In general, bright sources are saturated in the UKIDSS frames, and thus in the final catalog, magnitudes for the sources brighter than $J = 13.25$ mag, $H = 12.75$ mag, and $K = 12.0$ mag are replaced by the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) magnitudes (Cutri et al. 2003).

2.2. Mid-infrared Data

The MIR images and photometric magnitudes of point-like sources are obtained from the Spitzer-Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE; Benjamin et al. 2003) survey archive. The Spitzer-IRAC images have a spatial resolution of ~2″. The photometric magnitudes of point sources are obtained from the GLIMPSE-IRAC Spring ’07 highly reliable catalog. The Multiband Infrared Photometer for Spitzer (MIPS) Inner Galactic Plane Survey (MIPSGAL; Carey et al. 2005) 24 μm photometric magnitudes of point sources (Gutermuth & Heyer 2015) are also used in the analysis.

2.3. Far-infrared and Millimeter Data

The 2.5–7.0 μm processed Herschel 70–500 μm images are utilized mainly to construct column density and temperature maps of the region. The Herschel images have beam sizes of 5″, 12″, 18″, 25″, and 37″ at 70, 160, 250, 350, and 500 μm, respectively (Griffin et al. 2010; Poglitsch et al. 2010).

2.4. Molecular Line Data

In order to investigate the molecular gas related to the S53 complex in detail, we retrieve the $^{13}$CO ($J = 1–0$) line data from the Galactic Ring Survey (GRS; Jackson et al. 2006). The GRS line data have a velocity resolution of 0.21 km s$^{-1}$, an angular resolution of 45″ with 22″ sampling, a main-beam efficiency ($\eta_{mb}$) of ~0.48, a velocity coverage of ~5 to 135 km s$^{-1}$, and a typical rms sensitivity ($1\sigma$) of ~0.13 K (Jackson et al. 2006).

2.5. Radio Continuum Data

We obtained the archival 610 and 1280 MHz radio continuum data from the Giant Metrewave Radio Telescope (GMRT) archive. The 610 and 1280 MHz data were observed on 2005 April 08 and 2005 March 12, respectively (Project Code: 07PKS01). The GMRT data have been reduced using the Astronomical Image Processing Software (AIPS), following the similar procedures described in Mallick et al. (2013). The synthesized beam sizes of these 610 and 1280 MHz maps are $6.7\times5.7$ and $7.8\times3.0$, with rms of 1.0 and 0.5 mJy beam$^{-1}$, respectively.

3. The Selected Region and Morphology

The Sh 2-53 region is located at a distance of 4.0 kpc (Paron et al. 2013). Using $^{13}$CO data, Paron et al. (2013) reported the existence of a large molecular shell ($\sim$70 pc × 28 pc; see Figure 9 of Paron et al. 2013), which was traced in a velocity range from 51 to 55 km s$^{-1}$, and they have pointed out that the S53 complex is situated near the edge of the large molecular shell. Also a supernova remnant (SNR), G18.1-0.1 (Green 2014), is seen close to the center of the large molecular shell. However, Paron et al. (2013) discarded any connection of the SNR with the large shell. Later, Leahy et al. (2014) and Kilpatrick et al. (2016) found that the SNR is located at a different distance (5.6 kpc) with a higher local standard rest velocity ($V_{LSR}$ ~ 100 km s$^{-1}$). A few small-scale studies are available mainly to address the star formation scenario of the individual H II regions separately (see, e.g., Watson et al. 2008; Ji et al. 2012; Sherman 2012). However, a detailed multi-wavelength analysis of the large area to address the overall star formation scenario is not yet explored. For example, the analysis of the dust clumps using the Herschel data is not performed. Moreover, the dynamics of the molecular gas is yet to be analyzed carefully. The complex is also reported to be associated with several photometrically identified massive stars. However, none of the previous studies addressed the formation mechanism of massive stars and the S53 complex. A color-composite map of the complex (red: 70 μm; green: 8.0 μm; blue: 3.6 μm) of our selected 30′ × 30′ area is presented in Figure 1(a). The 610 MHz radio continuum contours are also overlaid on the map. The selected area contains several important sources, i.e., two MIR bubbles (N21 and N22; Churchwell et al. 2006), at least six H II regions (see radio continuum contours toward G18.197-00.181, G18.237-0.240, G18.30-0.39, Sh 2-53, and bubbles N21 and N22 in Figure 1(a)), IRDCs, and the SNR G18.1-0.1 (Green 2014). However, based on the local standard of rest velocity ($V_{LSR}$), we find that not all these sources are physically linked with the S53 complex. Table 1 lists the designations of these sources along with their Galactic coordinates, $V_{LSR}$, kinematic distances, and comments on their physical association with the S53 complex. Paron et al. (2013) identified three O-type stars toward this region, which are marked by white stars in Figure 1(a). In this paper, we have adopted an average distance of 4.0 kpc for the S53 complex. In the following paragraphs, we have provided a brief description for only those sources that are associated with the S53 complex (see Table 1).

The MIR Galactic bubble N21 ($l = 18^\circ 190, b = -0^\circ 396$) has been classified as a broken or incomplete ring with an average angular radius and thickness of 2′/16 and 0′/5 (Churchwell et al. 2006), respectively (also see Figure 1(a) in this paper). The distance to the bubble is reported to be 3.6 kpc (Anderson & Bania 2009). The velocity of the radio recombination line associated with bubble N21 is 43.2 km s$^{-1}$ (Lockman 1989). One of the sources toward this bubble is spectroscopically identified to be a late O-type giant (Watson et al. 2008). Later, Paron et al. (2013) also confirmed this
recombination line associated with bubble N22 is 50.9 km s\(^{-1}\) (Lockman 1989). Ji et al. (2012) suggested a possibility of the interaction between the expanding H\(\text{II}\) region linked with this bubble and the surrounding molecular clouds. Using the optical spectrum, Paron et al. (2013) identified an O-type star toward this bubble (see the white star in Figure 1(a)).

The ionized gas linked with the Sh 2-53 region is traced in a velocity range of 50–53.9 km s\(^{-1}\), and the distance to the region is reported to be 4.3 kpc (Blitz et al. 1982; Kassim et al. 1989; Kolpak et al. 2003). The velocity and the corresponding estimated distance are also in good agreement with the values reported for the molecular cloud associated with the ultracompact H\(\text{II}\) region, U18.15-0.28 (Anderson & Bania 2009). Paron et al. (2013) identified three B-type sources toward this region using the spectroscopic observations.

Another H\(\text{II}\) region in our selected area, G18.237-0.240, has a \(V_{\text{LSR}}\) of 47 km s\(^{-1}\) (Kassim et al. 1989), which also hosts a spectroscopically confirmed O-type star (Paron et al. 2013; marked in Figure 1(a)). A velocity of this region similar to that of the MIR bubbles indicates that they could be part of the same molecular cloud.

The complex nature of this region has made it very intriguing. Understanding the ongoing physical processes in such a complex region requires a thorough multwavelength analysis. We present a two-color-composite image (red: 350 \(\mu\)m; cyan: 2.2 \(\mu\)m) of the region in Figure 1(b). The GMRT 1280 MHz radio contours are also overlaid on the image. The emission at 350 \(\mu\)m, a good tracer of cold dust, is mainly seen surrounding the MIR bubbles and the Sh 2-53 region. The IRDCs, which appear dark at shorter wavelengths (<70 \(\mu\)m), are visible at longer wavelengths (see Figure 1(b)).

4. Physical Conditions toward the Region

In this section, we first present the analysis of the radio continuum data, followed by the analysis of \textit{Herschel} images to construct the column density and temperature maps for identification of cold condensations and the distribution of cold dust. The identification and clustering analysis of YSOs are presented in the final subsection.

4.1. Radio Continuum Emission and the Dynamical Age

The strong Lyman continuum flux from massive stars ionizes the surrounding matter and develops H\(\text{II}\) regions. The integrated radio continuum flux of an H\(\text{II}\) region is often used to determine the spectral type of the ionizing source. We first estimate the radio continuum flux density at 1280 MHz and the size of the H\(\text{II}\) region (see radio contours in Figure 1) using the \textsc{tvstat} task of AIPS. The corresponding Lyman continuum flux (photons s\(^{-1}\)) needed to develop each individual H\(\text{II}\) region is estimated using the following equation from Moran (1983):

\[
S_{\text{Lyc}} = 8 \times 10^{43} \left( \frac{S_{\nu}}{\text{mJy}} \right) \left( \frac{T_{e}}{10^{4} \text{ K}} \right)^{-0.45} \times \left( \frac{D}{\text{kpc}} \right)^{2} \left( \frac{\nu}{\text{GHz}} \right)^{0.1},
\]

where the different parameters in the equations are as follows.

The symbol \(\nu\) is the frequency of observations, \(S_{\nu}\) is the integrated flux density, \(T_{e}\) is the electron temperature, and \(D\) corresponds to the distance to the source. In this calculation, it source as an O-type star using the optical spectrum. Two more sources that are photometrically identified as probable O-type stars (Watson et al. 2008) are also marked by red stars in Figure 1(a).

Bubble N22 (\(l = 18^\circ 254, b = -0^\circ 305\)) has a complete or closed ring-like appearance with an average angular radius of 1'69 (which corresponds to \(\sim 2.5 \text{ pc}\) at a distance of 4.0 kpc; Churchwell et al. 2006; Anderson & Bania 2009). It also encloses an H\(\text{II}\) region. The velocity of the radio

![Figure 1](http://example.com/figure1.png)

**Figure 1.** (a) Color-composite image (red: 70 \(\mu\)m; green: 8.0 \(\mu\)m; blue: 3.6 \(\mu\)m) of a 30' \(\times\) 30' area around the Sh 2-53 region. The 610 MHz GMRT radio contours at levels of 3, 4, 5, 6, 8, 10, 12, 15, 20, 25, 30, and 40 mJy are also overlaid on the image. Several H\(\text{II}\) regions, two MIR Galactic bubbles, IRDCs, and an SNR are seen along the line of sight. The positions of the bubbles and of the Sh 2-53 region and the SNR are marked by ellipses and circles, respectively. The positions of spectroscopically confirmed O stars (Paron et al. 2013) are also marked by white stars, while two more photometrically identified O stars toward the N21 bubbles (Watson et al. 2008) are marked by red stars. (b) Two-color-composite image of the region (red: 350 \(\mu\)m; cyan: 2.2 \(\mu\)m). The 1280 MHz GMRT contours at levels of 2.0, 2.5, 3.0, 5.0, 8.0, 12.0, 15.0, 20.0, 30.0, and 100.0 Jy are also overlaid on the image.
is assumed that all the H II regions are homogeneous and spherically symmetric. They are also assumed to be classical H II regions \( (T_e \approx 10,000 \, \text{K}) \), and a single source is responsible to develop each of them. The 1280 MHz integrated flux, corresponding Lyman continuum flux, and probable spectral types of the sources responsible for developing H II regions associated with both the bubbles and the Sh 2-53 region are listed in Table 2. The estimated Lyman continuum flux for bubble N21 is \( 10^{48.23} \) photons s\(^{-1}\), which fits to a single ionizing source having spectral type of O8V for solar metallicity (Smith et al. 2002). This spectral type is also in agreement with the spectral type determined by Paron et al. (2013).

Similarly, the estimated Lyman continuum fluxes for the other two H II regions associated with bubble N22 and Sh 2-53 are \( 10^{48.32} \) and \( 10^{48.79} \) photons s\(^{-1}\), respectively, and these fluxes correspond to the ionizing sources of O8V and O7V stars, respectively. However, it should be mentioned here that the spectral types determined using the radio continuum flux are prone to large error depending on the adopted distance and the size of the H II region. Hence, the determinations of the spectral types using spectroscopic observations are always more robust. Paron et al. (2013) reported the presence of an O-type star and a B-type star toward bubble N22 and three B-type sources toward the Sh 2-53 region.

The dynamical age of an H II region helps us to understand whether an H II region is old enough to influence the formation of YSOs seen around it. The ionization front of an H II region expands until an equilibrium is achieved between the rate of ionization and recombination. A theoretical extent of the H II region, known as the Strömgren radius \( (R_S; \text{Strömgren } 1939) \), can be computed with the following formula:

\[
R_S = \left( \frac{3S_{\text{Lyc}}}{4\pi n_0^2 \beta_2} \right)^{1/3},
\]

where \( n_0 \) is the initial ambient density and \( \beta_2 \) is the recombination coefficient. The value of \( \beta_2 \) is taken to be \( 2.60 \times 10^{-13} \) cm\(^3\) s\(^{-1}\) for a classical H II region (Stahler & Palla 2005).

Once the ionized region developed, a shock front is generated at the interface of the ionized gas and the surrounding cold material because of the large difference in temperature and pressure. The shock front is further evolved with time by propagating into the surroundings. The radius of such an ionized region at any given time can be formulated as (Spitzer 1978)

\[
R(t) = R_S \left( 1 + \frac{7c_\text{H}t_{\text{dyn}}}{4R_S} \right)^{4/7},
\]

where \( t_{\text{dyn}} \) is the dynamical age of the H II region and \( c_\text{H} \) is the sound speed in an H II region that is \( 11 \times 10^3 \) cm s\(^{-1}\) (Stahler & Palla 2005). We have estimated the dynamical ages of all three H II regions toward bubbles N21 and N22 and the Sh 2-53 region. The radii of the H II regions, \( R(t) \), were estimated by using the TVSTAT task of the AIPS. The calculated dynamical age might vary substantially depending on the initial ambient density. Hence, the Strömgren radius and the dynamical age of the H II regions are calculated for a range of ambient density from 1000 to 10,000 cm\(^{-3}\) (i.e., from classical to ultracompact H II regions; Kurtz 2002). The calculated dynamical ages for ambient densities of 1000, 2000, 5000, and 10,000 cm\(^{-3}\) are

| Name of the H II Region | Integrated 1280 MHz Flux (Jy) | Log of Lyman Continuum Flux (photons s\(^{-1}\)) | Spectral Type | Physical Association with the S53 Complex |
|-------------------------|-------------------------------|-----------------------------------------------|---------------|----------------------------------------|
| N21                     | 1.30                          | 48.23                                         | O8V           | Yes                                    |
| N22                     | 1.60                          | 48.32                                         | O8V           | Yes                                    |
| Sh 2-53                 | 4.74                          | 48.79                                         | O7V           | No                                     |

Table 1

| Details of Different Sources and Their Association with the S53 Complex |
|------------------------------------------------------------------------|
| Name of the Source | \( l \) (deg) | \( b \) (deg) | \( V_{lsr} \) (km s\(^{-1}\)) | Kinematic Distance (kpc) | Physical Association with the S53 Complex |
|---------------------|---------------|--------------|-------------------------------|---------------------------|------------------------------------------|
| Bubble N21          | 18.190        | −0.396       | 43.2                          | 3.6\(^a\)                 | Yes                                      |
| Bubble N22          | 18.254        | −0.305       | 50.9                          | 4.0\(^b\)                 | Yes                                      |
| Sh 2-53             | 18.210        | −0.320       | 52.0                          | 4.3\(^c\)                 | Yes                                      |
| G18.237-0.240       | 18.237        | −0.240       | 47.0                          | ...                       | Yes                                      |
| G18.1-0.197          | 18.106        | −0.195       | 100.0                         | 5.6\(^d,e\)               | No                                       |
| G18.197-0.181\(^f\) | 18.197        | −0.181       | ...                           | 12.4\(^f\)               | No                                       |
| G18.30-0.398         | 18.303        | −0.390       | 32.3                          | 2.8\(^f\)                 | No                                       |

Notes.

\(^a\) Churchwell et al. (2006).
\(^b\) Kolpak et al. (2003).
\(^c\) Green (2014).
\(^d\) Leahy et al. (2014).
\(^e\) Kilpatrick et al. (2016).
\(^f\) Anderson & Bania (2009).
\(^g\) Wienen et al. (2012).

Table 2

The Dynamical Ages of the H II Regions Associated with the S53 Complex Seen in the 1280 MHz Radio Continuum Map

| Name of the H II Region | Integrated 1280 MHz Flux (Jy) | Log of Lyman Continuum Flux (photons s\(^{-1}\)) | Spectral Type | Dynamical Age (Myr) for Ambient Density of 1000 cm\(^{-3}\) | Dynamical Age (Myr) for Ambient Density of 2000 cm\(^{-3}\) | Dynamical Age (Myr) for Ambient Density of 5000 cm\(^{-3}\) | Dynamical Age (Myr) for Ambient Density of 10,000 cm\(^{-3}\) |
|------------------------|-------------------------------|-----------------------------------------------|---------------|-----------------------------------------------------------|----------------------------------------------------------|-----------------------------------------------------------|-----------------------------------------------------------|
| N21                    | 1.30                          | 48.23                                         | O8V           | 0.29                                                      | 0.43                                                      | 0.69                                                      | 0.99                                                      |
| N22                    | 1.60                          | 48.32                                         | O8V           | 0.28                                                      | 0.41                                                      | 0.66                                                      | 0.94                                                      |
| Sh 2-53                | 4.74                          | 48.79                                         | O7V           | 0.18                                                      | 0.27                                                      | 0.45                                                      | 0.65                                                      |
also listed in Table 2. As can be seen in Table 2, dynamical ages for all the ambient densities are less than 1 Myr. However, it must be noted that the region is assumed to be uniform and spherically symmetric. Hence, the calculated dynamical ages of all the HII regions should be treated as a qualitative value.

4.2. Distribution of Molecular Gas and Cold Dust

A careful examination of the \(^{13}\)CO \((J = 1-0)\) spectrum in the direction of the S53 complex reveals the presence of at least three molecular components in a velocity range of 36–60 km s\(^{-1}\). Figure 2 shows the \(^{13}\)CO spectrum toward the S53 complex. The spectrum is generated by averaging the whole emission from our selected field containing the S53 complex. As can be seen in the spectrum, three molecular cloud components are traced in the full velocity ranges of 36–45 km s\(^{-1}\) (hereafter MC18.20–0.50), 46–55 km s\(^{-1}\) (hereafter MC18.15–0.28), and 56–60 km s\(^{-1}\) (hereafter MC18.20–0.40). In Figure 3(a), the molecular emission integrated over the velocity range of 36–60 km s\(^{-1}\) is overlaid on the Spitzer 8 \(\mu\)m image. The \(^{13}\)CO emission contours integrated over three different velocity ranges (i.e., 36–45 km s\(^{-1}\), 46–55 km s\(^{-1}\), and 56–60 km s\(^{-1}\)) are also overlaid on the Spitzer 8 \(\mu\)m image, revealing the three molecular components (see Figures 3(b)–(d)) in the direction of our selected target field. It is to be noticed in Figure 3 that the Sh 2-53 region and bubble N22 are mainly associated with MC18.20–0.50 and MC18.15–0.28 molecular clouds. However, the molecular gas associated with bubble N21 is traced in the cloud MC18.20–0.40, which has a velocity range from 56 to 60 km s\(^{-1}\). This velocity of molecular gas is higher than the velocity of the radio recombination line \(V_{\text{LSR}} \sim 43.2 \text{ km s}^{-1}\) associated with bubble N21 (Lockman 1989). The discrepancy of about 10 \text{ km s}^{-1} between the velocity of the radio recombination line toward bubble N21 and the velocity of the associated molecular gas can be explained by noncircular motion (Jones et al. 2013). Several molecular condensations are seen in the integrated intensity map (see the velocity-integrated \(^{13}\)CO map of the region in Figure 3(a)).

In order to examine the cold condensations toward the selected region, we have employed the Herschel images to construct the column density and temperature maps. We have performed a pixel-by-pixel modified blackbody fit on the Herschel 160, 250, 350, and 500 \(\mu\)m images. The 70 \(\mu\)m image is excluded, as the flux in this band includes emission from the warm dust. All the higher-resolution images were convolved to the lowest resolution of 37\(^{\prime}\) (beam size of the 500 \(\mu\)m image) after converting them to the same flux unit (i.e., Jy pixel\(^{-1}\)). The background flux was estimated from a nearby dark patch of the sky \((l = 18^\circ 50, b = 0^\circ 86\), for an area of \(15^\prime \times 15^\prime\) and was subtracted from the corresponding image (see Mallick et al. 2015, for more details).

Finally, the pixel-by-pixel basis modified blackbody fit was carried out using the formula (Launhardt et al. 2013)

\[
S_{\nu}(\nu) - I_{bg}(\nu) = B_{\nu}(\nu, T_d)\Omega (1 - e^{-\tau(\nu)}),
\]

where optical depth can be written as

\[
\tau(\nu) = \frac{\mu_{H_2}m_{H_2}\kappa_{\nu}N(H_2)}{\Omega}.
\]

where the notations are as follows: \(S_{\nu}(\nu)\) is the observed flux density, \(I_{bg}\) corresponds to the background flux density, \(B_{\nu}(\nu, T_d)\) is the Planck function, \(T_d\) stands for the dust temperature, \(\Omega\) is the solid angle subtended by a pixel, \(\mu_{H_2}\) represents the mean molecular weight, \(m_{H_2}\) stands for the hydrogen mass, \(\kappa_{\nu}\) is the dust absorption coefficient, and \(N(H_2)\) is the column density. Here, we assumed a gas-to-dust ratio of 100 and used the following values in the calculation: \(\Omega = 4.612 \times 10^{-5}\) sr (i.e., the area of a pixel of 14\(^\prime\) \times 14\(^\prime\)), \(\mu_{H_2} = 2.8\) and \(\kappa_{\nu} = 0.1 \text{ (}\nu/1000 \text{ GHz})^3 \text{ cm}^2 \text{ g}^{-1}\), and a dust spectral index \(\beta\) of 2 assuming that sources have thermal emission in the optically thick medium (Hildebrand 1983).

The final column density and temperature maps of the region are presented in Figures 4(a) and (b), respectively. Identification of the molecular clumps and estimation of their column densities are performed using the CLUMPFIND software (Williams et al. 1994). The mass of each clump is estimated using the formula (Mallick et al. 2015)

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

where \(A_{\text{pix}}\) is the area subtended by a single pixel.

A total of 72 clumps are identified toward the 30\(\prime\) \times 30\(\prime\) area of the region. However, a careful visual examination of the spatial distribution of these identified clumps with respect to the integrated \(^{13}\)CO map reveals that only 40 clumps are associated with MC18.20–0.50, MC18.15–0.28, and MC18.20–0.40 clouds (see Figure 4(a), where all 40 clumps are marked by diamonds). The masses of the identified Herschel clumps are in the range of \(3 \times 10^{3}–3.0 \times 10^{4} M_{\odot}\)\(., \) These calculated masses of Herschel clumps are generally high and possibly overestimated because of the presence of multiple molecular clouds at different velocities along the line of sight (all are not discussed in this paper) that are integrated in the Herschel column density map. One of the massive condensations with a mass of about \(2.3 \times 10^{4} M_{\odot}\) is identified toward the junction of the bubbles, which is reported to be a collapsing massive prestellar core (see clump \#5 of Zhang et al. 2017).

4.3. Young Stellar Population

It is always required to have a detailed knowledge of YSOs and their clustering behavior in a given star-forming region to characterize the areas of the ongoing star formation. Hence, we...
have identified YSOs in our selected area of the S53 complex using the NIR and MIR color–magnitude and color–color schemes. Furthermore, we have performed the nearest-neighbor analysis to look for the clusterings of YSOs and hence the areas of active star formation. An elaborative description of the adopted schemes to identify YSOs is given below.

4.3.1. Selection of YSOs

We have utilized four different MIR/NIR schemes to identify and classify YSOs among the point sources detected in the selected 30' × 30' area. Note that these schemes are not mutually exclusive. In fact, the successive scheme(s) may include YSOs that are identified in the previous scheme(s). We have arranged the schemes as per their robustness to classify the YSOs. If the same source is identified in multiple schemes with different classes, then preference is given to the class characterized in the preceding scheme.

1. We first employed an MIR color–magnitude scheme to separate out young sources. We found a total of 570 sources to be common in 3.6 and 24 μm bands. The [3.6]−[24]/[3.6] color–magnitude diagram of these 570 point sources is shown in Figure 5(a). The color criteria given in Guieu et al. (2010) and Rebull et al. (2011) were adopted to separate out different classes of YSOs. Finally, we identified a total of 144 YSOs (27 Class I, 28 flat-spectrum, and 89 Class II) and 246 Class III sources following this particular scheme.

Figure 3. (a) Velocity-integrated 13CO contours for a velocity range from 36 to 60 km s\(^{-1}\) overlaid on the Spitzer 8 μm image. In the direction of the S53 complex, three molecular clouds are traced within this velocity range. (b–d) Velocity-integrated contours for velocity ranges of 36–45 km s\(^{-1}\), 46–55 km s\(^{-1}\), and 56–60 km s\(^{-1}\), respectively, overlaid on the Spitzer 8 μm image.
2. The MIPSGAL 24 μm images of star-forming regions often suffer from strong nebulosity, and more point sources are expected to be detected in the Spitzer-IRAC bands compared to 24 μm images. Therefore, we have also constructed a [5.8]−[8.0]/[(3.6)−[4.5]] color−color diagram of the point sources to identify YSOs (see Figure 5(b)). The YSOs identified using the criteria given in Gutermuth et al. (2009) are categorized into different evolutionary stages based on their slopes of the spectral energy distribution (SED) in the IRAC bands (i.e., ωIRAC; see Lada et al. 2006, for more details). Accordingly, a total of 249 YSOs (71 Class I and 178 Class II) and 4158 Class III sources were identified using this scheme.

3. Nebulosity also affects the IRAC 8.0 μm band, and hence many point sources may not be seen in the 8.0 μm image. Therefore, in addition to the schemes mentioned above, the [3.6]−[4.5]/[4.5]−[5.8] color−color diagram was also constructed to identify YSOs (see Figure 5(c)). All the sources with [4.5]−[5.8] ≥ 0.7 mag and [3.6]−[4.5] ≥ 0.7 mag in this color−color diagram are considered as Class I YSOs (Hartmann et al. 2005; Getman et al. 2007). A total of 140 Class I YSOs were identified following this scheme.

4. In general, YSOs appear to be much redder than the nearby field stars in the NIR color–magnitude diagram because of the presence of circumstellar material. Hence, we have also constructed an NIR color–magnitude diagram (H−K/K) of the point sources to identify YSOs (Figure 5(d)). It is assumed in this scheme that all the sources above a certain H − K color cutoff are probable YSOs. The H − K color cutoff of 2.0 was estimated from the H−K/K color–magnitude diagram of a nearby field region (l = 18h12m, b = 0°04; field of view: 12° × 12°). Using this scheme, a total of 3023 red sources were identified above the cutoff value.

As mentioned before, it is not necessary for YSOs identified using four different schemes to be mutually exclusive. Hence, to have a complete catalog of YSOs, they were cross-matched. Accordingly, we have found a total of 393 YSOs (i.e., 139 Class I, 28 flat-spectrum, and 226 Class II), 4260 Class III sources, and 2691 red sources (identified using an NIR color–magnitude scheme) in our selected 30′ × 30′ region. All the identified Class I and Class II YSOs are marked on the 500 μm image of the region (see Figure 6(a)). It can be seen in the figure that YSOs, mainly Class I sources, are situated toward the periphery of the bubbles and the Sh 2-53 region.

4.3.2. Surface Density Analysis of YSOs

Clustering of YSOs in a given region helps us identify the areas of active star formation. To examine the clustering behavior of YSOs toward the S53 complex, we have performed a 20-nearest-neighbor (20NN) surface density analysis of identified YSOs, as it is shown by Schmeja et al. (2008) that 20NN surface density analysis is capable enough to identify clusters of 10−1500 YSOs. Note that in this analysis all the YSOs are assumed to be located at the same distance of 4.0 kpc. The surface density contours drawn at 5, 7, 9, 12, 16, 20, 25, and 30 YSOs per μm², overlaid on the 5.8 μm image, are shown in Figure 6(b). It can be seen in the figure that YSOs are mainly clustered around the H II regions (i.e., N21, N22, and Sh 2-53 regions). A cluster of YSOs is also seen toward the Galactic east of bubble N22. However, this particular cluster of YSOs is associated with the molecular cloud in the velocity range of 66−76 km s⁻¹; hence, they have no physical association with the S53 complex, having a velocity range of 36−60 km s⁻¹.

5. Molecular Filaments and Star Formation Activity

Earlier studies (Watson et al. 2008; Ji et al. 2012; Paron et al. 2013) reported that the ionizing feedback from massive stars has influenced the star formation activity toward bubbles N21 and N22 and the Sh 2-53 region. But the estimated dynamical ages of these H II regions (see Table 2) are not consistent enough to influence the formation of Class I and Class II YSOs. For example, with a typical ambient density of 1000 cm⁻³, the calculated dynamical ages of the H II regions (≤0.3 Myr) suggest that they might not have induced the formation of Class I and Class II YSOs, having average ages of 0.46 and 1−3 Myr, respectively (Evans et al. 2009). However, it must be noted that the derived dynamical ages of the H II regions are qualitative values. Hence, the possibility of influence of the ionized gas on the star formation in surrounding molecular clouds cannot be ruled out totally. Yet, we have analyzed the 13CO data in detail to examine the physical condition and the dynamics of the
molecular gas, which might be helpful to understand other possible mechanisms for the ongoing star formation activity.

The velocity-integrated $^{13}$CO intensity map for a larger $1^{\circ}2 \times 1^{\circ}2$ area for a velocity range from 36 to $60 \text{ km s}^{-1}$ is presented in Figure 7(a). A zoomed-in view of the intensity map for the central part of the complex is also presented in Figure 7(b). At least five molecular filamentary structures having a typical length of 5–10 pc are identified in the velocity-integrated $^{13}$CO map (see marked filaments labeled as F1–F5 in Figures 7(a) and (b)). The filaments are found to be connected to the central “hub” hosting the S53 complex (see Figure 7(b)). The positions of Class I and Class II YSOs are also marked in Figure 7(b). Though YSOs are primarily seen toward the central “hub,” a few YSOs are also found toward the filamentary structures (see, e.g., F1, F2, and F5). We have constructed the moment maps of the central part of the complex, which are presented in Figure 8. The molecular zeroth-, first-, and second-moment maps are shown in Figures 8(a)–(c), respectively. The zeroth-moment map (or integrated intensity map) is similar to that shown in Figure 7(b). The first-order moment map is the measure of the intensity-weighted mean velocity of the emitting gas (see Figure 8(b)). The velocity dispersion map is usually represented by the second-order moment map. A large velocity dispersion is seen toward...
the S53 complex. Generally, a large dispersion could arise owing to a broad single-velocity component and/or may indicate the presence of two or more narrow components with different velocities along the line of sight (see Figure 8(c)).

We have also constructed $p - v$ diagrams for all five identified filaments separately for the velocity range from 36 to 60 km s$^{-1}$ (see Figure 9). All the $p - v$ diagrams are constructed along the filaments, and the distance of each filament is measured in parsecs from the central “hub,” which hosts the S53 complex. Note that a single heliocentric distance of 4.0 kpc is assumed for all five filaments to calculate their lengths. Also, in this analysis, no projection effects or inclination angles have been taken into account, and all of them are assumed to be projected on the plane of the sky. The peak velocities corresponding to each filament and the central “hub” are marked by red and blue lines, respectively.

As the S53 complex is located at the junction of at least five molecular filaments (see Figures 7(a) and (b)), there is a strong possibility that the star formation in the S53 complex is influenced by these filaments. We therefore search for the possibility of an active role of these filaments in the formation of the S53 complex. A gradient in the peak velocity at a range
Figure 8. (a) Velocity-integrated $^{13}$CO map of the central region around the S53 complex for the velocity range of 36–60 km s$^{-1}$. (b) First moment or the velocity map of the region. (c) Second moment map or the velocity dispersion map of the S53 complex. Dispersion in the gas velocity can be clearly noted toward the S53 complex.

Figure 9. (a)–(e) The $p - v$ diagrams for filaments F1–F5 marked in Figure 7. The peak velocities corresponding to the filaments and the central "hub" are marked by red and blue lines, respectively. A gradient in velocities ranging from 2 to 3 km s$^{-1}$ is noted almost for all the filaments within 5 pc toward the central "hub." The broadening of the velocity profile can also be easily noted in the $p - v$ diagrams, as these filaments move to the central "hub."
of 2–3 km s\(^{-1}\) can be easily noticed in almost all the filaments, within 5 pc length near the central “hub” except for F5 (see marked lines in all the panels of Figure 9). Note that the identified velocity gradients are significantly higher than the velocity resolution of GRS (0.21 km s\(^{-1}\)). Velocity gradients seen in all the filaments are also an order higher than the sound speed of \(~0.2\) km s\(^{-1}\) at a typical filament temperature of about 10 K (Omukai et al. 2005). Such supersonic velocity gradients imply that there could be significant substructures along the filaments (see Hacar et al. 2013; André et al. 2016, for more details).

Gradients in the velocity could also be interpreted by rotation. However, the presence of a substantial velocity gradient in all the filaments that are oriented at different directions from the central “hub” discards any such possibility. Such “hub–filament” configurations are also seen in the simulations of a magnetized cloud. The dissipation of the magnetized cloud causes the cloud to condense along its field lines into a dense layer (see Nakamura & Li 2008). It has also been discussed in Dobashi et al. (1992) that the filaments may form because of the twisting of the magnetized gas. In this form, the filamentary cloud rotates along its major axis, which gives rise to the gradient in the velocity of the filaments toward the central “hub.”

The broadening of the velocity profiles of all the filaments is also noted as they move toward the central “hub.” It has been discussed by Olmi et al. (2016), Nakamura et al. (2014), and Kirk et al. (2013) that filaments feeding a central “hub” generally show a velocity gradient toward the central “hub” and might appear with a larger velocity dispersion toward the “hub.” This result indicates that the molecular cloud (velocity range of 36–60 km s\(^{-1}\)) hosting the S53 complex is possibly fed by at least five filaments. Also, an active star formation process is noted toward this central “hub” by the presence of cold clumps and YSO clusters (see Sections 4.2 and 4.3.2). Though not many YSOs are seen along the filaments, YSOs are, however, found to be clustered toward the central “hub” (see Figure 7(b)). Several such “hub–filament” systems are reported in the literature that also occasionally host massive stars (see, e.g., Schneider et al. 2012; Peretto et al. 2013; Baug et al. 2015; Dewangan et al. 2015).

Overall, from the observational signatures, it seems that the star formation activity in the S53 complex is possibly influenced by channeling of matter along five molecular filaments toward the S53 complex.

6. Conclusions

In this work, we have carried out a detailed multiwavelength analysis of a selected 30’ × 30’ area around the Sh 2-53 region (i.e., S53 complex) to probe the ongoing star formation activities. Several authors reported that the star formation activity toward this region is influenced by the ionizing feedback of massive stars. However, we find a different mechanism to be operating in this S53 complex than those reported in the literature. The major findings of the study are the following:

1. The molecular cloud hosting the Sh 2-53 region is well traced in a velocity range of 36–60 km s\(^{-1}\), which also harbors two MIR bubbles (namely, N21 and N22) and three H\(\text{II}\) regions. At least three molecular components are identified having velocity ranges of 36–45 km s\(^{-1}\), 46–55 km s\(^{-1}\), and 56–60 km s\(^{-1}\) that host the S53 complex.

2. Considering our estimates of Lyman continuum photons using the GMRT 1280 MHz data, we find that the primary ionizing sources for the H\(\text{II}\) regions linked with the Sh 2-53 region and both the bubbles are O7V and O8V stars, respectively. This result is also in agreement with the spectral type of the ionizing sources reported in the literature.

3. The dynamical ages of the H\(\text{II}\) regions associated with the bubbles and the Sh 2-53 region are estimated to be \(\leq 0.3\) Myr for a typical ambient density of 1000 cm\(^{-3}\). Hence, it appears that they might not be capable enough for triggering the formation of Class I and Class II YSOs on their surrounding cloud.

4. Using the \(^{13}\)CO line data, at least five molecular filaments are identified in the integrated intensity map, and they appear to be radially directed to the central molecular condensation. It resembles more of a “hub–filament” system, and the central molecular condensation contains the S53 complex.

5. The Herschel column density map traces several condensations in the selected area around the S53 complex. A massive clump (\(M_{\text{clump}} \sim 2.3 \times 10^4 M_{\odot}\)) is identified toward the intermediate area between bubbles N21 and N22. YSOs identified using the NIR and MIR photometric schemes are also found to be clustered toward this central molecular condensation. It is suggestive of active star formation in this “hub–filament” system.

6. The identified molecular filaments have noticeable velocity gradients (i.e., 2–3 km s\(^{-1}\)) as they move toward the central “hub.” Such supersonic velocity gradients indicate the presence of significant substructures along the filaments. All these filaments also show a wider velocity profile toward the “hub.” These are indicative of molecular gas flow toward the central “hub” along these filaments.

Based on our observational findings, we conclude that molecular filaments have influenced the formation of the massive stars and clusters of YSOs in the S53 complex, by channeling the molecular gas to the central “hub” hosting the complex.

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