HIGH-MASS STAR FORMATION TOWARD SOUTHERN INFRARED BUBBLE S10

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ABSTRACT

An investigation in radio and infrared wavelengths of two high-mass star-forming regions toward the southern Galactic bubble S10 is presented here. The two regions under study are associated with the broken bubble S10 and Extended Green Object, G345.99-0.02, respectively. Radio continuum emission mapped at 610 and 1280 MHz using the Giant Metrewave Radio Telescope, India, is detected toward both of the regions. These regions are estimated to be ionized by early-B- to late-O-type stars. Spitzer GLIMPSE mid-infrared data is used to identify young stellar objects (YSOs) associated with these regions. A Class-I/II-type source, with an estimated mass of 6.2 $M_\odot$, lies $\sim$7″ from the radio peak. Pixel-wise, modified blackbody fits to the thermal dust emission using Herschel far-infrared data is performed to construct dust temperature and column density maps. Eight clumps are detected in the two regions using the 250 μm image. The masses and linear diameter of these range between $\sim$300–1600 $M_\odot$ and 0.2–1.1 pc, respectively, which qualifies them as high-mass star-forming clumps. Modeling of the spectral energy distribution of these clumps indicates the presence of high luminosity, high accretion rate, massive YSOs possibly in the accelerating accretion phase. Furthermore, based on the radio and MIR morphology, the occurrence of a possible bow wave toward the likely ionizing star is explored.

Key words: H II regions – ISM: individual objects (S10—IRAS 17036-4033, G345.99-0.02) – radio continuum: ISM – stars: formation

1. INTRODUCTION

High-mass stars play a crucial role in the dynamical and chemical evolution of the Galaxy considering that their feedback to the interstellar medium (ISM) is in the form of energy and heavy elements. However, these most massive members of the stellar population pose theoretical as well as observational challenges in the way of our understanding of the formation processes involved. For massive stars ($M \gtrsim 8 M_\odot$), the Kelvin–Helmholtz timescale is less than the accretion timescale, which implies that the star “switches on” (reaches the main-sequence) while still accreting (McKee & Tan 2003). This invokes the “radiation pressure problem” that would inhibit further accretion to form a massive star. In spite of various theories proposed to counter this problem, the decision is still not sealed on whether high-mass stars are formed via mechanisms like competitive accretion or coalescence of low-mass stars in dense protoclusters (Bonnell et al. 2004) or their formation is just a scaled up version of the processes in play in the low-mass regime, which includes formation via monolithic collapse, disk accretion (with a larger accretion rate), and outflow (Yorke & Sonnhalter 2002; McKee & Tan 2003). Furthermore, since high-mass stars form in clustered, highly obscured, and distant ($\sim$1 kpc or beyond) environments, observing them is a challenging task. Hence, lack of good and adequate observational guidance has kept the theoretical models debatable. A recent review by Tan et al. (2014) discusses the current theoretical and observational scenario of high-mass star formation. Observational manifestations of the interplay between high-mass stars and the surrounding ISM are important probes for studying the various evolutionary phases involved in their formation. The very early stages are marked by the presence of energetic outflows and jets. Once the “switching-on” takes place, the outpouring of UV photons ionize the surrounding neutral medium, forming H II regions (Wood & Churchwell 1989; Churchwell 2002). The H II region around a newly formed massive star expands into the ambient ISM driven by various feedback mechanisms like thermal overpressure, powerful stellar winds, radiation pressure, or a combination of all of them (Churchwell et al. 2006; Deharveng et al. 2010; Simpson et al. 2012). The result is a “bubble” that shows up as a dense shell of swept up gas and dust between the ionization and the shock fronts encompassing a relatively low-density, evacuated cavity around the central star (Weaver et al. 1977). A detailed discussion on bubbles is presented in Section 4.5.

In this paper, we present an observational study of a high-mass star-forming region that includes the southern Galactic bubble S10 and an Extended Green Object (EGO) G345.99-0.02 (hereafter EGO345), which is located $\sim$5′ toward the northeast of S10. Both of these regions are shown to harbor massive protostellar candidates (Fontani et al. 2005; Beltrán et al. 2006). Figure 1 shows the mid-infrared image of the two regions studied in this paper.

The southern infrared (IR) bubble S10 is listed in Churchwell et al. (2006) as one having a broken morphology. Broken morphologies of bubbles are believed to be due to non-uniform density of the ambient ISM and/or anisotropic stellar winds and radiation fields. Based on the 24 μm MIPS GAL image, these authors suggest identification of possible central driving star(s). S10 is also identified as a bubble in the Milky Way Project (Simpson et al. 2012). In Figure 1, we trace the elliptical and almost spherical morphologies of S10, as suggested by Churchwell et al. (2006) and Simpson et al. (2012), respectively. We support the larger spherical morphology of Simpson et al. (2012) given the extended southern part of the bubble. However, the thickness of 0′′98 estimated by them is on the higher side compared to 0′/3 quoted by Churchwell et al. (2006). We have adopted the latter value. A bright IRAS source (IRAS 17036-4033), with a bolometric luminosity of $2.5 \times 10^4 L_\odot$ (Beltrán et al. 2006), is located...
toward the eastern arm of S10. The estimated center position of S10 as given by these authors lies within the error ellipse of the IRAS point source position. An arc-type structure with an opening in the northeast direction is seen toward the west of the likely center of the bubble.

The second region, which includes EGO345, shows an extended emission to the northeast and a bright compact emission to the southwest of the EGO. The EGOs, which display enhanced 4.5 μm emission (given common color coding of green in the Spitzer-GLIMPSE color composite images and hence the name), are likely candidates tracing outflows from massive young stellar objects (YSOs; Cygano-

Figure 1. IRAC 8.0 μm image of the regions (shown as black circles) probed in this paper. The “+” marks show the positions of the associated IRAS point sources, IRAS 17036-4033 (S10) and IRAS 17039-4030 (EGO345). The filled black triangle shows the location of the EGO. We show the various morphologies proposed for the bubble—white dashed (Churchwell et al. 2006); white solid (Simpson et al. 2012) and black dashed (our estimate).

nowski et al. 2008; Chambers et al. 2009; De Buizer & Vacca 2010; Lee et al. 2012, 2013; Caratti o Garatti et al. 2015). In Figure 2, we display the color composite (3.6, 4.5, and 8.0 μm) image, which shows the location of the EGO. This region is associated with IRAS 17039-4030 (Cyganowski et al. 2008). It has no association with any Infrared Dark Clouds (IRDCs) or OH masers but is associated with Class I and Class II methanol masers, which are signposts of high-mass star-forming regions (Caswell et al. 2010; Chen et al. 2011).

Both of these regions have been studied in the rotational transition lines of CS and C17O molecules, and 1.2 mm continuum emission as part of the survey for the search of massive protostellar candidates using the SEST telescope (Fontani et al. 2005; Beltrán et al. 2006). As discussed in Beltrán et al. (2006), the 1.2 mm dust continuum emission map shows the presence of six massive clumps with derived masses between 85 and 423 M⊙. Four of these clumps are located in the eastern periphery of S10 and associated with IRAS 17036-4033. The other two clumps are toward the northeast and associated with EGO345. Beltrán et al. (2006) assume these six clumps to belong to the same star-forming region. This is supported by the distance estimates to IRAS 17036-4033 and EGO345. Using the CS line velocity, Fontani et al. (2005) estimate the near and far kinematic distances for IRAS 17036-4033 to be 5.7 and 10.8 kpc, respectively. In this paper, we adopt the near distance. The distance to the region EGO345 is also estimated to be 5.6 kpc (Chen et al. 2011). Furthermore,

Figure 2. Color composite image of EGO345 with 8.0 μm (red), 4.5 μm (green), and 3.6 μm (blue) color coding. The arrow points to the position of EGO345 and “+” mark shows the position of associated IRAS point source.

the location of the four clumps in the periphery of S10 strongly suggests a fragmented shell interacting and shaped by the expansion of the bubble. Similar dust clumps have been observed at the borders of several IR bubbles (Zavagno et al. 2010; Ji et al. 2012; Liu et al. 2016).

In this paper, we study these two regions in detail in radio and IR. Section 2 outlines the observation and data reduction of the radio continuum observations. Section 3 describes the various archival databases used for this study. In Section 4, we discuss the results obtained and Section 5 summarizes the conclusions.

2. OBSERVATION AND DATA REDUCTION

2.1. Radio Continuum Observations

In order to study the ionized gas component associated with our regions of interest, we carried out radio continuum mapping with the Giant Metrewave Radio Telescope (GMRT), Pune India on 2011 July 17 and 20. GMRT has a hybrid configuration of 30 antennae in a “Y” shaped layout. Each antenna is a parabolic reflecting dish of 45 m diameter. The central square has 12 randomly placed antennae within a compact area of 1 x 1 km² with shortest baselines of ~100 m. This is sensitive to large-scale diffuse emission. The remaining 18 antennae are placed six each in the three arms. The largest baseline possible with GMRT is ~25 km, which accounts for the high angular resolution. Details regarding the GMRT configuration can be found in Swarup et al. (1991).

The radio continuum observations were carried out at 1280 and 610 MHz with a bandwidth of 32 MHz in the spectral line mode to minimize the effects of bandwidth smearing and narrowband RFI. Radio sources 3C48 and 3C286 were used as primary flux calibrators and 1626-298 was used as phase calibrator for estimating the amplitude and phase gains for flux and phase calibration of the measured visibilities. Data reduction is performed using the Astronomical Image Processing System (AIPS) using standard procedures. The task
TVFLG is used to identify bad data and also channels affected by RFI. The calibrated data was averaged in frequency to the extent to keep the bandwidth smearing effects negligible. The wide-field imaging technique is employed to account for w-term effects (non-coplanarity). Several iterations of “phase-only” self calibration are performed in order to minimize amplitude and phase errors and obtain better rms noise in the maps. The primary beam correction is applied using the task PBCOR.

While observing close to the Galactic plane, the Galactic diffuse emission becomes significant and contributes toward increasing the system temperature, which becomes relevant at low frequencies. At the frequencies of our radio observations (especially at 610 MHz), a rescaling of the final image is essential. To determine the scaling factor at 1280 MHz, we follow the general method of estimating the sky temperature, \( T_{\text{sky}} \), using the measurements obtained from the all-sky 408 MHz survey of Haslam et al. (1982). This method assumes the Galactic diffuse emission to follow a power-law spectrum and \( T_{\text{sky}} \) at frequency \( \nu \) for the target position is determined using the following equation

\[
T_{\text{sky}} = T_{\text{sky}}^{408} \left( \frac{\nu}{408 \text{ MHz}} \right)^{\gamma}
\]

where \( \gamma \) is the spectral index of the Galactic diffuse emission and is taken as \( -2.55 \) (Roger et al. 1999). Using this, we obtain a scaling factor of 1.2 at 1280 MHz. For 610 MHz, we obtain the scaling factor from the observed self-power of the antennas following the procedure outlined in Marcote et al. (2015). Self-power of each antenna is measured at the position of the flux calibrator and the target at similar elevations. After retaining only the antennas with stable self-power, the ratio of individual data points of S10 and 3C286 is calculated for each antenna and polarization. Median of the ratios removes the outliers and gives a scaling factor of \( 1.7 \pm 0.02 \).

3. AVAILABLE DATA FROM ARCHIVES

3.1. Mid-infrared Data from Spitzer

Mid-infrared (MIR) data have been obtained from the archives of the Spitzer Space Telescope. Photometric data in the four IRAC bands (3.6, 4.5, 5.8, and 8.0 \( \mu \text{m} \)) have been retrieved from the “highly reliable” catalog of the Galactic Legacy Infrared Midplane Survey Extraordinaire (GLIMPSE) survey (Benjamin et al. 2003). 24 \( \mu \text{m} \) images have been obtained from the MIPS/GAL survey (Rieke et al. 2004). The angular resolution of the images in the IRAC bands are \(<2''\) whereas it is \~6'' at 24 \( \mu \text{m} \). These data are used to study the population of YSOs and warm dust associated with the regions.

3.2. Far-infrared Data from Herschel

Far-infrared (FIR) data used in this paper have been obtained from the Herschel Space Observatory archives. Level 2.5 processed 70–500 \( \mu \text{m} \) images from the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) and Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) observed as part of the Herschel infrared Galactic plane Survey (HI-GAL; Molinari et al. 2010) in parallel mode are retrieved. Resolutions of the images are 5'', 11''4, 17''9, 25'', and 35''7 for 70, 160, 250, 350, and 500 \( \mu \text{m} \) respectively. We use the FIR data to study the physical properties of cold dust emission associated with the regions.

3.3. 843 MHz Data from SUMSS

The radio map at 843 MHz used in this study is obtained from the Sydney University Molonglo Sky Survey (SUMSS) archives. Details regarding this survey can be found in Mauch et al. (2003). The map has a resolution of 45'' and a pixel size of 11''. SUMSS is similar in sensitivity and resolution to the northern NRAO VLA Sky Survey (NVSS).

4. RESULTS AND DISCUSSION

4.1. Ionized Emission

For understanding the distribution of ionized gas associated with S10 and EGO345, we generate continuum maps at 610 and 1280 MHz by setting the “robustness” parameter to +1 (on a scale where +4 represents nearly natural weighting and −4 is close to uniform weighting of the baselines) while running IMAGR. We further use the task UVTAPER to weigh down the long baselines. The above procedures enable us to probe larger spatial scales of the extended diffuse emission in the regions. Figure 3 shows the radio continuum maps overlaid on the 8 \( \mu \text{m} \) IRAC image. Table 1 gives the details of the observation and the maps.

The region associated with S10 shows the presence of faint diffuse emission mostly distributed in the second quadrant in the interior of the bubble. The 610 MHz emission displays a relatively steep density gradient with enhanced emission toward the likely center of the bubble and a more extended emission toward the northeast. However, the higher frequency map at 1280 MHz is seen to be less extended in the southeast and northwest directions, but follows the general morphology seen at 610 MHz. The radio contours near the center are enveloped in the southwest direction by an arc-type 8 \( \mu \text{m} \) structure. Apart from this, in the 1280 MHz map, we see ionized emission beyond the west periphery of the bubble. This emission is not detected in the 610 MHz map down to the 3\( \sigma \) level. This could be due to a combination of the nature of the ISM there as well as the lower sensitivity achieved at 610 MHz.

For optically thin and free–free emission, the excitation parameter, \( u \), and the total flux of ionizing Lyman continuum photons, \( N_{\text{photons}} \), at a given frequency, \( \nu \), can be estimated using the following formulation from Schraml & Mezger (1969) and Panagia (1973),

\[
\left[ \frac{u}{\text{pc cm}^{-2}} \right] = 4.5526 \left[ a(\nu, T_e)^{-1} \left( \frac{\nu}{\text{GHz}} \right)^{0.1} \right] \times \left[ \frac{T_e}{\text{K}} \right]^{0.35} \left[ \frac{S}{\text{Jy}} \right] \left[ \frac{D}{\text{kpc}} \right]^{1.1}
\]

(2)
...the IRAS point sources associated with both the regions. Position angle with EGO345. The contour levels are 3, 4, 5, 6, 7, and 8 times $\sigma$ (0.7 mJy/beam). (c) Same as (a), but for the region associated with EGO345. The contour levels are 3–7 times $\sigma$. (d) Same as (b), but for the region associated with EGO345. The contour levels are 3, 4, 5, 7, 9, and 13 times $\sigma$. The circles in (a) and (b) shows the extent of the bubble S10. The “+” marks indicate the position of the IRAS point sources associated with both the regions.

![Figure 3.](image)

**Table 1**

Details of the Radio Interferometric Continuum Observations

| Details               | 610 MHz  | 1280 MHz |
|-----------------------|----------|----------|
| Date of obs.          | 2011 Jul 17 | 2011 Jul 20 |
| Flux calibrators      | 3C286, 3C48 | 3C286, 3C48 |
| Phase calibrators     | 1626–298 | 1626–298 |
| Synth. beam           | $14^4.4 \times 8^5$ | $8^5.8 \times 4^7.4$ |
| Position angle (degree) | 10.61 | 15.02 |
| rms noise (mJy/beam)  | 0.7      | 0.2      |
| Int. flux (mJy)       | 203 (S10) | 44 (S10) |
| (Integrated up to 3$\sigma$ level) | 43 (EGO345) | 132 (EGO345) |

$$u = 2.01 \times 10^{-19} \left[ \frac{N_{\text{HIC}}}{\beta_{\text{RR}}} \right]^3 \text{pc cm}^{-2}$$

where, $a(\nu, T_e)$ is the correction factor taken as 0.99 (Mezger & Henderson 1967). $T_e$ is the electron temperature, $S$ is the integrated flux density, and $D$ is the distance to the source. $\beta_{\text{RR}}$ is the recombination rate to the excited levels of hydrogen, which is assumed to be $3.43 \times 10^{-13}$ for an electron temperature of 7000 K (Panagia 1973). We determine $T_e$ using the Galactic temperature gradient relation given in Deharveng et al. (2000). The Galactocentric distance to our regions is determined to be 2.8 kpc using the expression given in Xue et al. (2008). This Galactocentric distance corresponds to $T_e$ of 5300 K. To account for the corresponding value of $\beta_{\text{RR}}$ for this temperature, we have applied a scaling factor of 1.0976 to Equation (3) as discussed in Panagia (1973).

As discussed in Churchwell et al. (2006), the probability of chance alignments of bubbles with H II regions is very small (<1%), hence the detected ionized emission can be assumed to be due to the massive star(s) driving the bubble S10. To determine the excitation parameter, total flux of ionizing Lyman continuum photons and the spectral type of the ionizing source responsible for the bubble S10, we assume the emission to be free–free and optically thin at 1280 MHz. We integrate the flux densities up to the 3$\sigma$ level and plug in the values in Equations (2) and (3). For an integrated flux density of 44 mJy and an electron temperature, $T_e$, of 5300 K, we derive values of 13.3 pc cm$^{-2}$ for the excitation parameter ($u$) and 47.0 for the logarithm of the ionizing Lyman continuum photon flux ($\log N_{\text{HIC}}$). Assuming a single exciting source responsible for the ionized emission, we estimate the zero-age main-sequence (ZAMS) spectral type to lie between B0.5–B0 (see Table II of Panagia 1973). This estimate is with the assumption of optically thin emission and hence serves as a lower limit because the emission could be optically thick at 1280 MHz. Various studies in the literature have shown that dust absorption of Lyman continuum photons can be very high (Inoue et al. 2001; Arthur et al. 2004; Paron et al. 2011). With limited knowledge of the dust properties, we have not accounted for the dust absorption here. We determine the...
spectral index, $\alpha$ defined by $S \propto \nu^\alpha$, using the peak flux densities from the two maps after convolving the 1280 MHz map to the resolution of the 610 MHz map (14″x8″). The estimated spectral index of $-0.1$ is consistent with what is expected from optically thin free–free emission. Close to the radio peak ($\alpha_{2000} = 17.07:04.20, \delta_{2000} = -40:37:11.00$), there is a red NIR source (hereafter IRS1 ($\alpha_{2000} = 17.07:03.60, \delta_{2000} = -40:37:10.70$) with colors $J-H = 2.44$ and $H-K = 1.67$. The nature of this source will be discussed later to ascertain whether it is the NIR counterpart of the ionizing star.

Using the integrated flux density of 132 mJy at 1280 MHz and following the above formulation, we also estimate the physical parameters for the region associated with EGO345. The excitation parameter, total flux of ionizing Lyman continuum photon, and spectral type range are determined to be $18.9$ pc $cm^{-2}$, 47.45, and B0–O9.5, respectively. It should be noted here that the peaks at 610 and 1280 MHz are offset from each other by $\sim 10''$. A possible reason for this offset could be the nature of the ISM in this region. If there is an inhomogeneous density distribution, then it could lead to varying optical thickness. EGOs are known to harbor outflows and jets; hence one would also expect thermal emission from jets giving rise to positive spectral indices. Shock-induced nonthermal emission could also coexist in such environments.

Apart from S10 and EGO345, the radio maps (Figure 3) show the presence of a relatively strong radio emitting region $\sim 1''$ to the southwest of the position of EGO345 with integrated flux densities of 21 and 7.5 mJy and peak flux densities of 16.9 and 6.5 mJy/beam at 610 and 1280 MHz, respectively. From the peak flux density values, we infer the associated emission to be nonthermal with a steep negative spectral index of $\sim -1.3$. It is unclear whether this emission is associated with EGO345. No counterpart is reported in NED or Simbad. The SUMSS map shows a faint blob coincident with the location of this source.

4.2. Population of YSOs

In order to understand the stellar population and probe the star-forming activity in the two regions, we identify and classify the associated YSOs. Infrared colors have been proven to be a powerful tool for the identification of YSOs (Allen et al. 2004; Simon et al. 2007; Gutermuth et al. 2008). We have used the GLIMPSE “highly reliable” catalog to retrieve the IRAC band magnitudes within $120''$ of the expected center of the bubble ($\alpha_{2000} = 17.07:05.45, \delta_{2000} = -40:37:04.80$) and within $60''$ centered on the position of EGO345 ($\alpha_{2000} = 17.07:27.60, \delta_{2000} = -40:34:45.00$). We retrieved 65 and 23 sources with good quality data in all IRAC bands for the regions associated with S10 and EGO345, respectively. The red source IRS1 has photometric magnitudes available in the first three IRAC bands only. Using IRAF task $gphot$, we estimate its magnitude at $8\mu m$. Using the IRAC colors, we have identified YSOs in our field adopting the procedures followed by these authors, the details of which are outlined below.

1. Based on the IRAC colors of the models of protostellar envelopes (Class I) and protoplanetary disks (Class II) described in Allen et al. (2004), we identified regions on the [3.6]–[4.5] versus [5.8]–[8.0] color–color plot (CCP) to isolate the Class I and II YSOs. Figure 4 shows the CCP where the boxes drawn to demarcate the regions occupied by Class I and Class II models are adopted from Vig et al. (2007). Using this method, we have identified 10 candidate YSOs out of which 6 are Class I, 1 is Class II, and 3 are either Class I/II type sources in the S10 region. IRS1 falls in the region for Class I YSOs. One candidate YSO of either Class I/II type is identified in the region associated with EGO345.

2. Simon et al. (2007) have proposed a set of criteria based on the IRAC colors for the identification of YSOs, which includes the removal of contaminants like galaxies, PAH sources. These criteria does not differentiate between Class I and II YSOs. The color cuts adopted are $[3.6]–[4.5] > 0.6 \times ([4.5]–[8.0]) – 1.0$ $[4.5]–[8.0] < 2.8$ $[3.6]–[4.5] < 0.6 \times ([4.5]–[8.0]) + 0.3$ $[3.6]–[4.5] > –([4.5]–[8.0]) + 0.85$

In Figure 4, we show the location of YSOs in the CCP based on the above equations. Using this method, we have identified 11 candidate YSOs including IRS1 in the region S10 and 3 candidate YSOs in the region EGO345.

3. Gutermuth et al. (2008) have used the [4.5]–[5.8] color for identifying YSOs. They use various criteria based on the IRAC colors to remove contaminants such as PAH dominated galaxies, active galactic nuclei, and sources dominated by shock emission. This ensures a confident YSO sample.

i. Sources are likely protostars (Class I) if they have an extremely red discriminant color $([4.5]–[5.8] > 1)$. Sources having moderate red discriminant color $0.7 < [4.5]–[5.8] \leq 1$ and $[3.6]–[4.5] > 0.7$ are also considered to be likely protostars.

ii. Class II sources satisfy $[4.5]–[8.0] > 0.5$ $[3.6]–[5.8] > 0.35$ $[3.6]–[5.8] \leq 0.14 \times ([4.5]–[8.0]) – 0.5 + 0.5$.

The location of protostars (Class I) and Class II sources following the criteria by Gutermuth et al. (2008) is shown in Figure 4. Using this, we have detected 11 candidate YSOs out of which 4 are likely protostars (Class I) and the rest including IRS1 are Class II type sources in the region S10 and 4 Class II type YSOs in the region EGO345.

Adopting the various criteria described above, we have identified 14 YSOs including IRS1 in the region associated with S10 and 5 YSOs in the region associated with EGO345. Table 2 lists the identified YSOs in S10 and EGO345. In Figure 5, we show the spatial distribution of the identified YSOs overplotted on the 8 $\mu m$ image. In the figure, we mark the location of two additional sources, which are listed as extreme red sources in Robitaille et al. (2008). The distribution of the identified YSOs are mostly toward the western part of the bubble and the northeastern part of EGO345. It should be kept in mind that the identified YSOs are a sub-sample given the fact that we are concentrating only on those detected in all four IRAC bands.

4.3. Nature of IRS1

As discussed in the previous section, IRS1 is a likely Class I (Allen et al. 2004) or Class II (Gutermuth et al. 2008) YSO. It is located $\sim 7''$ westward from the peak position of the ionized emission probed in the radio frequencies. To derive the
physical parameters of IRS1, we have carried out spectral energy distribution (SED) modeling using the online SED fitting tool of Robitaille et al. (2007). The basic models are computed using a Monte Carlo based radiative transfer algorithm, which uses various combinations of central star, disk, infalling envelope, and cavities carved out by bipolar outflows. A reasonably large parameter space is explored in these models. Assuming that IRS1 is associated with the bubble S10, we have used a distance range of 5.5–5.9 kpc in the model fitting tool. As discussed in Section 4.1, IRS1 is a reddened source and its location in the JHK CCP (not presented in the paper) gives an estimate of $A_v \sim 15$ mag. Hence, for the model fitting, we use a range of $A_v = 1–20$ mag. Apart from the MIR fluxes, we use the NIR JHK fluxes from 2MASS. IRS1 is

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3 This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center, California Institute of Technology, funded by the NASA and the NSF.
| Source | R.A. (J2000)(hh:mm:ss) | decl. (J2000)(dd:mm:ss:ss) | Allen et al. (2004) | Gutermuth et al. (2008) | Simon et al. (2007) |
|--------|-----------------------|-----------------------------|---------------------|------------------------|---------------------|
| YSOs in S10 | | | | | |
| 1 | 17:06:55.51 | −40:36:46.33 | Class I | Class II | YSO |
| 2 | 17:06:56.03 | −40:37:39.68 | Class I | Class II | YSO |
| 3 | 17:06:57.34 | −40:37:28.67 | Class I | Class II | YSO |
| 4 | 17:06:58.25 | −40:36:44.42 | Class II |
| 5 | 17:06:58.26 | −40:36:15.30 | Class I | Class II |
| 6 | 17:06:58.57 | −40:37:58.73 | Class I | Class II | YSO |
| 7 | 17:07:03.43 | −40:36:32.22 | ... | Class II | YSO |
| 8 | 17:07:03.60 | −40:37:10.70 | Class I | Class II | YSO |
| 9 | 17:07:03.84 | −40:37:48.76 | Class I | Class II | YSO |
| 10 | 17:07:05.56 | −40:36:37.40 | ... | Class II | YSO |
| 11 | 17:07:06.63 | −40:36:26.24 | Class II | Class II | YSO |
| 12 | 17:07:10.66 | −40:38:44.02 | ... | Class II | YSO |
| 13 | 17:07:11.98 | −40:37:06.42 | Class I | Class II | YSO |
| 14 | 17:07:14.77 | −40:36:15.84 | Class I | Class II | YSO |

| YSOs in EGO345 | | | | | |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1 | 17:07:25.85 | −40:34:03.97 | ... | ... | YSO |
| 2 | 17:07:29.23 | −40:33:54.29 | ... | Class II | YSO |
| 3 | 17:07:31.10 | −40:34:47.86 | Class I | Class II | YSO |
| 4 | 17:07:31.66 | −40:35:12.88 | ... | Class II | ... |
| 5 | 17:07:32.74 | −40:34:19.45 | ... | Class II | ... |

Notes.

* Extreme red sources from Robitaille et al. (2008).
* The NIR source IRS1.

Table 2. List of YSOs Detected in S10 and EGO345 Based on the Three Classification Schemes.

Figure 5. YSOs (white filled circles) identified by the various methods discussed in the text are marked over the 8.0 μm image. The “+” and “−” marks show the positions of IRAS 17036-4033 and IRAS 17039-4030 in the regions associated with S10 and EGO 345, respectively. The cross marks are the extreme red sources identified by Robitaille et al. (2008). The position of IRS1 is highlighted.

Figure 6. Best-fit SED models of IRS1 using the online tool of Robitaille et al. (2007). NIR and MIR fluxes are shown as solid circles. Flux densities for MIPSGAL 24 μm, PACS 70, 160 μm, SPIRE 250, 350, 500 μm, ATLASGAL 870 μm and 1200 μm are given as upper limits (filled triangles). The best-fit model is shown as a solid black line. The plots shown in gray are the models satisfying the criteria $\chi^2 - \chi_{\text{best}}^2$ (per data point) < 3. The photosphere of the central source is shown as the dashed curve (with interstellar extinction but with the absence of circumstellar dust).

4 This project is a collaboration between the Max Planck Gesellschaft (MPG: Max Planck Institute for Radioastronomy, MPIR Bonn, and Max Planck Institute for Astronomy, MPIA Heidelberg), the European Southern Observatory (ESO) and the Universidad de Chile.

4.4. Emission from the Dust Component

4.4.1. Temperature and Column Density Maps

Emission from dust continuum in the regions associated with S10 and EGO345 is shown in Figure 7. Warm dust is seen in localized areas near the bubble and the EGO, whereas, the cold dust emission is seen to be distributed in a diagonal stretch along the northeast and southwest directions.

The Raleigh–Jeans part of the thermal emission from cold dust is covered by the Herschel FIR bands (160–500 μm). Hence, we use the Herschel data to study the physical properties of the cold dust emission associated with both the regions. We generate the temperature and the column density enclosed within an FIR clump (discussed later). Taking the retrieved clump aperture with an effective diameter of ~12″, we extract the flux densities at 24, 70, 160, 250, 350, 500, 870,
maps using a pixel-by-pixel SED modeling of the dust emission to a gray/modified blackbody. In generating the maps, we have excluded 70 μm data since this band has contribution from both warm and cold dust. Hence, a single modified blackbody model would possibly overestimate the cold dust temperatures and a two-temperature graybody is therefore essential to represent the emission from 70 μm (Galametz et al. 2012). Prior to the SED modeling, the following preliminary steps are carried out using the Herschel data compatible software HIPE.5

1. Using the task “Convert Image Unit,” the image units of the SPIRE images (MJy Sr⁻¹) are converted to a common surface brightness unit of Jy pixel⁻¹ of the PACS images.
2. The plug-in “Photometric Convolution” is then used to project all the images onto a common grid with the same pixel size and resolution of 14″ and 35″/pixel, respectively, which are the parameters of the 500 μm image (the lowest among the four bands).

Subsequent to this, we model the dust emission in each pixel to a modified blackbody using the following expression (Ward-Thompson & Robson 1990; Faimali et al. 2012; Pitann et al. 2013; Mallick et al. 2015),

\[ S_{\nu}(\nu) - I_{bkg}(\nu) = B_{\nu}(\nu, T_{d})\Omega(1 - e^{-\tau_{\nu}}) \tag{4} \]

where \( S_{\nu}(\nu) \) is the observed flux density, \( I_{bkg}(\nu) \) is the background flux, which in our case is obtained from the Gaussian fit explained below, \( B_{\nu}(\nu, T_{d}) \) is the Planck’s function, \( T_{d} \) is the dust temperature, \( \Omega \) is the solid angle (in steradians) from where the flux is obtained (solid angle subtended by a 14″ × 14″ pixel) and \( \tau_{\nu} \) is the optical depth. The optical depth in turn is given by

\[ \tau_{\nu} = \mu_{H_2} m_{H_2} \kappa_{\nu} N(H_2) \tag{5} \]

where \( \mu_{H_2} \) is the mean molecular weight, \( m_{H_2} \) is the mass of hydrogen atom, \( \kappa_{\nu} \) is the dust opacity, and \( N(H_2) \) is the column density. We assume a value of 2.8 for \( \mu_{H_2} \) (Kauffmann et al. 2008). The dust opacity \( \kappa_{\nu} \) is defined to be \( \kappa_{\nu} = 0.1 (\nu/1000 \text{GHz})^{3/2} \text{cm}^2 \text{g}^{-1} \), \( \beta \) is the dust emissivity spectral index, which is assumed to be 2 (Hildebrand 1983; Beckwith et al. 1990; André et al. 2010).

The background flux density, \( I_{bkg} \), is estimated from a relatively “smooth” (free of clumpy emission) and “dark” (free of bright dust emission) region. This is done by visual inspection. We select a region ~1° away from S10 and EGO345. The background fluxes in the four bands are estimated by fitting a Gaussian to the distribution of individual pixel values in the selected region (Battersby et al. 2011; Launhardt et al. 2013; Mallick et al. 2015). The fitting is done iteratively by rejecting the pixel values outside ±2σ, until the fit converges to a value. The resultant background flux levels at 160, 250, 350, and 500 μm are ~3.22, 1.45, 0.72, 0.26 Jy pixel⁻¹, respectively. The negative flux value at 160 μm is due to the arbitrary scaling of the PACS images. The SED modeling is then carried out using nonlinear least square Levenberg–Marquardt algorithm pixel wise. We use a conservative 15% uncertainty on the background subtracted flux densities (Launhardt et al. 2013). Dust temperature and column density are taken as free parameters in the code. From the best-fit values, the temperature and column density maps are generated and shown in Figure 8.

The temperature map shows two peaks (~23 K) close to the IRAS point sources in the two regions. From the overlay of radio contours, it is evident that the ionized regions are traced by a warmer dust component compared to the other regions of the map. The peak temperature positions are ~1′ and 24″ toward northeast of the radio peaks in region S10 and EGO345, respectively. The column density map for the region associated with S10 shows a high density elongated clump toward the southwest of the bubble mostly outside the periphery. A high density region is also seen stretching in the southeast and northwest direction on the opposite periphery. The column density map also shows a dense clump associated with the EGO345 region. Another dense clump is seen toward the southwest of EGO345 and north of the position of the bright radio emitting region mentioned in Section 4.1. Apart from

| \( \log t_{d} \) (year) | Mass (M_\odot) | \( \log M_{\text{disk}} \) (M_\odot) | \( \log M_{\text{disk}} \) (M_\odot yr⁻¹) | \( \log M_{\text{env}} \) (M_\odot) | \( \log T_{d} \) (K) | \( \log L_{\text{total}} \) (L_\odot) | \( A_{\nu} \) (mag) |
|------------------------|----------------|-------------------------------|---------------------------------|-------------------------------|-----------------|--------------------------|------------------|
| 5.70 (6.19)            | 4.75 (6.24)    | −4.02 (−6.70)                 | −9.50 (−12.04)                 | −2.46 (−5.60)                 | 3.96 (4.28)    | 2.42 (3.31)              | 14.29 (14.33)    |
| 3.03–7.00              | 1.04–10.23     | −7.13–0.17                    | −13.51–4.36                    | −7.67–2.65                    | 3.60–4.32      | 1.43–3.37                | 2.92–20.00       |

Note. Values in the parenthesis are from the best-fit model. Second row lists the range for each parameter fitted by all the models satisfying \( \chi^2 - \chi^2_{\text{best}} \) (per data point) < 3.
this, an extended filamentary structure is seen connecting the two regions.

4.4.2. Properties of Dust Clumps

The resolution of the column density map is low (35\arcsec) and hence does not allow us to detect sub-structures in the map. In order to identify dust clumps or condensations associated with the region around S10 and EGO345, we use the 250 \(\mu m\) image, which has a optimum resolution of 18\arcsec. The threshold for detecting the clump peaks was set to 1.9 Jy pixel\(^{-1}\) (=20\(\sigma\)) to avoid spurious clump detection. The positions of peak intensities in the map are determined by identifying the pixels having the highest value in 3 \times 3 pixel matrices, with flux values above the estimated threshold. Subsequent to the peak identification, contours are generated to isolate the clumps around these peaks. Using these generated contour levels in the 2D variation of the clumpfind algorithm (Williams et al. 1994), we detect a total of eight clumps (six in region S10 and two in region EGO345). Figure 9 shows the clumps detected using the 250 \(\mu m\) image overlaid on 24 \(\mu m\) Spitzer-MIPS and the five Herschel bands. In Figure 9(a), we also show the six 1.2 mm clumps of Beltrán et al. (2006). As seen from the figure, there is an overall overlap of the clumps detected in this work and those from Beltrán et al. (2006). The different numbers, shapes, and sizes of the clumps could be attributed to the different wavelength of the maps and the threshold and contour spacing adopted. The above reason would mostly justify the non-detection of Clumps 4, 5, and 6 by Beltrán et al. (2006).

We determine the masses of the clumps from the column density as well as the 250 \(\mu m\) maps. The expressions used are outlined below.

1. From column density map: the masses of the clumps are estimated by determining the mass in each pixel and then summing over all the pixels inside the clump by using the following equation,

\[
M_{\text{clump}} = \mu_{\text{H}_2} m_{\text{H}_2} A_{\text{pixel}} \Sigma N (\text{H}_2)
\]

where \(m_{\text{H}_2}\) is the mass of the hydrogen nucleus, \(A_{\text{pixel}}\) is the pixel area in cm\(^2\), \(\mu_{\text{H}_2}\) is the mean molecular weight, and \(\Sigma N (\text{H}_2)\) is the integrated column density within the clump apertures. The clump apertures are retrieved from the clumpfind algorithm.

2. From 250 \(\mu m\) image: here, the masses of the clumps are estimated from the 250 \(\mu m\) integrated flux values obtained using the clumpfind algorithm and the following expression from Kauffmann et al. (2008)

\[
M = 0.12 M_\odot \left( \frac{\epsilon}{1.439 (\lambda / \text{mm})^{-1} (T_d / 1000 \text{ K})^{-1} - 1} \right) \times \left( \frac{\kappa_\nu}{0.01 \text{ cm}^2 \text{ g}^{-1}} \right)^{-1} \left( \frac{S_\nu}{100 \text{ pc}} \right)^2 \left( \frac{\lambda}{\text{mm}} \right)^3
\]

where \(T_d\) is the dust temperature, \(\kappa_\nu\) is the dust opacity, which is taken as 0.1 \(\left( \frac{\nu}{1000 \text{ GHz}} \right)^{0.1} D\) is the distance, and \(S_\nu\) is the integrated flux. For \(T_d\), we use the mean dust temperatures of the clumps estimated from the temperature maps.

The derived masses and other physical properties of the clumps are listed in Table 4. As seen from the table, the masses derived from the column densities are lower (by an average factor of \(~0.9\)) compared to those derived from the 250 \(\mu m\) image alone. The masses derived from the column density map would be a better estimate given that it uses data from four bands. The table also lists the diameters of the clumps. We have estimated the deconvolved sizes following the method outlined in Beltrán et al. (2006). We also list the diameters derived based on the physical size of the clump (Kauffmann & Pillai 2010) in parenthesis. The latter does not have the beam effect removed, and we refer to it as the effective diameter.

In order to understand the nature of the sources toward these clumps, we use the online SED model fitting tool of Robitaille et al. (2007) to fit the clump fluxes with the inbuilt YSO models. This is along the lines discussed in Zavagno et al. (2010). Here, we assume that each clump will produce a single high-mass star. Apart from the MIPS and Herschel data, we have used 870 \(\mu m\) ATLASGAL and 1.2 mm (Beltrán et al. 2006) fluxes. We use the clump apertures retrieved from the clumpfind algorithm to obtain flux densities in all wavelengths. The same apertures were used on nearby “smooth” and “dark” regions to estimate the background emission, which is subtracted out from the clump fluxes. As was done earlier, we take a conservative uncertainty of 15% on the background subtracted flux densities. Figure 10 shows the results of the fits toward the clumps. In Table 5, we list the range of values of various parameters of the first 10 best fitting SED models with the best-fit values in parenthesis. The envelope masses retrieved from fitting the SED models are seen
to be \( \sim 1.5 \)–3 times larger than the derived masses of the clumps, except for Clump 4 where both the masses are similar. All clumps are seen to harbor high luminosity, high envelope accretion rate, and massive YSOs. As mentioned in Section 4.3, the retrieved values of the parameters are to be used as indicative only as these models involve a large range in parameters with limited data points. Hence, instead of fitting to a unique combination, the models return a range in the parameter space.

Kauffmann & Pillai (2010) suggest an empirical mass–radius relation to define a threshold for clouds to form massive stars. They derive this relation by comparing the mass–radius relation
Table 4
Physical Parameters of the Clumps

| Clump No. | R.A. (2000) (dd:mm:ss:ss) | decl. (2000) (dd:mm:ss:ss) | $F_{250}$ (Jy) | Linear Diameter (pc) | Mean $T_d$ (K) | Mean $N$(H$_2$) ($\times10^{22}$ cm$^{-2}$) | $M_{250}$ ($M_\odot$) | $\Sigma$ $N$(H$_2$) ($\times10^{23}$ cm$^{-2}$) | $M_{CD}$ ($M_\odot$) |
|-----------|--------------------------|-----------------------------|----------------|----------------------|----------------|---------------------------------------------|------------------|---------------------------------------------|------------------|
| 1         | 17:07:12.02               | -40:36:33.00                | 222            | 1.1 (1.9)            | 20.6           | 2.0                                         | 1436             | 4.2                                          | 1390             |
| 2         | 17:07:12.02               | -40:36:57.00                | 85             | 0.2 (1.1)            | 20.8           | 1.7                                         | 533              | 1.1                                          | 354              |
| 3         | 17:07:09.40               | -40:37:09.09                | 131            | 0.6 (1.4)            | 21.5           | 1.7                                         | 750              | 2.1                                          | 685              |
| 4         | 17:07:03.08               | -40:37:15.40                | 63             | 0.3 (1.0)            | 21.0           | 1.6                                         | 390              | 1.0                                          | 337              |
| 5         | 17:07:04.70               | -40:38:27.90                | 134            | 0.6 (1.5)            | 20.5           | 1.8                                         | 875              | 2.5                                          | 845              |
| 6         | 17:06:58.90               | -40:38:37.60                | 143            | 0.7 (1.6)            | 19.6           | 2.1                                         | 1074             | 2.6                                          | 852              |

Note. $F_{250}$ is total flux density in 250 $\mu$m. The listed positions correspond to the peaks of the clumps as derived from the 250 $\mu$m image using the clumpfind algorithm. The linear diameters listed here are the deconvolved (without parenthesis) and the effective diameter (within parenthesis). $T_d$ and $N$(H$_2$) are the mean dust temperature and column density respectively. $M_{250}$ is mass calculated using fluxes from 250 $\mu$m and $M_{CD}$ is the mass calculated using the column density map.

Figure 10. Results of the online SED modeling of Robitaille et al. (2007) for the eight clumps. The gray lines are the 10 best fitting models and the black line is the best-fit model.

Table 5
Physical Properties Derived from the 10 Best Fitting SED Models of Robitaille et al. (2007) for the Eight Detected Clumps

| Clump No. | $M_\odot$ ($M_\odot$) | $M_{env}$ ($10^{-3}M_\odot$ yr$^{-1}$) | $M_{env}$ ($M_\odot$) | Luminosity ($10^3 L_\odot$) |
|-----------|----------------------|--------------------------------------|----------------------|-----------------------------|
| 1         | 12–22 (19.7)         | 5–9 (9.2)                            | 2000–5000 (2200)     | 6–15 (12.3)                 |
| 2         | 9–14 (10.8)          | 2–7 (5.0)                            | 400–2000 (613)       | 2–6 (4.5)                   |
| 3         | 11–22 (11.7)         | 2–9 (2.3)                            | 1000–2000 (1450)     | 10–31 (15.1)                |
| 4         | 8–12 (11.8)          | 1–5 (3.3)                            | 100–700 (333)        | 2–9 (4.1)                   |
| 5         | 11–18 (17.8)         | 3–7 (6.9)                            | 600–2500 (1990)      | 4–10 (8.9)                  |
| 6         | 12–18 (17.8)         | 4–7 (6.9)                            | 2000–5000 (1990)     | 4–9 (8.9)                   |

Note. The values in parenthesis are for the best-fit models.
of clouds with and without massive star formation. The clouds devoid of massive star formation are shown to generally obey the relation, \( m(r) \leq 870M_\odot (r/\text{pc})^{3.3} \). In Figure 11(a), we plot the estimated mass (from column density map) as a function of the effective radius of the clumps. It should be noted here that the threshold estimated by Kauffmann & Pillai (2010) is based on effective radii derived using the physical area of the clumps. Hence, if we look at the filled circles in the figure, most of the clumps detected in the regions associated with S10 and EGO345 are above the threshold. Two clumps are seen just below, but very close to, the dividing line. This implies that all the clumps are potential high-mass star-forming regions. We have also plotted the deconvolved radius of the clumps as open circles. The dashed line denotes the slope from Urquhart et al. (2013) and the region lying above that marks the location of high-mass star-forming clumps. The relation given in Urquhart et al. (2013) is based on deconvolved sizes. Both these empirical mass–radius relations strongly suggest that the clumps detected in these regions are capable of forming high-mass stars.

Clumps 3, 4, and 7 show the presence of 24 \( \mu \)m emission peaks of which Clumps 4 and 7 also include radio peaks. Clump 7 includes the EGO and Class I and II methanol masers. An intermediate-mass YSO, IRS1, is shown to be located in Clump 4. Given these signatures of star formation, these three clumps can be considered to be active high-mass star-forming clumps. Of these, Clump 3 seems to be in the earliest evolutionary phase prior to the formation of the UCHII region. The peak of the bright radio emitting region lies in Clump 8. Apart from this, the rest of the clumps do not reveal any signposts of active star formation. Following the discussion in Molinari et al. (2008) and Giannetti et al. (2013), these could be regarded as either being starless or with a deeply embedded ZAMS star. All clumps in our sample have luminosities of \( L > 10^3 L_\odot \) and hence are likely to host ZAMS stars (Giannetti et al. 2013).

To further understand the evolutionary phase of these clumps, we follow the discussion in Molinari et al. (2008), which is based on the SED of massive YSOs. They discuss the evolutionary sequence of massive YSOs on a \( L_{\text{bol}}-M_{\text{env}} \) plot (see their Figure 9). Their plot also includes the regime of low-mass YSOs from Saraceno et al. (1996) and shows the behavior of the bolometric luminosity, \( L_{\text{bol}} \) and the envelope mass, \( M_{\text{env}} \) as the YSO moves from the accelerating accretion phase to the end of it reaching the ZAMS (or close to it) and then proceeding to the envelope clean-up phase. In Figure 11(b), we plot the clump masses (and the corresponding envelope masses determined from the SED models) as a function of the derived luminosities. The loci demarcating the accelerating accretion and onset of envelope clearing phases, adopted from Figure 9 of Molinari et al. (2008), are also plotted in this figure. Our plot shows the high-mass end of their figure. Two of the active clumps (4 and 7), which show radio peaks, are possibly in the early envelope clearing phase. This is consistent with the fact the ZAMS phase is marked by detectable ionized emission. Apart from clump 2, which is also close to the demarcating loci, the rest of the clumps lie in the region associated with the accelerating accretion phase of evolution. As discussed by these authors, the end of the ascending phase is accompanied by very high accretion rates, which is consistent with the values obtained from the SED modeling of the clumps.

Figure 12(a) plots the envelope mass as a function of the final mass of the star, \( M_\ast \) based on the best-fit SED model values. The derived envelope mass can be considered here as the initial mass of the envelope given the almost vertical evolutionary track in the \( L_{\text{bol}}-M_{\text{env}} \) plot of Molinari et al. (2008), where the mass of the envelope remains the same from the initial to the end of accelerating accretion phase. As seen from the figure, the final mass of the star follows a decreasing
Figure 12. (a) The final mass of the massive star, $M_*$ as a function of the envelope mass (assumed to be the initial mass of the envelope here). The straight line is the fit adopted from Molinari et al. (2008). (b) The star-forming efficiency of the clumps as a function of the envelope mass.

4.5. Possible Bow Wave in S10?

Detailed studies on the formation and nature of bubbles have been in focus since the first published catalogs of Churchwell et al. (2006, 2007) based on the Spitzer-GLIMPSE and MIPSGAL survey images. The observed bright-rimmed morphology in the MIR is a combination of UV radiation, excited polycyclic aromatic hydrocarbons (PAHs), emission in the IRAC bands, and thermal emission from hot dust surrounding the newly formed star. Given the prominent MIR morphology, these are more commonly known as IR bubbles. The general bubble structure is a photodissociation region (PDR) visible at 5.8 and 8 μm and an evacuated cavity within this (Churchwell et al. 2006, 2007; Watson et al. 2008, 2009; Anderson et al. 2010; Deharveng et al. 2010; Zavagno et al. 2010; Kendrew et al. 2012). More recently, another catalog of IR bubbles was published by Simpson et al. (2012)—The Milky Way Project.

As mentioned in the Introduction, several feedback mechanisms are believed to be responsible for the formation of the bubbles. Even though the relevance of each depends on the nature of the ionizing star, the traditional picture of wind-blown bubbles (Weaver et al. 1977) lacks observational support as outlined in Ochsendorf et al. (2014a). The non-detection of X-ray emission inside bubbles and the presence of dust in the H II regions are observations that challenge the wind-blown bubble model. The view that evaporation of dense cloudlets replenishes the interior of bubbles with a new generation of dust grains could explain the presence of dust seen in the H II regions associated with the bubbles (Everett & Churchwell 2010). However, this mechanism fails to account for the growing evidence of arc-type structures seen at 24 μm in the interior of bubbles and the observation of incomplete shells in H II bubbles (Watson et al. 2008; Kang et al. 2009; Deharveng et al. 2010).

Ochsendorf et al. (2014a, 2014b) have explored the formation of infrared bubbles for weak wind stars ($\log (L/L_\odot) \lesssim 5$), which invokes the thermal pressure of the ionized gas instead of stellar wind. The two-dimensional hydrodynamical simulations of this model by Ochsendorf et al. (2014b) focuses on the formation of arc-type structures seen to exist close to the ionizing star in the bubble interior. Referring to Figure 2 of Ochsendorf et al. (2014b), the newly born massive star starts of with ionizing the surrounding and forming an expanding sphere of ionized gas. The thermal pressure in the interior causes the bubble to expand, sweeping up neutral gas in a dense encompassing shell. The formation of a shock front may occur provided the expansion is supersonic. In the case of a density gradient or a break in the bubble shell, the ionized gas is shown to flow toward the low-density regions.
arc-type feature in the 610 MHz GMRT gas, the dust is also dragged along but is halted in the pressure of the overpressurized bubble. Along with the ionized gas, the dust leaks out to the surrounding ISM. This releases the pressure of the overpressurized bubble. Along with the ionized gas, the dust leaks out to the surrounding ISM. This releases the pressure of the overpressurized bubble. This model simulation finds observational validation in the arcs seen at 24 μm around σ Ori AB (Ochsendorf et al. 2014a), which is possibly the first detection of the predicted radiation driven dust wave around a weak wind star. Similar arcs are detected in the interiors of bubbles RCW 120 and RCW 82 and are also well explained by this model (Ochsendorf et al. 2014b).

The scenario associated with bubble S10 is rather interesting. In Figure 13, we show the three-color composite image of S10 using 8 μm (Spitzer-IRAC), 24 μm (Spitzer-MIPS), and 610 MHz (GMRT). As mentioned earlier, 8 μm emission is seen as a prominent outer shell and an inner arc-type feature. 24 μm emission shows enhanced distribution mostly in three localized regions. These are (1) near the eastern limb of the outer shell coincident with the position of the IRAS point source, (2) toward the center of the bubble with the inner 8 μm arc enveloping it, and (3) beyond the periphery of the broken western part of the bubble. The 8 μm emission shows a rupture in the outer shell, which seems to be aligned (at a PA of ~50° north of east) with the opening direction of the inner arc-type feature as is seen clearly in the right panel of Figure 13. The arc-type inner structure and the ruptured outer shell morphology is also clearly seen at 5.8 μm. The ionized emission at 610 MHz displays a fan-like morphology aligned in this direction. Though less extended, the 1280 MHz map also reveals a similar structure (see Figure 3). The radio emission displays a picture wherein a flow of ionized gas is seen from the position of the radio peak (considered to be the position of the ionizing star) toward lower density regions and further leaking out of the rupture in the outer shell. This interesting morphology prompted us to investigate the presence of a bow wave, but at shorter wavelengths compared to the 24 μm arcs discussed in Ochsendorf et al. (2014a, 2014b). This is supported by the fact that the likely ionizing star responsible for S10 falls in the “weak-wind” category with an estimated log (L/L⊙) lying between 4.04 (B0.5) and 4.40 (B0).

We assume the expansion of the H II region around the massive B0.5–B0 star (located at the radio peak) to be responsible for the formation of the bubble that is seen as the outer (and larger) shell. This implies that the 8 μm band emission seen in this outer shell is largely due to PAH emission in the PDR with contribution from thermal emission from dust as well (Watson et al. 2008; Pomarès et al. 2009). It is well known that intense UV radiation close to the ionizing star destroys the PAH molecules (Watson et al. 2008). Hence, the 8 μm inner arc-type feature close to the possible ionizing star is likely to be due to thermal emission from dust alone. As seen in the figure, a bright 24 μm blob overlaps the radio emission toward the center of the bubble. 24 μm emission arises mostly near the hot star when the dust is heated to ~100 K. The 8 μm arc-type emission is also seen to be coupled to the ionized gas. As discussed in Ochsendorf et al. (2014b), the gas and dust coupling depends on the efficiency of momentum transfer between gas and dust, which would result in either a dust wave (gas and dust decoupled) or a bow wave (gas and dust spatially correlated). The gas and dust couple well in relatively slower flow of ionized gas. The bow wave is similar in appearance to the stellar-wind bow-shock (van Buren et al. 1990). However, in case of the bow wave, the dust grains are stalled at a distance (rmin) exceeding the stand-off distance (rs) of the bow-shock in the flow direction (Ochsendorf et al. 2014a).

The stand-off distance, rs, is determined using the following expressions based on Mac Low et al. (1991), which equates the momentum flux of the stellar wind with the ram pressure of the star moving through the ISM.

\[
r_s = 1.78 \times 10^3 \left( \frac{M_{\text{w}}}{\mu_m n_H v^2_{\text{w,ISM}}} \right)^{\frac{1}{2}} \text{pc}
\]

\[
\dot{m} = 2.0 \times 10^{-7} (L/L_{\odot})^{0.25}
\]

\[
\log v'_w = -38.2 + 16.23 \log T_{\text{eff}} - 1.70 (\log T_{\text{eff}})^2
\]
where, $\dot{M} (= m \times 10^{-6} M_\odot \text{ yr}^{-1})$ is the mass-loss rate from the star and $v_{\infty} (= v'_{\infty} \times 10^3 \text{ km s}^{-1})$ is the terminal velocity of the stellar wind, $n_H$ is the mean number per hydrogen nucleus, $n_H$ is the hydrogen gas density in cm$^{-3}$, $v_{\infty}$-ISM is the velocity of the star with respect to the ISM in km s$^{-1}$, $L$ is the stellar luminosity, $L_\odot$ is the solar luminosity, and $T_{\text{eff}}$ is the effective temperature of the star, respectively. The hydrogen gas density $n_H$ is determined from the column density maps obtained using the Herschel images (see Section 4.4.1). Assuming uniform density in a spherical region within $\sim 15''$ of the peak of radio emission (position of the ionizing source), we estimate $n_H$ to be $1.6 \times 10^4 \text{ cm}^{-3}$. This is of the same order obtained for the clumps by Beltrán et al. (2006). Taking $\mu_H = 1.4$ and assuming a typical velocity, $v_{\infty}$-ISM, of 10 km s$^{-1}$, we get a stand-off distance between $(0.8-1.5) \times 10^{-2} \text{ pc}$, which corresponds to $0''3-0''5$ at a distance of 5.7 kpc for a spectral type of B0.5–B0 estimated for the ionizing star. The values for $L$ and $T_{\text{eff}}$ are taken from Panagia (1973). From the 5.8 and 8 $\mu$m images, we estimate the arc to be at a distance ($r_{\text{min}}$) of $\sim 15''$ from the radio peak, which corresponds to $\sim 0.4 \text{ pc}$, far exceeding the stand-off distance, $r_s$. This is consistent with what is expected for a bow wave to occur. In Ochsendorf et al. (2014a), a similar dust structure qualifying as a dust wave is seen at a distance of 0.1 pc from $\sigma$ Orionis AB. Further, Figure 13 of Ochsendorf et al. (2014a) shows $r_s$ and $r_{\text{min}}$ as a function of the ISM density for the strong and weak wind regimes and clearly shows that the formation of dust and bow-waves are more efficient around weak-wind stars. The ratio $r_{\text{min}}/r_s$ roughly estimated from the figure for the $n_H$ value of S10 ($1.6 \times 10^4 \text{ cm}^{-3}$) is around 45. This is fairly consistent with the range $\sim 25-50$ obtained in our case.

Driven by the radio and MIR morphology and based on the above calculations, we propose that the inner arc-type structure seen in the mid-infrared bands at 5.8 and 8 $\mu$m surrounding the weak-wind ionizing star is a radiation pressure driven dust structure: a bow wave. The radiation pressure of the ionizing star of S10 stops the dust that is being dragged along the structure: a bow wave. The radiation pressure of the ionizing star is a radiation pressure driven dust seen in the mid-infrared bands at 5.8 and 8 $\mu$m. However, it is possible that the direction of the flow of ionized gas and hence the dust drag is dictated by the local density gradient close to the ionizing source. The aforementioned discrepancies suggest that a detailed study of the dust grain characteristics and its wavelength dependence is necessary before we can conclusively address the possibility of occurrence of a bow wave at shorter MIR wavelengths.

5. SUMMARY

In this paper, we have done a multiwavelength study toward southern infrared bubble S10. We probed two regions, S10 and EGO345, and arrive at the following conclusions.

1. The radio maps at 610 and 1280 MHz show the presence of ionized emission in the interior of the bubble with the emission being more extended at 610 MHz. A steep density gradient is also evident from the 610 MHz emission, which increases toward the likely center of the bubble. Assuming optically thin, free–free emission from a single ionizing star, the spectral type of it is determined to be B0.5–B0. The region associated with EGO345 also shows the presence of ionized emission at both the above radio frequencies. The morphology is compact and nearly spherical at 610 MHz compared to a relatively clumpier and extended one at 1280 MHz. The spectral type of the ionizing source responsible for this emission is estimated to be B0–O9.5.

2. An intermediate-mass YSO of Class I/II, IRS1, with estimated mass of $6.2 M_\odot$ lies $\sim 7''$ to the west of the radio peak of S10. It is unlikely that this is the NIR counterpart of the ionizing star. The massive star responsible for the ionized region could likely be a deeply embedded source.

3. Dust temperature and column density maps are generated using SED modeling of the thermal dust emission from Herschel FIR data. The distribution of ionized gas traced by the radio emission is found to be consistent with the location of warmer dust. The column density map reveals the presence of several high density clumps and filaments.

4. Using the 250 $\mu$m image and the 2D variation of the clumpfind algorithm, eight clumps are detected in both of the regions. The masses of clumps as derived from the column density maps range between $\sim 337-1564 M_\odot$. The mass and effective radii of the clumps place them in the high-mass star-forming clumps regime. Clumps 3, 4, and 7 show signatures of active star formation with Clumps 4 and 7 coincident with the radio peaks of S10 and EGO345, respectively.

5. SED modeling for sources toward these clumps show that they harbor high luminosity, high envelope accretion rate, massive YSOs. Based on the fitted values of the mass of the star and envelope, these clumps are seen to lie in the accelerating accretion phase of massive YSOs.

6. The MIR images show the presence of an arc-like feature near the likely center of the bubble aligned with a rupture seen in the outer shell of the bubble. The arc encompasses the radio emission on the southwest side. The ionized emission at both the radio frequencies is consistent with the picture of a flow of ionized gas toward the outer shell originating from the center of the bubble. The above
scenario indicates at a possible detection of a bow wave at the MIR wavelengths. This is supported by the standoff distance, which is estimated to be much smaller than the distance of the arc from the radio peak as is the case with bow-waves.

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