# Probing Star-formation activity towards IR Dust Bubble S6

Ajay Potdar[1], Swagat Ranjan Das[2], Namitha Isaac[1], Anandmayee Tej[1] and Sarita Vig[1]

1. Indian Institute of Space Science and Technology (IIST), Trivandrum
2. Indian Institute of Science Education and Research(IISER), Tirupati

ajaypotdar99@gmail.com

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## Introduction

High-mass (M $\geq$8 $M_{\odot}$) stars profoundly influence the surrounding interstellar medium (ISM). A combination of thermal pressure of the expanding HII region, powerful stellar wind, and radiation pressure associated with the newly formed massive star sculpts the ISM resulting in a 'bubble'. Bubbles are ubiquitous in the Galactic plane and observationally manifest as shells of enhanced density of swept up gas and dust between the ionization and the shock fronts encompassing a relatively low-density, evacuated cavity around the central star. Bubbles display striking mid-infrared (MIR) morphology with 24 μm emission sampling the hot dust enclosed within bright-rimmed 8 μm emission. The MIR emission is attributed to polycyclic aromatic hydrocarbon molecules in the photodissociation regions surrounding O and early-B stars. The association with OB stars and HII regions make these ideal laboratories to probe high-mass star formation and their interaction with the surrounding medium. In this work, we present a mulit-wavelength study of the southern infrared (IR) dust bubble S6. The associated ionized emission is investigated using low-frequency radio observations and physical properties of the associated dust environment is studied in far-infrared (FIR) wavelengths.

## Observations and Archival Data

- Radio continuum observations at 610 and 1280 MHz were obtained with the GMRT and data reduction was carried out using standard procedures with AIPS.
- PACS and SPIRE data in the wavelength range 70 - 500 μm was obtained from the Herschel Space Observatory archives.
- Molecular line data were retrieved from the archives of the MALT90 survey.

## Dust Bubble S6

- Located at a distance of 2.0 kpc [1].
- Classified as a bubble showing closed ring morphology [6].
- Associated with a $H_2O$ maser and a $H_2$ jet [1].
- Likely ionized by a central Ionizing star of spectral type O5V - O6V [4].
- Associated with three dense cores [1].
- Associated with a NIR star cluster [4].

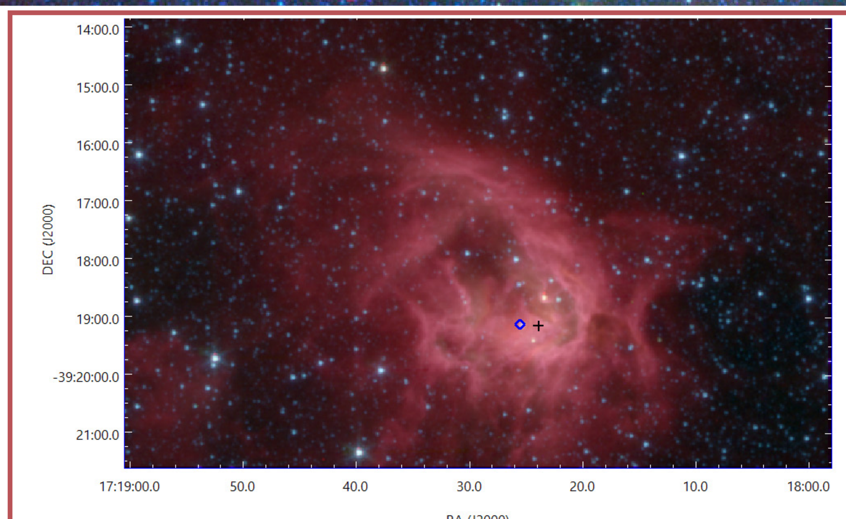

Fig.1 : *Spitzer*-IRAC colour composite (3.6 (B), 4.5 (G), 8.0 μm (R)) of the region towards S6. The blue diamond marks the central Ionizing star. "+" : nominal position of IRAS 17149-3916.

## Associated Ionized Emission

- The ionized emission associated with S6 displays distinct cometary morphology at both frequencies.
- The cometary head is towards the west with a fan-like diffuse emission towards the east.
- The radio emission is more extended in the north-south direction.
- The location of radio peak is ~20 arcsec towards south-west of NIR identified ionizing star.

| Details | 610 MHz | 1280 MHz |
|---|---|---|
| Synth. beam | 10.69″ × 6.16″ | 4.41″ × 2.24″ |
| *rms* noise (mJy beam$^{-1}$) | 0.32 | 0.17 |
| Integrated flux (Jy) | 14.3 | 12.8 |

Table 1: Details of the Radio interferometric continuum maps

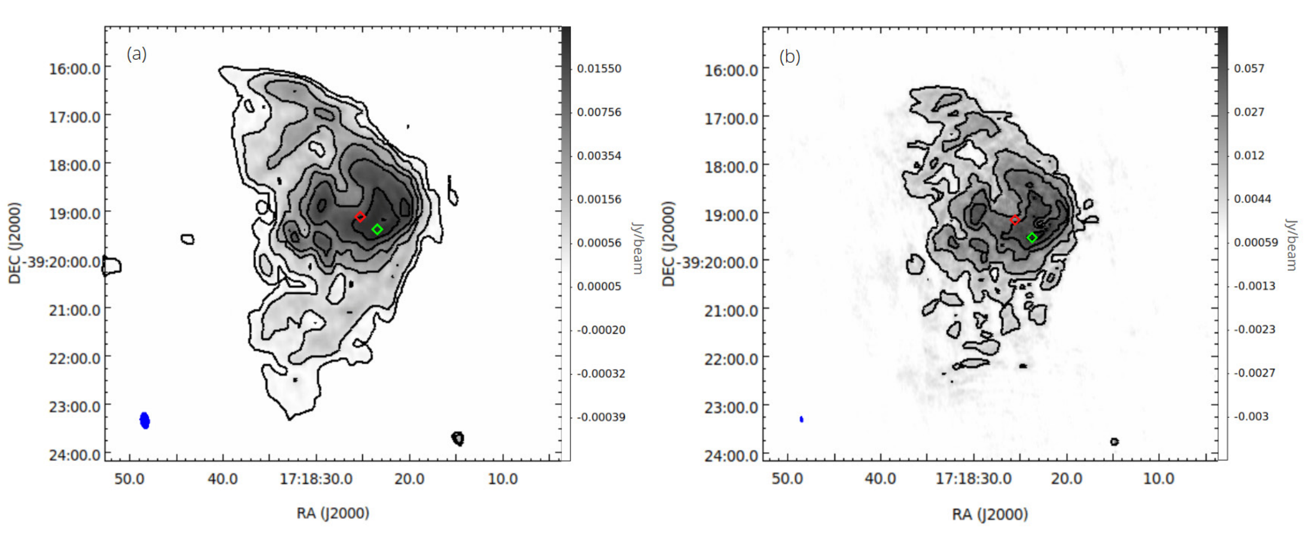

Fig. 2 : a) 610 MHz map of the region towards S6. Contours are 3, 10, 30, 60, 120, 240 σ where σ = 0.32mJy/beam b) 1280 MHz map of the region towards S6. Contours are 3,10, 30, 60, 120 σ where σ = 0.17mJy/beam. Red diamond: position of the ionizing star [4], green diamond : radio emission peak.

- Assuming the radio emission at 1280 MHz to be optically thin and emanating from a homogeneous, isothermal medium, the Lyman continuum flux required to maintain ionization in the nebula is determined using the following expression [3]:

$$\left[\frac{N_{ly}}{sec^{-1}}\right] = 4.771 \times 10^{42} \left(\frac{S_\nu}{Jy}\right)\left(\frac{T_e}{K}\right)^{-0.45}\left(\frac{\nu}{GHz}\right)\left(\frac{D}{pc}\right)^{2} \qquad N_{ly} = 5.37 \times 10^{48}\ sec^{-1}$$

where, $T_e$ is the electron temperature determined using the Galactic Temperature gradient relation[2]:

$$T_e = (5780 \pm 350) + (287 \pm 46)R_{Gal} \qquad T_e \sim 8200\ K$$

here, $R_{Gal}$: Galactocentric distance which is 8.5 kpc for the IR bubble S6 [4].

- The ZAMS spectral type of the central ionizing star is estimated to be O7 - O8.5.

## Dust Temperature and Column Density Maps

- Line-of-sight average molecular hydrogen column density and the dust temperature maps are generated by pixel-wise modified blackbody fits to the 70, 160, 250, 350 and 500 μm data:

$$S_\nu(\nu) - I_{bg}(\nu) = B_\nu(\nu, T_d)\Omega(1 - e^{-\tau_\nu})$$

$$\tau_\nu = \mu_{H_2} m_H \kappa_\nu N(H_2)$$

$$\kappa_\nu = 0.1(\nu/1000GHz)^{\beta}$$

$I_{bg}$ : background flux, $B_\nu$ : Planck's function $\Omega$: solid angle subtended by a pixel, $\tau_\nu$: optical depth $\mu_H$ : mean molecular weight, $m_H$ : mass of hydrogen atom and $\kappa_\nu$: dust opacity, $\beta(=2)$: dust emissivity spectral index.

- The dust temperature map peaks towards the northern portion of the ionized gas.
- Two column density peaks are seen lying towards the head of the cometary ionized gas distribution.

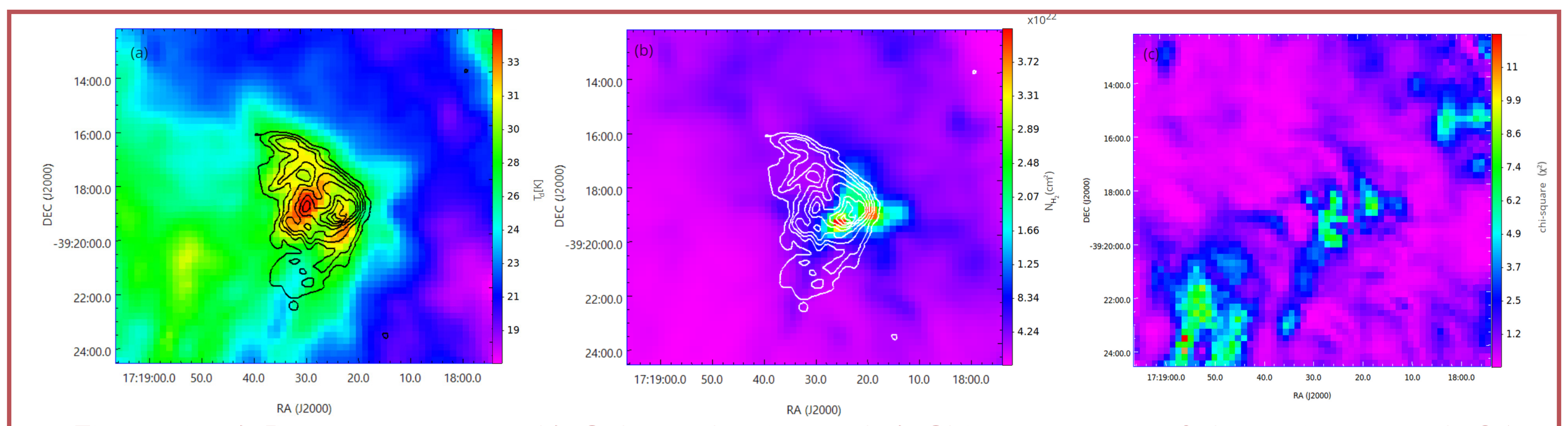

Figure 4 : a) Dust temperature, b) Column density, and c) Chi-square map of the region towards S6. GMRT 610 MHz contours are overlaid.

## Dust Clumps

- Cold dust clumps are identified from the 250 m image using the Fellwalker algorithm[5] with a 4σ (σ = 598 MJy sr$^{-1}$) threshold.
- Three clumps (I, II and III) are identified to be associated with the cold dust emission.
- Mass of the dust clumps are estimated using the column density map and the equation:

$$M_{clump} = \mu_{H_2} m_H A_{pixel} \Sigma N(H_2)$$

where, $A_{pixel}$ : pixel area.

| Clump | $\Sigma N(H_2)$ ($\times 10^{23} cm^{-2}$) | Radius (pc) | Mass ($M_{\odot}$) | Mean $T_d$ (K) | Mean $N(H_2)$ ($\times 10^{22} cm^{-2}$) | No. Density ($n_{H_2}$) ($\times 10^{4} cm^{-3}$) |
|---|---|---|---|---|---|---|
| I | 8.1 | 0.5 | 338 | 26.7 | 1.9 | 3.9 |
| II | 4.9 | 0.4 | 203 | 29.1 | 1.4 | 2.6 |
| III | 6.5 | 0.5 | 268 | 30.5 | 1.7 | 3.1 |

Table 2 : Physical parameters of the identified dust clumps

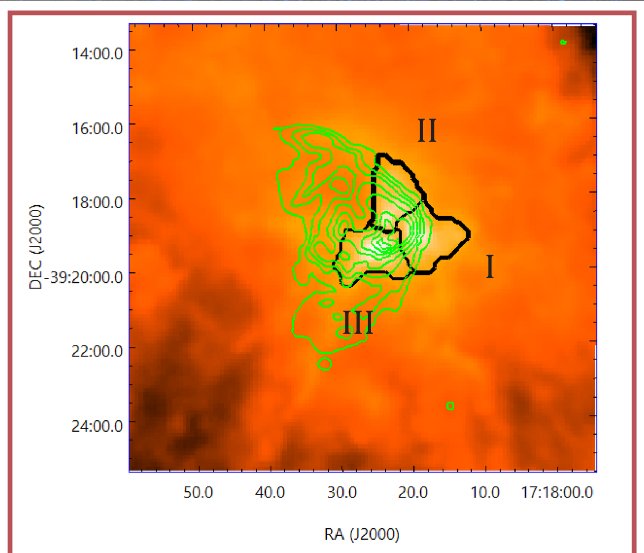


Figure 5 : 250 μm *Herschel* map of the region towards S6. The overlaid apertures corresponds to that of three clumps as determined using the Fellwalker algorithm. Green contours correspond to 610 MHz contours.

## Emission from Dust Component

- Cold dust emission sampled in the FIR wavelengths traces the bubble morphology seen in the MIR.
- Dust clumps are seen towards the south-west of the bubble being more prominent as we go to longer wavelengths.
- A long, extended filamentary structure is seen below the south-east rim of the bubble
- The ionized gas emission extends beyond the bubble rim in the south-east direction.

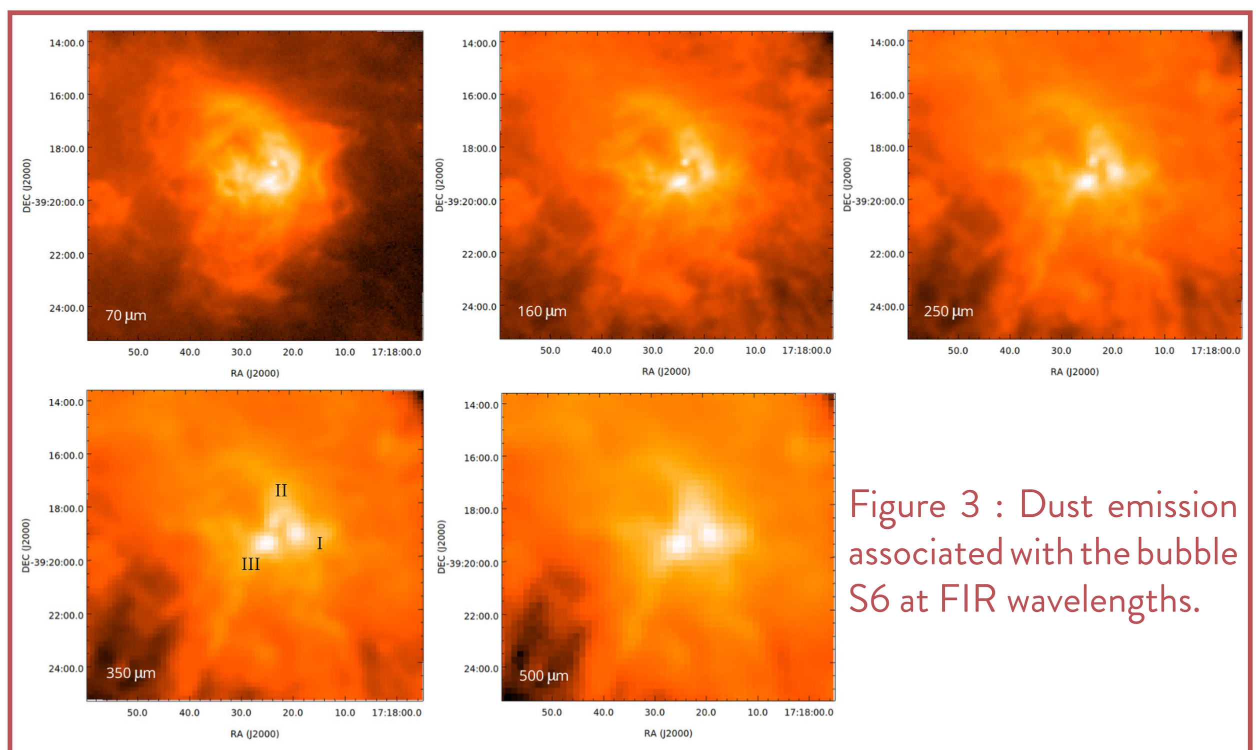


Figure 3 : Dust emission associated with the bubble S6 at FIR wavelengths.

## Kinematics of the Dust Clumps

- Of the sixteen molecular-line transitions covered in the MALT90 Survey, four ($N_2H^+$, $HCO^+$, HCN and HNC) are detected towards Clumps I, II, and III.
- $N_2H^+$ molecular line spectra is used to determine the $V_{LSR}$ of the clumps.
- Clump II displays double-peaked, blue-asymmetric $HCO^+$ line profile with self-absorption dip coinciding with the $V_{LSR}$ and peak of optically thin $N_2H^+$ line. This indicates infall activity.
- Derived mass infall rates are consistent with other high-mass star forming regions.

$$V_{inf} = V_{N_2H^+} - V_{HCO^+} = -13.2 - (-13.9)$$

$$V_{inf} = -0.7\ km/s$$

$$\dot{M}_{inf} = 4\pi R^2 V_{inf}\,\rho = 9.7 \times 10^{-4}\ M_{\odot}/yr$$

| Clumps | I | II | III |
|---|---|---|---|
| $V_{LSR}$ (km $s^{-1}$) | -13.7 | -13.2 | -12.8 |

Table 3: $V_{LSR}$ corresponding to each dust clump

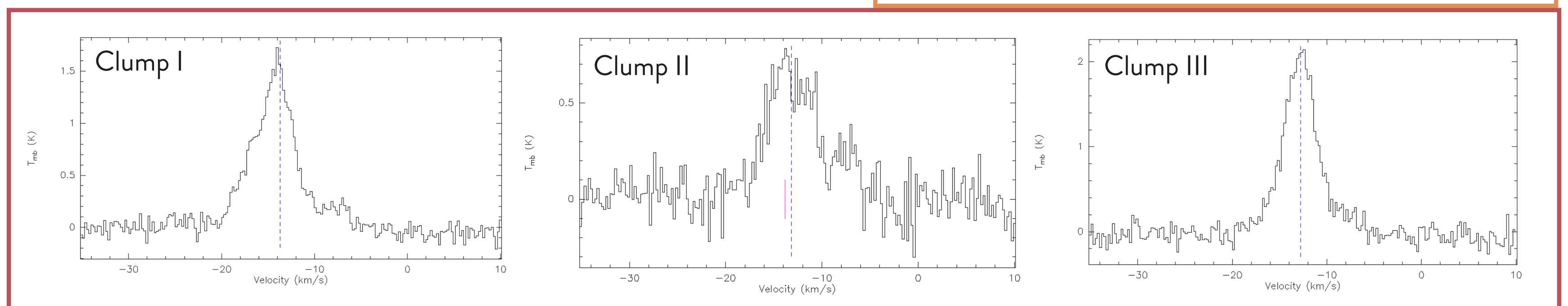


Figure 6 : $HCO^+$ spectra of clumps associated with dust bubble S6. Blue dotted line denotes $V_{LSR}$. The magenta line denotes location of blue shifted peak in Clump II.

## Conclusions

- Ionized emission from the region towards S6 displays cometary morphology.
- The spectral type of the ionizing star is estimated to be O7 - O8.5.
- Three clumps are detected using Fellwalker algorithm.
- Using the dust temperature and column density maps, the clumps' physical properties are determined.
- Molecular line spectra of $HCO^+$ displays infall activity in clump II. The mass infall rate is calculated to be 9.7 x $10^{-4}$ $M_{\odot}$/yr .

## References

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