Interstellar Matter and Star Formation:
A Multi-wavelength Perspective
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Multi-wavelength studies of Galactic HII regions

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Abstract. We present the recent results obtained with multi-wavelength observations of three Galactic HII regions. Our findings suggest these regions are likely candidates of triggered star formation, where star formation in their vicinity has occurred recently due to compression or heating of the molecular gas by UV radiation from the OB stars.

Keywords : HII regions – interstellar matter – star formation process –pre-main-sequence

1. Introduction

High-mass stars (M > 8 $M_\odot$) play a major role in the physical and chemical evolution of their host galaxies through strong ultraviolet radiation, stellar winds, and supernova explosions. There are several ways these energy inputs from massive star(s) can lead to second generation star formation via sequential star formation or the collect and collapse process (Elmegreen & Lada 1977; Zavagno et al. 2006). Statistically, it has been shown that the most luminous protostars form in molecular clouds associated with H II regions, created by

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UV radiation from these star(s) (Dobashi et al. 2001). The question whether the mechanical and radiative luminosities of OB stars can lead to the formation of next generation massive star(s) is important, as it provides a possible different environment and/or mechanism for massive star formation. Therefore, studies of samples of star forming regions (SFRs) containing accreting high mass protostars adjacent to evolved HII regions are always interesting. But, the interplay of stellar radiation field with the associated gas and dust, makes the environment more complex. Studies of these regions therefore require multi-wavelength observations to constrain the fundamental parameters of the region, the nature of embedded objects, their morphological correlations with the evolved HII regions and their relative importance to the energy input from the OB stars. Now with the advent of new detectors and bolometers in the mid infrared and sub-mm to mm regime, it is possible to dig-out high mass young stellar objects (YSOs), which are usually embedded in clouds of high visual extinction. Therefore, the identification & characterization of a potential site, which shows signatures of triggered star formation, is essential for follow up observations with new upcoming instruments. Here, we present preliminary results of likely evidence of induced star formation in the vicinity of three Galactic HII regions, namely Sh 2-294 (Samal et al. 2007), Sh 2-100 (Samal et al. 2010) and Sh 2-255-257 (Ojha et al. 2010, in preparation).

2. Observations

We used optical photometry from the 104-cm Sampurnanand Telescope (ST) of ARIES, Nainital and narrow band imaging and spectroscopy from the Himalayan *Chandra* Telescope (HCT) of IIA, Bangalore, to estimate extinction, distance, age of the associated cluster and spectral type of the ionizing star(s) of the evolved HII regions. We used near-infrared (NIR) data from 2MASS, the SIRIUS camera on the 1.4 m Infrared Survey Facility (IRSF) Telescope, South Africa and the 2-m University of Hawaii telescope, along with mid-infrared data from *Spitzer* Telescope to detect the embedded YSOs. Observations at radio wavelengths from the Giant Metrewave Radio Telescope (GMRT) are used to trace ionization front, probable dynamical age and radio emission from ultra-compact HII regions associated with massive protostars. We supplement these observations with archive data of mid-infrared band from MSX and mid to far infrared band from $IRAS$ satellite, to look for warm dust as well as cold dust of the associated interstellar medium.

3. Results

3.1 Sh 2-294

Sh 2-294 is a Galactic HII region (Sharpless 1959). In the optical band, it looks like a butterfly with two wings separated by a dark lane (see Fig. 1; *left panel*). From optical photometry, we estimated the minimum reddening to be $E(B-V)$

= 1.35 mag and a distance of $\sim$ 4.8 kpc to the region. We identified the ionizing source of the HII region; the spectral type estimate is consistent with a $\sim$ B0-B0.5 V star and the position of the star in optical colour-magnitude diagram suggests an age of $\sim$ 4 Myr. The 2MASS JHK_s images reveal a partially embedded cluster associated with the ionizing source along with a small cluster towards the eastern border of Sh 2-294. We traced the ionization front seen along the direction of the small cluster in radio continuum and Hα images. This might be due to the interaction of ionizing sources with the nearby molecular cloud. We found an arc-shaped diffuse molecular hydrogen emission at 2.12 μm and a half ring of MSX dust emission which surrounds the ionized gas towards the direction of the ionization front. The $HIRES$ processed $IRAS$ maps show two clumpy structures of high optical depth (τ_{100}) and low colour temperature ($T(60/100)$) at the eastern border of the nebula. Self-consistent radiative transfer model of mid- to far-infrared continuum emission detected near the small cluster is in good agreement with the observed spectral energy distribution of a B1.5 zero-age-main-seqeunce (ZAMS) star. Yun et al. (2009) based on SED model fitting to the observed data points of the luminous star of the embedded cluster, found a possible 8-12 $M_{\odot}$ star still accreting matter with an envelope accretion rate of $\sim 5 \times 10^{-3}$ $M_{\odot}$ yr^{-1}. The results based on morphological correlation between the ionized and molecular gas, along with the probable time scale involved between the ionizing star, evolution of HII region and small cluster, though not conclusive, indicate that star-formation activity observed at the border is probably triggered by the expansion of the HII region.

3.2 Sh 2-100

Sh 2-100 is a diffuse nebula consisting of seven HII regions, both compact and ultra-compact, in its vicinity and is itself a part of the W58 molecular cloud complex (see Fig. 1; *right panel*) situated at a distance of $\sim$ 8.7 kpc (Israel 1976). Using NIR photometry, we identified the most probable ionizing sources for six HII regions. Their approximate photometric spectral type estimates suggest that they are massive early-B to mid-O ZAMS stars. This agrees well with radio continuum observations at 1280 MHz within a subclass. The morphology of the complex shows a non-uniform distribution of warm and hot dust well mixed with the ionized gas, which correlates well with the variation of average visual extinction ($\sim$ 4.2 - 97 mag) across the region. We estimated the physical parameters (optical depth, electron density and emission measure) of ionized gas with the help of radio continuum observations. The physical parameters indicate that the HII regions are in different stages of evolution; the ages derived by placing the optically detected ionizing sources in the HR diagram, range from $\leq$ 1-2 Myr. We detected several infrared excess stars (i.e possible YSOs), selected from NIR and IRAC colour-colour diagram. Their spatial distribution

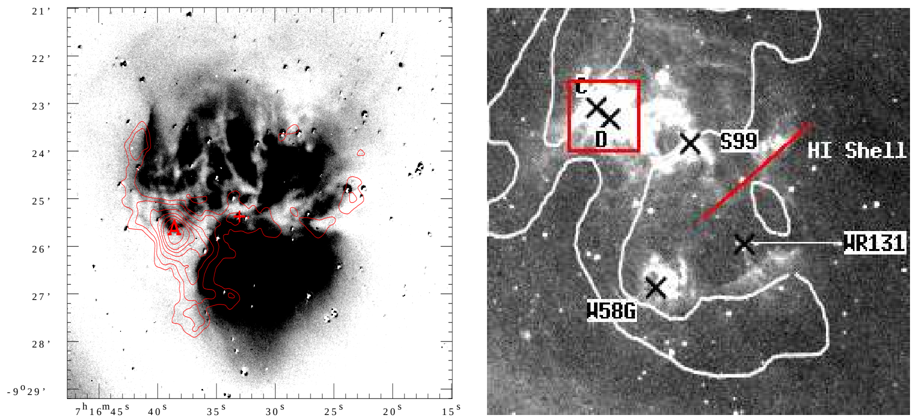

Figure 1. (*left panel*): Contour diagram from the MSX A-band image (8.28 μm), overlaid on an Hα line image. The "A" symbol represents the position of a small cluster at the eastern border of Sh 2-294. The plus sign represents the position of the central ionizing star. (*right panel*): MSX A-band image marked with area of HI emission (thick solid line) taken from Israel (1980). The rectangle box represents the Sh 2-100 SFRs, where the symbols "C" and "D" represent the two compact HII regions out of seven in this SFRs. The cross marks represent the positions of different sources (e.g., HII regions and WR star) in the W58 cloud complex. North is up and east is to the left.

correlates well with the association of gas and dust, indicating an active site of star formation. The position of this group of HII regions and embedded YSOs at the periphery of an HI shell (see Fig. 1; *right panel*), possibly created by a WR star of WN7h subtype (progenitors of such stars are believed to be core hydrogen burning Of star) inside the shell of expected age $\sim$ 4-4.5 Myr, indicates that star formation in the vicinity of Sh 2-100 region might have been induced/enhanced by the interaction of the expanding HI shell.

3.3 Sh 2-255 -Sh 2-257 complex

These are groups of HII regions situated at a distance of 2.4 kpc, located in the Gemini OB association (Itoh et al. 2001 and references therein). Klein at al. (2005) found three prominent cloud cores in millimeter dust continuum emission, which are sandwiched between two evolved HII regions, S255 and S257. We detected an embedded cluster containing several likely YSO candidates, spatially distributed along the dust ridge shown in the Fig. 2 (*left panel*), indicating an active star forming site. Our detection of radio emission at 610 MHz in two cores shown in the Fig. 2 (*right panel*), along with detec-

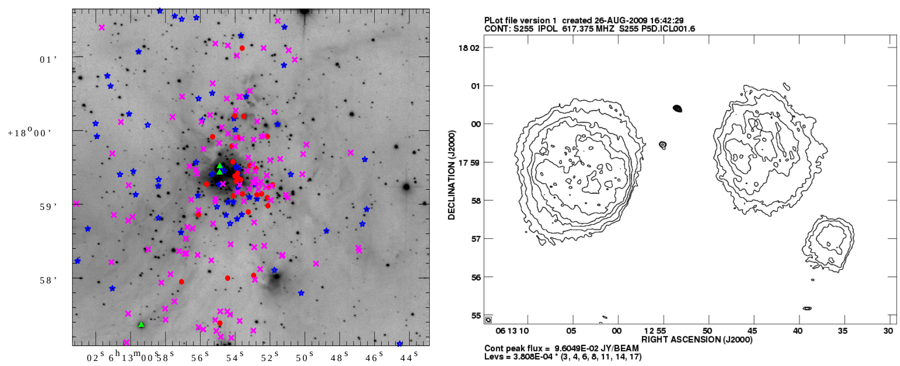

Figure 2. (*left panel*): Spatial distribution of likely YSO candidates selected from NIR colour-colour and colour-magnitude diagrams, superimposed on the K_s-band image of Sh 2-255. (*right panel*): Radio continuum image at 610 MHz from GMRT at resolution of $5.4'' \times 4.7''$.

tion of astronomical water and methanol masers (Minier et al. 2005; Goddie et al. 2007), suggests that massive star formation has occurred at least in two cores. We identified the ionizing sources of the evolved nebulae (S255 & S257) and their spectral types based on optical spectroscopy, suggest that they are massive O9-B1 main-sequence stars. The age of these ionising sources is of $\sim$ 2-3 Myr, whereas the age of the embedded cluster based on K-band luminosity function suggests $\sim$ 1 Myr (Ojha et al. 2006). The arc structure of the molecular cloud along with polycyclic aromatic hydrocarbon (PAH) emission at the border of S255 and S257 towards the embedded cluster, subject to the uncertainty in age assigned to the regions, gives tentative evidence of triggered star formation. The details of the result will be presented elsewhere.

4. Conclusions

Our multi-wavelength studies of the surroundings and stellar contents of three HII regions/bubbles created by OB stars some 3-4 Myr ago, indicate induced star formation at their peripheries and currently detected as near-mid infrared sources of Class I and Class II nature. The detection of compact radio emission in these young regions, confirms the presence of high mass stars, which are still accreting matter to gain their final mass. Our conclusions of induced star formation based on morphological correlation of gas and dust, spatial distribution of stellar young sources and the possible age difference between the stellar contents, may not be conclusive and these HII regions deserve further study using molecular observations to study their kinematics, as well as spectroscopic observations in search of shock or radiation heated molecular lines along the direction of the ionization front. It is important to note that these claims strongly increase their likely chance of induced star formation.

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