Massive Young Star Clusters Near and Far: From the Milky Way to Reionization
2013 Guillermo Haro Conference, Eds. Y. D. Mayya, D. Rosa González & E. Terlevich
INAOE & AMC, June 2014. ISBN: 978-607-8379-01-9

Stellar Content and Star Formation in Young Clusters Influenced by Massive Stars

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Abstract Star Formation (SF) in extreme environment is always challenging and can be significantly different from that in quiet environments. This study presents the comprehensive multi-wavelength (optical, NIR, MIR and radio) observational analysis of three Galactic star forming regions associated with H II regions/young clusters and located at > 2 kpc, which are found to be evolving under the influence of massive stars within their vicinity. The candidate massive stars, young stellar objects, their mass, age, age spread, the form of K-band Luminosity Function (KLF), Initial Mass Function (IMF) and a possible formation history of each region are studied. The major results on Sh2-252, an extended H II region that appears to be undergoing multiple episodes of SF, are highlighted. Our analysis shows that all the regions are undergoing complex SF activity and the new generation of stars in each region seem to be an outcome of the influence by the presence of massive stars within them. SF process in these regions are likely to be multi-fold and the results suggest that multiple modes of triggering mechanism and hierarchial modes of SF are a common phenomena within young clusters.

1 Introduction

One of the most important current questions in the field of SF concerns the effect that environment and especially, feedback may have on the SF process, in particular the stellar IMF and the Star Formation Rate (SFR) or Efficiency (SFE). Stars appear to form in two main modes. Spontaneous SF is the predicted result of the naturally turbulent molecular-cloud environment (see e.g. Padoan & Nordlund 2002; Klessen et al. 2004; Heitsch et al. 2006) and is expected to produce a low background SFR. Triggered SF, on the other hand, is an increase in SFR or SFE due to the effects of a mechanical interaction on molecular cloud gas, usually caused by the winds, radiation or expanding H II regions associated with massive stars (see e.g. Elmegreen 1998; Deharveng, Zavagno & Caplan 2005; Ginsburg, Bally & Williams 2011).

However, it seems that we are yet to develop an understanding of the major physical outcome of the star formation in extreme conditions. Since underlying theories of SF processes lie with understanding the cause of molecular cloud collapse, it is worth to study SF in the extreme conditions such as in the environment of OB stars, H II regions, supernovae etc. In this context, we carried out a multi-wavelength analysis of three young clusters (Stock 8, NGC 1624 and NGC 2175) associated with the H II regions (Sh2-234, Sh2-212 and Sh2-252) and located at distance > 2 kpc, with an aim to explore their hidden young stellar population as well as to understand their structure and SF history. The results of Sh2-252 have been highlighted here (see Jose et al. 2008, 2011, 2012, 2013, for details).

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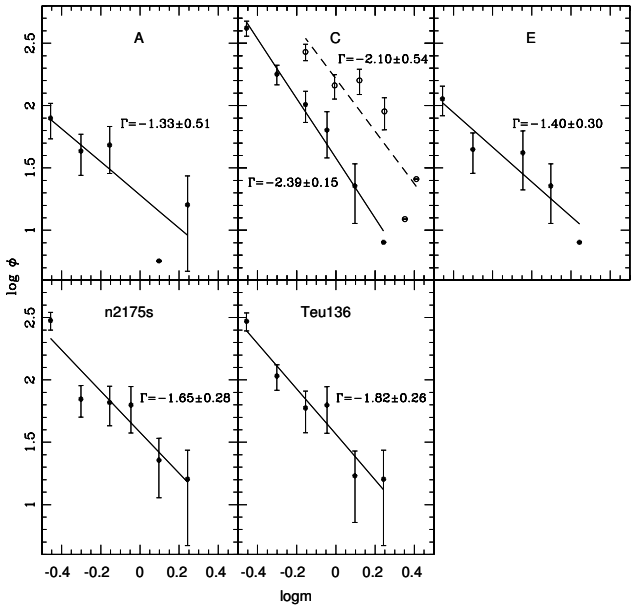
2 Data sets used

Low resolution optical spectroscopy was used to classify the massive stars of the H II regions. Optical, NIR, MIR (*Spitzer*-IRAC, MIPS), radio (GMRT) and Hα slitless spectroscopy data were used to derive the properties of these regions and to identify and classify their members. MIR (MSX), mid to far-IR (IRAS), sub-mm (BOLOCAM) and radio (NVSS) surveys were also used to look for the warm and cold dust components as well as the ionized regions of the associated interstellar medium of these regions.

3 Sh2-252

Sh2-252 is an extended H II region ionized by an 06.5V star HD 42088 and is a part of the Gemini OB1 association. The stellar content and their properties are analyzed using deep optical, NIR, $H\alpha$ survey, spectroscopy along with *Spitzer*- IRAC and MIPS observations. Based on the stellar surface density analysis, five prominent embedded clusters have been identified associated with the sub-regions A, C, E, NGC 2175s and Teu 136 within Sh2-252. Low-resolution spectroscopic analysis identified nine massive stars of spectral class earlier than B3V and most of them are found to be associated with the sub-regions of Sh2-252. Using NIR and MIR photometry, 577 Young Stellar Objects (YSOs) of Class I and Class II types are identified, suggesting a moderately rich number of YSOs within the complex. Spatial distribution of the candidate YSOs shows that they are mostly clustered around the sub-regions in the western half of the complex, suggesting enhanced star formation activity towards its west. Using the Spectral Energy Distribution (SED) and optical Color-Magnitude Diagram (CMD) based age analyses, we derived probable evolutionary status of the sub-regions of Sh2-252. Our analysis shows that the region A is the youngest ($\sim$ 0.5 Myr), the regions B, C and E are of similar evolutionary stage ($\sim$ 1-2 Myr) and the clusters NGC 2175s and Teu 136 are slightly evolved ($\sim$ 2-3 Myr). Morphology of the region in the 1.1 mm map shows a semi-circular shaped molecular shell composed of several clumps and YSOs bordering the western ionization front of Sh2-252. Our analyses suggest that next generation star formation is currently under way along this border and that possibly fragmentation of the matter collected during the expansion of the H II region as one of the major processes responsible for such stars. We observed the densest concentration of YSOs (mostly Class I, $\sim$ 0.5 Myr) at the western outskirts of the complex, within a molecular clump associated with water and methanol masers and we suggest that it is indeed a site of cluster formation at a very early evolutionary stage. The morphology of the region in H_2-band as well as in 1280 MHz gives evidences for molecular matter sandwiched between the two relatively evolved compact H II regions A and B.

We calculated the *K*-band Luminosity Functions (KLFs) for the sub-regions A, C, E, NGC 2175s and Teu 136. Within errors, the KLFs for all the sub-regions are found to be in the range 0.2–0.4, and are consistent with the KLFs estimated for other young clusters of age $<$ 5 Myr. We also estimated the IMFs of the pre-main sequence sample of the individual regions in the mass range of $0.3-2.5\,M_{\odot}$. In general, the slopes of the IMFs of all the sub-regions are found comparable to the Salpeter value (Salpeter 1955).



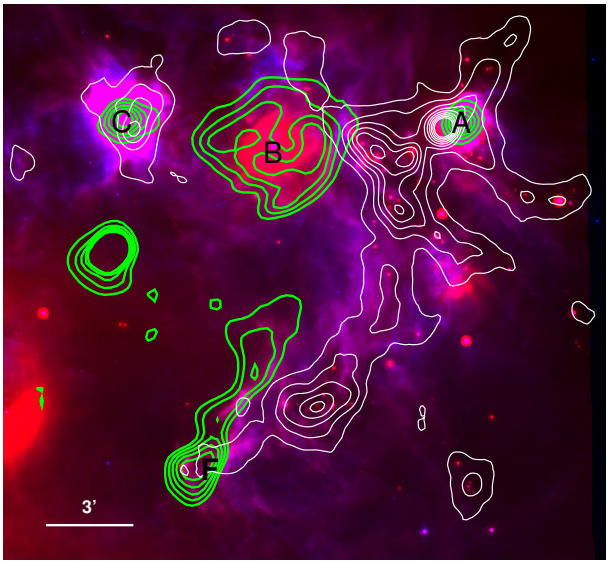


Fig. 1: Top: IMFs obtained from the optical data for the five sub-regions of Sh2-252 after correcting for the field star contamination and data incompleteness. Bottom: Color composite image of the western half of Sh2-252 made from the 8.0 and 24 μm bands along with the 1.1 mm dust continuum map (white contours) and the low resolution continuum map at 1280 MHz from GMRT (green contours). The sub-regions are marked in the figure.

4 Sh2-234 and Sh2-212

We have also analyzed the young clusters Stock 8 and NGC 1624 associated with the H II regions Sh2-234 and Sh2-212. Stock 8 is found to be surrounded and influenced by several massive stars in its vicinity, whereas, Sh2-212 is ionized by a single massive star at its center and is not externally influenced. The analysis based on the CMDs, SEDs, Class I/II fractions, NIR excess fraction etc. shows that there is a clear evidence for second generation SF in both regions. For Stock 8, it is in the form of an elongated filament towards its east, which contains an embedded NIR cluster and a chain of YSOs aligned along the filament. The average age of Stock 8 is estimated as $\sim$ 2-3 Myr, however, the YSOs along the filament is found to be very young ($\sim$ 0.5 Myr) and contains many low massive stars ($<$ 1 $M_{\odot}$). The CO observations of the H II region Sh2 212 by Deharveng et al. (2008) shows the presence of semi-circular ring morphology at its periphery, suggesting that Sh2-212 is undergoing a collect & collapse mode of triggering mechanism followed by a 'Champagne flow'. Our radio continuum observations at 1280 MHz shows the presence of an ultra compact H II region at one edge of this ring, which is ionized by a massive star of spectral class B0. The ultra compact H II region and the associated YSOs in Sh2 212 are found to be very young ($\sim$ 0.1 Myr), whereas, the average age of the main, evolved H II region is estimated as $\sim$ 2-3 Myr. The field star decontaminated KLFs are found to be similar to that of Sh2-252 and the IMFs above 1 $M_{\odot}$ are found to be similar to that of Salpeter slope for both regions.

In conclusion, multi wavelength observational analysis of three clusters associated with H II regions shows that all the regions are of diverse in nature and are undergoing complex SF activity with a probable age spread of $\sim$ 5 Myr. However, the KLFs and IMFs of these regions are found to be consistent with each other and are unaltered irrespective of their diverse environments.

Acknowledgements I sincerely thank my supervisor A. K. Pandey and collaborators D.K. Ojha, K. Ogura, M. R. Samal and Neelam for their help. Financial support from the organizers of the Guillermo Haro conference and DST, India are thankfully acknowledged.

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