31st ASI Meeting
ASI Conference Series, 2013, Vol. 9, pp 59 – 62
Edited by Pushpa Khare & C. H. Ishwara-Chandra

Star formation and initial mass function studies in young star clusters

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Abstract. This thesis presents results from the comprehensive multi wavelength observational analysis of three young clusters associated with HII regions. The fundamental properties of each region such as radius, distance, reddening etc. are analyzed and their massive members are identified. We observed signatures of both clustered and distributed star formation (SF) in these regions. The *K*-band luminosity functions (KLFs) and initial mass functions (IMFs) of these regions are found to be consistent with each other and with the Salpeter IMF and are seen to be unaltered irrespective of their diverse environments. The candidate YSOs are identified, their mass, age, age spread, circumstellar disk fraction and SF history of each region are studied. The spatial distribution of the identified YSOs shows that there is a correlation between the locations where YSOs are forming and the locations of ionization fronts created by the massive stars. The three regions are found to be diverse in nature and each region is experiencing multiple epochs of SF at various locations within it during the last $\sim$ 5 Myr. The newly formed stars are seen to be influenced by the presence of massive stars and the modes of triggering mechanism in each region is found to be different. The results suggest that the multiple epochs of SF and multiple modes of triggering mechanism are a common phenomena within young clusters.

Keywords : stars: formation – stars: pre−main−sequence, luminosity function, mass function – infrared: ISM – HII regions

1. Introduction

Most of the stars in the universe form in clusters and they are the basic units of SF (Lada & Lada 2003). Young clusters (age $\leq$ 5-10 Myr) are generally associated with

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HII regions or OB associations, where the presence of massive stars can influence the successive generation of low-mass stars via, their strong stellar winds and UV radiations (e.g., Zavagno et al. 2006). Hence, the key products of SF process such as IMF, circumstellar disk evolution of young stellar objects (YSOs) etc. are expected to be significantly affected by their presence. So far, the extensive studies on IMF and disk evolution are focused on the nearby regions. However, systematic study on IMF, SF and disk properties of intermediate massive clusters located outside of 2 kpc is still lacking. With this aim, multi wavelength observational analysis of three not so well studied young clusters (Stock 8, NGC 1624 and NGC 2175) associated with the HII regions (Sh2-234, Sh2-212 and Sh2-252) and located at distance > 2 kpc have been performed in this thesis (for details see Jose et al. 2008; 2011; 2012; 2013).

2. Data sets used

We used optical spectroscopy to classify the exciting stars of the HII 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. We also used the MIR (MSX), mid to far-IR (IRAS), sub-mm (BOLOCAM) and radio (NVSS) surveys to look for the warm and cold dust components as well as the ionized regions of the associated interstellar medium of these regions.

3. Results

3.1 Stellar contents, luminosity functions and initial mass functions

The basic cluster properties such as radius, distance, reddening, age etc. and their massive members are analyzed in each region. The stellar surface density analyses showed signatures of both clustered and distributed populations in these regions. Stock 8 and NGC 1624 are single clustered whereas, Sh2-252 contains five prominent embedded clusters associated with it. All the regions are found to have differential reddening and also have the presence of multiple number of massive sources of spectral type earlier to B1V. Stock 8 is found to be surrounded by 9 massive stars whereas no massive stars are found outside Sh2-212. We identified 12 massive stars (>B6V) within Sh2-252. The candidate YSOs are identified and classified based on their Hα emission, IR excess and spectral energy distribution (SED) analysis. Using the stellar evolutionary models by Girardi et al. (2002) and Siess et al. (2000), we obtained an age spread of $\sim$ 0.1-5 Myr in these regions (e.g., Fig. 1 left). We analyzed the physical properties of the YSOs in Sh2-252 using SED fitting models by Robitaille et al. (2006) in the wavelength range 0.45 to 24 μm. The models suggest that the disk accretion rates for Class II sources in the mass range 0.5-2.5 $M_{\odot}$ are of the order of 10^{-7}-10^{-8} Myr^{-1}, which is typically found in the case of T-Tauri stars. The ages and masses predicted by the models are found to be consistent with estimates from the colour-magnitude diagrams (CMDs). The field star decontaminated KLFs

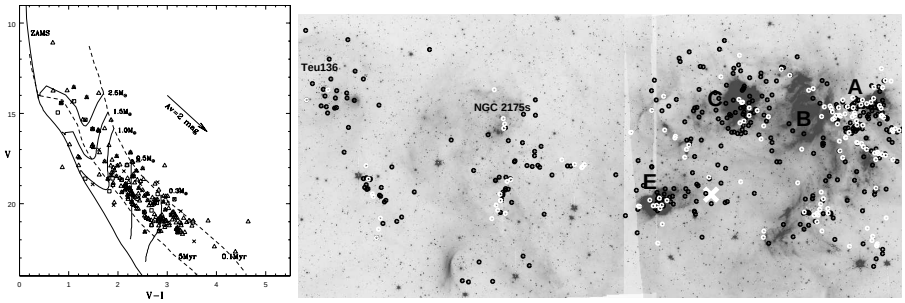

Figure 1. *Left:* $V/(V-I)$ CMD of the candidate YSOs in Sh2-252. The Class I, Class II and $H\alpha$ emission line sources are shown by using squares, triangles and crosses, respectively. The thick solid curve is the locus of ZAMS from Girardi et al. (2002), dashed curves are the PMS isochrones of age 0.1 and 5 Myr, respectively, and the thin continuous curves are the evolutionary tracks for various mass bins by Siess et al. (2000). All the isochrones and tracks are corrected for the distance and reddening. *Right:* Spatial distribution of candidate YSOs in Sh2-252 overlayed on the 4.5 μm mosaic image. Class I and Class II sources are shown using white and black circles, respectively. The cross mark represents the location of the main ionizing source and the important sub-regions of Sh2-252 are also marked in the figure.

of these regions are found to be in the range of 0.2-0.4, and are consistent with the KLFs estimated for other young clusters. After statistically subtracting the field star contribution and correcting for the data incompleteness, we calculated the IMFs of the individual regions using the stellar evolutionary models. The IMFs of the regions are found to be consistent with the Salpeter IMF (Salpeter 1995) above 1 $M_{\odot}$ and for the cluster Stock 8, a break with shallower slope has been noticed towards low mass.

3.2 Evidences for triggered star formation

Spatial distribution of the candidate YSOs (e.g., Fig. 1 right) in the regions shows that there is a correlation between the locations where YSOs were formed and the locations of ionization fronts created by the massive stars. Each region is found to be experiencing multiple epochs of SF at various locations within it and the newly formed stars are found to be influenced by the presence of massive stars within their proximity. Using the stellar evolutionary models as well as the SEDs of the candidate YSOs, the evolutionary status of the various sub-regions of each region have been analyzed. We have noticed the signs of recent SF activity in these regions with a probable age spread of $\sim$ 5 Myr. The analysis based on the CMDs, SEDs, Class I/II fractions, NIR excess fraction in Sh2-252 shows that there is a clear evolutionary sequence among the sub-regions within it and suggests that SF activity has proceeded at multiple sites of this cloud complex at multiple epochs. The modes of triggering mechanism in each region is found to be different. For e.g., the Radiation Driven Implosion (RDI) mechanism is found to be acting towards the cluster Stock 8 while

Sh2-212 is experiencing a collect and collapse (C&C) mode of triggering followed by a 'Champagne flow' whereas both the mechanisms are found to be at work within Sh2-252. We have identified filaments associated with infra-red dark clouds (IRDCs) within Stock 8 and Sh2-252, with water and methanol maser emissions in their proximity. These structures host the earliest phase of protocluster formation. The YSOs in the filaments are found to be significantly younger (< 0.5 Myr) than the average age of the HII regions (∼ 2-3 Myr). We have also noticed that the shock front of the expanding HII region is probably causing the molecular cloud collected at its periphery to take the filamentary shape and initiate the second generation SF in such regions.

4. Conclusion

Multi wavelength observational analysis of three clusters associated with HII regions shows that all the regions are diverse in nature and are undergoing complex SF activity with a probable age spread of ∼ 5 Myr. However, the KLFs and IMFs of these regions are found to be consistent with each other and with the Salpeter IMF and are seen to be remain unaltered irrespective of their diverse environments. The new generation of stars in each region is an outcome of the influence of massive stars present within them. SF process in these regions are likely to be multi-fold and the results suggest that multiple modes of triggering mechanism and hierarchical modes of SF are a common phenomena within young clusters.

Acknowledgements

I sincerely thank my supervisor Dr. Anil K. Pandey and collaborators Prof. D. K. Ojha, Prof. K. Ogura, Manash R. Samal and Neelam Chauhan for their help.

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