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Star formation in and around bright-rimmed clouds

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Abstract. In this paper I shall discuss the results of our recent studies of a few bright-rimmed clouds. Based on the optical and infrared photometric studies of the regions, we found quantitative age gradients in the sense that the young stellar objects (YSOs) located on/inside the rims are younger than those located outside the rims. The disk evolution in T-Tauri stars as well as cumulative mass function of the YSOs associated with the BRCs will also be discussed.

Keywords : stars: pre-main-sequence – stars: formation – ISM : Hii regions

1. Introduction

Bright-rimmed clouds (BRCs) are small molecular clouds located at the interface of evolved Hii regions and molecular clouds with their 'bright rims' facing towards ionising star(s) side. They are believed to be the potential sites of triggered star formation due to the pressure exerted by the incoming ionising radiation from the massive ionising star(s). Thus, they are good examples of the radiation driven implosion (RDI) mode of triggered star formation. Morphologically they are classified into *types A, B* and *C* according to their length-to-width ratios with *type C* being the most elongated.

Sugitani, Tamura & Ogura (1995) indicated that BRCs are often associated with small star clusters, showing not only an asymmetric spatial distribution, but also a possible age gradient and they proposed the hypothesis of "*small-scale sequential star formation*" (S^4F). The qualitative evidences for the S^4F hypothesis includes the work by Ogura et al. 2002 (an asymmetric distribution of Hα emission stars) and Matsuyanagi et al. (2006) but there were no study for the quantitative confirmation of

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the S^4F in BRCs. The present study aims to examine quantitative evidences for S^4F in BRCs.

2. Data: observations and reduction

The objects studied in our study are observed using two optical telescopes, i.e., 1.04-m Sampurnanand Telescope of ARIES and 2.0-m Himalayan Chandra Telescope of IIA, India (for details see Pandey et al. 2008, Chauhan et al. 2009). The pre-processing of the data frames was done using the various tasks available under the IRAF data reduction software package. The photometric measurements of the stars were performed using the DAOPHOT II software package. The optical observations are supplemented with the archival infrared (IR) data from Two-Micron All Sky Survey and *Spitzer Space Telescope*.

3. Membership, reddening and age-mass estimation

Membership: Since BRCs are found at low Galactic latitudes, the fields can be significantly contaminated by foreground/background stars. To understand star formation in BRCs it is necessary to identify stars directly related to them. We selected probable members associated with the BRCs using the following criteria.
1. The spectra of some pre-main-sequence (PMS) stars, specifically (T-Tauri stars (TTSs), show emission lines, among which usually Hα is the strongest. Therefore, Hα emission stars can be considered as good candidates for PMS stars associated with BRCs. In the present study we used Hα emission stars found by Ogura et al. (2002) in the vicinity of BRCs.
2. Since many PMS stars also show near infrared (NIR) excesses caused by circumstellar disks, NIR photometric surveys emerged as powerful tools to detect low-mass PMS stars. We used NIR $(J - H)/(H - K)$ colour-colour (CC) diagram to identify NIR excess stars (cf. Chauhan et al. 2009).
3. Infrared array Camera (IRAC) and multiband imaging photometer for Spitzer (MIPS) on board the *Spitzer Space Telescope*, are used to measure infrared excesses due to circumstellar-disk and envelops. YSOs occupy distinct regions in the IRAC colour plane; this makes mid-infrared (MIR) CC diagram a very useful tool for the classification of YSOs. We identified and classified the MIR excess stars adopting the approach given in Allen et al. (2004).

Reddening (A_V) and NIR excess determination of the YSOs: Since BRCs are associated with the recent star forming activity. The presence of variable amount of reddening due to the dust and gas in the BRC and/or HII regions makes the reddening correction a difficult task. In order to overcome this difficulty we used the NIR CC diagram, where A_V value for each star has been measured by tracing back to the intrinsic lines along the reddening vector found in Meyer et al. (1997). The $E(V - I_c)$ and $E(B - V)$ values from A_V values have been estimated. NIR excess ($\Delta(H - K)$) of each YSO candidate is derived from the NIR CC diagram. $\Delta(H-K)$ is defined as the horizontal displacement of the NIR excess stars from the middle reddening vector in $(J-H)/(H-K)$ CC diagram (see Ogura et al. 2007, Chauhan et al. 2009, 2011).

Age-mass determination of the YSOs: The age and mass of each YSO was estimated by referring to the PMS isochrones of Siess et al. (2000). In our analysis we have estimated age and mass of the YSOs using the $V_0/(V-I_c)_0$ colour-magnitude diagram (CMD) (see Pandey et al. 2008, Chauhan et al. 2009). The errors in age and mass of the YSOs are also determined (for details, see Chauhan et al. 2009, 2011).

4. Results

Age sequence in BRCs: We have studied the S^4F as well as global star formation in HII regions associated with the BRCs 2, 11, 12, 13, 14, 27, 37, 38 and BRC NW using the optical BVI_c photometry. The comparison of the average ages of the YSOs lying on/ inside and outside bright rim regions represents quantitative age gradients in the BRCs studied (see fig. 1). Spatial distribution of IRAC class 0/I and Class II sources shows that mostly Class 0/I sources are embedded inside the clouds while class II sources are widely distributed. Here we would like to mention that although our sample is small and errors are large, we are finding the same age trend in all the BRCs shown in Fig. 1. The inclusion of newly detected YSOs on the basis of Spitzer MIR data from Koenig et al. (2008), e.g. in the case of BRC 14 (Fig.1), further supports the trend.

Global star formation in and around BRC regions: The distribution of NIR-excess stars in the studied HII regions indicates that they are aligned from the ionizing source to the BRC direction. The age indicators, viz., infrared excess ($\Delta(H-K)$) and A_V as well as the age itself of the YSOs manifest an age gradient toward the ionizing source. This global distribution indicates that a series of RDI processes formation might have taken place in the past from near the central O star(s) towards the peripheries of the HII region.

Disk evolution of T-Tauri Stars in BRCs: TTSs are divided into two subclasses, classical T-Tauri Stars (CTTSs) and weak-line T-Tauri stars (WTTSs). The idea that CTTSs lose their disks and evolves into WTTSs is still in debate. To study the disk evolution of TTSs in BRC regions, we used ages of the Hα emission stars and their equivalent widths (EWs) in the above mentioned BRC regions. We found that in general WTTSs are somewhat older than CTTSs, which is in accordance with the recent conclusion by Bertout et al. (2007) that CTTSs evolve into WTTSs. However, based on the age distribution of Class II and Class III sources in the BRC regions associated with W5 E HII region we found that, in general, the age distributions of the Class II (CTT) and Class III (WTT) sources are the same. This result is apparently in contradiction with the conclusion made above that CTTSs evolve to WTTSs. This difference may be due to fact that the classification of CTTS and WTTS in the BRCs

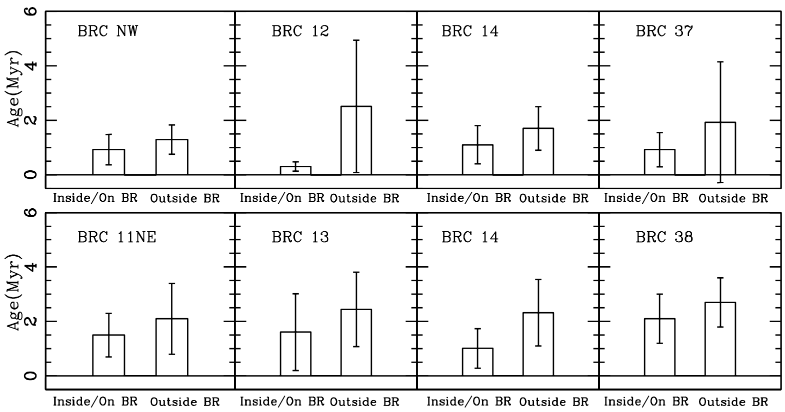

Figure 1. Histogram for the average ages and respective standard deviations of the YSOs according to their locations with respect to bright rim in each BRC. Histogram for BRC 14 in the upper panel is from the results in Chauhan et al. (2009) and the lower panel from Chauhan et al. (2011).

associated with W5 E region is based on the *Spitzer* MIR observations, whereas in the case of different BRC regions (BRCs 2, 11, 12, 13, 14, 27, 37 and 38) the classification was based on the EWs of Hα emission stars (CTTS : EW $\geq$ 10 Å, WTTS : EW < 10 Å). Hα surveys may fail to detect Class III sources which have smaller EWs, whereas those sources can be identified using the MIR observations.

Cumulative mass functions of the YSOs associated with BRCs: The mass function (MF) is an important tool to compare the star formation process/scenario in different regions. To study the MF of the YSOs associated with the different morphological type BRCs, we estimated the masses of all the YSOs associated with studied BRCs. The cumulative mass function (CMF) of the aggregates associated with the BRCs of the morphological type 'A' seems to follow that found in young open clusters, whereas 'B/C' type BRCs show significantly steeper MF in the mass range $0.2 \leq M/M_{\odot} \leq 0.8$. Since we have statistically significant sample for YSOs in the BRC NW, 13 and 14 regions, we estimated the CMF for individual BRCs and a comparison of CMFs indicates that in the mass range $0.2 \leq M/M_{\odot} \leq 0.8$, BRC NW has relatively more low mass YSOs in comparison to BRCs 13 and 14.

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