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Young stellar objects and their environment*

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Abstract. This paper presents the results of a Ph.D thesis emphasizing the studies of various characteristics of Young Stellar Objects (YSOs) and their environment. The main objective of the thesis is to study the effects of mechanical and radiative feedback of massive stars on their surroundings including triggered star formation in Cometary Globules (CGs) and Bright-Rimmed Clouds (BRCs) situated at the borders of Galactic H II regions and time dependent interaction of Pre-Main Sequence (PMS) stars with their circumstellar environment through accretion and outflow processes. Some of the important results of this thesis are (i) star formation in BRC SFO 38 is triggered by massive OB type stars in H II region IC 1396 (ii) distribution of CGs at the border of H II region Gum Nebula is shaped by photoevaporation powered by UV radiation of massive stars in Vela OB2 association (iii) interaction of Herbig Ae star V351 Ori with its circumstellar environment is time-dependent and episodic in nature. Dynamic magnetospheric accretion and disk wind emerge as the most satisfactory model for interpreting the observed line profile variations of V351 Ori. The full version of the thesis is available from the Indian Institute of Astrophysics Repository webpage: `http://prints.iiap.res.in/handle/2248/5529`

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1. Introduction

Massive stars interact with their parent Giant Molecular Clouds (GMCs) and also affect the large scale structure of the galaxies. Low- and intermediate mass stars strongly interact with their circumstellar environment and affect their ambient interstellar medium up to a few pc, through the energetic outflows known as Herbig-Haro

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objects. Observational evidences of radiative and mechanical feedbacks of massive stars, (e.g. *Radiation Driven Implosion (RDI)*, *Rocket Effects*, supernova explosion etc.) on their parent GMCs have been studied in this thesis using selected BRCs and CGs in H II regions IC 1396 and Gum Nebula. Bright-Rimmed Clouds (BRCs) and Cometary Globules (CGs) are produced by the effect of RDI on the pre-existing globules in the GMCs. Low- and intermediate mass stars mainly build up their masses through accretion from their circumstellar disks. Accretion rates seem to decrease with the age of the PMS stars. Low accretion rates of the PMS stars are diagnosed by their weak $H\alpha$ emission. V351 Ori is a weak $H\alpha$ emission line star with significant infrared excesses in near infrared wavelengths. An extensive high resolution spectroscopic study of V351 Ori over timescales of hours, days and months has been carried out to explore the dynamic interaction of the star with its circumstellar environment. Important results of this thesis work are summarized in the subsequent sections.

2. Triggered star formation in SFO 38

H II region IC 1396 is associated with Cep OB2 association and contains ~11 BRCs, distributed in a circular pattern around the O type star HD 206267. The northern massive globule SFO 38 has been studied extensively to examine the observational signatures of triggered star formation. Choudhury, Mookerjea & Bhatt (2010) have presented multi-wavelength photometric study of SFO 38 from optical BVRI to Spitzer IRAC and MIPS observations along with optical spectroscopy of the selected objects. A total of 40 Young Stellar Objects (YSOs) (Classes 0/I/II) and 13 YSO candidates are identified based on mid infrared (MIR) color indices and we also confirm $H\alpha$ emission from 2 YSOs which are not known in the literature. We further identify 4 additional YSOs based on $H\alpha$ emission and thus we find 44 YSOs in and around SFO 38. We find that $H\alpha$ emission line YSOs are mostly KM type stars with an age spread of 1-8 Myr and mass range of 0.3-2.2 $M_{\odot}$. Some of the YSOs show photometric variation in optical and near infrared (NIR) bands and variable $H\alpha$ emission in the medium resolution spectra. Mass accretion rates estimated from broad $H\alpha$ line profiles are of the order of 10^{-8} to 10^{-10} $M_{\odot}$ yr^{-1}. Mass, luminosity and age of the different components of the protostellar cluster at IRAS 21391+5802, have been estimated by fitting the Spectral Energy Distribution (SED). Continuum subtracted $H\alpha$ line image of SFO 38 (Fig. 1(a)) shows asymmetric $H\alpha$ emission at the bright-rim (see also Choudhury & Bhatt (2010)). Two OB type stars e.g. HD 206267 (O6.5) and HD 206773 (B0V) are proposed as the potential ionizing sources for the globule. We also find that Class II to Class 0/I objects are distributed, in a systematic pattern, from the rim to the core part of the globule respectively. We also identify at least two different axes of elongation of the YSO distribution. The spatial gap between the two different classes of YSOs is consistent with the difference in the arrival time of a shock wave propagating into the globule. The spatio-temporal gradient in the distribution of YSOs along two different axes that are aligned with either of the ionizing stars indicates triggered star formation due to Radiation Driven Implosion.

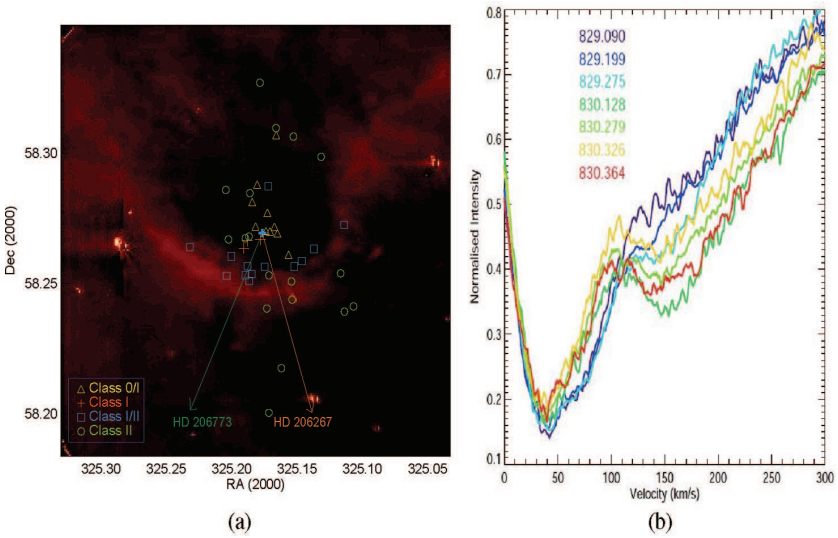

Figure 1. (a) Continuum subtracted $H\alpha$ emission line image of SFO 38. Class 0/I to Class II YSOs are overplotted with different symbols. The directions towards HD 206267 and HD 206773 are marked with two different arrows. (b) Selected $H\alpha$ emission line profiles on 28 and 29 December 2008 in the rest frame velocity of V351 Ori are overplotted. Modified HJDs (Heliocentric Julian Day–2454000) of the respective profiles are displayed using the same colors as of the profiles.

3. Distribution of Cometary Globules in Gum Nebula

Galactic H II region, Gum Nebula is associated with two OB associations i.e. Vela OB2 and Tr 10 and contains ∼30 CGs. Signatures of ongoing star formation are found in some of the globules. We listed the known YSOs in this region and their proper motion measurements, associated with CGs (Choudhury & Bhatt 2009). Two YSOs, NX Pup and PHa 92, are found to be embedded in their parent CGs i.e. CG 1 and CG 22. We traced back the proper motions of NX Pup and PHa 92 back in time to determine their trajectories. The relative spatial positions of these two YSOs in past, lead us to discard the supernova explosion of the companion of ζ Pup, about 1.5 Myr ago being the cause of the expansion of the system of the CGs. We also compared the relative proper motion of these two YSOs with respect to the O-type star ζ Pup and Vela OB2 association. We argued that this relative velocity can be used as a proxy for the velocity due to the Rocket Effect. We also extended this analysis for the YSOs with proper motion measurements, in at least one component, greater than the given error . Almost null values of the relative proper motions within the error-bar, do not support the value of Rocket Effect velocity of ∼ 40 km/s, and indicate a lower value of the velocity less than 5 km/s. We suggest that the nearly circular distribution of CGs with an average radius of ∼ 70 pc is created due to the photoevaporation by massive stars of the nearest OB associations.

4. Variable circumstellar activity of V351 Ori

High resolution echelle spectra of V351 Ori spanning over timescales of ∼1 hour to 7 months have been used to study the temporal variation in $H\alpha$ line profiles of V351 Ori (Choudhury, Bhatt & Pandey 2011). Most of the $H\alpha$ line profiles were asymmetric and significant night to night variations of $H\alpha$ line profiles were observed. In Fig. 1(b), we plot selected $H\alpha$ emission line profiles of the star on 28 and 29 December 2008 to show the rapid line profile variation in timescales of hours and days. One of the important features of the spectra was the simultaneous presence of infall and outflow processes represented by the red-shifted and blue-shifted components of the spectra. The average $H\alpha$ emission line profile is inverse P Cygni type in nature which supposed to be originated due the infall of the circumstellar material onto the central star. We also detected a number of Transient Absorption Components (TACs) in $H\alpha$ emission line profiles on several epochs. TACs originate due to the infall or outflow of the clumpy circumstellar gaseous material close to the star. We tabulated the velocity of the TACs at different epochs and from this data we estimated the rate of change in velocity of the TACs. Both infalling and outflowing materials detected in our observations are found to be decelerated with a rate of a few to fractions of m s^{-2}. The presence of elongated red-shifted components at some epochs supports the episodic nature of accretion. Dynamic magnetospheric accretion and disk wind emerge as the most satisfactory model for interpreting the observed line profile variations of V351 Ori.

5. Future perspective

Various properties of the YSOs has been used in this study to understand their environment. In future we want to pursue our investigation further in this direction to understand the disk evolution of Young Stellar Objects in OB association and impact of triggered star formation on Initial Mass Function (IMF).

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