Low-mass young stellar population and star formation history of the cluster IC 1805 in the W4 HII region

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ABSTRACT

W4 is a giant HII region ionized by the OB stars of the cluster IC 1805. The HII region/cluster complex has been a subject of numerous investigations as it is an excellent laboratory for studying the feedback effect of massive stars on the surrounding region. However, the low-mass stellar content of the cluster IC 1805 remains poorly studied till now. With the aim to unravel the low-mass stellar population of the cluster, we present the results of a multiwavelength study based on deep optical data obtained with the Canada-France-Hawaii Telescope, infrared data from 2MASS, Spitzer Space Telescope and X-ray data from Chandra Space Telescope. The present optical dataset is complete enough to detect stars down to 0.2 M\textsubscript{☉}, which is the deepest optical observations so far for the cluster. We identified 384 candidate young stellar objects (YSOs; 101 Class I/II and 283 Class III) within the cluster using various colour-colour and colour-magnitude diagrams. We inferred the mean age of the identified YSOs to be $\sim$ 2.5 Myr and mass in the range 0.3 – 2.5 M\textsubscript{☉}. The mass function of our YSO sample has a power law index of -1.23 ± 0.23, close to the Salpeter value (-1.35), and consistent with those of
other star-forming complexes. We explored the disk evolution of the cluster members and found that the diskless sources are relatively older compared to the disk bearing YSO candidates. We examined the effect of high-mass stars on the circumstellar disks and found that within uncertainties, the influence of massive stars on the disk fraction seems to be insignificant. We also studied the spatial correlation of the YSOs with the distribution of gas and dust of the complex to conclude that IC 1805 would have formed in a large filamentary cloud.

**Key words:** stars : formation - stars : pre-main-sequence - ISM : globules H II regions - open cluster: initial mass function; star formation.

1 INTRODUCTION

Most recent studies show that stars are formed in clusters or groups and nearly half of the low-mass populations are born in massive young clusters or OB associations (Lada & Lada 2003; Allen et al. 2007). Young clusters are natural laboratories for testing the star formation processes and the stellar evolutionary theory as the cluster members have a wide mass spectrum while sharing the same chemical composition and distance.

However, the presence of very luminous (O- or early B-type) stars in such systems profoundly influences their environment by compressing and sweeping the surrounding material because of their strong ionizing radiation and powerful stellar winds (see e.g., Preibisch et al. 2002; Zavagno et al. 2004; Povich et al. 2009; Chauhan et al. 2009, 2011; Deharveng et al. 2010; Jose et al. 2013; Samal et al. 2014). Ultraviolet (UV) radiation from massive stars not only affects the surrounding molecular cloud and its star formation but also causes photoevaporation of disks around the young low-mass stars in their vicinity (see e.g., Bally et al. 1998; Adams et al. 2004; Balog et al. 2007; Gorti & Hollenbach 2009), thereby playing a key role in shaping the fundamental properties of the cluster such as stellar mass function (MF), total star formation efficiency, and evolution of circumstellar disks around the young stars.

IC 1805, also known as Melotte 15 or OCL 352, is a young open cluster associated with the HII region W4 (the Heart Nebula) which is a part of the W3-W4-W5 complex, and contains dozens of massive OB-type stars (Massey, Johnson & Degioia-Eastwood 1995). The W4 complex evacuated by the combined energetic winds of the OB stars within IC 1805 (Goudis & White 1980; Ninkov et al. 1995), appears to be a void in the atomic hydrogen...
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layer with a width of about 100 pc (Taylor et al. 1999). The W4 complex also contains several cometary-shaped bright-rimmed clouds (BRCs) or pillars, pointing towards the luminous stars of IC 1805 (Sugitani, Fukui & Ogura 1991; Lefloch, Lazareff & Castets 1997), similar to those found in Ogura, Sugitani & Pickles (2002), and Chauhan et al. (2011). Such structures are generally the result of compression and erosion of pre-existing clouds by massive stars (Bisbas et al. 2009; Miao et al. 2009), indicating that stellar feedback is playing a strong role in altering the morphology and physical conditions of the W4 complex. Therefore, the complex has been a subject of numerous investigations for understanding the role of massive stars on the star formation process in the surrounding cloud (e.g., Lada et al. 1978; Taylor et al. 1999; Oey et al. 2005; Koenig et al. 2012; Jose et al. 2016).

IC 1805 is located at a moderate distance of $\sim 2.0$ kpc (Straižys et al. 2013), similar to the adjacent HII regions W3 (2.0 kpc, Hachisuka et al. 2006; Xu et al. 2006) and W5 E (2.1 kpc, Chauhan et al. 2011). It is embedded in a very low extinction cloud of $E(B-V) \sim 0.8$ mag or visual extinction ($A_V \sim 2.4$ mag (Joshi & Sagar 1983; Stražys et al. 2013). Also, according to Guetter & Vrba (1989a), Sagar & Yu (1990), and Hanson & Clayton (1993) the extinction law in the direction of IC 1805 is normal. Hence, it is a good target for studies on star formation and evolution of low-mass stars; in particular, how they are influenced by OB type stars. Though the cluster has been investigated by several authors at optical bands (Joshi & Sagar 1983; Kwon & Lee 1983; Sagar 1987; Guetter & Vrba 1989b; Massey, Johnson & Degioia-Eastwood 1995; Sung & Lee 1995; Ninkov et al. 1995; Broos et al. 2013), most of these studies were limited to the high-mass stars only. These observations were not only too shallow to detect the low-mass stellar populations but also cover only a relatively small area of the complex. Though several attempts have been made to identify young stellar objects (YSOs) in the complex (Koenig et al. 2012; Povich et al. 2013; Stražys et al. 2013; Broos et al. 2013), no adequate attention has been paid to the characterization of low-mass young stellar population of the cluster using deep optical photometric data.

Since low-mass stars constitute the majority of the stellar population in a cluster and even in the Galaxy (Kroupa 2002), the low-mass stellar content and its MF are essential to understand the nature of the star formation process and the properties of open clusters. Young stars can be identified using multiwavelength observations depending on their evolutionary stages and spectral types (e.g. Carpenter et al. 2006; Dahm & Hillenbrand 2007). Overall, the Spitzer results suggest that though primordial circumstellar disks around solar
and sub-solar mass stars can last for up to 10 Myr, disk lifetimes are a factor of 2 shorter for higher mass objects (see Williams & Cieza 2011, references therein).

The infrared (IR) observations are particularly useful to identify pre-main-sequence (PMS) stars exhibiting IR excess emission. Also, with the help of X-ray data, young stars can be identified from their excess X-ray emission due to magnetic reconnection flares similar to those seen on the solar surface, but with X-ray fluxes 2 to 3 orders of magnitude larger in comparison to solar-type stars (Feigelson & Montmerle 1999; Preibisch & Feigelson 2005; Güdel et al. 2007). While near infrared (NIR), mid-infrared (MIR) and X-ray observations are suitable to identify PMS stars, they have limitations in characterization of these stars themselves (e.g., age and mass determinations). This can be done best by optical observations as PMS stars possess little or no circumstellar emission at optical wavelengths.

In the present work, we attempt to investigate the low-mass stellar content of the cluster IC 1805 based on high spatial resolution, deep optical photometric observations taken with the Canada-France-Hawaii Telescope (CFHT) in combination with Spitzer, Two Micron All Sky Survey (2MASS), and X-ray data available for the region. We identify and characterize a sample of low-mass young cluster members with circumstellar disks and evolved diskless candidate members. We examine the physical properties of the cluster (e.g., cluster extent, age, disk evolution and mass-function) and try to understand the star formation process in this region.

2 OBSERVATIONS AND DATA REDUCTION

Fig. 1 shows the DSS2-R image of the IC 1805 region. The regions marked in the blue, green and red are the areas covered by X-ray, optical and Spitzer-Infrared Array Camera (IRAC) observations, respectively. Multi-band Imaging photometer for Spitzer (MIPS) observations are available for the entire area covered by the IRAC observations. The individual observations and photometric catalogs are described below.

2.1 Optical Observations

The pre-processed deep V and R band images of the IC 1805 region were obtained from the CFHT archive. The data were obtained with CFH12K, a mosaic CCD camera on CFHT, on 2002, January 07 (P. I. - Sung H.). With a plate scale of 0.21 arcsec per pixel, CFH12K provides a $42' \times 28'$ field of view (FOV). Three exposures of 150s were taken in V and
Figure 1. The DSS2-R image of the IC 1805 H\textsuperscript{ii} region. The area covered by X-ray, optical and Spitzer-IRAC observations are shown with blue, green and red colours, respectively (also marked as ‘1’, ‘2’ and ‘3’).

$R$ bands each and the typical seeing during the observations was $\sim 0''.9$. We obtained the photometry of the stars by using the standard IRAF tasks and DAOPHOT II software package \cite{Stetson1987}. We used the DAOFIND task in IRAF to extract the point sources, and selected only those sources having S/N $5\sigma$ above the background. We then performed point-spread function (PSF) photometry on the selected sources using the ALLSTAR routine. These deep optical observations were obtained from the archive with the aim to characterize the low-mass members (in particular to obtain the age and mass of the low-mass young stellar population) of the cluster IC 1805. To calibrate these deep images, we obtained the $V$ and $R$ band observations of the central region of IC 1805 on 2012, October 26 by using a $2048 \times 2048$ pixel$^2$ CCD camera mounted at the f/4 Cassegrain focus of the 1.3-m Devasthal Optical Telescope (DOT) at Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital, India. The CCD camera with a pixel size 13.5 $\mu$m and a plate scale 0.54 arcsec per pixel, covers a $\sim 18' \times 18'$ FOV. During the observations the seeing was $\sim 1''.5$. To standardize the observations, the SA 98 field of Landolt \cite{Landolt1992} was also observed on the same night at various airmasses. A number of bias and twilight flat frames were also taken during the observations.

The DOT images were reduced using various tasks available in the IRAF software package. Instrumental magnitudes were obtained by using the IRAF/DAOPHOT II package via PSF fitting. The PSF was obtained for each frame by using several isolated stars in the frames. The atmospheric extinction coefficients and zero-point magnitudes obtained from
Table 1. The zero-point constants, colour coefficients and extinction coefficients

| Parameters          | Constants     |
|---------------------|---------------|
| Zero-point constants|               |
| c1                  | -0.226 ± 0.016 |
| c2                  | 3.114 ± 0.014  |
| Colour coefficients |               |
| m1                  | 1.058 ± 0.022  |
| m2                  | 0.099 ± 0.024  |
| Extinction coefficients |         |
| K_v                 | 0.158 ± 0.015  |
| K_r                 | 0.109 ± 0.011  |

The SA 98 standard field observations are given in Table 1. The instrumental magnitudes were converted to the standard values by using a least-square linear regression procedure outlined by Stetson (1992).

The following transformation equations were used to calibrate the observations:

\[
(V - R) = m_1(v - r) + c_1, \\
V = v + m_2(v - r) + c_2,
\]

where \( v, r \) are the instrumental magnitudes corrected for the atmospheric extinctions, and \( V, R \) are the standard magnitudes; \( c_1, c_2 \) and \( m_1, m_2 \) are zero-point constants and colour coefficients, respectively. The final photometry from the DOT observations is used to calibrate the CFHT photometry. We obtained 27,427 sources with a magnitude uncertainty \( \leq 0.2 \) mag in both \( V \) and \( R \) bands.

2.2 SPITZER IRAC Observations

The NIR/MIR data from the Spitzer space telescope (Werner et al. 2004) using IRAC (Fazio et al. 2004) centered at 3.6, 4.5, 5.8 and 8.0 \( \mu \)m, were obtained from the Spitzer archive. The IRAC camera provides simultaneous \( 5'.2 \times 5'.2 \) images in four bands at 3.6, 4.5, 5.8 and 8.0 \( \mu \)m and at a spatial resolution of \( \sim 2 \) arcsec. IC 1805 was observed in 2006, September (P.I. - S. Wolff, Program ID - 20052). The corrected Basic Calibrated Data (cBCD) images of the region (Spitzer Science Center’s IRAC pipeline, version S18.14.0) were obtained by using the Leopard software. The images were taken in High Dynamical Range mode. Both short (0.6s) and long (12s) integration cBCD frames in each channel were separately mosaicked using MOPEX (version 18.3.1). The MOPEX - APEX pipeline was used to detect the point sources and to perform the point response function (PRF) fitting photometry. Since the nebular emissions can mimic point-like sources, especially in 5.8 and

1  http://archive.spitzer.caltech.edu/
8.0 µm, all the sources were visually examined and ambiguous sources were removed. In addition, we also included point sources manually which were not automatically detected by APEX and supplied the list of these sources to Apex – user – list pipeline to perform the PRF photometry. We have adopted the zero-points for the conversion between flux densities and magnitudes to be 280.9, 179.7, 115.0 and 64.1 Jy in the 3.6, 4.5, 5.8 and 8.0 µm bands, respectively, as given in the IRAC Data Handbook (Reach et al. 2006). The sources with photometric uncertainties \( \leq 0.2 \) mag in each band were considered as good detection. To obtain the final catalogue of the sources detected in all IRAC bands, we made a catalog for each channel from the short and long exposures separately and then looked for the closest match within 1".2. The final catalog contains 32,014 sources which are detected at least in two IRAC bands, of which 5288 sources have photometry in all IRAC bands.

2.3 SPITZER MIPS Observations

The region was observed at MIPS 24 µm in 2005 September (P.I. - J. S. Greaves, Program ID - 3234). We downloaded the MIPS post-BCD images from the archive, which were created at the image scale of 2".45 per pixel and at a spatial resolution of \( \sim 6" \). We supplied a list of coordinates of visually identified sources to the Apex – user – list module and performed the PRF fitting to extract the fluxes of the sources. The zero point value 7.14 Jy (adopted from MIPS Data Handbook\(^2\)) is used to convert the flux densities to magnitudes. We cross matched the MIPS catalogue to the IRAC source catalogue using a matching radius of 2".5 (Megeath et al. 2012; Jose et al. 2016) and found that 164 sources have counterparts in one or more IRAC bands.

2.4 Near-infrared photometry from 2MASS

NIR JHK\(_s\) data for the point sources within the HII region (shown in Fig. 1) have been obtained from the 2MASS Point Source Catalog (PSC, Cutri et al. 2003). Sources with uncertainty \( \leq 0.2 \) mag and quality flag ‘AAA’ in all the three bands were selected to ensure good quality data. The spatial resolution of 2MASS JHK\(_s\) bands is \( \sim 2" \).

\(^2\) http://irsa.ipac.caltech.edu/data/SPITZER/docs/mips/mipsinstrumenthandbook/
3 RESULTS

3.1 Identification and Classification of Young Stellar Objects

Full understanding of cluster properties and its star formation history requires proper identification of cluster members. In the absence of spectroscopic observations, one robust approach is to identify young stellar content using multiwavelength photometric observations. Since IC 1805 is located at a low Galactic latitude, the contamination from background/foreground stars may significantly affect the analyses at infrared bands (e.g. Getman et al. 2006; Roccatagliata et al. 2011). Hence, careful identification and classification of probable YSO members is essential. During their early phase, stars possess circumstellar disks and hence show excess emission at IR wavelengths. The IR excess properties of YSOs can be used to identify and classify them. Class ‘0’ sources emit most of their radiation in far infra-red (FIR) to submillimetre regime of the electromagnetic spectrum (André 1995). In the Class ‘I’ phase, YSOs radiate mostly in MIR-FIR wavelengths, whereas Class ‘II’ sources exhibit NIR-FIR excess emission. Class ‘III’ sources possess little or no excess in IR (Lada 1987; Adams, Lada & Shu 1987; André, Ward-Thompson & Barsony 1993; André 1995) but show enhanced X-ray activities as explained in Section 3.1.4. However, sources which lack inner disks and show excess emission in MIR wavelengths are referred to as ‘transition disk’ sources (Muzerolle et al. 2006; Hernández et al. 2006). We used optical, Spitzer-IRAC-MIPS, 2MASS and X-ray datasets to identify and classify the YSOs in IC 1805. The various selection criteria adopted for identification and classification of those YSOs are given below.

3.1.1 YSOs selected by IRAC colours

Since YSOs occupy distinct positions on the IRAC colour-colour diagrams due to their different characteristics, the colour-colour diagrams are widely used to identify and classify YSO population in a star-forming region (Megeath et al. 2004; Allen et al. 2004). Gutermuth et al. (2009) developed a method consisting of a series of IRAC/MIPS colour criteria to identify and classify YSOs. Though the mid-IR and far-IR observations can penetrate deep into the thick layers of dust and gas and reveal the embedded YSO population, they also enhance the chances of inclusion of background contaminants in the YSO sample. For example, polycyclic aromatic hydrocarbon (PAH)-emitting galaxies, active galactic nuclei (AGN), unresolved blobs of shocked emission etc., may mimic YSOs and, thus, can contaminate our
YSO sample. In order to weed out possible contaminants, we used the customized cuts in the
$[4.5] - [5.8]$ vs. $[5.8] - [8.0]$ and $[3.6] - [5.8]$ vs. $[4.5] - [8.0]$ colour-colour spaces, as described by Gutermuth et al. (2009). After excluding the contaminants based on the Gutermuth et al. (2009) approach, we identified 238 YSO candidates. Of these, 4 sources satisfy the colour
criteria of Class I sources ($[4.5] - [5.8] > 0.7$ & $[3.6] - [4.5] > 0.7$) and 234 sources (satisfying
the following conditions) were classified as Class II candidates:

- $[4.5] - [8.0] - \sigma > 0.5$,
- $[3.6] - [5.8] - \sigma > 0.35$,
- $[3.6] - [5.8] + \sigma \leq (0.14/0.04) \times (([4.5] - [8.0] - \sigma) - 0.5) + 0.5$, and
- $[3.6] - [4.5] - \sigma > 0.15$.

Here, $\sigma$ is the photometric uncertainty in respective colours. The rest of the sources may

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be Class III or field stars. However, it is to be noted that in a few cases, due to reddening and disk inclination effects, a Class II source could mimic the colours of a Class I source (Whitney et al. 2003; Gutermuth et al. 2009). Fig. 2a shows the \([3.6] - [4.5] \) vs. \([5.8] - [8.0] \) colour-colour diagram for all the uncontaminated IRAC sources. The Class I and Class II sources are shown as red squares and blue diamonds, respectively.

3.1.2 YSOs from 2MASS/IRAC

At the central region of W4, in the vicinity of IC 1805, the background emission at 5.8 and 8.0 \( \mu \)m is high compared to the emission at 3.6 and 4.5 \( \mu \)m. This high background emission is often observed in massive star forming regions (e.g., Indebetouw et al. 2007; Koenig et al. 2008; Ojha et al. 2011). Many of the sources detected in 3.6 and 4.5 \( \mu \)m may be missing in 5.8 and 8.0 \( \mu \)m bands due to the enhanced nebulosity of the background. To ascertain the nature of those sources, we combined the IRAC 3.6 and 4.5 \( \mu \)m data with those of 2MASS H and K\( _s \) bands. Gutermuth et al. (2009) used the intrinsic \((K_s - [3.6]) \) vs. \([3.6] - [4.5] \) colour criteria to identify the sources which are detected in 3.6, 4.5 \( \mu \)m and possess counterparts in 2MASS bands.

To identify the YSOs using IRAC and 2MASS data, we first created an extinction map based on 2MASS data following the method discussed in Panwar et al. (2014), and then derived the intrinsic colours of the YSOs by correcting for the extinction values read off from this map. To generate the extinction map, we divided the region into small cells and computed the colour excess in each cell using the relation \( E = (H - K_s)_{obs} - (H - K_s)_{int} \), where \((H - K_s)_{obs} \) is the observed median colour of the stars in a cell and \((H - K_s)_{int} \) is the intrinsic median colour of the control field stars. The colour excess ratios presented in Flaherty et al. (2007) have been adopted to calculate the extinction in \( K_s \) band \((A_{K_s}) \) for each cell by using the relation \( A_{K_s} = 1.82 E \). Based on the extinction map, the mean \( A_{K_s} \) in the cluster direction corresponds to \( A_V \sim 2.6 \) mag, which is comparable to the value reported in the literature (Joshi & Sagar 1983). We calculated the \((K_s - [3.6])_0 \) and \([3.6] - [4.5])_0 \) colours of the sources and used various colour cuts as described in Gutermuth et al. (2009) to select Class I and Class II sources. By this method, we obtained 161 Class II and 6 Class I candidates. Among these, based on the IRAC colours, 5 Class I sources have been classified as Class II (Sec. 3.1.1), and for further analyses we have considered them as Class II candidates. Out of these 167 Class I/II candidates 133 were identified by using IRAC colour-
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3.1.3 YSOs from MIPS 24 µm

To identify the transition disk candidates, we used the 24 µm data in addition to 4.5 and 5.8 µm data. Following Muzerolle et al. (2006) and Hernández et al. (2006), sources mainly with photospheric radiation in the IRAC or IRAC/2MASS classification but having excess emission at 24 µm ([5.8]−[24] > 2.5 and/or [4.5]−[24] > 2.5) are reconsidered as transition disk sources. We identified 8 such sources. Since heavily embedded Class II sources can be misclassified as Class I based on the IRAC colour criteria (see Section 3.1.1), those Class I sources with 24 µm data were re-checked to ensure that their SEDs rise from the IRAC to MIPS bands. All Class I candidates were considered as Class II, if they do not have [5.8]−[24] > 4 or [4.5]−[24] > 4. Out of 4 Class I sources identified in Section 3.1.1, 2 are re-classified as Class II, while the remaining 2 do not possess 24 µm measurements. Fig. 2c shows the IRAC/MIPS colour-colour diagram for the sources in the region. In Fig. 2, transition disk candidates based on the MIPS photometry are marked as magenta filled circles.

3.1.4 YSOs from Chandra X-ray Data

YSOs are often strong X-ray emitters compared to their main-sequence (MS) counterparts (e.g., Feigelson & Montmerle 1999; Getman et al. 2005; Preibisch & Feigelson 2005; Güdel et al. 2007). Hence, X-ray surveys of star forming regions are used to uncover YSO populations. For the detection of diskless YSOs, i.e., Class III sources, X-ray observations complement the IR YSO sample to have a more complete census of stellar content of clusters (e.g., Preibisch & Feigelson 2005; Pandey et al. 2013b, 2014). The Massive Star-Forming Regions Omnibus X-ray Catalog (MOXC, Townsley et al. 2014) detected X-ray sources in a sample of massive star-forming regions, including IC 1805. They characterized the X-ray properties of 647 stars in the IC 1805 using Chandra/ACIS observations. ACIS-I consist of four 1024 × 1024 pixel² CCD chips that cover a 17′ × 17′ field of view, and covers the 0.5 - 8.0 keV energy band with a spectral resolution of ∼ 150 eV at 6 keV and a PSF radius of 0′′.5 within ∼ 2′ of the on-axis position, degrading to ∼ 6′ at a 10′ off-axis angle.

We checked these Chandra X-ray sources for the counterparts of our optical dataset with a less stringent matching radius of 3 arcsec (Pandey et al. 2013b) because of the large off-axis...
beam. The agreement between X-ray and optical positions is excellent in majority of the cases (∼80%), with offsets <1″. In a few cases, where there was more than one source within the matching radius, we considered the closest one as the best match. This search revealed possible optical counterparts to 403 (62%) of the X-ray sources.

Fig. 3 shows $V$ vs. $(V - R)$ colour-magnitude diagram (CMD) for the stars in the area covered by X-ray observations. The MS from Girardi et al. (2002) for the solar metallicity is also plotted. Joshi & Sagar (1983) have found that in the direction of IC 1805, $E(B-V)$ = 0.7 – 0.9 mag, indicating a small variation of extinction within the cluster in agreement with the $A_V = 2.2 – 2.7$ mag, estimated by Stražys et al. (2013) from the 39 members of the cluster. The MS is shifted for the adopted distance of 2.0 kpc and the minimum reddening $E(B-V)$ of 0.7 mag. Our approach of using the minimum reddening is consistent with the studies of open clusters (e.g., Sung & Bessell 2004; Sharma et al. 2006; Pandey et al. 2013b). The optical counterparts of the X-ray sources are shown with red circles. In Fig.3, at the low-luminosity end, one can notice a few X-ray sources scattered close to MS. Similar distribution of X-ray sources close to MS has also been observed in the CMD of other young clusters. For example, the distribution of X-ray sources on the $V$ vs. $(V - I)$ diagram of NGC 6530 (median age ∼ 2.3 Myr and mean $E(B-V)$=0.35 Prisinzano et al. 2003), shows 90% of PMS stars are within 0.3 – 10 Myr, and ∼10% of the X-ray sources are outside this age range. Prisinzano et al. (2003) argued that the latter sources are mainly contaminants.
Marino, Micela & Peres (2000) have discussed that the coronal activity of X-ray active field stars such as foreground dwarf M star (dMe) and background giants could lead to misidentification as young stars. For example, in Fig. 3, a few X-ray emitting sources are falling to the left or close to MS. Based on spectroscopic observations of the MS stars, Massey, Johnson & Degioia-Eastwood (1995) have inferred that the cluster is likely to be younger than 5 Myr. Considering the young age of the cluster, these sources are unlikely to be part of the cluster. Similarly, extended extragalactic objects seen along the line of sight could also be misidentified as young stars (Getman et al. 2006). Since we have performed PSF photometry on our optical images, we expect that the contamination due to extended objects is minimal in our sample; however we can not rule out the possible presence of a few point-like extra-galactic objects such as quasars. The field star contamination in our sample is quantified in Sect. 3.1.5, but at least quantitatively, it appears to be consistent with the amount of foreground X-ray contamination expected in the direction of IC 1805.

To remove the X-ray active field stars from our X-ray YSO sample, we considered only those X-ray sources which are located in the empirical YSO zone on the \( V \) vs. \( (V−R) \) CMD (e.g., Allen et al. 2012). To determine the YSO zone, we used the following process iteratively. We arranged the X-ray sources in 0.75 mag bins between \( V=15.0 \) to \( V=24 \) mag. The median and standard deviation (\( \sigma \)) of the \( (V−R) \) colour of the YSOs in each bin were calculated and the YSOs having colours greater than 3\( \sigma \) from the median were considered as outliers. The median colour and \( \sigma \) were recalculated. The lower and upper limits of the YSO zone in each bin are then taken to be 1.25 \( \sigma \) and 2 \( \sigma \) around the median colour of the bin. These upper and lower limits are then fit with polynomials and the YSOs lying within these upper and lower bounds are taken to be probable members. As discussed in Allen et al. (2012), the lower limits of the magnitude bins are taken closer to the median value because the density of sources quickly increases in the direction perpendicular to the isochrone towards the MS. In particular, foreground dwarfs and background giants may disguise as YSOs by appearing more luminous for a given colour. We note that although the above statistical approach is likely to remove non-YSO X-ray sources, some actual YSOs may also be eliminated. For example, a few X-ray sources located near the MS (where majority of the field stars are populated), could be YSOs, although their chances of being so are low. Spectroscopic observations are needed to ascertain the nature of such sources, because some of them could be YSOs with disk systems seen edge-on that appear under luminous for their
Table 2. Completeness limit of the data in IRAC and optical bands.

| Wavebands | V  | R  | [3.6] | [4.5] | [5.8] | [8.0] |
|-----------|----|----|-------|-------|-------|-------|
| Completeness (in mag) | 22.5 | 22  | 16    | 16    | 14    | 13.5  |

Figure 4. Histograms for the sources detected in optical (V,R) and IRAC bands showing the limiting magnitude and completeness limit for each band.

colours because of scattering (Sicilia-Aguilar et al. 2005) or members that are significantly older than the mean cluster age.

Using the above approach, we obtained 337 X-ray emitting YSO candidates in the region covered by Chandra X-ray observations (for details; see the Section 3.2.2). Of these, 40 sources have shown the characteristics of Class I/II candidate YSOs on the basis of 2MASS and Spitzer colours (discussed in Sections 3.1.1, 3.1.2, 3.1.3), so the rest 297 X-ray sources are considered as Class III candidates.

3.1.5 Data completeness and contamination

As in the c2d legacy project (Evans et al. 2003), the peak of the observed luminosity function can be assumed to estimate $\geq 90\%$ completeness limit (see also Jose et al. 2016). We constructed the luminosity functions for each band by using the histogram method (see Fig. 4). The resultant completeness limits of the optical and IRAC data are given in Table 2.
For cross-checking, the completeness limits of $V$ and $R$ bands were also estimated by the artificial star experiment by using ADDSTAR routine in IRAF (e.g., Pandey et al. 2013; Jose et al. 2013). We randomly added artificial stars of various magnitudes into each image. The luminosity distribution of artificial stars was chosen in such a way that more stars were inserted towards the fainter magnitude bins. The frames were then re-reduced by using the same procedure as used for the original frames (see Section 2.1). The ratio of the number of stars recovered to those added in each magnitude interval gives the completeness factor as a function of magnitude. We thus obtained >90% completeness of the photometry to be 22.5 and 22 mag in $V$ and $R$ bands, respectively, which agrees with that of the histogram analysis.

The estimation of the completeness census of the YSO sample obtained by various colour combinations is rather difficult as it is limited by several factors. For example, bright extended nebulosity in the IRAC bands significantly limits the point source detection. The YSO identification from the 2MASS/IRAC colours is limited by the sensitivity of the 2MASS survey, while that from the IRAC/MIPS colours suffers from the significant saturation in the IRAC 8 $\mu$m and MIPS 24 $\mu$m images caused by the central luminous sources as well as the bright nebulosity. Similarly, the variable reddening and stellar crowding characteristics across the region could also affect the local completeness limit. All these effects are difficult to quantify. Since 3.6 and 4.5 $\mu$m bands are the most commonly used colour combination for identifying Class II YSOs, we calculate the approximate completeness limit of our Class II YSOs by using the completeness limit of these two bands. The 90% photometry completeness limits of 3.6 and 4.5 $\mu$m bands are estimated to be $\sim$ 16 mag. Assuming a distance of 2.0 kpc for IC 1805 and an average extinction $A_V$ of $\sim$ 2.5 mag, we find the photometric completeness limit corresponds to an approximate stellar mass in the range 0.2-0.3 $M_\odot$ for a YSO of age $\sim$ 2-3 Myr (using the evolutionary tracks of Siess, Dufour & Forestini 2000). The identification of Class III sources in our sample is primarily based on their detection in both the X-ray and optical bands. Only 62% of the X-ray sources have optical counterparts. This indicates that the completeness limit of Class III YSOs is primarily dictated by the sensitivity limit of the optical data. The 90% photometry completeness limits of $V$ and $R$ bands lead to the completeness limit of our Class III YSOs as $\sim$ 0.3 $M_\odot$ at the assumed distance, mean $A_V$ and age $\sim$ 2.5 Myr (using the evolutionary tracks of Siess, Dufour & Forestini 2000). Adopting different sets of evolutionary tracks would provide different values of stellar masses. However, for low-mass objects, the tracks of Siess, Dufour & Forestini (2000) are
close to those of Baraffe et al. (1998). The agreement between masses of these two models is within 10-20%. In summary, we considered that our YSO sample is expected to be largely complete above 0.3 $M_\odot$.

In the case of IC 1795, based on Franceschini et al. (2006) measurements from the IRAC/GOODS sample, Roccatagliata et al. (2011) calculated that the contamination of extragalactic sources in IRAC data is about 72 sources down to 15.5 mag at 3.6 $\mu$m for an area $0.26^\circ \times 0.26^\circ$. IC 1805 is at the same distance and is associated with the same cloud complex as IC 1795, so similar fraction of extragalactic contamination is expected in our IRAC catalog. Scaling their values to our cluster area (i.e., the region covered by most of our observations; see Sect. 3.1.6), we expect $\sim 20$ extragalactic IRAC sources. In addition to these, other contaminants such as broad-line AGNs, unresolved knots of shock emission and faint sources contaminated by copious PAH nebulosity (expected to be prevalent in distant massive star-forming regions) are also likely to affect our YSO selection. Using the criteria of Gutermuth et al. (2009), we have removed these contaminants from our catalog. Although Gutermuth et al. (2009) criteria for a region at $\sim 2$ kpc may provide an overestimation of the contamination, but this would ensure the high reliability of our YSO sample. Our X-ray YSO sample is selected based on the X-ray and optical observations. The majority of the extragalactic contaminants and distant background stars are expected not to have optical (V-band) counterparts. Moreover optical images being at high spatial resolution and with our PSF photometry, extended objects like galaxies are unlikely to be the major contaminants in our sample. In the optical CMD, most of the likely members are located in the PMS zone and there are $\sim 40$ X-ray sources located near the MS. As discussed in Sect. 3.1.4, these sources are likely foreground sources of the region, and seem to agree well with the expected foreground contamination in the direction of IC 1805. So overall, we expect that the likely number of X-ray contaminants in our YSO sample should be low.

3.1.6 Final catalog of YSOs

Our final catalog includes the YSO candidates identified from Spitzer IRAC/MIPS, 2MASS and X-ray datasets. In total, we have 297 Class III, 8 transition disk and 272 Class I/II candidates in the direction of W4 complex. However, there are only 101 Class I/II and 283 Class III candidates in the cluster (i.e., within $\sim 9'$; see Section 3.2.1). The cluster radius is well within the common area covered by the X-ray, IRAC-MIPS as well as optical...
observations and our main aim is to explore and characterize the young stellar population associated with the cluster IC 1805. To determine the cluster properties, such as age (see Sect 3.2.2), mass function, disk-fraction and disk evolution of YSOs (discussed in sections 4.1, 4.2, and 4.3), we have used YSOs within the cluster radius, whereas to get an idea on the large scale star-formation history, we have used all the YSOs identified in this work (discussed in Sect. 4.4). A sample list of the YSO candidates with their magnitudes in different bands for the cluster area is given in Table 3. The entire table is available in electronic form only.

In the W4 complex, using Bayes classifier and combining several criteria in a probabilistic approach, Broos et al. (2013) defined the list of MYStIX Probable Complex Members (MPCM). Within 9 arcmin of the cluster center, Broos et al. (2013) identified 389 YSOs (Xcl flag=2). Although a direct comparison with Broos et al. (2013) is not possible because of different methods used to extract photometric magnitudes on the Spitzer images (aperture photometry by them versus PRF photometry by us), and in the approach of YSO classification and contamination removal (for details see Broos et al. 2013). Nonetheless we find reasonable agreement between both the works. For example, within the cluster area we obtained 384 sources, whereas Broos et al. (2013) have identified 389 sources and only $\sim15\%$ sources are missing in either of the catalog.

In this work, we are more interested in studying the optical properties of the YSOs associated with the cluster. Unlike, NIR colours, the optical filters are more sensitive to the temperatures of late-type stars. Thus, in the low-extincted regions like IC 1805, the optical CMDs are expected to be more reliable in separating PMS members from the field stars and also better for the characterization of YSOs.

### 3.2 Properties of the Cluster IC 1805

#### 3.2.1 Physical Extent of the Cluster

The radial extent is one of the important parameters to study the dynamical properties of clusters. To estimate the cluster radius of IC 1805, we applied the star count technique and assumed a spherically symmetric distribution of stars in the cluster.

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Table 3. YSOs from 2MASS, IRAC/MIPS and X-ray data for the cluster area. The entire table is available in an electronic form.

| Id | RA (J2000) | DEC (J2000) | J±eJ | H±eH | K±eKs | [3.6]±e[3.6] | [4.5]±e[4.5] | [5.8]±e[5.8] | [8.0]±e[8.0] | [24]±e[24] |
|----|------------|------------|------|------|-------|-------------|-------------|-------------|-------------|------------|
| 1  | 38 240929  | 61 37441   | 13.63±0.04 | 12.65±0.02 | 11.99±0.02 | 12.38±0.01 | 10.34±0.01 | 9.58±0.01 | 8.33±0.01 | 6.94±0.02 |
| 2  | 38 142250  | 61 46653   | 12.15±0.02 | 11.65±0.04 | 11.02±0.03 | 9.58±0.01 | 8.88±0.01 | 8.03±0.01 | 6.72±0.01 | 4.15±0.01 |
| 3  | 38 464651  | 61 40662   | 14.31±0.04 | 13.88±0.05 | 13.65±0.04 | 13.61±0.01 | 13.39±0.01 | 13.02±0.02 | 12.48±0.03 | -          |
The point of maximum stellar density ($\alpha_{2000} = 02^h32^m42^s; \delta_{2000} = +61^\circ27'21''$) taken from the WEBDA\footnote{https://www.univie.ac.at/webda/} is considered as the centre of IC 1805. It is worthwhile to mention that the adopted cluster centre is very close to the location of most massive star of the region (see Sec. 4.3). We then created the radial density profile (RDP) using our YSOs catalog to study the radial structure of the cluster. We divided the region into a number of concentric circles. The projected stellar density in each concentric annulus was obtained by dividing the number of stars by the respective annular area. The densities thus obtained are plotted as a function of radius in Fig. 5. The error bars are derived by assuming Poisson statistics. From the RDP, the cluster radius appears to be $\sim 9'$ (5 pc).

For comparison, we also estimated the extent of the cluster ($r_{cl}$) using 2MASS data. Within uncertainties, the $r_{cl}$ obtained from the YSO sample and 2MASS data are matching. The RDP is parametrised with the empirical model of \cite{King1962},

$$\rho(r) \propto \frac{\rho_0}{1 + \left(\frac{r}{r_c}\right)^2},$$

where $r_c$ is the core radius at which the surface density $\rho(r)$ becomes half of the central density, $\rho_0$. The best fit (solid line) to the radial density obtained by a $\chi^2$ minimization technique is shown in Fig. 5.
3.2.2 Colour-Magnitude Diagram of YSOs : Age and Mass Estimation

The ages and masses of the cluster members were estimated by comparing their locations on the CMD with PMS isochrones of various ages after correcting for the distance and extinction. The minimal differential extinction ($\Delta A_V \sim 0.6$ mag) towards the cluster is an advantage to examine the position of the YSOs on the CMD in order to confirm their youth, to determine their optical properties and to study the star formation history of the region.

Fig. 6 shows $V$ vs. $(V - R)$ CMD for the YSOs in the cluster area. The MS from Girardi et al. (2002) as well as the PMS isochrones for 1, 5 and 10 Myr for the solar metallicity from Siess, Dufour & Forestini (2000), corrected for the adopted distance and reddening are also overplotted. The Class I and Class II sources (squares and diamonds, respectively) within the cluster area are identified based on the Spitzer IRAC/MIPS photometry. The location of X-ray emitting (likely Class III) sources are shown with the crosses. The age distribution of the majority of these sources is in the range of 0.5 - 7 Myr, concentrated around an age in the range of 2-3 Myr (mean age $2.5 \pm 1.5$ Myr). We find that masses for a majority of the YSOs are in the range of $0.2 M_\odot - 2.5 M_\odot$. As discussed in Sect. 3.1.4, our approach to select the Class III candidates might have removed some YSOs, which may affect the mean age of the cluster. Hence, we also estimated the age of the cluster using only...
the disk-bearing sources (i.e., sources that have shown excess emission in the 2MASS and IRAC bands). This method resulted an age $\sim 2.3$ Myr for the cluster, which is comparable to the mean age estimated using all the YSOs.

Age spread is common in young clusters and is probably due to the combined effect of differential reddening, circumstellar extinction, variability, binarity and/or different evolutionary stages (Jose et al. 2017). However, the reddening vector is nearly parallel to the isochrones, hence differential reddening does not have much effect on the age estimation of YSOs. The circumstellar extinction may affect the age and mass determination of Class 0/I sources, but its effect should be minimal in optically visible PMS sources such as Class III YSOs. Though the exact role of circumstellar disks requires detailed SED modelling or spectroscopic observations, which is beyond the scope of this paper, it is worthwhile to mention that Jose et al. (2013) performed SED modeling on a set of optically visible PMS sources and found that SED based ages are largely in agreement with those estimated from the optical CMDs. Binary companion will apparently brighten the star, consequently CMD will yield a younger age. For example, in the case of equal-mass binaries, cluster is expected to show a sequence in the CMD which is shifted by 0.75 mag upwards. The effect of binarity can be seen more prominently in some older clusters ($\sim 10$ Myr) for which the isochrones are close together (e.g., NGC 7160; Sicilia-Aguilar et al. 2005) whereas in the case of young clusters like Tr 37 ($\sim 4$ Myr), which is similar to IC 1805, the isochrones are well separated, hence the effect of binarity on age estimation will be less compared to the natural age spread of the stars in clusters (see discussion in Sicilia-Aguilar et al. 2005). Similarly, though TTSs tends to show variability at optical bands (e.g., Herbst et al. 1994; Briceño et al. 2001; Rodríguez-Ledesma, Mundt & Eislöffel 2010; Lata et al. 2015), the variability tends to move the objects parallel to the isochrones, resulting in little effect on the age estimation of YSOs (Burningham et al. 2005). Despite of low differential reddening and presence of large number of disk-less sources in the cluster, some degree of age spread due to the combination of the above factors is expected, but since the observed spread in colour due to member YSOs is larger than their mean uncertainties due to photometric colours (see Fig [5]), we expect that the YSOs are at different evolutionary stages.

We considered that the errors associated with the determination of age and mass are mainly of two kinds; random errors in photometry, and systematic errors due to different theoretical evolutionary tracks. We estimated the effect of random errors by propagating them to the observed estimations of $V$, $(V - R)$ and $E(V - R)$ by assuming a normal error
Table 4. Magnitudes, age and mass of the YSOs in the cluster region. Complete table is available in an electronic form.

| Id | RA (J2000) | DEC (J2000) | V ± eV | R ± eR | Age ± error Age (Myr) | Mass ± error in Mass (M⊙) |
|----|------------|-------------|--------|--------|------------------------|--------------------------|
| 1  | 37.888229  | 61.429279   | 22.10 ± 0.02 | 20.66 ± 0.01 | 3.01 ± 0.65 | 0.31 ± 0.02 |
| 2  | 37.895050  | 61.506271   | 21.28 ± 0.01 | 19.79 ± 0.01 | 1.20 ± 0.30 | 0.30 ± 0.02 |
| 3  | 37.919338  | 61.502380   | 19.87 ± 0.01 | 18.61 ± 0.01 | 1.57 ± 0.57 | 0.57 ± 0.08 |
| ...| ...        | ...         | ...     | ...    | ...                    | ...                      |

Figure 7. The mass function of the candidate YSOs in the mass range (0.3 < M/M⊙ < 2.5), derived from the optical data. The error bars represent ± √N errors. The continuous line shows the least-square fit to the mass ranges described in the text. The value of the slope obtained is given in the figure.

distribution and using Monte Carlo simulations (see e.g., Chauhan et al. 2009). Since we have used the evolutionary model by Siess, Dufour & Forestini (2000) for all the PMS stars, the age and mass estimations given in Table 4 should not be affected by systematic errors. A sample of Table 4 is given here and the complete table is available in the electronic version.

4 DISCUSSION

4.1 Mass function of the YSOs

Young clusters are the best objects to study the initial MFs. Since young low-mass stars have limited time to segregate from the cluster and/or loose mass through evolutionary processes, the variation of the MF gives clues about the physical conditions of the star formation process. The MF is defined as the number of stars per unit logarithmic mass interval, and is generally represented by a power law with a slope, $\Gamma = d \log N(\log m)/d \log m$, 

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where $N(\log m)$ is the distribution of the number of stars per unit logarithmic mass interval. Most of the star clusters in the solar neighborhood have MF slopes near the Salpeter MF slope, i.e., $\Gamma = -1.35$.

Since our YSO sample is complete down to 0.3 $M_\odot$, for the MF study we have taken only those YSOs which have masses in the range $0.3 \leq M/M_\odot \leq 2.5$. The mass distribution of our YSO sample has a best-fit slope, $\Gamma = -1.23 \pm 0.14$ (see Fig. 7). Ninkov et al. (1995) studied the cluster IC 1805 and found a slope of $\Gamma = -1.38 \pm 0.19$ for masses between 2.5 and 30 $M_\odot$. A similar value of $\Gamma (= -1.3 \pm 0.2)$ has been reported by Massey, Johnson & Degioia-Eastwood (1995) for the massive stars of the W4 complex. Our YSO MF is consistent with those reported for other active star forming regions. Erickson et al. (2011) derived the MF of an extinction limited YSO sample (with masses $> 0.2 M_\odot$) consistent with the field star MF. Kang et al. (2009) did not find any difference in the YSO MF slopes of the star-forming regions W51 A ($\Gamma = -1.17 \pm 0.26$) and W51 B ($\Gamma = -1.32 \pm 0.26$). We note that a few older Class III sources might have been excluded as contaminants due to our conservative selection criteria (see Sec. 3.1.4). Even then, we believe our result should represent the IMF for the cluster, for example, and low-mass isochrones are very close to each other.

4.2 Evolution of T-Tauri Stars in IC 1805

TTSs are low-mass stars ($< 3M_\odot$) which are contracting towards the MS. They are generally classified into weak-line TTSs (WTTSs) and classical TTSs (CTTSs) on the basis of the strength of the H$_\alpha$ emission line (Strom et al. 1989). WTTSs exhibit a weak, narrow H$_\alpha$ (EW $\leq 10$ Å) in emission with no or little infrared excess, while CTTSs display a strong H$_\alpha$ emission line (EW $\geq 10$ Å) and large infrared excesses. Class II sources are generally considered to correspond in the optical category to CTTSs and Class III sources to WTTSs (e.g., Hartmann et al. 2005; Pandey et al. 2013b). The ‘standard model’ by Kenyon & Hartmann (1993) postulates that the CTTSs evolve to WTTSs by losing their circumstellar disks or at least their inner parts. In the Taurus region the WTTSs are systematically older than the CTTSs (Bertout, Siess & Cabrit 2007), but the statistical significance is low (Kenyon & Hartmann 1995; Hartmann 2001; Armitage, Clarke & Palla 2003). Contrary to the above results, there are studies which favour the assumption that CTTSs and WTTS are coeval and possess indistinguishable stellar properties (Lawson, Feigelson & Huenemoerder 1996; Gras-Velázquez & Ray 2003). The coevality of CTTSs and WTTSs in a star-forming
Figure 8. (a) Histograms of the age distribution of the Class II and Class III candidates, (b) Cumulative distributions of CTTSs and WTTSs in the cluster region as a function of stellar age.

region can be explained by assuming that YSOs have intrinsically a wide range of disk masses and their accretion activity and/or the dispersal of the disk takes place in a correspondingly wide range of time scales (Furlan et al. 2006; Bertout, Siess & Cabrit 2007).

In the present work, we have derived the ages of a large sample of YSOs in the IC 1805 cluster, hence, it is worthwhile to attempt to address the problem of the evolutionary status of CTTSs and WTTSs. Fig. 8a shows the histograms of the ages of the CTTS and WTTS candidates within the cluster region in the mass range $0.3 \text{ – } 2.5 \, M_\odot$. This manifests that the CTTSs are relatively younger (mean age $\sim 2.3$ Myr) than the WTTSs (mean age $\sim 2.6$ Myr). The cumulative distribution of the ages of CTTSs and WTTSs are shown in Fig. 8b. We obtained the Kolmogorov-Smirnov (KS) test value of 11% that the two samples are drawn from the same population, which is marginally significant. Although the statistical significance is less, our result is in agreement with those of Bertout, Siess & Cabrit (2007) for the Taurus-Auriga T-association and of Chauhan et al. (2009) for the BRC regions, that WTTSs are relatively older than CTTSs, which supports the notion that CTTSs evolve into WTTSs. Here again, we would like to remind readers that these results are affected by the uncertainty associated with the membership of the stars (see Sec. 3.1.4), particularly the WTTSs (Spectroscopic information is needed to confirm the true nature of WTTSs and CTTSs).
Figure 9. The upper panel shows the surface distribution of WTTSs (blue circles) and CTTSs (red circles) superposed on the Spitzer 4.5 µm image of the cluster. The concentric annuli have a width of 1'.8. The massive stars are shown with diamond symbols and cluster centre with cross. The lower panel shows the CTTS fraction as a function of the radial distance from the cluster centre. The two filled squares represent the locations of the two massive stars near the cluster centre.

4.3 Disk Fraction Variation in the Cluster

The disk fraction of YSOs in clusters decreases with ages (e.g., Haisch, Lada & Lada 2001; Hernández et al 2008). Haisch, Lada & Lada (2001) quantitatively concluded that in young clusters an initially very high (80% - 90%) disk fraction decreases to 50% in ∼ 3 Myr and reaches almost 10% at ∼ 5 Myr. Generally massive stars seem to lose their disks earlier than lower-mass stars. For example, most low-mass stars (spectral type K5 and later) lose their disks in 5−7 Myr (e.g., Sicilia-Aguilar et al. 2005), whereas for the intermediate-mass Herbig Ae/Be stars the corresponding time scale is <3 Myr (e.g., Hernández et al. 2005).

In a young cluster the disk fraction depends also on the spatial position. Theoretical calculations predict that external UV radiation of high-mass stars can photoevaporate outer
Low-mass young stellar population of the cluster IC 1805

Disks only within 0.3 – 0.7 pc (Johnstone, Hollenbach & Bally 1998; Adams et al. 2004). Decrease in disk frequencies in the immediate vicinity of massive stars has been found in several massive clusters, e.g., NGC 2244, NGC 6611 and Pismis 24 (Balog et al. 2007; Mercer et al. 2009; Fang et al. 2012), suggesting rapid destruction of circumstellar disks in such environments. IC 1805 is a young cluster (age \( \sim 2.5 \) Myr) with several low-mass (< 2.5 \( M_\odot \)) stars that have disks, thus the cluster represents a good site for studying the influence of massive stars on the evolution of disks.

In IC 1805, it is argued that the region is mainly powered by three O-type stars (Lefloch, Lazareff & Castets 1997). BD +60502 and BD +60501 are of spectral type O4.5III (Sota et al. 2014) and O7V (Sota et al. 2011), respectively and are located near the assumed cluster centre (see Fig. 9), whereas HD 15570 is an O4I star (Sota et al. 2011), located \( \sim 4.7' \) east of the cluster centre. The radial velocities of BD +60502 and BD +60501 are \(-42 \) km/s (Kharchenko et al. 2007) and \(-52 \) km/s (Kharchenko et al. 2007), respectively, consistent with the molecular cloud velocity (–55 to –32 km/s) associated with the W3/W4 complex (Heyer & Terebey 1998). The radial velocity of HD 15570 is \(-24.00 \) km/s (Gontcharov 2006), thus unlikely to belong to the W3/W4 complex, but seems consistent with that of an object in an inter-arm cloud, whose velocity lies between –32 to –18 km/s (Heyer & Terebey 1998). We conclude that the cluster is dominated by the O4.5III and O7V stars located near the cluster center.

To study the influence of these massive stars on the evolution of nearby low-mass stars, we divided the cluster area into five concentric annuli (each of width 1.8'). Fig. 9 (upper panel) displays the distribution of CTTSs (red circles) and WTTSs (blue circles) in the mass range 0.3 - 2.5 \( M_\odot \) from the catalogue of YSOs for which we have mass estimations from the optical CMDs. Our aim is to examine the disk fraction variation of the low-mass stars within the cluster due to external influence, as massive stars can self-destroy their disk, because evolution of protoplanetary disks is faster around higher mass stars (e.g. Kennedy & Kenyon 2009; Yasui et al. 2014). Fig. 9 (lower panel) displays the fraction of low-mass CTTSs (i.e., the ratio between CTTSs and CTTSs+WTTSs in each annular area) as a function of the projected radial distance from the cluster centre which is only 0.03 pc away from BD +60502. In the Figure, the substantial uncertainties shown as solid lines originate from the low statistics of IR excess sources in each bin. We also checked the distribution of disk frequency by re-centering the analysis on the O7 star and find the disk frequency variation to be nearly the same. Although we see a dip in the disk-fraction vs. distance plot in the vicinity of the O-type star, due to large statistical error, we do not have a strong evidence of variation...
in the disk fraction within the cluster. However, we note that the disk fraction estimation can be affected by many factors, such as various methods used to identify YSOs, the variation in stellar density (e.g., Spezzi et al. 2015), sensitivity of different bands and the uncertainty in the membership of the older WTTs. For example, Spitzer observations of high mass star forming regions suffer from high, non-uniform nebulosity, primarily emission from PAHs at IRAC bands and is strong close to the massive stars near the center of rich clusters, where stellar crowding is high. In contrast Chandra’s sensitivity is less affected by nebulosity and moreover it has several times better on-axis spatial resolution than Spitzer. So IRAC bands can lead to severe decrease in sensitivity of the disk-bearing YSOs compared to disk-less YSOs near the cluster center. Nonetheless, our result is in agreement with Roccatagliata et al. (2011), who found no variation of the disk fraction as a function of the distance from the high-mass stars in IC 1795, which has similar number of high mass stars and located in the same cloud complex.

### 4.4 Star Formation History

Figure 10 shows the Canadian Galactic Plane Survey (CGPS; Taylor et al. 2003) 1.4 GHz emission in the direction of the W4 bubble, superimposed on the WISE 12 µm emission and Herschel in 250 µm emission. We have also marked the BRCs in the region (Sugitani, Fukui & Ogura 1991). The 12 µm WISE band contains 11.7 µm emission commonly attributed to PAH molecules excited in the photon dominated regions (PDRs) at the interface of HII regions and their adjacent molecular clouds by the far-UV photons leaking from the HII regions (Pomarès et al. 2009). Therefore, PAHs are good tracers of the warm PDR that surrounds the HII region. PAH emission is also a good tracer of newly formed, embedded B-type star formation (Peeters, Spoon & Tielens 2004), as these stars heat the surrounding dust to high temperatures enough to excite the PAH bands and fine-structure lines. Figure 10 reveals a filamentary distribution of the 12 µm emission with its long axis in the east-west direction that bisects the HII region and also in the PDRs at the periphery of the bubble. The dust emission detected by the Herschel 250 µm also has an elongated distribution similar to that of the 12 µm emission. Compared to the PAH and dust emission, the ionized gas appears to be distributed orthogonal to the long axis of the filamentary

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4 http://irsa.ipac.caltech.edu/applications/wise/
5 http://www.cosmos.esa.int/web/herschel/science-archive/
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Figure 10. Colour composite image of IC 1805 region reproduced with CGPS 1.4 GHz emission (blue colour) superimposed on those of the WISE 12 μm emission (green colour) and Herschel 250 μm emission (red colour). BRCs associated with the region and cataloged in Sugitani, Fukui & Ogura (1991) are also marked in the figure. The red contours display the surface density distribution of the YSOs with the plus symbol representing the cluster centre.

structure, with decreasing intensity away from the filament axis. The ionized gas seems to be bounded more towards the east and west directions than in the north and south. The overall morphology of the nebula looks bipolar. Such a bipolar morphology has been noticed in NIR to MIR bands in a few HII regions and/or bubbles (see e.g., Saito et al. 2009; Samal et al. 2012; Mallick et al. 2013; Deharveng et al. 2012). Recently Herschel observations have clearly shown the presence of a cold dense neutral filament in bipolar HII regions that bisects ionized lobes (e.g., Deharveng et al. 2015), similar to the one observed here. Thus, the elongated nature of the 250 μm emission most likely represent the long axis of the parental filament.

It has been suggested that the stellar distribution in star forming regions is governed by the structure of the parental molecular cloud as well as how star formation proceeds in the cloud (e.g., Chen, Chen & Shu 2004; Sharma et al. 2006; Schmeja, Kumar & Ferreira...
Although our survey does not sample all the YSOs of the W4 complex, it is good enough to provide clues on the star formation history. We generated the YSO stellar surface density map using the nearest neighborhood method (Gutermuth et al. 2005). At each sample position \([i, j]\) in a uniform grid, we measured \(r_N(i, j)\), the projected radial distance to the \(N^{th}\) nearest star. The value of \(N\) is allowed to vary depending upon the desired smallest scale structures of interest. We generated a map using \(N=20\), which, after a series of experiments, was obtained as a good compromise between the resolution and signal-to-noise ratio of the map. In the stellar surface density distribution (see Fig. 10), the YSOs show a centrally concentrated clustering. At the same time, the overall distribution has an elongation along the east-west direction, following the structure revealed by the 250 µm emission. Thus it appears that the formation of the cluster IC 1805 possibly started in a filamentary cloud, where the density was high along the axis of the filament and low towards the perpendicular directions. With time the O stars of the cluster developed an H\(_{\text{II}}\) region, which subsequently grew in size, first inside the dense filament, then opening out in a hole in the low density direction of the filament, resulting a large cavity in the north and south direction. Based on the distribution of young stars on the Herschel images, Deharveng et al. (2012) have suggested that young clusters in the W5 complex were also formed in a filamentary cloud. In the W4 complex, we could see a few BRC structures in the north and south directions facing the IC 1805 cluster (see Fig. 10). This could be due to the fact that as the ionized gas streams away in the low density side, it encounters a few small, dense clouds along its way, forming the BRC structures.

The YSO distribution along the filament axis of the W4 bubble suggests that some of them could have resulted from the fragmentation of the original filament as are the cases found in other filamentary systems (e.g., Jackson et al. 2010; Hacar & Tafalla 2011; Samal et al. 2015) and/or due to compression of dense gas of the primordial filament by an expanding H\(_{\text{II}}\) region. Though precise characterization (e.g., proper motion and age) of individual YSOs projected on the filament is needed to understand their origin, the overall morphology of the W4 H\(_{\text{II}}\) region and the distribution of the associated YSOs suggest that IC 1805 could have been formed in a filamentary cloud.
5 CONCLUSIONS

With the aim of unraveling the less known low-mass YSO population of the cluster IC 1805 which is rich in massive OB stars, we studied the region using optical, IR and X-ray datasets. Our results suggest that despite the less favorable conditions for star formation around the high-mass stars, IC 1805 shows signs of low-mass star formation similar to other clusters in the solar vicinity. We identified and characterized a large number of low-mass YSO candidates in the region. Most of them have masses in the range \(0.2 - 2.5 \, M_\odot\) and age \(0.1 - 5\) Myr. The slope of the MF in the mass range \(0.3 \leq M/M_\odot \leq 2.5\) is found to be \(\Gamma = -1.23 \pm 0.14\), similar to the Salpeter MF. The mean age of the candidate YSOs is found to be \(\sim 2.5\) Myr. The candidate WTTSs are found to be relatively older when compared to the CTTS candidates. We do not find strong evidence for disk dispersal due to massive stars. The spatial distribution of the YSOs, dust and gas in the H\textsc{ii} complex shows a filamentary distribution, which suggests the filamentary morphology of the parental molecular cloud.

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