Subaru Hyper Suprime-Cam Survey of Cygnus OB2 Complex - I: Introduction, Photometry and Source Catalog

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ABSTRACT

Low mass star formation inside massive clusters is crucial to understand the effect of cluster environment on processes like circumstellar disk evolution, planet and brown dwarf formation. The young massive association of Cygnus OB2, with a strong feedback from massive stars, is an ideal target to study the effect of extreme environmental conditions on its extensive low-mass population. We aim to perform deep multi-wavelength studies to understand the role of stellar feedback on the IMF, brown dwarf fraction and circumstellar disk properties in the region. We introduce here, the deepest and widest optical photometry of 1.5 arcsecond diameter region centred at Cygnus OB2 in r2, i2, z and Y-filters using Subaru Hyper Suprime-Cam (HSC). This work presents the data reduction, source catalog generation, data quality checks and preliminary results about the pre-main sequence sources. We obtain 713,529 sources in total, with detection down to 28 mag, 27 mag, 25.5 mag and 24.5 mag in r2, i2, z and Y-band respectively, which is 3 - 5 mag deeper than the existing Pan-STARRS and GTC/OSIRIS photometry. We confirm the presence of a distinct pre-main sequence branch by statistical field subtraction of the central 18 arcminute region. We find the median age of the region as ~ 5 ± 2 Myrs with an average disk fraction of ~ 9%. At this age, combined with AV ~ 6 - 8 mag, we detect sources down to a mass range ~ 0.01 - 0.17 M⊙. The deep HSC catalog will serve as the groundwork for further studies on this prominent active young cluster.

Key words: stars:low-mass – stars: pre-main-sequence – stars: imaging – methods: observational – techniques: photometric – catalogues

1 INTRODUCTION

The complete stellar life cycle is significantly shaped by its mass, which is in-turn determined by the less understood evolutionary stages of star formation and its related processes (Luhman 2012; Armitage 2015; Manara et al. 2017 and references therein). As low-mass stars (< 1-2 M⊙) spend comparatively longer time in the rudimentary stages than their massive counterparts (> 8 M⊙), comprehensive studies on low-mass star formation can provide useful insight into the interesting underlying processes like protoplanetary disk formation and evolution (Hartmann 2008; Williams & Cieza 2011; Armitage 2015), brown dwarf formation and the factors affecting them (Basu 2017; Megeath et al. 2019). Moreover, since most of the stars form in clusters, hence cluster environment plays a crucial role in stellar evolution and related processes (Sicilia-
Aguilar, Aurora et al. 2013; Samal et al. 2015; Jose et al. 2016; Parker et al. 2021; Damian et al. 2021). For example, disk evolution has been observed to be affected by various factors like viscous accretion (Gori et al. 2015; Ercolano & Pascucci 2017), stellar density (Winter et al. 2018), external photoevaporation in diverse harsh environments like ONC (O’Dell et al. 1993), NGC 1977 (Kim et al. 2016), Cygnus OB2 (Wright et al. 2012; Guarcello et al. 2016; Winter et al. 2019). Another intriguing question which requires further investigation is the ambiguous uniformity of Initial Mass Function (IMF) and its behavior in the low-mass and sub-stellar regime. Although many recent and past studies suggest a uniform IMF across various star forming regions in the Milky Way (Bastian et al. 2010; Offner et al. 2014; Moraux 2016; Jose et al. 2017; Damian et al. 2021), variation has been observed in the extreme environments like the Galactic Center (e.g. Lu et al. 2013; Hosek et al. 2019), least luminous Milky Way satellites (Geha et al. 2013; Gennaro et al. 2018) and massive elliptical galaxies (van Dokkum & Conroy 2010; Cappellari et al. 2012).

Since, both Galactic and extragalactic star formation principally occurs in clusters and OB-associations (e.g. Carpenter 2000; Lada & Lada 2003; Pfalzner et al. 2012), an empirical model for low mass star formation developed by ecletic inferences drawn from both Galactic as well as extragalactic studies, is a pre-requisite to answer these fundamental questions. However, due to observational constraints with the current technology, we can only start by analysing the relatively distant young massive Galactic star forming regions using powerful observing facilities. The nearby clusters (for e.g Gould Belt regions), which are the focus of most of the studies (Dunham et al. 2015; Dzib et al. 2018; Bobylev & Bajkova 2020; Kubiak et al. 2021; Damian et al. 2021) are not the representative samples of extragalactic star-forming regions, where most of the star formation occurs in the extreme cluster environments of giant molecular complexes. The deep and wide field surveys of distant young massive Galactic clusters are need of the hour as such clusters are less dynamically evolved and hence, provide a robust sample of stars with similar history of formation in extreme environments (e.g. Portegies Zwart et al. 2010; Longmore et al. 2014). The primary goal of this work is to obtain good quality deep observations and use them to carry out an elaborate study of Cygnus OB2, a young massive Galactic cluster with extreme environmental conditions analogous to that of extragalactic star forming regions.

Cygnus OB2 (Right Ascension: 20:33:15, Declination: +41:18:54), located at ~1.6 kpc (Lim et al. 2019) from the Sun, is a typical analogue of the extragalactic massive star forming regions located outside the solar neighborhood. It is the central massive OB-association (2 – 10 × 10$^4$ M$_\odot$ as determined by Knödlseder (2000); Wright et al. (2010)) embedded in the giant Cygnus X molecular complex (Schneider et al. 2006; Reipurth & Schneider 2008) and harbors ~220 OB-type stars (Comerón & Pasquali 2012; Berlanas et al. 2020) along with tens of thousands of low mass stars (Albacete Colombo et al. 2007; Drew et al. 2008; Wright & Drake 2009). The OB2 association has an estimated age of ~ 3 – 5 Myrs (Drew et al. 2008; Wright et al. 2010; Wright et al. 2015) and is affected by variable extinction, $A_V$ ranging between ~4 - 8 mag (Wright et al. 2015). With a cluster environment impinged by high energy radiation from massive OB-stars in the association, Cygnus OB2 is an ideal laboratory to study the role of stellar feedback on the surrounding low-mass stellar population in the region. The presence of globules and proplyds (see Figure A1 in Appendix A for HSC r$_2$-band images of the known proplyds from Wright et al. (2012)) in the surrounding region (Schneider et al. 2012; Wright et al. 2012; Schneider et al. 2016) and a reduced circumstellar disk fraction in the vicinity of massive O-type stars (Guarcello et al. 2016) suggest the effect of ongoing external photoevaporation on disk evolution. Approximately 1843 candidate young stellar objects (YSOs) have been identified based on their NIR excess properties (Guarcello et al. 2013) within an area ~$1'\times1'$ of Cygnus OB2. The GTC-OSIRIS optical study by Guarcello et al. (2012) covers the central 40' x 40' region of the Cygnus OB2 with photometry of the sources reaching down to ~25 mag in r'-band, however photometric error exceeds 0.1 mag for ~ 40% of the total sources in the catalog. Similarly, previous studies regarding the kinematics, structure as well as mass function of Cygnus OB2 are confined to a stellar mass of ~ > 1 M$_\odot$ (Wright et al. 2010; Wright et al. 2015; Comerón & Pasquali 2012; Arnold et al. 2020). However, the low mass regime of the region covered by < 0.5 M$_\odot$ stars, remains unexplored. Cygnus OB2 is thus, a potential young massive cluster for which deep and wide-field optical and NIR studies are essential. This paper is a step towards a detailed study of one of the most massive star forming regions outside the solar neighbourhood with detections reaching down to the sub-stellar regime (≤ 0.07 M$_\odot$).

We present here the deepest ($r_2 \sim 28$ mag) and the widest (1.5" diameter) (see Figures 1) optical catalog of one of the most massive Galactic star forming regions i.e Cygnus OB2 along with the preliminary analysis for a limited area using the presented HSC data. Thanks to the superb wide-field imaging capabilities of Subaru Hyper Suprime-Cam (HSC), we have obtained high quality deep optical photometry which is useful to give an insight into the low mass star formation, proto-planetary disk evolution and the effect of feedback from massive stars on the cluster properties like Initial Mass Function (IMF), star formation efficiency and star to brown dwarf ratio.

This paper is divided into the following sections: The Section 2 interprets the Subaru Hyper Suprime-Cam observations, data reduction and catalog generation using HSC pipeline. Section 3 presents the data quality in terms of photometry, astrometry, completeness of the HSC data along with comparison relative to already available optical photometry. In Section 4 we present the data analysis and results obtained, aided with color-magnitude diagrams, age analysis and disk fraction analysis. We then discuss and interpret the results obtained with this data so far in Section 5 and encapsulate the entire work along with our future plans, finally in Section 6.

2 OBSERVATIONS AND DATA REDUCTION

2.1 HSC Observations

Subaru is an 8.2 m class optical-infrared telescope built and operated by the National Astronomical Observatory of Japan (NAOJ). With an 870 Megapixels mosaic CCD camera comprising of 116 2k × 4k CCDs with a pixel scale ~0.17", the Hyper Suprime-Cam (HSC) instrument installed at the prime focus of the telescope provides an excellent image quality over a wide field of view (FOV; 1.8 deg$^2$) (Miyazaki et al. 2012; Komiyama et al. 2017; Furusawa et al. 2017; Miyazaki et al. 2018). We observed a region of 1.5° diameter centered at Cygnus OB2 (see Figure 1) with Subaru HSC in 4 broadband optical filters, namely, r$_2$, i$_2$, z and Y (Kawanomoto et al. 2018)
Figure 1. RGB image of the 1.5° diameter region centred at Cygnus OB2 (RA: 20:33:15; Dec: +41:18:54) obtained with r2, i2 and Y-bands of Subaru HSC. The inset white box covers the 40′ × 40′ (18.6 pc × 18.6 pc) region observed by the past GTC/OSIRIS observations (Guarcello et al. 2013). The inset green box covers 1′ × 1′ region (RA: 20:32:12.7220; Dec: +41:06:58.778), further zoomed in the right corner of the image which gives a vivid view of the abundance and high resolution of the point stellar sources achieved by our observations of the target region.
on 17th September 2017 (PI: J.Jose; Program ID: S17B0108N), using EAO (East Asian Observatory) time. Several long exposure and short exposure frames (details given in Table 1) were taken to enhance the photometric accuracy of both faint as well as bright stars. The excellent seeing conditions (~ 0.5 '-' - 0.7 'prime) atop Mauna Kea during the observations (1.07 ≤ airmass ≤ 1.35) and superb optics of the camera with a focal length ~ 18320 mm have effectively enabled the otherwise difficult pairing of a wide field of view with detailed spatial resolution (see Figure 1). The mean FWHM values achieved in individual HSC filters are indicated in Table 1 and Figure 2. The achieved FWHM in individual filters is approximately uniform across the observed FOV (Figure 2). Hitherto, HSC has primarily been used for extra-galactic observations (e.g. Matsuoka et al. 2019; Ishikawa et al. 2020; Jelaini et al. 2020). However, there is a dire lack of similar observations in Galactic stellar fields with HSC. This study is a pioneering work to utilize the powerful and highly sensitive imaging capabilities of Subaru Hyper Suprime-Cam for observations of young Galactic star forming regions. A summary of the various procedures followed and the modifications introduced in the default pipeline parameters to reduce the observed HSC data is presented below.

2.2 Data Reduction and Catalog Generation

The observed raw data was downloaded from STARS (Subaru Telescope Archive System) and reduced with the help of HSC Pipeline version 6.7. The entire process of the data reduction by HSC pipeline (hscPipe) can be broadly classified into (1) Single-visit Processing (2) Joint Calibration (3) Coaddition (4) Coadd Processing/ Multiband Analysis. For details regarding the following processes, refer to Bosch et al. (2017); Aihara et al. (2017); Aihara et al. (2019).

The hscPipe initiates the data reduction with single-visit processing. The detrending of the raw data includes overscan subtraction, bias correction, dark current subtraction, flat-fielding, and fringe subtraction. The hscPipe then performs Instrument Signature Removal (ISR) to mask and interpolate the defects such as bad pixels, cross-talk, and saturated pixels. A few bright sources short-listed using a 50σ threshold value are used as reference to model the Point Spread Function (PSF) using PSFEx software. The astrometric and photometric calibration of these sources is performed with respect to the Pan-STARRS DR1 PV3 reference catalog using the ‘Pessimistic B’ matching algorithm. We discard the default ‘Optimistic B’ algorithm as it is well-suited for low density fields like extragalactic realms and has failure modes in comparatively high density Galactic regions, which results in false matches and incorrect astrometry of the detected sources. After performing sky subtraction and source measurements, the previously generated PSF model is used to generate a deeper catalog of stars using a 5σ threshold. The above explained process including the source extraction using 5σ detection threshold, is performed for each CCD during single visit processing. An internal calibration is then carried out across different observing shots, termed as visits. The astrometric and photometric calibrations are carried out by matching the wcs and flux scale of each visit with the previously generated matched list of reference bright stars and corresponding corrections are then applied to each visit.

In the next step, the hscPipe coadds the images from various visits to create a single deeper image and a PSF model is constructed for the coadded image. The sky correction applied prior to the coadd process is turned off as it contaminates our coadded images due to high amount of nebulosity present in the region. The sky correction applied at this step merely writes a new background model without modifying the photometry of detected sources. We coadd the long exposure visits and short exposure visits separately for individual filters, to obtain precise photometry for some of the bright sources which get saturated in the long exposure images. Eventually, hscPipe performs multiband analysis in order to generate the final photometric catalog for each band. The source extraction is performed again, this time on the coadded images using 5σ threshold value to detect sources and photometry is subsequently performed on the coadded images in each filter. As a result of the source extraction, certain above-threshold regions called footprints are generated each of which, comprises of one or more discrete sources. These footprints, containing several peaks are merged together across different filters. The overlapping footprints from different filters are then combined. Within each of such combined footprints, the peaks close enough to each other (that is, lying within 0.3'' of the nearest peak) are merged as one peak, otherwise are assigned as an individual new peak. This results in consistent peaks and hence, footprints across individual filters. Each of the peak corresponds to individual objects. The peaks within individual footprints are further deblended in individual filters and the total flux is apportioned into them.

The number of stellar sources detected during image coaddition relies upon the footprint size as each footprint consists of several blended individual peaks. The larger the size of the footprint, the more peaks or distinct objects it can hold. As the hscPipe is designed primarily for sparse regions, the default footprint size defined by the pipeline i.e. 10⁶ pixels is insufficient to detect all stellar point sources in a comparatively dense Galactic star forming region like Cygnus OB2. Hence, after performing rigorous checks with several footprint sizes, we finally increased it to 10¹⁰ pixels for r, z and Y filters. The footprint size is increased to 10¹¹ pixels for r2 filter however, to ensure maximum detection inspite of it’s high sensitivity to the extensive nebulosity present in the region. The modified footprint sizes in individual filters aid in yielding an exhaustive catalog of point sources to be detected in the images. Finally, hscPipe performs source measurements and photometry for the detected sources and thus, both long exposure and short exposure catalogs are obtained in r2, r12, z and Y bands. However, these catalogs in individual filters are contaminated with plenty of spurious detections. Hence, we have applied certain flags and external constraints to eradicate such spurious detections, which we explain in the following section.

1 This EAO time for Cygnus OB2 observations was a compensatory time given to us for the ToO event GW170817, which happened during our scheduled night
2 refer https://dmtn-031.lsst.io/#pessimism-of-the-algorithm for details
3 See https://dmtn-031.lsst.io/
4 The source measurement step includes centroiding, shape measurements, aperture corrections, etc.
5 detections with no visible source present
### 2.3 Point Source Selection

We apply certain flags (see Table 2) and external constraints to remove the spurious contamination from the obtained long and short exposure catalogs (Section 2.2) with minimal loss of genuine point sources in individual filters. For more details on catalog flags, please refer to Bosch et al. (2017). Additionally, we select sources with photometric error $\leq 0.1$ mag in individual bands for both long and short exposure catalogs. We impose an additional constraint of internal astrometric error $\leq 0.1''$ to remove spurious sources without any loss of good point sources. This error in astrometry of a source is with respect to its peak PSF position in different visits (For more details please refer to Section 3.2). We consider only those sources which have detection in at least two filters. Since the seeing conditions during our observations varied between 0.5$''$–0.7$''$, we have chosen the upper limit of seeing i.e 0.7$''$, as the maximum matching radius and best match as the match selection criteria to cross match the sources between any two bands using TOPCAT tool\(^6\), in order to avoid loss of any genuine counterparts (Mehta et al. 2018; Murata et al. 2020). The cross-matching radius, even if reduced (e.g 0.5$''$) or increased (e.g 0.8$''$ or 1$''$) varies the census of genuine sources almost by a few hundreds, which is a negligible amount when compared to the total number of detected sources. Similarly, the specified constraints of 0.1 mag in photometric error and 0.1$''$ in the internal astrometric error have been chosen after checking and discarding several values ranging between 0.07 mag – 0.2 mag (in photometric error) and 0.08$''$–0.5$''$ (in astrometric error) as it results either in loss of numerous faint point sources or an increment in spurious detection by 5–10%.

The availability of both short exposure and long exposure photometry for the sources has enabled us to deal with the saturated sources effectively. We consider long exposure photometry in all the bands for those sources with magnitude in Y-band $> 18$ mag. In a similar fashion, sources with $Y \leq 18$ mag are incorporated from short-exposure catalog in all the filters. However, in addition to this, we also include short exposure photometry for sources with $18$ mag $\leq Y \leq 22$ mag and without any long exposure photometry available for them. This is specifically done in order to include the sources which lie close to bright stars and have been missed in the photometry from long exposure. The particular threshold of $Y \leq 22$ mag is chosen after verifying that the sources with only short exposure photometry and $Y > 22$ mag, are spurious detections and hence, discarded. This merging of short and long exposure photometry can result in missing sources or repetition of sources near the merging threshold i.e $Y = 18$ mag and its corresponding counterparts in other filters. Hence, to deal with this we take an average of the long and short exposure magnitudes for the sources with 17.8 mag $\leq Y \leq 18.2$ mag and their corresponding counterparts in other filters. An important point to note here is that the long and short exposure photometry is merged on the basis of the threshold values 18 mag or 22 mag taken in Y-band and applied to the corresponding counterparts in other bands. Finally, we perform an internal matching of the sources in the entire output catalog with the upper value of astrometric uncertainty, i.e 0.1$''$ as the matching radius to avoid any repetition of sources. Any duplicates (0.5% of the total sources) of the already detected sources in the catalog are removed in this step.

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\(^6\) http://www.star.bris.ac.uk/mbt/topcat

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### Table 1.

Details about short and long exposure frames and FWHM in individual filters.

| Filters | HSC-Y | HSC-z | HSC-i2 | HSC-r2 |
|---------|-------|-------|--------|--------|
| Exposure Time\(_{\text{short}}\) | 30s $\times$ 5 frames | 25s $\times$ 3 frames | 25s $\times$ 3 frames | 30s $\times$ 3 frames |
| Exposure Time\(_{\text{long}}\) | 200s $\times$ 3 frames | 300s $\times$ 4 frames | 300s $\times$ 10 frames | 300s $\times$ 16 frames |
| Mean FWHM | 0.61$''$ | 0.68$''$ | 0.62$''$ | 0.53$''$ |
Table 2. shows various flags applied with their description.

| Flagging Condition                      | Description                                      |
|----------------------------------------|--------------------------------------------------|
| deblend_nchild != 0                    | Objects which consist of multiple child peaks     |
| deblend_skipped                        | Objects which contain multiple blended peaks      |
| base_PixelFlags_flag_crCenter         | Objects overlaps cosmic ray contaminated pixels   |
| base_PixelFlags_flag_suspectCenter    | Object overlaps a pixel with unreliable linearity correction |
| base_PixelFlags_flag_saturatedCenter  | Object with saturated pixels                      |
| base_PixelFlags_flag_interpolatedCenter | Object with interpolated pixels from surrounding pixels |

* Each individual source peak obtained after deblending each footprint

Figure 3. This flowchart summarizes the external conditions imposed after applying flags mentioned in Table 2. These conditions ensure the maximum point source detection and remove spurious sources from both long exposure and short exposure catalogs separately, obtained after data reduction using mscPipe. The short and long exposure photometry are then concatenated and merged based on conditions mentioned above. For details please refer to Section 2.3.

We have finally secured 713,529 point sources all of which have at least a 2-band detection. Approximately, 699,798 (~ 98%) sources have Y-band photometry, 685,511 sources (~ 96%) have z-band photometry, 622,011 sources (~ 90%) have i-band photometry, and 358,372 sources (~ 50%) have r-band photometry. Figure 4 presents a sample of our exemplary detection in different bands for a particular region (RA: 20:34:10.483, Dec: +40:57:48.783) of 2' x 2'. Almost all the visible sources, although faint, have been successfully detected in the final HSC catalog. The adopted approach of selecting genuine point sources as described in this section has yielded the deepest and the widest comprehensive optical catalog of one of the most massive regions in the Galaxy outside the solar neighborhood.

3 DATA QUALITY

In the following sections, we discuss the data quality in terms of the photometry, astrometry, limiting magnitude of detection, completeness of the reduced HSC data with respect to the existing Pan-
Figure 4. A 2' × 2' area (RA: 20:34:10.4835 Dec: +40:57:48.783) in different filters is overplotted with sources detected in each individual band i.e Top Left: r\textsubscript{2}-band, Top Right: i\textsubscript{2}-band, Bottom Left: z-band and Bottom Right: Y-band.

STARRS DR1\textsuperscript{7} (Chambers et al. 2019) and GTC/OSIRIS (Guarcello et al. 2012) optical data. We also perform a comparison of the obtained HSC photometry with respect to Pan-STARRS DR1 photometry with the help of magnitude offset plots and check the astrometric offset with respect to Pan-STARRS DR1 and Gaia EDR3 data (Brown et al. 2016; Gaia Collaboration et al. 2020).

3.1 Photometric Quality

The error versus magnitude plots shown in Figure 5 for the individual HSC filters i.e r\textsubscript{2}, i\textsubscript{2}, z and Y-filter, summarize the accuracy of the obtained HSC photometry. The plot illustrates that the photometric error is ≤ 0.05 mag for sources with magnitudes down to ~ 26.0 mag in i\textsubscript{2}-band, 27.5 mag in r\textsubscript{2}-band, 24.7 mag in z and 24.0 mag in Y-band. Approximately 91% and 95% of the total sources have a photometric error ≤ 0.05 mag in Y and z-band respectively. Similarly, 93% of the sources detected in i\textsubscript{2}-band and almost 90% of the detected sources in r\textsubscript{2}-band have an error ≤ 0.05 mag. A comparative error versus magnitude plot is presented in Figure 6 for an area of 30' radius centred on Cygnus OB2 to juxtapose the accuracy of HSC photometry with previous optical studies of the region such as with Pan-STARRS, GTC/OSIRIS. Since GTC/OSIRIS observations are available for a limited FOV (40' × 40'), the chosen area (30' radius centred at Cygnus OB2) allows a fair comparison of photometric accuracy among the HSC, Pan-STARRS and GTC/OSIRIS sources. The maximum detection limit within a photometric error ≤ 0.1 mag attainable with Pan-STARRS and GTC/OSIRIS photometry is ~ 22.5 mag–24.0 mag (i-band), which is at least 3 mag shallower when compared to the high accuracy attained by the HSC photometry down to the very faint sub-stellar regime (i\textsubscript{2} ~ 27.0 mag ; ≤ 0.07 M\(_\odot\)) (see Section 3.3 and Section 4.1 for details).

In order to assess the photometric quality, we check the offset between HSC and the counterpart Pan-STARRS DR1 photometry in the individual filters. To compare the photometry, we transformed the Pan-STARRS DR1 photometry from Pan-STARRS filter system

\textsuperscript{7} downloaded from https://vizier.u-strasbg.fr/viz-bin/VizieR
Figure 5. Scatter plots of HSC magnitudes versus error in individual HSC filters. All the sources have error ≤ 0.1 mag. The discontinuity at Y = 18 mag in magnitude-error plot of Y-band (Top Left) is due to the merging of long and short exposure photometry. Y = 18 mag is taken as the threshold magnitude for this merging (see Section 2.3 for details on the merging procedure.). The multiple branches observed in these plots are due to the long and short exposure photometry merged to obtain the final catalog.

Figure 6. A comparative magnitude versus error scatter plot for HSC (blue) with the existing photometry from Pan-STARRS (Green) and GTC/OSIRIS (Guarcello et al. 2012) (Red) in $i_2$-band for an area of 30' radius centred on Cygnus OB2. The two branches observed in the HSC $i_2$-band plot correspond to the long and short exposure photometry.

To HSC system using the equations given in Appendix B. The sources with good quality Pan-STARRS photometry have been selected by giving an error cut off ≤ 0.05 mag and number of stack detections > 2 (Chambers et al. 2019). We observe a moderate uniformity in the magnitude offset across the entire region as presented in the spatial distribution map in Figure 7. Figure 8 shows the scatter plots of magnitude offset i.e HSC magnitudes–Pan-STARRS magnitudes versus HSC magnitudes, in all HSC filters. A mean offset of 0.01±0.07 mag is observed in z-band with respect to the Pan-STARRS magnitudes. Similarly, other bands i.e $r_2$, $i_2$, Y-band exhibit an offset of 0.01±0.03 mag, 0.01±0.03 mag and 0.03±0.06
Figure 8. Scatter plots for determining magnitude offset of HSC photometry with respect to Pan-STARRS photometry in different individual bands. An offset of 0.03±0.06 mag, 0.01±0.07 mag, 0.01±0.03 mag and 0.01±0.03 mag is observed in Y, z, i$_2$, r$_2$-band respectively for the range of magnitudes marked by dashed black lines. The marked magnitude ranges have been selected to calculate the mean magnitude offset in order to avoid the saturation of HSC photometry towards the brighter end and unreliable photometry of Pan-STARRS towards fainter end of sources. The blue sources lie within 3σ range from mean offset whereas grey sources lie beyond 3σ range from mean offset.

3.2 Astrometric Quality

We present a graphical interpretation of the high precision astrometry of point sources in the HSC catalog in Figure 9 and 10. Due to our strict selection criteria (see Section 2.3), all the sources have both Δ RA and Δ Dec ≤ 0.1″. This astrometric uncertainty of each source is attributed to the uncertainty in the position of its observed peak flux in different exposures. Hence, the mentioned astrometric error threshold of 0.1″ is a quality measure of the internal astrometric calibration relative to different visits. The internal astrometric error, mainly ranging between 0.01″–0.03″ appears to be uniform across the observed region (see Figure 9) with a mean value ~ 0.016″ for the detected sources. However, the census of sources decreases rapidly with increasing internal astrometric error (Figures 10 Top Left and Top Right).

We perform an additional check of the astrometry of the detected HSC sources with respect to the external data such as Pan-STARRS DR1 and Gaia EDR3 available for the observed area of Cygnus OB2. The histograms in Figure 10 Bottom Left and Bottom Right show the offset between HSC, Pan-STARRS DR1 and Gaia EDR3 astrometry in the HSC FOV (1.5° diameter region centred at Cygnus OB2). The absence of any visible offset between HSC and Pan-STARRS astrometry is attributed to the astrometric calibration performed with respect to Pan-STARRS PV3 DR1 data to develop a PSF model during the single-visit processing (refer Section 2.2). However, a mean offset of ~ 1.9 ± 2″ × 10^{-5} in Right Ascension and ~ 6.6 ± 8″ × 10^{-6} in Declination is observed with respect to the Gaia EDR3 astrometry for both HSC and Pan-STARRS data and is well in accordance with the astrometric accuracy estimated in Aihara et al. (2019) with these two data sets. We also present the spatial distribution of the astrometric offsets of HSC with respect to the GAIA EDR3 and Pan-STARRS DR1 astrometry in Figure C1 and observe an excellent uniformity throughout the observed region.

3.3 Completeness

The analysis of the final data gives the 5σ limiting magnitude i.e the magnitude of the faintest star detectable with our observations in individual HSC filters. The histogram shown in Figure 11 (Top) indicates the detection limit of HSC photometry in different bands. In-spite of the high amount of nebulosity and moderate extinction...
Figure 9. Spatial plots signifying the variation of internal error in Right Ascension (Left) and Declination (Right) across the entire region. The spatial maps are obtained by binning the RA and Dec parameter space into $10' \times 10'$ bins across the entire observed region. The colorbar indicates the mean uncertainty in RA (Left) and Dec (Right) of each bin. The observed internal astrometric error ranges between $0.01'' - 0.03''$, with almost uniform distribution throughout the region.

Figure 10. Histograms of internal error in Right Ascension (Top Left) and in Declination (Top Right). Histograms of the observed offset in astrometry of HSC with respect to Pan-STARRS (blue), astrometry of Pan-STARRS with respect to Gaia EDR3 (black) and astrometry of HSC with respect to Gaia EDR3 (red) in Right Ascension is shown in the Bottom left panel and in Declination is shown in the Bottom Right panel (See Section 3.2 for details).
prevalent in Cygnus OB2 (Drew et al. 2008; Wright et al. 2010; Guarcello et al. 2012), the limiting magnitude reaches down to $^8$28.0 mag in $r_2$-band, 27.0 mag in $i_2$-band, 25.5 mag in $z$ and 24.5 mag in $Y$-band. At a distance of 1600 pc, age $\sim 5 \pm 2$ Myrs (see Section 4.3) and an average extinction $A_V$ ranging between 6 – 8 mag (refer Section 4.1), the mentioned detection limit of 27.0 mag in $i_2$-band corresponds to a stellar mass of 0.02 – 0.03 $M_\odot$ (using isochrones of Baraffe et al. (2015)) i.e less than the Lithium-burning limit. The final HSC photometry is $\sim$ 90% complete down to 26.5 mag, 25.5 mag, 24.0 mag and 23.5 mag in $r_2$, $i_2$, $z$ and $Y$-band respectively, as indicated by the turn-over point in the histogram (denoted by dashed lines in Figure 11). The turnover point in source count approach to evaluate the 90% completeness limit gives similar results to the artificial star-count method (Jose et al. 2016; Jose et al. 2017; Damian et al. 2021; Das et al. 2021). Since $Y$-band has the highest number of detections, we take it as reference and calculate the number of counterpart sources in $r_2$, $i_2$ and $z$-band in each 0.5 mag bin to assess the completeness of other HSC filters relative to $Y$-band. The completeness of the photometry in various filters relative to $Y$-band attained by this method is presented in Figure 11 Bottom. We provide a summary of the useful quality parameters in individual HSC filters, for an age $\sim 5 \pm 2$ Myrs and $A_V$ = 6 - 8 mag in the Table 3. The obtained HSC photometry is found to be deeper by an order of 3 - 5 mag , when compared with the existing Pan-STARRS and GTC/OSIRIS photometry (limited to $\sim$ 21.5 mag and 23.5 mag, respectively in $r$-band), and thus provides a substantial sample of faint low mass sources in Cygnus OB2.

4 DATA ANALYSIS AND RESULTS

We present here some preliminary analysis based on the HSC data to illustrate the significance of Cygnus OB2 as an ideal target for low-mass star formation studies with the help of a few color-magnitude diagrams (CMDs) presented in this section. We also perform a statistical field decontamination using a peripheral control field to obtain a statistical estimate of member stars and use that to obtain the approximate median age and average disk fraction of the central 18$''$ region of Cygnus OB2.

4.1 Color-Magnitude Diagrams

Color-magnitude diagrams (CMDs) are integral to segregate the cluster members from foreground and background contaminants (e.g Jose et al. 2017; Esplin & Luhman 2020; Damian et al. 2021) and estimate the age, temperature and spectral type of member stars in a star-forming cluster. We present the Hess plot of the $z-Y$ vs $z$ Color-Magnitude Diagram (CMD) in Figure 13, plotted with our optical catalog obtained for the entire 1.5$''$ diameter area of Cygnus OB2. A similar $i_2-Y$ vs $i_2$ and $r_2-i_2$ vs $r_2$ CMD in Figure 14 (Left) and (Right) have been plotted for the sources lying in the central region of 18$''$ radius. This area has been particularly selected due to the high concentration (~ 50% of the total) of YSOs (identified previously by Guarcello et al. (2013)) present in this region. Cygnus OB2 exhibits a distinct pre-main sequence branch which is a prominent feature observed in CMDs of young clusters (Jose et al. 2013, 2017; Panwar et al. 2018;
celfetal.2013), overplotted as red circles, are located within the 10 to HSC filter system. Magnitudes of Baraffe isochrones (in Pan-STARRS filter system) (given in Appendix B) have been used to convert the obtained Sun (Lim et al. 2019). Consequently, the transformation equations = 6.0 mag and 1600 parsecs as distance of Cygnus OB2 from the Wang & Chen (2019) for Pan-STARRS filter system, taking A = 6 mag. The isochrones have been reddened using the extinction laws of Damiani et al. 2019; Biazzo et al. 2019; Ksoll et al. 2020; Damian et al. 2021). In order to analyse the approximate age of the cluster, we over-plot isochrones of age 0.5, 3 and 10 Myr and evolutionary tracks for various masses from Baraffe et al. (2015) on the i2-Y vs i2 CMD. As per the past studies, an extinction of Av = 4 – 5 mag has been observed towards the north-west of Cygnus OB2 along with Av = 5.5 – 7.0 mag observed towards centre and south of the association (Wright et al. 2015). Hence, we choose a mean value of extinction as Av = 6.0 mag in order to redden our isochrones. The isochrones have been reddened using the extinction laws of Wang & Chen (2019) for Pan-STARRS filter system, taking Av = 6.0 mag and 1600 parsecs as distance of Cygnus OB2 from the Sun (Lim et al. 2019). Consequently, the transformation equations (given in Appendix B) have been used to convert the obtained magnitudes of Baraffe isochrones (in Pan-STARRS filter system) to HSC filter system.

The majority (~ 88%) of the previously detected YSOs (Guarcello et al. 2013), overplotted as red circles, are located within the 10 Myr isochrone overplotted on the i2-Y vs i2 CMD in Figure 14 Left and thus, occupy the characteristic pre-main sequence branch. The source population occupying the young pre-main sequence branch consists of both cluster members as well as background contaminants. We obtain a statistical estimate of the membership in the central 18’ using the field decontamination process further in Section 4.2. The color of these sources (i.e i2 – Y ≥ 2) reinforces the claim that they constitute the pre-main sequence population present in the central 18’ radius region of Cygnus OB2.

We emphasize the cluster membership of the sources in the pre-main sequence branch with the aid of a comparative study between an 18’ radius circular region towards the centre and an equal rectangular area towards the periphery of Cygnus OB2 (RA: 308.2665; Dec: 41.7497), as shown in Figure 15. The Hess plot of r2-Y vs r2 CMD (Figure 15 (Left)) is plotted for the sources in the central 18’ radius region, which is prolific in pre-main sequence cluster members and a similar Hess plot is plotted in Figure 15 (Right) for the sources lying towards the outskirts of Cygnus OB2. The absence of a distinguished pre-main sequence branch in the CMD of the sources towards the periphery as compared to the central region, suggests that it is mainly populated by the non-cluster members in the foreground or background. Hence, in accord with the literature (Knödlseder 2000; Wright et al. 2010; Guarcello et al. 2013; Wright et al. 2015; Guarcello et al. 2016), our optical data analysis advocates that Cygnus OB2 is an active young star formation site rich in pre-main sequence, low mass as well as sub-stellar population with a suggested age ≤ 10 Myrs.

### Table 3. Details of final HSC catalog in individual filters. (For more details of the given parameters, please refer to Sections 3.1, 3.2, 3.3 and 4.1)

| Filters     | HSC-Y | HSC-z | HSC-i2 | HSC-r2 |
|-------------|-------|-------|--------|--------|
| Number of sources | 699,798 | 685,511 | 622,011 | 358,372 |
| Fraction of sources ≤ 0.05 mag error | 91% | 95% | 93% | 90% |
| Brightness limit (mag) | 14.0 | 14.2 | 15.3 | 15.6 |
| Limiting magnitude (mag) | 24.5 | 25.5 | 27.0 | 28.0 |
| Limiting magnitude upto 90% completeness (mag) | 23.5 | 24.0 | 25.5 | 26.5 |
| Limiting mass (in M⊙) | 0.02-0.03 | 0.03-0.04 | 0.03-0.06 | 0.15-0.30 |

*a Magnitude of the brightest object detected
*b Magnitude of the faintest object detected
*c Magnitudes rounded off to 0.2 mag
*d Mass corresponding to magnitude with 90% completeness for Av: 6 – 8 mag and age: 5 ± 2 Myrs.

![Hess plot](image)

Figure 13. Hess plot of z-Y vs z Color-Magnitude Diagram (CMD) with HSC sources detected in the entire area of 1.5° diameter centred at Cygnus OB2. The Hess plot is obtained by binning the color and magnitude parameter space into bins of size 0.01 mag and 0.03 mag respectively. The black arrow marks the direction of reddening vector of Av = 6 mag.

4.2 Field Star Decontamination

The background and foreground contaminants, also termed as field star contaminants, generally lie in the line of sight of the observed target region and can overlap with the young pre-main sequence population in the CMDs as mentioned in Section 4.1. Hence, the identification of cluster members is particularly crucial for an accurate estimation of various cluster parameters like age, distance, disk fraction which can otherwise be biased by the presence of field stars. Although, kinematic parameters like proper motion, radial velocity and other methods such as spectroscopy and SED analysis provide the most precise membership identification (Panwar et al. 2017; Dutta et al. 2018; Herczeg et al. 2019; Bhardwaj et al. 2019; Jose et al. 2020; Das et al. 2021), such data is available only for a handful of the sources with Gaia eDR3 counterparts complete down to ~ 20 mag, which is inadequate for the low mass pre-main sequence members in Cygnus OB2. Hence, a statistical field star...
Figure 14. **Left**: $i_2$-Y vs $i_2$ CMD within the central 18' radius of Cygnus OB2. Isochrones of age 0.5, 3 and 10 Myr and evolutionary tracks for various masses (Baraffe et al. 2015), which are corrected for an $Av$=6 mag and distance = 1600 pc are shown using solid curves. The previously known YSOs of the complex (Guarcello et al. 2013) are overplotted as red dots. **Right**: $r_2$-i$_2$ vs $r_2$ CMD for the same 18' radius region. The black arrow marks the direction of reddening vector for $A_V$ = 6 mag.

Figure 15. The comparative Hess diagrams of $r_2$-Y vs $r_2$ CMDs to emphasize cluster membership for sources located within **Left** the inner 18' radius of Cygnus OB2 (RA: 308.2785; Dec: 41.7477) and **Right** a rectangular region of the same area towards the outskirts of Cygnus OB2 (RA: 308.2655; Dec: 41.7497). The black arrow marks the direction of reddening vector for $A_V$ = 6 mag.

We perform the statistical field decontamination for a cluster field of 18' radius centred at Cygnus OB2, which encloses ~ 50% of the known YSOs in the region. In the absence of a control field external to the observed region, we choose a rectangular control field located towards the outskirts of the Cygnus OB2 (centred at RA: 308.2655; Dec: 41.7497) of an area equal to that of the cluster field. This control field is the same as used above for Figure 15 **(Right)**. We observe a higher source density in the control field as compared to the cluster field, which may either be due to differences in the stellar density or could be attributed to the different extinction observed in the two directions. Although, the subtraction using an appropriate control field is useful to obtain a statistical estimate of the probable cluster members down to faint low mass limits ($r_2$ ~ 28 mag) (eg. Jose et al. 2017; Kaur et al. 2020; Damian et al. 2021).

CO maps and mid-IR images from MSX from Schneider et al. (2006) and Reipurth & Schneider (2008) suggest an approximate uniform extinction across the Cygnus OB2, the extinction mapping performed by us using deep near-IR UKIDSS data (to be discussed in the forth-coming work.) reveals moderate differential reddening across the region with the control field being less extincted than the cluster field by 1 - 1.5 mag. To address the stellar density fluctuation, we chose a box in the color magnitude diagram where we do not expect to see any pre-main sequence stars in the cluster field (such as the one shown in Figure 16 **(Left)**). We scale down the counts in the color magnitude diagram of the control field by a constant factor $f$, such that the number of detected objects in this box is consistent between the cluster and the control field within Poisson fluctuations. We infer the posterior distribution of the parameter $f$ using Monte Carlo Markov sampling using the package emcee (Foreman-Mackey et al. 2013). We performed
multiple iterations over several smaller box areas (located over the entire $r_2$ magnitude range and $r_2 - i_2$ color $\leq 2$) in the CMD of the control field, and obtain a median likelihood value of 0.73 that is used to scale the bin counts of the control field in the entire color magnitude diagram. This median likelihood value scales down the overdensity of sources in the control field, which can otherwise result in the over subtraction of the sources while performing field decontamination of the cluster field.

We then perform the field subtraction using $r_2$-$i_2$ versus $r_2$ CMD and divide the color and magnitude parameter space into 0.1 and 0.2 mag bins. For each bin, we first scale down the count of sources in the control field and then, subtract the control field count from the cluster field count. The resultant count thus obtained, is a floating point number which represents the average number of sources to be selected randomly as the field subtracted sources in each bin. Hence, in order to obtain an integer count, we randomly select an integer value within the Poisson fluctuations of the average count obtained as a result of subtraction. The derived integer count is considered as the number of sources to be selected as field subtracted sources in the cluster field per bin. We emphasize here that this field decontamination is purely statistical and the resultant field subtracted sources may not be the confirmed members of the cluster. The Figure 16 shows the Hess plots of $r_2$-$i_2$ versus $r_2$ CMD for the cluster and control field along with that for the field subtracted sources. We observe that the field subtracted sources distinctly occupy the pre-main sequence branch in the CMD with a few scattered sources, which can be attributed to the statistical uncertainty in the field decontamination process. We repeated the field subtraction with another control field located in the outskirts of Cygnus OB2, and find that the statistics remain comparable within 10% uncertainty. Hence, we consider the field subtracted sources for further analysis to estimate the median age and disk fraction of the chosen cluster field area as described in the following sections.

4.3 Age distribution of Cygnus OB2

The information about the age of the sources, combined with an estimate of the disk bearing sources (YSOs) in a cluster is helpful in constraining the star formation history of the region. However, the age estimation can be biased if the sample is contaminated with field stars. Hence, we use the statistically subtracted sources obtained after the field decontamination process, described above in Section 4.2, to estimate the age of the chosen cluster field area. However, to eliminate any possible contaminants due to statistical error in the field decontamination process which may bias our age estimation, we consider only those sources with 20.5 mag $\leq r_2 \leq 26.5$ mag, in accordance with the completeness limit of $r_2$-band. The upper limit of 20.5 mag corresponds to 1.4 $M_{\odot}$ source (the upper mass limit in Baraffe isochrones) at an age $\sim 5$ Myrs. Since, approximately 90% of the total field subtracted sources have mass less than the considered upper limit, it will not modify our results significantly. To further refine our selection, we define an empirical pre-main sequence (PMS) locus and select only those sources which are within 1 $\sigma$ limits of this empirical locus. We refer to these sources as the selected sources. The PMS locus is obtained by dividing the $r_2$ magnitude range into 0.5 mag bins. For each bin then, we take the mean of the $r_2$ magnitude and median of the $r_2 - i_2$ color of the sources inside the bin. This mean magnitude and the median $r_2 - i_2$ color in each magnitude bin thus, defines the empirical PMS locus (see Damian et al. (2021) for details).

We determine the age of these selected sources by fitting the Baraffe isochrones of various ages (available at an interval of log(t) = 0.01). The age is then assigned to each source based on its distance to the different isochrones. Since for any particular age, the available isochrones are a set of few discrete points (color and magnitude values), the age estimation based on the distance to these few points can be biased. Hence, we fit these discrete points using linear regression model with fifth order polynomial distribution to interpolate the isochrones. This interpolation generates a larger set of discrete points for any particular age and the accuracy of these predicted values (color and magnitude values) is $\geq 99\%$ for all the isochrones of different ages. The interpolation of the isochrones thus, helps in improving the overall accuracy of this age estimation method. We then proceed to find, for each source, the two nearest isochrones with ages, say $t_1$ and $t_2$ and distances $D_1$ and $D_2$ respectively, from the source. The age is then calculated as the weighted average of the two ages $t_1$ and $t_2$. The inverse of the distances $D_1$ and $D_2$ are used as weights in order to calculate the weighted average (t) of the ages of the two isochrones as given in equation below:

$$t = \frac{t_1D_1 + t_2D_2}{D_1 + D_2}$$

The weighted average $t$ is thus, assigned as the age of the source. The process is repeated for all the selected sources. The median age of the field decontaminated sources within 18’ is thus, obtained to be 6.5 $\pm$ 5 Myrs. We further converge this distribution to within 2 $\sigma$ limits from the mean age of the entire distribution after performing 8 iterations. The median age for the 2 $\sigma$ converged sample turns out to be 5 $\pm$ 2 Myrs. The Figure 18 shows histogram plot for the age distribution of the sources for the un-converged sources. Although for the above age calculation, we have reddened the Baraffe isochrones for an $A_V = 6$ mag, we derive similar results (median age within 4 -- 6 Myrs) for an extinction variation between $A_V = 4.5 - 7.5$ mag (Wright et al. 2010; Wright et al. 2015). This is expected because the reddening vector stays parallel to the isochrones for optical wavelengths. Hence, a variation in the extinction simply shifts the sources along the isochrones without thus, introducing any significant modification in the derived ages. Also, the derived age of the region remains within 4 - 6 Myrs for a distance variation ranging between ~ 1500 - 1700 pcs (distance to Cygnus OB2 = 1600 $\pm$ 100 pcs (Lim et al. 2019)). The other possible factors like binarity, optical variability, although add to the broadening of the color in CMDs of young star forming regions, however, may not affect the true age spread as well as the cluster parameters like IMF significantly (Jose et al. 2017; Damian et al. 2021). The above analysis thus, confirms the median age of the central 18’ region with that of $\leq$ 10 Myrs as estimated by the previous studies (Drew et al. 2008; Wright et al. 2015; Berlanas et al. 2018).

4.4 Disk Fraction

Circumstellar disk evolution sets the timescale for planet formation and hence, measuring the disk fraction, that is, the fraction of stars surrounded by circumstellar disks for a certain cluster age, is an important parameter to give an insight into the star and planet formation in a young cluster (Haisch et al. 2001; Williams et al. 2009).
& Cieza 2011; Helled et al. 2014; Ribas et al. 2014). Although in a young cluster, disk fraction depends upon various factors such as the metallicity, stellar density, environmental factors like external and internal photoevaporation (Yasui et al. 2016; Yasui 2021; Thies et al. 2010; Guarcello et al. 2016; Reiter & Parker 2019), a general trend of disk fraction declining with age is observed. It ranges between 60% - 80% for clusters like NGC 1333 (Ribas et al. 2014), NGC 2023, RCW36 (Richert et al. 2018) with an age < 1 Myr (e.g.) to 5% - 10% for clusters like LowCent-Crux (Hernández et al. 2007), 25 Orionis (Pecaut & Mamajek 2016) with age ~ 10 Myrs. In this section we calculate the disk fraction for the central 18’ region of Cygnus OB2.

In order to calculate the disk fraction, we consider the previously identified YSOs by Guarcello et al. (2013) within the cluster field area of 18’ radius. The previously identified YSOs are complete between 0.7 M\(_\odot\) – 2 M\(_\odot\) (Guarcello et al. 2013), which corresponds to 18.5 mag $\leq$ r\(_2\) $\leq$ 22.5 mag at a distance $\sim$ 1600 pc and A\(_V\) $\sim$ 6 mag. Hence, for estimating the disk fraction, we consider only those YSOs with optical counterparts within the mentioned r\(_2\)-band magnitude completeness range. The sample data used to calculate the disk fraction thus consists of only those field subtracted member sources which lie within 1 $\sigma$ limit of the pre-main sequence locus (Section 4.3) and 18.5 mag $\leq$ r\(_2\) $\leq$ 22.5 mag. Figure 19 shows the Hess plot of r\(_2\) - i\(_2\) versus r\(_2\) CMD for the field subtracted sources. This Hess diagram is overplotted with the YSOs (Red circles) along with the sample selected to calculate the disk fraction (i.e the total number of candidate members) (White

\[\text{(Middle) the control field and (Right) the field subtracted sources. For the hess plot of control field (Middle), the control field data count per bin is scaled by the median log likelihood value, i.e 0.73. A sample box area chosen to calculate this log likelihood value is shown as the white box in the Hess plot of the cluster field (Left). Several such box areas are considered to calculate the median log likelihood value. The white arrow marks the direction of reddening vector for A\(_V\) = 6 mag.}

\[\text{This is overplotted with the selected sources (red dots) i.e within 1 $\sigma$ limits of the empirical pre-main sequence (PMS) locus (green solid curve) and 20.5 mag $\leq$ r\(_2\) $\leq$ 26.5 mag. These selected sources are considered for the age estimation. Also, the 20 Myr Baraffe isochrone corrected for an A\(_V\) = 6 mag and distance = 1600 pc is shown as the black dashed curve. The white arrow marks the direction of reddening vector for A\(_V\) = 6 mag. Right: Histograms for r\(_2\) - i\(_2\) color distribution in each r\(_2\) magnitude bin of 0.5 mag (the legend in each histogram shows the respective magnitude bin for which the histogram of color distribution is plotted).} \]
crosses). We find that the ratio of the number of YSOs to that of the total number of sources, also termed as the disk fraction, turns out to be ~9%. This is however, a lower limit on the disk fraction as the previously identified YSOs are limited by the Spitzer IRAC Channel 2 sensitivity. This reason accounts for the lower total number of sources, also termed as the disk fraction, turns out to be ~9%. This is however, a lower limit on the disk fraction as the previously identified YSOs are limited by the Spitzer IRAC Channel 2 sensitivity. This reason accounts for the lower disk fraction, in comparison to other young clusters like NGC 2264, CepOB3-East and West, which could be a result of external photoevaporation of circumstellar disks as a result of massive stars in vicinity.

**5 DISCUSSION**

Rigorous studies of the low mass star formation in young massive Galactic clusters using multi-wavelength data sets are crucial to understand and solve some of the important yet unanswered questions such as the nature of IMF for stellar masses < 0.5 M☉, the role of feedback driven cluster environment on the evolution of circumstellar disks, proportion of sub-stellar objects etc. The young massive association of Cygnus OB2 is a promising target for such purpose with its substantial massive as well as pre-main sequence population (Albacete Colombo et al. 2007; Wright & Drake 2009). This paper presents the deepest and the widest optical photometry of Cygnus OB2 available as of yet. We detect a total of 713,529 sources with reliable data quality for objects detected down to the faint low mass end (Section 3). The preliminary data analysis performed with the deep HSC catalog suggests the presence of two sequences in various CMDs (Section 4.1), the rightward sequence occupied by the PMS cluster members along with background contaminants. The previously identified YSOs overplotted on i2-Y vs i2 CMD in Figure 14 (Left) occupy the pre-main sequence branch in the CMD, mostly towards the right side of the isochrones of age < 10 Myrs, as expected for a young association like Cygnus OB2 (e.g. Jose et al. 2017; Damian et al. 2021). We observe that the pre-main sequence segregation in various CMDs (Figure 15) for the central region is consistent with most of the star formation being significantly clustered around the centre of this dynamically unevolved region (Wright et al. 2016; Arnold et al. 2020). The isochrone fitting done in Figure 14 Left suggests that ~45% of the total 713,529 sources detected in the region, lie within age less than 10 Myrs and a significant fraction of these sources (~12%) lie below the evolutionary track of mass less than 0.08 M☉. However, we caution the readers that this is an upper limit of candidate pre-main sequence population in the region as the estimated fraction is likely to be contaminated by the reddened background sources. More qualitative identification and classification of the YSOs in the entire HSC FoV of Cygnus OB2, both disk and diskless will be done in a future follow-up study using multi-wavelength photometry.

We perform the field decontamination of the central 18’ region to get a statistical estimate of membership of the sources, using a control field located towards the periphery, which may be mostly contaminated with foreground and background stars. Approximately, 70% of the field decontaminated sources distinctly occupy the PMS branch with age less than 10 Myrs (Figure 16). Since these statistically decontaminated members are used further to calculate age and disk fraction in the cluster field, we refine the membership with the help of an empirical PMS locus (see Section 4.3 for details). The median age of the central 18’ region is ~5 ± 2 Myrs. The age obtained by our analysis agrees quite well with that estimated by several other studies of the region. For example, Drew et al. (2008) analyse 200 A-type stars across the Cygnus OB2, using IPHAS photometry and find the age to be ~5 Myrs. Similarly, Wright et al. (2015) used a list of 169 massive OB stars to derive the age of the region as ~4 - 5 Myrs using rotating stellar evolutionary models from Ekström et al. (2012) while Wright et al. (2010) use X-ray sources to obtain 3.5 - 5.2 Myrs as the average age of the region. Recent studies by Berlanas et al. (2018); Comerón et al. (2020) perform spectroscopy of ~60 OB-type stars (observed with INT, ISIS, OSIRIS instruments) and find that the age of the region ranges between 1 - 6 Myrs irrespective of the stellar model used for age estimation. We
corroborate this result by verifying our age estimation with Parsec isochrone models (Bressan et al. 2012) in addition to the Baraffe models, for a mass range of 0.3 M⊙ - 1.4 M⊙ and derive the median age ~ 4.5 ± 2 Myrs. Cygnus OB2 is a part of the larger Cygnus X giant molecular cloud which formed approximately 40 - 50 Myrs ago. The star formation towards Cygnus OB2 region however, has mainly taken place in the last 10 - 20 Myrs with the last star formation activity peaking around 3 - 5 Myrs ago (Reipurth & Schneider 2008; Comerón & Pasquali 2012; Comerón et al. 2016; Berlanas et al. 2018; Comerón et al. 2020). This may suggest the substantial pre-main sequence population with the median age ~ 5 Myrs in the region as obtained with our data analysis.

We obtain a disk fraction of ~ 9% for this cluster field using the already known YSOs in the region. There is a wide variety of disk fractions measured in young clusters. An average disk fraction of 30% - 50% is observed in several young clusters (within age ~ 3 – 6 Myrs) such as NGC 2264 (Sung et al. 2009), CepOB3b-East and West (Allen et al. 2012), AFGL 333/W3 (Jose et al. 2016), IC348/U (Richert et al. 2018) and NGC 2282 (Dutta et al. 2015). However, recent studies of some nearby young clusters (Hernández et al. 2010; Guarcello et al. 2016; Richert et al. 2018) show considerably smaller disk fractions. For example, the recent study by Richert et al. (2018) with 69 MYStIX and SFINCs young clusters reveals that the disk fraction could drop to values ~ 15% for a cluster age ≥ 4 Myrs, which is consistent with our results. The particularly low disk fraction obtained for the central region of Cygnus OB2 and such other clusters which lie at the lower end of the spectrum of disk fractions, may be attributed to either the evolutionary effect or the feedback effect from the massive OB-type stars in vicinity (Guarcello et al. 2016). In this work we cannot conclusively pinpoint the exact reason, however, evolutionary effects or external photo-evaporation could be some of the possible reasons for the observed low disk fractions.

The significant census of low mass and sub-stellar sources detected with deep HSC photometry (r2 ~ 28 mag) will serve as an excellent statistical sample for further studies to test the effect of feedback driven environmental conditions of Cygnus OB2 on low mass population across the region. To conclude, we find from our preliminary analysis that in accordance with the literature, Cygnus OB2 is a young active star-forming region (age < 10 Myr) with a substantial pre-main sequence population. The deep multi-wavelength studies are essential to understand low mass star formation in the region and will be the area of focus in our future works.

6 SUMMARY AND FUTURE WORKS

This paper presents the deepest and the widest optical catalog of the young feedback-driven OB association of Cygnus OB2.

1) A 1.5″ diameter area of Cygnus OB2 was observed with Subaru Hyper Suprime-Cam (HSC) in 4 filters namely r2, i2, z and Y. The observations were taken in excellent seeing conditions ranging between 0.5″-0.7″. The observed raw data was reduced using HSC pipeline version 6.7.

2) The final HSC catalog contains only those point sources which have at least 2-band detection and additionally, have internal astrometric error ≤ 0.1″ along with photometric error ≤ 0.1 mag in individual bands. A total of 713,529 sources are detected with 699,798 sources having a must detection in Y-band, 685,511 sources in z-band, 622,011 in i2 and 358,372 sources in r2-band.

3) We detect sources down to 28.0 mag, 27.0 mag, 25.5 mag and 24.5 mag in r2, i2, z and Y-band respectively. Coupled with a distance of 1600 pc for an age ranging between 5 ± 2 Myrs and extinction AV ~ 6 – 8 mag, we achieve ~ 90% completeness down to a stellar mass ~ 0.03 – 0.06 M⊙ and ~ 0.03 – 0.04 M⊙ i.e < Lithium burning limit, in i2 and z-band respectively. The corresponding mass completeness limit is down to ~ 0.02-0.03 M⊙ and ~ 0.15-0.30 M⊙ in Y and r2-bands, respectively.

4) The median age of the central region of Cygnus OB2 ranges between 4 – 6 Myrs for an AV ranging between 4.5 – 7.5 mag and distance between 1500 – 1700 pcs. We obtain a disk fraction ~ 9% in the central cluster, which is however a lower limit given the restricted completeness of the already known YSOs.

As the next step, we plan to adopt a multi-wavelength approach by combining the presented HSC optical data with other existing data from UKIDSS, 2MASS and Spitzer surveys to carry out a detailed analysis of the YSOs present in the region. In addition to this we would use our deep optical photometry presented in this paper, coupled with other data sets to evaluate cluster parameters like IMF for very low mass stars (< 0.1 M⊙) along with identification and characterization of sub-stellar objects like brown dwarfs and understand the role of feedback-driven environment of Cygnus OB2 on such parameters.

7 DATA AVAILABILITY

A sample table of the HSC catalog is presented in Table 4. The complete catalog is provided as online material.

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### Table 4. Sample table of HSC catalog data. The complete table is available as online material.

| Source | RA (deg) | Dec (deg) | $r_2$ (mag) | $r_{2err}$ (mag) | $i_2$ (mag) | $i_{2err}$ (mag) | $z$ (mag) | $z_{err}$ (mag) | Y (mag) | $Y_{err}$ (mag) |
|--------|----------|-----------|-------------|------------------|------------|-----------------|--------|----------------|--------|----------------|
| 1      | 308.69298 | 41.86609  | 25.728      | 0.019            | 23.568     | 0.006           | 22.090 | 0.008          | 21.434 | 0.008          |
| 2      | 308.83647 | 41.86581  | 24.790      | 0.010            | 22.666     | 0.003           | 21.175 | 0.004          | 20.515 | 0.004          |
| 3      | 308.70283 | 41.86674  | 26.425      | 0.044            | 24.641     | 0.018           | 22.859 | 0.015          | 22.154 | 0.016          |
| 4      | 308.84554 | 41.86651  | 25.894      | 0.028            | 22.267     | 0.002           | 20.231 | 0.002          | 19.183 | 0.001          |
| 5      | 308.79625 | 41.86680  | 24.398      | 0.007            | 22.314     | 0.005           | 21.279 | 0.005          | 20.026 | 0.002          |

Bosch J., et al., 2017, *Publications of the Astronomical Society of Japan*, 70

Bressan A., Marigo P., Girardi L., Salasnich B., Dal Cero C., Rubele S., Nanni A., 2012, *MNRAS*, 427, 127

Brown A. G. A., et al., 2016, *Astronomy & Astrophysics*, 595, A2

Cappellari M., et al., 2012, *Nature*, 484, 485

Chambers K. C., et al., 2019, The Pan-STARRS1 Surveys (arXiv:1612.05568)

Comerón F., Pasquale A., 2012, *A&A*, 543, A101

Comerón F., Djupvik A., Schneider N., Pasquale A., 2016, *Astronomy and Astrophysics*, 586

Damaso B., Jose J., Samal M. R., Moraux E., Das S. R., Patra S., 2021, *MNRAS*, 504, 2557

Damasin F., Prisinzano L., Pillitteri I., Micela G., Sciortino S., 2019, *A&A*, 623, A112

Das S. R., Jose J., Samal M. R., Zhang S., Panwar N., 2021, *MNRAS*, 500, 3123

Drew J. E., Greimel R., Irwin M. J., Sale S. E., 2008, *MNRAS*, 386, 1761

Dumham M. M., et al., 2015, *The Astrophysical Journal Supplement Series*, 220, 11

Duatta S., Mondal S., Jose J., Das R. K., Samal M. R., Ghosh S., 2015, *MNRAS*, 454, 3597

Duatta S., Mondal S., Joshi S., Jose J., Das R., Ghosh S., 2018, *MNRAS*, 476, 2813

Dzib S. A., Loinard L., Ortiz-León G. N., Rodríguez L. F., Galli P. A. B., 2018, *The Astrophysical Journal*, 867, 151

Ekström S., et al., 2012, *A&A*, 537, A146

Ercolano B., Pascucci I., 2017, *Royal Society Open Science*, 4, 170114

Espín-T. L., Luhman K. L., 2020, *The Astronomical Journal*, 159, 282

Foster-Mackey D., Hogg D. W., Goodman J., 2013, *PASP*, 125, 1206

Furusawa H., et al., 2017, *Publications of the Astronomical Society of Japan*, 70

Gaia Collaboration Brown A. G. A., Vallenari A., Prusti T., de Bruijne J. H. J., Babusiaux C., Biermann M., 2020, arXiv e-prints, p. arXiv:2012.01533

Geha M., et al., 2013, *ApJ*, 771, 29

Gennaro M., et al., 2018, *ApJ*, 855, 20

Gorti U., Hollenbach D., Dullemond C. P., 2015, *ApJ*, 804, 29

Guarrin M. G., Wright N. J., Drake J. E., García-Avarez D., Drew J. E., Aldcroft T., Kashyap V. L., 2012, *ApJS*, 202, 19

Guarrin M. G., et al., 2013, *The Astrophysical Journal*, 773, 135

Guarrin M. G., et al., 2016, arXiv e-prints, p. arXiv:1605.01773

Haasch Karl E. J., Lada C. J., 2001, *ApJ*, 553, L153

Hartmann L., 2009, *Physica Scripta*, T130, 014012

Helled R., et al., 2014, in Beuther H., Klessen R. S., Dullemond C. P., et al., *Protostars and Planets VI*. p. 643 (arXiv:1311.1142)
doi:10.2458/azu_uapress_9780816531240-ch028

Herczeg G. J., et al., 2019, *ApJ*, 878, 111

Hernández J., et al., 2007, *ApJ*, 671, 1784

Hernández J., Morales-Calderón M., Calvet N., Hartmann L., Muzerolle J., Gutermuth R., Luhman K. L., Stauffer J., 2010, *ApJ*, 722, 1226

Hosek Matthew W. J., Lu J. R., Anderson J., Najarro F., Ghez A. M., Morris

REFERENCES

Ahara H., et al., 2017, *Publications of the Astronomical Society of Japan*, 70

Ahara H., et al., 2019, *PASJ*, 71, 114

Albacete Colombo J. F., Flaccomio E., Micela G., Sciortino S., Damiani F., 2007, *A&A*, 464, 211

Allen T. S., et al., 2012, *ApJ*, 750, 125

Armidtage P. J., 2015, arXiv e-prints, p. arXiv:1509.06382

Arnold B., Goodwin S. P., Wright N. J., 2020, *MNRAS*, 495, 3474

Baraffe I., Homeier D., Allard F., Chabrier G., 2015, *A&A*, 577, A42

Bastian N., Covey K. R., Meyer M. R., 2010, *ARA&A*, 48, 339

Basu S., 2017, *Perspectives on Low-Mass Star Formation* (arXiv:1703.01542)

Berlanas S. R., Herrero A., Comerón F., Pasquale A., Bertelli Motta C., Sota A., 2018, *A&A*, 612, A50

Berlanas S. R., et al., 2020, *A&A*, 642, A168

Bhardwaj A., Panwar N., Herczeg G. J., Chen W. P., Singh H. P., 2019, *A&A*, 627, A135

Biazzo K., Beccari G., De Marchi G., Panagia N., 2019, *ApJ*, 875, 51

Bobylev V. V., Bajkova A. T., 2020, *Astrophysical Bulletin*, 75, 267

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M. R., Clarkson W. I., Albers S. M., 2019, ApJ, 870, 44
Ishikawa S., et al., 2020, The Astrophysical Journal, 904, 128
Jaelani A. T., et al., 2020, Monthly Notices of the Royal Astronomical Society, 495, 1291
Jose J., et al., 2013, MNRAS, 432, 3445
Jose J., Kim J. S., Herczeg G. J., Samal M. R., Rieger J. H., Meyer M. R., Sherry W. H., 2016, The Astrophysical Journal, 822, 49
Jose J., Herczeg G. J., Samal M. R., Fang Q., Panwar N., 2017, ApJ, 836, 98
Jose J., et al., 2020, ApJ, 892, 122
Kaur H., Sharma S., Dewangan L. K., Ojha D. K., Durgapal A., Panwar N., 2020, ApJ, 896, 29
Kawanomoto S., et al., 2018, PASJ, 70, 66
Kim J. S., Clarke C. J., Fang M., Facchini S., 2016, ApJ, 826, L15
Knodlseder J., 2000, A&A, 360, 539
Komiyama Y., et al., 2017, Publications of the Astronomical Society of Japan, 70
Komiyama Y., et al., 2018, The Astrophysical Journal, 853, 29
Kolliv F. V., et al., 2020, arXiv e-prints, p. arXiv:2012.00524
Kubiak K., Mužić K., Sousa I., Almendros-Abad V., Köhler R., Scholz A., Ksoll V. F., et al., 2020, arXiv e-prints, p. arXiv:2012.00524
Lada C. J., Lada E. A., 2003, Annual Review of Astronomy and Astrophysics, 41, 57
Lim B., Nazé Y., Gosset E., Rauw G., 2019, Monthly Notices of the Royal Astronomical Society, 490, 440
Longmore S. N., et al., 2014, in Beuther H., Klessen R. S., Dullemond C. P., Henning T., eds, Protostars and Planets VI. p. 291 (arXiv:1312.5326)
Lu J. R., Do T., Ghez A. M., Morris M. R., Yelda S., Matthews K., 2013, The Astrophysical Journal, 764, 155
Luhman K. L., 2012, Annual Review of Astronomy and Astrophysics, 50, 65
Manara C., Prusti T., Voirin J., Zari E., 2017, Proceedings of the International Astronomical Union, 12
Matsuoaka Y., et al., 2019, ApJ, 883, 183
Megaath T., et al., 2019, BAAS, 51, 333
Mehta V., et al., 2018, ApJS, 235, 36
Miyazaki S., et al., 2012, in McLean I. S., Ramsay S. K., Takami H., eds, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Proceedings of the International Astronomical Union, 495, 1291
Miyazaki S., et al., 2018, PASJ, 70, 66
Moraux E., 2016, in EAS Publications Series. pp 73–114
Murara T., Sunayama T., Oguri M., More S., Nishizawa A. J., Nishimichi T., Osako K., 2020, PASJ, 72, 64
O’dei C. R., Wen Z., Hu X., 2013, ApJ, 410, 696
O’Farrill S. R. R., Clark P. C., Hennebelle P., Bastian N., Bate M. R., Hopkins P. F., Moraux E., Whitworth A. P., 2014, in Beuther H., Klessen R. S., Dullemond C. P., Henning T., eds, Protostars and Planets VI. p. 53 (arXiv:1312.5326), doi:10.2458/azu_uapress_9780816531240-
Panwar N., et al., 2017, MNRAS, 468, 2684
Panwar N., Pandey A. K., Samal M. R., Battinelli P., Ogura K., Ojha D. K., Chen W. P., Singh H. P., 2018, The Astronomical Journal, 155, 44
Parker R. J., Nicholson R. B., Alcock H. L., 2021, MNRAS, 502, 2665
Peacut M. J., Mamajek E. E., 2016, MNRAS, 461, 794
Pfalzner S., Kuczewski T., Olczak C., 2012, A&A, 545, A122
Portegies Zwart S. F., McMillan S. L., Gieles M., 2010, Annual Review of Astronomy and Astrophysics, 48, 431
Reipurth B., Schneider N., 2008, Star Formation and Young Clusters in Cygnus. p. 36
Reiter M., Parker R. J., 2019, MNRAS, 486, 4354
Ribas A., Merin B., Bouy H., Mard I. T., 2014, A&A, 561, A54
Richert A. J. W., Getman K. V., Feigelson E. D., Kuhn M. A., Broos P. S., Povich M. S., Bate M. R., Garmire G. P., 2018, MNRAS, 477, 5191
Samal M. R., et al., 2015, A&A, 581, A5
Schneider N., Bontemps S., Simon R., Jakob H., Motte F., Miller M., Kramer C., Sutizki J., 2006, A&A, 458, 855
Schneider N., et al., 2012, A&A, 542, L18
Schneider N., et al., 2016, A&A, 591, A40
Sicilia-Aguilar, Aurora Kim, Jinyoung Serena Sobolev, Andrej Getman, Konstantin Henning, Thomas Fang. Min 2013, A&A, 559, A3
Sun H., Stawer F. R., Bessell M. S., 2009, AJ, 138, 1116
Thies I., Kroupa P., Goodwin S. P., Stamalellos D., Whitworth A. P., 2010, The Astrophysical Journal, 717, 577
Wang S., Chen X., 2019, The Astrophysical Journal, 877, 116
Williams J. P., Cieza L. A., 2011, ARA&A, 49, 67
Winter A. J., Clarke C. J., Rosotti G., Ish J., Facchini S., Haworth T. J., 2018, MNRAS, 478, 2700
Winter A. J., Clarke C. J., Rosotti G. P., 2019, MNRAS, 485, 1489
Wright N. J., Drake J. J., 2009, ApJS, 184, 84
Wright N. J., Drake J. J., Drew J. E., Viak J. S., 2010, ApJ, 713, 871
Wright N. J., Drake J. J., Drew J. E., Guarcello M. G., Gutermuth R. A., Hora J. L., Kraemer K. E., 2012, ApJ, 746, L21
Wright N. J., Drew J. E., Mohr-Smith M., 2015, Monthly Notices of the Royal Astronomical Society, 449, 741
Wright N. J., Bouy H., Drew J. E., Sarro L. M., Bertin E., Cuillandre J.-C., Barrado D., 2016, MNRAS, 460, 2593
Yasui C., 2021, arXiv e-prints, p. arXiv:2104.11764
Yasui C., Kobayashi N., Saito M., Izumi N., 2016, AJ, 151, 115
van Dokkum P. G., Conroy C., 2010, Nature, 468, 940

APPENDIX A:

We present in Figure A1, interesting images from HSC-Starrs system to Subaru HSC system in individual bands in order to plot the magnitude offsets are given below:

\[ y_{HSC} = y_{Pan-STARRS} - 0.001952 + (0.19957(y - z))_{Pan-STARRS} \]
\[ + (0.216821(1 - z)^2)_{Pan-STARRS} \]

(B1)

\[ z_{HSC} = z_{Pan-STARRS} - 0.005585 - (0.220704(z - Y))_{Pan-STARRS} \]
\[ - 0.298211((Y - z)^2)_{Pan-STARRS} \]

(B2)

\[ i_{2HSC} = i_{2Pan-STARRS} + 0.001653 - (0.206313(i - z))_{Pan-STARRS} \]
\[ - 0.016085((i - z)^2)_{Pan-STARRS} \]

(B3)

\[ r_{2HSC} = r_{2Pan-STARRS} + 0.000118 - (0.00279(r2 - i))_{Pan-STARRS} \]
\[ - 0.014363((r2 - i)^2)_{Pan-STARRS} \]

(B4)

\[ \delta \]

During the data reduction the coefficients used by the pipeline are as mentioned in the transformation equations

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The reddening laws (Wang & Chen 2019) adopted by us to correct the Baraffe isochrones for extinction in the Pan-STARRS are mentioned below:

\[
\begin{align*}
A_r/A_V &= 0.843 \pm 0.006 \\
A_i/A_V &= 0.628 \pm 0.004 \\
A_i/A_V &= 0.487 \pm 0.003 \\
A_y/A_V &= 0.395 \pm 0.003
\end{align*}
\]

These equations were used to convert the absolute Pan-STARRS magnitudes to apparent magnitudes using distance = 1600 parsecs and \(A_V = 6\) mag. The transformation equations mentioned above are then used to convert to HSC photometric system to redden the isochrones appropriately.

APPENDIX C:

We present here the spatial distribution of astrometric offset of HSC data with respect to Pan-STARRS DR1 and Gaia EDR3 data.

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