

SEJONG OPEN CLUSTER SURVEY (SOS) – V. THE ACTIVE STAR FORMING REGION SH 2-255 – 257

BEOMDU LIM^{†1}, HWANKYUNG SUNG², HYEONOH HUR², BYEONG-CHEOL LEE^{1,3}, MICHAEL S. BESSELL⁴,
JINYOUNG S. KIM⁵, KANG HWAN LEE⁶, BYEONG-GON PARK^{1,3}, AND GWANGHUI JEONG^{1,3}

¹Korea Astronomy and Space Science Institute, 776 Daedeokdae-ro, Yuseong-gu, Daejeon 305348, Korea
bdlim1210@kasi.re.kr

²Department of Astronomy and Space Science, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul 143747, Korea
sungh@sejong.ac.kr

³Astronomy and Space Science Major, University of Science and Technology, Gajeong-ro, Yuseong-gu, Daejeon 305333, Korea

⁴Research School of Astronomy and Astrophysics, Australian National University, MSO, Cotter Road, Weston, ACT 2611, Australia

⁵Steward Observatory, University of Arizona, 933 N. Cherry Ave. Tucson, AZ 85721-0065, USA

⁶Gwacheon National Science Museum, 110 Sanghabeol-ro, Gwacheon-si, Gyeonggi-do 427060, Korea

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Abstract: There is much observational evidence that active star formation is taking place in the H II regions Sh 2-255 – 257. We present a photometric study of this star forming region (SFR) using imaging data obtained in passbands from the optical to the mid-infrared, in order to study the star formation process. A total of 218 members were identified using various selection criteria based on their observational properties. The SFR is reddened by at least $E(B - V) = 0.8$ mag, and the reddening law toward the region is normal ($R_V = 3.1$). From the zero-age main sequence fitting method it is confirmed that the SFR is 2.1 ± 0.3 kpc from the Sun. The median age of the identified members is estimated to be about 1.3 Myr from a comparison of the Hertzsprung-Russell diagram (HRD) with stellar evolutionary models. The initial mass function (IMF) is derived from the HRD and the near-infrared ($J, J - H$) color-magnitude diagram. The slope of the IMF is about $\Gamma = -1.6 \pm 0.1$, which is slightly steeper than that of the Salpeter/Kroupa IMF. It implies that low-mass star formation is dominant in the SFR. The sum of the masses of all the identified members provides the lower limit of the cluster mass ($169 M_\odot$). We also analyzed the spectral energy distribution (SED) of pre-main sequence stars using the SED fitting tool of Robitaille et al., and confirm that there is a significant discrepancy between stellar mass and age obtained from two different methods based on the SED fitting tool and the HRD.

Key words: open clusters and associations: individual: Sh 2-255 – 257 (IC 2162) – dust, extinction – stars: luminosity function, mass function.

1. INTRODUCTION

Young open clusters provide useful test beds for the study of star formation processes because about 80 – 90% of young stars are found in embedded clusters with more than 100 members (Lada & Lada 2003; Porras et al. 2003). Furthermore, the fundamental parameters of clusters such as reddening, distance, and age can be properly constrained. These advantages allow us to derive a more reliable stellar initial mass function (IMF) to investigate star formation processes.

Sh 2-254 – 258 is a famous star forming region (SFR) in the Gem OB1 association (Sharpless 1959). The main ionizing sources of the H II regions are known to be one late-O and four early-B-type stars (Chavarría et al. 2008). A number of previous works found a few maser sources (Turner 1971; Lo & Burke 1973; Goddi et

al. 2007) as well as various molecular lines (Morris et al. 1974; Blair et al. 1975; Evans et al. 1977; Bieging et al. 2009; Zinchenko et al. 2012) in the region. Several sub-structures such as clumps and cores were also reported from infrared (IR), sub-millimeter, millimeter, and centimeter observations (Beichman et al. 1979; Jaffe et al. 1984; Howard et al. 1997; Minier et al. 2005; Zinchenko et al. 2012). These observational properties commonly indicate that active star formation is in progress.

Chavarría et al. (2008) took a census of young stellar objects (YSOs) using extensive near- to mid-IR imaging data. Most of the young stars ($\sim 80\%$) were found in several embedded sub-clusters. Mucciarelli et al. (2011) continued their search for low-mass YSOs in the quiescent phase, with a deep *Chandra* X-ray observation, and found that the total number of YSOs was consistent with that expected from the Kroupa IMF (Kroupa 2001) scaled to the number of ionizing sources. On the other hand, sequential star formation scenarios within the SFR have been proposed (Howard

CORRESPONDING AUTHOR: Beomdu Lim

[†]Korea Research Council of Fundamental Science & Technology Research Fellow

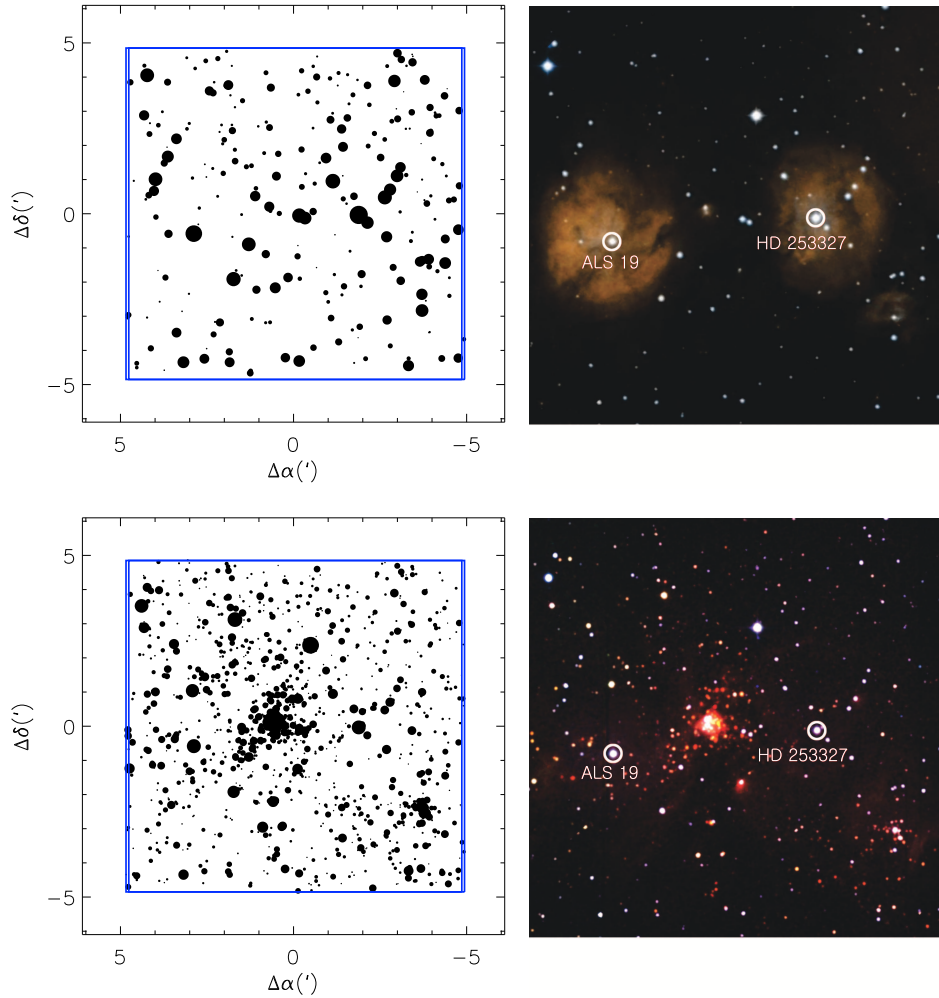


Figure 1. Finder chart and color composite image of the observed region in optical passbands (upper panels) and near-infrared passbands (lower panels). Stars brighter than $V = 18$ mag and $K_S = 16$ mag are plotted in left-hand panels, respectively. The size of the circles is proportional to the brightness of individual stars. The positions of stars are relative to $\alpha = 06^{\text{h}} 12^{\text{m}} 52^{\text{s}}.1$, $\delta = +17^{\circ} 59' 16''.4$. Squares outlined by blue solid lines represent the field of view of the Mont4K CCD camera. The color composite images were obtained from the Digital Sky Survey-2 and Two Micron All Sky Survey. The position of two ionizing sources is marked by open circles in each image.

et al. 1997; Minier et al. 2007; Chavarría et al. 2008; Bieging et al. 2009; Wang et al. 2011; Mucciarelli et al. 2011). Circumstantial evidence, such as the age difference among H II regions, and the number ratio of YSOs at different evolutionary stages, indicates that star formation activity propagated from Sh 2-255 and 257 into the molecular clouds behind the H II bubbles. Hence, this SFR is one of the most interesting sites to study star and cluster formation processes.

The present work on the embedded young open clusters in the H II regions Sh 2-255 – 257 (hereinafter IC 2162) is the sixth paper of the Sejong Open cluster Survey (SOS) project. Sung et al. (2013a, hereinafter Paper 0) presented the overview of the SOS project. Comprehensive studies of several open clusters IC 1848, NGC 1624, NGC 1893, NGC 1931, and NGC 2353 were carried out as part of the project (Lim et al. 2011, 2014a,b, 2015). In this work, we revise the fundamental

parameters of the SFR in a homogeneous manner, and constrain the IMF to study star formation processes. The observational data we used are described in Section 2. In Section 3, we present several fundamental parameters of IC 2162 obtained from photometric diagrams and discuss the reddening law toward the SFR. The IMF is derived in Section 4, and the spectral energy distribution (SED) of pre-main sequence (PMS) members is investigated in Section 5. Finally, the comprehensive results from this study are summarized in Section 6.

2. OBSERVATIONAL DATA

2.1. Optical Imaging Data

The observations of IC 2162 were made on February 5, 2013 using the Kuiper 61" telescope (f/13.5) of Steward Observatory on Mt. Bigelow in Arizona, USA. Images

Table 1
Atmospheric Extinction Coefficients and Photometric Zero Points

Filter	k_1	k_2	ζ (mag)
<i>I</i>	0.045 ± 0.008	—	22.170 ± 0.009
<i>V</i>	0.120 ± 0.008	—	23.560 ± 0.007
<i>B</i>	0.232 ± 0.008	0.023 ± 0.002	23.548 ± 0.006
<i>U</i>	0.444 ± 0.018	0.031 ± 0.005	22.069 ± 0.008
H α	0.085	—	19.565

were taken with the Mont4K CCD camera and 5 filters (Bessell *U*, Harris *BV*, Arizona *I*, and H α) in a 3×3 binning mode. The field of view (FOV) is about $9.7' \times 9.7'$. The target images comprise 12 frames that were taken in two sets of exposure times for each band (5 and 180 s $\times 2$ in *I*, 5 and 180 s $\times 2$ in *V*, 7 and 300 s in *B*, 30 and 600 s in *U*, and 30 and 600 s in H α). We also observed several equatorial standard stars (Menzies et al. 1991) at air masses of 1.2 – 2 on the same night in order to transform the instrumental magnitudes to the standard magnitudes and colors. Additional standard stars with extremely blue and red colors in the Landolt standard star field Rubin 149 (Landolt 1992) were observed to determine the secondary extinction coefficients.

All the pre-processing to remove the instrumental signals was carried out using the IRAF¹/CCDRED packages. Simple aperture photometry was performed for the standard stars with an aperture size of $14.''0$ (16.3 pixels). The primary and secondary atmospheric extinction coefficients were determined from the photometric data of the standard stars using a weighted least-square method. We present the coefficients and photometric zero points in Table 1. The point spread function (PSF) photometry of stars in the target images was performed with a small fitting radius of one full width at half-maximum ($\leq 1.''0$) using IRAF/DAOPHOT. The aperture photometry of bright, isolated stars with a photometric error smaller than 0.01 mag in individual target images was obtained to correct for the aperture difference. The instrumental magnitudes of stars in the target images were transformed to the standard magnitudes and colors using the transformation relations as described in the appendix of Lim et al. (2015). The finder chart for the stars brighter than $V = 18$ mag is shown in the upper left-hand panel of Figure 1.

A total of 811 stars were detected from the optical photometry. The completeness of our photometry was assessed from the luminosity function of all observed stars. The luminosity function exhibits a single linear slope in the magnitude range of $V = 13 - 19$ mag. If we assume that the linear slope is applicable down to the faint stars, the turn-over magnitude gives the completeness limit. As a result, our photometry seems

to be about 90% complete down to $V = 19.3$ mag.

2.2. Optical Spectroscopic Data

The optical spectra of two main ionizing sources (ALS 19 and HD 253327) were obtained on March 10, 2015 with the fiber-fed echelle spectrograph BOES (Bohyunsan Observatory Echelle Spectrograph – Kim et al. 2007) attached to the 1.8 m telescope at Bohyunsan Optical Astronomy Observatory in Korea. A single frame for each target was taken with a $300 \mu\text{m}$ fiber ($R = 30,000$), and the exposure time was 3600 seconds. The 3×3 binning mode allowed us to improve the signal-to-noise ratio of the spectra. For the wavelength calibration, the spectra of a ThAr lamp were also acquired on the same night.

Pre-processing and extraction of those spectra were made with the IRAF/ECHELLE package. A sigma clipping method was used to minimize the influence of cosmic rays on the individual frames in a given order. We normalized the spectra using the best solution found from a cubic spline interpolation, and finally smoothed them by a box size of 33 pixels, corresponding to $\sim 2.1\text{\AA}$. The spectra of ALS 19 and HD 253327 are shown in Figure 2. For comparison, the spectra of standard stars [AE Aur (O9.5V), HD 36960 (B0.5V), HD 42401 (B2V), and η Aur (B3V) – Walborn 1971; Sota et al. 2011] observed with the same instrument on October 29, 2014 are also plotted in the same figure.

2.3. Archival Infrared Data

We transformed the CCD coordinates ($x_{\text{CCD}}, y_{\text{CCD}}$) of the optical photometric data into celestial coordinates ($\Delta\alpha, \Delta\delta$) using the Two Micron All Sky Survey catalogue (2MASS; Skrutskie et al. 2006). Optical counterparts of near-IR sources in the 2MASS catalogue were searched for, with a matching radius of $1''$. A total of 361 optical counterparts were found.

Chavarría et al. (2008) has made an extensive IR imaging survey across the entire molecular complex incubating the H II regions Sh 2-254 – 258. This survey covers an area of $25' \times 20'$. Their catalogue includes the near-IR *JHK_S* and *Spitzer* InfraRed Array Camera (IRAC) 4-band photometry of 26,821 sources. The near-IR photometry in the IR source catalogue is reasonably tied to the 2MASS photometric system within 0.03 mag. Only stars within the FOV of the optical imaging observations were used in our analysis. A total of 3,426 sources were found within our FOV ($\sim 9.7' \times 9.7'$), of which 792 sources have optical counterparts within a matching radius of $1''$. We present the finder chart of these stars in the lower left panel of Figure 1.

A post-BCD (basic calibrated and mosaiced) image of the *Spitzer* Multiband Imaging Photometer (MIPS) $24 \mu\text{m}$ image was taken from the data archive of the *Spitzer* Science Center (ObsID: 40005, PI G. Fazio). We carried out PSF photometry for stars in the image using the IRAF/DAOPHOT with a fit radius of 2.4 pixels and a sky annulus of $20'' - 32''$ (see Sung et al. 2009). The photometric zero point of 11.76 mag was

¹Image Reduction and Analysis Facility is developed and distributed by the National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy under cooperative agreement with the National Science Foundation.

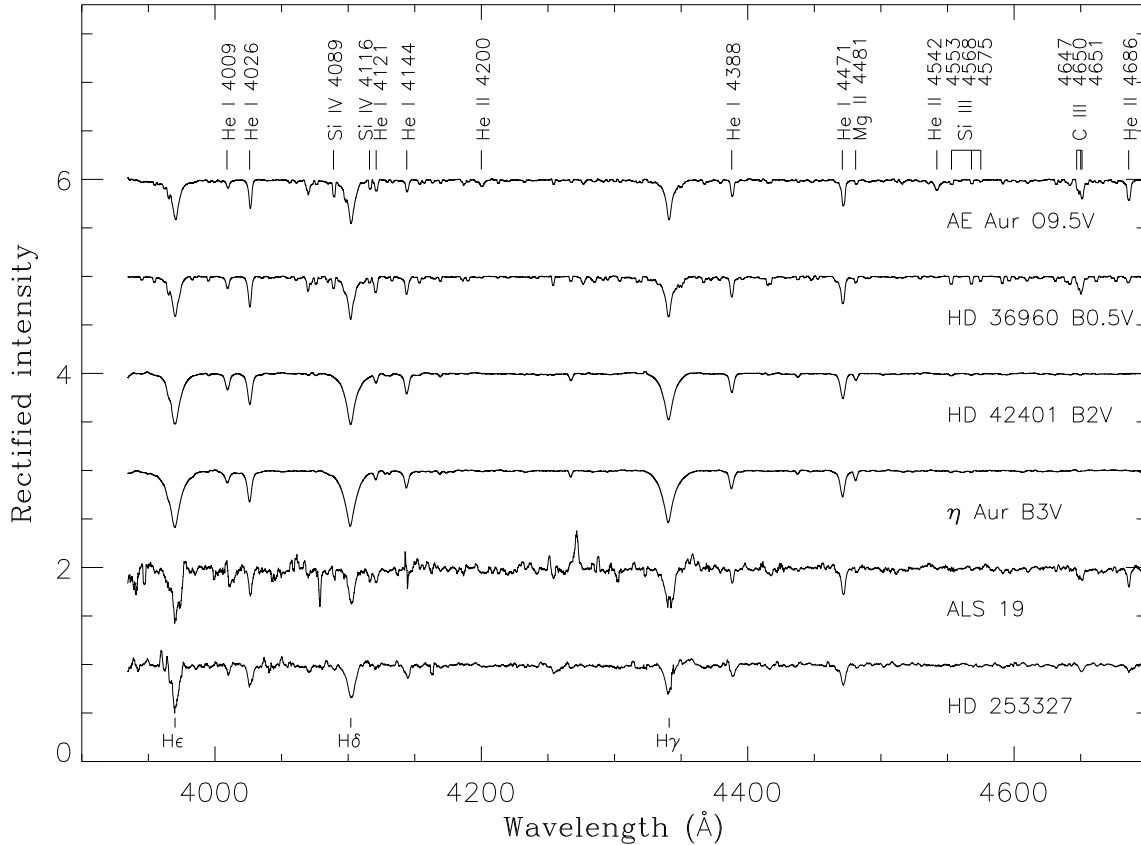


Figure 2. Optical spectra of four standard stars and two ionizing sources (from top to bottom) in the observed field of view. The object name is indicated below each spectrum. Main spectral lines used in the spectral classification are identified at the top of the figure.

calculated using the pixel scale and the flux of a zeroth magnitude star, as described in the MIPS Handbook. Within our FOV, a total of 207 sources were detected, of which 13 and 30 have counterparts in the optical and IR catalogues, respectively.

3. FUNDAMENTAL PARAMETERS

As seen in Figure 1, the finder charts and color composite images in the optical and near-IR passbands exhibit completely different stellar distributions. This implies that the majority of young stars are embedded behind the H II regions. Because only about a quarter of the stars were detected in the optical passbands, the canonical analysis based on optical photometric diagrams is limited. For this reason, the IR photometry of Chavarría et al. (2008), which is less sensitive to the effect of extinction, is a powerful tool to probe embedded populations. However, several visible stars are still very helpful to determine fundamental parameters such as reddening and distance. In this section, we describe the identification of the main ionizing sources, the membership selection criteria, and the determination of reddening, distance, and age based on the optical spectra and photometric diagrams as presented in Figures 2 – 4.

3.1. Spectral Types of Two Ionizing Sources

The influence of high-mass stars on the surrounding environment involves destructive and constructive processes. The strong stellar wind and radiation pressure of high-mass stars can disperse their natal clouds, and thereby terminate star formation. On the other hand, H II bubbles created by these stars can accumulate and compress material as they expand into the molecular clouds. The condensed material can then form a new generation of stars (Elmegreen & Lada 1977). High-mass stars can also drive the formation of the second generation of stars radiatively in pre-existing clumps (Lefloch & Lazareff 1994). Therefore, the identification of ionizing sources is essential for studying such feedback of high-mass stars.

The brightest stars ALS 19 and HD 253327 (ALS 18) are known to be the main ionizing sources of IC 2162. In order to classify the spectral type of these stars, we adopted the O and B-type star classification scheme of Walborn & Fitzpatrick (1990) and Sota et al. (2011). The spectra of the stars in Figure 2 contain several emission-like features that are the residuals of cosmic rays. In the case of ALS 19, He II λ 4200 and λ 4542 are invisible in the spectrum, while the He II λ 4686 absorption is clearly seen. The spectral type of this star is

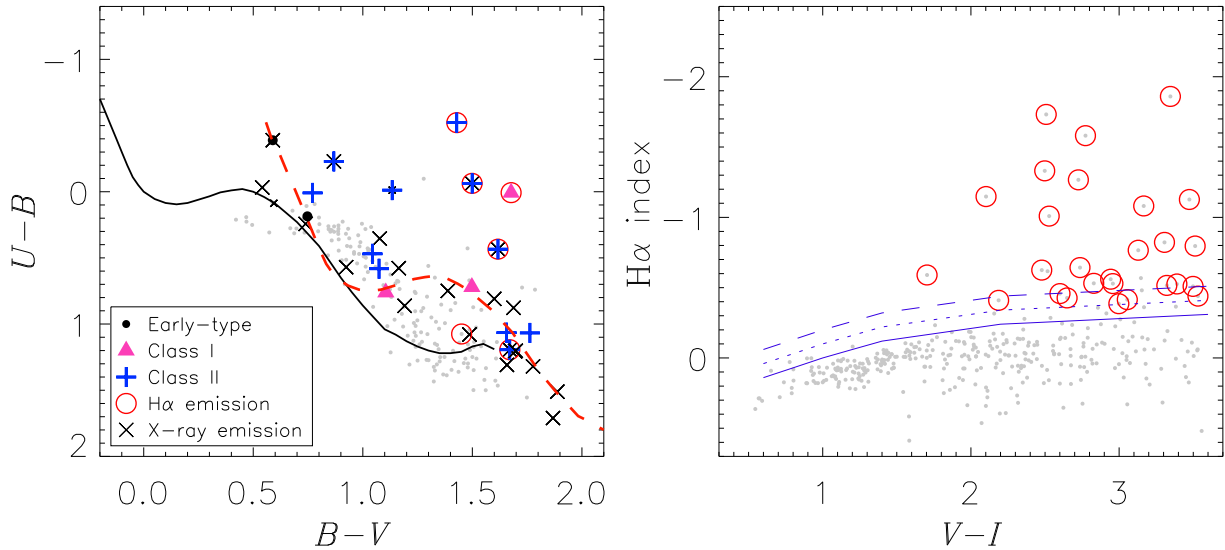


Figure 3. Color-color diagrams of stars in IC 2162. Small dots (grey) represent all the stars. Other symbols denote early-type members (black bold dots), Class I (magenta triangles), Class II (blue pluses), X-ray emission stars (large crosses), X-ray emission candidates (small crosses), and $H\alpha$ emission stars or candidates (red open circles), respectively. The solid line (black) in the left-hand panel exhibits the intrinsic color-color relation of Sung et al. (2013a), and its reddened relation $[E(B - V) = 0.88 \text{ mag}]$ is shown by a dashed line (red). The solid line in the right-hand panel represents the empirical photospheric level of unreddened main sequence stars, while the dashed and dotted lines are the lower limit of $H\alpha$ emission stars and $H\alpha$ emission candidates, respectively.

likely to be B0V; however, it is also possible that ALS 19 is a late-O-type star (O9.5V or O9.7V), given the strength of He II $\lambda 4686$ and the line ratio between Si IV $\lambda 4116$ and He I $\lambda 4121$. Since the star was classified as Class II (Chavarría et al. 2008), the spectrum of this young star shows a mixture of late-O and early-B-type star characteristics.

He II $\lambda 4200$ and $\lambda 4542$ are also absent in the spectrum of HD 253327. Si III $\lambda 4552$ is invisible, while a weak He II $\lambda 4686$ absorption is authentically seen. Hence, the spectral type of HD 253327 is likely to be B0V. The spectrum of this star is, indeed, similar to that of ALS 19. Our spectral classification is in a good agreement with previous studies (Georgelin et al. 1973; Chavarría et al. 2008).

3.2. Membership Selection

Early-type main sequence (MS) stars (putatively B-type stars) can be selected from the optical photometric diagrams (Figure 3 and 4) as they are bright in V and very blue in $U - B$. In addition, the reddening and distance of individual stars can be reliably determined because the intrinsic colors and absolute magnitudes of such stars have been well calibrated in the optical passbands. Probable early-type members are firstly selected from magnitude and color cuts as $V \leq 15 \text{ mag}$, $0.5 \leq B - V \leq 0.9$, $-0.6 \leq U - B \leq 0.5$, and $Q' \leq -0.3$, where $Q' \equiv (U - B) - 0.72(B - V) - 0.025E(B - V)^2$ (Papper 0). We then removed several foreground late-type stars (probably F- or G-type) restricting the reddening range to $E(B - V) > 0.8 \text{ mag}$ and color excess ratios. In addition, a few stars identified as YSOs by Chavarría et

al. (2008) were also excluded from the MS member list. Only two stars were finally selected as the early-type MS members of IC 2162.

We utilized $H\alpha$ photometry as a criterion to identify PMS stars in the SFR. A series of studies demonstrated that $H\alpha$ photometry can effectively detect a number of low-mass PMS stars at the T Tauri stage in young open clusters (Sung et al. 1997; Sung et al. 1998, 2000; Park et al. 2000; Park & Sung 2002; Sung et al. 2004; Sung & Bessell 2004; Sung et al. 2008; Sung et al. 2013b; Lim et al. 2014a,b, 2015). In order to detect objects with an $H\alpha$ emission line, the $H\alpha$ index $[\equiv H\alpha - (V + I)/2]$ is used as the detection criterion (Sung et al. 2000). As shown in the right-hand panels of Figure 3, stars with an $H\alpha$ index smaller than the empirical photospheric level (solid line) of normal MS stars by -0.2 (dashed line), or -0.1 mag (dotted line), were selected as $H\alpha$ emission stars and candidates, respectively. We found 21 $H\alpha$ emission stars and six candidates. However, the $H\alpha$ emission star ID 659 ($V = 18.84$, $V - I = 1.70$, $B - V = 1.45$, and $U - B = 1.07$) is likely an active late-type star in the field because its colors are similar to those of other field stars. A total of 26 $H\alpha$ emission stars and candidates were selected as PMS members of IC 2162.

The excess emission at IR wavelengths, particularly the mid-IR, is a useful membership selection criterion because a large fraction of PMS stars in young open clusters ($\leq 3 \text{ Myr}$) have been found to have warm circumstellar disks or envelopes (Lada et al. 2000; Sung et al. 2009; Bell et al. 2013). Chavarría et al. (2008) identified 252 YSOs (87 Class I and 165 Class II) in the H II

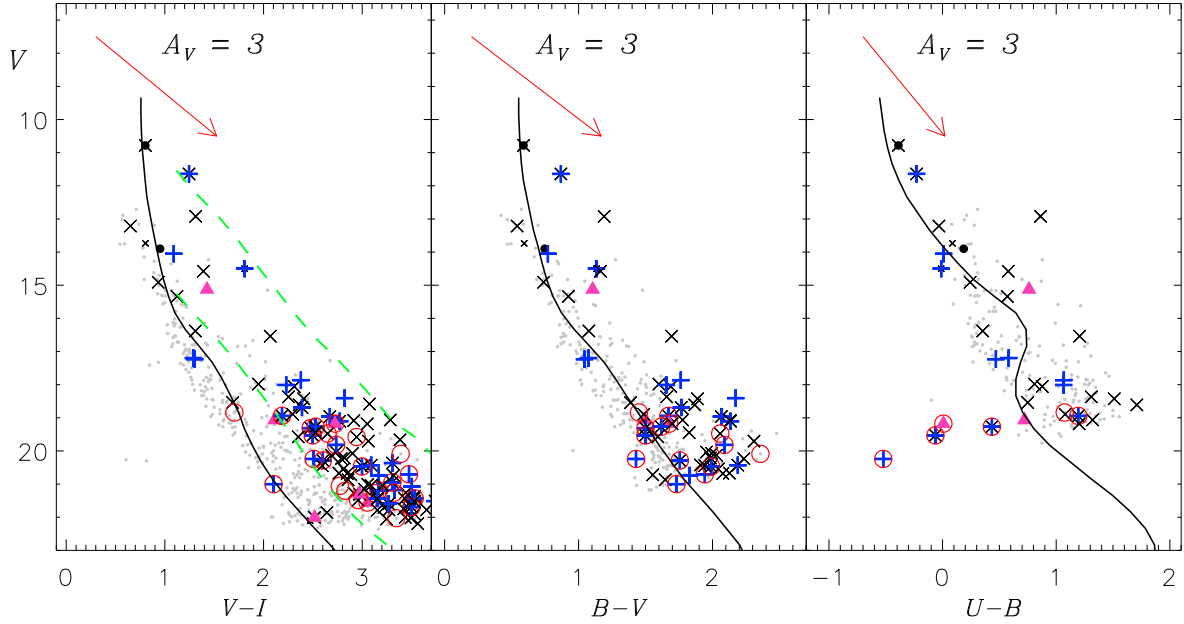


Figure 4. Color-magnitude diagrams in the optical passbands. Left-hand panel: $V - I$ versus V diagram. The location of pre-main sequence stars is confined between the green dashed lines. Middle panel: $B - V$ versus V diagram. Right-hand panel: $U - B$ versus V diagram. The solid lines represent the reddened zero-age main sequence relation of Sung et al. (2013a). The arrow denotes the reddening vector corresponding to $A_V = 3$ mag. The other symbols are as in Figure 3.

regions Sh 2-254 – 258 using *Spitzer*/IRAC images. We used their YSO list and found optical counterparts for 64 YSOs (11 Class I and 53 Class II) within our FOV. However, only 41 IR sources (6 Class I and 35 Class II) were detected in the V band.

PMS stars are also known as X-ray emitting objects (Flaccomio et al. 1999; Sung et al. 2004; Caramazza et al. 2012; Hur et al. 2012; Sung et al. 2013b; Lim et al. 2014b; Hur et al. 2015). Mucciarelli et al. (2011) made deep X-ray observations of these SFRs down to $0.5 M_{\odot}$ with the *Chandra* X-ray observatory. The observations covered a $17' \times 17'$ field, and detected a total of 364 X-ray sources. We used their X-ray source list to select X-ray emitting PMS members. The optical counterparts of the X-ray sources and candidates were searched for with matching radii of $1.''0$ and $1.''5$, respectively. We confirmed that 86 X-ray sources and three candidates were detected in the V band. Among them, 73 X-ray sources and one candidate are associated with PMS stars, and the early-type MS star HD 253327 also turns out to be an X-ray source. The other 14 sources and candidates seem to be X-ray active field stars from their colors.

A total of 102 members were identified in the optical passbands. In addition, members of IC 2162 were independently selected from the IR source catalogue of Chavarría et al. (2008) in the same way. We found 216 members observed in the J and H bands (2 early-type MS stars, 20 Class I, 61 Class II, 158 X-ray sources, 7 X-ray candidates, 19 $H\alpha$ emission stars, and 6 $H\alpha$ candidates). The membership list from the IR source catalogue (216 stars) was compared with that from the

optical data (102 stars). As a result, 100 stars were found in both lists; however, the other two members were observed only in the J or H bands. These membership lists were merged into a membership catalogue. The total number of members identified in this work is 218.

Mucciarelli et al. (2011) estimated about 58 field interlopers scaling the number of contaminants in the FOV of the *Chandra* Carina Complex Project (Broos et al. 2011) to that in the FOV of $17' \times 17'$. If we assume that the surface density of field interlopers is uniform across these SFRs, the number of field interlopers in the FOV of $\sim 9.7' \times 9.7'$ is about 18. According to the X-ray source classification toward the Carina region (Getman et al. 2011; Broos et al. 2011), extragalactic sources are so faint that the contribution of these sources should be negligible in this study. Probable interlopers in our FOV may therefore be foreground and background stars. However, since the stellar density in the direction of IC 2162 is much lower than that of the Carina region located toward the tangential direction of the Sagittarius spiral arm, the expected number of field interlopers with X-ray emission in our FOV may be much smaller than 18. Since we identified 14 X-ray sources and candidates as field interlopers, the number of field interlopers in our member catalogue may be less than four.

3.3. Interstellar Extinction and the Reddening Law

Light from stars is obscured by interstellar material distributed along the line of sight. Therefore, the effect of extinction on the measured flux or magnitude

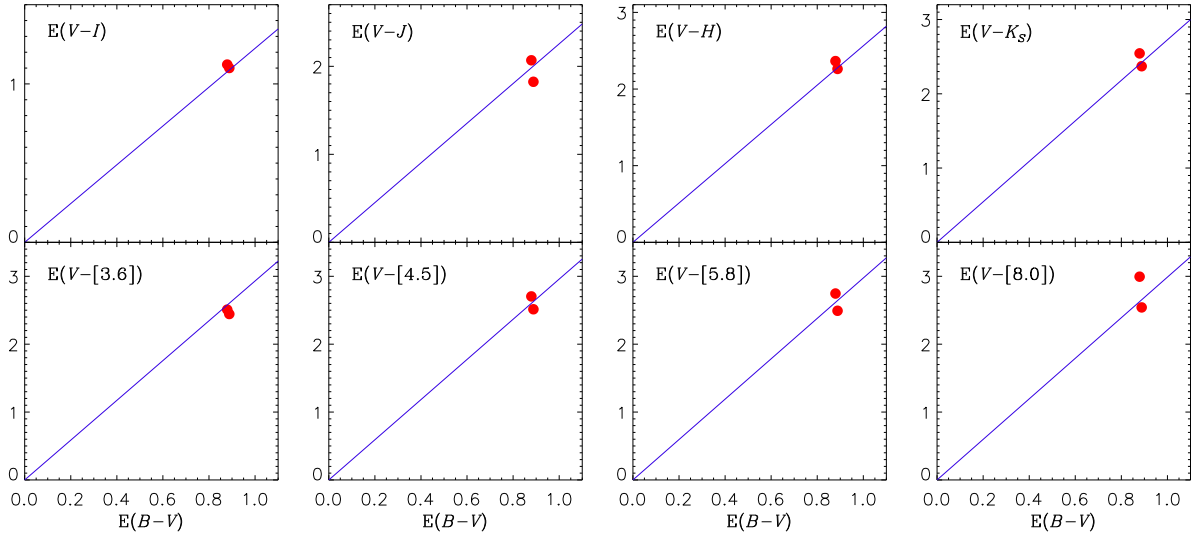


Figure 5. Color excess ratios obtained from the early-type main sequence members. The solid line corresponds to $R_V = 3.1$. The color excess ratios from optical to mid-infrared data suggest that the reddening law toward IC 2162 is normal.

should be properly corrected. The reddening of young open clusters can be estimated by comparing the observed colors of early-type stars with their intrinsic colors in the $(U - B, B - V)$ two color diagram along the reddening slope (Paper 0). The reddening determined from two early-type MS members is about $E(B - V) = 0.88$ mag. In addition, the spectral type of two early-type PMS members ALS 19 (B0V) and 2MASS J06123651+1756548 (B0.9V) is available from this work and Chavarría et al. (2008). The reddening of these stars obtained from the spectral type-color relation (Table 5 in Paper 0) is about $E(B - V) = 1.41$ and 1.17 mag, respectively. The result is consistent with previous studies, e.g. $E(B - V) = 0.88 - 1.16$ mag (Pismis & Hasse 1976), 0.64 – 1.47 mag (Moffat et al. 1979), and 0.82 – 1.20 mag (Hunter & Massey 1990). More severe differential reddening is expected across IC 2162 because a large number of stars are embedded in molecular clouds.

The ratio of total-to-selective extinction (R_V) is an essential diagnostic tool to investigate the extinction law toward SFRs or young open clusters. The general interstellar medium (ISM) in the solar neighbourhood is known to have, on average, $R_V = 3.0 - 3.1$ (Fitzpatrick & Massa 2007; Lim et al. 2011). On the other hand, R_V may be larger than the normal value in some dusty SFRs (Greve 2010). The extinction law depends on the size distribution of dust grains (Draine 2003). A large R_V implies that the size of dust grains is, on average, larger than that found in the general ISM.

We investigated various color excess ratios of early-type MS members to study the reddening law toward IC 2162. R_V can be determined from the color excess ratios between two different colors (Guetter & Vrba 1989; Sung et al. 2013b). The color excess $E(V - \lambda)$ (where $\lambda = I, J, H, K_S, [3.6], [4.5], [5.8],$ and $[8.0]$) can be computed from the intrinsic color relations of Paper 0 and from Sung et al. (in preparation). Figure 5 displays

the color excess ratios of the early-type MS members.

The color excess ratios at different wavelengths are reasonably matched with the slope corresponding to $R_V = 3.1$ (solid lines in the figure). This result is acceptable given the R_V variation with Galactic longitude (Whittet 1977; Sung & Bessell 2014). The normal reddening law implies that the dust evolution in the front side of the region had already progressed. However, this result may not represent the reddening law of the embedded cluster.

3.4. Distance

The distance to an object is fundamental in determining its physical quantities. We determined the distance of IC 2162 using the zero-age main sequence (ZAMS) fitting method. The ZAMS relations and reddening-independent indices introduced in Paper 0 are adopted in the present work. Our ZAMS fitting procedure is based on $UBVIJHK_S$ multicolor photometry, and therefore the distance can be determined consistently in the optical and near-IR passbands.

Figure 6 shows $Q_{V\lambda}-Q'$ diagrams of the bright members ($J < 12.5$). Since the luminosity of stars can be affected by stellar evolution and binary effects, the ZAMS relations should be fitted to the lower ridge line of the MS in the $Q_{V\lambda}-Q'$ planes as shown in the figure. We adjusted the ZAMS relations above and below the faint members at a given Q' index and adopted a distance modulus of 11.6 mag. The lower ridge line could be confined between the ZAMS relations shifted from the adopted value by ± 0.3 mag, and therefore the upper and lower envelopes are the uncertainty in the distance. Our result (2.1 ± 0.3 kpc) is in reasonable agreement with previous studies within the uncertainties, e.g., 1.9 kpc (Chavarría-K et al. 1987; Armandroff & Herbst 1981), 2.4 kpc (Hunter & Massey 1990), and 2.5 kpc (Pismis & Hasse 1976; Moffat et al. 1979; Rus-

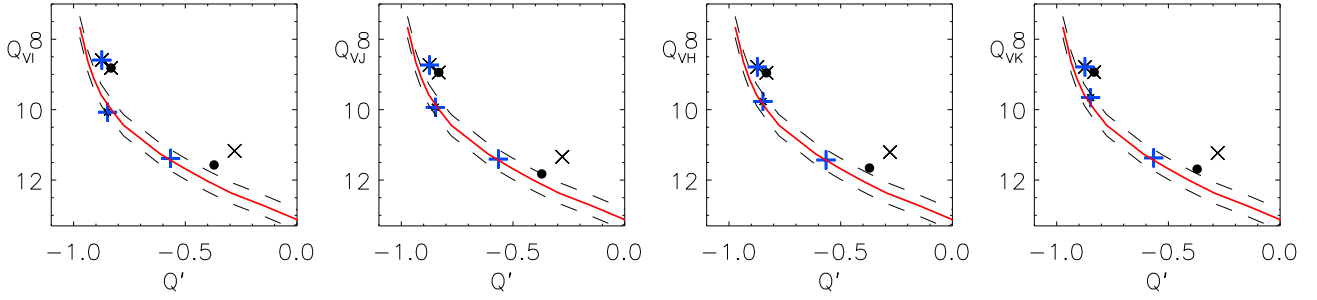


Figure 6. Zero-age main sequence (ZAMS) fitting to the bright members in the $Q_{V\lambda}$ - Q' diagrams. The ZAMS relations of Sung et al. (2013a) are fitted to the lower ridge line of the members. The solid line (red) represents the adopted distance modulus of 11.6 mag, equivalent to 2.1 kpc. The dashed lines indicate a 0.3 mag error in the ZAMS fitting. The other symbols are as in Figure 3.

seil et al. 2007).

3.5. Age

The Hertzsprung-Russell diagram (HRD) provides a comprehensive view of the evolutionary status of stellar systems. The reddening of individual members was corrected using the weighted mean reddening of four early-type MS and PMS members, where the weight is exponentially decreased as the distance between the early-type stars and a given member increases. We converted the reddening-corrected color-magnitude diagrams (CMDs) in the optical passbands to the HRD using several relations (Bessell 1995; Bessell et al. 1998; Paper 0). The effective temperature T_{eff} of a star was basically estimated from the color- T_{eff} relations, and the spectral type- T_{eff} relation was also used for the three early-type members ALS 19, HD 253327, and 2MASS J06123651+1756548. The weighted mean value of the temperatures was adopted as the T_{eff} of four early-type MS and PMS members. Only the $V-I$ versus T_{eff} relation (Bessell 1995; Bessell et al. 1998) was used for the temperature scale of the PMS members to avoid the effect of excess emission due to accretion activities. Bolometric correction values were estimated from the T_{eff} of the individual members using Table 5 of Paper 0.

We present the HRD of IC 2162 in Figure 7. The mass of the main ionizing sources in Sh 2-255 and 257 is larger than $10M_{\odot}$. It is difficult to estimate the age from the MS turn-off because the stars seem to be still at the MS or PMS stage. On the other hand, the majority of PMS members are evolving along Hayashi tracks, while only several members are approaching the ZAMS along Henyey tracks. There are five PMS members near or below the ZAMS. These stars may have edge-on disks (Sung et al. 1997; Sung & Bessell 2010). The upper mass range of the PMS members appears to be as large as $15M_{\odot}$, and the PMS lifetime of high-mass stars is very short. These facts imply that IC 2162 is very young. Using the evolutionary models for PMS stars (Siess et al. 2000, $Z = Z_{\odot}$ with convective overshooting), we estimated the ages of the PMS members and found a median age of 1.3 Myr, with an age spread of 3.3 Myr. The age distribution is very similar to that

obtained from evolutionary models for half solar metallicity ($Z = 0.01$). The age of IC 2162 is probably about 1 Myr. However, as the majority of PMS members are still deeply embedded in the molecular clouds, the age of these stars may be much younger.

4. TOTAL MASS AND THE INITIAL MASS FUNCTION

The masses of optically visible members are estimated by comparing their T_{eff} and M_{bol} with those of the evolutionary tracks in the HRD. The evolutionary tracks of Ekström et al. (2012) were used for the early-type MS and PMS members, while those of Siess et al. (2000) were adopted for the low-mass PMS members. The solar metallicity was assumed for both models. These theoretical evolutionary masses can be used as a good mass scale reference for those inferred from the near-IR data.

The masses of the members selected from the IR source catalogue were inferred from the $(J, J-H)$ diagram, because the J magnitude is less affected by excess emission from a disk or envelope compared to the K magnitude (Kim et al. 2007). Figure 8 shows the near-IR CMD of IC 2162. The PMS members have a wide color range, from $J-H = 0.5$ to 2.9. A few factors such as high differential reddening, excess emission from disks and envelopes in the H band, age spread, and photometric errors for faint stars may be responsible for such a large color spread. Only stars brighter than $J = 16.5$ mag were used, to minimize the inclusion of stars with large photometric errors. In order to treat differential reddening, a model grid was constructed from several isochrones reddened by $E(J-H) = 0.25, 0.64, 0.96, 1.27$, and 1.91 mag [equivalently $E(B-V) = 0.8, 2.0, 3.0, 4.0, 6.0$ mag], respectively.

We attempted to estimate the masses of the PMS members, especially those in the embedded sub-clusters, using the model grid and compared the masses with those obtained from optical data. We found the difference between the mass inferred from the near-IR CMD and that from the HRD to be a strong function of the age of the adopted isochrones, due to the luminosity evolution of PMS stars. For a given PMS star, the mass estimated from the reddened isochrone is larger

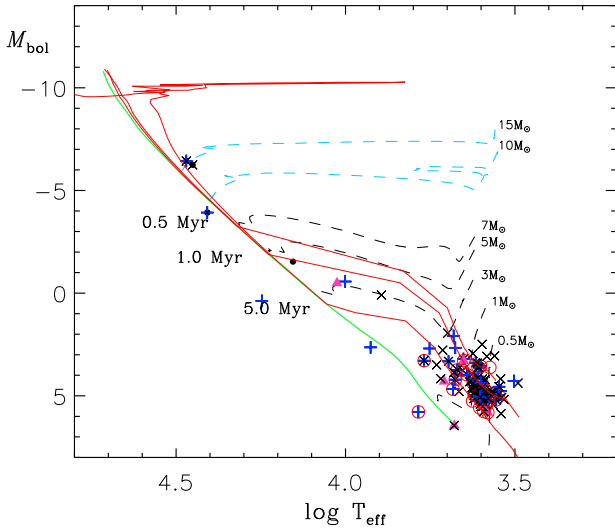


Figure 7. Hertzsprung-Russell diagram of IC 2162. A few isochrones (red solid lines) for the age of 0.5, 1, and 5 Myr are superimposed on the diagram with the evolutionary tracks of several initial masses (Siess et al. 2000; Ekström et al. 2012). The solar metallicity is assumed. The other symbols are as in Figure 3.

for older isochrones. We found that the difference in masses from the two different methods showed a minimum for a grid of 0.1 Myr isochrones.

On the other hand, the mass of PMS stars ($J > 11.5$ mag) bluer than $J - H = 1.59$ was obtained from the grid of isochrones with different ages (0.1, 0.5, 1, 2, 5, and 10 Myr) assuming the minimum reddening of $E(J - H) = 0.25$ mag, equivalent to $E(B - V) = 0.8$ mag. We compared the masses of all the PMS members with those from optical data, and confirmed that there was a systematic difference of -0.3 to $0.4 M_{\odot}$ between them over the mass range of 0.2 to $1.6 M_{\odot}$. The systematic difference could be approximated by a combination of two straight lines. The mass from the near-IR data was converted into the mass scale obtained from optical data using those relations. Finally, the masses of four early-type members and two members observed only in either J or H were obtained from analysis of optical data.

In order to examine the metallicity effect on the mass estimation, we also inferred the masses of the PMS stars using PMS star evolution models for half solar metallicity. The mass difference from the two models ($Z = Z_{\odot}$ and $Z = 1/2 Z_{\odot}$) is about $0.13 M_{\odot}$. It was confirmed that this difference yields a negligible effect on the resultant IMF in the mass range of $1 - 100 M_{\odot}$.

We obtained the cluster mass of $169 M_{\odot}$ from the sum of the masses of all the identified members. This is definitely a lower limit, because a number of sub-solar mass stars below the completeness limit were not considered. IC 2162 seems to be the smallest SFR among the young open clusters studied by our research group, e.g., $> 510 M_{\odot}$ for NGC 1624 and NGC 1931 (Lim et al. 2015), $> 576 M_{\odot}$ for NGC 2264, $> 1,300 M_{\odot}$ for NGC

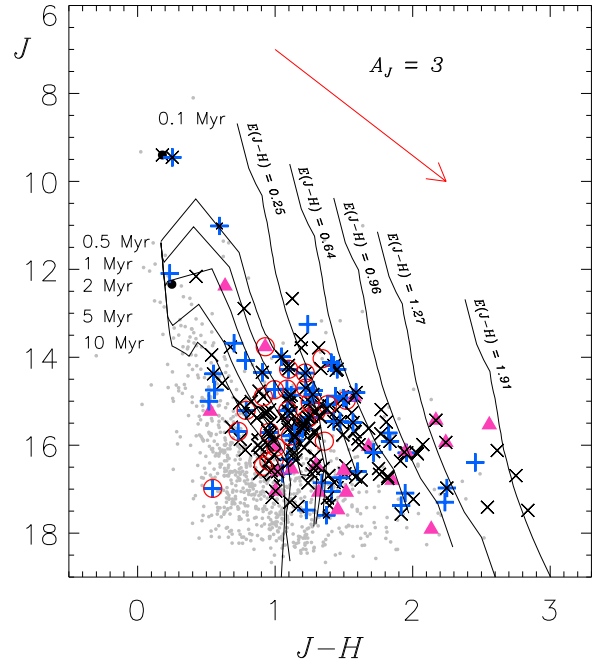


Figure 8. Near-infrared color-magnitude diagram. The solid lines represent pre-main sequence star isochrones with different ages (0.1, 0.5, 1, 2, 5, and 10 Myr) from Siess et al. (2000), where the model parameters are the same as in Figure 7. The isochrones are reddened by $E(J - H) = 0.25, 0.64, 0.96, 1.27$, and 1.91 mag, respectively, after correction for the distance modulus of 11.6 mag. The arrow denotes the reddening vector corresponding to $A_J = 3$ mag. The other symbols are as in Figure 3.

1893 (Lim et al. 2014b), $> 2,600 M_{\odot}$ for NGC 6231 (Sung et al. 2013b), $> 7,400 M_{\odot}$ for Westerlund 2 (Hur et al. 2015), and $> 50,000 M_{\odot}$ for Westerlund 1 (Lim et al. 2013).

The IMF is, in general, expressed by the following relation (Salpeter 1955):

$$\xi(\log m) \equiv \frac{N}{\Delta \log m \cdot S} \quad (1)$$

where N , $\Delta \log m$, and S represent the number of stars in a given mass bin, the size of a logarithmic mass bin, and the area of the observed region, respectively. The size of the mass bin was set to be 0.4 to avoid uncertainties from small sample statistics. We assumed the upper limit of stellar mass to be $100 M_{\odot}$, and adopted a larger bin size of 1 for the highest mass bin ($10 < M/M_{\odot} \leq 100$) because the number of high-mass stars was insufficient to sample across various mass bins. We counted the number of stars in each mass bin, and then divided the total by the size of the mass bin and the area of IC 2162 (the area of our FOV). In order to prevent the binning effect, the IMF was re-derived for the same stars by shifting the mass bin by 0.2 .

Figure 9 shows the IMF of IC 2162. We also plotted the IMF of the young open cluster NGC 2264 (Sung &

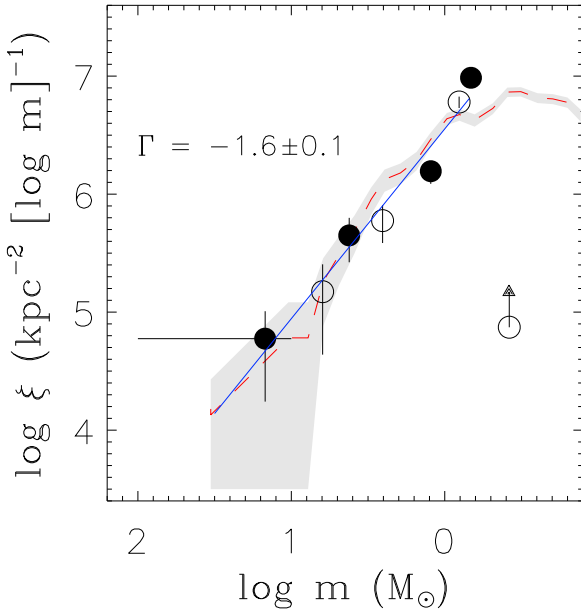


Figure 9. The initial mass function (IMF) of IC 2162. The IMF (open and filled circles) was derived using different binning of the same stars to avoid the binning effect. The dashed line and shaded area represent the IMF of NGC 2264 and its uncertainty (Sung & Bessell 2010), respectively. The arrow indicates the IMF below the completeness limit.

Bessell 2010) for comparison. The shapes of the IMFs are similar to each other in the mass range from $1M_{\odot}$ to the upper limit of the stellar mass. The IMF is generally quantified by its slope (Γ) to compare it with that of other SFRs. We computed the slope of the IMF using a linear least square fitting method. The slope of the IMF is about $\Gamma = -1.6 \pm 0.1$. This result is consistent with that of NGC 2264, although the slope is slightly steeper than that of the Salpeter/Kroupa IMF (Salpeter 1955; Kroupa 2001). It implies that the underlying star formation processes in IC 2162 are optimized to produce low-mass stars, rather than high-mass stars.

5. SPECTRAL ENERGY DISTRIBUTION ANALYSIS

The SED of the members was also analyzed using the SED fitting tool (called the SED fitter) of Robitaille et al. (2007). In order to increase the number of samples, we included 43 stars with X-ray and mid-IR excess emission in the membership catalogue. A total of 261 members were used in this analysis. All the selected members were observed in more than 3 passbands, and their photometric errors were better than 0.15 mag in the optical to near-IR passbands and 0.20 mag in the mid-IR passbands.

In order to minimize the degrees of freedom, we limited the distance to 2.1 ± 0.3 kpc based on the result of the ZAMS fitting above. The total extinction A_V was set to be $2.48 - 100$ mag. The SED fitter suggests various models with χ^2 values for a given SED. To select the most appropriate model among them, we followed the guidelines introduced by Sung & Bessell

(2010). The guidelines recommended the model that gives the smallest stellar mass out of the 10 suggested models if $\chi^2/\chi^2_{\min} \leq 2.0$. If χ^2_{\min} is less than 1.0, the mass-minimum model with $\chi^2 < 2.0$ is adopted.

The model adopted from the SED fitter provides various physical quantities of the disks and envelopes, as well as stellar parameters (mass and age). The disk parameters such as mass, outer radius, and accretion rate evolve with time by a few orders of magnitudes over 10 Myr. A strong correlation between the disk accretion rate and the disk mass was also found [$\log(dM_{\text{disk}}/dt) = -4.89(\pm 0.12) + 1.15(\pm 0.03) \log(M_{\text{disk}}/M_{\star})$]. It appears that the envelope mass decreases dramatically after 1 Myr. While the angle of the cavity rises with time, its density, in contrast, declines as a function of time. The circumstellar extinction is proportional to the envelope mass and shows a sharp increase for stars with large envelope mass ($\log M_{\text{env}}/M_{\star} > -3$). Stars with a massive envelope accrete much more material than low-mass counterparts. These correlations between the results obtained from the SED fitter are very similar to those found by Sung & Bessell (2010, see their Figures 3 and 4).

We also compared the stellar mass and age inferred from the SED fitter with those from the analysis of the HRD. For less reddened members, the masses obtained from the different methods are reasonably consistent, while the SED fitter underestimated the ages of the PMS members. On the other hand, the SED fitter tends to overestimate the masses and ages of highly reddened stars. This discrepancy has also been reported by Sung & Bessell (2010, see their Figure 2).

6. SUMMARY

IC 2162 is an active SFR in which very young subclusters are embedded. We present a multiwavelength study of the SFR as part of the SOS project. This work provided homogeneous optical photometric data, as well as a comprehensive result for the young stellar population in IC 2162.

The main ionizing sources in Sh 2-255 and 257 are two B0 stars (ALS 19 and HD 253327). A total of 218 members were identified from the various photometric diagrams, the X-ray source list (Mucciarelli et al. 2011), and the YSO list (Chavarría et al. 2008). It appears from the two early-type MS members that IC 2162 is reddened by at least $E(B - V) = 0.8$ mag. A large portion of the color spread in the near-IR CMD may be attributed to the presence of severe differential reddening, because a large number of stars are actually embedded in the molecular cloud behind the H II bubbles. The reddening law toward IC 2162 was investigated with various color excess ratios and the ratio of the total-to-selective extinction was found to be consistent with the normal value ($R_V = 3.1$). It implies that the dust evolution in the front side of the SFR has been completed. We also revisited the distance to IC 2162 with the ZAMS fitting method and determined a distance of 2.1 ± 0.3 kpc.

The ages of the members were estimated from the

HRD using several evolutionary models (Siess et al. 2000; Ekström et al. 2012) for the solar metallicity. The median age of the optically visible stars in IC 2162 was about 1.3 Myr, and an age spread of 3.3 Myr was found. We derived the IMF of IC 2162 by analyzing the HRD and the $(J, J - H)$ diagram. The shape of the IMF is similar to that of the nearby young open cluster NGC 2264 in the mass range $1M_{\odot}$ to the upper limit of the stellar mass. The slope of the IMF was $\Gamma = -1.6 \pm 0.1$, which is slightly steeper than that of the Salpeter/Kroupa IMF. This result indicates that it was low-mass star formation that mostly took place throughout IC 2162. The lower limit on the cluster mass ($> 169M_{\odot}$) was also constrained from the sum of the masses of all the identified members.

The SEDs of the members were also analyzed with the SED fitter (Robitaille et al. 2007). The results included the disk and envelope parameters of PMS stars, as well as stellar parameters such as age and mass. The properties of the disk and envelope were investigated as a function of stellar age or mass, respectively. A discrepancy between the results from the SED fitter and the analysis based on the HRD was also pointed out.

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