STAR-FORMING REGION Sh 2-233IR. I. DEEP NEAR-INFRARED OBSERVATIONS TOWARD THE EMBEDDED STELLAR CLUSTERS

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ABSTRACT

We observed the Sh 2-233IR (S233IR) region with better sensitivity in the near-infrared than in previous studies of this region. By applying statistical subtraction of the background stars, we identified member sources and derived the age and mass of three distinguishable sub-groups in this region: Sh 2-233IR NE, Sh 2-233IR SW, and the “distributed stars” over the whole cloud. Star formation may occur sequentially with a relatively small age difference (∼0.2–0.3 Myr) between subclusters. We found that the slopes for the initial mass function (Γ ~ −0.5) of two subclusters are flatter than those of Salpeter, which suggests that more massive stars were preferentially formed in those clusters compared to other Galactic star-forming regions. These subclusters may not result from the overall collapse of the whole cloud, but have formed by triggering before the previous star formation activities disturbed the natal molecular cloud. Additionally, high star formation efficiency (≳40%) of the subclusters may also suggest that stars form very efficiently in the center of the northeast.

Key words: infrared: stars – ISM: clouds – ISM: jets and outflows – stars: formation – stars: individual (Sh 2-233IR) – stars: pre-main sequence

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1. INTRODUCTION

Within 2 kpc, 70%–90% of stars have been found to form in clusters (Lada & Lada 2003). These newly formed stars, however, are embedded deeply in a dense molecular cloud and various difficulties in identifying sources and deriving physical parameters exist. Several statistical tools, such as the K-band luminosity function (KLF), the color–color or color–magnitude diagrams (CMDs), etc., have been successfully used to constrain the characteristics of deeply embedded stellar clusters (e.g., Lada & Lada 2003). The development of new sensitive equipment, such as the large mosaic IR array, enables us to observe embedded stellar clusters in greater detail than in previous efforts. The Sh 2-233IR region is a well-studied star-forming region in our Galaxy (e.g., Porras et al. 2000) and it provides an ideal laboratory for understanding properties of embedded clusters. Therefore, we revisit this region with higher sensitivity near-infrared data taken toward a wider region to better constrain the properties of the embedded stellar cluster compared with previous studies.

Toward the direction of the Galactic Anticenter, Sh 2-233IR (hereafter S233IR), as a part of the Sh 2-235 giant molecular cloud (GMC) complex (Reipurth & Yan 2008), is located at a distance of about 1.8 kpc (Porras et al. 2000), in association with four extended H II regions, Sh 2-231, 232, 233, and 235 (Heyer et al. 1996). Its position coincides with an IRAS source, IRAS 05358+3543 (α2000 = 05h39m10s, δ2000 = +35°45′19″). S233IR is classified as a massive star formation region (Sridharan et al. 2002), showing CO outflows (Snell et al. 1990) and various maser emissions associated with this region (Henning et al. 1992; Tofani et al. 1995; Beuther et al. 2002b; Menten 1991; Minier et al. 2005). The K'-band image of this region shows many bright stellar sources and also extended nebulous features associated with dust emission (Hodapp 1994). The two embedded young clusters, Sh 2-233IR SW (hereafter SW, located in the southwest direction from the center) and Sh 2-233IR NE (hereafter NE, in the northeast direction), are notable in this region, with remarkable H2 bow shocks associated with the NE cluster (Porras et al. 2000). In addition, numerous studies have been reported, especially for the NE cluster, including polarimetric observations (Jiang et al. 2001; Yao et al. 2000), molecular outflows (Beuther et al. 2007; Mao & Zeng 2004; Beuther et al. 2002a; Cesaroni et al. 1999; Larirov et al. 1999), and mid-infrared sources (Longmore et al. 2006).

In this paper, we revisit this S233IR region with a wider field of view, higher resolution, and better sensitivity data in near-infrared and radio wavelengths. Our goal is to understand star formation history in terms of age, star formation efficiency (SFE), and initial mass function (IMF). We summarize our observations in the radio and near-infrared in Section 2, and the observed results in Section 3. A discussion is given in Section 4, and the summary is given in Section 5. This is the first paper in the series of our work on S233IR and the associated region. Here we focus on properties of the embedded stellar clusters in the S233IR region. The H2 shock features and cloud kinematics have been studied by Ginsburg et al. (2009), and the extended nebulous K'-band features, young stellar object (YSO), and star formation in a larger area will be discussed in our second paper (C.-H. Yan et al. 2010, in preparation).

2. OBSERVATIONS AND DATA ANALYSIS

2.1. CFHT Observations

Near-infrared data were obtained using the Wide-field Infrared Camera (WIRCam; Puget et al. 2004) equipped
3. RESULTS

3.1. The S233IR Molecular Cloud

The CO $J = 3–2$ emission shows that the molecular cloud associated with S233IR is located on the ridge connecting two other star-forming regions in the northwest and southeast directions about 3.5 pc away from the S233IR cloud at a distance of 1.8 kpc (Figure 1(a)). The northwest region coincides with the H II region Sh 2-233 (IRAS 05351+3549; Casoli et al. 1986), which is excited by a B1.5II star (Hunter & Massey 1990). High-velocity CO $J = 1–0$ emission was found near this region (Jiang et al. 2000). Toward the southeast of S233IR, there is another star-forming core called G173.58+2.45 (IRAS 05361+3559; Shepherd & Churchwell 1996), where a small YSO cluster (Varricatt et al. 2005) and a molecular outflow exist in the east–west direction (Shepherd & Watson 2002).

The main goal of the CO $J = 3–2$ observations was to determine the boundary of the molecular cloud embedding the S233IR cluster. Figure 1(a) shows that the dense region of the S233IR cloud is centered on the density peak with a roundish shape. The two extended $K_S$ emission features near the center of the CO $J = 3–2$ emission correspond to the NE and SW clusters. At the 20 K km s$^{-1}$ level, there is a common envelope for three star formation regions. The average size of the 30 K km s$^{-1}$ contour level of the CO ($J = 3–2$) emission is about 1.5 pc and the half-power width (HPW) is $\sim$0.8 pc. We set the boundary of the S233IR cloud with this 30 K km s$^{-1}$ ($r \sim 2.5$) contour level and checked the member sources of the embedded cluster within this boundary.

The column density of molecular hydrogen can be calculated from the velocity integrated main-beam temperature ($T_{mb} = T_{mb}^\prime$):

$$N_H_2 = \frac{\frac{H_2}{CO}}{C_6} \frac{1}{\int \frac{Q(T)}{g_s} e^{E_{rel}/kT_{ex}} d\nu} \int T_{mb} d\nu,$$

(1)

where $A_{uv}$ is the Einstein coefficient, $Q(T)$ is the partition function, $\frac{H_2}{CO}$ is the abundance ratio of molecular hydrogen and CO, $g_s$ is the statistical weight of the states, and $J(T_{ex})$ is defined as

$$J(T_{ex}) \equiv \frac{h\nu}{k} \frac{1}{e^{h\nu/kT_{ex}} - 1}.$$

(2)

Equation (1) can be simplified as

$$N_H_2 = \frac{H_2}{CO} 1.94 \times 10^3 \nu^2 [GHz] \frac{Q(T)}{A_{uv}} e^{E_{rel}/kT_{ex}} \int T_{mb} d\nu,$$

(3)

where $\nu$ is in the unit of GHz, $A_{uv} = A_{32} = 2.6 \times 10^{-6}$, $E_{rel} = 33.2$ K. Here we use $H_2/CO \approx 10^5$ as suggested by Lequeux (2005) and $T_{ex}$ is assumed to be 20 K (Ginsburg et al. 2009). The peak intensity was found at $\alpha = 05^h39^m10^s$ $\delta = +35^d45^m46^s$ with $T_A = 107$ K, and the derived column density is $N_{H_2} \sim 1.1 \times 10^{22}$ cm$^{-2}$. The total mass of the cloud was estimated to be $\sim 1000 M_\odot$.

We also estimated the column density using the relation derived by Frerking et al. (1982) for dust extinction from the average extinction value, $A_V \sim 13.0$ mag (see Section 3.2), of the S233IR cloud,

$$N_{H_2} = A_V \times 0.94 \times 10^{21} cm^{-2}.$$

(4)

The derived column density of S233IR is $1.2 \times 10^{22}$ cm$^{-2}$, which gives a total gas mass 1100 $M_\odot$, within 30 K km s$^{-1}$.
3.2. Stellar Photometry and Extinction Correction

S233IR is a complicated region, which contains embedded stellar clusters, extended nebulous emissions, and shocked outflow gas, as shown in Figure 1(b). Properties of outflow gas in the H$_{2}$ band are discussed by Ginsburg et al. (2009) and the extended emissions will be discussed in detail in the forthcoming paper. Here we focus on the properties of the embedded stellar sources. The identified point sources within the cloud boundary were categorized into three groups, the SW cluster, the NE cluster, and the “distributed sources” associated with the molecular cloud S233IR except for the NE (Figure 1(c)) and SW clusters (Figure 1(d)). The centers of NE and SW are at $\alpha = 05^h39^m12^s$, $\delta = +35^\circ45^\prime59^\prime$ and $\alpha = 05^h39^m09^s$, $\delta = +35^\circ45^\prime10^\prime$, respectively. The radii of both clusters are set to be about 30$''$ based on the morphology and distribution of the extended nebulae.

Figure 2 shows the luminosity histogram of the identified point sources (solid line) in different filter bands ($J$, $H$, and $K_S$) with 0.5 mag bin. Compared with previous data by Porras et al. (2000), our observations were made with deeper limiting magnitudes ($\sim$ 2 mag) and better image resolution ($\sim$ 3 times better), which results in a much larger number of detected sources. For example, a bright source (IR 93) in the NE cluster, which was considered as one point source in Porras et al. (2000) data, was resolved into several fainter sources in our data. The two histograms are almost identical for the sources brighter than $\sim$ 15 mag.

Figure 3 is the color–color diagram ($H - K_S$ versus $J - H$) for the identified sources in the S233IR cloud. The stars detected in the SW and NE cluster regions are marked with squares and triangles, respectively, and the other sources (“distributed sources”) are marked with circles. Filled symbols are for the sources within the classical T-Tau star (CTTS) range. The
fraction of IR excess (non-\(J\)-band detection) stars, which include the stars in the CTTS region or not detected in the \(J\) band, are 35\% (12/34) and 36\% (13/26) for the SW and NE clusters, respectively. The CTTS and infrared-excess (\(H - K_S > 1.5\)) sources are identified in Figure 4, with red crosses and green boxes, respectively. Some very red objects located at the outskirts of this molecular cloud seem to be isolated star-forming sources. The nature of these sources will be discussed in the second paper.

We identified about 800 sources in total within the cloud boundary. It was expected that a significant number of background sources exist toward the target cloud in the observed bands. It is an important but very difficult job to separate the member sources from the background. Without proper motion data for the cluster, statistical subtraction is the only way to determine the member stars. To subtract the background stars, we chose a region outside the molecular boundary, centered at \(\alpha = 05^h38^m10^s\) and \(\delta = +35^\circ 42' 07''\), as a reference field with no extinction. The reference field was chosen in the area well outside the cloud boundary based on radio observations. By assuming that the same background stars exist in the target cloud (the S233IR cloud), we statistically removed expected background sources following the procedure summarized by Jose et al. (2008): select a star on the CMD of the reference field, and eliminate the star with same color and magnitude on the CMD of the target field within the observed uncertainties (\(\Delta (H - K_S) \leq 0.08\) and \(\Delta K_S \leq 0.07\)). By repeating this procedure for all sources in the CMD, we subtract background sources in the target field. There were 254 sources cleaned in a 5\arcmin radius region. This leads to a number of ~2 background sources in the 30\arcsec radius region. In other words, 92\% and 94\% of the sources are associated with SW and NE clusters, respectively.

Figure 5 shows the CMD (\(K_S\) versus \(H - K_S\)) for the sources in the S233IR cloud, the reference field, and the background cleaned “member sources,” respectively. The red
The error of dereddened $K_S$ magnitudes is expected $\leqslant 0.2$ from the mean isochrone we used (Masui et al. 2006). The extinction can be derived by comparing the observed and intrinsic color of each star. On the other hand, extinctions of the CTTSs (filled symbols in the figures) were corrected by projecting them back to the CTTS locus in Figure 3. The average extinction ($A_V$) was found to be $9.8 \pm 5.2$ (the SW cluster, 36 stars), $28.9 \pm 10.4$ (the NE cluster, 25 stars), and $13.0 \pm 10.4$ (“distributed stars,” 124 stars). These extinctions are larger than the previous values by a factor of about 1.3–2 (PCS), which result from deeper observations and also from more reliable analysis by using both diagrams (Figures 3 and 5) in deriving extinction amounts.

3.3. KLF Modeling

For decades, the most reliable method in optical astronomy for determining the age of a cluster is the H-R diagram (HRD), to compare the positions of member stars with theoretical evolutionary tracks on the HRD. For an embedded young cluster, this method is not validated because most of the members are not in the main-sequence stage and can be observed only in longer wavelengths than the optical. The KLF is a simple tool used to study the properties and estimate the age of an embedded cluster (Lada & Lada 2003; Yasui et al. 2006). The KLF can be expressed by the following equation:

$$\frac{dN}{dm_k} = \frac{dN}{d \log M_*} \times \frac{d \log M_*}{dm_k},$$

(5)

where $m_k$ is the $K$-band luminosity and $M_*$ is the stellar mass (Lada & Lada 2003). The first term on the right-hand side is the underlying stellar mass function and the second term is the mass–luminosity relation (MLR). Notice that the KLF of clusters peaks at different magnitudes, depending on the difference between ages and star formation history (Muench et al. 2000).

Simple Monte Carlo simulations were carried out to construct the model KLFs. The simulation was done in three steps. The first step is to assume an IMF. Two IMFs were used in our simulation, which are Trapezium IMF (Muench et al. 2000) and the IMF from Miller & Scalo (1979, hereafter MS79). Then, we convert the mass function to the luminosity function using an MLR from the isochrones of the PMS models (D’Antona & Mazzitelli 1994, 1997, 1998; Siess et al. 2000). The stellar luminosities were finally converted to the $K$-band luminosity, $m_k$ with bolometric correction (Flower 1996) and stellar intrinsic color correction (Bessell & Brett 1988). By repeating this procedure with different age inputs, we fit model KLFs to observed KLFs and estimate the ages of clusters. In Figure 6, we show a result derived for embedded clusters in S233IR, which is to be discussed in the following section.

3.4. Age Estimates from KLFs and Derived IMFs of the Embedded Clusters

Ages of the clusters embedded in the S233IR cloud were estimated by comparing the observed and model KLFs (Yasui et al. 2006). Using the method mentioned in Section 3.3, we constructed model KLFs for ages from 0.07 to 50 Myr. By comparing the model and observed KLFs (Figure 6), we derived the ages of $-0.5 \pm 0.1$, $-0.25 \pm 0.1$, and $-1.5 \pm 0.3$ Myr for the SW, NE, and the distributed stars, respectively. Although the MLR for the age younger than 1 Myr is uncertain between different PMS models (Baraffe et al. 2002; Yasui et al. 2006), this method allows us to estimate cluster ages quantitatively. The age difference of these stellar groups was first noticed by Porras et al. (2000) based on the J-band data analysis. It is understood that there are uncertainties in estimating cluster ages because we detect 25 and 36 IR sources in the NE and SW clusters, respectively. However, the model KLFs are not sensitive to the IMFs used. Therefore, the current results do suggest that relative age differences exist among these clusters roughly with the amounts mentioned here. Using the estimated ages of the clusters, the luminosity function was converted to mass with the model isochrones (D’Antona & Mazzitelli 1994, 1997, 1998; Siess et al. 2000) by applying the bolometric correction (Flower 1996) to the expected stellar intrinsic colors (Bessell & Brett 1988). Total masses of $\gtrsim 46, \gtrsim 30, \text{and } \sim 110 M_\odot$ were derived for the NE, SW, and the distributed stars, respectively.

With the determined age, the IMFs of the embedded clusters can be calculated using the MLR and its slope $\Gamma$, which is defined as $dN/d \log(m) = M^\Gamma_*$ (cf. Muench et al. 2002), to constrain the cluster properties. The size of the IMF bin was set to be 0.5 $M_\odot$, which is larger than the uncertainty of mass estimation propagated from luminosity error. We derived $\Gamma \sim -0.42 \pm 0.11$, $-0.10 \pm 0.08$, and $-0.46 \pm 0.07$ for the SW, NE, and distributed stars, respectively. Although the derived $\Gamma$ values for the NE and SW clusters are uncertain due to small numbers (25 sources for NE and 36 sources for SW), it still indicates that the $\Gamma$ values in this region are much flatter than the Salpeter slope. This may suggest that more massive stars have efficiently formed in the S233IR region compared to other star-forming regions in our Galaxy, such as the sources.

![Figure 5. CMDs ($K_S$ vs. $H - K_S$). Source symbols are the same as in Figure 3. Red lines represent the age-averaged isochrone between 1.0 and 10.0 Myr from D’Antona & Mazzitelli (1994).](image-url)
listed by Muench et al. (2002), Figueredo et al. (2002, 2005), Leistra et al. (2005, 2006), Jose et al. (2008), Harayama et al. (2008), Pandey et al. (2008) and others, who have derived slopes \( \Gamma \sim -1 \) in young embedded stellar clusters.

### 3.5. Star Formation Efficiency

The SFE is defined as the ratio of the total stellar mass to the total stellar and gas mass (cf. Wilking & Lada 1983). Typically, the SFE ranges from \( \sim 10\% \) to 30\% (Lada & Lada 2003, see Table 2 and reference there in). SFEs have been found to be low in young or low-mass star formation regions (e.g., Serpens, Rho Oph, and NGC 1333) but increase to about 30\% in more evolved massive star-forming regions (Lada & Lada 2003). We have determined the total gas mass of S233IR, \( \sim 1100 \, M_\odot \), and the embedded cluster mass, \( \sim 180 \, M_\odot \) (Section 3.4). The SFE is \( \sim 17\% \) for the S233IR region. Our analysis covers the whole S233IR region and the member stars were determined more carefully than in previous studies of this region (for example, Beuther et al. 2002a, 2002b; Mao & Zeng 2004).

It should be noted that the derived SFE may represent the lower limit, since a significant number of sources have not been identified because of the extended emission features and high extinction environments in the central parts of the embedded clusters, this caveat also applies to \( \Gamma \). The latest star-forming cores are found in the NE cluster. Young massive stars are still deeply embedded in the dense molecular cores (Beuther et al. 2007; Leurini et al. 2007) and associated with maser emissions and energetic shocked H\(_2\) gas (Menten 1991; Porras et al. 2000; Ginsburg et al. 2009). Because of the age differences among stellar groups, it is possible that the star formation has not resulted from the overall collapse of the S233IR molecular cloud at the same time. If stars form continuously, the single SFE value for the whole cloud may not represent a measure of the final gas-to-stars efficiency. We therefore investigated SFEs at different radii in the S233IR cloud. Since the total gas mass in local areas is difficult to separate from the whole cloud, the SFEs were derived by comparing the stellar mass and the total gas mass along the ring, centered at \( \alpha = 05^h39^m11^s, \delta = +35^\circ 45^\prime 51^\prime\prime \), with annuli of width \( \Delta r = 0.2 \). The SFE changes with the location in the cloud, as shown in Figure 7. The center is at \( \alpha = 05^h39^m11^s, \delta = +35^\circ 45^\prime 51^\prime\prime \), which corresponds to the peak of the integrated CO emission. As expected, the SFE changes with the location in the cloud. High SFE values up to \( \sim 40\% \) are found in the central region \( (r \lesssim 1') \). This radius covers the region of the NE and SW clusters and both of them represent later stages of star formation. The high value may suggest that there are local enhancements in massive star formation, possibly triggered by nearby star formations within the S233IR cloud.

### 4. DISCUSSION

Based on the radio and extinction map (Heyer et al. 1996; Reipurth & Yan 2008), the S233IR molecular cloud is a part of the much larger Auriga GMC complex, which is associated with several large H\(_\alpha\) regions and active star-forming regions. The large-scale \( \sim \) a few degrees) morphology of this GMC complex looks very clumpy and is composed of several H\(_\alpha\) regions, such as Sh 2-231, 232, 233, and 235 (Reipurth & Yan 2008). The CO emission shows a filamentary and arc-like structure associated with three H\(_\alpha\) regions. In the NE direction, an H\(_\alpha\) region, Sh 2-231, is \( \sim 10' \) away from S233IR (Mao & Zeng 2004). In addition, there are many newly formed OB stars, such as those in Aur OB1, associated with this GMC complex (Reipurth & Yan 2008, Figure 1). The S233IR clump appears to be the latest of the star formation events.

Three groups of stars were identified in the S233IR region—SW, NE, and the distributed stars. The background contamination in the distributed stars was eliminated by a statistical method. The age differences among these subgroups were first noticed by Porras et al. (2000) using the J-band analysis. Based on the better data quality of our work, we derived ages of \( \sim 0.5 \) Myr for SW, \( \sim 0.3 \) Myr for NE, and \( \sim 1.5 \) Myr for the distributed stars. The distributed stars could be the first gen-
eration of stars formed in this cloud. The SW and NE clusters, with a relative distance of about 0.5 pc at a 1.8 kpc distance, are later generations. The age differences between stellar groups suggest sequential star formation, which has also been found in other star-forming regions, such as NGC 7538 (Ojha et al. 2004), Sh 2-247 (Puga et al. 2008), Sh 2-157 (Chen et al. 2009), and NGC 3576 (Purcell et al. 2009). It is interesting that the S233IR cloud, a typical star-forming cloud in size (r ∼ 1.5 pc) and mass (∼1100 M⊙), contains sub-clusters formed in different epochs and star formation still continues without disrupting its natal molecular cloud. Stars appear to be forming continuously in the youngest NE cluster. For the distributed stars, the derived IMF slope, Γ ∼ −0.5, is flatter than in other star-forming regions in our Galaxy, which indicates that more massive stars have been formed preferentially in this cloud than in other typical star-forming regions. The Γ value of the NE cluster, the latest star-forming sub-core in this cloud, is even flatter than the distributed stars, suggesting that the probability of massive star formation is higher in this region. This result is consistent with the radio observation toward the center of the NE cluster (Beuther et al. 2002a). Eventually the cluster will disperse the natal molecular cloud and appear as visible stars. Once the massive stars are formed, the radiation from massive star will clear the molecular cloud and stop the star formation process in the core region.

The enhancement of the local SFE is also found in the central dense core as we derived in Section 3.5, although we have to take various uncertainties into consideration, for example, the uncertain total H2 density, the cloud boundary, member star determination, undetected sources especially near the central part of the sub-clusters showing saturated infrared emission, etc. The local high SFE (≥40%) suggests that the later generation of stars can be formed very efficiently in dense cores in the same molecular cloud. In the outskirts of the cloud, where the first stellar generation is located, the SFE is consistent with a typical molecular cloud. The triggered star formation may have enhanced the formation of massive stars, which results in a high SFE and flatter IMF slope in the central region. It is known that the NE cluster is the latest star-forming core in S233IR, which is associated with powerful energetic features, such as shocked H2 gas flows (Ginsburg et al. 2009). These energetic activities are thought to be a part of the massive star formation process. The S233IR region provides an interesting example of active and energetic massive star formation, which could be further studied with next generation instruments.

5. SUMMARY

We revisited the S233IR (Sh 2-233IR) region with a wider field of view and more sensitive near-infrared data than previous studies. Three distinguishable sub-clusters exist in this region: the NE and SW clusters, and the distributed stars. Using the color–color diagrams (H − Ks versus J − H) and the CMDs (Ks versus H − Ks), we statistically subtracted background stars and identified 25, 33, and 151 stellar sources for the NE cluster, the SW cluster, and the distributed stars, respectively. We derived ages of ∼0.3, ∼0.5, and ∼1.5 Myr, and masses of 45, 30, and 107 M⊙, for SW, NE, and the distributed stars, respectively. The flatter IMF slope (Γ ≥ −0.5) for subclusters suggests that more massive stars were preferentially formed in S233IR. The first stellar generation is the distributed stars located in the GMC complex in which S233IR is embedded. Afterward, the sequential star formation in this cloud may have been triggered before its natal molecular cloud is disturbed by previous star formation events. The average SFE of this region is ∼17%, and ≥40% at the center of S233IR, the NE and SW clusters. This result suggests that stars form very efficiently in local dense cores within the cloud center.

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