Mass Function of a Young Cluster in a Low-metallicity Environment. Sh 2-209

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Abstract

We present deep near-infrared (NIR) imaging of Sh 2–209 (S209), a low-metallicity ([O/H] = −0.5 dex) H II region in the Galaxy. From the NIR images, combined with astrometric data from Gaia EDR3, we estimate the distance to S209 to be 2.5 kpc. This is close enough to enable us to resolve cluster members clearly (≈1000 au separation) down to a mass-detection limit of ≈0.1 M⊙, and we have identified two star-forming clusters in S209, with individual cluster scales ≈1 pc. We employ a set of model luminosity functions to derive the underlying initial mass functions (IMFs) and ages for both clusters. The IMFs we obtained for both clusters exhibit slightly flat high-mass slopes (Γ ≈ −1.0) compared to the Salpeter IMF (Γ = −1.35), and their break mass of ≈0.1 M⊙ is lower than those generally seen in the solar neighborhood (∼0.3 M⊙). In particular, because the S209 main cluster is a star-forming cluster with a larger number of members (∼1500) than the number (∼100) in regions previously studied in such environments, it is possible for the first time to derive the IMF in a low-metallicity environment with high accuracy over the wide mass range of 0.1–20 M⊙.

Unified Astronomy Thesaurus concepts: H II regions (694); Star formation (1569); Pre-main sequence stars (1290); Low mass stars (2050); Infrared sources (793); Open star clusters (1160); Galaxy abundances (574); Luminosity function (942); Stellar mass functions (1612)

Supporting material: machine-readable table

1. Introduction

Stars are fundamental components of galaxies, and because the stellar mass determines a star’s subsequent evolutionary path, the initial mass function (IMF)—i.e., the initial distribution of masses for a population of stars—is one of the fundamental parameters that determines the physical and chemical evolution of a stellar system. In addition to informing our understanding of stellar origins and evolution, the IMF provides important input to many astrophysical studies (Bastian et al. 2010). The IMF was first introduced by Salpeter (1955), and detailed derivations have been carried out for various regions, including the field, young clusters and associations, and old globular clusters. The results indicate that the vast majority of stellar systems originated from a universal IMF that follows a power law with the Salpeter index Γ = 1.35 for masses ≳1 M⊙, and which flattens (Γ ≈ 0) around 0.5 M⊙. The IMF is also known to exhibit a turnover at M∗ ≈ 0.3 M⊙, which is called the “characteristic mass” (Elmegreen et al. 2008). However, because there are many different physical and chemical environments in the universe, whether the IMF is universal or whether it is sensitive to environmental conditions remains a crucial question.

Metallicity—the abundance of elements heavier than hydrogen and helium—is known to increase during cosmic evolution due to the synthesis of elements in stars and supernovae. At present, only 2% (by mass) of the baryons in our solar system are heavy elements. Nevertheless, metallicity is believed to be one of the most critical factors for star formation because it sensitively affects the heating and cooling processes during star formation as well as radiative transfer. Because of these effects, theoretical studies have suggested that the IMF will move away from the Salpeter form in low-metallicity environments (e.g., Omukai et al. 2005). Some observations also indicate that high-mass IMFs tend to become top-heavy as the metallicity decreases. However, there is currently no conclusive evidence for this, so at present it should be considered just as suggestive evidence (Kroupa et al. 2013). Observations of globular clusters show that—with decreasing metallicity coupled with increasing density—the stellar IMF shifts toward a top-heavy form (Marks et al. 2012). However, because globular clusters are very old (∼10^10 yr), they have already experienced mass segregation and self-regulation, so the present-day mass function (PDFM) may not reflect the IMF. Conversely, in young clusters that have not undergone much N-body relaxation or mass segregation, it is reasonable to assume that the PDFM is similar to the IMF (Lee et al. 2020). In addition, in young clusters (∼10^6 yr), massive stars (≥20 M⊙) have not yet ended their lives, which makes it possible to derive IMFs over a wide mass range, while in contrast the mass range of stars in globular clusters is only ≤ 1 M⊙ (Paresce & De Marchi 2000).

The most typical examples of such studies in low-metallicity environments involve the Large and Small Magellanic Clouds (LMC/SMC). They are nearby dwarf galaxies at a distance D ≈ 50 kpc. Based on observations of star-forming regions in
the solar neighborhood, the scale of an individual star-forming cluster—the minimum unit of star formation where many stars are born almost simultaneously—has been estimated to be $\sim 1$ pc (Adams et al. 2006). This corresponds to the very small scale of $\sim 4''$ at the distance of the LMC/SMC. However, star-forming regions in the LMC/SMC generally extend to $\sim 1'$, which corresponds to $\sim 15$ pc, a much larger spatial scale than the scale of an individual cluster. For this reason, a single star-forming region can have a complex star formation history, and the existence of multiple generations of stars has been pointed out (De Marchi et al. 2017). In addition, based on observations in the solar neighborhood, the separation of individual stars in a star-forming cluster has been estimated to be $\sim 0.1$ pc on average (Adams et al. 2006), which corresponds to $0''.4$ in the LMC/SMC. However, this is only an average value; in reality, the high stellar density in the center of a cluster makes it challenging to observe individual stars in the cluster with sufficient resolution. Although it is not clear whether this is the direct reason, in some regions investigators have derived the standard IMF (Kerber & Santiago 2006), while in others the IMF is flatter (e.g., R136; Sirianni et al. 2000). For a large variety of the physical environments found in the Galaxy and the LMC/SMC, observations based on spectroscopic classifications of stars in OB associations and in star clusters have obtained IMFs that are comparable to the Salpeter IMF for massive stars ($M \gtrsim 10M_\odot$; Massey 2003). However, a recent result that took into account the star formation history found indications of a top-heavy IMF in the mass range $15$–$200M_\odot$ in the 30 Doradus starburst star-forming region in the LMC (Schneider et al. 2018). In any case, it is difficult to obtain IMFs extending down to low-mass stars using the mass coverage characteristic of LMC/SMC observations, and some effort to bridge the gap between detailed observations in the solar neighborhood and LMC/SMC observations is needed.

In order to extend detailed derivations of IMFs in low-metallicity environments to lower stellar masses, we have been focusing on the outer Galaxy to Galactocentric distances $R_G \gtrsim 15$ kpc. Despite the relatively small distances to these regions ($D \sim 5$–$10$ kpc), their metallicities have been found to be as low as $\sim 1$ dex, which is similar to the metallicity at $z \approx 2$ in the cosmic chemical evolution (e.g., Pei & Fall 1995). Due to these relatively small distances, the spatial resolution in these regions is about 10 times higher than that in the LMC/SMC, which are commonly observed low-metallicity environments, making it much easier to resolve individual stars. Furthermore, the relatively high sensitivity of these observations makes it possible to achieve a low mass limit. Therefore, the outer Galaxy provides good alternative targets to nearby dwarf galaxies. In our previous systematic studies of low-metallicity regions in the outer Galaxy, we have explored star-forming regions traced by molecular clouds and Hα and have selected regions for which low metallicities ([O/H] $\lesssim -0.5$ dex) have actually been determined: Cloud 2 (Yasui et al. 2006, 2008b), S207 (Yasui et al. 2016b), S208 (Yasui et al. 2016a), and S127 (Yasui et al. 2021). From Subaru near-infrared (NIR) imaging of these star-forming regions, we have confirmed that we can detect stars down to mass $\sim 0.1M_\odot$, which allows us to cover the peak of the IMF sufficiently. The observations also allow us to observe individual star-forming clusters on scales $\sim 1$ pc, which are comparable to those observed in the solar neighborhood. This enables us get closer to the genuine IMF because the effects of complex star formation histories are eliminated. Based on the fitting of K-band luminosity functions (KLFs), we found that the IMF in the outer Galaxy is consistent with that in the solar neighborhood with regard to both the high-mass slope and the characteristic mass (Yasui et al. 2017, 2008a), suggesting that—down to $\sim 1$ dex—the IMF does not depend on metallicity down to the substellar mass regime ($\sim 0.1M_\odot$). However, previously targeted star-forming clusters have only about 100 members (Yasui et al. 2010, 2021), so their IMFs could not be determined with high accuracy.

From our Subaru NIR imaging survey of star-forming clusters in the outer Galaxy, we found active star formation activity in Sh 2–209 (S209), which—from previous studies—is thought to be located in a low-metallicity environment ([O/H] $= -0.5$ dex) at $R_G = 18$ kpc. There are two star-forming clusters in S209, one of which has been confirmed to have approximately 1500 cluster members (Yasui et al. 2010). The scale of S209 is comparable to that of one of the largest star-forming regions in the solar neighborhood, the Orion Nebula Cluster (ONC; Hillenbrand 1997), and S209 can thus be regarded as a prototype star-forming region in the outer Galaxy. Both mid-infrared (MIR) and radio observations (Klein et al. 2005; Richards et al. 2012) also suggest that high-mass star formation is occurring in this region. Therefore, S209 is the best (and currently the only) star-forming region that can be targeted for deriving a detailed IMF in a low-metallicity environment.

In this paper, we report the first deep NIR imaging of S209 and the derivation of IMFs for the two young clusters in this region. One of the advantages of deriving the IMF based on imaging rather than spectroscopy is that it allows detections down to low-mass stars with higher sensitivities and thus enables the derivation of IMFs down to such masses. Our IMF derivation mainly follows the method used by Muñch et al. (2002), who derived the IMF for the Trapezium cluster, which has an age $\sim 1$ Myr and which is a star-forming region of the same scale as S209. However, because there are no previous studies of the age of the cluster in S209, we have developed our own method, which includes age as a parameter in fitting the KLF. In Section 2, we summarize the properties of this region from previous studies and archival data for S209: distance, metallicity, and star formation activity. In addition to the previous distance estimate of 10 kpc to S209, the possibility has recently been raised that the distance may actually be 2.5 kpc. In Section 3, we describe NIR imaging observations and data analysis obtained with the Multi-Object near-InfraRed Camera and Spectrograph (MOIRCS) at the Subaru Telescope. In Section 4, we present NIR imaging results for the two young clusters in S209. In Section 5, we discuss the properties of the two S209 clusters using the results from Section 4: the high-mass stars in S209, the distance, the environments around the star-forming clusters, and the cluster scales. In Section 6, we construct model KLFs, which we use to derive the IMF (Section 6.1), and we present the best-fit IMFs we obtained for both S209 clusters (Section 6.2). In Section 7, we discuss the IMFs obtained for the S209 clusters (Section 7.1), compare them with the IMF derived for the solar neighborhood (Section 7.2), compare them with the IMFs derived for low-metallicity environments, and finally discuss a possible metallicity dependence of the IMFs (Section 7.3). In Section 8, we conclude and discuss future prospects.
Table 1

| Name                | Sh 2-209          |
|---------------------|-------------------|
| Galactic longitude  | 151.6062 (1)      |
| Galactic latitude   | −0.2400 (1)       |
| R.A. (J2000.0)      | 04 11 06.7 (1)    |
| Decl. (J2000.0)     | +51 09 44 (1)     |
| Photometric heliocentric distance (kpc) | 10.9 (2) |
| Kinematic heliocentric distance (kpc)  | 10.6 (3) |
| Photometric/kinematic Gaoticentric distance | ≃18 |
| Gaia astrometric distance (kpc)       | ≃2.5 (4) |
| Gaia astrometric Galactocentric distance (kpc) | ≃10.3 |
| Oxygen abundance 12 + log(O/H)       | 8.15±0.16 (5.6, 6) |
|                             | 8.44±0.15 (6.7, 7) |
| Metallicity [O/H] (dex)             | ≃−0.5 |

Notes. References are shown in the parentheses.

*a* Assumed Solar Galactic distance $R_*$ = 8.0 kpc.

*b* Assumed solar abundance $2 + \log(O/H)$ = 8.73 (Asplund et al. 2009).

References. (1) SIMBAD (Wenger et al. 2000), (2) Chini & Wink (1984), (3) Foster & Brunt (2015), (4) Gaia Collaboration et al. (2021), (5) Vílchez & Esteban (1996), (6) Rudolph et al. (2006), and (7) Caplan et al. (2000).

2. Sh 2-209

The nebulosity Sh 2-209 is an extended H II region listed in a catalog obtained from Ha surveys (Sharpless 1959). It is located at $l = 151^°16'06''$ and $b = -0^°24'00''$ in the Galactic plane, with coordinates $(\alpha_{2000.0}, \delta_{2000.0}) = (0^h11^m06^s.7, +51^°09'44''4)$ from SIMBAD (Wenger et al. 2000). In this section, we summarize the properties of the targeted star-forming region Sh 2-209 obtained from previous works, which we list in Table 1. The Sh 209 nebulosity also produces strong MIR emission. We show a large-scale NIR and MIR pseudocolor image of Sh 209 in Figure 1 and an Ha and radio-continuum image in Figure 2.

2.1. Distance

From spectroscopic and photometric observations of three possibly dominant exciting stars—with spectral types B1III, O9III, and B1 (hereafter CW1, CW2, and CW3, respectively)—Chini & Wink (1984) estimated the photometric distance to Sh 209 to be 10.9 kpc. The kinematic Gaoticentric distance of the Sun to be $R_* = 8.0$ kpc, then the Gaoticentric distance to Sh 209 is $R_G \approx 18$ kpc. The kinematic Gaoticentric distance has also been estimated to be $\sim 10$ kpc, taking the radial velocity of the local standard of rest to be $V_{LSR} \sim 50$ km s$^{-1}$, as derived from observations: $V_{LSR} = -52.2$ km s$^{-1}$ from CO observations by Blitz et al. (1982); $V_{LSR} = -50.0$ km s$^{-1}$ from Hα Fabry–Perot observations by Fich et al. (1990); $V_{LSR} = -52.2$ km s$^{-1}$ from Fabry–Perot observations of H II regions by Caplan et al. (2000); and $V_{LSR} = -48.8$ km s$^{-1}$, $V_{LSR} = -50.11$ km s$^{-1}$, and $V_{LSR} = -48.3$ km s$^{-1}$ from CO, Hα, and Hβ, respectively, by Foster & Brunt (2015). According to Foster & Brunt (2015), who obtained the most recent determination, the estimated distance is 10.58 ± 0.57 kpc, which is very consistent with the photometric distance.

Astrometric distances have also been obtained from Gaia Early Data Release 3 (Gaia EDR3; Gaia Collaboration et al. 2021). For the probable dominant exciting stars CW1, CW2, and CW3, the parallaxes were derived with relatively high accuracy. The stars CW1, CW2, and CW3 were identified with the Gaia source IDs 271701112917796096, 27170100983634752, and 271701112917794176, respectively; the parallaxes of these sources divided by the corresponding parallax errors are 14.7, 5.2, and 3.8, respectively. Following Lindegren et al. (2021), we corrected the parallax zero-point and obtained the distance to each source and its error. In this way, we found the distances to CW1, CW2, and CW3 to be $2.6_{-0.1}^{+0.2}$, $3.0_{-0.4}^{+0.6}$, and $3.1_{-0.6}^{+1.0}$ kpc, respectively, all of which lie in the range $\sim 2.5$–3.0 kpc. The properties obtained from Gaia EDR3 are summarized in Table 2.

2.2. Oxygen Abundance and Metallicity

For eight H II regions, Vilchez & Esteban (1996) measured several optical emission-line fluxes—e.g., [O II] $\lambda \lambda 3727, H \beta$, [O III] $\lambda \lambda 4959$ and 5007, He I $\lambda \lambda 5876$, Hα, [O II] $\lambda \lambda 3729$ and 7330, and P8–P15—and they found the oxygen abundance of S209 to be $12 + \log(O/H) = 8.3$. Based on Fabry–Perot observations, Caplan et al. (2000) measured several optical emission-line fluxes in 36 H II regions: [O II] $\lambda \lambda 3726$ and 3729, Hβ, [O III] $\lambda \lambda 5007$, [He I] $\lambda \lambda 5876$, and Hα. Subsequently, Deharveng et al. (2000) determined the oxygen abundances for several H II regions, as well as the extinctions, electron densities and temperatures, and ionic abundances ($O^+/H^+$, $O^{++}/H^{++}$, and $He^+/H^+$). They found the oxygen abundance of S209 to be $12 + \log(O/H) = 8.18$. Rudolph et al. (2006) reanalyzed the elemental abundances of 117 H II regions with updated physical parameters. They determined the oxygen abundance of S209 using the data of Vilchez & Esteban (1996) and Caplan et al. (2000) to be $12 + \log(O/H) = 8.15_{-0.16}^{+0.26}$ and $8.44_{-0.22}^{+0.15}$, respectively. These abundances correspond to $\sim -0.5$ dex, assuming a solar abundance of $12 + \log(O/H) = 8.73$ (Asplund et al. 2009). The electron temperatures $(T_e)$ are also sensitive indicators of heavy-element abundances, with higher temperatures corresponding to lower abundances (Shaver et al. 1983). The estimated temperatures are very high for S209: $\sim 11,000$ K (8055 ± 3670 K by Omar et al. 2002); 10,510 ± 90 K for the central region and 12,570 ± 360 K for the northern region from Quireza et al. 2006; and 10795 ± 985 K from Balser et al. 2011. These are among the highest temperatures of any H II regions in the Galaxy (see Figure 3 in Quireza et al. 2006), which suggests that S209 is in a very-low-metallicity region. According to the relationship between electron temperature and oxygen abundance obtained by Shaver et al. (1983) $-12 + \log(O/H) = 9.82 - 1.49T_e/10^4$—the temperature of S209 ($\sim 11,000$ K) suggests an oxygen abundance of 8.2, which is consistent with the abundance determinations discussed above. Fernández-Martín et al. (2017) also estimated the oxygen abundance from the derived electron temperature for S209, obtaining a value that is in very good agreement with the above estimate.

2.3. Star-forming Activity

Figure 1 shows an NIR and MIR pseudocolor image of S209 with a wide field of view ($\sim 30' \times 30'$) that is centered at $(l, b) = (151^°16', -0^°24')$ in Galactic coordinates. We produced this figure by combining Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) Ks band (2.16 $\mu$m, blue), Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) band 1 (3.4 $\mu$m; green), and WISE band 3 (12 $\mu$m; red) images. The positions of two sources in the IRAS Point Source...
Catalog (Beichman et al. 1988)—IRAS 04073+5102 and IRAS 04073+5100—are shown with red plus signs. The 12 μm emission is mainly from polycyclic aromatic hydrocarbons, and it traces the photodissociation regions around H II regions. This figure shows that the star-forming region extends over 10 square arcminutes. The star-forming cluster [BDS2003]65 has been identified by Bica et al. (2003) from 2MASS images; it is centered at \((\alpha_{2000,0}, \delta_{2000,0}) = (0^h4^m11^s0^s, +51^\circ09'58''0)\) in Equatorial coordinates and \((l, b) = (151°60', -0°24')\) in Galactic coordinates. Here, 1′ corresponds to 0.75 pc (3.0 pc) for a distance to S209 of 2.5 kpc (10 kpc). We produced this image by combining the 2MASS K_s band (2.16 μm; blue), WISE band 1 (3.4 μm; green), and WISE band 3 (12 μm; red). The small white boxes show the locations and sizes of the MOIRCS fields of view (solid and dashed lines for the S209 and sky frames, respectively), while the cyan box shows the location and size of Figure 2. The red plus signs show the locations of IRAS point sources.

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consistent with Figure 1. From the radio-continuum properties of H II regions, Richards et al. (2012) estimated that S209 contains $\sim 2800$ M$_\odot$ of ionized gas, which is comparable to the masses of the W49a and Quintuplet H II regions, and that the Lyman-continuum photon flux is $\sim 10^{49}$ s$^{-1}$. Based on these physical parameters, they suggested that the star-forming cluster is very massive ($> 10^3$ M$_\odot$). This is consistent with our previous results (Yasui et al. 2010), in which we detected more than 2000 sources in NIR observations. However, note that Richards et al. (2012) assumed a distance of 9.8 kpc (based on the kinematic distance), and the estimates of these values can change significantly if the distances are significantly different, as discussed in Section 2.1.

Molecular-cloud cores are traced by millimeter-wavelength continuum emission. Klein et al. (2005) obtained a millimeter-continuum map of the S209 H II region with the Heinrich Hertz Submillimeter Telescope. They identified seven molecular cores (the magenta boxes in Figure 2) with a total mass of $\sim 2 \times 10^4$ M$_\odot$. From the coincidence of the millimeter-continuum emission with a dark region in the faint optical-emission nebula, they suggested that the molecular cores are located in front of the H II region. They also found indications of triggered star formation from a ring of cloud cores around the star cluster, and they suggested the existence of another cluster around IRAS 04073+5100.

3. Observations and Data Reduction

3.1. Subaru MOIRCS Imaging

We obtained deep $JHK_S$-band images for each band with the 8.2 m Subaru telescope using the wide-field NIR camera and spectrograph, MOIRCS (Ichikawa et al. 2006; Suzuki et al. 2008). The MOIRCS instrument uses two 2K “HAWAII-2” imaging arrays, which yield a $4' \times 7'$ field of view ($3.5' \times 4'$ for each channel), with a pixel scale of 0.117 pixel$^{-1}$. The instrument uses the Maunakea Observatory (MKO) NIR photometric filters (Simons & Tokunaga 2002; Tokunaga et al. 2002).

We performed these observations on 2006 September 3 UT. The observing conditions were photometric, and the seeing was excellent ($\sim 0.35$–0.45) throughout the night. Because linearity of the detector output is not guaranteed for counts over $\sim 20,000$ analog-to-digital units (ADUs), we also obtained short-exposure images on 2006 November 8 UT, when the conditions were very humid ($\sim 45$%–75%) and the seeing was $\sim 1.2'$. For the long-exposure images, the exposure times were 120, 20, and 30 s for the $J$, $H$, and $K_S$ bands, respectively, whereas the exposure time for the short-exposure images was 13 s for all bands. The total integration times for the long-exposure images were 480, 480, and 720 s for the $J$, $H$, and $K_S$ bands, respectively, whereas the total integration time for the
Properties from Gaia EDR3 for the Probable Dominant Exciting Sources of S209 Suggested by Chini & Wink (1984)—CW1, CW2, and CW3—and Sources in the Cluster Regions for which Parallaxes Are Derived with Parallax-over-error >5

| Gaia Source ID | P (mas) | σP (mas) | ZP Corr | Pfinal (mas) | D (kpc) | Member? | Notes |
|---------------|---------|----------|---------|-------------|---------|---------|-------|
| **S209 main cluster** | | | | | | | |
| 271701112917796096 | 0.35 | 0.02 | −0.04 | 0.39 | 2.6 ± 0.2 | Y | CW1 |
| 271701009838634752 | 0.29 | 0.06 | −0.04 | 0.34 | 3.0 ± 0.6 | Y | CW2 |
| 271701112917794176 | 0.29 | 0.08 | −0.03 | 0.32 | 3.1 ± 0.6 | Y | CW3 |
| 271701009838583168 | 0.91 | 0.06 | −0.03 | 0.94 | 1.1 ± 0.1 | N | |
| 27170108615685760 | 0.39 | 0.02 | −0.04 | 0.43 | 2.3 ± 0.1 | Y | |
| **S209 sub-cluster** | | | | | | | |
| 271697951821873792 | 0.69 | 0.03 | −0.04 | 0.73 | 1.38 ± 0.05 | N | |
| 271701009838585856 | 1.80 | 0.03 | −0.04 | 1.84 | 0.54 ± 0.008 | N | |

Note. References are shown in the parentheses. Column (2): Absolute stellar parallax. Column (3): Standard error of absolute stellar parallax. Column (4): Parallax zero-point correction. Column (5): Final stellar parallax considering parallax zero-point correction. Column (6): Distance obtained from the parallax in Column 5 (Pfinal). Column (7): Possibility of whether each source is a member of S209. “Y” and “N” represent yes and no, respectively.

Log of Observations

| Mode          | Date       | Band | ttotal (1) | t (2) | coadd (3) | ntotal (4) | seeing | sky condition |
|---------------|------------|------|------------|-------|-----------|------------|--------|---------------|
| **J-long**    | Sep 3, 2006 | J    | 480 (360)  | 120   | 1         | 4 (3)      | 0"4   | P             |
| **H-long**    | Sep 3, 2006 | H    | 480 (360)  | 20    | 6         | 4 (3)      | 0"4   | P             |
| **Ks-long**   | Sep 3, 2006 | Ks   | 720 (540)  | 30    | 3         | 8 (6)      | 0"4   | P             |
| **J-short**   | Nov 8, 2006 | J    | 52 (39)    | 13    | 1         | 4 (3)      | 1"5   | H             |
| **H-short**   | Nov 8, 2006 | H    | 52 (39)    | 13    | 1         | 4 (3)      | 1"8   | H             |
| **Ks-short**  | Nov 8, 2006 | Ks   | 52 (39)    | 13    | 1         | 4 (3)      | 1"2   | H             |

Note. Column (1): Total exposure time (seconds). The values for the sky frames are shown in parentheses. Column (2): Single-exposure time (seconds). Column (3): Number of coadds. Column (4): Total number of frames. The values for the sky frames are shown in parentheses. Column (5): “P” refers to photometric, and “H” refers to high humidity.

short-exposure images was 52 s for all bands. We centered the images of S209 at α2000 = 04h11m09.3, δ2000 = +51°09′29″, so they covered the central region of the H II region described in Section 2.3 (see the white boxes in Figures 1 and 2 for the MOIRCS field; hereafter, the “S209 frame”). For background subtraction, we also obtained images of the sky (hereafter, the “sky frame”) away from the S209 nebulosity. For the long-exposure observations, the images were centered ~9′ north of S209, at α2000 = 04h11m09″, δ2000 = +51°18′24″ with a 4′ × 7′ field of view. For the short-exposure observations, they were centered 7 arcmin north of S209, at α2000 = 04h11m08″, δ2000 = +51°16′33″, which is slightly south of the sky frame used for the long-exposure images. The sky frames are shown as dashed white boxes in Figure 1). We summarize the details of the observations in Table 3.

3.2. Data Reduction and Photometry

We reduced all of the data in each band using standard IRAF procedures, including flat fielding, bad-pixel correction, median-sky subtraction, image shifts with dithering offsets, and image combination. We used sky flats kindly provided by the MOIRCS support astronomer, Dr. Ichi Tanaka, who obtained them using data from the closest run. In addition to the above standard procedures, we applied distortion corrections before combining the images using the “MCSRED” reduction package for the MOIRCS imaging data. We constructed a pseudocolor image of S209 by combining the long-exposure images for the J (1.26 μm, blue), H (1.64 μm, green), and Ks (2.15 μm, red) bands (Figure 3).

For the long-exposure images, we obtained photometry by fitting the point-spread function (PSF) using IRAF/DAPHOT. To derive the PSF, we selected stars that were bright but not saturated, with their highest pixel counts below the nonlinear sensitivity regime (20,000 ADU), that did not have any nearby stars with magnitude differences <4 mag. We performed the PSF photometry in two iterations using the ALLSTAR routine: the first used the original images, and the second used the images remaining after the sources from the first iteration had been subtracted. We obtained PSF-fit radii of 3.2, 3.5, and 3.5 pixels for the FWHMs in the J, H, and Ks bands, and we set the inner radii and the widths of the sky annuli to be, respectively, four and three times as large as the PSF-fit radii. We used the MKO standard GSPC P330-E (Leggett et al. 2006) to calibrate the photometry. Based on the pixel-to-pixel noise in the long-exposure images for the S209 frame, the 10σ limiting magnitudes are J ≈ 22.0 mag, H ≈ 21.0 mag, and Ks ≈ 20.6 mag. The limiting magnitudes are slightly different for MOIRCS channel 1 and channel 2, while those for the sky

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* IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

http://www.naoj.org/Staff/Ichi/MCSRED/mcsred_e.html
Figure 3. We produced this color image by combining the $J$ (1.26 μm)–, $H$ (1.64 μm)–, and $K_S$ (2.14 μm)–band images obtained with MOIRCS at the Subaru telescope in 2008 September. The field of view of the image is $\sim 4' \times 7'$. 
frames are $J \approx 22.4$ mag, $H \approx 21.2$ mag, and $K_S \approx 21.0$ mag. The limiting magnitudes in the all $JHK_S$ bands for the S209 frames are slightly brighter than those for the sky frames, despite the longer exposure times, probably due to the S209 frames being slightly brighter than those for the sky frames, as noted in Table 4.

Bright stars with magnitudes $J \lesssim 17$ mag, $H \lesssim 16$ mag, and $K_S \lesssim 15$ mag are saturated in the long-exposure images for both the S209 frames and the sky frames. We therefore used the short-exposure images for the photometry of such bright stars, employing the same procedure as for long-exposure images but using PSF-fit radii of 13, 15, and 10 pixels for the $J$, $H$, and $K$ bands, respectively. For the photometric calibration, we used stars for which magnitudes can be determined with small uncertainties in both the short- and long-exposure images (magnitudes $J < 18$ mag, $H < 17$ mag, and $K_S < 16$ mag, with magnitude uncertainties $<0.05$ mag). However, in the sky frames, note that the overlap between the long-exposure image and the short-exposure image was only about half of the field of view (Figure 1). Although it is possible to use only the overlapped area as the sky frame, we actually used the photometric data for all the stars in the frames of the long- and short-exposure images, aiming to obtain a higher signal to noise ratio by including the wider area, because we use the sky frames as control fields in later sections. The photometric results show that the short-exposure images are properly photometric in all $JHK$ bands for all sources with $K < 16.8$ mag—except for the saturation of very bright sources—and that the long-exposure images are properly photometric except for very faint sources with $K \gtrsim 16.8$ mag, which are below the sensitivity limit. Therefore, for the stars in the sky frame, we decided to use the long-exposure images for stars with $K \gtrsim 16.8$ mag and the short-exposure images for stars with $K < 16.8$ mag. For the stars in the S209 frame, we preferentially adopted infrared luminosities from the photometry obtained from the long-exposure images because they have higher sensitivities and higher angular resolution. Finally, in both the S209 and the sky frames, we found that very bright stars—with magnitudes $J \lesssim 12$ mag, $H \lesssim 11$ mag, and $K_S \lesssim 11.5$ mag—were saturated even in the short-exposure images. The photometry results for sources in the S209 frame are shown in the Appendix.

### 4.1. Identification of the Young Clusters

Using the pseudocolor image (Figure 3), we identified enhancements in the stellar density, compared to the surrounding area, on the northeast and southwest sides of the field observed with MOIRCS. Hereafter, we refer to these enhancements as the “main cluster” and the “sub-cluster,” respectively. Both clusters seem to be associated with, or at least are located close to, IRAS objects: the main cluster with IRAS 04073 +5102 and the sub-cluster with IRAS 04073 +5100.

First, we defined the cluster regions. We positioned many circles, each with a radius of 50 pixels ($\sim 6''$), in the S209 frame, moved the centers in 1 pixel steps, and counted the numbers of stars included in all the circles ($4.1 \pm 3.4$ stars on average). From these circles, we found two regions of localized high density that contain maxima in the numbers of stars (84 for the northern and 110 for the southern regions), and this enabled us to define the centers of the clusters with an accuracy of $\approx 5''$: $(\alpha_{2000}, \delta_{2000}) = (0^h41^m10^s.9, +51^\circ09'56.5'')$ and $(\alpha_{2000}, \delta_{2000}) = (0^h41^m03^s.7, +51^\circ07'53.8'')$. Figure 4 shows the radial variation of the projected stellar density using stars detected at 10$\sigma$ and above ($K_S \lesssim 20.5$ mag). The horizontal dashed gray lines represent the stellar density of a region located more than 800 pixels from the main cluster and more than 400 pixels from the sub-cluster (hereafter, the “background region”). We defined each cluster as a circular region with a radius defined such that the stellar density exceeds that of the entire sky frame by 3$\sigma$: 700 pixels (82$''$) for the main cluster and 350 pixels (41$''$) for the sub-cluster. The main and sub-cluster regions defined here are shown in Figure 5 as solid and dotted yellow circles, respectively. The estimated cluster radii of 82$''$ and 41$''$ correspond to 1.0 pc and 0.5 pc, respectively, at $D = 2.5$ kpc and to 4.1 pc and 2.1 pc at $D = 10$ kpc.

The main cluster corresponds to that identified as [BDS2003] 65 in Bica et al. (2003), and the existence of the sub-cluster was suggested by Klein et al. (2005) from a Midcourse Space Experiment (MSX) source and faint NIR emission. Both clusters are located near the region where the WISE band 3 (12 $\mu$m) emission is very strong (Figure 1); this combination is often seen in clusters (Koenig et al. 2012). Among the seven cores identified from millimeter-continuum emission by Klein et al. (2005; see Section 2.3)—which are shown as magenta squares in Figure 5—core 7 is closest to the center of the cluster, with an offset of $\sim 20''$, and cores 1, 2, 3, and 4 surround the cluster. In addition, the center of the sub-cluster is almost coincident with core 5.

The cluster region probably should be identified by comparison with the stellar density in the control field, rather than with that of the background region in the S209 frame. In Figure 4, the black horizontal solid lines represent the density of stars in the control field. They show that the stellar density in the control field is overall lower than that in the background region. This may be due to the occurrence of star-forming activities throughout the S209 frame, as suggested in Figures 1 and 2. For the S209 frame and control frame, we counted the number of stars in a circle of $r = 40$ pixels in 20 pixel steps. In the control field, the number is estimated to be $N = 2.8 \pm 2.1$. Based on the counts in the control field, the distribution of the counts in the S209 frame is shown as dotted contours for 1$\sigma$ and 2$\sigma$, and solid contours for 3$\sigma$, 4$\sigma$, ..., and 23$\sigma$ (Figure 5). This figure also shows the high counts compared to the control field over the entire S209 frame, except for a part of area in the

### 4. The Two Young Clusters in S209

In this section, we identify the two star-forming clusters found in the MOIRCS NIR images and study their reddening properties. To reduce contamination by foreground stars and enable the mass-detection limit to extend below $\sim 0.1$ $M_{\odot}$, we next extract a sample from each cluster for delimited ranges of extinction and mass, which we term “mass-A$_V$-limited” samples (see Section 4.3). We use these samples to derive the cluster KLFs, which we employ in later sections to obtain reliable IMFs by fitting them to the model KLFs.

### Table 4

| Target | $J$ (ch1/ch2) | $H$ (ch1/ch2) | $K_S$ (ch1/ch2) |
|--------|--------------|--------------|-----------------|
| Cluster | 21.9/22.0 | 20.9/21.0 | 20.5/20.7 |
| Sky    | 22.3/22.4 | 21.2/21.2 | 20.8/21.0 |
north, indicating the presence of star-forming regions over the entire frame. The identified clusters generally cover a region of 3σ or larger, while there are regions with higher density than the control field over a wider area, and the star-forming cluster may actually be a bit larger than defined here.

A similar situation is seen in the well-known nearby star-forming region IC 348, as suggested by, e.g., Muench et al. (2003). They defined the central region as the “core” and the surrounding region as the “halo.” Using this nomenclature, we are discussing the star-forming activities in the core region of S209 in the present paper. As the main purpose of this paper is to derive the IMF more precisely in a low-metallicity environment, we therefore limit the cluster regions strictly as a first step. This avoids defining cluster regions that are too large, which would lead to a large age spread and the inclusion of many generations of star formation activity. We have been working on multiwavelength observations in a larger area of S209 (see N. Izumi et al. 2022, in preparation, for radio observations using the NRO 45 m radio telescope and the Very Large Array) to elucidate the star formation history in this region. We will discuss the differences in the IMF at different locations in the clusters along with these results in future work.

4.2. Reddening Properties

Stars in star-forming regions often exhibit both extinction due to the interstellar medium and to the intracluster medium, as well as an infrared color excess due to circumstellar media such as dust disks (e.g., Lada & Adams 1992). Using the JHK color–color diagram, we estimate the extinction and infrared excess of each source, and derive the distributions of extinction and infrared excess for the S209 clusters. We constructed $J - H$ versus $H - K_S$ color–color diagrams for stars in the S209 main and sub-cluster regions in the left and right panels of Figure 6, respectively. All sources that are detected at more than 10σ in all $JHK$ bands are plotted. The dwarf-star track from Yasui et al. (2008b) for spectral types from late B to M6 in the MKO system is shown as a blue curve in each panel. The locus of classical T Tauri stars (CTTS), originally derived by Meyer et al. (1997) in the CIT system, is shown as a cyan line in the MKO system (Yasui et al. 2008b). The arrow shows the reddening vector for $A_V = 5$ mag.

We derived the distributions of extinction and infrared excess for the S209 clusters, which we use in Section 6.1 as probability distribution functions for modeling. First, we determined the extinction and the infrared excess for each source in the S209 cluster regions using the JHK color–color diagram following the procedure of Muench et al. (2002). We estimated the extinction ($A_V$) and the intrinsic $(H - K)$ color $[(H - K)_0]$ for each star by dereddening it along the reddening vector to the young-star locus in the color–color diagram. For convenience, we approximated the young-star locus by extending the CTTS locus, and we used only those stars that are above the CTTS locus. We derived the $A_V$ values based on the distance required to achieve the obtained amount of dereddening with the reddening law of Rieke & Lebofsky (1985). When each star is dereddened to the young-star locus on the color–color diagram, we regard the $H - K$ value on the young-star locus as $(H - K)_0$. The obtained distributions of $A_V$ and $(H - K)_0$ are shown as thick lines in Figures 7 and 8, respectively.

The obtained distributions include all sources in the cluster regions, some of which are expected to be foreground or background stars. To remove these effects, we also derived the distributions in the control field. Using the JHK color–color diagram for stars in the control field, shown in Figure 9, we derived distributions of $A_V$ and $(H - K)_0$. The obtained distributions were normalized to match the total area of each cluster region and are shown as thin lines in Figures 7 and 8. Figure 7 shows the distribution obtained by subtracting the distribution for stars in the control field from the distribution.

Figure 4. Radial variation of the projected stellar density of stars (filled circles) in the Sh 2-209 main-cluster region (left) and the sub-cluster region (right). The error bars represent Poisson errors (3σ). The gray horizontal solid lines and dashed lines represent the density of stars in the background region and their Poisson errors (3σ), respectively. The black horizontal solid lines represent the density of stars in the control field.
for stars in the cluster regions—the red lines—which we consider to be the distribution for cluster members.

The $A_V$ distribution for stars in the control field decreases monotonically as the $A_V$ value increases, and it becomes almost zero at $A_V = 5$ mag. In contrast, the distributions for stars in both cluster regions increase from $A_V = 0$ mag to 7–8 mag and then decrease, and they become almost zero at $A_V = 20$ mag. We therefore consider that most of the stars with large $A_V$ values belong to the star-forming region. The reason why stars in the cluster region have such large $A_V$ values may be that they are subject to large extinction by the interstellar medium due to the relatively large distance to S209. In addition, the large dispersion of the $A_V$ values suggests that star-forming molecular clouds still exist in this star-forming region.

The $(H - K)_0$ distributions for stars in both cluster regions and in the control field increase from $(H - K)_0 = 0$ mag to 0.2–0.3 mag and then decrease. The distributions for the cluster stars extend up to $(H - K)_0 \approx 1.5$ mag, whereas the distribution for field stars reaches zero around $(H - K)_0 = 0.8$ mag. The larger $(H - K)_0$ values for stars in the cluster region are due to the color excess produced by circumstellar material around the young stars. Here, we assume that this excess is only a $K$-band excess ($K$-excess). We estimate the average value of $(H - K)_0$ for stars in the control field to be 0.3 mag, and—for simplicity—we use this as a typical $(H - K)_0$ value for stars without circumstellar material $[(H - K)_0,\text{crit} = 0.3]$.

We consider stars with $(H - K)_0 \geq (H - K)_0,\text{crit}$ to be stars with a $K$-excess, which we define as $(H - K)_0$ minus $(H - K)_0,\text{crit}$, while stars with $(H - K)_0 \leq (H - K)_0,\text{crit}$ are considered to be stars without a $K$-excess. The resulting distributions of $K$-excess are shown in Figure 10. The distributions for stars in the S209 main and sub-cluster regions...
are shown in the left and right panels, respectively. As in Figures 7 and 8, distributions for stars in the cluster regions are shown with thick lines, while those for stars in the control field are shown with thin lines. The subtracted distributions are shown with red lines. In a later section, we use the subtracted distributions of stars for the S209 main and sub-clusters to construct model KLFs when evaluating the IMF.

4.3. Mass-\(A_V\)-limited Samples

In this section, we extract mass-\(A_V\)-limited samples from the color–magnitude diagram for each cluster. In our previous papers about young star-forming clusters in low-metallicity environments in the Galaxy, we used the \(J - K\) versus \(K\) color–magnitude diagram to select members of star-forming clusters (e.g., Yasui et al. 2021). The main goal of that paper was to obtain rough estimates of the cluster IMF and age and to identify stars with protoplanetary disks. In contrast, the aim of the present paper is to derive a precise IMF down to the regime of substellar masses. Because stars in star-forming regions usually have large extinctions—especially for targets at large distances—the longer NIR wavelengths are more effective for deep detections (Muench et al. 2002). Here, we therefore used the longer-wavelength \(H - K\) versus \(K\) color–magnitude diagram to select star-forming cluster members.

We constructed the \(H - K_S\) versus \(K_S\) color–magnitude diagrams for the point sources detected in the S209 cluster regions (Figures 11 and 12 for the main and sub-cluster regions, respectively). All point sources that are detected with more than 10\(\sigma\) in both the \(H\) and \(K_S\) bands are shown. The dashed lines mark the 10\(\sigma\) limiting magnitudes. The CW sources (CW1, CW2, and CW3) are shown as filled circles labeled with their names. Stars that are very bright and that are saturated in the MOIRCS images are also plotted in this figure, shown with the open squares.

The gray lines in these figures show isochrone tracks: from Lejeune & Schaerer (2001) for masses \(M/M_\odot > 7\); from Siess et al. (2000) for the mass range \(3 < M/M_\odot \leq 7\); and from D’Antona & Mazzitelli (1997, 1998) for the mass range \(0.017 < M/M_\odot \leq 3\). Because the distances and ages remain to be determined for the two S209 clusters, we assumed the distance to be either 2.5 kpc, which is the astrometric distance from Gaia EDR3, or 10 kpc, which is the kinematic/photometric distance (see Section 2). Also, because the ages of these clusters are not yet known, for the S209 main cluster, we used isochrone tracks here for the ages 0.5 and 5 Myr as examples. These ages correspond to the youngest and oldest extreme cases for which young stars still have disks traced with \(K\)-band excess (Lada 1999; Yasui et al. 2010). In the sub-cluster, we used the intermediate age of 3 Myr. The tickmarks on the isochrone models, which are shown in the same colors as the isochrone tracks, correspond to the positions of stellar masses 0.1, 1, 3, 5, 10, 20, 30, 40, and 60 \(M_\odot\). The arrows show the reddening vector for \(A_V = 10\) mag.

Here, we define the mass-\(A_V\)-limited sample for each assumed distance and age. To limit the extinction range, we note that Figure 7 shows that the number of stars in the control field is large when \(A_V\) is smaller, so more contamination is expected to exist in both cluster regions in this \(A_V\) range. Therefore, we set the minimum value of \(A_V\) to be 4 mag in selecting the \(A_V\)-limited samples, so that the number of stars in the cluster region is significantly larger than that in the control field. On the large-\(A_V\) side, for \(A_V > 10\) mag there are almost no stars in the control field. Therefore, the larger the value of \(A_V\), the more stars can be extracted in the cluster field. However, if the extinction range is set to a very large value, the mass-detection limit becomes large, even though the number of stars in the cluster is not very large. To take smaller masses into account in deriving the IMF, the upper limit of the \(A_V\) range must therefore be a reasonable value. In this case, we set \(A_V = 15\) mag, which allows the mass-detection limit to extend.
regions are shown as thick lines, while those in the control field are shown as thin lines. The distributions for stars in the control field are normalized to match the total area of each cluster region. The distributions obtained by subtracting the normalized distribution for stars in the control field from the distribution for stars in the cluster regions are shown as red lines.

down to $\lesssim 0.1 M_\odot$ for ages $\leq 5$ Myr at the distance of 2.5 kpc (0.04 $M_\odot$ for 0.5 Myr and 0.09 $M_\odot$ for 5 Myr), while it only reaches $\lesssim 1.0 M_\odot$ for the distance of 10 kpc (0.25 $M_\odot$ for 0.5 Myr and 1.0 $M_\odot$ for 5 Myr).

Similarly to the lower-mass stars, the estimated masses of higher-mass stars vary greatly with the assumed age and distance. At a distance of 2.5 kpc and an age of 0.5 Myr, the masses of CW1 and CW2 are both estimated to be $\sim 10 M_\odot$ and that of CW3 is $\lesssim 1 M_\odot$. In contrast, at the same distance but an age of 5 Myr, the masses of CW1 and CW2 are again estimated to be $\sim 10 M_\odot$ while that of CW3 becomes $\sim 3 M_\odot$. Conversely, at the distance of 10 kpc and an age of 0.5 Myr, the masses of CW1 and CW2 are estimated to be $\sim 40 M_\odot$ while that of CW3 is $\lesssim 10 M_\odot$. Finally, for the same 10 kpc distance but an age of 5 Myr, the masses of CW1 and CW2 are estimated to be $\sim 20–30 M_\odot$ while that of CW3 becomes $\sim 10 M_\odot$. We discuss this issue further in Section 5.2.

In Figures 11 and 12, the mass-$A_V$-limited samples selected here are shown in red, while others are shown in black. Because the samples obtained here do not completely exclude foreground (and sometimes background) sources, we obtained a pseudo-mass-$A_V$-limited sample for the control field using the same method as for the cluster regions (Figure 13). By subtracting the number of pseudo-sources obtained in the control field—which we normalized to match the total area of each cluster region—from the number of sources in each cluster region, we estimate the final numbers of sources for the S209 main and sub-clusters to be $\sim 1500$ and 350, respectively.

### 4.4. Cluster KLFs

We constructed the KLF for each cluster using the mass-$A_V$-limited samples extracted in Section 4.3, assuming various ages (0.5–10 Myr) and distances (2.5 and 10 kpc). Figure 14 shows an example for an age of 3 Myr and a distance of 2.5 kpc. In this figure, the KLFs for sources in the cluster regions (the cluster region KLFs) are shown with thick black lines, and those for sources in the control field (the control field KLF) are shown with thin lines (the main and sub-clusters are shown in the left and right panels, respectively). The control field KLF is normalized to match the total area of each cluster region. We subtracted the normalized counts from the control-field KLF from the counts for each cluster region KLF to obtain the cluster KLFs, which are shown as thick red lines in Figure 14. For the distances and ages assumed here, the KLFs for the S209 clusters increase monotonically up to $K \sim 18$ mag for both clusters, peak in the 18.0–18.5 mag bins for the main cluster and in the 17.5–18.5 mag bins for the sub-cluster, and then decrease at still larger $K$ magnitudes.

Because the ages and distances of the S209 clusters are not yet known, we derived the cluster KLFs using the same method for different distances and ages. In Figure 15, the black filled symbols and gray open symbols show the results for distances of 2.5 kpc and 10 kpc, respectively (the left and right panels for the main and sub-clusters, respectively). For both clusters, the KLF increases almost monotonically up to the peak magnitude, and then decreases monotonically. For the same distance, the peak magnitude of the KLF is independent of age over the entire range 0.5–10 Myr, but the peak value is different at different distances (18.0–18.5 mag for the 2.5 kpc distance and 18.5–19.0 mag for the 10 kpc distance for the main cluster; 17.5–18.5 mag for the 2.5 kpc distance and 18.5–19.0 mag for the 10 kpc distance for the sub-cluster).

In general, the KLF peak reflects the IMF peak. However, the counts may just appear to decrease after $K \sim 18$ mag due to the way in which we extracted the mass-$A_V$-limited sample here. In fact, the color–magnitude diagrams (Figures 11 and 12) show that for $K \lesssim 18$ mag there are stars in all $A_V$ ranges, whereas for $K \gtrsim 18$ mag there are stars only in the larger $A_V$ ranges. In particular, the counts in the faintest K-magnitude bin are extremely low for the same reason that the range of $A_V$ sampled for the faintest stars in K magnitudes is very narrow in the diagram. We discuss this point further in Section 7.1.

In later sections, we compare the cluster KLFs obtained here with model KLFs to derive the IMFs. In creating the model KLFs, we consider the same mass-$A_V$-limited sample as for the observations. A similar method was used for the Trapezium cluster by Muench et al. (2002). However, for nearby clusters such as Trapezium, it was necessary to consider background sources as contamination in addition to foreground sources. The background sources are complicated to consider because
they can be subject to reddening by molecular clouds in star-forming regions. In contrast, for a region in the outer Galaxy, previous studies have shown that most of the contamination can be considered as due to foreground objects (Yasui et al. 2008b, 2016a, 2021), so it is not necessary to take into account the complex reddening of background sources; instead, we can simply subtract the number of stars.

5. Discussion of Results from MOIRCS NIR Imaging

Based on the results obtained from NIR imaging in Section 4, we here further discuss the two young S209 clusters. We discuss the masses of high-mass stars from the color–magnitude diagram in Section 5.1; discuss which distance is most reliable, 10 kpc (kinematic/photometric distance) or 2.5 kpc (astrometric distance) in Section 5.2; and summarize the scales of the clusters in Section 5.3.

5.1. High-mass Stars in the S209 Region

From spectroscopic observations by Chini & Wink (1984), the spectral types of CW1 and CW2—two of the three sources that are particularly bright at optical wavelengths—are estimated to be B1 III and O9 III, respectively (see Section 2.1). These spectral types correspond to masses of about 20 $M_\odot$ (Drilling & Landolt 2000). On the NIR color–magnitude diagram (Figure 11), these two sources are shown by large circles labeled with their names. This figure shows that the K-band magnitudes for stars $\geq 10 M_\odot$ become brighter as the cluster age increases from 0.5 Myr to 5 Myr. From this diagram, the masses of CW1 and CW2 for the distance of $D = 10$ kpc are estimated to be $\sim 40 M_\odot$ at the very young age of 0.5 Myr, while they lie between 20 and 30 $M_\odot$ at an age of 5 Myr; all of these masses are larger than 20 $M_\odot$. Conversely, assuming $D = 2.5$ kpc, their masses are estimated to be $\sim 3–10 M_\odot$ at the very young age of 0.5 Myr and $\lesssim 10 M_\odot$ at 5 Myr, which are all smaller than 20 $M_\odot$. None of the masses estimated here agree very well with the masses obtained from the spectral types, assuming either distance. This is probably due to the fact that the spectral type was derived using photographic plates (not a CCD as in the present observations), which may lead to large uncertainties in the derivation of the spectral types. For example, the mass of a B5 III star—a slightly later type than B0—is 7 $M_\odot$, which seems to be consistent with the estimate for $D = 2.5$ kpc. Conversely, the mass of the slightly earlier type O6 V is 37 $M_\odot$, which seems to be consistent with the estimate for $D = 10$ kpc. Therefore, it seems that no strong constraints can be imposed from the CW sources.

Although the previous study considered stars that are bright at optical wavelengths, in the NIR bands we detected two brighter stars in the S209 cluster region. Because these star images are saturated in the MOIRCS images, we obtained their magnitudes from the 2MASS Point Source Catalog (Skrutskie et al. 2006). They are shown with open squares in Figure 11. Of these two, 2MASS 04110946+5110005 [$K$ (2MASS) = 10.295, $H$ (2MASS) = 10.877, and $J$ (2MASS) = 11.932] is

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10 The values of masses are from Drilling & Landolt (2000), but the values in luminosity class V are used for those without information on luminosity class III below.
the brightest source in the K band, suggesting that it is the highest-mass source. It is located about 8′ south of CW3, which is located near the center of the S209 main cluster. The location of this star near the center of the main cluster, together with the fact that its estimated extinction is large (>10 mag, from the color–magnitude diagram), suggests that this star is located within S209 and that it is the most massive source, which is responsible for exciting the H II region. From the NIR color–magnitude diagram, the mass of this star is estimated to be about 20 $M_\odot$ at $D = 2.5$ kpc for the cluster age of 0.5–5 Myr, whereas it is estimated to be $\gg 60 M_\odot$ at $D = 10$ kpc for a young age of 0.5 Myr. The KLF fitting in a later section (Section 6.2) suggests that an age of 5 Myr is most plausible at $D = 2.5$ kpc, whereas an age of 0.5 Myr is considered most plausible at $D = 10$ kpc (although the probability of this was very small and was rejected from the fitting results). Because the cluster mass of S209 is estimated to be about $\sim 1000 M_\odot$ (see Section 2.3 and estimates in later sections), the relation between the maximum stellar mass and the cluster mass (Weidner & Kroupa 2006) suggests that the maximum stellar mass is consistent with $\sim 20 M_\odot$, while 60 $M_\odot$ seems to be too large. Therefore, $D = 2.5$ kpc seems to be the more plausible distance. However, note that analyses based on individual high-mass candidates identified toward the clusters, some of which have previously determined spectral types, allowed relatively weak constraints on their individual masses and hence on the clusters distances and ages. Stronger constraints will be presented in Section 6, where a full modeling of the clusters KLF will be discussed.

5.2. Implications for the Distance of S209 from Gaia Sources

In Section 2.1, we checked the astrometric distance from Gaia EDR3, but only for the CW sources, and we found the distance to be 2.5–3.0 kpc. However, we cannot yet reject the possibility that the three CW sources may not lie within S209. In the MOIRCS images, a bright rim can be seen in the region of the main cluster in the direction from west to north (Figures 3 and 5). This rim has a very similar morphology to the ring-like morphology of the molecular cores—traced with millimeter-continuum emission in Klein et al. (2005)—that surrounds the S209 main cluster around Core 1. The NIR image shows a dark region just outside this rim, as judged by the very low stellar density (Figure 5), suggesting that the bright rim is located at the boundary between the molecular cloud and H II region, where a shock is thought to occur (Elmegreen & Lada 1977). The rim is particularly bright in the west, and it overlaps CW1, or may even originate from CW1. The right panel of Figure 4 shows an enlargement of the MOIRCS $K_s$-band image around CW1 ($20^\prime \times 20^\prime$). This suggests that the star is at least in the region where star formation activity is occurring.

In addition to the CW sources, we also checked the astrometric distances from Gaia EDR3 for all sources in the cluster regions for which the parallaxes divided by parallax errors are $\geq 5$ (Table 2). We identified two other sources in the main cluster region; they have the Gaia source IDs 271701009838585856. Following the same procedures that we used for the CW sources (Section 2.1), we found the distances to these sources to be $1.1 \pm 0.1$ and $2.3 \pm 0.1$ kpc, respectively. The distance to the latter source is relatively close to those of the CW sources while the distance to the former source is much different, suggesting that only the latter source lies within the S209 region. Because the latter source is located near the center of the S209 main cluster, where some bright (and therefore relatively massive) stars exist, while the former source is located at the edge of the cluster region, this is a consistent result.

Two other sources in the sub-cluster region also have parallaxes obtained from Gaia EDR3 for which the parallaxes divided by parallax errors are $\geq 5$: they have the Gaia source IDs 271697951821873792 and 271701108615685760. Following the same procedures that we used for the CW sources (Section 2.1), we found the distances to these sources to be $1.38 \pm 0.05$ and $0.544 \pm 0.008$ kpc, respectively, which are significantly different from the estimates for the S209 cluster (2.5–3.0 kpc). This may suggest that this region is in a different location from the main cluster to the north. However, because it seems somewhat unnatural that completely different star-forming regions should exist coincidentally in a very close regions on the sky (the separation between the centers of the two clusters is only 2′3),
it is likely that the two objects for which Gaia parallaxes were obtained with relatively high accuracy do not lie within S209; instead, they are likely to be foreground stars. In fact, our radio observations \((N. Izumi et al. 2022, in preparation)\) indicate that the molecular clouds associated with the main and sub-clusters both exist at \(\sim -50 \text{ km s}^{-1}\), suggesting that both clusters exist in the same location.

The four sources identified here from Gaia EDR3 and the CW sources are shown as large filled circles in the color–magnitude diagrams (Figures 11 and 12 for the S209 main and sub-cluster regions, respectively). For the main cluster region, Gaia 271701009838585856 has small extinction from its position, \((H-K, K) = (0.1, 14)\), while Gaia 271701009838583168 exhibits large extinction from its position, \((H-K, K) = (0.6, 11)\). The former source is included in the mass-\(A_V\)-limited sample in Section 4.3 (hence shown in red), while the latter source is not included in the sample (hence shown in black). This also supports the idea that only the former is a foreground star. Meanwhile, for the sub-cluster region, both Gaia sources (Gaia 271701009838585856; shown with black filled circles) exhibit relatively small extinctions, from their respective positions: \((H-K, K) \approx (0.3, 13)\) and \((H-K, K) \approx (0.2, 12.6)\), respectively. Both show marginal colors, whether or not they are included in the mass-\(A_V\)-limited sample, but there is no major contradiction in considering them as foreground stars. Table 2 shows whether each Gaia source is likely to be a member of S209 (column 7). The Gaia survey is still an ongoing project, and more precise distance derivations will be released in the future. To derive the most reliable distances from the current data, we calculated the weighted averages of the distance for the objects considered here to be members of S209, considering the standard errors of the absolute stellar parallax \((\sigma_p)\).
for each object. The weighted average is calculated to be 2.5 kpc, which we adopt as the astrometric distance in later sections.

5.3. Size Scales of the Clusters

Most stars are formed almost simultaneously in star-forming clusters, which are the smallest units of star formation (Lada & Lada 2003). For young clusters in the solar neighborhood, there is a clear correlation between cluster size and the number of cluster members from their embedded stage up to ages of \( \sim 10 \) Myr (Adams et al. 2006), as shown by the open squares in Figure 16. The figure shows that most clusters contain \( \sim 10–500 \) cluster members (\( N_{\text{stars}} \)) and have radii \( R \sim 0.2–2 \) pc. Adams et al. (2006) suggested that the data can be fitted by a relation of the form \( R(N_{\text{stars}}) = R_{300} \sqrt{N_{\text{stars}}}/300 \) with \( R_{300} = \sqrt{3} \) pc. This relation is shown in Figure 16 as a solid line, and most data points are scattered within a factor of \( \sqrt{3} \) of \( R_{300} \), shown with dotted lines.

In Section 4, we identified two clusters in S209—the main cluster and the sub-cluster—and we extracted mass-\( A_V \)-limited samples for both clusters. We found the main cluster to have \( \sim 1500 \) cluster members within a circular region of radius 82\( ' \), whereas the sub-cluster has \( \sim 350 \) cluster members within a circular radius of radius 41\( ' \). Because 1\( ' \) corresponds to 0.75 pc at the 2.5 kpc distance of S209, these cluster radii for the main and sub-clusters correspond to 1.0 and 0.5 pc, respectively. We plot the values for the S209 main and sub-clusters in Figure 16 as red and blue filled circles, respectively. The plot shows that both clusters have radii comparable to those of star-forming clusters in the solar neighborhood (\( r \sim 1 \) pc), suggesting that the S209 clusters can be considered to have similar scales to those of individual star-forming clusters in the solar neighborhood. However, they have relatively large values of \( N_{\text{stars}} \) (the main cluster has among the largest values of \( N_{\text{stars}} \) compared to nearby clusters; it is comparable to that of ONC/Trapezium). Thus, although the two S209 clusters have comparable densities, both densities are higher than the range shown by the dotted line on the high-density side of the diagram, second only to that of the Trapezium cluster. Although there are two possible distances for S209—2.5 kpc and 10 kpc (see Section 2.1)—we present the 2.5 kpc distance case here because the discussion in Sections 5.1 and 5.2 suggests that 2.5 kpc is more plausible. However, for completeness, we also show the 10 kpc case in Figure 16, using red and blue open circles for the S209 main and sub-clusters, respectively. In either case, the result that the S209 clusters are comparable in size to the scale of individual clusters is confirmed.

In the following sections, we derive the IMFs for the S209 clusters. Note that these clusters constitute a very good laboratory for exploring the metallicity dependence of the IMF because they are individual star-forming clusters that have the same spatial scale as in the local region of the Galaxy (\( \sim 1 \) pc), but they exist in a different metallicity environment. In addition, the high spatial resolution enables 1000 au separations to be resolved—as estimated for the seeing of \( \lesssim 0.4 \) (Section 3.1)—at a distance of 2.5 kpc. In particular, the main cluster is a very suitable target for the first high-precision derivation of the IMFs in low-metallicity clusters because it is the first large-scale target (\( N_{\text{stars}} > 10^3 \)) in a low-metallicity environment with detections down to the substellar mass region (\( \lesssim 0.1 M_\odot \) from Section 4.3).

6. Derivation of the S209 Clusters’ IMFs

In general, information about the ages of regions and individual stars is necessary in order to derive the IMF. There are two main methods for determining the age: one is to combine imaging and spectroscopic observations, and the other is to use only imaging observations. In the former method, the temperature of each star is determined from spectroscopic observations and the luminosity from imaging observations, and the age and mass of each star is derived by comparing these data with stellar-evolution tracks in the H–R diagram. This method has often been used to derive IMFs for nearby star-forming regions (e.g., Hillenbrand 1997; Luhman et al. 2000). However, this method is not very practical when dealing with somewhat distant regions such as the target here, because it requires too much observation time to achieve sufficient sensitivity, and it is therefore difficult to derive the IMF down to sufficiently low stellar masses.

The latter method has often been used to derive ages by comparing imaging observations with stellar-evolution tracks in a color–magnitude diagram. Classical methods derive the age of a star cluster from the property that stars in the cluster...
turn to the red as they leave the main sequence. However, these methods can only be used for relatively old regions (>10 Myr) or for regions with large numbers of massive stars. The presence of an HII region in S209 (Section 2.3) and the fact that it appears very red in NIR and MIR images suggest that it is very young (<10 Myr). It is therefore difficult to apply this method to S209. Recently, various attempts have been proposed for determining ages by using NIR wavelengths as well as optical wavelengths (see Soderblom et al. 2014), but S209 has large extinction and large infrared disk excesses ($A_V \sim 4$–15 mag and a K-excess of $0$–1.0 mag)—as well as large dispersions in these values—making it difficult to derive ages using these methods due to the large color dispersion of the stars.

In this paper, we therefore derive the IMF and the cluster age simultaneously as a set, rather than deriving the age independently. The KLF has often been used to derive the IMF because it has a large dependence on the IMF (Lada & Lada 1995). Because the KLF is also known to be highly dependent on age (Muench et al. 2000), we here consider both the cluster age and the IMF as parameters, and we determine the most reliable age and IMF together by comparing model KLFs with the KLFs obtained from observations of the S209 clusters. Although there are two different possibilities for the distance of S209—10 kpc and 2.5 kpc (Section 2.1)—because the discussion in Section 5 (in particular, Section 5.2) suggests that 2.5 kpc is more plausible, we primarily consider this distance here.

### 6.1. Modeling of the S209 Clusters’ KLFs

In this section, we discuss how to construct model KLFs for the S209 clusters, and we use them to derive the cluster IMF from the observational cluster KLF obtained in Section 4.4. Our modeling of the cluster KLF basically follows the method of Muench et al. (2000, 2002). They derived the IMF for the ONC cluster from the KLF obtained in the solar neighborhood. We utilized only two break masses because the S209 clusters’ KLFs appear to show at most one cycle of an increasing-then-decreasing pattern: $m_1$, where the IMF transitions from decreasing to roughly flat, and $m_2$, where the IMF transitions from flat to decreasing. In our modeling, we first generated stars with masses determined probabilistically according to the IMF defined here. The IMF mass range is set to include all possible ranges that can be obtained from the mass-$A_V$-limited samples at each assumed age and distance.

Our specific procedure is as follows. First, we assume that the IMF follows a power law: $dN/d\log m \propto m^{\alpha}$. The IMFs obtained in the solar neighborhood have negative slopes when the mass is relatively high ($>1 M_\odot$), and the slope becomes constant or positive when the mass exceeds a certain value (e.g., Elmegreen et al. 2008; Bastian et al. 2010). Based on this behavior, we define the mass at which the slope changes to be the “break mass.” Actually, in the S209 clusters’ observed KLFs, as the magnitudes become fainter (i.e., as the mass gets smaller), the counts are seen first to increase and then to decrease. Although Muench et al. (2002) employed three break masses—because their KLF shows a tendency to increase, decrease, and then increase again—we utilized only two break masses because the S209 clusters’ KLFs appear to show at most only one cycle of an increasing-then-decreasing pattern: $m_1$, where the IMF transitions from decreasing to roughly flat, and $m_2$, where the IMF transitions from flat to decreasing. In our modeling, we first generated stars with masses determined probabilistically according to the IMF defined here. The IMF mass range is set to include all possible ranges that can be obtained from the mass-$A_V$-limited samples at each assumed age and distance.

At this stage, it is not clear whether the turnover in the S209 clusters’ KLF counts reflects a similar trend in the IMF (Section 4.4), and the actual IMF can take one of three possible shapes: a one-power law (a monotonic increase), a two-power law (an increase followed by an almost flattening), or a three-power law (a decrease followed by a flattening and an increase). Therefore, the two break masses are allowed to overlap for all three possibilities to be represented. This allows a one-power-law IMF to be represented by two break masses, both taking the minimum value of the mass range; a two-power-law IMF to be represented by two break masses that can take values other than the minimum or maximum value of the mass range; and a three-power-law IMF represented by two different break masses that can take values other than the minimum or maximum of the mass range.

The masses we obtained next need to be converted to magnitudes. We determined the NIR luminosities using the mass–luminosity ($M$–$L$) relation at each age. We used the $M$–$L$ relations employed in Section 4.3 for the isochrone tracks in the color–magnitude diagram (Figures 11 and 12). After

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**Figure 13.** Same figure as Figure 11, but for the control field. For reference, isochrone tracks for an age of 3 Myr and a distance of 2.5 kpc (10 kpc) are shown in the left (right) panel.
We generated the reddening taking the distance into account, we added the effects of converting to luminosities and then to NIR magnitudes by finding that variations in the cluster-age spread have only a small effect on the form of the KLF and would likely be difficult to distinguish observationally. In addition, in this paper we defined the cluster region strictly as a first step in deriving the IMF for this region (Section 4.1) in order to avoid a large age spread and the inclusion of star-forming activity. However, the cluster in reality will have a certain age spread, which may vary significantly depending on the metallicity. We will therefore revisit this question in future work, in combination with the results of ongoing multi-wavelength observations of a large area of S209, in order to elucidate the star formation history in this region.

3. Selection of isochrone models: Muench et al. (2000, 2002) found that variations in the pre-main-sequence (PMS) $M$–$L$ relation, which result from differences in the adopted PMS tracks, produce only small effects in the form of the model luminosity functions, and these effects are mostly likely not detectable observationally. Here, we adopted standard PMS isochrone models: D’Antona & Mazzitelli (1997, 1998) for the low-mass side and Siess et al. (2000) for intermediate masses. Both sets of models are included among the models discussed by Muench et al. (2000, 2002). Because the targets here—the S209 clusters—are located in a low-metallicity environment, models with such metallicities must be considered. D’Antona & Mazzitelli (1997, 1998) and Siess et al. (2000) included models for $Z = 0.01$ (i.e., $[\text{M/H}] = -0.3$). In addition, Baraffe et al. (1998) provided models with $[\text{M/H}] = -0.5$ (for the mass range 0.079–1.0 $M_\odot$ and the age range >2 Myr), which is also included in the discussion in Muench et al. (2002). Baraffe et al. (1997) also provided models with $[\text{M/H}] = -2.0$ to $-1.0$. We compared these models to the solar-metallicity models and confirmed that differences in the $M$–$L$ relation due to changes in metallicity within the same group of models were very small. We also found the metallicity differences to be significantly smaller than the differences among the models by different groups. Therefore, we adopted the models with solar metallicity ($[\text{M/H}] = 0.0$) here.

Figure 14. Examples of cluster KLFs for the S209 main cluster (left) and sub-cluster (right). Both examples are for an age of 3 Myr and a distance of 2.5 kpc.
6.2. Best-fit IMFs

By comparing the model KLFs obtained in Section 6.1 with the S209 cluster KLFs obtained in Section 4.4, we derived a reduced $\chi^2$ and probability for each model KLF. The parameter ranges are essentially the same as those in Muench et al. (2002) ($\Gamma_1 = -2.0$ to $-1.0$, $\Gamma_2 = -0.4$ to $0.4$, $\Gamma_3 = -0.4$ to $2.0$, $\log m_1 = -1.1$ to $0.1$, and $\log m_2 = -1.4$ to $0.1$). However, we have made some changes to these values. First, we chose the wider range $\Gamma_1 = -2.0$ to $+0.5$, because this parameter can be either larger or smaller than the Salpeter IMF index, which is generally found in the solar neighborhood. We set the minimum values of $\log m_1$ and $\log m_2$ to be the minimum mass used in the modeling for each age (Section 6.1), although we fixed their maximum values to be 0.1, as in Muench et al. (2002). We assume that the parameters $\log m_1$ and $\log m_2$ satisfy $\log m_1 \geq \log m_2$ within these ranges.

The best-fit IMF results we obtained for each age for the S209 main and sub-clusters are shown in Tables 5 and 6, respectively. For the S209 main cluster, we obtained a reduced $\chi^2$ value of almost 1 at 5 Myr, corresponding to a probability of 50%, and we obtained larger values for both younger and older ages. For the S209 sub-cluster, the $\chi^2$ value takes its smallest value at 3 Myr (1.01), corresponding to a probability of 72%, and here, too, we obtained larger values for both younger and older ages. In Figures 17 and 18, respectively, we also show the model KLFs and IMFs for S209 main and sub-clusters using the parameters for the best-fit IMFs.

For completeness, we also calculated the cases for which the distance is 10 kpc. We show these results in Tables 7 and 8 for the S209 main and respectively. For the main cluster, although we obtained a smaller reduced $\chi^2$ when we assumed a younger age, even for the youngest age assumed here (0.5 Myr), the value of $\chi^2$ we obtained was significantly greater than 1 (2.07). This corresponds to a probability of 2%, which indicates that this possibility can be rejected. However, for the sub-cluster, $\chi^2$ is close to 1 at the young ages of 1 and 2 Myr, so this result alone does not allow us to reject this possibility. In the next section, we discuss the reasons for the different results for the two clusters, despite the suggestion that they exist in the same environment (Section 5.2).

7. The IMF in A Low-metallicity Environment

7.1. The IMFs Derived for the S209 Clusters

The bottom rows of Tables 5 and 6 show the parameters of the best-fit KLF for the S209 main and sub-clusters, with the ranges corresponding to the 90% confidence levels shown in brackets. The right panels of Figures 17 and 18 show the best-fit IMF (black lines) and the 90% confidence level (the gray highlighted regions). For the model KLFs, we assumed IMFs...
The best parameter set for each age is obtained when the reduced \( \chi^2 \) value is closest to 1. The obtained reduced \( \chi^2 \) values and corresponding probabilities shown for each age are the smallest and largest values, respectively. For parameters within the 90\% confidence level, the ranges are shown in brackets. The bottom line shows the best-fit IMF parameters for all ages combined, with the ranges of the parameters within the 90\% confidence level shown in parentheses.

| Age (Myr) | \( \log m_1 \) | \( \log m_2 \) | \( \Gamma_1 \) | \( \Gamma_2 \) | \( \Gamma_3 \) | \( \chi^2_{\text{red}, \min} \) | \( P_{\max} \) |
|-----------|----------------|----------------|--------------|--------------|--------------|----------------|---------------|
| S209 main cluster (\( D = 2.5 \) kpc) |
| 0.5 | -1.4 | -1.5 | -1.3 | 0.3 | 1.8 | 5.11 | <0.001 |
| 1 | -1.4 | -1.5 | -1.3 | -0.1 | 0.3 | 11.67 | <0.001 |
| 2 | -1.4 | -1.5 | -1.1 | 0.1 | 1.2 | 11.24 | <0.001 |
| 3 | -1.5 [-1.5, -1.4] | -1.6 [-1.6, -1.5] | -0.9 [-0.9] | 0.1 [-0.4, 0.4] | 1.7 [-0.4, 2.0] | 1.60 | 0.08 |
| 5 | -0.9 [-1.2, -0.7] | -1.2 [-1.6, -1.0] | -1.0 [-1.2, -0.9] | -0.4 [-0.4, 0.4] | 1.0 [-0.4, 2.0] | 0.96 | 0.50 |
| 7 | -0.7 [-0.7] | -1.2 [-1.2] | -1.1 [-1.1] | -0.4 [-0.4] | -0.4 [-0.4] | 1.66 | 0.07 |
| 10 | -0.4 | -1.0 | -2.0 | 0.3 | -0.2 | 128.1 | <0.001 |
| 5 [3, 7] | -0.9 [-1.5, -0.7] | -1.2 [-1.6, -1.0] | -1.0 [-1.2, -0.9] | -0.4 [-0.4, 0.4] | 1.0 [-0.4, 2.0] |

Note. The best parameter set for each age is obtained when the reduced \( \chi^2 \) value is closest to 1. The obtained reduced \( \chi^2 \) values and corresponding probabilities shown for each age are the smallest and largest values, respectively. For parameters within the 90\% confidence level, the ranges are shown in brackets. The bottom line shows the best-fit IMF parameters for all ages combined, with the ranges of the parameters within the 90\% confidence level shown in parentheses.

| Age (Myr) | \( \log m_1 \) | \( \log m_2 \) | \( \Gamma_1 \) | \( \Gamma_2 \) | \( \Gamma_3 \) | \( \chi^2_{\text{red}, \min} \) | \( P_{\max} \) |
|-----------|----------------|----------------|--------------|--------------|--------------|----------------|---------------|
| S209 sub-cluster (\( D = 2.5 \) kpc) |
| 0.5 | -0.8 | -1.2 | -1.8 | -0.4 | 1.0 | 52.58 | <0.001 |
| 1 | -1.2 | -1.5 | -1.6 | 0.3 | -0.1 | 3.67 | 0.0005 |
| 2 | -1.3 | -1.4 | -1.1 | 0.3 | -0.4 | 2.35 | 0.02 |
| 3 | -1.0 [-1.5, -0.6] | -1.2 [-1.6, -0.9] | -0.9 [-1.4, -0.7] | 0.2 [-0.4, 0.4] | -0.3 [-0.4, 2.0] | 1.01 | 0.72 |
| 5 | -0.7 [-0.9, -0.6] | -1.0 [-1.6, -0.8] | -1.0 [-1.3, -0.9] | -0.4 [-0.4, 0.4] | 1.8 [-0.4, 2.0] | 1.35 | 0.22 |
| 7 | -0.6 [-0.7, -0.5] | -0.9 [-1.2, -0.7] | -1.2 [-1.3, -1.0] | -0.1 [-0.4, 0.4] | 0.7 [-0.3, 2.0] | 1.59 | 0.13 |
| 10 | -0.3 | -1.0 | -1.5 | -0.4 | 1.2 | 2.14 | 0.04 |
| 3 [3, 7] | -1.0 [-1.5, -0.5] | -1.2 [-1.6, -0.7] | -0.9 [-1.4, -0.7] | 0.2 [-0.4, 0.4] | -0.3 [-0.4, 2.0] |

Note. The best parameter set for each age is obtained when the reduced \( \chi^2 \) value is closest to 1. The obtained reduced \( \chi^2 \) values and corresponding probabilities shown for each age are the smallest and largest values, respectively. For parameters within the 90\% confidence level, the ranges are shown in brackets. The bottom line shows the best-fit IMF parameters for all ages combined, with the ranges of the parameters within the 90\% confidence level shown in parentheses.

The best-fit IMF parameters we obtained for both the IMF slope and the break mass on the high-mass side are very similar for S209 main and sub-clusters (\( \Gamma_1 = -1.0, \log m_1 = -0.9 \)). However, the uncertainties are relatively small for the S209 main cluster IMF, while they are somewhat larger for the sub-cluster IMF. The main reason for this may be the large difference in the number of members in the two clusters (\( N_a \approx 1500 \) for the main cluster and 350 for the sub-cluster). This is directly related to our motivation for using the main cluster—which has a particularly large number of members—to derive the IMF with high accuracy in a low-metallicity environment. The number of cluster members (\( N_a \)) in the S209 main cluster is about the same as that in the Trapezium (\( N_a \approx 1500; \) Muench et al. 2002), while the number in the sub-cluster is of the same order as that in IC 348 (\( N_a \approx 150; \) Muench et al. 2003), but slightly larger. We primarily based the present paper on their method of deriving the IMF, except that we obtained not only the IMFs of the clusters but also their ages from KLF fitting. The 1\( \sigma \) uncertainties in \( \Gamma_1 \) and \( \log m_1 \) are \( \Delta \Gamma_1 \approx 0.1 \) and \( \Delta \log m_1 \approx 0.1 \), respectively, for the Trapezium cluster, and they are \( \Delta \Gamma_1 \approx 0.3 \) and \( \Delta \log m_1 \approx 0.2 \), respectively, for the IC 348 cluster. The uncertainties for the Trapezium and IC 348 clusters are comparable to those for the S209 main and sub-clusters, respectively, which suggests that the relationship between \( N_a \) and the obtained IMF uncertainty appears to be quantitatively consistent with these previous studies of nearby clusters.

As a result of the KLF fitting discussed in Section 6.2, we found solutions for the S209 main cluster when we assumed the distance to be \( D = 2.5 \) kpc, but we found no solutions when the distance was 10 kpc. However, for the sub-cluster, solutions exist in both cases. Although this result seems to contradict the suggestion in the discussion in Section 5 that the two clusters are located in the same environment at the distance \( D = 2.5 \) kpc, the reason for this difference seems to be that the uncertainties in the IMF derivation are due to the differences in \( N_a \) between the main and sub-clusters. In the main cluster, the possibility \( D = 10 \) kpc can be rejected due to the small uncertainties that result from the large value of \( N_a \), while in the sub-cluster, KLF fitting alone cannot constrain which possible distance is the more plausible because the uncertainties in the IMF derivation are large due to
to the small value of $N_n$. In other words, KLF fitting as carried out here indicates that when $N_n$ is large, fitting that includes distance as a parameter in addition to IMF and age can be effective.

The other parameter besides the IMF that we obtained in the KLF fitting is the age of the cluster. The most plausible ages for the best-fit KLF are 5 Myr for the S209 main cluster and 3 Myr for the sub-cluster. The positions of the S209 main cluster and the molecular cores traced with millimeter-continuum emission in Klein et al. (2005; cores 1, 2, 3, and 4 surrounding the cluster) suggest that some high-mass stars in the main cluster (candidates are discussed in Section 5.1) are dissipating the molecular cloud that was originally the material for the formation of these stars and that they are also ionizing the molecular cloud at the position of the bright rim. Meanwhile, the S209 sub-cluster seems to be completely embedded within the molecular cloud (core 5). It is known that stars are born in molecular clouds. They are initially embedded within those clouds at very young ages ($\lesssim 3$ Myr), but the clouds gradually dissipate by ages $\gtrsim 3$ Myr (Lada & Lada 2003). The relationship between the S209 clusters and their associated molecular clouds thus suggests that the age of the S209 main cluster is $\gtrsim 3$ Myr while that of the sub-cluster is $\lesssim 3$ Myr. The ages derived as best-fit values from the KLF fitting roughly match this discussion.

In summary, for the S209 clusters, we have succeeded in deriving the IMF for star-forming regions in a low-metallicity environment on the ($\sim 1$ pc) scales of individual clusters down to stellar masses as low as $\sim 0.1 M_\odot$. In particular, because of the large number of cluster members for the S209 main cluster,
we have obtained its IMF with high accuracy for the first time. In addition, by targeting such young star-forming clusters, one can treat a wide range of masses, extending up to 20 $M_\odot$ on the high-mass side. Because these clusters have not yet experienced much $N$-body relaxation or mass segregation, we consider the IMF obtained here to be reasonably similar to the true IMF (Lee et al. 2020).

### 7.2. Comparison with IMFs in the Solar Neighborhood

We first compared the high-mass slopes obtained for the IMFs of the S209 clusters to those in the solar neighborhood. In the solar neighborhood, derivations of the slope have been performed for various regions, fields, young clusters and associations, and old globular clusters, and they can generally be explained by Salpeter slope ($\Gamma_1 = -1.35$). Although examples that differ somewhat from the Salpeter slope have been reported for some regions, reviews such as Bastian et al. (2010) note that the differences occur in a very small number of cases and that where non-Salpeter slopes are reported, the results are often of low statistical significance or are due to systematic differences in the approaches. In contrast, the IMF slopes we derived for the two S209 clusters are $\Gamma_1 = -1.0$, which is slightly top-heavy compared to the Salpeter slope. The method we used to derive the IMF for S209 is basically the same as that used by Muench et al. (2002, 2003) to derive the IMF for the Trapezium and for IC 348. They confirmed that their IMF derivations were not significantly different from other derivations, e.g., from detailed spectroscopy. The differences we found here therefore should not be due to major systematic differences in the methods used to derive the IMF. However, Table 9 shows that, while the result for the S209 main cluster has a small scatter ($\Delta \Gamma_1 = 0.1$) and is somewhat robust, there is a large scatter for the sub-cluster ($\Delta \Gamma_1 = 0.2$–0.3) so this result is not conclusive.

Next, we compare the first break mass ($m_1$), which is the mass at which the IMF slope first transitions from the high-mass side to the lower-mass side. This mass is often discussed together with the characteristic mass ($M_C$), which is the mass at the peak of the IMF. In a power-law IMF, $M_C$ is defined as the midpoint of the plateau between the two break masses (defined as $m_1$ and $m_2$ in this paper). From the compilation by Elmegreen et al. (2008) for the solar neighborhood, the break mass ($m_1$; the upper mass of the IMF plateau) is about 0.5–1 $M_\odot$, and $M_C$ is about 0.3 $M_\odot$ ($\log(M_C/M_\odot) \sim -0.5 \pm 0.5$) (see also Figure 3 of Bastian et al. 2010). For comparison, we estimate the value of $m_1$ for the S209 clusters to be $\approx 0.1 M_\odot$. Because the break mass ($m_1$) is an upper limit for $M_C$, it is suggested that $M_C$ in the S209 clusters are smaller than in the solar neighborhood, even considering the scatter in the values of $m_1$ in S209 for both the main and sub-clusters ($m_1$ is at most 0.2 $M_\odot$ for both S209 clusters, considering the $1\sigma$ uncertainties). However, in order to determine the actual mass range of the IMF plateau and the characteristic mass, it is necessary to extend detection to stars in the mass range where the IMF begins to fall. In the future, deeper observations using next-generation telescopes (e.g., JWST) will thus be important.

### 7.3. Comparison with Previous IMF Derivations for Low Metallicity

As introduced in Section 1, for the LMC/SMC, which are the most typical examples used for IMF studies in low-metallicity environments, detailed observations based on spectroscopic classification have shown that the IMFs are generally comparable to the Salpeter IMF for massive stars ($M > 10 M_\odot$). Although some studies have suggested that the IMFs may differ from the Salpeter IMF, this may be due to the fact that only size scales much larger than the scales of individual clusters (generally $\sim 10$–100 pc) can be resolved as star-forming regions. The star formation history is consequently more complex in those regions due to the presence of multiple generations of stars. One recent result pointed out indications of a top-heavy IMF in the mass range 15–200 $M_\odot$, taking into account the star formation history in the 30 Doradus starburst star-forming region in the LMC (Schneider et al. 2018). This is consistent with our results presented here for S209, although the mass ranges of the targets are different. However, a review by Kroupa et al. (2013) pointed out that biases due to crowding, resolution, and mass estimates from photometric data make studies of such regions very challenging. Also, because the detection of low-mass stars in the LMC/SMC has been difficult due to limited observational sensitivity, there has been no observational discussion of the characteristic mass in such regions.

We have been carrying out IMF derivations for star-forming clusters in low-metallicity environments in the Galaxy (Yasui et al. 2006, 2008a, 2008b, 2016a, 2016b, 2017, 2021). Although

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### Table 8

Same as Table 5 but for the S209 Sub-cluster, Assuming a Distance of 10 kpc

| Age (Myr) | $\log m_1$ | $\log m_2$ | $\Gamma_1$ | $\Gamma_2$ | $\Gamma_3$ | $\chi^2_{\text{red}, \text{min}}$ | $P_{\text{max}}$ |
|-----------|------------|------------|------------|------------|------------|-----------------|--------------|
| S209 sub cluster ($D = 10$ kpc) | | | | | | | |
| 0.5 | -0.7 | -0.8 | -0.9 | 0.2 | 1.4 | 2.41 | 0.02 |
| 1 | -0.1 [-0.2, 0.1] | -0.7 [-1.0, 0.0] | -1.5 [-2.0, -1.1] | 0.4 [-0.4, 0.4] | 0.6 [-0.4, 2.0] | 1.00 | 0.70 |
| 2 | 0.1 [0.0, 0.1] | -0.1 [-0.7, 0.0] | -1.8 [-2.0, -1.5] | 0.1 [-0.4, 0.4] | -0.3 [-0.4, 2.0] | 1.33 | 0.23 |
| 3 | 0.1 | -0.5 | -1.9 | -0.2 | -0.3 | 2.82 | <0.001 |
| 5 | 0.1 | -0.4 | -1.7 | -0.1 | 0.6 | 5.29 | <0.001 |
| 7 | 0.1 | -0.3 | -1.9 | -0.2 | 1.6 | 5.67 | <0.001 |
| 10 | 0.0 | -0.1 | -2.0 | -0.2 | 1.8 | 7.00 | <0.001 |

### Table 9

Parameters of the Best-fit IMF for the S209 Main and Sub-clusters

| Cluster | $\Gamma_1$ | $\log m_1$ ($M_\odot$) | Age (Myr) |
|---------|------------|------------------------|----------|
| Main    | -1.0 ± 0.1 | -0.9 ±0.1               | 5        |
| Sub (again) | -1.0±0.3 | -0.9±0.4               | 3        |

Note. The $1\sigma$ uncertainties are shown.
there are similar difficulties for such studies as for LMC/SMC studies, at least the spatial resolution and sensitivity are significantly higher than for the LMC/SMC due to the much smaller distances to sources within the Galaxy. In particular, for this study of S209, the distance is 20 times smaller (50/2.5), and the spatial resolution is about five times better than that of an LMC/SMC study using the Hubble Space Telescope (HST) ($\Delta \theta \sim 0''1$; cf. $\Delta \theta \sim 0''4$). Indeed, we achieved a separation of 1000 au at the S209 distance of 2.5 kpc with seeing of 0''4, and our mass-detection limits extend down to $\sim 0.1 M_\odot$. Furthermore, because the clusters in S209 allow us to derive data on the scale of an individual cluster ($\sim 1$ pc), the star formation history is not complex, so the IMF derivation becomes simpler and with fewer assumptions. As a result, the high-mass slope and characteristic mass of the IMF we obtained are similar to those of the Salpeter IMF obtained for clusters in previous studies, which appears to contradict the results for the S209 clusters. This is probably due to the fact that the number of cluster members was not very large ($N_\star \sim 100$; see Figure 12 in Yasui et al. 2021) for the previous samples, and thus it was not possible to derive the IMF with high accuracy and determine the presence of differences. In addition, in those previous samples, cluster members were identified only from limited $A_V$ ranges (e.g., Figure 5 in Yasui et al. 2021), without considering mass-$A_V$-limited samples, as in this paper. We used the masses of stars with limiting magnitudes at the minimum of the $A_V$ range as the mass-detection limit. For objects with large $A_V$ values—even though they have only been detected up to stars of higher masses than the adopted mass-detection limit—this effect was not strictly taken into account in our previous models. This may have led to a lower estimate of the number of low-mass stars, resulting in an estimate of the characteristic mass of $\sim 0.5 M_\odot$, which is similar to the values seen in the solar neighborhood.

For globular clusters in the Galaxy, the metallicity dependence of the IMF has been discussed in combination with the density dependence. Metal-poor globular clusters, which are subject to weaker tidal fields, are denser than slightly metal-rich globular clusters (Marks & Kroupa 2010), and higher-density clusters are thought to have top-heavy IMFs because they provide sufficient feedback energy to blow off the residual gas (Marks et al. 2012). At the density of a globular cluster, the slope of the Salpeter IMF is constant until the metallicity is $[\text{Fe/H}] \sim -0.5$, and it increases gradually when the metallicity is $[\text{Fe/H}] < -0.5$, gradually becoming a top-heavy IMF (Marks et al. 2012). This trend appears to be consistent with the slightly top-heavy IMF seen in S209, although the difference in the IMF slope by as much as 0.35 at $-0.5$ dex seems to be a more pronounced change than the results for globular clusters. In addition, because the star-forming region in S209 has a low density of star-forming clusters—comparable to that of young open clusters in the solar neighborhood (although the initial density may be slightly different due to the lower metallicity)—it seems unlikely that a theory appropriate for globular clusters can explain the rather top-heavy IMF in S209. On the other hand, because globular clusters are generally old ($\sim 10^{10}$ yr), and their relatively massive stars have already completed their lives, the IMFs are obtained for the very small mass range $\lesssim 1 M_\odot$. In contrast, for S209, we were able to derive IMFs up to a mass $\sim 20 M_\odot$, which is one of the significant features of this study.

For globular clusters, Paresce & De Marchi (2000) showed that the characteristic mass does not change significantly from that of the solar metallicity ($\sim 0.3 M_\odot$) in the metallicity range $-0.7$ to $-2.2$ dex. From this result, they concluded that the global mass functions of globular clusters should not have changed significantly due to evaporation or tidal interactions within the Galaxy and should thus reflect the initial distribution of stellar masses. Nevertheless, it has been pointed out that, for globular clusters, considering their old age, a significant number of low-mass stars may have been scattered outside the cluster due to dynamical evolution. Therefore, when studying the mass function of a very dense stellar system, it is necessary to take account of the dynamical state of the cluster (Portegies Zwart et al. 2010). In contrast, because it is considered to be largely unaffected by these processes in the case of younger clusters, it is reasonable to assume that the PDMF is similar to the IMF (e.g., Lee et al. 2020). If we assume that the low characteristic masses suggested for the S209 clusters are indicative of a metallicity dependence of the IMF, this may have been true for the globular clusters in the early stages. If this is the case, then the observational results by Paresce & De Marchi (2000) may simply indicate PDMFs with a characteristic mass similar to that of the IMF in the solar neighborhood as a result of the dispersion of very low-mass stars during their evolutionary phase, even though the globular clusters also had a lower characteristic mass than the IMF in the solar neighborhood at the beginning.

Theoretical studies also suggest that a metallicity-dependent difference may appear in the high-mass slope of the IMF due to dust cooling, resulting in a more top-heavy IMF in a low-metallicity environment. This trend in the metallicity dependence of the high-mass slope of the IMF appears to be similar to the results we obtained here. However, this difference is expected to occur in environments with much lower metallicities than the metallicity of interest here; the critical metal content is expected to be $Z \sim 10^{-6}$–$10^{-7}$ (e.g., Omukai et al. 2005). Therefore, although the trend of the metallicity dependence of the high-mass slope of the IMF is similar to our results, these theoretical studies cannot be applied directly.

Theoretical investigations have identified two main explanations for the metallicity dependence of the characteristic mass:

1. The Jeans mass ($M_J \propto \rho^{-1/2} T^{3/2}$) is expected to be higher for a gas with lower density and higher temperature, which results in a higher average stellar mass. The temperature and density of the gas depend on the metallicity, and because the cooling efficiency decreases in low-metallicity environments, more massive stars should form from low-metallicity gas.

2. A forming star self-regulates its mass by radiative feedback (Adams & Fatuzzo 1996), which is also metallicity dependent. Because this effect works more effectively in a low-metallicity environment, more high-mass stars should be produced in such environments.

Comparison with the results for S209 clusters obtained here shows that the above two effects are at least consistent with the top-heavy IMF suggested for the clusters, but the characteristic mass of the clusters seems to contradict both of these effects. However, in the future, it will be important to treat a larger number of objects, discuss them statistically, and use deeper observations to detect even smaller-mass stars, where the IMF starts to decrease. If this can be confirmed, it will be necessary to develop a theory to explain this. It is also important to note that lower-mass stars (thus fainter sources) have generally the greater effect of residual field stars.
8. Conclusions

The low-metallicity environments in the Galaxy are the closest—and so far the only—suitable sites for population studies of resolved stars (1000 au separation in this study) on the same basis as for the solar neighborhood. However, the relatively small number of members (∼100) in previously studied regions has prevented us from deriving the IMFs with high precision. In the present study, we have focused on the star-forming region Sh 2–209, which contains two young clusters (one of which has ∼1500 members), with the goal of obtaining the IMFs with high precision for the first time. These clusters have been identified as young star-forming clusters (≤5 Myr) that exist in a low-metallicity environment ([O/ H] ∼−0.5 dex) at the very close distance of 2.5 kpc, as summarized later in this section. By observing individual star-forming clusters (on scales ∼1 pc), which are the smallest units where many stars are born almost simultaneously, we can get closer to the genuine IMF because the effects of complex star formation histories are eliminated. The derivation of IMFs in young star-forming regions has several advantages, such as the ability to derive IMFs over a wide range of masses (∼0.1–20 M⊙ in the case of S209). Also, the PDMFs are likely to be close to the IMFs because such young clusters have been subject to little N-body relaxation and mass separation. Therefore, we consider S209 to be a prototype star-forming region for deriving IMFs in low-metallicity environments.

Our main results can be summarized as follows:

1. The H II region S209 has been identified previously as a star-forming region due to the presence of Hα, MIR, and radio-continuum emission. Although previous studies considered the distance to this nebula to be ∼10 kpc, based on its photometric/kinemetric distance, we pointed out—based on recent results from Gaia EDR3—that the distance may actually be as close as 2.5 kpc. From optical spectroscopic observations of this H II region, the estimated oxygen abundance of S209 is ∼−0.5 dex. Also, its electron temperature (Te)—which is a very sensitive indicator of abundance—is one of the highest temperatures among the H II regions in the Galaxy, which is consistent with this low-metallicity estimate.

2. We obtained deep JHK-s-band images using Subaru/MOIRCS with a 4′×7′ field of view, which covers the central part of the S209 H II region. The 10σ limiting magnitudes, based on pixel-to-pixel noise for the S209 frames, reach up to J ≃ 22.0 mag, H ≃ 21.0 mag, and Ks ≃ 20.6 mag.

3. From the spatial distribution of stellar densities detected in the Subaru/MOIRCS JHK imaging, we identified two clusters, one in the north and one in the south. Their radii are 82′′ and 41′′, respectively, and we named them the S209 main and sub-clusters. Using the JHK color–color diagram for the detected sources, we derived the distributions of reddening, extinction (Aν), and K-band disk excess (κexcess). Using the resulting distribution of Aν, we extracted mass-Aν-limited samples using the color–magnitude diagram and derived the cluster KLFs.

4. We compared the cluster scale to the mass of the most massive star in the S209 main cluster, which we estimated from the NIR imaging results assuming two possible distances for S209 (10 kpc or 2.5 kpc). The results indicate that the 2.5 kpc distance is the more plausible. In fact, the NIR images show that one of the Gaia sources lies exactly on the bright rim in the shock plane of the molecular cloud and the H II region and is not a foreground or background star. We therefore consider the 2.5 kpc distance to be the most plausible distance to S209. In addition, the CO data confirm that the velocities of the molecular clouds associated with the S209 main and sub-clusters are the same, confirming that the two regions probably exist in the same environment. For the 2.5 kpc distance, the radii are 1.0 pc for the S209 main cluster and 0.5 pc for the sub-cluster. These radii and the resulting densities of these clusters are similar to those of nearby young clusters. In other words, we found S209 to be an optimal environment for deriving IMFs at the scale of individual clusters on the same basis as for clusters in the solar neighborhood.

5. In general, the derivation of IMFs requires independent information about the age of the region and of individual stars. However, because no age information exists so far for S209, in this paper we derived the IMF and the cluster age together as a set. Using the characteristic that the KLF is highly dependent on both the IMF and the age, we estimated the most reliable age and IMF by comparing various models with the KLF of the S209 cluster obtained from observations. Although our procedure is based on previous studies (Muens et al. 2000, 2002), a unique point of this paper is that we added age as a fitting parameter. To construct the model KLFs, we assumed a three-power-law IMF, used reddening properties derived from observations, employed standard model M–L relations, and considered mass-Aν-limited samples.

6. For the 2.5 kpc distance, the estimated ages of the S209 main and sub-clusters are 5 Myr and 3 Myr, respectively, both roughly consistent with the ages suggested by the morphology of the CO molecular cloud. For both clusters, we found no second break mass above the mass-detection limit, suggesting that the underlying IMF actually has a two-power-law form.

Although the IMF parameters we obtained were very similar for the two clusters (Γ1 ∼ −1.0 and log m1 ∼ −1.0), the parameters for the S209 main cluster, with Ntars ∼ 1500, were determined with relatively high accuracy (Γ1 = 1.0 ± 0.1, log m1 = −0.9 ± 0.1), while those for the sub-cluster, with Ntars ∼ 350, have large scatter (Γ1 = −1.0 ± 0.3, log m1 = −0.9 ± 0.1).

7. Compared to the Salpeter IMF (Γ = 1.35), which is commonly found in the solar neighborhood, the IMFs we obtained for two S209 clusters are slightly top-heavy. However, note that while the results for the S209 main cluster are relatively robust, the results for the sub-cluster show large scatter. In addition, the break mass in the solar neighborhood is 0.5–1.0 M⊙, while the values obtained for the S209 clusters are smaller. However, because there is relatively large scatter in the estimated value of m1 for both S209 clusters, this difference is not significant. In order to determine the actual mass range of the IMF plateau and the characteristic mass, it will be necessary to extend detections to stars in the mass range where the IMF begins to fall. In the future, deeper observations using next-generation telescopes (e.g., JWST) will therefore be important.
8. Previous IMF studies for low-metallicity environments (−1 dex)—both theoretical and observational—have shown little clear difference in the high-mass slope and characteristic mass from the IMF obtained for the solar neighborhood, at least for clusters of similar scale to the S209 clusters. This seems to contradict the results obtained here, where we found slightly top-heavy high-mass slopes and slightly low characteristic masses for the S209 clusters. However, this is the first derivation of the IMF for very young open clusters—and on the scale of individual star-forming clusters—and the IMF we obtained is literally close to the initial and genuine IMF. In the future, statistical discussions based on observations of more objects will be necessary to confirm whether the IMF we obtained for S209 reflects the IMF produced at low metallicity.

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Facilities: Subaru Telescope, Gaia.
Software: IRAF (Tody 1993), MATPLOTLIB, a PYTHON library for publication quality graphics (Hunter 2007), and NUMPY (van der Walt et al. 2011).

Appendix

Subaru/ MOIRCS Point-source Catalog for S209

The photometric results of the Subaru/MOIRCS imaging for S209, obtained as described in Section 3, are shown in Table 10. The astrometry was performed using the IRAF task of the IMCOORD package with the 2MASS Point Source Catalog as a reference.

| ID | R.A. (J2000.0) | Decl. (J2000.0) | J (mag) | H (mag) | Ks (mag) | Notes |
|----|----------------|----------------|---------|---------|----------|-------|
| 1  | 62.683425      | 51.156903      | 18.96 (0.03) | 19.40 (0.04) | 20.23 (0.07) | ...  |
| 2  | 62.684710      | 51.156051      | 19.93 (0.06) | 20.79 (0.07) | ... (--) | ... |
| 3  | 62.684945      | 51.152882      | 21.10 (0.13) | 20.99 (0.10) | 21.45 (0.18) | ... |
| 4  | 62.685047      | 51.158731      | 19.64 (0.04) | 20.33 (0.07) | 19.82 (0.16) | ... |
| 5  | 62.685150      | 51.157613      | 18.76 (0.03) | 19.33 (0.03) | 21.40 (0.12) | ... |
| 6  | 62.685374      | 51.152773      | 19.17 (0.04) | 19.80 (0.08) | 21.19 (0.11) | ... |
| 7  | 62.685571      | 51.153886      | 17.38 (0.02) | 17.78 (0.02) | 18.92 (0.05) | ... |
| 8  | 62.685782      | 51.159704      | 20.78 (0.13) | 21.05 (0.17) | 19.85 (0.18) | ... |
| 9  | 62.686496      | 51.157573      | 19.04 (0.02) | 19.75 (0.04) | 21.62 (0.09) | ... |
| 10 | 62.686930      | 51.156448      | 18.05 (0.01) | 18.41 (0.02) | 19.25 (0.07) | ... |

Note. This table is available in its entirety in machine-readable form. Only a portion is shown here for guidance regarding its form and content. Columns (2) and (3): R.A. and decl. in degrees. Columns (4)–(7): Subaru/MOIRCS magnitudes. The J-band magnitudes are in Column (4), the H-band magnitudes are in Column (5), and the Ks-band magnitudes are in Column (6). Magnitude errors are shown in parentheses. Column (7): Sources in the S209 main and sub-cluster regions are labeled “Main” and “Sub,” respectively.

(This table is available in its entirety in machine-readable form.)
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