Formation and Evolution of Galaxy Outskirts
Proceedings IAU Symposium No. 321, 2016
A. Gil de Paz, J.H. Knapen & J.C. Lee, eds.

doi:10.1017/S174392131600942X

A spatially-resolved study of initial mass function in the outer Galaxy

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Abstract. Outskirts of spiral galaxies, including our own, and dwarf irregular galaxies are known to have a different environment from the solar neighborhood, e.g., low metallicities (~ -1 dex). Among them, the outer Galaxy is the closest and hence is so far the only site suitable for population studies of resolved stars on the same basis as solar neighborhood. We have obtained NIR images of young clusters in the outer Galaxy, using the Subaru 8.2-m telescope, and clearly resolved cluster members with mass detection limits of $\sim 0.1\,M_\odot$. Based on the fitting of K-band luminosity functions (KLFs) for four clusters, we found that the initial mass function (IMF) in the outer Galaxy is consistent with that in the solar neighborhood in terms of the high-mass slope and IMF peak. Upcoming observations with a higher spatial resolution and sensitivity, using JWST, TMT, etc., will allow us to extend spatially-resolved studies of the IMF to Local Group galaxies.

Keywords. Galaxy: abundances, stars: luminosity function, mass function, stars: formation, open clusters and associations: general

1. Introduction

The IMF is one of the most fundamental parameters which determines physical and chemical evolution of stellar systems, from star clusters to galaxies. In the solar neighborhood, almost all the IMFs have a similar shape, i.e., high-mass slopes of Salpeter IMF of $\Gamma = 1.35$ for $dN/d\log m = m^{-\Gamma}$ (Salpeter 1955), and the IMF peak (characteristic mass) of $\sim 0.3\,M_\odot$ (Elmegreen *et al.* 2008). Whether the IMF is universal or sensitive to environmental conditions is still under debate (Bastian *et al.* 2010). Some studies have been published for the inner Galaxy. For example, Arches cluster located near the Galactic center ($R_g \sim 25$ pc) was reported to have a top-heavy IMF. However, recent studies derived IMF, based on observations with a higher spatial resolution, and found it to be closer to the standard IMF (Bastian *et al.* 2010). The results suggest that resolved studies are crucial for deriving an IMF. We have been studying young clusters in the outer Galaxy ($R_G \gtrsim 15$ kpc), where the environment is significantly different from that in the solar neighborhood, e.g., low metallicity, very low gas density, and no or very small perturbation from the spiral arms. Because the environment is very similar to that of nearby dwarf galaxies and that in the epoch of Galaxy formation, the outer Galaxy serves as a good laboratory for studying the IMF in such conditions (Kobayashi *et al.* 2008).

2. Observations

We searched the literature for star-forming regions in the outer Galaxy ($R_G \gtrsim 15\,\mathrm{kpc}$) with metallicities [O/H] < -0.5 dex, and selected $\sim$10 young clusters. In this paper, we summarize the results for four clusters: two clusters in Digel Cloud 2 (Cloud 2-N and Cloud 2-S; Kobayashi *et al.* 2008, Yasui *et al.* 2006, 2008b, 2009) and one each in Sh 2-207 (S207; Yasui *et al.* 2016a) and Sh 2-208 (S208; Yasui *et al.* 2016b). The metallicities of the four clusters are -0.6–-0.8 dex, which are significantly lower than the solar metallicity. Their distances are $\sim$5–10 kpc, which are much smaller than nearby galaxies, e.g., $\sim$50 kpc for LMC and SMC. Deep JHK_S-band images of the target star-forming regions were obtained with the 8.2 m Subaru telescope equipped with MOIRCS (Suzuki *et al.* 2008). The high spatial resolution ($\lesssim$0.5") and relatively small distances to the clusters enabled us to resolve individual cluster members in each cluster. The limiting magnitudes of $K_S \sim 18$–21 mag (10σ) are achieved, which correspond to the mass of $\sim 0.1\,M_\odot$ at their distances.

3. K-band luminosity function (KLF)

The shape of the IMF is very sensitive to that of a KLF. Hence, we use the KLF for each cluster for deriving an IMF. We first identified cluster members that have a larger A_V excess than normal field stars (Muench *et al.* 2002). We then constructed the KLF for each cluster with the identified members (black lines in Figure 1 left panel and Figure 2). The number count in the KLFs is found to have a general trend of increasing toward the fainter magnitude. However, it turns around to decrease at a certain magnitude, which generally corresponds to the peak of the IMF. Since the detection completeness of stars with a significance of $>10\sigma$ is almost one, the peaks at magnitudes that are significantly brighter than the detection limit should be real. We emphasize that *the outer Galaxy is so far the only site suitable for detecting IMF peaks in significantly different environments from those in the solar neighborhood.*

4. IMF

IMF fitting for the Cloud 2-N and 2-S clusters. For both the two Cloud 2 clusters, the ages were estimated as 0.5 Myr in a previous study (Kobayashi *et al.* 2008). With the ages, we performed a chi-square test between the observed KLFs and model KLFs, assuming a simple IMF, $dN/d\log M = A \cdot \exp\{-c_1(\log M - c_2)\}^2$ (the log-normal IMF; Miller & Scalo 1979), in the same way as Yasui *et al.* (2008a). The first results for Cloud 2-N were given in Yasui *et al.* (2008a), whereas the best-fit KLF and the most reliable IMF for Cloud 2-S are shown as hatched regions in Figure 1, with the obtained parameters of $c_1 = 2.0 \pm 0.2$ and $c_2 = 0.5 \pm 0.1$ for 20 % confidence level. The obtained IMFs for both the clusters are found to be consistent with "universal" IMF in the solar neighborhood, in terms of high-mass slope and characteristic mass, $\sim 0.3\,M_\odot$.

Implication for IMF of the S207 and S208 clusters The ages of S207 and S208 are unknown, and therefore two major unknown parameters remain for deciding the KLFs: the age and IMF. For the first trial, we estimated the ages of the clusters in the KLF fitting, assuming a typical IMF in the solar neighborhood (Muench *et al.* 2002). The estimated ages are $\sim$0.5 Myr and $\sim$2–3 Myr for S207 and S208, respectively, which are well consistent with rough estimations based on other independent information (e.g., extinctions, H_2 column densities; Yasui *et al.* 2016a, b). This suggests that the IMFs of both the clusters can be approximated by the typical IMF of the solar neighborhood ($\sim$0 dex) for the mass range of $\gtrsim 0.1\,M_\odot$.

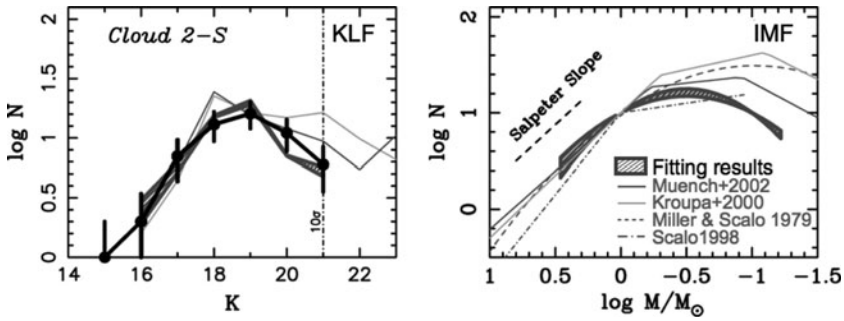

Figure 1. Results of KLF fitting for the Cloud 2-S cluster. The observed KLF is shown with a black line. The best-fit KLF and resultant IMF are shown with gray hatched regions.

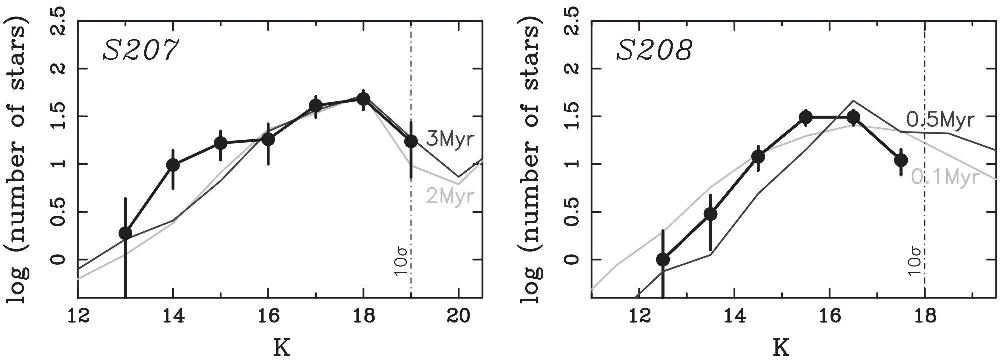

Figure 2. Comparison of the observed KLFs (black lines) with model KLFs of various ages (gray lines) for S207 and S208 in the left and right panels, respectively.

In summary, we found that the IMFs of the four young clusters are consistent with that in the solar neighborhood. Considering that this is the case for all of our independent targets so far, the results may imply that the IMF has no dependence on metallicity down to ~ -1 dex. We pursue this approach to derive more precise IMFs in the outer Galaxy, considering more realistic conditions (e.g., age spread and extinction distributions), or using clusters with a larger number of members ($N > 1000$, as opposed to $N \sim 100$ in the current study) to achieve a higher S/N.

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https://doi.org/10.1017/S174392131600942X Published online by Cambridge University Press