The IMF of Field OB Stars in the Small Magellanic Cloud

J. B. Lamb, M. S. Oey, A. S. Graus, and D. M. Segura-Cox

University of Michigan
Department of Astronomy, 830 Dennison Bldg., Ann Arbor, MI 48109-1042, USA

Abstract. The population of field OB stars are an important component of a galaxy’s stellar content, representing 20-30% of the massive stars. To study this population, we have undertaken the Runaways and Isolated O Type Star Spectroscopic Survey of the SMC (RIOTS4). RIOTS4 surveys a spatially complete sample of >350 field OB stars in the Small Magellanic Cloud and will serve as a key probe of runaways, binaries, and the stellar IMF in the field massive star population. Here, we focus on the field IMF, which provides an empirical probe of the star-forming process and is a fundamental property of a stellar population. Together with photometry from the OGLE survey, RIOTS4 will yield a definitive stellar IMF for the SMC field massive star population. We present preliminary results that suggests the field IMF is much steeper, \( \Gamma = 2.9 \), than the canonical stellar IMF of \( \Gamma = 1.35 \). Despite the steep slope, we see no evidence of a stellar upper mass limit, up to our highest mass star of 65\( M_\odot \).

1. Introduction

From an observational standpoint, our understanding of massive star formation is mostly derived from the products of this process: the stars themselves. One of the fundamental observable properties of star formation is the stellar initial mass function (IMF). For high mass stars, the IMF follows a simple power law given by \( \frac{dn}{d \log m} \propto m^{-\Gamma} \), where \( n \) is number of stars, \( m \) is stellar mass and \( \Gamma = 1.35 \) (Salpeter, 1955). This Salpeter IMF is uniformly applicable to a large variety of cluster environments, from OB associations to super star clusters. However, the field massive stars are one astrophysical environment where the IMF slope may deviate from Salpeter. Despite the robust nature of the Salpeter slope in clusters, there is evidence that the IMF of field massive stars is much steeper than Salpeter, with measurements of \( \Gamma = 3 \) to 4 in the Magellanic Clouds (Massey et al. 1995, Massey 2002). Within the Galaxy, van den Bergh (2004) confirms that the field population is biased towards later spectral types, indicating they are either older or less massive than the cluster population. However, the field population around the 30 Dor region of the Large Magellanic Cloud exhibits a Salpeter slope (Selman et al. 2011), and \( \Gamma = 1.8 \) in NGC 4214 (Ubeda et al. 2006). Thus, the null hypothesis of a universal IMF slope for both clusters and the field cannot easily be rejected.

We believe that the field massive stars consist of both in-situ stars and runaway stars formed in clusters (Oey & Lamb, this volume). Thus, the IMF parameters, which include both the slope and the upper-mass limit, are important diagnostics for theories of massive star formation. For example, competitive accretion models require that massive stars only form in clusters, and that the mass of the most massive star in a cluster
$m_{\text{max}}$ is related to the total cluster mass $m_{\text{cl}}$ by $m_{\text{max}} \propto m_{\text{cl}}^{2/3}$ (e.g. Bonnell et al. 2004). Whereas, monolithic collapse models more readily allow for the formation of isolated massive star formation is (e.g. Krumholz & McKee 2008).

To investigate the mass function of field massive stars, we present here first results from the Runaways and Isolated O Type Star Spectroscopic Survey of the SMC (RIOTS4; Oey & Lamb, this volume). In this contribution, we present the slope and upper mass limit of the stellar IMF for field massive stars, which may provide key insights about the process of massive star formation and illuminate any differences between isolated and clustered star formation.

2. RIOTS4 Observations

RIOTS4 is an extensive spectroscopic survey of a spatially complete sample of field massive stars, which covers the entire star-forming area of the Small Magellanic Cloud (SMC). The initial sample of all massive stars in the SMC was selected using the reddening-free parameter $Q \leq -0.84$ and $B \leq 15.21$ from the $UBVR$ photometry of Massey (2002). To identify the field stars, Oey et al. (2004) ran a friends-of-friends algorithm (Battinelli, 1991) on the OB candidate sample, which sets a physical clustering length such that the total number of clusters, defined as $n_{\text{stars}} \geq 3$, is maximized. The field population are those OB stars that are at least one clustering length (28 pc) away from the nearest OB star. We have obtained spectra for the majority of these stars with the IMACS multi-object spectrograph ($R \sim 2600$) on the Magellan-Baade telescope. Our completeness is nearly 100% for the SMC bar and over 85% for the SMC wing.

We obtain spectral types from our spectra following the classification scheme and atlas prepared by Walborn & Fitzpatrick (1990). Spectral types are converted into stellar effective temperature, $T_{\text{eff}}$, using the calibration for SMC O stars from Massey et al. (2005) and for B stars from Crowther et al. (1997). The Crowther conversion was chosen due to the smooth transition at the overlapping B0 spectral type with the Massey calibration. The absolute V magnitudes of our stars are obtained from the photometry of Massey (2002), assuming a distance modulus of 18.9 (Szewczyk et al. 2009) and applying SMC extinction maps from Zaritsky et al. (2002). We convert the absolute V magnitude into a bolometric magnitude, $M_{\text{bol}}$, using $T_{\text{eff}}$ to calculate the bolometric correction following the equations of Massey et al. (2005).

Using the derived $T_{\text{eff}}$ and $M_{\text{bol}}$, we plot an H-R diagram of our field massive stars in Figure 1. Additionally, we plot Geneva stellar evolutionary tracks at SMC metallicity ($Z = 0.004$; Charbonnel et al. 1993), which are labelled according to the stellar mass of the evolutionary track. Our survey is complete to 25$M_{\odot}$ along the Zero Age Main Sequence (ZAMS). One notable feature of this H-R diagram is the offset of our observations from the theoretical main sequence provided by the evolutionary tracks. This problem is not unique to our data, however, as spectroscopic data for massive SMC stars plotted in Massey (2002) are similarly plagued by this issue. It is unclear whether this is an issue with the observational data, or a problem with the SMC metallicity stellar evolutionary models.
3. Field Massive Star IMF

To construct the IMF of the field population, we follow the formalism of Koen (2006), where the IMF is constructed as a cumulative distribution function (CDF) given by

$$F(m) = \int_{L}^{U} m^{-(\Gamma+1)} \, dm = \frac{j}{(N+1)}$$  \hspace{1cm} (1)

with $L$ and $U$ being the lower and upper stellar mass limits. The final term represents an empirical CDF using a ranked order of stellar masses, $j$, where $j = 1$ is the lowest mass star, $j = N$ is the highest mass star, and $N$ is the number of stars in our sample. From this empirical CDF, we can reconstruct a mass function by plotting $\log[1 - F(m)]$ versus $\log m$, which is shown in Figure 2. However, since we are dealing with field stars, we are actually measuring the present day mass function (PDMF) rather than the IMF. We measure the slope of the PDMF using two methods: a linear least squares fit and a maximum likelihood method given by Koen (2006; his equation 10). The least squares fit yields a PDMF slope of $\Gamma = 3.8$ while the maximum likelihood method yields $\Gamma = 3.2$. We note that the PDMF is linear across the entire mass range, from our completeness limit of $25M_\odot$ to our most massive star at $65M_\odot$. The absence of a high mass turn-off in this distribution indicates that we do not observe an upper mass limit in the field. This is consistent with the universal upper-mass limit found in Milky Way and LMC clusters, $\sim 150M_\odot$ (Oey & Clarke 2005; Koen 2006).

To derive the intrinsic field IMF, we devise a simple Monte Carlo code to generate theoretical stellar populations with the assumption of continuous star formation and an IMF slope varied from $\Gamma_{\text{IMF}} = 2.0$ to 4.0 in steps of 0.1 and $10^4$ iterations at each step. For each input IMF slope, we compare the distribution of PDMF slopes from the model to the observed PDMF slope, finding a best fit when the input $\Gamma_{\text{IMF}} = 2.9$. Although this slope is significantly steeper than the canonical Salpeter IMF, it is in agreement with the field IMF found in the Magellanic Clouds by Massey et al. (1995) and Massey (2002).
4. **IMF for 7 – 20 \(M_\odot\) Stars**

We plan to supplement our high mass field IMF by measuring the field IMF from 7 – 20\(M_\odot\) using photometric data from the Optical Gravitational Lensing Experiment (OGLE; Udalski et al. 1998, 2008). OGLE provides BVI photometry of the SMC bar and VI photometry for the entire SMC, with completeness to 7\(M_\odot\), allowing for up to two magnitudes of extinction. However, it is difficult to extract individual stellar masses from just BVI photometry, so we will adopt a statistical approach to determine the IMF. We create \(10^4\) realizations of each star in the OGLE database, which are given random gaussian photometry and extinction errors, as defined by the observational uncertainties. Using the stellar evolution tracks of Charbonnel et al. (1993) and their conversion into optical colors by Girardi et al. (2002), we can count the number of realizations for each star that falls into different mass bins and in this manner, assign each star a fractional probability of belonging to specific mass bins.

OGLE also will allow us to redefine our field star sample using a more stringent mass constraint for isolation. Instead of requiring a field OB star to be at least one clustering length from other OB stars, we can strengthen the requirement to at least one clustering length from stars \(> 7\,M_\odot\). This analysis will allow us to examine how the method for defining a field star affects the IMF of the field population.

5. **Discussion and Conclusions**

We measure the IMF of our spatially complete sample of field massive stars in the SMC to be \(\Gamma = 2.9\), much steeper than the canonical Salpeter IMF of \(\Gamma = 1.35\). We find no evidence of an upper stellar mass limit for field stars, up to our most massive star of 65\(M_\odot\). This suggests that despite the steep IMF, the field is not limiting the formation of the most massive stars. Our results confirm the steep field IMF that Massey et al. (1995) and Massey (2002) found in the both the Magellanic Clouds. This steep IMF may indicate a different mode of star formation is happening in the field.
However, our results are affected by a number of uncertainties. Firstly, there is some concern in the ability of evolutionary models to properly estimate stellar masses (Massey et al. 2005). Secondly, the contribution from runaway stars in both their number and mass function is also an unknown quantity. However, since the fraction of O stars that are runaways is higher than B stars (Gies & Bolton 1986), the runaway population tends to flatten, rather than steepen, the IMF. Thus, runaways will affect, perhaps significantly, our observed IMF compared to the IMF of in situ field stars, which may be even steeper than our measurements. Other sources of uncertainty arise from Oe/Be stars in our survey, whose stellar emission lines make spectral classification difficult or impossible; and finally, the binary fraction of the field, which the preliminary results from our survey suggest is > 50% (Oey & Lamb, this volume), may also affect the IMF. Future results from our survey will better quantify the degree and magnitude of the uncertainty that runaways, binaries, and Oe/Be stars impart on the stellar IMF of the field.

Acknowledgments. I thank the organizers for a delightful venue and quality science program. This work was supported by funding from NSF grant AST-0907758. Travel support was provided by the University of Michigan Rackham Graduate School.

References

Battinelli, P. 1991, A&A, 244, 69
Bonnell, I. A., Vine, S. G., & Bate, M. R. 2004, MNRAS, 349, 735
Charbonnel, C., Meynet, G., Maeder, A., Schaller, G., & Schaerer, D. 1993, A&AS, 101, 415
Crowther, P. A. 1997, in IAU Symposium, edited by T. R. Bedding, A. J. Booth, & J. Davis, vol. 189 of IAU Symposium, 137
Gies, D. R., & Bolton, C. T. 1986, ApJS, 61, 419
Girardi, L., Bertelli, G., Bressan, A., Chiosi, C., Groenewegen, M. A. T., Marigo, P., Salasnich, B., & Weiss, A. 2002, A&A, 391, 195
Koen, C. 2006, MNRAS, 365, 590
Krumholz, M. R., & McKee, C. F. 2008, Nat, 451, 1082
Lada, C. J., & Lada, E. A. 2003, ARA&A, 41, 57
Massey, P. 2002, ApJS, 141, 81
Massey, P., Lang, C. C., Dégioia-Eastwood, K., & Garmany, C. D. 1995, ApJ, 438, 188
Massey, P., Puls, J., Pauldrach, A. W. A., Bresolin, F., Kudritzki, R. P., & Simon, T. 2005, ApJ, 627, 477
Oey, M. S., & Clarke, C. J. 2005, ApJ, 620, L43
Oey, M. S., King, N. L., & Parker, J. W. 2004, AJ, 127, 1632
Salpeter, E. E. 1955, ApJ, 121, 161
Selman, F. J., Espinoza, P., & Melnick, J. 2011, in Astronomical Society of the Pacific Conference Series, edited by M. Treyer, T. Wyder, J. Neill, M. Seibert, & J. Lee, vol. 440 of Astronomical Society of the Pacific Conference Series, 39
Szewczyk, O., Pietrzynski, G., Gieren, W., Ciechanowska, A., Bresolin, F., & Kudritzki, R.-P. 2009, AJ, 138, 1661
Úbeda, L., Maíz-Apellániz, J., & MacKenty, J. W. 2007, AJ, 133, 932
Udalski, A., Soszyński, I., Szymański, M. K., Kubiak, M., Pietrzyński, G., Wyrzykowski, Ł., Szweczyk, O., Ulaczyk, K., & Poleski, R. 2008, Acta Astronomica, 58, 329
Udalski, A., Szymanski, M., Kubiak, M., Pietrzynski, G., Wozniak, P., & Zebrun, K. 1998, Acta Astronomica, 48, 147
van den Bergh, S. 2004, AJ, 128, 1880
Walborn, N. R., & Fitzpatrick, E. L. 1990, PASP, 102, 379
Zaritsky, D., Harris, J., Thompson, I. B., Grebel, E. K., & Massey, P. 2002, AJ, 123, 855