The Magellanic System: Stars, Gas, and Galaxies
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The sub-solar initial mass function in the Large Magellanic Cloud†

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Abstract. The Magellanic Clouds offer a unique variety of star forming regions seen as bright nebulae of ionized gas, related to bright young stellar associations. Nowadays, observations with the high resolving efficiency of the *Hubble Space Telescope* allow the detection of the faintest infant stars, and a more complete picture of clustered star formation in our dwarf neighbors has emerged. I present results from our studies of the Magellanic Clouds, with emphasis in the young low-mass pre-main sequence populations. Our data include imaging with the Advanced Camera for Surveys of the association LH 95 in the Large Magellanic Cloud, the deepest observations ever taken with *HST* of this galaxy. I discuss our findings in terms of the initial mass function, which we constructed with an unprecedented completeness down to the sub-solar regime, as the outcome of star formation in the low-metallicity environment of the LMC.

Keywords. Magellanic Clouds, galaxies: star clusters, open clusters and associations: individual (NGC 346, NGC 602, LH 52, LH 95), stars: evolution, stars: pre–main-sequence, stars: luminosity function, mass function

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1. Introduction

The conversion of gas to stars is determined by the star formation process, the outcome of which are stars with a variety of masses. The distribution of stellar masses in a given volume of space at the time of their formation is known as the Initial Mass Function (IMF), given that all stars were born simultaneously. The IMF dictates the evolution and fate of stellar systems, as well as of whole galaxies. The evolution of a stellar system is driven by the relative initial numbers of stars of various masses, from the short-lived high-mass stars ($M \gtrsim 8$ M$_\odot$), which enrich the ISM with elements heavier than H and He, to the low-mass stars ($M \lesssim 1$ M$_\odot$), which lock large amounts of mass over long timescales. It is therefore of much importance to quantify the relative numbers of stars in different mass ranges and to identify systematic variations of the IMF with different star-forming conditions, which will allow us to understand the physics involved in assembling each of the mass ranges.

There are various parameterizations of the IMF (see Kroupa 2002 and Chabrier 2003 for reviews), of which a commonly used is that of a power law of the form $\xi(\log M) \propto M^{\Gamma}$, or alternatively $\xi(M) \propto M^{\alpha}$. The IMF, thus, is characterized by the derivatives

$$\Gamma = \frac{d \log \xi(\log M)}{d \log M} \quad \text{or} \quad \alpha = \frac{d \log \xi(M)}{d \log M},$$

depending on whether stars are distributed according to their masses in logarithmic or linear scales. The above derivatives, which relate to each other as $\alpha = \Gamma - 1$, correspond to the so-called slope of the IMF. A reference value for the IMF slope, as found by

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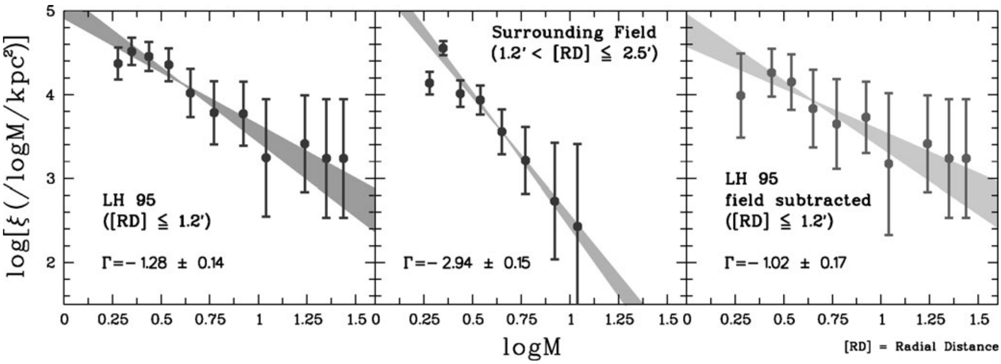

Figure 1. The main-sequence MF of the association LH 95 from observations with the 1-m telescope at Siding Spring Observatory. *Left*: The MF of the system (radial distance $r \lesssim 1\rlap{.}'2$ from its center) with the field population included. *Middle*: The main-sequence MF of the considered surrounding field within radial distance $1\rlap{.}'2 \lesssim r \lesssim 2\rlap{.}'5$. *Right*: The main-sequence MF of the association after the field contribution has been subtracted, which accounts for the IMF of the system. The lack of stars with masses $\gtrsim$10 $M_{\odot}$ in the surrounding field introduces a steep MF for its stellar population. The shaded regions represent the uncertainties of the MF. The corresponding MF slopes Γ are given for stars up to the higher observed mass, which in the region of the system is $\sim$ 28 $M_{\odot}$. The slope of the IMF of LH 95 is a bit shallower than a Salpeter (1955) IMF because of its high-mass content. Data from Gouliermis *et al.* (2002).

Salpeter (1955) in the solar neighborhood for stars with masses between 0.4 and 10 $M_{\odot}$, is $\Gamma = -1.35$ (or $\alpha = -2.35$). In general, although the IMF appears relatively uniform when averaged over whole clusters or large regions of galaxies (Chabrier 2003), the measured IMF shows local spatial variations, which could be the result of physical differences, or even purely statistical in nature (Elmegreen 2004).

The Large Magellanic Cloud (LMC) is the nearest undisrupted neighboring dwarf galaxy to our own. It has a spatially varying sub-solar metallicity of $Z \sim 0.3$–$0.5\ Z_{\odot}$, while its star formation rate is almost the same as the Milky Way (Westerlund 1997). It demonstrates an energetic star formation activity with its H I shells (Kim *et al.* 1999), H II regions (Davies *et al.* 1976), and molecular clouds (Fukui *et al.* 1999), all linked to ongoing star formation. A wide variety of young stellar systems, the stellar associations (Gouliermis *et al.* 2003), located at regions of recent star formation in the LMC form a complete sample of targets with various characteristics for the study of the stellar IMF in this galaxy. Therefore, the LMC, being so close to us, has provided an ideal alternative environment for the study of extragalactic star formation and the derived IMF.

Photometric and spectroscopic investigations of young stellar associations in the LMC, limited so far to ground-based observations, revealed that the IMF of the high-mass stars in these systems is consistent from one system to the other. All measured IMF slopes are found to be clustered around the Salpeter value, not very different from that of OB associations of our Galaxy (Massey 2006), suggesting that the massive IMF appears more or less to be universal with a typical Salpeter slope (Massey 2003). It should be noted that there are small but observable differences in the constructed IMF and its slope between different systems, which may imply that the IMF is probably determined by the local physical conditions (Hill *et al.* 1995), or that the variability in the slope of the IMF could be the result of different star formation processes (Parker *et al.* 1998). However, taking into account the constraints in the construction of the IMF, one may argue that the IMF variations are possibly observational and/or statistical in nature (Kroupa 2001). An example of the spatial dependence of the IMF and the effect of the contamination by the field population is demonstrated in Fig. 1, where the massive IMF in the LMC association LH 95 constructed earlier by the author and collaborators is shown.

2. The IMF in the low-mass regime

Complete investigations concerning the low-mass stars are so far available only for the Galactic IMF, which is found to become flat in the sub-solar regime (Reid 1998), down to the detection limit of 0.1 $M_{\odot}$ or lower (Lada *et al.* 1998). Observed variations from one region of the Galaxy to the next in the numbers of low-mass stars and brown dwarfs over intermediate- and high-mass stars affect the corresponding IMF, which seems to depend on the position (e.g., Luhman *et al.* 2000; Briceño *et al.* 2002; Preibisch *et al.* 2003). Explanations suggested for the low-mass IMF variations include stochasticity in the ages and ejection rates of proto-stars from dense clusters (e.g., Bate *et al.* 2002), differences in the photo-evaporation rate from high-mass neighboring stars (e.g., Kroupa & Bouvier 2003), or a dependence of the Jeans mass on column density (Briceño *et al.* 2002) or Mach number (Padoan & Nordlund 2002), and they may also be affected by variations in the binary fraction (Malkov & Zinnecker 2001).

While the discussion over the low-mass part of the Galactic IMF continues, more information on the IMF toward smaller masses in other galaxies is required for the understanding of its dependence on the global properties of the host-galaxy and for addressing the issue of its universality. The LMC, due to its proximity, can serve as the best proxy for the study of extragalactic young low-mass stellar populations, and due to its global differences from the Milky Way, it provides a convenient alternative environment for the investigation of the IMF variability. Under these circumstances, issues that should be addressed can be summarized to *what is the low-mass stellar population of young stellar associations in the LMC*, *what is the shape of the corresponding IMF*, and *how it compares to that of the Milky Way*. A substantial amount of such information in both the Magellanic Clouds (MCs) was thus far lacking, mostly due to observational limitations. However, recent observations of the MCs with the *Hubble Space Telescope* (*HST*) changed dramatically our view of star formation in these galaxies.

3. Low-mass PMS populations in the Magellanic Clouds

In the Galaxy previous observations have confirmed the existence of faint pre-main sequence (PMS) stars as the low-mass population of nearby OB associations and star-forming regions (e.g., Hillenbrand *et al.* 1993; Brandl *et al.* 1999; Preibisch *et al.* 2002; Sherry *et al.* 2004). The only extragalactic places where such stars could be resolved are the MCs, and recent imaging with *HST* revealed the PMS populations of their stellar associations, and allowed their study. Our investigation of the LMC association LH 52 with WFPC2 observations extended the stellar membership of MCs associations to their PMS populations for the first time (Gouliermis *et al.* 2006a). Subsequent photometry with the *Advanced Camera for Surveys* (ACS) of the association NGC 346 in the Small Magellanic Cloud (SMC) led to the discovery of an extraordinary number of low-mass PMS stars in its vicinity (Nota *et al.* 2006; Gouliermis *et al.* 2006b), providing the required statistical sample for the investigation of the clustering behavior (Hennekemper *et al.* 2008) and the IMF (Sabbi *et al.* 2008) of these stars.

Our photometric study of another young SMC star cluster, NGC 602, with *HST*/ACS revealed a coherent sample of PMS stars, ideal for the study of the low-mass IMF in the SMC and the complications in its construction (Schmalzl *et al.* 2008). The IMF of the PMS population of NGC 602 was constructed by counting the stars between evolutionary tracks on the CMD (Fig. 2 - *left*). While this method is independent of any age-gradient among the stars, it still depends on the selected models. As a consequence, the shape of

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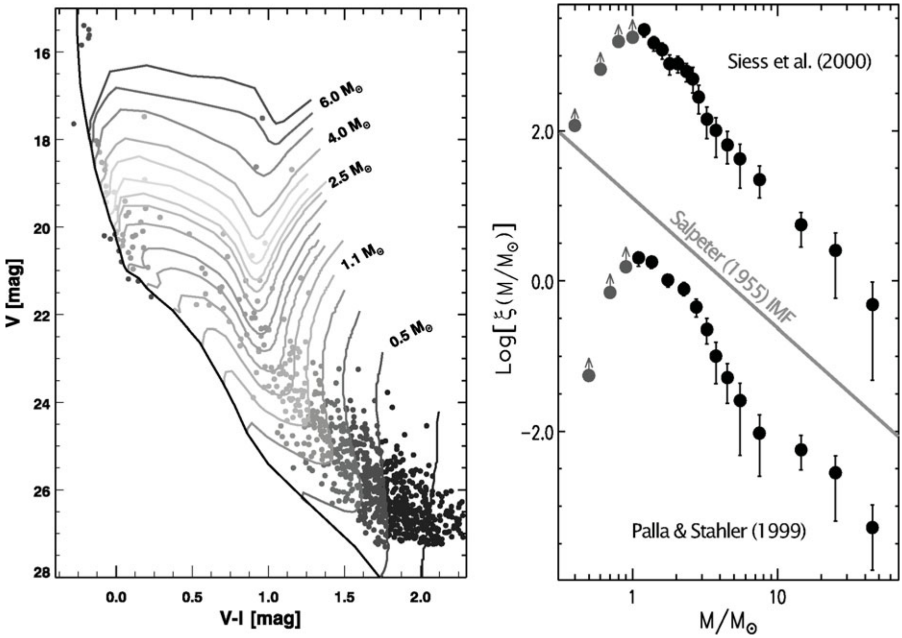

Figure 2. Construction of the IMF of the young SMC cluster NGC 602. *Left*: The CMD of the stars of the system after the contamination by the field population is removed, with PMS evolutionary tracks from the models by Siess *et al.* (2000) overlaid. The ZAMS from the models by Girardi *et al.* (2002) is also shown. The IMF of NGC 602 for the PMS stars is constructed by counting stars between evolutionary tracks using both Palla & Stahler (1999) and Siess *et al.* (2000) PMS tracks, while the ZAMS is used for the construction of a mass-luminosity relation for the bright MS stars with $M \gtrsim 6$ $M_\odot$ for the derivation of their masses. *Right*: The derived IMF, as it is constructed with use of both the models by Siess *et al.* (2000) (top) and Palla & Stahler (1999) (bottom). The grey line corresponds to a Salpeter (1955) IMF with $\alpha \simeq -2.3$. Stellar numbers are corrected to a bin-size of 1 $M_\odot$. Data from Schmalzl *et al.* (2008).

the derived IMF for stars with $M \lesssim 2$ $M_\odot$ appears somewhat different with the use of different PMS tracks (Fig. 2 - *right*). Although this IMF seems to flatten for masses close to solar, no important change in the slope is identified. We found that, in general, a single-power law with a slope of $\alpha \simeq -2.2 \pm 0.3$ represents well the average IMF of the system as it is constructed with the use of all considered grids of models (Schmalzl *et al.* 2008). This result is in line with that of Sabbi *et al.* (2008) for NGC 346. The IMF of both NGC 346 and NGC 602 is limited to stars of 1 $M_\odot$ due to the observations, which did not allow the detection of statistically significant numbers of sub-solar PMS stars.

4. The sub-solar IMF in the Large Magellanic Cloud

The first complete sample of extragalactic sub-solar PMS stars is detected by the author and collaborators by utilizing the *high sensitivity and spatial resolving power* of ACS in combination with its *large field of view* in the LMC association LH 95 (Gouliermis *et al.* 2007). Two pointings, one on LH 95 and another on the general field, were observed in the filters F555W ($\approx V$) and F814W ($\approx I$) with the longest exposures ever taken with *HST* of the LMC (in total 5,000 sec per filter per field). These state-of-the-art observations allowed us the construction of the CMD of the association in unprecedented detail and to decontaminate it for the average LMC stellar population (Fig. 3 - *left*). Although LH 95 represents a rather modest star-forming region, our photometry, with a detection limit of $V \lesssim 28$ mag (at 50% completeness), revealed more than 2,500 PMS stars with masses down to ~ 0.3 $M_\odot$.

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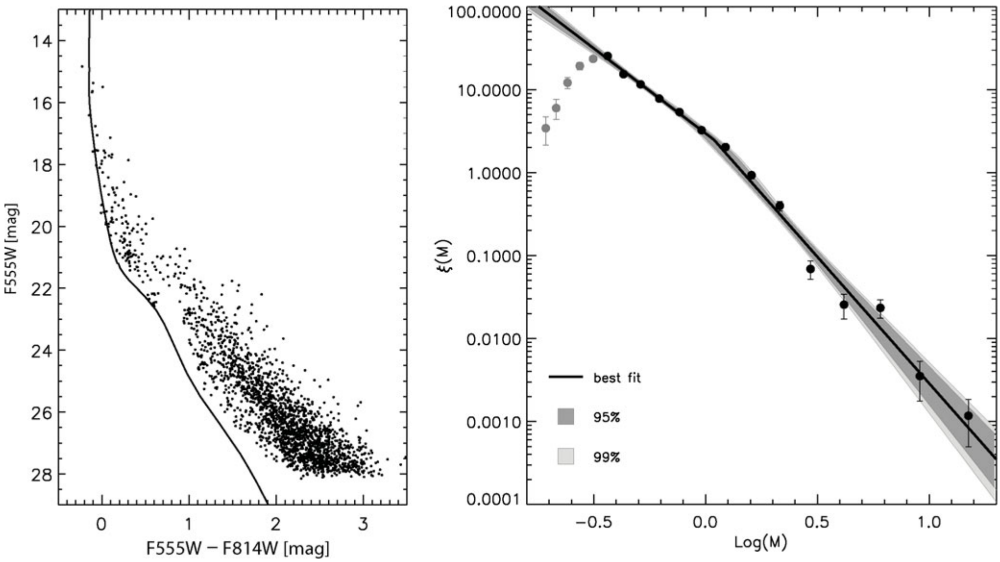

Figure 3. *Left*: The F555W−F814W, F555W CMD of the stars detected with *HST*/ACS in the LMC association LH 95, after the contamination of the LMC field has been statistically subtracted (Gouliermis *et al.* 2007). The ZAMS from Girardi *et al.* (2002) grid of models is also plotted. This is the most complete CMD of an extragalactic star-forming region ever constructed. *Right*: The IMF of the association LH 95 constructed from our ACS photometry with the use of a new observable plane for the PMS models by Siess *et al.* (2000) designed by us for the metallicity of the LMC and the photometric system of ACS. The best two-part power-law fit is drawn with solid line, while the shaded areas represent the 95% and 99% confidence uncertainties in the slope determination and the break point (the "knee"). Units of the IMF, $\xi(M)$, are logarithmic number of stars per solar mass per pc^2. Data from Da Rio *et al.* 2009.

The subsequent interpretation of these observations by Da Rio, Gouliermis & Henning 2009 led to the introduction of a new set of observational evolutionary models, derived from the theoretical calculations by Siess *et al.* (2000). We converted luminosities from these evolutionary tracks into observable magnitudes in the ACS photometric system by taking into account the parameters $T_{\rm eff}$, $\log(g)$ and $[M/H]$ for a large variety of stellar objects. We used these models with the observations of LH 95 to derive the IMF of the system by assigning a mass value to each PMS star. This IMF, shown in Fig. 3 (*right*), is reliably constructed for stars with masses down to ~ 0.3 M$_{\odot}$, the lowest mass ever observed within reasonable completeness in the MCs. Consequently, its construction offers *an outstanding improvement in our understanding of the low-mass star formation in the LMC*. We verified statistically that the field-subtracted completeness-corrected IMF of LH 95 has a definite change in its slope for masses $M \lesssim 1$ M$_{\odot}$, where it becomes more shallow (Da Rio *et al.* 2009). In general, the shape of this IMF agrees very well with a multiple power-law, as the typical Galactic IMF down to the sub-solar regime. A definite change is identified, though, in the slope of the IMF (the "knee of the IMF") at ~ 1 M$_{\odot}$, a higher mass-limit than that of the average Galactic IMF derived in various previous investigations (e.g., Kroupa 2001, 2002). As far as the slope of the IMF of LH 95 is concerned, it is found to be systematically steeper than the classical Galactic IMF (e.g., Scalo 1998; Kroupa 2002) in both low- and high-mass regimes. No significant differences in the shape of the average IMF of LH 95 from that of each of the three individual PMS sub-clusters of the association is also found. This clearly suggests that the IMF of LH 95 is not subject to local variability.

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