A *HUBBLE* VIEW OF STAR FORMING REGIONS IN THE MAGELLANIC CLOUDS

Dimitrios A. Gouliermis*[1], Thomas K. Henning[1], Wolfgang Brandner[1], Michael R. Rosa[2], Andrew E. Dolphin[3], Markus Schmalzl[1], Eva Hennekemper[1], Hans Zinnecker[4], Nino Panagia[5], You-Hua Chu[6], Bernhard Brandl[7], Sascha P. Quanz[1], Massimo Robberto[5], Guido De Marchi[8], Robert A. Gruendl[6], and Martino Romaniello[2]

[1]*Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany*
[2]*European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching, Germany*
[3]*Raytheon Corporation, USA*
[4]*Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany*
[5]*Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA*
[6]*Department of Astronomy, University of Illinois, 1002 West Green Street, Urbana, IL 61801, USA*
[7]*Sterrewacht Leiden, P.O. Box 9513, Niels Bohrweg 2, 2300 RA Leiden, The Netherlands*
[8]*ESA, Space Science Department, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands*

ABSTRACT

The Magellanic Clouds (MCs) offer an outstanding variety of young stellar associations, in which large samples of low-mass stars (with $M \lesssim 1$ M$_{\odot}$) currently in the act of formation can be resolved and explored sufficiently with the *Hubble* Space Telescope. These pre-main sequence (PMS) stars provide a unique snapshot of the star formation process, as it is being recorded for the last 20 Myr, and they give important information on the low-mass Initial Mass Function (IMF) of their host environments. We present the latest results from observations with the *Advanced Camera for Surveys* (ACS) of such star-forming regions in the MCs, and discuss the importance of *Hubble* for a comprehensive collection of substantial information on the most recent low-mass star formation and the low-mass IMF in the MCs.

Key words: Magellanic Clouds; stellar associations; pre-main sequence stars; H II regions; star clusters: individual (LH 95, NGC 346, NGC 602).

1. INTRODUCTION

The Large and Small Magellanic Cloud (LMC, SMC) are the closest undisrupted neighboring dwarf galaxies to our own. They have four to five times lower metallicities than the Milky Way (MW), while their gas-to-dust ratio is much higher, forming environments resembling those of the early universe. The Magellanic Clouds (MCs) show clear evidence for energetic star formation activity with H I shells [21], [18], H II regions [16], [6], and molecular clouds [7], [32], all linked to ongoing star formation, as it is observed in young stellar systems, the *Stellar Associations* [19], [1], [10]. Both MCs contain a variety of such stellar systems, the age and IMF of which become very important sources of information on their recent star formation. They provide a rich sample of targets for the comprehensive study of current star formation in low-metallicity environments. Considering that the MCs are so close to us ($\sim$ 50 kpc and 60 kpc), they are indeed ideal laboratories for a detailed study of clustered star formation and the IMF in the early universe, and *Hubble*'s contribution is fundamental in such a study.

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2. A NEW VIEW OF MCS ASSOCIATIONS

Stellar associations contain the richest sample of young bright stars in a galaxy. Consequently our knowledge on the young massive stars of the MCs has been collected from photometric and spectroscopic studies of young stellar associations [20]. However, the picture of these stellar systems changed when *Hubble* observations revealed that MCs associations are not mere aggregates of young bright stars alone, but they also host large numbers of faint PMS stars [12], [23]. Although nearby galactic OB associations are known to be significant hosts of such stars [27], [29], [4], PMS studies in the MCs with *Hubble* were focused only on the surrounding field of the supernova 1987A [26], cluster NGC 1850 [8], and the star-burst of 30 Doradus [3], [28] all in the LMC. However, these studies are limited by crowding, even at the angular resolution facilitated by *Hubble*.

To learn more about low-mass PMS stars in the MCs, one has to study less crowded regions like young stellar associations. Indeed, an investigation on the main-sequence IMF of the LMC association LH 52 with HST/WFPC2 observations by [11] revealed $\sim$ 500 low-mass candidate PMS stars easily distinguishable in the $V-I$, V Color-Magnitude Diagram (CMD) [12]. More recently,

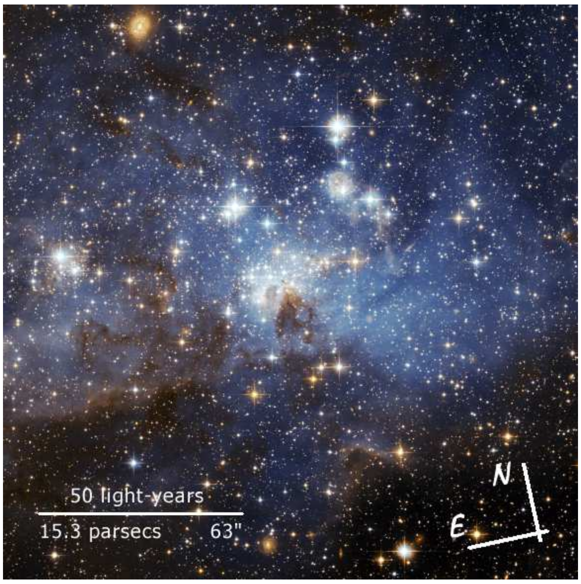

Figure 1. Color-composite image from ACS/WFC observations in the filters $F555W$ and $F814W$ (V- and I-equivalent) of the LMC star-forming region LH 95/N 64. This sharp image, presented at the 2006 General Assembly of the International Astronomical Union, reveals a large number of low-mass infant stars coexisting with young massive ones. These observations, being the deepest ever taken towards the LMC, allow us to explore the scientific gain that can be achieved for MCs studies using high spatial resolution photometry from Hubble. *Image credit: NASA, ESA and D. A. Gouliermis (MPIA). Acknowledgments: Davide de Martin (ESA/Hubble).*

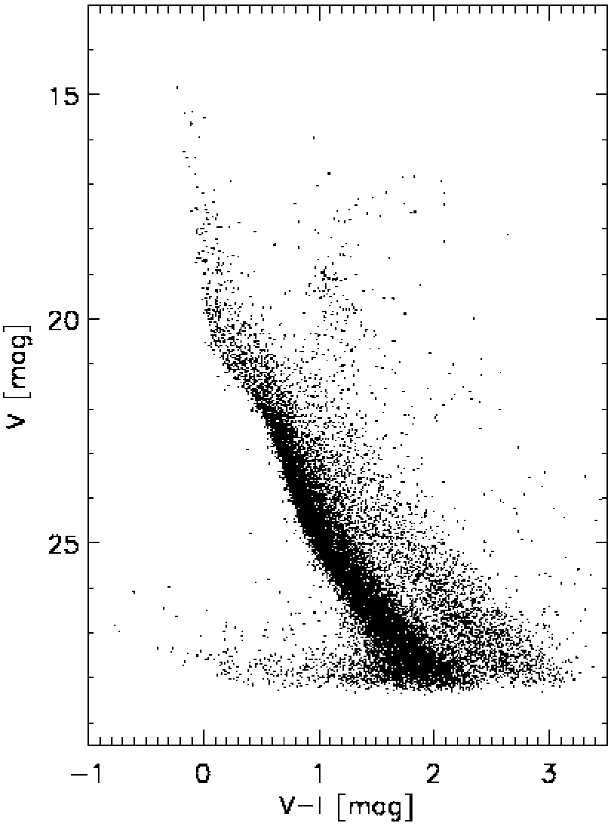

Figure 2. The $V - I$, V CMD of the stars detected with ACS/WFC in the region of LH 95/N 64. These observations, with a detection limit of $V \simeq 28.4$ mag ($M \lesssim 0.5\ M_{\odot}$), reveal a unique sample of $\sim$ 2,450 PMS stars, easily distinguished as a secondary red sequence, almost parallel to the faint part of the main sequence. These stars are found to be concentrated in the central part of the association and in surrounding compact clusters, and their spatial distribution is in excellent coincidence with the loci of the brightest MS stars [15].

deeper observations with the Wide-Field Channel (WFC) of ACS of another LMC association (the star-forming region LH 95/N 64) revealed the coexistence of PMS stars and early-type stars in such stellar systems (Figure 1).

These one-of-a-kind observations dramatically changed the picture we had for stellar associations in the MCs by revealing a unique rich sample of PMS stars in LH 95/N 64 (Figure 2). The spatial distribution of these low-mass members demonstrates the existence of significant substructure ("subgroups"), as in the case of galactic OB associations. This stellar sub-clustering has its origins possibly in short-lived parental molecular clouds within a Giant Molecular Cloud Complex. Each of these "*PMS clusters*" in LH 95/N 64 includes a few early-type stars. Such stars have been identified as candidate Herbig Ae/Be (HAeBe) stars due to their strong Hα emission [9]. Near-IR spectroscopic study with VLT/SINFONI (ESO Program 078.D-0200) will clarify their nature.

2.1. Stellar Subgroups in MCs Associations

A spatial behavior similar to the PMS population of LH 95/N 64 is seen in PMS stars of the association NGC 346 in the SMC [13], from observations with ACS/WFC. NGC 346 is located in the brightest H II region of the SMC, N 66, and ACS uncovered the richness of this region in PMS stars [13], [23]. The surface density map of the region of NGC 346/N 66 constructed from star counts of the PMS stars in the observed field is shown in Figure 3. Apart from the association itself (seen as the central large concentration) there are at least five distinct concentrations of PMS stars with surface stellar density $\gtrsim 3\sigma$ above the background (where σ is the standard deviation of the background density), which fit the description of "PMS clusters". The size of each cluster is defined by the isopleth corresponding to the local mean density around it, and the time-scale within which each PMS cluster was presumably formed is defined by their individual CMDs. Although the loci of the PMS stars in the CMD exhibit a broadening, which prevents an accurate estimation of their age, it was found that the PMS clusters located away from NGC 346 to the north, represent the most recent star formation activity in the region [17].

2.2. CMD Broadening of PMS Stars

The loci of PMS stars in the CMD often show a widening, which could be evidence for an age-spread [25]. The low-mass population in subgroups within OB associations of the MW exhibits little evidence for significant age-spreads on time-scales $\gtrsim$ 10 Myr [4]. Although this time-scale is in agreement with a scenario of rapid star formation and cloud dissipation, age differences of the order of 10 Myr may be very important for understanding of how sequential star formation proceeds.

Moreover, there are several factors apart from age-spread, such as variability and binarity, which can cause considerable deviations of the positions of the PMS stars in the CMD [29]. A broadening in the CMD is also observed for the PMS stars of NGC 346/N 66 (Figure 4). Simulations showed that apart from photometric uncertainties, binarity and variability, reddening seems to play the most important role in the observed widening of the PMS stars, providing false evidence for an age-spread if the region suffers from high extinction [17].

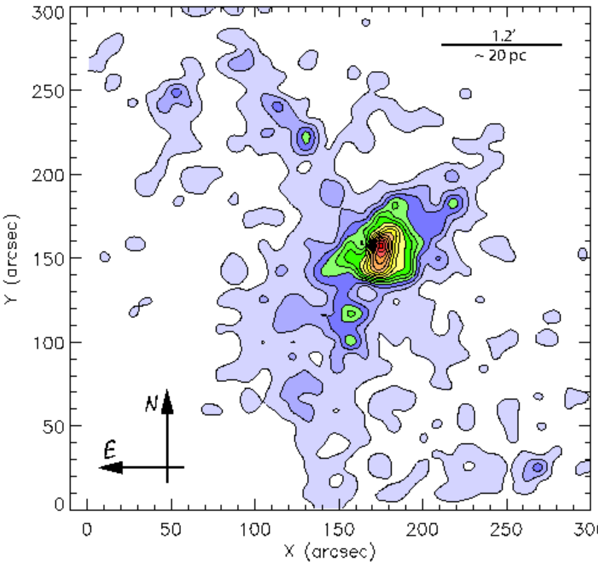

Figure 3. Isodensity contour map of the region of NGC 346/N 66 in the SMC from ACS/WFC observations, constructed from star counts of the PMS stars [13]. Isopleths are plotted in steps of 1σ, σ being the standard deviation of the background surface density. This map demonstrates the existence of statistically significant concentrations of PMS stars outside the main body of the association NGC 346 (located at the center). Such PMS clusters are suspected to be the product of sequential star formation triggered by the action of the OB stars in NGC 346, which shape the southern part, and a supernova, which affects the northern part of the region [17].

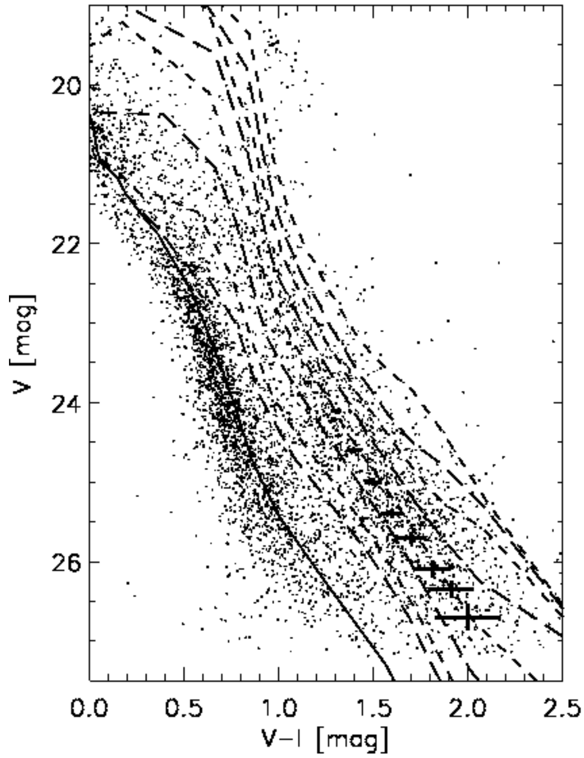

Figure 4. Detail of the $V-I$, V CMD of all stars detected with ACS/WFC imaging in the area of NGC 346 (0.′6 around its center). PMS isochrone models by [31] for ages 0.5 to 15 Myr are overplotted to demonstrate that the observed broadening of the PMS stars can be easily misinterpreted as an age-spread. Simulations showed that this spread can be explained as the result of interstellar reddening of $E(B-V) \simeq 0.08$ mag alone, or of two star formation events (a true age-spread) ∼5 Myr apart if the reddening is lower. Typical photometric uncertainties in brightness and color are also shown [17].

3. THE IMF OF MCS ASSOCIATIONS

Young stellar systems, which host newborn PMS stars, naturally provide the testbed for a comprehensive study of the stellar IMF. A coherent sample of PMS stars is found with *Hubble* from ACS imaging in the vicinity of another SMC association, NGC 602, located in the H II region N 90 [30]. The region of NGC 602/N 90 includes no distinct subgroups, and therefore, being less complicated than NGC 346/N 66, is more suitable for the investigation of the low-mass IMF. For the construction, though, of this IMF a mass-luminosity relation derived from evolutionary models cannot be used due to the spread of the PMS stars, also apparent in the CMD of NGC 602. Instead, counting the PMS stars between evolutionary tracks, which represent specific mass ranges, seems to be the most accurate method for the construction of their mass spectrum (Figure 5).

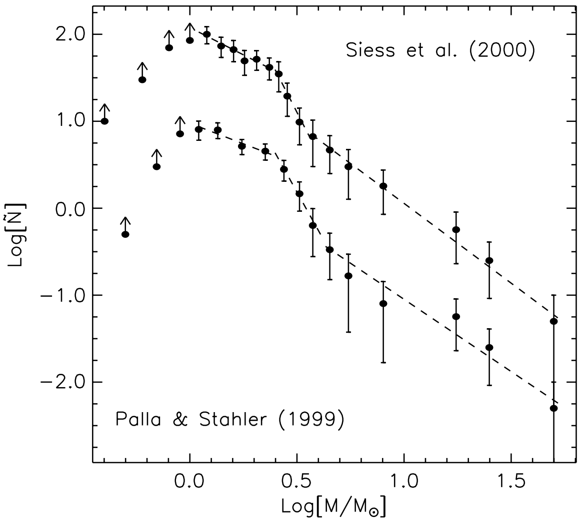

Figure 5. The stellar mass spectrum of NGC 602 for the whole mass range observed with ACS/WFC. The low-mass part ($\lesssim$ 6 M$_\odot$) was constructed by counting PMS stars between evolutionary tracks, with the use of two sets of PMS grids [24], [31]. It is found that the IMF seems to be model-independent and is well represented by a three-part power law [30].

4. ON-GOING STAR FORMATION IN THE MCS

The coexistence of H II regions and PMS stars in stellar associations of the MCs indicate that star formation may be still active in their vicinity. Indeed, observations with the *Spitzer* Space Telescope revealed objects classified as candidate Young Stellar Objects (YSOs) in such regions [22], [2], and *Hubble*'s contribution has been very important in disentangling their nature [5]. The region of NGC 602/N 90 is also found with *Spitzer* to host possible YSOs, and the comparison of the loci of these IR-bright sources with the *Hubble* images interestingly showed PMS stars to be their optical counterparts [14]. A variety of objects is discovered to coincide with these candidate YSOs, such as single highly embedded sources, small compact PMS clusters, as well as features similar to "Elephant Trunks", all located at the periphery of NGC 602, along the dust ridges of the molecular cloud presumably blown-away by the action of the association itself [14].

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