Low-mass pre–main-sequence stars in the Magellanic Clouds

Dimitrios A. Gouliermis

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Abstract The stellar Initial Mass Function (IMF) suggests that stars with sub-solar mass form in very large numbers. Most attractive places for catching low-mass star formation in the act are young stellar clusters and associations, still (half-)embedded in star-forming regions. The low-mass stars in such regions are still in their pre–main-sequence (PMS) evolutionary phase, i.e., they have not started their lives on the main-sequence yet. The peculiar nature of these objects and the contamination of their samples by the fore- and background evolved populations of the Galactic disk impose demanding observational techniques, such as X-ray surveying and optical spectroscopy of large samples for the detection of complete numbers of PMS stars in the Milky Way. The Magellanic Clouds, the metal-poor companion galaxies to our own, demonstrate an exceptional star formation activity. The low extinction and stellar field contamination in star-forming regions of these galaxies imply a more efficient detection of low-mass PMS stars than in the Milky Way, but their distance from us make the application of the above techniques unfeasible. Nonetheless, imaging with the Hubble Space Telescope within the last five years yield the discovery of solar and sub-solar PMS stars in the Magellanic Clouds from photometry alone. Unprecedented numbers of such objects are identified as the low-mass stellar content of star-forming regions in these galaxies, changing completely our picture of young stellar systems outside the Milky Way, and extending the extragalactic stellar IMF below the persisting threshold of a few solar masses. This review presents the recent developments in the investigation of the PMS stellar content of the Magellanic Clouds, with special focus on the limitations by single-epoch photometry that can only be circumvented by the detailed study of the observable behavior of these stars in the color-magnitude diagram. The achieved characterization of the low-mass PMS stars in the Magellanic Clouds allowed thus a more comprehensive understanding of the star formation process in our neighboring galaxies.

Keywords Magellanic Clouds · HII regions · Hertzsprung–Russell and C–M diagrams · open clusters and associations · stars: formation · stars: luminosity function, mass function · stars: pre–main-sequence

Dimitrios A. Gouliermis
Max Planck Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
E-mail: dgoulier@mpia-hd.mpg.de
1 Introduction

The Large and Small Magellanic Clouds (LMC, SMC) are the closest undisrupted neighboring galaxies to our own. They are characterized by their low metal abundance, which is 2.5 and 5 times respectively lower than Solar (Westerlund 1997; Luck et al. 1998; Venn 1999), and their dust-to-gas ratios, which vary from 2 up to 10 times lower than in the Milky Way (Stanimirović et al. 2000; Gordon et al. 2003). Their metallicities suggest that the environments of the Magellanic Clouds (MCs) are closer to that of the early universe during the epoch of its peak star formation at $z \sim 1.5$ (Madau et al. 1996; Pei et al. 1999). They are, therefore, the best local templates of primitive star formation. As such, both the MCs offer an outstanding variety of young stellar clusters and associations, the age and Initial Mass Function (IMF) of which become very important sources of information on their recent star formation. Young star clusters and associations contain the richest samples of bright OB-type stars in a galaxy. Consequently our knowledge on the young massive stars of the MCs has been collected from photometric and spectroscopic studies of such systems (see, e.g., Massey 2006, and references therein). In particular, recent spectroscopic studies in the optical (see, e.g., Evans et al. 2006; Hunter et al. 2009; Evans et al. 2011) and infrared (e.g., Bonanos et al. 2010; Sewiło et al. 2010) provide a unique insight of the properties of young massive stars in the MCs. However, a more comprehensive picture of young stellar systems in these galaxies has emerged when Hubble Space Telescope (HST) observations revealed that star-forming regions of the MCs host large numbers of faint pre–main-sequence (PMS) stars.

The youngest star clusters and associations with ages $< 10$ Myr are embedded in bright HII regions, comprising high-mass stars on the main-sequence (MS) as well as intermediate- and low-mass young stellar objects (YSOs), i.e., stars in the earliest stages of their evolution. There are two principal kinds of YSOs, protostars, denoting stars in their early stages of formation, and PMS stars (see, e.g., Lada & Murdin 2001). According to the classification by Robitaille et al. (2006), analogous to the traditional scheme of Lada (1987), stage 0-I YSOs have ages $< 0.1$ Myr and are characterized by infalling envelopes. Stage II YSOs have ages between 0.1 and a few Myr and demonstrate thick disks. The more evolved stage III YSOs have optically thin disks or no disks at all. PMS stars are usually associated with YSOs of stages II-III (Lada 1999). The high-mass (OB-type) MS stars and intermediate-mass PMS populations (with typical example the Herbig Ae/Be stars; Waters & Waalkens 1998) are the direct signature of the youthfulness of their hosting stellar systems, but they represent only the latest phases of star formation. On the other hand, the low-mass PMS stars of these systems preserve a record of the complete recent star formation history of the star-forming region over long periods, because their evolution is extremely slow and can last up to many tens of Myr. Indeed, the star formation history of star-forming regions in the Galaxy is usually constrained by the study of their PMS stars (see e.g., Preibisch et al. 2003; Sherry 2004; Briceño et al. 2007; Reipurth 2008a, 2008b; Preibisch et al. 2011). However, the samples of these stars are significantly contaminated by the field of the Galactic plane, and therefore various observational techniques are developed for the correct identification of faint PMS stars, and in particular T Tauri stars (TTS; Appenzeller & Mundt 1989) as the typical paradigm of such stars, in star-forming regions of the Milky Way.

PMS stars exhibit periodic fluctuations in light that indicate large, rotating starspots. Therefore, optical variability surveys are used for the collection of large samples of such stars.

1. Typical contraction time for a 1 M$_\odot$ PMS star is 50 Myr and for a 0.5 M$_\odot$ PMS star 200 Myr (Karttunen et al. 2007).
stars in the Galaxy. Prominent optical emission lines, as well as X-ray emission, are thought to stem from chromospheric heating. Spectroscopy is thus quite useful for the detection of Galactic PMS stars, and X-ray observations have been especially useful in locating PMS objects in dense molecular cloud environments. Moreover, since these stars are still accreting material through circumstellar disks, deep UV and Hα imaging is also applied for accretion studies through the detection of excess emission in these wavelengths. Excess in near-IR wavelengths is a positive signature of disks around young stars, and therefore PMS stars are also identified through their near-IR colors. Other techniques for the investigation of Galactic PMS stars involve Lithium abundance measurements and dating of the stars from Li depletion (e.g., Jeffries & Oliveira 2005, Mentuch et al. 2008), far- and mid-IR imaging (e.g., Mérand et al. 2008, Baume et al. 2011), and interferometry for the study of circumstellar disks properties (e.g., Ragland et al. 2011). While such techniques are proven to be profitable in studying faint Galactic PMS stars, at the distance of the MCs (∼ 50 - 60 kpc) finding such stars can only be achieved through imaging at the angular resolution and wide-field coverage facilitated with HST. In addition, observational and technical limitations do not allow the successful application of techniques such as multi-object spectroscopy, time-dependent imaging for variability studies, or X-ray surveys, among others, and thus investigators have to rely on single-epoch photometry alone for detecting and characterizing faint PMS stars in the MCs. Nevertheless, considering the aforementioned characteristics of PMS stars, the positions of these stars in the color-magnitude diagram (CMD) can be misleading and introduce biases that affect their interpretation.

This problem can be overcome by the successful distinction of the PMS stars from their surrounding field populations, and the thorough study of the behavior of these stars in the CMD through modeling of their physical properties. To this end, a successful study of significant numbers of such stars in star-forming regions of the MCs concern the complete understanding of observational and physical factors that affect the measured magnitudes and colors of these stars, in order to achieve a comprehensive assessment of their photometric behavior as members of a young stellar cluster, and the accurate determination of the IMF and the age of this cluster. This paper is an overview of all studies focused on the investigation of PMS stars in the MCs from HST photometry. Based on the lack of previous concrete data on PMS stars in the MCs, the fundamental assumption, i.e., the working hypothesis, of such studies is that the observable behavior of low-mass PMS stars in the MCs does not differ from that of their Milky Way TTS counterparts (see, e.g., Gouliermis et al. 2010). This review is constructed as the following. In §2 I present the recent detections of faint PMS stars in various star-forming regions of both the MCs with HST. The optical CMD of a typical young cluster in the MCs is discussed in §3 where I also give a detailed account of the biasing factors that affect the observed CMD-positions of the detected PMS stars. Calculations of PMS evolutionary models, and their transformation to the observable plane, i.e., the CMD, are extremely useful for the accurate translation of magnitudes and colors into masses and ages of PMS stars. Methods for this translation are discussed in §4. In the following sections an account of statistical analyses of the rich samples of PMS stars found with HST in MCs star-forming regions is given. In particular the determination of the stellar IMF in MCs young clusters from their PMS populations is described in §5 and methods for the assessment of the age of PMS clusters, and their intrinsic age-spreads are presented in §6. Finally, conclusive remarks are given in §7.
2 Detection of PMS stars in the MCs

2.1 Early detections

In the Galaxy earlier investigations confirmed the existence of faint PMS stars in a variety of star-forming environments, from open clusters and associations, such as, e.g., NGC 6611 (Hillenbrand et al. 1993), Upper Scorpius (Preibisch & Zinnecker 1999), and Orion OB1, (Sherry 2004; Briceño et al. 2005) to compact massive starbursts (e.g., NGC 3603, Brandl et al. 1999; Stolte et al. 2004). Pioneering studies on PMS stars in the MCs were focused mostly on the starburst of 30 Doradus in the LMC. Historically, Brandl et al. (1996) were the first to detect 108 “extremely red sources”, which are most likely PMS stars of low or intermediate mass from adaptive optics near-IR imaging of the central region of 30 Dor. They constructed the IMF of these stars down to $\sim 3 \, M_\odot$. Sirianni et al. (2000), using imaging from the Wide-Field Planetary Camera 2 (WFPC2) onboard HST, detected in the same region stars down to $1.35 \, M_\odot$ and they found that the red population in the CMD is well traced by PMS isochrones. Brandner et al. (2001) observed again the area of 30 Dor with the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) onboard HST and they found no evidence for a lower mass cutoff in the IMF for PMS stars, in contrast to what was earlier reported. These studies revealed for the first time the PMS stellar content of the Tarantula nebula starburst. However, the region of 30 Dor in known to suffer from significant stellar crowding and high extinction, factors which limit the detection of complete samples of low-mass PMS stars to about $2 \, M_\odot$ (Romaniello et al. 2006).

In contrast, less crowded clusters and associations, embedded in typical HII regions of the MCs, do not suffer severely from these factors, and thus faint PMS stars are easier detectable in such systems, proving them to be important hives of low-mass PMS populations. Brandner et al. (1999) reported the detection of about 150 objects with excess emission in the SMC association NGC 346 with observations from HST NICMOS. These authors explained this observation as the detection of candidate PMS stars with masses between 1 and $2 \, M_\odot$. Other early PMS studies in the MCs were conducted on the surrounding area of the supernova remnant SN 1987A in the LMC. A small number of 492 stellar sources was identified as 1 - 2 $M_\odot$ field PMS stars based on their conspicuous Hα excess (Panagia et al. 2000). Subsequent studies in star-forming regions less crowded than 30 Dor are significantly benefitted by the angular resolution and wide-field coverage provided by HST.

The discovery of sub-solar PMS stars in a star-forming region of the MCs less crowded than 30 Dor was originally made with the use of archival imaging taken with WFPC2 of the LMC stellar association LH 52 (Gouliermis et al. 2006b). The locations of the detected PMS candidates in the optical CMD were found to be in excellent agreement with those of TTS of $M \lesssim 2 \, M_\odot$ in the Galactic association Ori OB1 (Sherry 2004; Briceño et al. 2005). The WFPC2 images of LH 52 provided the first discovery of such stars in LMC star-forming regions, with the identification of about 500 sources down to $\sim 0.3 \, M_\odot$. However, this sample being limited by incompleteness did not allow a thorough statistical investigation. Nevertheless, this study demonstrated that low-mass PMS stars can be directly identified in the CMD from photometry in $V$- and $I$-equivalent filters, providing that the local background field of the galaxy has been adequately observed. Subsequent deep imaging with the Wide-Field Channel (WFC) of the Advanced Camera for Surveys (ACS) onboard HST of the young clusters NGC 602 in the SMC and LH 95 in the LMC, and the bright star-forming regions N66 (NGC 346) in the SMC and N11 in the LMC, provided an outstanding insight of the low-mass stellar population in such regions. I present these findings in the following section.
Fig. 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/N64. These observations revealed an outstanding number of low-mass infant PMS stars coexisting with young massive giant stars. The smooth continuum in the image is due to the diffuse Hα emission. Image credit: NASA, ESA and D. A. Gouliermis (MPIA). Acknowledgments: Lars Lindberg Christensen (ESO/ESA/ST-ECF), Davide de Martin (ESA/Hubble).

2.2 PMS stars in young star clusters of the MCs

The photometric study with ACS/WFC imaging of the association NGC 346 and its surrounding field, embedded in the HII region LHα 115-N66 (in short N66; Henize 1956), the brightest in the SMC, led to the discovery of an extraordinary number of PMS stars in its vicinity (Nota et al. 2006; Gouliermis et al. 2006b). Almost 100,000 stars in various evolutionary stages were detected over a magnitude range $11 \lesssim m_{555} \lesssim 28$, in three overlapping WFC pointings, covering a field about $5' \sim 85$ pc wide. The bright MS stars of the association have been the subject of thorough investigation of massive stellar evolution in low metallicities (Massey et al. 1989; Walborn et al. 2000; Evans et al. 2006). The ACS observations demonstrated that the ‘evolved’ bright MS stellar content is extended to the PMS regime at fainter luminosities. The majority of the low-mass PMS stars in the region NGC 346/N66 was found to be mostly concentrated in the association and several individual small subclusters in the vicinity of the HII region (Sabbi et al. 2007; Hennekemper et al. 2008; Schmeja et al. 2009).

The young SMC cluster NGC 602 is associated with the ring-shaped HII region N90 (Henize 1956), located in the wing of the SMC. The photometry of a single ACS/WFC pointing of the system revealed that this cluster is characterized by no more than $\sim 750$ faint PMS stars (with $m_{555} \gtrsim 22.5$), which are found to be well concentrated toward
the center of the HII ring (Carlson et al. 2007; Schmalzl et al. 2008; Cignoni et al. 2009). The stellar population of the young cluster is known to comprise massive hot stars (e.g. Battinelli & Demers 1998; Massey et al. 2000), with the ten brightest having spectral types between O6 and B5 (Hutchings et al. 1991). They belong to a sample of over 60 MS stars, with $m_{555} \lesssim 22.5$, which are identified as members of the cluster with HST. A small fraction of the faint PMS population of the region NGC 602/N90 is found in very compact concentrations, embedded in the dusty rim at the edge of the HII cavity. Some of these concentrations coincide with bright sources, and almost all of them appear very bright in the mid-IR, as revealed from Spitzer/IRAC imaging of the region (Gouliermis et al. 2007a; Carlson et al. 2011), demonstrating their youthfulness.

The large HII region LHα120-N11 (Henize 1956), in short N11, in the LMC is characterized by a central hole, surrounded by seven distinct bright nebulae and filaments. It comprises four known stellar associations, named LH 9, LH 10, LH 13 and LH 14 (Lucke & Hodge 1970). The central cavity of the region is presumably evacuated by the OB stars in LH 9, located almost at the center of N11. Archival ACS photometry complemented by archival IR data from Spitzer Space Telescope revealed a large population of PMS candidates with masses in the range 1.3 - 2 M⊙ and ages between 2 and 10 Myr (Vallenari et al. 2010). Embedded YSOs with ages of about 0.1 - 1 Myr are found to be intermixed with the PMS stars. The spatial distribution of all these young sources, compared with previous observations at different wavelengths and with the distribution of OB and candidate Herbig Ae/Be stars, showed that they are the product of clustered star formation, which is a long-lasting process in N11.

The successful detection of the PMS population of a young star cluster down to the smallest possibly detectable mass at the distance of the MCs requires high sensitivity and resolving efficiency in a wide-field coverage. Such observations naturally call for HST, and in the optical regime ACS/WFC with its unique combination of sensitivity, resolution and coverage, is the most appropriate camera even in the post-WFC3 era. In order to eliminate the confusion in the detectability of the faintest stars, loose clusters should be targeted, and complementary observations of a carefully selected control-field should also be performed. Such a program designed to obtain ACS images of the young LMC cluster LH 95 and its nearby general field led to the deepest LMC observations ever taken with HST (Gouliermis et al. 2007b), see also Fig. 1. These observations allowed the construction of the CMD of the cluster in unprecedented detail and its accurate decontamination from the average LMC stellar population (Fig. 2). While N64, the HII region where LH 95 is embedded, represents a rather modest star-forming region, the photometry of these images, with a detection limit of $m_{555} \lesssim 28$ (at 50% completeness), revealed more than 2,500 PMS stars with masses down to $\sim 0.2$ M⊙ in a single WFC pointing on the system.

3 The optical CMD of PMS stars: Biases in its interpretation

The CMD of LH 95 shown in Fig. 2 (right panel) represents a typical optical CMD of a young star cluster in the MCs. It demonstrates that the early-type massive stellar members of such clusters are well aligned with the main-sequence down to about $m_{555} \simeq 21$, which corresponds roughly (depending on the model) to PMS stars of about 2 M⊙. In fainter magnitudes all the stars of the cluster diverge from the main-sequence. They occupy the PMS part of the CMD, as is the case for typical star-forming regions in the Milky Way (see, e.g., Reipurth 2008a, 2008b, and contributions therein). These faint PMS stellar members of young star clusters spend extremely long periods of time remaining in this phase of their
Fig. 2 The F555W–F814W, F814W \( (V-I)\)-equivalent CMDs of the stars detected with ACS/WFC within HST Program GO 10566 in the young LMC cluster LH 95 and its nearby background field (Gouliermis et al. 2007b). Left: The CMD of all stars found in the observed pointing of the system. Middle: The corresponding CMD of the control field, located about 5′ (\( \sim 75\) pc) west of the system. The comparison of these CMDs exhibits the differences in stellar content of the two observed regions, and demonstrates the richness of PMS stars in the cluster region, as it is emphasized by the complete lack of such stars in the LMC field. Right: The CMD of the main area of the system, only for stars which are selected as members of the cluster, after the contamination of the LMC field has been statistically subtracted. The ZAMS from the Padova grid of evolutionary models (Girardi et al. 2002) is overlaid for guidance. PMS evolutionary models suggest that the observed PMS population covers stellar masses down to \( \sim 0.2\) M\(_{\odot}\).

This task can only be achieved with the correct use of accurate theoretical PMS evolutionary models, because the use of different models can affect significantly the interpretation of the observed CMDs. Nevertheless, the simple direct “translation” of magnitudes and colors into masses and ages, as is usually the case for evolved stars, only accounting for photometric errors and reddening, cannot be applied in the case of such faint PMS populations, as it will not be reliable. The reason lays on the peculiar emission behavior of PMS stars and observational constrains that affect significantly the true positions of these stars in the CMD, introducing important biases that must be first taken into account in the interpretation. In particular, a number of factors that can bias the age determination and the assessment of any age spread among PMS stars have been widely discussed in the literature. Two nominal studies on the matter are those by (Hartmann 2001), who discuss a number of biases that could produce a spread of low-mass PMS stars in the CMD without requiring a genuine spread in ages, and by (Hillenbrand 2009), who presents an overview of the age dating methods available for young sub-solar mass stars. Factors that bias the CMD positions of PMS stars are discussed here in §3.3.
3.1 The effect of the theoretical PMS evolutionary models

There are several different published calculations of PMS evolutionary models (see, e.g., Hillenbrand & White 2004 for an overview), which are constructed based on different assumptions, physics, and methods. Indicative references for seven families of widely used PMS evolutionary models are these published by Swenson et al. (1994), D’Antona & Mazzitelli (1997), Baraffe et al. (1998), Siess et al. (2000), Palla & Stahler (1999), Yi et al. (2003), and Degl’Innocenti et al. (2008), updated by Tognelli et al. (2011). Hillenbrand et al. (2008) assess the systematic trends between the various sets of tracks by considering the predictions for some fiducial stars of given temperature and luminosity. These authors found that for sub-solar stars, systematic effects between the tracks are observed at the level of 0.75 dex at the youngest ages. As a consequence, cluster age estimates are strongly dependent on the adopted set of PMS evolutionary theory. There is a better agreement, particularly towards older ages, for solar-type stars. In a recent study of the ability of current evolutionary models in recovering the observed properties of PMS stars, Gennaro et al. (2011) used 25 PMS objects with well-measured dynamical masses, sixteen belonging to binary systems. These authors found that while the masses of PMS stars in eclipsing binaries are generally well recovered within 10%, for one third of the binary systems, the ages derived for the two components are not in agreement. This implies an inefficiency of current PMS models in

Fig. 3 The F555W − F814W, F814W CMD of the stellar population of LH 95 with evolutionary models calculated with the FRANEC code (Chieffi & Straniero 1989, Degl’Innocenti et al. 2008) for the LMC metallicity (Z = 0.01) overlaid. Left: PMS isochrones covering ages from 0.5 (red line) to 100 Myr (black line) from the FRANEC family of models. Right: Evolutionary tracks for PMS stars covering masses from 0.2 (red line) to 6 M⊙ (black line) from the same family of models. The theoretical models are converted into observable colors and magnitudes for the ACS filter system in terms of use of model atmospheres for cool stars (Da Rio et al. 2010a, see also §3). Models are appropriately corrected for distance and average extinction.
recovering precise stellar ages or alternatively that undetected systematics partly affect the interpretation of PMS binary observations.

For all families of PMS models with ages younger than 50-80 Myr, high-mass stars are predicted to be older than low-mass stars in the same clusters (Hillenbrand 2009). While this effect has often been ascribed to the influence of the stellar birthline (Stahler 1983; Hartmann et al. 1997), it can also be due to the effect of magnetic fields, stellar rotation, or disk accretion. Hillenbrand et al. (2008) note that the trend of age with mass seems to persists longer than the influence of birthline effects is expected to last. In line to this, the recent models by Baraffe et al. (2009) suggest that for low-mass stars the concept of stellar birthline has no significance, because the first appearance of these stars in the HR diagram is random and depends on the accretion history. This can mimic an age dispersion. Da Rio et al. (2010b) in their recent study of the Orion Nebula Cluster (ONC) assign this mass-age relation to a bias due to incompleteness in source detection.

In Fig. 3 the PMS evolutionary models constructed with the Frascati Raphson Newton Evolutionary Code (FRANEC, Chieffi & Straniero 1989; Degl’Innocenti et al. 2008) are shown overlaid on the optical CMD of the young LMC cluster LH 95 from ACS photometry (shown also in Fig. 2 right). Isochrones covering ages from 0.5 to 100 Myr – with the older isochrones being progressively bluer that the younger ones – are overplotted to demonstrate that the observed PMS part of the CMD may include a great range in ages (left panel). In addition, evolutionary tracks on the CMD corresponding to 0.2 $M_{\odot}$ up to 6 $M_{\odot}$ stars – with tracks of larger masses being bluer and brighter that those of smaller ones – show the variety in stellar masses of the PMS stars in LH 95 (right panel).

3.2 PMS evolutionary models: From the HRD to the CMD

Theoretical models computed for the PMS stellar evolution are generally expressed in terms of physical quantities, i.e., the effective temperature and the total bolometric luminosity, describing the evolution of stars in the HR diagram. However, one of the primary aims of stellar evolution theory is the explanation of the observed photometric data of stars in order to extract their masses and ages from their magnitudes and colors, and therefore a conversion between physical and observable quantities of the models is required. Such a conversion is specifically described by Siess et al. (2000), who include the transformation between $T_{\text{eff}}$ and $L$ to colors and magnitudes in the $UBVRI$ Cousins system and $JHKL$ infrared bands for their models. These authors use simple relations $T_{\text{eff}}$ versus color, as well as bolometric corrections from either Siess et al. (1997) or Kenyon & Hartmann (1995). These conversion tables, derived from observations of stellar clusters, are valid for solar metallicity dwarf stars, but the discrepancies can be significant when one deals with populations with different stellar parameters. In particular, the age of a star is related to the stellar radius and therefore to the surface gravity, which introduces differences in the spectral behavior, and therefore a population of different ages or metallicities may require different conversion relations. This issue can be important for e.g. cool M-type stars, for which the broad molecular absorption bands dominate the optical spectra, affecting integrated colors and color corrections.

A more thorough method to analyze this issue is to make use of synthetic atmosphere models, performing photometry directly on synthetic spectra. Girardi et al. (2002) applied this method for their evolutionary models for evolved populations, which were converted in several photometric systems using a grid of atmosphere models described by three parameters ($[M/H]$, $\log T_{\text{eff}}$, $\log g$). The choice of a reliable atmosphere grid is critical for cool stars, since their spectral energy distributions (SEDs) are dominated by broad molecular
bands. These spectral features are gravity dependent, and since the stellar surface gravity varies during PMS contraction, optical colors of young PMS stars are age-dependent. This method has been applied for stars with $M < 1 M_\odot$ and brown dwarfs by Baraffe et al. (1998, 2001). Concerning the MCs, there are only two published studies of such calculations, by Cignoni et al. (2009) for the SMC and by Da Rio et al. (2009) for the LMC.

In their conversion of the theoretical PMS models of Siess et al. (2000) into the observable plane Da Rio et al. (2009) followed an approach similar to that of Girardi et al. (2002). These authors utilized the NEXTGEN (Hauschildt et al. 1999) synthetic spectra to convert the theoretical models into colors and magnitudes, extended with the Kurucz (1993) grid for the highest temperatures ($T_{\text{eff}} > 8000$ K). Observational models (both tracks and isochrones) were constructed for four assumed metallicities and several photometric systems, including that of ACS (see Da Rio et al. 2009, for a detailed description). Cignoni et al. (2009) converted the FRANEC evolutionary models (Degl’Innocenti et al. 2008) into the observable plane, using the transformations for the HST VEGAMAG photometric system, calculated by Origlia & Leitherer (2000). In a subsequent study, for the conversion of the FRANEC grid of models Da Rio et al. (2010a) applied the same method with Da Rio et al. (2009), utilizing the AMES family of synthetic spectra with updated opacities (Allard et al. 2000). For these calculations, opacity tables are taken from Ferguson et al. (2005) for $\log T_{\text{eff}} < 4.5$ and Iglesias & Rogers (1996) for higher temperatures. The equation of state (EOS) is described in Rogers et al. (1996). Both opacity tables and EOS are calculated for a heavy elements mixture equal to the solar mixture of Asplund et al. (2005). In Fig. 3 a selected sample of the evolutionary stages covered by these calculations are shown overlaid the CMD of LH 95.

3.3 CMD-broadening of the positions of PMS stars

The positions of low-mass PMS stars in the CMD demonstrate a widening, which may be interpreted as indication of an age-spread, meaning that the star formation process may have lasted several Myr, a time period easily detectable on the HR diagram (Fig. 3 - left). However, PMS stars show several peculiar characteristics due to surface activity and circumstellar accretion, which along with observational biases, such as unresolved binarity, crowding and photometric uncertainties, can cause considerable deviations of the stars from their theoretical positions in the observed CMD, giving false evidence of an age-spread and wrong mass evaluation for individual stars. Below I describe the factors that can affect more severely the apparent CMD positions of PMS stars.

3.3.1 Variability

Low-mass PMS stars exhibit variability in brightness thought to be caused by large starspots on the rotating stellar surface. For example, TTS in the Orion OB1 association are found to exhibit significant variability in optical bands (Briceno et al. 2005). Variable low-mass PMS stars that exhibit hydrogen emission lines, and frequently various forbidden emission lines, are classified as classical TTS (CTTS). In addition to excess IR continuum emission, these stars demonstrate also excess emission at UV wavelengths, which is believed to be consequence of disk accretion onto the stars. The accretion rates are typically $\sim 10^{-8} M_\odot$ yr$^{-1}$, relatively low compared to the typical infall rates during protostellar evolution (Lada & Murdin 2001). On the other hand, variable low-mass PMS stars that typically
produce little or no Hα line emission, with Hα equivalent widths less than 10 Å, are classified as weak-lined TTS (WTTS). The V-band variability is found to differ between CTTS and WTTS, showing an amplitude up to 3 mag for the former and between 0.05 and 0.6 mag for the latter (Herbst et al. 1994). A variability survey of the Orion Nebula Cluster (ONC) in the Cousins I-band over 45 nights by Herbst et al. (2002) provided accurate light-curves for 767 stars between 12.5 and 16 mag, with about half having a peak-to-peak variation exceeding ~ 0.2 mag, and 10% exceed ~ 1 mag. Variability is found to correlate with infrared excess continuum emission, as diagnostic of circumstellar disks (Hillenbrand et al. 1998), in the sense that it is largely due to a combination of magnetically induced dark spots and a variable accretion, which becomes increasingly important for the higher amplitude variables. This correlation is more apparent for stars with $M \gtrsim 0.25 M_\odot$. On the other hand, slowly rotating stars in the ONC seem to have, on average, greater infrared excess emission than their more rapidly rotating counterparts, providing evidence supportive to the disk-locking hypothesis.

In general the canonical view of PMS variability dictates that cool spots on WTTS are responsible for most or all of their variations, while hot spots on CTTS resulting from variable mass accretion from an inner disk contribute to their larger amplitudes and more irregular behavior. Indeed CTTS are characterized by irregular and extremely rapid photometric variability (e.g., Sherry 2003). In young ($\lesssim 3 - 5$ Myr) star-forming regions the ordinary fraction for CTTS is 30% - 50% (Preibisch & Zinnecker 1999), and this fraction decreases with age so that by an age of a few Myr most low-mass PMS stars are WTTSs (Sherry 2004). Under these circumstances, the effect of variability to the observed CMD broadening of PMS stars should become increasingly weaker with age, since these stars would be mostly WTTS. A relation between peak-to-peak variations in optical bands is derived for the Orion OB1b subassociation to be $\Delta I = \alpha \Delta V$ with $\alpha$ varying from 0.39 to 0.88 (Sherry 2003).

A correlation between rotation rate and position in the CMD is recently discovered for PMS stars in the Galactic associations Cepheus OB3b, NGC 2264, NGC 2362 and the ONC by Littlefair et al. (2011). These authors found that stars which lie above an empirically determined median PMS rotate more rapidly than stars which lie below this sequence. If the position within the CMD is interpreted as being due to genuine age spreads within a cluster, then this would imply that the most rapidly rotating stars in an association are the youngest, and hence those with the highest likelihood of ongoing accretion. Such a result, however, is in conflict with the existing picture of angular momentum evolution, according to which the stars are braked effectively by their accretion disks until the disk disperses. Instead, Littlefair et al. (2011) argue that, for a given association of young stars, position within the CMD is primarily a function of accretion history, which can lead to spreads in radii and luminosity matching those observed.

### 3.3.2 Differential extinction

Extinction, the absorption and scattering of the starlight by the interstellar matter (ISM), does not appear to be uniform in star-forming regions. As the ISM in these regions is clumpy, so is extinction, which thus is characterized as differential. Numerous studies have quantified the effect in star-forming regions of the Milky Way. Indicatively, Riaz et al. (2013) find in NGC 6823 in the Vulpecula OB1 association a significant differential reddening, and a bimodal distribution for $A_V$, with a peak at ~ 3 mag and a broader peak at ~ 10 mag. Pang et al. (2011) also find significant differential reddening across the area centered on the HD 97950 star cluster in the giant HII region NGC 3603, as the result of stellar radiation and
winds interacting with an inhomogeneous dusty local ISM. They observe an increase from $A_V \approx 4.5$ mag to $\sim 7$ mag while moving from the central cavity to either the north or south at a distance of 2 pc from the cluster. These authors also note that differential reddening could be one of the causes why the age spread among PMS stars in HD 97950 appears to be as large as up to 10 Myr. In the MCs, extinction is typically lower than in the Galaxy, and so is its variation. For example De Marchi et al. (2011) quantify the total extinction toward massive MS stars younger than $\sim 3$ Myr in 30 Dor to be in the range $1.3 < A_V / \text{mag} < 2.1$. Gouliermis et al. (2011) in four LMC star-forming regions find an even smaller $A_V$ variability with a maximum value above 0.8 and 1.5 mag. Nevertheless, differential extinction can naturally dislocate PMS stars from their original CMD positions in a non-uniform manner, and therefore it can be an important factor that affects the broadening of the positions of PMS stars in the CMD. Comparisons of PMS stars detected in HII regions of the MCs with reddening maps show that indeed the PMS stars located in the more obscured areas seem to occupy preferentially redder loci in the CMD (Sabbi et al. 2007; Hennekemper et al. 2008).

3.3.3 Circumstellar disks: Irradiation and accretion

Emission above stellar photospheric levels in PMS stars is attributed to dust and gas heating processes by a combination of irradiation and accretion associated with circumstellar disks. Optical and near-IR imaging surveys provide efficient means for diagnosing the presence of such disks, and the complete appreciation of our ability to detect them requires an understanding of the expected excesses over stellar photospheric flux levels. A combination of near-IR and optical databases assembled for PMS stars in the ONC showed that as a function of $V - I_c$ color, the mean value of near-IR excess, expressed in $\Delta (I_c - K)$, generally rises from the bluest stars to a peak around $V - I_c = 1.75$ and then declines toward redder colors. Earlier type, higher mass stars have smaller mean 2$\mu$m excesses than the average star, while later type, lower mass stars ($V - I_c \sim < 2.5$) have mean near-IR excesses distributed with mass roughly as expected from the disk models, i.e., stars of lower masses appear to have smaller excesses (Hillenbrand et al. 1998). This dependence of excess fluxes due to circumstellar disks to the brightness of the PMS star suggests that the corresponding dislocation of PMS stars in the CMD is variable and not constant for the complete observed samples. Mid- and far-IR excess emission from dusty circumstellar disks and envelopes is also found with the Spitzer Space Telescope around PMS stars and YSOs in the Galaxy (e.g., Povich et al. 2011), and the MCs (e.g., Whitney et al. 2008; Gruendl & Chu 2009).

In the optical, there are two components contributing to excess due to accretion; optically thin emission is generated in the infalling flow, while optically thick emission comes from photospheric heating below the shock (Calvet & Gullbring 1998). The optically thin emission is line-dominated similar to that of HII regions. As a consequence bright Balmer emission is commonly used to derive mass accretion rates for PMS stars (see, e.g., De Marchi et al. 2010, 2011, for recent results in the LMC and SMC respectively). Optically thick emission due to accretion dominates in $V$ and $I$, producing the phenomenon of veiling, which strongly affects also shorter wavelengths, i.e., $U$ and $B$ (Robberto et al. 2004). Veiling, as well as the existence of surrounding dusty reflection nebulae, can alter the $V - I$ colors of PMS stars, locating them thus closer or on the MS (Guarcello et al. 2010), challenging the suggestion that stars with Hα excess close to the MS are old PMS stars (e.g., De Marchi et al. 2010, see also discussion in §6.3).

Flux excess is expected to vary with time due to both variations in the mass accretion, and stellar rotation. The age of the population plays also important role, as more evolved young clusters have partially dispersed the circumstellar disks of their PMS low-mass stars.
and halt accretion in a significant fraction of them (Sicilia-Aguilar et al. 2006). In these clusters, only a small fraction of the PMS stars fluxes may be scattered by circumstellar material (e.g., Kraus & Hillenbrand 2009).

### 3.3.4 Unresolved binarity

Simulations of the PMS population with $24 \leq V \leq 27$ mag and $1.0 \leq V - I \leq 2.2$ mag in $\sigma$ Orionis cluster suggest that binaries shift the center of the PMS locus to a CMD position brighter and redder than the center of the PMS locus for single stars (Sherry 2004). In many young clusters in the Milky Way, a clear binary sequence is observed to lie $\approx 0.75$ magnitudes above the single star main-sequence (Tout 1991), and this is almost equal to the brightness shift that a single star will suffer toward brighter magnitudes, if it is an unresolved binary system with equal mass components (de Bruijne et al. 2001). Naturally, the overall effect of unresolved binarity to the PMS CMD positions depends on the binary fraction in the cluster. In principle, early-type stars are known to have both higher binary fraction and higher mass ratio than those of late spectral types (e.g., Zinnecker & Yorke 2007). Galactic OB associations show a binary fraction that does not differ significantly from the field (Mathieu 1994), which is found for G dwarfs to be around $\approx 58\%$ (Duquennoy & Mayor 1991). For M-type stars two thirds of the investigated populations seem to have been born as single stars, with a binary fraction in this spectral type of about $31\%$ (Lada 2006). The well-studied ONC is also found to be consistent with the field binary fraction (e.g., Prosser et al. 1994, Petr et al. 1998, Köhler et al. 2006), with only $30\%$ of the stars in $\sigma$ Ori cluster expected to have unresolved binary companions (Sherry 2004). The mass ratio of PMS binaries is found to follow a comparatively flat distribution for $M_2/M_1 \geq 0.2$ (Woitas et al. 2001).

### 3.3.5 Source confusion and photometric accuracy

The spatial distribution of PMS stars along the line of site can play an important role in dislocating them in the CMD, producing a broadening of their positions in star-forming regions of the Galaxy (Sherry 2003). The significance of this phenomenon depends naturally on the crowding of sources in the observed cluster, which demonstrates itself as source confusion in the photometry. Crowded regions produce higher confusion in the detection of stars and thus broader CMD widening in the PMS positions.

Photometric accuracy depends on brightness, being higher for the brighter stars. Therefore, photometric uncertainties in both magnitudes and colors for the faint PMS stars naturally contribute to the broadening in their CMD positions, which then would be wider for the fainter stars. While, however, photometric errors provide a reasonable explanation for the observed CMD widening of PMS stars, they cannot be considered a major factor, as in all cases of young clusters and associations observed with HST the CMD broadening is proved to be much wider than the mean photometric errors per magnitude range (see e.g., Nota et al. 2006, Gouliermis et al. 2007a, Vallenari et al. 2010).

### 4 Disentangling the masses and ages of PMS stars from their optical CMD

Considering the aforementioned physical and methodological factors that can alter the disentangling of the true nature of PMS stars from their positions in the optical CMD alone, one understands that the interpretation of the observed colors and magnitudes for the extraction of the basic parameters of the stars, i.e., their age and mass, is a difficult task. As
discussed earlier, while methods developed for the detection of TTS in the Galaxy allow the accurate determination of the characteristics of these stars, in the case of PMS stars in the MCs one must rely on space imaging alone. As a consequence, new treatments that can take advantage of the rich but single-epoch ACS photometry of star-forming regions in the MCs are developed. These methods are based on the statistical/probabilistic extraction of the parameters of the observed PMS stars through modeling of the observed CMDs and the application of populations synthesis techniques. There are only two examples of such methods for the MCs, one developed by Cignoni et al. (2009) for the SMC star-forming region NGC 346/N66, and that by Da Rio et al. (2010a) for the LMC cluster LH 95. In both cases ACS imaging provides rich samples of PMS stars, which are absolutely necessary for the use of good number statistics in these treatments. Nevertheless, the success of these investigations depends further on the PMS evolutionary models and their transformation from the theoretical H-R plane ($T_{\text{eff}}, L$) to the observable C-M plane (e.g., $V - I, I$) for the photometric filter system of ACS and the metallicity of the MCs, as described in §3.2.

4.1 Modeling the CMD-broadening of PMS stars

The observed spread in brightness at a given color for PMS stars in the MCs can be explained in terms of various astrophysical sources of scatter (discussed in §3.3), and therefore the broad age coverage that fit the observed CMDs (as shown in Fig. 3, left) does not necessarily correspond to any real age spread among PMS stars. It may well be the result of biases introduced by observational constraints, i.e., photometric accuracy and confusion, and the physical characteristics of these stars, such as variability, binarity, and circumstellar extinction. Indeed, in star-forming regions of the Milky Way, whilst there probably is a true luminosity dispersion in the observed CMDs, there is little evidence to support age spreads larger than a few Myr (see, e.g., Jeffries 2011). Burningham et al. (2005) investigated the role of photometric variability in causing the apparent age spreads observed in the CMDs of Galactic OB associations and they found that the combination of binarity, photometric uncertainty and variability on time-scales of few years is not sufficient to explain the observed age spreads in either of the studied associations. In addition, Jeffries (2007) estimated the radii of PMS stars in ONC, using their rotation periods and projected equatorial velocities, and he showed that the apparent age spreads in the HR diagram of the ONC are associated with a genuine spread in stellar radii.

In the MCs, Hennekemper et al. (2008) demonstrated the impact of the CMD scattering factors to the interpretation of the observed CMDs in the SMC star-forming region NGC 346/N66 by constructing a simple toy-model of the influence of some of these factors on a “perfect” single-age sequence of PMS stars. These authors found that indeed a single-age PMS population may appear in the optical CMD broad enough to be misinterpreted as the result of multi-epoch star formation. They specify the importance of reddening and binarity of low-mass PMS stars to this broadening, while variability also plays an important role depending on the nature of these stars. Although each of these factors acting alone cannot cause the observed widening of PMS loci in the CMD, it is their cumulative action that leads to the broadening of the sequence of PMS stars. When applying their models to NGC 346, they find that an evolutionary age of about 10 Myr proved to fit best the observed sequence of PMS stars and their broadening. This result is in line with previous claims that although the location of the bright stars of NGC 346 in the CMD implies an age of less than 5 Myr for the association, there is a spatial distinct subgroup of evolved $\sim 15 M_{\odot}$ stars in the system with ages $\sim 12$ Myr (Massey et al. 1989). Moreover, the simulations
by Hennekemper et al. (2008) showed that the possibility of multi-epoch star formation in the region of NGC 346 cannot be excluded. Typical ages derived from the simulations of a double star formation event (assuming that 50% of the stars are formed in each epoch) are 3 - 4 and 10 - 12 Myr.

In subsequent studies, in order to assess the source of the brightness scattering of PMS stars in CMDs observed in star-forming regions of the MCs Cignoni et al. (2009, 2010) and Da Rio et al. (2009, 2010a) make use of evolutionary models, as they transformed them into the C-M plane (see §3.2) and simulate their observed CMDs with more sophisticated populations synthesis techniques. They derive, thus, the most probable stellar parameters for the detected PMS stars, according to their CMD positions. They utilize their results for the determination of the age and age-spread and the low-mass IMF in star-forming regions of the MCs. I discuss their results, as well as those from other studies, in the following sections.

5 The low-mass IMF in the Magellanic Clouds from their PMS stars

The IMF of a young star cluster, i.e., the distribution of its stars according to their mass at the time of their formation, is generally parameterized as

\[ \xi(M) \, dM \propto M^{-(1+x)} , \]

(1)

described by a series of power-laws with exponents changing in different mass ranges (e.g., Scalo 1986, 1998; Kroupa 2002). Reference value of the single power-law index of the IMF for stars with \( 0.4 < M/M_\odot < 10 \) in the Solar neighborhood is that established by Salpeter (1955), \( x = 1.35 \). Considering that the stellar IMF provides a deep insight into the star formation process, its universality, or its dependence to environmental conditions is of critical importance (Bastian et al. 2010). The investigation of whether the IMF is universal or not requires data from other galaxies, where stars can be fairly resolved, and the MCs are the best environments for such a study. However, while the high-mass IMF in the MCs is well known not to vary significantly from that in the Galaxy (Massey 2003), the lack of deep data did not allow a thorough investigation of the low-mass IMF in the MCs, until the discovery of rich samples of low-mass PMS stars with HST.

5.1 The low-mass stellar IMF in the Magellanic Clouds

Once the stellar masses in a complete observed sample are established, the construction of their IMF is in principle straightforward. There are, though, three issues, which should be taken into account for the construction of the IMF of PMS populations in the MCs. (1) **Field decontamination of the stellar sample.** The general field of the MCs is consisted mainly by evolved MS, sub-giants, and red giant branch stars (e.g., Castro et al. 2001; Smecker-Hane et al. 2002; Javiel et al. 2005; Sabbi et al. 2009), and therefore it is completely different from star-forming regions, which comprise hot MS and cool PMS stars. Under these circumstances the field subtraction from the observed stellar samples can be achieved fairly well. (2) **Fitting the IMF.** Typical linear regression methods, used for obtaining the functional form of an observed IMF, are based on the assumption that the measurement uncertainty associated to each mass-bin follows a Gaussian distribution. However, the uncertainty in the number of counts within a mass-bin is the overall effect of both the Poissonian error that naturally comes from the counting process, and the uncertainty that arises from the field subtraction. Although the first can be well approximated with a Gaussian for
large numbers, the latter depends on the CMD positions of stars in relation to the evolutionary tracks. (3) Correction for incompleteness. In the low-mass regime corrections for the incompleteness of the stellar sample are required to estimate the actual number of stars. However, given the fact that the low-mass evolutionary tracks are very close to each other in the CMD (Fig.3) and considering the large variation of completeness in both magnitudes and colors, this correction is not the same for all stars counted in a considered mass-bin.

Recently, the sensitivity and resolving efficiency of HST imaging provided sufficient numbers of PMS stars in the MCs for the construction of their low-mass stellar IMF. Nevertheless, the required sensitivity is so high that even among the few available investigations with ACS photometry, all but one are well limited to stars with masses $\gtrsim 1 \, M_\odot$ due to insufficient completeness in the detected stellar samples. These investigations, as well as those based on WFPC2 imaging, agree that the PMS IMF down to this mass-limit in both the LMC and the SMC can be well represented by a Salpeter power-law. In particular, Gouliermis et al. (2006a) established the low-mass stellar IMF of the young LMC cluster LH 52 from PMS stars detected with WFPC2 imaging. They find an IMF slope of $x \approx 1.26$ in the mass range 0.8 - 1.4 $M_\odot$. The low-mass IMF of the bright star-forming region NGC 346/N66 in the SMC is determined by Sabbi et al. (2008) from ACS imaging of its PMS population. These authors find a stellar IMF slope of $x = 1.43 \pm 0.18$ in the mass range 0.8 - 60 $M_\odot$. This slope changes, as a function of the radial distance from the center of NGC 346, indicating, according to these authors, primordial mass segregation. The IMF of the young SMC cluster NGC 602 is addressed with photometry of ACS images by Schmalzl et al. (2008) and Cignoni et al. (2009), the latter shown in Fig.4 (left). The results of both studies are in agreement, with the first deriving an IMF slope of $x = 1.2 \pm 0.2$ for $1 \lesssim M/M_\odot \lesssim 45$, and the second $x = 1.25 \pm 0.22$. More recently Vallenari et al. (2010) using imaging from five ACS/WFC fields provide the IMF of clusters and associations in the bright HII complex N11 in the LMC. These authors find that the low-mass IMF slope varies between $x \approx 1.0$ and $x \approx 2.0$ for the PMS populations in the sub-clusters of the stellar associations LH 9, LH 10, and LH 13. All aforementioned investigations note that the IMF slope becomes steeper if the stellar samples are corrected for binarity.

5.2 The sub-solar stellar IMF in the Magellanic Clouds

Concerning the IMF of PMS stars with masses $\lesssim 1 \, M_\odot$ in the MCs, Liu et al. (2009a) used imaging obtained with both WFPC2 and the Space Telescope Imaging Spectrograph (STIS) to derive the sub-solar IMF of the compact LMC cluster NGC 1818. They found that this IMF could be well approximated by both a multi-power law function (e.g., Kroupa 2001) and a lognormal distribution (e.g., Chabrier 2003). They extended their analysis to five more clusters in the LMC with the use of the same observational material and they found that their IMF down to the sub-solar regime is not significantly different from the IMF in the solar neighborhood (Liu et al. 2009b). In these studies the sub-solar PMS populations are retrieved from the photometry obtained with STIS through only one filter, the F28×50LP (central wavelength $\lambda_c = 7230$ Å), and therefore with no color information available for these stars. From comparison between evolutionary models for MS (Girardi et al. 2002) and PMS (Baraffe et al. 1998) stars these authors assess the percentage of the stars detected by STIS that may be PMS stars. The lack of any color information about these stars naturally introduces important uncertainties in the determination of their masses and IMF, which cannot be established from their HR positions. The masses of the STIS sources were determined from a mass-luminosity relation derived from the Baraffe et al. (1998) PMS isochrone for
The IMF in the MCs. Left: The IMF constructed for the PMS stars of the young SMC cluster NGC 602 (Cignoni et al. 2009), reproduced by permission of the AAS. The shallowness of the observations did not allow the construction of the IMF for the sub-solar PMS populations, because of insufficient completeness in their detection. This IMF is well represented by a single power law with a slope comparable to that found by Salpeter (1955), Scalo (1998) or Kroupa (2002) for masses larger than 1 $M_\odot$. Right: The stellar IMF of the young LMC cluster LH 95 derived from its PMS population detected with ACS imaging (Da Rio et al. 2009). The deeper observations of LH 95 allowed to extend the stellar IMF to the sub-solar regime. The knee of this IMF at $\sim 1 M_\odot$, indicated by the arrow, and its multi-power law slopes are found to be comparable to the Galactic IMF (e.g., Kroupa 2002).

The only study, which addresses the sub-solar stellar IMF in the MCs with the use of both magnitudes and colors for low-mass PMS stars in a young cluster is that by Da Rio et al. (2009). These authors utilize the deep photometry of the LMC star-forming region N64 (Henize 1956), where the young cluster LH 95 (Lucke & Hodge 1970) is embedded, imaged with ACS/WFC (Gouliermis et al. 2007b). A value of mass to each PMS star in LH 95 is been assigned by interpolating between the PMS evolutionary tracks, based on the observational PMS evolutionary models for the ACS photometric system and the average LMC metallicity, developed by these authors (see § 3.2). For the IMF construction, PMS stars were counted on the CMD in variable-sized logarithmic mass-bins, with sizes in $\log(M)$ that increase towards higher masses. Variable-sized bins yield very small biases, which are only weakly dependent on the number of stars, in contrast to uniformly binned data (Maiz-Apellániz & Ubeda 2005).

For the derivation of the functional form of this IMF Da Rio et al. (2009) made the assumption that it should be represented by multiple power-laws, with the positions of the break points along the IMF, i.e., the number of power-laws and the corresponding slopes being the free parameters of the fitting process. The best fit to the IMF was derived with the application of a Levenberg-Marquardt non-linear least square minimization technique (Levenberg 1944; Marquardt 1963). The results of the fitting algorithm for different number of power-laws were normalized with the so-called statistical “F test” based on the Fisher-Snedecor distribution (e.g., Abramowitz & Stegun 1965). This test showed that the IMF of
LH 95 is best approximated by a two-phase power-law (Fig. 4 right). The slope of this IMF is found within 99% confidence to be $x = 1.05^{+0.20}_{-0.29}$ for $-0.5 < \log(M/M_\odot) < 0.04$ and $x = 2.05^{+0.32}_{-0.53}$ for $\log(M/M_\odot) > 0.04$, comparable to the average Galactic IMF (Kroupa 2002). The measured 99% confidence uncertainties, however, did not rule out variations of the IMF, possibly due to incomplete stellar numbers. Da Rio et al. (2009) found no significant differences in the shape of the overall IMF of LH 95 from that of each of its three individual PMS sub-clusters, suggesting that this IMF is not subject to local variability.

6 Timing the star formation process in the Magellanic Clouds

Low-mass PMS stars, as mentioned in the introduction, are excellent timers of the star formation process in their hosting regions, due to their long stay in this phase of their evolution. Therefore they are targeted by several studies for extracting the recent star formation history (SFH) of their ambient star-forming regions, determining the ages of their hosting star clusters and identifying any age spreads among them, as indication of star formation over extended periods of time. However, as mentioned in § 3 since these studies rely on single-epoch photometry of these stars, they deal with problems rising by the physical characteristics and observational limitations that act as sources of the brightness broadening of these stars in the CMDs. As a consequence, age determination of PMS stars cannot be achieved by simple isochrone fitting to the available models, but more sophisticated populations synthesis techniques are developed, as described in § 4. In this section I discuss the results of these studies, along with others on dating the star formation process in the MCs from their PMS populations.

6.1 Star formation histories derived from PMS stars

Cignoni et al. (2009) presented a set of model stellar evolutionary tracks, calculated with the FRANEC evolutionary code for the typical SMC metallicity (see also § 3.2). They used these models with a stellar population synthesis code that takes into account a large range of stellar evolution phases, to derive the best estimate for the SFH in the SMC star-forming region NGC 602/N90. By comparing synthetic CMDs with those constructed for the PMS stars detected with ACS/WFC in the region, these authors found that the star formation rate has been quite high, and increased with time on a scale of tens of Myr, reaching a peak of $(0.3 - 0.7) \times 10^{-3} \text{ M}_\odot \text{ yr}^{-1}$ in the last 2.5 Myr, comparable to what is found in Galactic OB associations (e.g., Preibisch & Zinnecker 1999). In a subsequent investigation Cignoni et al. (2011) apply the same methodology to derive the SFH of another star-forming region in the SMC, NGC 234/N66, based on ACS images. They found that this region experienced different regimes of star formation, and in particular a “high-density mode”, with sub-clusters hosting both hot MS and cool PMS stars, and a diffuse “low-density mode”, as indicated by the presence of low-mass PMS sub-clusters. According to these authors, star formation in the oldest sub-clusters started about 6 Myr ago with remarkable synchronization, it continued at a high rate (up to $2 \times 10^{-5} \text{ M}_\odot \text{ yr}^{-1} \text{ pc}^{-2}$) for about 3 Myr and is now progressing at a lower rate.

In a recent study, Gouliermis et al. (2011) analyzed the PMS stellar content of four star-forming regions located at the periphery of the super-giant shell LMC 4 (Shapley Constellation III) with WFPC2 imaging. While the low sensitivity of WFPC2 limited the detected samples of PMS stars, this investigation provided information about the star for-
mation process around the shell without any age determination for the stars. Specifically, 
Gouliermis et al. (2011) compared the distributions of low-mass PMS stars along cross-
sections of the observed CMDs in the different regions. These authors found that these dis-
tributions in the regions LH 60/63/N51 and LH 72/N55 exhibit an extraordinary similarity,
suggesting that these PMS stars share common characteristics, as well as common recent SFH. Considering that the regions are located at different areas of the edge of LMC 4, at
distance of about 500 pc, this finding suggests that star formation along the whole shell may
have occurred at the same time.

6.2 Age determination of a cluster from its PMS stars

In the LMC HII complex N11, Vallenari et al. (2010) determined the ages of individual clus-
ters and associations from ACS/WFC imaging using the luminosity function of the PMS
populations. While this approach does not take into account the uncertainties introduced
by the CMD-broadening of these stars, its results provide a uniform set of ages of clusters
within a large LMC star-forming region, and thus allow a coherent understanding of its re-
cent star formation process. These authors found from the PMS population of clusters in the
association LH 9 a prolonged formation of stars from 2 to 10 Myr, in agreement with pre-
vious spectroscopic studies of the hot blue stellar content of the system (Walborn & Parker
1992; Mokiem et al. 2007), with the majority of the stars being older than 6 Myr. On the
other hand, they found that the dominant PMS populations in the neighboring associations
LH 10 and LH 13 have ages of 2 to 3 Myr and 2 to 5 Myr respectively, again in agree-
ment with results from spectroscopy of their bright stars (Heydari-Malayeri et al. 2000;
Mokiem et al. 2007). Candidate YSOs with ages from 0.1 to 1 Myr are found by the same
authors at the location of the PMS stars in the region with observations with the Spitzer
Space Telescope. This indicates that several generations of stars are present in the region
of N11. Vallenari et al. (2010) propose a star formation scenario for the region, according
to which the formation of the first generation of stars in LH 10 was triggered by supernova
shocks in the association LH 9.

A more sophisticated method for the determination of the age of individual sub-clusters
in a star-forming region from its PMS stars is developed by Cignoni et al. (2010). These
authors use the Turn-On (TO), i.e., the point in the observed CMD where the PMS joins
the MS, and apply a method akin to that by Piskunov et al. (2004). According to this method
it is possible to reliably identify the TO, which in the MS luminosity function (LF) of the
cluster appears as a peak followed by a dip, from the monitoring of the spatial distribution
of MS stars. Cignoni et al. (2010) simulated synthetic simple stellar populations covering a
set of five different ages by using PMS evolutionary models, and through a polynomial fit
to the corresponding model LFs they established a functional relation between age and the
magnitude that corresponds to the TO. According to the authors this CMD analysis can
provide a reliable age of extragalactic clusters, but it should be used with caution because
of uncertainties in the comparison between the observed and theoretical LFs, emanating
from incompleteness and photometric errors, Poissonian fluctuations in the stellar numbers,
reddening, the assumed IMF, binarity and the star formation duration. The application of this
technique, which is complementary to the turnoff dating and avoids the systematic biases
affecting the PMS phase, to three sub-clusters of the region NGC 346/N66 showed that
all sub-clusters have different ages, varying between 3 and 18 Myr, supporting the idea of
complexity in the recent SFH of the region.
Da Rio et al. (2010a) assessed the age of the young LMC cluster LH 95 and determined the possible appearance of an age spread from the CMD-broadening of its PMS stars with the development of a self-consistent maximum-likelihood method, especially designed for ACS photometric data. With their method, which is similar to that presented by Naylor & Jeffries (2006), these authors aimed at the determination of the age of the cluster accounting simultaneously for the most significant biases that affect the CMD positions of the PMS stars, as they are discussed in §3. Da Rio et al. (2010a) performed calculations of PMS evolutionary models for the LMC metallicity using the FRANEC code and transformed them, as well as the Siess et al. (2000) family of models, into the ACS photometric system (see also §3.2). They converted these models to 2D probability distributions in the magnitude-magnitude plane, and consequently in the CMD, by applying the most important sources of displacement of the CMD positions of PMS stars among those discussed in §3, except of photometric errors. The assumed IMF for LH 95 is that derived by Da Rio et al. (2009, see also §5.2).

A maximum-likelihood method is then applied to derive the probability for each observed star to have a certain age, taking its photometric uncertainty into account, and considering the Gaussian distributions of the photometric errors as priors for the determination of the likelihood of each star as function of age. This process of modeling age-dependent probability distributions and maximizing their global likelihood functions is applied with the use of two different sets of evolutionary models, available for the metallicity of the LMC, that by Siess et al. (2000), and that computed by Da Rio et al. (2010a) with the FRANEC stellar evolution code (Chieffi & Straniero 1989; Degl’Innocenti et al. 2008) and for different assumed binary fractions. This treatment showed that the age determination is sensitive to the assumed evolutionary model and binary fraction; the age of LH 95 is found to vary from about 2.8 to 4.4 Myr, depending on these factors. The best-fit age of the cluster LH 95 derived for a binary fraction of \( f = 0.5 \), which was considered a reasonable value in the mass range of interest (Lada 2006), is determined by Da Rio et al. (2010a) to be between 3.9 and 3.8 Myr.

### 6.3 Assessment of an age spread in PMS clusters

Distinguishing if the observed CMD-broadening of PMS stars represents also a true age spread, or is the result of the intrinsic properties of these stars and their measurement uncertainties is one of the major tasks in our understanding of star formation in clusters of the MCs. With their method, Da Rio et al. (2010a) investigated whether the spread of the PMS stars in the observed CMD is wider or not than that of the simulated 2D density distributions as they are produced by accounting for the sources of CMD-broadening alone. If indeed the observed CMD-broadening of PMS stars was wider than the synthetic derived from a single isochrone, this would indicate the presence of a real age spread in LH 95. Da Rio et al. (2010a), by comparing the observed and modeled CMD distributions and evaluating the goodness-of-fit with a method similar to a standard \( \chi^2 \) minimization, showed that the observed sequence of PMS stars in the CMD of LH 95 is broader than what predicted by the 2D models for single ages, indicating that the cluster probably hosts a real age spread among its PMS stars. These authors quantified this spread to be of the order of \( \sigma_{\text{age}} = 1.8 \) Myr (FWHM\( \sim 4.2 \) Myr), as derived with the use of the FRANEC models, while it decreases to \( \sigma_{\text{age}} = 1.2 \) Myr (FWHM\( \sim 2.8 \) Myr) if Siess et al. (2000) models are considered. In both cases the uncertainty in \( \sigma_{\text{age}} \) is about 0.2 Myr.
6.4 Star formation histories from accretion studies of PMS stars

De Marchi et al. (2010), based on the original study by Panagia et al. (2000), developed a new self-consistent method to identify PMS objects actively undergoing mass accretion in a resolved stellar population, regardless of their age. The method combines HST broadband V- and I-equivalent photometry with narrowband Hα imaging to identify stars with excess emission and obtain their mass accretion rate $\dot{M}_{\text{acc}}$. The application of this method in a field around SN 1987A in the LMC derived a median mass accretion rate for the detected PMS stars of $26 \times 10^{-8} \, M_\odot \, \text{yr}^{-1}$, in agreement with previous determinations based on the U-band excess of PMS stars in the same field (Romaniello et al. 2004). This study revealed a sample of PMS stars located in the CMD at the MS. The ages of all identified objects were determined by De Marchi et al. (2010) by interpolating between the isochrones. These authors found that the detected PMS stars cover an age-range of 1 to $\sim 50$ Myr, with the CMD locations of the older PMS stars coinciding with those of MS stars.

More recently, in a subsequent study, De Marchi et al. (2011a) applied the same method and identified about 1150 PMS stars with a strong Hα excess in 30 Dor. Comparison of their location in the H-R diagram with theoretical PMS evolutionary tracks revealed that about one-third of these objects are younger than $\sim 4$ Myr, whereas the rest have ages up to $\sim 30$ Myr. These authors argue that this indicates that star formation has proceeded over an extended period of time, although they cannot discriminate between an extended episode and a series of short and frequent bursts that are not resolved in time. A bimodal age distribution of PMS stars with Hα excess, with two roughly equally numerous populations peaked respectively at $\sim 1$ Myr and $\sim 20$ Myr, is also been detected by the same team in the SMC star-forming region NGC 346/N66 (De Marchi et al. 2011b) with the application of their accretion determination method.

These studies, which reveal accreting ‘blue’ PMS stars, located close or on the MS, provide reasonable indications of large age spreads among PMS stars in star-forming regions of both the MCs. However, the age determination based on direct isochrone fitting on the H-R diagram, without considering the CMD-broadening sources of PMS stars discussed in §3, decrease considerably the accuracy of this determination. In particular, PMS isochrones representing ages older than $\sim 10$ Myr are very close to each other and to the lower MS (Prada Moroni, private communication; see also Fig 3), and thus the distinction of a 20 Myr old PMS population from that with age of 30, 50 (as presented by De Marchi et al.), or even 100 Myr is not straightforward. Moreover, ‘blue’ PMS stars in the Galaxy are suggested to be normal PMS stars with altered colors (Guarcello et al. 2010). This behavior has been previously documented and a possible explanation of the nature of these stars is that they are strong accretors, characterized by an intense veiling that alters their optical colors (e.g., Hartmann & Kenyon 1990) or their photometry might be contaminated by the nebula emission (e.g., Hillenbrand et al. 1998), or they are surrounded by dusty reflection nebulae (e.g., Damiani et al. 2006). Another possible explanation is that a significant fraction of stellar radiation is scattered into the line of sight by the circumstellar disk (Throop et al. 2001; Robitaille et al. 2006). Guarcello et al. (2010) found by simulating synthetic CMDs that this explanation holds for disks observed at high inclination around PMS stars in the Eagle nebula. However, more recent simulations suggest that the percentage of PMS stars with highly inclined disks is not enough to explain the large numbers of the detected ‘blue’ PMS stars in NGC 346 (De Marchi et al. 2011b).
7 Conclusive Remarks

I present results on the relatively unexplored field of PMS evolution in the MCs, and in particular the investigation of PMS stellar populations with optical space imaging. I specifically discuss the cases of star-forming regions in the MCs, which have been observed with ACS onboard HST. Low-mass PMS stars remain in the same evolutionary stage for several tens of Myr, and therefore host unprecedented information about the age and star formation process of their host cluster, as well as its stellar IMF. Since these stars demonstrate peculiarities in their physical properties due to coronal and circumstellar activity, their investigation requires demanding observations and their careful interpretation. Observational techniques, such as optical photometric monitoring, spectroscopy, and X-ray imaging are essential for the decontamination of the PMS stellar samples in star-forming regions of the Milky Way from the foreground and background stars of the Galactic plane. Considering that only HST can provide the appropriate combination of sensitivity and field-of-view coverage at the MCs, it is practically impossible to perform repeated imaging, spectroscopy of large samples, or X-ray monitoring of star-forming regions in these galaxies, and investigators rely on single-epoch photometry alone. There are, however, two major advantages in studying PMS stars in the MCs, which allow the derivation of important results concerning the properties of young clusters that host such stars. First, the observed PMS populations in the MCs can be quite easily distinguished from the evolved stellar populations of the general field of the galaxies directly on the CMD. Second, deep imaging with HST provides outstanding numbers of PMS stars in star-forming regions of these galaxies, which are large enough for detailed statistical analyses of their properties, provided that the behavior of PMS stars in the optical CMD is sufficiently modeled.

Such statistical treatments for the derivation of the stellar IMF and age of young half-embedded clusters in the MCs, are discussed, and important physical sources of the CMD-spread of PMS stars, which affect the outcome of these treatments, are presented. In particular, I discuss rotational variability, accretion and differential extinction, among others, as very important factors that naturally dislocate the PMS stars from their original (theoretical) CMD positions, and which should be taken into account in the interpretation of the observed CMDs. Since these studies are based on imaging, there are three additional factors that further bias the observed CMD loci of PMS stars: unresolved binarity, source confusion and photometric uncertainties. I also stress the importance of the use of accurate PMS evolutionary models that are appropriately designed for the metallicity of the MCs and correctly translated in the photometric system of the cameras. The use of such evolutionary tracks in combination with a detailed treatment for the contamination of the stellar sample by the field population can provide the best bias-free solution for the most probable age and IMF of young clusters in the MCs through their PMS populations, observed with HST.

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