Study of evolved stellar populations
in the
Magellanic Clouds

A Thesis
Submitted for the Degree of
Doctor of Philosophy
in the Faculty of Science
by
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Declaration

I hereby declare that the matter contained in this thesis titled, “Study of evolved stellar populations in the Magellanic Clouds”, is the result of research work carried out by me, under the Joint Astronomy Programme (JAP), in the supervision of Prof. Annapurni Subramaniam at the Indian Institute of Astrophysics, Bangalore and Dr. Tarun Deep Saini at the Department of Physics, Indian Institute of Science, Bangalore. I further declare that this thesis has not been submitted for the award of any degree, diploma, associateship, fellowship etc. of any university or institute.

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Department of Physics,
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Dedicated to my parents &
teachers ...
“I know that I am mortal by nature, and ephemeral; but when I trace at my pleasure the windings to and fro of the heavenly bodies I no longer touch the earth with my feet: I stand in the presence of Zeus himself and take my fill of ambrosia”

− Ptolemy, Ptolemy’s Almagest
Acknowledgements

“Men are most deeply moved not by the reaching of the goal but by the grandness of the effort involved in getting there.”

This above line by Max Lerner expresses perfectly the way I feel at the end of my Ph.D thesis. The past six years have been undoubtedly challenging, but a rewarding journey which has made me the person I am today. The work presented in this thesis would not have been possible without my close association with many people. I take this opportunity to extend my sincere gratitude and appreciation to all those who made this Ph.D thesis possible.

“No one keeps his enthusiasm automatically. Enthusiasm must be nourished with new actions, new aspirations, new efforts, new visions.”

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_Samyaday Choudhury_
List of Publications

• Refereed Journals


• Conference proceedings


Abstract

The Magellanic Clouds (MCs) consist of a pair of galaxies, the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC), which are located at a distance of $\sim 50$ kpc and $60$ kpc, with stellar masses of $\sim 10^{10} \, M_\odot$ and $10^9 \, M_\odot$, respectively. Morphologically they are categorized as irregular type galaxies. The MCs are gas rich and metal poor ($Z=0.008$ for LMC, and 0.004 for SMC) as compared to the Milky Way (MW), and have active star-forming regions. Their proximity and location at high galactic latitude enable us to resolve their individual populations as well as detect faint stellar populations. It is well known that the MCs are interacting with each other, as well as with the MW. The interaction is supported by the presence of the Magellanic Bridge and the Magellanic Stream.

The evolved stellar populations in the MCs help us to understand their evolution and interaction process. The MCs host both Population I as well as Population II stars. This extended range of star formation is a valuable source of information to understand the formation and evolution of galaxies in general, and the MCs in particular. Evolved stellar population means the stars that have evolved off the main sequence and the giants, such as red giants (RGs), red clump stars, and asymptotic giant branch stars. There is a dominant population of evolved stars present in the MCs, in star clusters as well as in the field.

The aim of the thesis is to study the evolved stellar populations for one of the component of the MCs, the LMC. The study is primarily divided into two parts. (1) **Study of sparse star clusters in the LMC:** To increase our understanding of sparse star clusters in the LMC, with well estimated parameters, using deep Washington photometric data for 45 LMC clusters. (2) **To estimate a metallicity map of LMC:** In order to understand the metallicity variation across the galaxy. This is done by creating a high spatial resolution metallicity map of the LMC, using
red giant branch (RGB) stars, with the help of photometric data and calibrated using spectroscopic studies of RGs in field and star clusters.

The introduction to the thesis study along with the aim are described in Chapter 1 of the thesis.

The three sets of photometric data used for this study are described in Chapter 2. The data sets are: $CT_1$ Washington photometric data for 45 star clusters within the LMC, the VI photometric data from the Optical Gravitational Lensing Experiment Phase-III survey (OGLE III), and the Magellanic Cloud Photometric Survey (MCPS).

*Study of sparse star clusters in the LMC:* A systematic study is performed to analyse the 45 cluster candidates, to estimate their parameters (radius, reddening, and age) using the main-sequence turn-off (MSTO), as well as the evolved portion of the colour–magnitude diagram (CMD). The basic parameters were estimated for 33 genuine clusters, whereas the other 12 cluster candidates have been classified as possible clusters/asterisms.

The study of 33 star clusters are presented in Chapter 3. These clusters are categorized as genuine star clusters based on their strong density enhancement and cluster features with respect to their surrounding field regions. Out of the 33 clusters, 23 are identified as single clusters and 10 are found to be members of double clusters. Detailed discussions of all the individual clusters are presented. The estimated parameters for the single and double clusters are listed in two different tables. About 50% of the clusters are in the age range $\sim 100$–300 Myr, the rest of them being older or younger. Comparison with previous age estimates shows some agreement as well as some deviation.

The remaining 12 clusters which could not be categorized as genuine star clusters are studied in Chapter 4. These clusters have poor (/suspicous) density enhancement and cluster features when compared to their surrounding fields. It is important to study such cluster candidates, as these objects probe the lower limit of the cluster mass function. Detailed discussion on these individual objects are presented and their estimated
parameters are tabulated in this chapter. A detailed discussion based on
the study of all the 45 inconspicuous clusters is presented in this chapter,
including the estimated sizes (radii \( \sim 2\text{--}10\text{ pc} \)), reddening with respect
to field, and location in the LMC. The mass limit estimated for genuine
clusters is found to be \( \sim 1000\ M_\odot \), whereas for possible clusters/asterisms
it is \( \sim \) few 100 \( M_\odot \), using synthetic CMDs.

The study of sparse clusters enlarged the number of objects confirmed
as genuine star clusters (33) and estimated their fundamental parameters.
The study emphasizes that the sizes and masses of the studied sample are
found to be similar to that of open clusters in the MW. Thus, this study
adds to the lower end of cluster mass distribution in the LMC, suggesting
that the LMC, apart from hosting rich clusters, also has formed small,
less massive open clusters in the 100--300 Myr age range. The 12 cases
of possible clusters/asterisms are worthy of attention, in the sense that
they can throw light on the survival time of such objects in the LMC.

**Photometric metallicity map of the LMC using RGB stars:** A metallicity
map of the LMC is estimated using OGLE III and MCPS photometric
data. This is a first of its kind map of metallicity up to a radius of 4--5 de-
grees, derived using photometric data and calibrated using spectroscopic
data of RGB stars. The RGB is identified in the V, (V–I) CMDs of small
areal subregions of varying sizes in both data sets. The slope of the RGB
is used as an indicator of the average metallicity of a subregion, and this
RGB slope is calibrated to metallicity using spectroscopic data for field
and cluster RGs in selected subregions.

The metallicity map estimated using OGLE III photometric data is
presented in **Chapter 5**. A method to identify the RGB of small subre-
gions within the LMC and estimate its slope by using a consistent and
automated method was developed. The technique is robust and indepen-
dent of reddening and extinction. The details of calibrating the RGB
slopes to metallicities, using previous spectroscopic results of RGs in field
and star clusters are presented. The OGLE III metallicity maps are pre-
sented, based on four cut-off criteria to separate regions with good fits. The OGLE III map has substantial coverage of the bar, the eastern and western LMC, but does not cover the northern and southern regions. The OGLE III metallicity map shows the bar region to be metal rich whereas the eastern and western regions to be relatively metal poor. The mean metallicity is estimated for three different regions within the LMC. For the complete LMC the mean [Fe/H] is \( \mu = -0.39 \text{ dex} \), \( \sigma = 0.10 \); for the bar region it is \( \mu = -0.35 \text{ dex} \), \( \sigma = 0.9 \); and for the outer LMC it is \( \mu = -0.46 \text{ dex} \), \( \sigma = 0.11 \). The metallicity histogram for these different regions are also estimated. A radial metallicity gradient is estimated in the de-projected plane of the LMC. The metallicity gradient is seen to remain almost constant in the bar region (till a radius of \( \sim 2.5 \text{ kpc} \)) and has a shallow gradient of \( -0.066 \pm 0.006 \text{ dex kpc}^{-1} \) beyond that till \( \sim 4 \text{ kpc} \).

In Chapter 6 the metallicity map based on MCPS photometric data is estimated. The MCPS data covers more of the northern and southern LMC (less of eastern and western regions) and is important to be analysed in order to reveal the metallicity trend of the overall disk. The systematic differences between the filter systems of MCPS and OGLE III are corrected, and the MCPS slopes are then calibrated using the OGLE III slope-metallicity relation. The MCPS metallicity maps are presented, based on four cut-off criteria to separate regions with good fits. The bar region is found to be metal rich as was found using OGLE III data, whereas the northern and southern regions are marginally metal poor. The mean metallicity estimated for the complete LMC is \( \mu = -0.37 \text{ dex} \), \( \sigma = 0.12 \); and for the outer LMC it is \( \mu = -0.41 \text{ dex} \), \( \sigma = 0.11 \). The metallicity histogram for these different regions are estimated and compared with the OGLE III distribution. The metallicity range of the complete LMC is found to be almost similar for both data sets. The metallicity distribution within the bar has a narrow range as found using both data sets. The slight difference between mean metallicity of outer
LMC for the two data sets is attributed to their coverage. We suggest that the northern and southern regions of the LMC could be marginally more metal rich than the eastern and western regions. The metallicity gradient of the LMC disk, estimated from MCPS data is found to be shallow $-0.049 \pm 0.002$ dex kpc$^{-1}$ till about 4 kpc.

We also constructed a metallicity map of outliers using both OGLE III and MCPS data, and identified subregions where the mean metallicity differs from the surrounding areas. We suggest further spectroscopic studies in order to assess their physical significance.

The detailed conclusion of the thesis and future work are presented in Chapter 7. From the study of sparse star clusters in the LMC, it is concluded that LMC has open cluster like star cluster systems. It is important to include them to understand the cluster formation history (CFH) and their survival time scale. Presently, our understanding of the CFH is dominated by rich clusters. The bar of the LMC is found to be the most metal rich region, and the LMC metallicity gradient though shallow, resembles the gradient seen in spiral galaxies. The gradient is also similar to that found in our Galaxy. The higher metallicity in the bar region might indicate an active bar in the past.
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<th>Description</th>
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<tbody>
<tr>
<td>AGB</td>
<td>Asymptotic Giant Branch</td>
</tr>
<tr>
<td>AMR</td>
<td>Age Metallicity Relation</td>
</tr>
<tr>
<td>CEH</td>
<td>Chemical Enrichment History</td>
</tr>
<tr>
<td>CFH</td>
<td>Cluster Formation History</td>
</tr>
<tr>
<td>CMD</td>
<td>Colour Magnitude Diagram</td>
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<tr>
<td>Dec</td>
<td>Declination</td>
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<tr>
<td>LMC</td>
<td>Large Magellanic Cloud</td>
</tr>
<tr>
<td>MCPS</td>
<td>Magellanic Cloud Photometric Survey</td>
</tr>
<tr>
<td>MCs</td>
<td>Magellanic Clouds</td>
</tr>
<tr>
<td>MS</td>
<td>Main Sequence</td>
</tr>
<tr>
<td>MSTO</td>
<td>Main Sequence Turn-Off</td>
</tr>
<tr>
<td>MW</td>
<td>Milky Way</td>
</tr>
<tr>
<td>OGLE</td>
<td>Optical Gravitational Lensing Experiment</td>
</tr>
<tr>
<td>RA</td>
<td>Right Ascension</td>
</tr>
<tr>
<td>RC</td>
<td>Red Clump</td>
</tr>
<tr>
<td>RDP</td>
<td>Radial Density Profile</td>
</tr>
<tr>
<td>RG</td>
<td>Red Giant</td>
</tr>
<tr>
<td>RGB</td>
<td>Red Giant Branch</td>
</tr>
<tr>
<td>SFH</td>
<td>Star Formation History</td>
</tr>
<tr>
<td>SFR</td>
<td>Star Formation Rate</td>
</tr>
<tr>
<td>SMC</td>
<td>Small Magellanic Cloud</td>
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Chapter 1

Introduction

1.1 History of the Magellanic Clouds

The Magellanic Clouds are two galaxies located in the southern sky and are by far the liveliest and most lustrous satellites of the Milky Way. The natives on the South Sea Islands called them ‘the Upper and Lower Clouds of Mahu (Mist)’ (Westerlund, 1997). The Australian aborigines, who considered the Milky Way as a river or track along which the spirits travelled to the sky world, regarded the Magellanic Clouds as two great black men who sometimes came down to the Earth and choked people while they were asleep (Westerlund, 1997). The indigenous Polynesian people of New Zealand, collectively called the Clouds as ‘Nga Patari-Kaihau’ or as ‘Te Reporepo’. In Sri Lanka, the Clouds have been referred to as the ‘Maha Meru Paruwathaya (the great mountain)’, as they look similar to the peaks of a far mountain range. Thus, the Magellanic Clouds were called by different names by inhabitants of various continents in the southern hemisphere. At the same time they found mention as characters of folks or star lores all over the hemisphere among various civilisations.

The first preserved mention of the Clouds is by the Persian astronomer Al Sufi (A.D. 964) in his book on stellar constellations, ‘Book of Fixed Stars’, written in Arabic. Al Sufi described the location of a strange object in the sky and called it as ‘Al Bakr (the White Ox)’ (presently identified
as the Large Magellanic Cloud). The two objects were also called the ‘the Cape Clouds’ for hundreds of years, because they were the most prominent objects appearing in the sky when ships approached the Cape of Good Hope. Due to their proximity to the South Pole, they served as an important navigation marker for sailors in the southern sea, like counterpart to Polaris. In the 15th century, the Italian explorer Andrea Corsali described the Magellanic Clouds as two bright clouds with a regular circular path around the South Pole. Portuguese explorer Ferdinand Magellan became the first person to circumnavigate the globe between 1519 and 1522. During the course of the expedition led by him, the crew noticed two cloudy patches in the night sky as they sailed through the Southern Hemisphere. Later in 1522, the Venetian scholar Antonio Pigafetta, who accompanied Ferdinand Magellan during the voyage, mentioned about the Clouds in his writings. The valuable narrative of Pigafetta about the historic voyage made the Clouds more popular to the common Western knowledge. The Clouds were named after Magellan posthumously some
time in the 18th century, after which the objects were commonly known as Clouds of Magellan. Modern astronomers refer to the Clouds of Magellan as the Large Magellanic Cloud and the Small Magellanic Cloud. The Large Magellanic Cloud is located in the Mensa and Dorado constellations, whereas the Small Magellanic Cloud is located in the Tucana constellation. Figure 1.1 shows a night sky image of the Large and the Small Magellanic Cloud.

In 1847, Sir John Herschel did the first authentic scientific examination of the Magellanic Clouds and recognized them as stellar systems. He presented the coordinates and brief descriptions of 224 objects in the Small Magellanic Cloud and 919 objects in the Large Magellanic Cloud. In 1867, Abbe inferred for the first time the Clouds to be two nearest external galaxies. It was only after the establishment of the southern stations of Harvard College Observatory at Arequipa in Peru (1889–1927) and Bloemfontain in South Africa, that detailed investigations of the Clouds began. The Lick Observatory estimated the radial velocities of bright-line nebulae in both the Clouds, from the beginning of 1914. Buscombe in 1954, presented the first most extensive review on the Magellanic Clouds. In 1956, Harlow Shapley, who was considered to be the cosmographer of the Magellanic Clouds, summarised the important astronomical contributions in this area. Later Westerlund (1997) presented a detailed review of the Magellanic Clouds.

The opportunities offered by the Magellanic Clouds for fundamental astronomical research has grown by leaps and bounds in the last few decades due to advent of larger telescopes and faster detectors in the Southern Hemisphere. Astronomers have focussed their research on their distances, structure, kinematics and composition, with the aim of understanding their formation and evolution.
1.2 The Magellanic System

The Magellanic system, located at a distance of about $\sim 57$ kpc (Cioni \textit{et al.}, 2000), comprises primarily four components. These are: the Large Magellanic Cloud (LMC), the Small Magellanic Cloud (SMC), the Magellanic Bridge, and the Magellanic Stream. The LMC and the SMC, as mentioned previously, are two neighbouring galaxies to the Milky Way (MW) and are together known as the Magellanic Clouds (MCs). The Magellanic Bridge refers to the inter cloud region, which is a stream of neutral hydrogen ($\text{H} \, \text{I}$) that links the LMC and the SMC. The Magellanic Stream refers to the long trail of neutral $\text{H} \, \text{I}$ gas attached to the MCs. Figure 1.2 shows the neutral $\text{H} \, \text{I}$ map taken from Putman \textit{et al.} (2003). The components of the Magellanic system are marked in the figure.

The MCs have a common envelope of neutral hydrogen, indicating that these two galaxies have been bound to each other for a long time. It was also believed that the MCs have had interactions with the MW as well as amongst each other (Murai and Fujimoto 1980; Tanaka 1981; Fujimoto and Murai 1984; Gardiner, Sawa, and Fujimoto 1994; Westerlund 1997). The Magellanic System moves in the gravitational potential of the MW and in the plane defined by the Local Group (LG), and hence is also vulnerable to the ram pressure because of its movement in the galactic halo. The System thus bears vivid signatures of the LMC-SMC-MW interaction. The Bridge and Stream are considered as signatures of these interactions. It was believed that the tidal forces due to these interactions have caused changes in structure of the Clouds. However, a majority of recent proper motion studies suggest that the MCs have only recently passed by the Milky Way for the first time (Kallivayalil \textit{et al.}, 2006; Besla \textit{et al.}, 2007; Piatek, Pryor, and Olszewski, 2008; Kallivayalil \textit{et al.}, 2013). Therefore it is unclear whether the structure of the different components of the Magellanic system are modified due to interactions with the MW or only due to their mutual interactions and/or previous merger events.
1.2 The Magellanic System

Figure 1.2: Neutral H i map from Putman et al. (2003) showing the four components of the Magellanic System.

We discuss the individual members of the MCs as well as the signatures of interaction in the following sections.

1.2.1 The Large Magellanic Cloud

The LMC is the third nearest galaxy to the MW at a distance of about 50 kpc, after the Sagittarius Dwarf Spheroidal (∼ 15 kpc) and the Canis Major Dwarf Galaxy (∼ 7 kpc). It is about 100 times less massive as compared to our Galaxy and is the fourth largest galaxy in the LG, after the Andromeda Galaxy (M31), the MW, and the Triangulum Galaxy (M33).

In the second column of Table 1.1 we have listed the basic parameters of the LMC. It is gas rich with recent star formation events, as well as metal poor compared to the MW. The LMC hosts the nearest vigorous star forming region in the LG, the Tarantula Nebula (also known as 30 Doradus or NGC 2070). The 30 Doradus (Dor) was the site of the recent supernova SN 1987A. The LMC has a fortuitous location in the sky, far enough from the plane of the MW that it is neither outshone by too many nearby stars, nor obscured by the dust in the galactic disk. Also, it is close enough to study in detail the individual stellar systems, and lies almost face-on to us, giving us a bird’s eye view. Thus, the LMC serves as a great celestial laboratory for studying star formation and evolution.
### Table 1.1: Fundamental parameters of the LMC and the SMC

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<th>LMC</th>
<th>SMC</th>
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<tr>
<td>Type</td>
<td>SB(s)m</td>
<td>SB(s)mp</td>
</tr>
<tr>
<td>(RA, Dec)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>(5&lt;sup&gt;h&lt;/sup&gt; 19&lt;sup&gt;m&lt;/sup&gt; 38&lt;sup&gt;s&lt;/sup&gt;, -69° 27′ 5.2″)</td>
<td>(0&lt;sup&gt;h&lt;/sup&gt; 52&lt;sup&gt;m&lt;/sup&gt; 12.5&lt;sup&gt;s&lt;/sup&gt;, -72° 49′ 43″)</td>
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<tr>
<td>Mass&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.3 × 10&lt;sup&gt;10&lt;/sup&gt; M&lt;sub&gt;☉&lt;/sub&gt;</td>
<td>2.4 × 10&lt;sup&gt;9&lt;/sup&gt; M&lt;sub&gt;☉&lt;/sub&gt;</td>
</tr>
<tr>
<td>Distance</td>
<td>~ 50 kpc</td>
<td>~ 60 kpc</td>
</tr>
<tr>
<td>Z&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.008</td>
<td>0.004</td>
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Note for Table 1.1: <sup>a</sup> J2000.0 de Vaucouleurs and Freeman (1972); <sup>b</sup> van der Marel, Kallivayalil, and Besla (2009); <sup>c</sup> Piatti and Geisler (2013), Piatti (2012a).

Previously the LMC had been considered as a planar face-on disk galaxy. Two primary parameters that define the geometry of the disk plane of the galaxy with respect to the sky plane are the angle of inclination ($i$) and the Position Angle of Line Of Nodes (PA<sub>lon</sub>). The studies on 21 cm H<sub>I</sub> isophotes (de Vaucouleurs and Freeman, 1972), Asymptotic Giant Branch stars (van der Marel and Cioni, 2001), Red Clump stars (Olsen and Salyk, 2002; Subramanian and Subramaniam, 2010), and Cepheids (Nikolaev <i>et al.</i>, 2004), estimated the structural parameters of the LMC disk ($i$ and PA<sub>lon</sub>) and confirmed its inclined geometry. Table 1 of Subramanian and Subramaniam (2013) presents a summary of these orientation measurements by various authors. The $i$ value varies from 23° ± 0°.8 to 37°.4 ± 2°.3 and the PA<sub>lon</sub> varies from 122°.5 ± 8°.3 to 170° ± 5°, using different tracers (Subramanian and Subramaniam, 2013). The gas distribution and stellar population in the LMC are confined to a disk even though their radial extents are different. The study of kinematical properties of different tracers suggests that the LMC disk system is kinematically cold. Also, the LMC disk is relatively thicker than the MW thick disk (van der Marel, 2006a).

The LMC has a prominent, off-centred and warped stellar bar and
suspected spiral arms. The bar is one of the most striking features of the LMC and is clearly visible in the optical bands. It is one of the least studied and understood features of the LMC (van der Marel, 2006b). Subramaniam (2003) studied the relative distance within the bar using the Red Clump stars and suggested that the LMC bar is warped and has extra planar structures. According to Zaritsky (2004), it is a levitating bar and is the consequence of viewing a triaxial stellar bulge that is embedded in a highly obscuring thick disk. An offset between the LMC bar and disk was proposed by Zhao and Evans (2000) as a possible explanation for microlensing events observed toward the LMC. Nikolaev et al. (2004) suggested that the bar is levitating above the disk by 0.5 kpc, whereas Subramaniam and Subramanian (2009) suggested that the bar is a part of the disk. Thus, the location of the bar with respect to the disk is still debated. The study by van der Marel and Cioni (2001), using near-infrared star count maps, suggested the LMC bar to be a smooth structure. On the other hand, the bar is neither visible in the H I distribution nor in the H I velocity maps (Staveley-Smith et al., 2003). Thus, when the bar is a prominent feature in the optical and near-infrared, such a feature is not visible in the gas and recent star formation (Subramaniam and Subramanian, 2009). This striking difference of the LMC bar has been an unsolved puzzle.

Minniti et al. (2003), using RR Lyrae stars as tracers presented the first possible evidence of a kinematically hot metal poor old halo in the LMC. Studies by Alves (2004) and Subramaniam (2006) showed that the RR Lyrae population follows the density distribution of the LMC disk rather than the halo. This suggests that the RR Lyrae stars in the LMC might have formed in the LMC disk, instead of in the halo, and their large dispersions may result from a combination of disk heating and the MW tidal forces (Weinberg, 2000). The studies on the outer disk regions of the LMC by Saha et al. (2010) and Carrera et al. (2011) do not suggest any evidence of a halo. To summarize, the halo of the LMC is still not
well understood.

There have been several chemical abundance studies of stellar populations within the LMC. Cole et al. (2005) reported the metallicities and radial velocities estimated using the near-infrared calcium triplet (CaT) for about 400 Red Giants in 200 arcmin sq. around the central LMC. The metallicity distribution for their sample was sharply peaked at the median value $[\text{Fe/H}]=-0.4$ dex, with a small tail of stars extending down to $[\text{Fe/H}]=-2.1$ dex. Carrera et al. (2008a) studied the Red Giant Branch stars within four fields (each of dimension 36 × 36 arcmin sq.), lying towards the north of the LMC bar, at different galactocentric distances (≈3°, 5°, 6°, and 8°) from the LMC centre. As mentioned by these authors, the mean metallicity remains constant until 6° ($[\text{Fe/H}]=-0.5$ dex), while for the outermost field, at 8°, the mean metallicity is substantially lower than in the rest of the disk ($[\text{Fe/H}]=-0.8$ dex). Metallicities of about 1000 LMC field giants that obeyed disk kinematics and 30 stars that were kinematically different were estimated by Olsen et al. (2011). For the LMC field, the authors found a median $[\text{Fe/H}]=-0.56\pm0.02$ with dispersion of 0.5 dex, while for the kinematically distinct stars the median $[\text{Fe/H}]=-1.25\pm0.13$ with a dispersion of 0.7 dex. According to the authors, the metallicity differences suggests that the kinematically distinct population is accreted from the SMC. The study by Van der Swaelmen et al. (2013) investigated the relation between the bar and the inner disc of the LMC in the context of the formation of the bar. Their analysis of 106 and 58 LMC field Red Giant stars located in the bar and the disk of the LMC, respectively, suggested the bar to be chemically enriched (primarily in $\alpha$-elements) compared to the disk, which was possibly due to the formation of a new stellar population in the central part of the LMC. All these above mentioned studies are spectroscopic and confined within small regions of the LMC and have small sample sizes. Cioni (2009) used a photometric technique to estimate the metallicity gradient of the LMC field using Asymptotic Giant Branch stars as tracers. The
1.2 The Magellanic System

[Fe/H] abundance was derived from the ratio between C- and M-type Asymptotic Giant Branch stars and its variation analysed as a function of galactocentric distance. The authors found that the metallicity of the LMC decreases linearly as $-0.047\pm0.003 \text{ dex kpc}^{-1}$ till $\sim 8 \text{ kpc}$ from the centre of the galaxy.

1.2.2 The Small Magellanic Cloud

The SMC is the smaller, less massive, and farther counterpart of the MCs. It was the study of Cepheids in the SMC, using which Henrietta Swan Leavitt established the famous ‘Period-Luminosity’ relation for the first time (Leavitt and Pickering, 1912). The work is considered to be a landmark in establishing Cepheid variables as standard candles for gauging the distance to star clusters and external galaxies. The basic parameters of the SMC are mentioned in the third column of Table 1.1. Similar to the LMC, the SMC is also a gas-rich galaxy with ongoing star formation. However, it is more metal poor as compared to the LMC.

The structure of the SMC is more complex compared to that of the LMC (Westerlund, 1997). The SMC has a less pronounced bar and an eastern extension called the “Shapley Wing” (Shapley, 1940). This Wing and the north-eastern part of the bar are closer to us compared to the southern parts (Hatzidimitriou, Cannon, and Hawkins, 1993). A salient feature of the SMC is the large extension along the line of sight as suggested by several studies (Mathewson, Ford, and Visvanathan, 1986, 1988). The presence of a bulge-like structure in the SMC was proposed by Subramanian and Subramaniam (2009), using Red Clump stars as tracers. According to observational and theoretical studies, the old and intermediate-age stellar populations in the SMC are found to be distributed in a regular smooth spheroidal/ellipsoidal component. The young stellar population and $\text{H I}$ gas, on the other hand, are distributed in a rotating extended disk which is irregular and highly disturbed. Recently, Subramanian and Subramaniam (2015) used a young stellar population
(Cepheids) to estimate disk parameters of the SMC \((i=64^\circ.4\pm0^\circ.7,\) and \(\text{PA}_{\text{lon}}=155^\circ.3\pm6^\circ.3\) for the SMC). In their Table 4, the authors present a summary of orientation measurements of the SMC disk by previous studies, who used either Cepheids or other young populations or H I gas as tracers. The concurrence of different components of the SMC can be due to its evolutionary and merger history.

The chemical enrichment history of the SMC was studied by Carrera et al. (2008b) using CaT spectroscopy for \(\sim\) 350 Red Giant Branch stars in 13 fields, scattered at different positions within \(\sim 4^\circ\) from the SMC centre. According to the authors, the innermost fields have a mean metallicity of \([\text{Fe/H}] = -1.0\) that decreases outward. However, Parisi et al. (2010) studied \(\sim 360\) Red Giants distributed in 15 SMC fields using CaT spectroscopy and did not detect any such gradient within the SMC. For their sample, the authors found a mean value of \([\text{Fe/H}]=-1.00 \pm 0.02\), with a dispersion of \(0.32 \pm 0.01\). Dobbie et al. 2014a,b carried out an extensive spectroscopic survey of 3037 field giants spread over 37.5 degree sq. around the centre of SMC, and found a median metallicity of \([\text{Fe/H}] = -0.99 \pm 0.01\) for the SMC. According to these authors, there exists a clear evidence for a metallicity gradient of \(-0.075 \pm 0.011\) dex deg\(^{-1}\) within the inner 5° for the galaxy. Using photometric data, Cioni (2009) estimated an almost constant metallicity \((-1.25 \pm 0.01\) dex) for the SMC, from the centre up to a de-projected distance of \(\sim 12\) kpc.

1.2.3 Signatures of interaction of the Clouds

The two primary signatures of the LMC-SMC-MW interaction are the Magellanic Bridge and the Magellanic Stream. The primary constituent for both these features is neutral H I gas. The Bridge and the Stream are considered to be high-velocity complexes connected to the Clouds. These interacting features are connected, but unique in their spatial and velocity distribution (Putman, 2000). The mechanism responsible for the formation of these features is still under discourse. The two signatures
are described briefly:

• **The Magellanic Bridge**: It is a continuous stream of H\textsc{i} gas that connects the LMC and the SMC. This bridge of gas, in the intercloud region, was first reported in H\textsc{i} observations by Hindman, Kerr, and McGee (1963). Apart from gas, the Bridge also hosts young stellar populations aged from a few 100 Myr to as young as a few 10 Myr (Irwin, Kunkel, and Demers, 1985; Demers and Battinelli, 1998; Harris, 2007). It is believed that the Bridge formed due to recent (~100–300 Myr) tidal interactions between the MCs (Besla et al., 2010; Diaz and Bekki, 2011; Besla et al., 2012). The young stellar population probably formed in situ in the Bridge, during its formation, thus making it the closest example of a stellar population whose formation was unambiguously triggered by a tidal interaction (Harris, 2007).

• **The Magellanic Stream**: It is an astonishing and prominent trail of H\textsc{i} extending from the MCs into the Galactic Halo. The Stream is about 10° wide with ~2 × 10⁸ M⊙ of neutral H\textsc{i} gas and stretches over 100° across the southern sky behind the MCs (Putman et al., 2003). The Stream was first recognised by Wannier and Wrixon (1972), and associated with the MCs by Mathewson, Cleary, and Murray (1974). The Stream has two primary components: the leading arm (Putman et al., 1998), and a bifurcated trailing arm (Putman et al., 2003). Several models have been proposed since the 1980’s to describe the formation of the Stream, based on tidal interaction or ram pressure stripping, a consequence of the LMC-SMC-MW interaction. However, as mentioned previously, the recent HST proper motion studies suggest that the MCs are approaching the MW for the first time. Taking this into consideration, the recent models justify the origin of the Magellanic Stream based on the tidal interaction between the MCs (Besla et al., 2010; Diaz and
According to Nidever et al. (2010), the length of the Stream is $\sim 140^\circ$, longer than previously known. The authors found the Stream to be aged about 2.5 Gyr, which coincides with bursts of star formation in the MCs and a possible close encounter between them.

### 1.3 Stellar evolution

Stellar evolutionary theories have majorly contributed to the understanding and reproduction of various evolutionary features in the Hertzsprung-Russell (H-R) diagram. The theories try to reproduce the evolutionary parameters of stellar populations of various astrophysical environments, which in turn have varying parameters which govern the evolution of stars. The H-R diagrams of star clusters are the classical template to compare and verify the predictions of theory. The H-R diagrams of field populations in the MW and nearby galaxies have important information on the star formation and chemical evolution history, and these pose a lot of challenges to the stellar evolutionary theory (Chiosi, Bertelli, and Bressan, 1992). The evolutionary stages easily observed in the nearby galaxies are the evolved stellar population, and hence a lot of importance is given in theory to understand the evolved phases of stellar evolution. Since a long time stellar populations in the MCs have been used to understand the evolution and interaction history of the MCs.

The MCs host both Population I as well as Population II type stars. This large range of star formation is a valuable source of information to understand the star formation history, chemical properties and evolution of MCs. The evolved stellar populations in the MCs, that are a few Gyr old, can help us understand their evolution and interaction process during that particular epoch. There is a dominant population of evolved stars present in the MCs, in star clusters as well as in the field. Evolved stellar population implies stars that have evolved off the Main Sequence and the
1.3 Stellar evolution

giants such as Red Giants, Red Clumps, and Asymptotic Giant Branch stars. We present a brief overview of these stages of stellar evolution.

Stars acquire different positions in the H-R diagram based on their mass. The majority of stars occupy a place in a more or less diagonal strip in the H-R diagram, known as the ‘Main sequence’ (MS) phase. The stars in the MS can be considered to be almost chemically homogeneous except for the core. Stars with mass similar to the Sun fuse Hydrogen (H) to form Helium (He) in the core using mostly the Proton–Proton cycle, whereas more massive stars generate He mostly via the Carbon–Nitrogen–Oxygen (CNO) cycle. In other words, one can define MS as the core H burning phase of a star, where it spends most of its luminous life time. One can easily deduce that the luminosity of a star is proportional to $M^4$ and the energy stored is proportional to $M$. The lifetime of a star in MS is then inversely proportional to $M^3$. It is to be noted that this relation is not applicable for very high and very low mass stars. Although the high mass stars have more fuel, they burn it out at a faster rate and evolve quickly out of the MS as compared to the low mass stars. The lifetime of Sun-like stars in the MS is $\sim 10$ Gyr, and it gets considerably shorter for more massive stars. The post main-sequence evolution of high-mass and low-mass stars are different. For the work presented in this thesis, we briefly explain below the evolution of low ($< 2 M_\odot$) and intermediate-mass stars ($\sim 3$–$8 M_\odot$).

- The evolution of a star from the main sequence is an inescapable consequence of the continuous force of gravity and change in chemical constituents due to nuclear reactions. After H in the core gets exhausted, nuclear reactions cease, and there is no force to balance the gravity, because of which the core begins to contract (in accordance with Kelvin–Helmontz theory). At this stage the H burning is ignited in a shell surrounding the inert He core. The continuous contraction of the core increases the density and temperature around its surrounding material, and the H burning shell generates
energy more vigorously. However, not all of this high luminosity generated by the shell reaches the stellar surface (limited by photon diffusion rate). The difference between the energy released by the shell and that emanating from the surface causes the outer envelope of the star to blot up. Thus, it grows bigger and cooler with minimal increase in luminosity (following the Stefan-Boltzman law of surface emission from black-bodies), and the star evolves towards the right of the MS via a short-lived ‘Sub-giant Branch’. As an example, the H-R diagram for a low-mass star is shown in Figure 1.3.

- As the stellar envelope expands and the star becomes increasingly cooler, the opacity due to H\(^+\) ions increases near the photosphere. This results in the development of a convective zone near the surface for both low and intermediate mass stars. The base of this zone

Figure 1.3: H-R Diagram of a low mass star. Figure courtesy: “The physical universe, An Introduction to Astronomy” by Frank Shu.
deepens down into the interior of the star as it grows bigger and cooler. Due to the nearly adiabatic temperature gradient associated with convection throughout much of the stellar interior, and the efficiency with which the energy is transported to the surface, the star starts to rise rapidly upward along the ‘Red Giant Branch’ (RGB), as seen in the H-R diagram. This vertical rise in luminosity at an almost constant effective temperature is along the Hayashi line. According to Hayashi and his co-workers (Hayashi and Hoshi, 1961; Hayashi, 1961; Hayashi, Nishida, and Sugimoto, 1961), stars cannot be cooler than this temperature barrier, because the stellar models corresponding to the right side of this line are unstable and therefore not expected to exist. A salient feature of the RGB phase is the ‘first dredge-up’, where elements produced by nuclear fusion in the deep interior are transported to the surface for the first time as a consequence of convection. The star in the RGB phase is called a ‘Red Giant’ (RG) star, and is cooler and more luminous compared to its MS counterpart.

- As the star appears near the RGB tip the density and temperature ($\sim 10^8$ K) of the core becomes sufficiently high so as to trigger the He-burning process, famously known as the ‘Triple-alpha reaction’. For low mass stars, this process occurs by a violent thermal runaway process in the degenerate He core known as the ‘Helium flash’. The He ignition begins in a shell around the core of the star, since the core region is ‘refrigerated’ due to loss of energy through neutrino emission, and very quickly the entire core gets involved. The reason behind this violent explosion is the weak temperature dependence of electron degeneracy pressure and the strong temperature dependence of the triple-alpha reaction. Much of the energy released during the flash goes into lifting the local degeneracy before it stabilizes. For intermediate-mass stars, the He ignition occurs in a non-degenerate core, hence is not very explosive. The high tem-
Figure 1.4: A schematic diagram of life cycle for a low mass star. Image courtesy: http://linus.highpoint.edu/mdewitt/phy1050/?page=week5

Temperature dependence of the triple-alpha reaction causes He core to expand, which pushes the H-burning shell outward, thus cooling it and making it weaker (rate of energy output decreases). This causes a decrease in the overall luminosity of the star. The envelope of the star shrinks and the effective temperature starts rising. The star then descends from the RGB tip to the ‘Horizontal Branch’ (HB), where it fuses He stably in the core (producing primarily Carbon and Oxygen), surrounded by a H burning shell. The exact location of a star in the HB will not only depend on the initial mass and composition of the star, but also on the envelope mass loss it suffered while ascending the RGB. Essentially the HB is the He-burning analogue of H-burning MS phase, with a shorter time scale. The HB is typically seen in metal poor populations (Population II), like the globular clusters. For metal-rich counterparts (Population I), the stars after evolving off the RGB tip settle as a clump near the RGB and are redder as compared to the HB stars. These stars, known as ‘Red Clump’ (RC) stars, are thus low-mass core He burning stars, that are metal-rich and have significant hydrogen envelope.

- After completing the HB phase the star evolves red ward, and as it approaches the Hayashi limit the track again bends upward in the
1.3 Stellar evolution

H-R diagram. The upward phase is known as the ‘Asymptotic Giant Branch’ (AGB), since it lies above and roughly parallel to the RGB. The AGB stars are characterized by an inert carbon–oxygen core, surrounded by two separate nuclear burning shells: an inner layer of He-burning shell and an outer layer of H-burning shell. AGB’s have large convective envelope, which cause the ‘second dredge-up’. As the star ascends the AGB, it can suffer from thermal pulsations due to periodic modifications in its structure, a consequence of successive turning on and off of the He and H-burning shells. For intermediate-mass stars, a ‘third dredge-up’ can also occur during this course, on multiple times. The star looses a lot of mass during the late AGB phase. Instabilities finally cause the AGB star to shed off its remaining outer envelope as a ‘Planetary Nebula’, which eventually dissipates into the interstellar medium thus enriching it. The remnant central object is a hot electron degenerate core stable against gravity, called a ‘White Dwarf’ which eventually cools off.

To make things clearer, a schematic diagram of various stages of evolution for a low mass star is shown as an example, Figure 1.4.

One of the main goals of stellar evolution models is predicting the correct location (temperature and slope) of the RGB, since it is used for the derivation of the age of resolved stellar population, and also provides a photometric estimate of their metallicity. The RGB is also expected to importantly contribute to the integrated colours of old stellar populations (Bressan et al., 2013). In spite of the great effort made in the last decades to improve our understanding of stellar evolution, significant uncertainties still remain due to our poor knowledge of some complex physical processes that still require an empirical calibration, such as the efficiency of convective heat transport and interior mixing. This is crucial when dealing with advanced evolutionary phases, e.g. RGB and AGB, and stellar populations that are not well represented in the solar vicinity or in our Galaxy (Bressan et al., 2013).
Figure 1.5: CMD showing RGBs of three different ages $\sim 3,6,9$ Gyr, plotted for three different metallicities: $Z=0.004$ (blue), 0.008 (green) and 0.02 (red).
In Figure 1.5, we have shown the colour-magnitude diagram (CMD) of stellar population for ages $\sim 3$, $6$, $9$ Gyr, for three different metallicity values ($Z = 0.004$, $0.008$ and $0.02$). The isochrones are taken from Padova models (Marigo et al., 2008). The figure shows that the RGB of the population in the age range $\sim 3$–9 Gyr are closely populated in the diagram. We also notice that this location, as well as the slope of the RGB changes with metallicity. This demonstrates the effectiveness of using the RGB population to estimate the chemical properties. We use this property of RGB stars to derive a metallicity map of the LMC.

1.4 Star clusters in the Magellanic Clouds

A star cluster is defined as an aggregate of stars that are located sufficiently close enough to be gravitationally bound to each other. The cluster members are presumed to have a common origin (i.e., they are born from the same molecular cloud at the same time) and consequently located at the same distance. Star clusters in our Galaxy can be primarily divided into two categories based on their appearance: globular clusters and open clusters. Globular clusters are almost as old as the Galaxy (10–15 Gyr), metal poor (Population II), distributed symmetrically in the halo of the MW. Open clusters are young objects ($\sim$ a Myr – few Gyr), metal rich (Population I), and distributed within the disk of the Galaxy. Globular clusters are comparatively tightly bound system with large stellar content (number of stars $\sim 10^4$–$10^5$), high density (central density $\sim 10^3$ pc$^{-3}$) and larger size (diameter $\sim 50$–100 pc) as compared to the open clusters (number of stars $\sim 50$–1000, density $\sim 0.1$–10 pc$^{-3}$, and diameter $\sim 5$ pc).

The characteristics of star clusters depend on the host galaxy, therefore providing information about its formation and evolution. Thus, star clusters hold an important position in research aimed to understand the structure and evolution of our Galaxy as well as in our neighbours, the
MCs. The advantage of MCs of being one can resolve the individual members of the cluster, and that the Clouds are characteristically different from the MW, have made study of star clusters in MCs to understand cluster formation and stellar evolution in such low metallicity environment, popular.

In the MCs there does not exist a clear-cut dichotomy between massive globular clusters and less massive open clusters, as in our Galaxy. There exist true globular clusters similar to those in our Galaxy (aged $\geq 10$ Gyr), with luminosity dominated by the evolved RG stars, that have been identified in the MCs, but their numbers are few. Hodge (1960) catalogued 35 clusters in the LMC and mentioned them as true globulars based on their CMDs. According to van den Bergh (1991), the LMC is surrounded by 7 real globular clusters (age $> 10$ Gyr), while the SMC has only one such object. The old globular clusters of MCs have a mean absolute magnitude similar to that of true globulars in M31 and in our Galaxy (van den Bergh, 1991), and thus similar objects as those observed in giant spiral galaxies. Apart from this, the MCs are home to a class of clusters with masses that are an order of magnitude less than an average globular cluster but an order of magnitude more than most of the open clusters of our Galaxy. This class is called “populous clusters” (Hodge, 1961; van den Bergh, 1975), and has been hardly found in our Galaxy. The populous clusters are generally intermediate-age (few times 100 Myr–1 Gyr), and some are even young (e.g. NGC 2100, 10 Myr old). So, not only there are massive old globular clusters in the MCs, such as NGC 121 (SMC) and NGC 1466 (LMC), but there also exist massive young clusters such as NGC 330 (SMC) and NGC 1866 (LMC) (van den Bergh, 1975). van den Bergh (1975) mentions that these moderately metal-poor objects of intermediate age are of particular importance because they do not have a Galactic counterpart. Thus, star clusters in the MCs have provided the evidence which conveys that the mass distribution during cluster formation varies within different galaxies.
1.4 Star clusters in the Magellanic Clouds

The age distribution of star clusters within the LMC and the SMC is different. There exists an infamous ‘age-gap’ for star clusters in the LMC Geisler et al. (1997). This noticeable gap exists between a large number of intermediate age clusters (age ~ 1–3 Gyr) and the classical globular clusters, with ages > 12 Gyr (Olszewski et al., 1991). ESO 121-SC03 is the sole exception, with an age of ~ 9 Gyr (Mateo, Hodge, and Schommer, 1986). Da Costa (1991) stressed that this age-gap prevents us from using the known clusters in the LMC to bring out any details about the chemical evolution of the galaxy over most of its lifetime, despite our ability to determine accurate ages and metallicities for them (Olszewski et al., 1991). Studies of cluster formation history suggest that the rate of cluster production in the LMC increased significantly about 3 Gyr ago, leading to formation of younger clusters. It is interesting to note that there does not exist any such gap in the field star population of the LMC (Piatti and Geisler, 2013). For the SMC star clusters also, no such age gap exists. Rather, the star cluster formation in the SMC seems to have occurred continuously over the last 10.5 Gyr, with some epochs of enhancement possibly due to the close gravitational interaction with either the MW or the LMC (Glatt et al., 2008). Maia, Piatti, and Santos (2014) mentioned that young and intermediate-age stellar clusters in particular, provide significant information on the recent (<1 Gyr) interactions between the MCs and the MW. The difference in cluster formation in the LMC and the SMC seems to suggest that cluster production in the SMC began a few Gyr later than the LMC and continued without significant interruption.

The mean metallicity of star clusters in the SMC varies from ~ −0.60 dex for young clusters to ~ −1.30 dex for the oldest (Westerlund, 1997). Whereas for the LMC the mean metallicity is considerably different for the three different age groups: ~ −0.30 dex for young, ~ −0.50 dex for the intermediate-age (1–3 Gyr), and ≤ −1.60 dex for old star clusters (Da Costa, 1991; Olszewski et al., 1991). Grocholski et al. (2006) studied 28
populous LMC clusters using near-infrared calcium triplet spectroscopy. Their cluster sample spans a large range of ages (1–13 Gyr) and metallicities ($\sim -0.30 \geq [\text{Fe/H}] \geq -2.0$), and the intermediate-age clusters in their sample showed a tighter distribution with mean $[\text{Fe/H}] = -0.48$ dex ($\sigma=0.09$), with no tail toward solar metallicities. The range of metallicity for intermediate and old clusters can also be observed in Figure 6 of Piatti and Geisler (2013), where the authors compare the age-metallicity relationship of field stars in the LMC with star clusters in both Clouds. The absence of clusters in the 3–12 Gyr age range in the LMC makes it difficult to understand if there has been a sudden increase in abundances or a constant rate of enrichment.

Hodge (1987) compared the distribution of cluster dimensions between the MCs and our Galaxy in their Figure 2. It is seen that in both Clouds the size distributions are different from that of the Galaxy, in the sense that there are larger clusters in both Clouds than in the Galactic sample. As mentioned by the author, about 1% of Galactic clusters have diameters larger than 25 pc, while the LMC sample has 5% that are larger than this limit. The SMC has only 2%, making it less different from the solar neighbourhood in this respect than the LMC but still somewhat richer in large clusters. This suggests that there are more ‘populous’ clusters in the LMC than the SMC. The mean diameter of clusters is about 7.7 pc for the LMC (Hodge, 1988a) and 5.8 pc for the SMC (Hodge, 1987). Bica and Schmitt (1995) presented an extensive catalogue of star clusters in the SMC and the Bridge, where the authors show the distribution of cluster sizes in logarithmic scale (their Figure 4). According to them, the largest SMC star clusters have a diameter $\sim 5'$, and the number strongly increases towards smaller sizes down to $\sim 0.'4$. Bica et al. (1999) presented an extensive catalogue of star clusters in the LMC. According to these authors (their Figure 3), the largest star clusters have diameter $\sim 5'$ and the number increases strongly toward smaller sizes down to $\sim 1'$. After which, there occurs a plateau and the diameter finally drops
to $\sim 24''$. For both Bica and Schmitt (1995) and Bica et al. (1999), the number distribution towards smaller sizes are affected by detection limits. The most recent, revised and extensive catalogue of star clusters in the Magellanic System is provided by Bica et al. (2008).

Previous studies of LMC star clusters have suggested that there is a non-uniform age distribution within the field, with certain areas showing high cluster production during certain epochs (Hodge and Flower, 1987; Hodge, 1988b; Olszewski, 1988; Linde, Lynga, and Westerlund, 1995). The studies focussed on primarily rich clusters located within small areas in the LMC and have small sample size. To learn more about the age/location relation, the sample size has to be increased over the complete LMC with a more accurate estimation of cluster parameters (Westerlund, 1997). Hodge (1987) analysed the cluster population in the SMC to faint limiting magnitudes. Also, the outer fields of the SMC have less young clusters when compared to the core area. The authors showed that the age distribution is non-uniform, which suggests that either the production of clusters has been very inconsistent (with almost all clusters formed in just the last few 100 Myr) or that the cluster lifetimes in the SMC are actually finite, with the later one being more probable. The lifetime of star clusters is greater in both the Clouds as compared to their galactic counterparts (Hodge, 1988b). This can be attributed to a less dynamic environment in the Clouds where the destruction by interstellar clouds is less frequent (Westerlund, 1997).

Studies of populous star clusters in the MCs in general have been significant in order to understand the rapid evolutionary phases in the H-R diagram (a consequence of their richness) which are unlikely to be observed in sparser Galactic open clusters. The poor star clusters of the LMC have not been well studied due to the difficulty in estimating cluster parameters from data of moderate telescopes and non-availability of deep photometric data, until very recently (e.g., Piatti 2012b, 2014; Palma et al. 2013). As they are an important component of the LMC cluster
system, we plan to study a good sample of poor and inconspicuous star clusters in the LMC.

1.5 Aim of the Thesis

The aim of the thesis is to study the evolved stellar populations for one of the components of the MCs, the LMC. The study is primarily divided into two parts.

1. Study of sparse star clusters in the LMC: Star clusters in the LMC have been the target of detailed studies to understand several processes such as star formation and chemical evolution of the galaxy (Olszewski et al., 1991; Pietrzynski and Udalski, 2000; Grocholski et al., 2006). The LMC was known to host only rich star clusters until very recently and thus, the previous studies targeted primarily the rich clusters. Bica et al. (2008) presented the most recent and extensive catalogue of known clusters (3740) in the MCs and the Magellanic Bridge. A large number of clusters in their catalogue are sparse, and are either unstudied or poorly studied due to a lack of deep photometric data. It is necessary to study such clusters in order to understand the cluster formation history (CFH) and survival processes. Thus, this study aims to increase our understanding of sparse star clusters in the LMC with well estimated parameters, using deep Washington photometric data for 45 objects.

2. Metallicity map of the LMC: Metallicity ([Fe/H]) has an impact on star formation and stellar evolution. The metallicity map of a galaxy can give us details of distribution of [Fe/H], its radial gradient, and also the chemical enrichment history (CEH) of the galaxy. Previous efforts to study the CEH of the LMC using spectroscopic or photometric data of star clusters (Olszewski et al., 1991; Grocholski et al., 2006) and field stars (Cole et al., 2005; Carrera et al.,
2008a; Olsen et al., 2011; Van der Swaelmen et al., 2013) suffered from small sample sizes, and covered only small pockets within the LMC, or had inconsistencies between tracers and calibrators (Cioni, 2009). We aim to create a high spatial resolution metallicity map of the LMC using RGB stars, with the help of photometric data, and calibrate it using spectroscopic data of field and cluster Red Giants (RGs).

1.6 Overview of the Thesis

A brief overview of the contents of the thesis is mentioned below.

- An introduction to the thesis along with the aim of the study is described in Chapter 1.

- **Chapter 2** describes the three sets of photometric data used for this study. The data sets are: \( CT_1 \) Washington photometric data for 45 star clusters within the LMC, the VI photometric data from the Optical Gravitational Lensing Experiment Phase-III survey (OGLE III, Udalski et al. 2008a), and the Magellanic Cloud Photometric Survey (MCPS, Zaritsky et al. 2004).

- **Study of sparse star clusters in the LMC:** A systematic study is performed to analyse the 45 cluster candidates and estimate their parameters (radius, reddening, and age), using the ‘Main-Sequence Turn-Off’ (MSTO) as well as the evolved portion of the CMD. The basic parameters are estimated for 33 genuine clusters, whereas the other 12 cluster candidates are classified as possible clusters/asterisms. The study is presented as two parts, in Chapter 3 and Chapter 4 for the genuine and possible clusters/asterisms respectively.

- **Metallicity map of the LMC:** A metallicity map of the LMC is estimated using OGLE III and MCPS data. This is a first of its kind.
map of metallicity up to a radius of 4–5 degrees, derived using photometric data and calibrated using spectroscopic data of RGB stars. The RGB is identified in the V, (V−I) CMDs of small subregions of varying sizes in both data sets. The slope of the RGB is used as an indicator of the average metallicity of a subregion, and the RGB slope is calibrated to metallicity by using spectroscopic data for field and cluster RGs in selected subregions. This study is presented in two different chapters: Chapter 5 (OGLE III data) and Chapter 6 (MCPS data).

- The summary and conclusions of the thesis work are presented in Chapter 7. The planned future projects are also discussed.
Chapter 2

Data

2.1 Introduction

The observations in stellar optical photometry are generally made through a well-defined set of filters that cover a certain energy band within the visible portion of the electromagnetic spectrum. This allows us to estimate the brightness of a star at the effective wavelengths of the sampled filters. The brightness of a star is expressed in an inverse logarithmic scale called apparent magnitude ($m$). The apparent magnitude ($m_V$) of a star can be related to the flux ($f_V$) collected for a particular choice of filter (V, where the effective wavelength falls in a region sensitive to human eye), by the famous relation established by Pogson in 1856:

$$m_V = -2.5 \times \log_{10}(f_V) + K$$  \hspace{1cm} (2.1)

where $K$ is a constant. Another measurable quantity that is closely connected to this apparent magnitude is the colour. The colour of a star refers to the ratio in the brightness of a star observed at two specified wavelength regions (or say two filters).

In the review article by Bessell (2005) on standard photometric systems in astronomy, the author discusses the different photometric passband systems as well as their categorization. The optical photometric system in general can be categorized into three fundamental categories based
Table 2.1: Broad-band filter systems, their effective wavelengths (Å), and widths (Å) from Bessell (2005)

<table>
<thead>
<tr>
<th>Filter</th>
<th>$\lambda_{\text{eff}}$</th>
<th>$\Delta\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>3663</td>
<td>650</td>
</tr>
<tr>
<td>B</td>
<td>4361</td>
<td>890</td>
</tr>
<tr>
<td>V</td>
<td>5448</td>
<td>840</td>
</tr>
<tr>
<td>R</td>
<td>6407</td>
<td>1580</td>
</tr>
<tr>
<td>I</td>
<td>7980</td>
<td>1540</td>
</tr>
<tr>
<td>C</td>
<td>3982</td>
<td>1070</td>
</tr>
<tr>
<td>M</td>
<td>5075</td>
<td>970</td>
</tr>
<tr>
<td>$T_1$</td>
<td>6389</td>
<td>770</td>
</tr>
<tr>
<td>$T_2$</td>
<td>8051</td>
<td>1420</td>
</tr>
</tbody>
</table>

on the width of the filter passbands selected for making measurements. The categories are broad-band ($400 \, \text{Å} < \Delta\lambda < 1000 \, \text{Å}$), intermediate-band ($70 \, \text{Å} < \Delta\lambda < 400 \, \text{Å}$), and narrow-band ($\Delta\lambda < 70 \, \text{Å}$) photometric systems. The broad-band photometric systems are among the oldest standard systems that are being used in modern photometric investigations. For our analysis the broad-band filter systems considered are the Johnson-Cousins (UBVRI) and the Washington ($CMT_1T_2$) filter systems. The effective wavelengths and FWHMs corresponding to each of these filters are mentioned in Bessell (2005) and the same are listed out in Table 2.1. However, it should be noted that the values of these quantities may vary a little depending upon the response of the filters used.

The Johnson-Cousins UBVRI filter system is the most common and old standard photometric system in astronomy. In the initial days the UBV system was developed by Johnson and collaborators (Johnson and Morgan 1953; Johnson and Harris 1954; Johnson 1955). During that era there were several other contemporary works about standardizing this UBV system. About a decade later the Johnson UBV system was ex-
tended when two more filters, R and I towards the redder side of the spectrum, were added to the extensive work published by Johnson et al. (1966). However, due to the limitations of photomultiplier tubes used during that era, it was difficult to measure the bluer and the redder bands with the same detector. There have been several other contemporary attempts to standardize the photometric systems, specially the redder ones (RI). One such work was by Kron and his collaborators (Kron and Smith 1951; Kron, White, and Gascoigne 1953; Kron, Gascoigne, and White 1957). Later on with the introduction of GaAs tubes, the RI filters were primarily revised with the excellent standardization work by Cousins (1974, 1976), which was later on expanded by Menzies et al. (1989). In modern times the UBVRI normally refers to the Johnson-Cousins UBV system and the Cousins RI system (Bessell, 2005).

The broad-band Washington photometric system ($CMT_1T_2$) was set up by Canterna (1976) for accurate measurements of temperature, abundances and $CN$ blanketing index for G and K giants. This was done by following the guidelines set by Wallerstein and Helfer (1966). According to Canterna (1976), the bandpasses $T_1$ and $T_2$ were devised for measuring the temperature parameter and were selected by avoiding the wavelength region $6800$–$7500$ Å where the blanketing effect of red $CN$ system is important. $M$ is supposed to be the metal abundance bandpass, and it was selected within a region ($\sim 4500$–$5500$ Å) in the spectrum which has sufficient but unsaturated metallic lines and avoids the violet $CN$ bands at $3595$, $3883$, and $4215$ Å and the G band at $4300$ Å. The $C$ bandpass was set within a region of $\sim 3500$–$4500$ Å to monitor the total effects of blanketing by the $CN$ and $G$ bands. This region also contains a large number of saturated metal lines. To check the response function and bandpasses of the initial $CMT_1T_2$ filter system set up by Canterna (1976), we direct the readers to their Figure 1.

A decade later, Geisler (1986) used the then available high resolution spectroscopic results of giants in the galactic field and in globular
clusters to empirically recalibrate the Washington photometric system. Over the years, the large accumulation of observations and an enlarged sample of abundance calibrators from high-dispersion spectroscopy was used to produce a revised and improved calibration of this photometric system (Geisler, Claria, and Minniti, 1991). The passbands of the Washington photometric system were revised by Bessell (2001), and using the derived passbands the author estimated theoretical colours using the Castelli (1999) model atmospheres of Kurucz. The theoretical isochrones of this system have been calculated (Lejeune and Schaerer 2001; Girardi et al. 2002; Marigo et al. 2008) and compared with other photometric systems. These theoretical studies agree well with the empirically determined properties of the Washington photometric system. Most of the colours in the Washington photometric system can be transformed to the standard broad-band colours.

Figure 2.1 is a schematic diagram from Bessell (2005), showing a comparison of Washington passbands with respect to the Johnson-Cousins as well as other broad-band photometric systems. One can think of the Washington $C$ filter to be a combination of $U$ and $B$. The $C$ filter is more sensitive to abundance than either individually $U$ or $B$. However, the $C$ filter has little luminosity sensitivity because it straddles the Balmer jump and the flux to the red part of the jump dominates. The Washington $M$ is almost identical to $V$. However, the centre of $M$ filter is slightly blue shifted and hence it has slightly more sensitivity to metallicity than $V$. The $T_1$ filter of Washington system is similar to Cousins R. According to Geisler (1996) the R filter is more efficient and transforms well to $T_1$ for all but the reddest stars. The $T_2$ filter is shown to be identical to the standard Cousins I filter.

The Washington photometric system ($CMT_1T_2$) is widely used by astronomers for accurate estimation of ages and metallicity of stellar populations within the Galaxy as well as for extragalactic sources. The system is used for abundance studies of globular clusters and open clusters (Can-
Figure 2.1: Schematic diagram from Bessell (2005) showing Washington passbands with respect to the passband of other broad-band photometric systems.
tern et al. 1986; Geisler, Minniti, and Claria 1992; Geisler, Claria, and Minniti 1992; Geisler and Sarajedini 1999; Piatti, Clariá, and Ahumada 2004). The Spaghetti Survey (Morrison et al., 2000, 2001) used this photometric system to map the Galactic halo and to find the distance of nearby giants. The Washington photometric system has also been widely applied to studies of metallicity and ages of intermediate-age and old clusters in the MCs (e.g. Geisler et al. 1997; Piatti et al. 2002; Piatti 2011a). There are several works directed towards studying the cluster candidates in the LMC using the $CT_1$ Washington photometric system, and the $(T_1, C-T_1)$ CMD has proved to be an excellent platform to estimate cluster ages and metallicities accurately (e.g., Piatti et al. 2009, 2011; Palma et al. 2013; Piatti 2011b, 2012b, 2014). The $CT_1$ Washington photometric system has also been used to understand the age-metallicity relation for field stars in the MCs (Piatti, 2012a; Piatti and Geisler, 2013).

In this thesis, 45 star clusters in the LMC are studied using $CT_1$ Washington Photometry data. 33 out of the 45 clusters are analysed in Chapter 3, while the analysis for rest of the 12 cluster candidates are presented in Chapter 4. The V and I band photometric data obtained from the Optical Gravitational Lensing Experiment Phase III survey are used to construct a photometric metallicity map of the LMC, which is presented in Chapter 5. A similar metallicity map is created using the V and I band photometric data obtained from the Magellanic Cloud Photometric Survey, presented in Chapter 6. The details of each data set are mentioned in the following sections.
2.2 $CT_1$ Washington photometric data from Cerro-Tololo Inter-American Observatory

As mentioned earlier, in our study we have focussed on 45 LMC star cluster candidates for which Washington $C$ and Kron-Cousins R and I data were retrieved from the National Optical Astronomy Observatory (NOAO) Science Data Management (SDM) Archives\(^1\). The cluster sample was selected from the catalogued clusters identified by Piatti (2011b) in the 21 LMC fields observed at the Cerro-Tololo Inter-American Observatory (CTIO) 4-m Blanco telescope with the Mosaic II camera attached (36 \times 36 \text{ arcmin}^2 \text{ field on to a 8K} \times 8K \text{ CCD detector array}) through program 2008B-0912 (PI: D. Geisler). The volume of images includes calibration frames (zeros, sky-flats, etc.), and standard and program fields observed through the Washington $C$, and Kron-Cousins R,I filters. Note that the R filter has a significantly higher throughput as compared to the standard Washington $T_1$ filter so that R magnitudes can be accurately transformed to yield $T_1$ magnitudes (Geisler, 1996).

The data were reduced following the procedures documented by the NOAO Deep Wide Field Survey team (Jannuzi, Claver, and Valdes, 2003) by utilizing the mscred package in IRAF\(^2\). The different tasks performed included overscan, trimming and cross-talk corrections, bias subtraction, getting an updated world coordinate system (WCS) database, flattened all data images, etc., once the calibration frames (zeros, sky- and dome-flats, etc.) were properly combined. Nearly 90 independent measures of standard stars were derived per filter for each of the three nights (2008, Dec. 18-20) during which the observations were carried out, in order to

\(^1\)http://www.noao.edu/sdm/archives.php.
\(^2\)IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
obtain the coefficients of the transformation equations:

\[ c = a_1 + T_1 + (C - T_1) + a_2 \times X_C + a_3 \times (C - T_1), \]  \hspace{1cm} (2.2)

\[ r = b_1 + T_1 + b_2 \times X_R + b_3 \times (C - T_1), \]  \hspace{1cm} (2.3)

\[ i = c_1 + T_1 - (T_1 - T_2) + c_2 \times X_I + c_3 \times (T_1 - T_2), \]  \hspace{1cm} (2.4)

where \( a_i, b_i, \) and \( c_i \) (\( i = 1, 2, \) and 3) are the fitted coefficients, and \( X \) represents the effective airmass. Capital and lowercase letters represent standard and instrumental magnitudes, respectively. These equations were solved with the `fitparams` task in IRAF and mean colour terms \( (a_3, b_3, c_3) \) resulted to be \(-0.090 \pm 0.003\) in \( C \), \(-0.020 \pm 0.001\) in \( T_1 \), and \(0.060 \pm 0.004\) in \( T_2 \) while typical airmass coefficients \( (a_2, b_2, c_2) \) resulted in \(0.31, 0.09\) and \(0.06\) for \( C, T_1 \) and \( T_2 \), respectively. The nightly rms errors from the transformation to the standard system were \( 0.021, 0.023 \) and \(0.017\) mag for \( C, T_1 \) and \( T_2 \), respectively, indicating these nights were of excellent photometric quality.

The star-finding and point-spread-function (PSF) fitting routines in the `daophot/allstar` suite of programs (Stetson, 1987; Stetson, Davis, and Crabtree, 1990) were used with the aim of performing the stellar photometry. For each frame, we selected \( \sim 960 \) stars to fit a quadratically-varying PSF, once the neighbours were eliminated using a preliminary PSF derived from the brightest, least contaminated \( \sim 240 \) stars. Both groups of PSF stars were interactively selected. We then used the `allstar` program to apply the resulting PSF to the identified stellar objects and to create a subtracted image which was used to find and to measure magnitudes of additional fainter stars. This procedure was repeated three times for each frame. Finally, we standardized the resulting instrumental magnitudes and combined all the independent measurements using the stand-alone `daomatch` and `daomaster` programs, kindly provided by
2.3 Optical Gravitational Lensing Experiment Survey

Peter Stetson. The final information gathered for each cluster consists of a running number per star, of the X and Y coordinates, of the measured $T_1$ magnitudes and $C - T_1$ and $T_1 - T_2$ colours, and of the observational errors $\sigma(T_1)$, $\sigma(C - T_1)$ and $\sigma(T_1 - T_2)$.

2.3 Optical Gravitational Lensing Experiment Survey

The primary aim of the Optical Gravitational Lensing Experiment (OGLE) project was to search for dark matter using the phenomena of gravitational microlensing. The MCs and the Galactic Bulge are excellent and most natural locations to conduct such searches, due to the numerous background stars that are potential targets for microlensing. The institutions collaborating in OGLE are the Warsaw University Observatory, Carnegie Institution of Washington, and the Princeton University. The OGLE project has successfully completed three phases and presently is in its fourth phase. The first phase was the project pilot phase, OGLE I, that started in 1992 and continued till 1995. During this phase the Galactic bulge was targeted in order to detect a statistically significant number of microlensing events. The observations were taken with the 1-m Swope telescope, with $2048 \times 2048$ Ford/Loral CCD camera, of the Las Campanas Observatory, operated by the Carnegie Institution of Washington. The project in its initial stage suffered from many limitations, one of severe problems being the availability of telescope time. Thus, the sky coverage was relatively small and the observations were limited only to the Galactic bulge. After the first phase there was a substantial upgrade of the project by building a dedicated telescope and new generation of instruments that were necessary to accomplish the main goals of the project.

The 1.3-m Warsaw telescope, at the Las Campanas Observatory, Chile has been used for the rest of the OGLE phases (II, III and IV). The second
phase of the survey, OGLE II (1997-2000) observed the Galactic bulge as well as the MCs. However, this phase covered only the central regions of the MCs including the bar, and presented a catalogue of a few million stars in the B, V, and I pass bands, for both the L&SMC (Udalski et al., 1998, 2000). The third phase of the project, OGLE III (2001-2009), was a remarkable addendum to the survey. During this phase, the use of a much larger detector system (second generation camera) made it possible to cover practically the entire area of the MCs, and a relatively larger area of the Galactic Bulge. The survey provided the mean calibrated photometry of stars in the V and I band filters. The regions in the sky observed during the second and third phases of OGLE are extremely interesting from the astrophysical point of view, and thus the OGLE maps have been widely used by astronomers around the world for many studies. The fourth phase, OGLE IV, began in 2009 and is still ongoing. The OGLE IV phase, equipped with the third generation camera and larger field of view as compared to OGLE III, recently published photometric images which cover the Magellanic Bridge (MB) region along with the Clouds and an extended area in the Galactic Bulge and Disk. It is to be noted that as an outcome of the second and third phases of the project, a large photometric data base of the MCs were published. We have utilized the OGLE III photometric catalogue for our study.

The OGLE III observations were carried out at Las Campanas Observatory, operated by the Carnegie Institution of Washington, with 1.3-m Warsaw telescope equipped with the second generation mosaic camera consisting of eight SITE 2048 × 4096 CCD detectors with 15 μm pixels which corresponds to 0.26 /pixel scale. One full mosaic image covers approximately 35′ × 35′ on the sky. More information about the instrumental set up is given by Udalski (2003). The OGLE III survey covered the bar as well as the surrounding regions of the LMC and SMC in the V and I bands. The V filter used in OGLE III in same as the Johnson V filter and the I band is more similar to the Cousins I filter. OGLE III
images of the LMC used for construction of the OGLE III Photometric Maps of this galaxy were collected between July 2001 and March 2008 and cover seven observing seasons of the LMC (Udalski et al., 2008a). The total observed area for LMC is about 40 square degrees, covering 116 LMC field regions. As the majority of observed fields have a high stellar density, the observations were carried out only in good seeing and transparency conditions. The median seeing of the V and I band for the OGLE III LMC datasets is equal to 1.″2. Udalski et al. (2008a) presented calibrated photometry in the V and I passbands for a 35 million stars in the LMC. For the SMC the observations were carried out between June 2001 and January 2008, covering a total area of about 14 square degrees, containing 41 SMC field regions. Udalski et al. (2008b) presented the OGLE III Photometric Maps of the SMC, that contained precise, calibrated V and I band photometry for a 6.2 million stars. The OGLE III observed fields for the LMC are shown in Figure 2.2.
2.4 Magellanic Cloud Photometric Survey

The Magellanic Cloud Photometric Survey (MCPS, Zaritsky, Harris, and Thompson 1997) was carried out using the 1-m Las Campanas Swope telescope and the Great Circle Camera (Zaritsky, Schectman, and Bredthauer, 1996) with a 2K CCD. The drift-scan images for both the LMC and the SMC were obtained in the Johnson U, B, and V and the Gunn I bands. The magnitudes were then placed on the Johnson-Kron-Cousins photometric system (Landolt, 1983, 1992). The survey began in 1995 and continued for about five years, providing photometry of virtually all stars in the MCs, that are brighter than 21 magnitude in V band. The pixel scale is 0.′70/pixel and the typical seeing is 1.′5. The data were reduced using a pipeline based on DAOPHOT II (Stetson, 1987) and IRAF. The details of the reduction procedure, construction of the catalogue, and quality assurance are presented in Zaritsky et al. (2002, 2004)
Zaritsky et al. (2004) presented the catalogue for over 24 millions stars in the LMC from the MCPS, covering a total area of about 64 square degrees (about $8.5^\circ \times 7.5^\circ$, with the longer direction corresponding to the east-west axis). Zaritsky et al. (2002) provided the catalogue for over 5 million stars in the SMC, within the central 18 square degrees of the SMC (about $4.5^\circ \times 4^\circ$, where the longer direction is along the north-south axis). The survey presented the photometric as well as extinction maps in U, B, V, and I passbands for both LMC and SMC. The MCPS observed fields for the LMC are shown in Figure 2.3.

The resolution of MCPS is $\sim 3$ times worse than OGLE III. However, it covers more area than OGLE III. The MCPS and OGLE III data thus complement each other such that, the OGLE III catalogue will make a better choice for analysing the finer details, whereas the MCPS catalogue will be more suitable for analysing global features.
Chapter 3

Deep Washington photometry of star clusters in the Large Magellanic Cloud

3.1 Introduction

Star clusters in the LMC have been the target of many detailed studies to understand several processes such as the star formation and chemical evolution of the galaxy (Olszewski et al., 1991; Pietrzynski and Udalski, 2000; Grocholski et al., 2006). The LMC hosts a large number of star clusters, and the most recent and extensive catalogue of known clusters in the Magellanic Clouds is by Bica et al. (2008) (hereafter B08). However, the cluster sample is still incomplete as mentioned by the authors. Most of the previous studies of LMC star clusters have targeted rich clusters which stand out from the field due to their high stellar density. Two of the profound studies of LMC star clusters using colour-magnitude diagrams are by Pietrzynski and Udalski (2000) (hereafter PU00) and Glatt, Grebel, and Koch (2010) (hereafter G10). PU00 estimated the ages of

The work presented in this chapter is a part of the paper published as: Choudhury, S., Subramaniam, A., & Piatti, A.E., 2015, AJ, 149, 52.
about 600 clusters utilizing the OGLE II (Udalski, Kubiak, and Szymański, 1997) data, whereas G10 identified 1193 star clusters and estimated their ages utilizing the MCPS (Zaritsky et al., 2004) data. Both PU00 and G10 carried out their work primarily for young clusters (aged less than 1 Gyr), aiming to understand the cluster formation history. Another method that is generally employed to estimate the masses and ages of clusters for a sufficiently large number of samples is the use of integrated photometry; see e.g., Hunter et al. (2003), Popescu, Hanson, and Elmegreen (2012). Popescu, Hanson, and Elmegreen (2012) (hereafter P12) estimated the age and mass for 920 LMC clusters based on previously published broadband photometry and the stellar cluster analysis package, MASSCLEANage.

Apart from rich clusters, the LMC also hosts a large number of clusters which have relatively fewer number of stars, similar to the open clusters of our Galaxy. Despite the aforementioned extensive studies, this category of clusters is, in general either unstudied or poorly studied, due to lack of deep photometric data. As these sparse clusters are also part of the cluster system of the LMC, it is necessary to study them in order to understand the cluster formation and survival processes. The recent works of Piatti (2012b, 2014) and Palma et al. (2013) were directed towards increasing the sample of poorly studied/unstudied clusters in the LMC. They used the cluster CMDs to estimate ages using deep Washington photometry.

In this chapter, we attempt to increase our understanding of star clusters in the LMC that are either unstudied/poorly studied. To do so, we have carried out a homogeneous analysis of 33 LMC star clusters using deep photometric data in the Washington system. As is well known, the Washington photometric system has been widely applied to studies of intermediate-age and old clusters in the Galaxy and in the MCs (e.g., Geisler et al. 1997; Geisler and Sarajedini 1999; Piatti et al. 2003; Piatti 2012b). Particularly, the depth reached by the present photometric data helps us to trace the poorly populated clusters as well as trace the fainter
end of the main-sequence of sparse clusters.

The chapter is organized as follows. Section 3.2 introduces the Washington photometric data used for this study and describes the methods adopted for estimating the cluster parameters (radius, reddening, and age). In Section 3.3, we present the results derived from our analysis and discussions on individual clusters. In Section 3.4, we discuss our results. We summarize our findings in Section 3.5.

3.2 Data and Analysis

The deep Washington photometric data for the 33 clusters have been obtained from CTIO. The acquisition and reduction of the data is described in Section 2.2. As mentioned there, the data for each cluster consists of a running number per star, the X and Y coordinates (in pixels), the measured $T_1$ magnitudes and $C - T_1$ and $T_1 - T_2$ colours, the observational errors $\sigma(T_1)$, $\sigma(C - T_1)$ and $\sigma(T_1 - T_2)$. In the following sections, we describe in detail, the steps carried out for estimation of cluster parameters (radius, reddening, and age).

3.2.1 Estimation of cluster parameters

For each of the selected cluster candidate fields, we made use of the measured stars within a radius of approximately $130''$ around the central coordinates provided by B08. The cluster candidates analysed here are small angular-sized objects projected toward densely populated star fields. Our first step in the analysis was to estimate the radius of each cluster from their radial density profiles (RDPs). The second step was to remove the field stars within the cluster radius that contaminate the cluster CMD. Finally, we dealt with estimating the age and reddening of the clusters by visually fitting isochrones to the cleaned cluster CMDs. The set of isochrones used in this study come from Marigo et al. (2008), with a metallicity of $Z = 0.008$, as judged from the observed LMC metallicity.
range for the last 3 Gyr (Piatti and Geisler, 2013)

3.2.2 Estimation of cluster centre and cluster radius

We assume the presence of a star cluster when a stellar density enhancement is identified in the spatial distribution of field stars. For visual identification, we created finding charts for all clusters using measured stars with sizes proportional to their $T_1$ magnitudes. The cluster centres were estimated through an iterative method, starting from an eye estimated centre $(X_e, Y_e)$, for stars brighter than $T_1 = 22.0$ mag. We computed the average of the coordinates $(X, Y)$ for all the stars distributed within 200 pixels around $(X_e, Y_e)$ to estimate the central coordinate of the cluster, $(X_c, Y_c)$. Iterations were carried out until the difference in the estimated centre of two consecutive iterations was less than 10 pixels (2.7 arcsec). The number of stars per unit area in rings of 10 pixel width around the cluster centre were used to build the RDPs. The RDPs were visually fitted with a King (1962) profile:

$$
\rho(r) = \frac{\rho_0}{1 + (r/r_c)^2} + \rho_b, \tag{3.1}
$$

where $\rho_0$ is the central density, $\rho_b$ is the background density, and $r_c$ is the core radius. We fix the value of $\rho_0$ to visually fit the peak, and the value of $\rho_b$ to visually fit the background field density of the RDP at large radial distances. The $r_c$ value is then adopted so as to obtain the best visual fit of King profile to the RDP. We adopted cluster radius ($r$) as the distance from the cluster centre at which the cluster density becomes equal to the background field density, which is taken as $3r_c$. This is found to hold for most of the clusters. The clusters studied here are sparse and hence we have used this radius to include most of the cluster members. The error in the estimation of cluster radii is expected to be about $\pm 10''$, which is about three times the bin size used in estimating the RDP.

In clusters where there is incompleteness of bright stars in the central cluster region due to saturation, we were unable to obtain their centres
from the method described above. For these clusters we adopted either the central coordinates given by B08 or the eye-estimated centres from the densest visible cluster regions. Likewise, when we were unable to reliably determine a cluster radius by visually fitting a King profile to the RDP or were unable to estimate an RDP, we chose the radius which brings out the cluster features clearly in the CMD. For some of the clusters, it was difficult to define a circular area; instead we used a rectangular region where the cluster might be most probably located. It is to be noted that the convention followed while mentioning the rectangular dimension is thus: size along $X$ coordinate times size along $Y$ coordinate, in arcseconds.

### 3.2.3 Cleaning the cluster Colour Magnitude Diagrams

In order to analyse the cluster CMDs using stars located within the adopted cluster radii, it is necessary to remove the contamination due to the field stars by performing a statistical field star subtraction. For field star subtraction, we selected field stars within an annular region of area equal to that of the cluster, with the inner radius of the annulus to be around twice or more than the cluster radius. The field stars in the cluster area are then removed by taking each star in the field CMD and finding the nearest one in the cluster CMD, considering a grid of magnitude-colour bins with different sizes, starting with $[\Delta T_1, \Delta(C - T_1)] = [0.01, 0.005]$ up to a maximum of $[0.4, 0.2]$, where the units are in magnitude. In order to minimize effects due to field star density fluctuations, we repeated the decontamination procedure using different annular regions for each cluster and then compared the different resultant cleaned cluster CMDs. The cleaned cluster CMDs thus primarily show the cluster features with minimum inescapable field characteristics.

In cases where we could not consider an annular field region, the field stars were removed by selecting field regions (not necessarily circular) of
equal cluster area in different parts of the observed field, located away from the cluster, and performing the cleaning procedure described above. The cluster features that stay irrespective of the field used are considered as genuine cluster features and are used for estimating parameters.

### 3.2.4 Estimation of age and reddening

We determine the ages of the clusters by a visual fit of theoretical isochrones from Marigo et al. (2008) with LMC metallicity (Z=0.008) to the cleaned cluster CMDs. For visually fitting theoretical isochrones to the observed CMDs, the \((C - T_1)\) colours and \(T_1\) magnitudes need to be corrected for reddening and distance modulus, respectively. Subramanian and Subramaniam (2010) have created a reddening map for the LMC field using OGLE III data. They provide \(E(V - I)\) colour excesses for small regions within the galaxy. For a given cluster, we find the closest region in the reddening map and assume \(E(V - I)\) of the field as the cluster reddening. The average of the distance between the clusters and their closest adopted field regions in the reddening map is approximately 6'. Finally, the theoretical isochrones were shifted to the observation plane according to equations 3.2 and 3.3:

\[
(C - T_1)_{\text{observed}} = (C - T_1)_o + E(C - T_1), \quad (3.2)
\]

where \(E(C - T_1) = 1.97E(B - V)\) (Geisler and Sarajedini, 1999) and \(E(B - V) = E(V - I)/1.25\) (Bessell and Brett, 1988). The expected error in reddening is less than ±0.05 mag, which includes the photometric error and the error in the estimation of field reddening.

\[
T_{1,\text{observed}} = M_{T_1} + 2.62E(B - V) + (m - M)_o, \quad (3.3)
\]

as given by Geisler and Sarajedini (1999).

We assume a true distance modulus of \((m - M)_o = 18.50\) for all the cluster samples, recently obtained by Saha et al. (2010) and Pietrzyński.
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The cleaned cluster CMDs were matched with different isochrones after incorporating the corrections due to reddening and distance modulus. The age of the isochrone that visually provides the best match to the observed cluster CMD was adopted as the cluster age. However, whenever a cluster exhibited a dispersion in its CMD features, particularly near the turn-off, we over-plotted additional isochrones in order to take into account the observed spread. Piatti (2014) discusses the error in the estimation of age. In general, the observed dispersions seen in the cluster CMDs encompass a spread of $\Delta \log(t) \sim 0.10$. We discuss cases with a large spread in age or a large uncertainty in the age estimation separately.

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The 33 clusters studied here have prominent cluster features (upper MS and/or MSTOs) and we could satisfactorily estimate the cluster parameters like radius, age and reddening. Out of these 33 clusters, 23 fields contain single clusters and 5 fields contain a pair of clusters. We have presented the finding chart, cluster CMD (before and after field star correction) and the estimated RDP (wherever possible) for the 33 clusters. We have carried out similar analysis for all these clusters and we present and explain Figure 3.1 as an example, to show the derived parameters for a single cluster (HS 411). Similar multi-panel plots have been created for all the analysed clusters unless stated otherwise. In the multi-panel plot, the top-left panel shows the schematic chart with the red dashed circle denoting the estimated extent of the cluster. The RDP is shown with a King profile in the top-right panel. The bottom-left panel shows the CMD of stars within the estimated radius and field stars located in adopted field region. The inner radius of the field region chosen is also indicated in the figure. The bottom-right panel shows isochrones visually fitted to the cleaned cluster CMD, with age mentioned in units of $\log(t)$. 
Figure 3.1: HS 411: (i) Top-left: spatial distribution of the stars in the cluster field (north is up, and east is left), along with the estimated cluster size (red dashed circle). (ii) Top-right: The King profile over-plotted (red dashed line) to the RDP (black solid line). (iii) Bottom-left: uncleaned cluster CMD (black filled circles) within the cluster radius, with the field CMD over-plotted (green open circles). The cluster radius and the inner radius of the field are indicated. (iv) Bottom-right: isochrones over-plotted (red solid and dashed lines) to the cluster CMD after removal of field stars.
We discuss the individual clusters (23 single clusters and 5 pair of double clusters) in the following sections.

### 3.3.1 Single clusters

We discuss the 23 single clusters in this section.

1. BRHT 45a (Figure 3.2) is a bright, young (~125 Myr) cluster with prominent upper MS and MSTO. Dieball, Müller, and Grebel (2002) (hereafter DMG02) identified a large number of double clusters in the LMC. The authors report a second cluster BRHT 45b at coordinates \((4^h 56^m 52^s, -68^\circ 00' 20'')\), which lies within the cluster radius \((2^7'')\) of BRHT 45a. G10 mentions that BRHT 45b is a young cluster aged \(~40\) Myr \((\log(t)=7.60, \text{with } 0.30 \leq \text{error} <0.50)\), which is similar to the age estimated by P12 using integrated photometry \((\log(t)=7.62^{+0.18}_{-0.32})\). We in fact identified three clumps of stars within the cluster region, and one of them could possibly be BRHT 45b. Piatti (2014) considered only the central clump as BRHT 45b and estimated the age as \(~80\) Myr \((\log(t)=7.90\pm0.10)\). However, given such a small spatial separation, it is difficult for us to identify BRHT 45a and BRHT 45b separately and estimate independent parameters for them. The age that we have determined is possibly the age of the youngest or the dominant among the clumps. The estimated reddening for BRHT 45a is found to be similar to the reddening of the corresponding field \((E(C-T_1) = 0.15 \text{ mag})\).

2. BSDL 77 (Figure 3.3) is a compact cluster (aged \(~800\) Myr) with a prominent MS, MSTO and a red giant branch. We also notice clumpy distribution of stars in the cluster region, which is reflected in the radial density profile. The cluster radius estimated from King profile fit to RDP is \(r = 24''\). The best fit isochrones yield a lower reddening \((E(C-T_1) = 0.0 \text{ mag})\) compared to the corresponding
Figure 3.2: Single cluster candidate: BRHT 45a. Panel description is the same as Figure 3.1.
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Figure 3.3: Single cluster candidate: BSDL 77. Panel description is the same as Figure 3.1.
field-reddening value \(E(C - T_1) = 0.10\) mag). This is one of the older clusters studied here.

3. H88-33 (Figure 3.4) is a small \((r = 18")\) compact cluster. The MSTO shows two possible turn-offs. As the cluster MS in very well populated, the scatter near the MSTO may be due to statistical effects. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field \(E(C - T_1) = 0.13\) mag. We have shown isochrones of \(\log (t) = 8.20-8.50\), suggesting that the age of the cluster is likely to be in this range.

4. H88-131 (Figure 3.5) is a moderately large \((r = 24")\) cluster as shown by the RDP. The field-subtracted CMD shows a MS with a number of stars bluer than the MSTO. A few red giants can also be identified in the CMD. We have estimated the age of the cluster to be \(\sim 1\) Gyr. As the reddening to the cluster \(E(C - T_1) = 0.06\) mag) is very small, the stars seen bluer than the MS demand attention.

5. H88-320 (Figure 3.6) is a fairly large \((r=27")\) cluster located in a relatively dense field, as shown by the RDP. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field \(E(C - T_1) = 0.33\) mag). The cluster MS is clearly identified in the field subtracted CMD and the age is estimated to be \(\sim 160\) Myr.

6. H88-331 (Figure 3.7) is a dense and rich cluster. The cluster radius is \(r = 24")\) estimated from the King profile fit to the RDP. The MS has a relatively large width, and the MSTO also shows scatter. This may be due to the presence of differential reddening in the field. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field \(E(C - T_1) = 0.23\) mag, which is relatively large). The age estimated for this cluster is \(\sim 500\) Myr.

7. HS 116 (Figure 3.8) is a small \((r = 18")\) cluster in a relatively dense
Figure 3.4: Single cluster candidate: H88-33. Panel description is the same as Figure 3.1.
Figure 3.5: Single cluster candidate: H88-131. Panel description is the same as Figure 3.1.
Figure 3.6: Single cluster candidate: H88-320. Panel description is the same as Figure 3.1.
Figure 3.7: Single cluster candidate: H88-331. Panel description is the same as Figure 3.1.
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Figure 3.8: Single cluster candidate: HS 116. Panel description is the same as Figure 3.1.

Field. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field \((E(C-T_1) = 0.08 \text{ mag})\). The field-subtracted CMD shows the cluster features well which can be visually fitted with isochrones aged \(~350 \text{ Myr}\).

8. HS 131 (Figure 3.9) is a dense rich cluster easily identified in the field. The RDP does not allow us to define the cluster radius, and the features in the CMD also show large scatter. A spatial plot of the evolved stars showed a density enhancement near the cluster centre and we estimated the extent of the cluster to be about \((27'' \times 27'')\) around that location. We thus considered all stars within
Figure 3.9: Single cluster candidate: HS 131. The top-right panel shows the CMD of stars within the estimated cluster size (black filled circles). The bottom-left panel shows the CMD of the annular field (green filled circles), whereas the bottom-right panel shows isochrones over-plotted to the unclean cluster CMD. The top-left panel description for HS 131 is the same as Figure 3.1.
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Figure 3.10: Single cluster candidate: HS 390. Panel description is the same as Figure 3.1.

this region, and the age of the cluster was estimated via visual fit of the isochrones, especially to the RC and the RGB stars, as $\sim 1.25$ Gyr. The estimated reddening for HS 131 is found to be similar to the reddening of the corresponding field ($E(C - T_1) = 0.16$ mag).

9. HS 390 (Figure 3.10) is a dense and slightly elongated cluster with a well populated MS. The cluster radius is $r = 20''$ estimated from King profile fit to RDP. The best fit isochrones yield a higher reddening ($E(C - T_1) = 0.45$ mag) compared to the corresponding field-reddening value ($E(C - T_1) = 0.30$ mag). The estimated age is $\sim 180$ Myr.
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10. HS 411 (Figure 3.1) is one of the smallest (r = 15") clusters where we could identify a narrow and well-populated MS. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field ($E(C - T_1) = 0.34$ mag). The cluster is aged $\sim$280 Myr.

11. HS 412 (Figure 3.11) shows a clumpy distribution of stars in the cluster region, giving rise to a RDP with multiple peaks. The RDP could not be fitted with a King profile, and the radius of the cluster is chosen at which the cluster profile becomes prominent (r = 25") in the CMD. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field ($E(C - T_1) = 0.34$ mag). The cluster MS is prominent, and we estimate the age to be $\sim$125 Myr.

12. KMHK 95 (Figure 3.12) is a moderately rich cluster with a well-defined cluster MS. The cluster radius is r = 21", estimated from a King profile fit to the RDP. The best fit isochrones indicate lower reddening value ($E(C - T_1) = 0.08$ mag) with respect to the corresponding field-reddening value ($E(C - T_1) = 0.13$ mag). The cluster MS is clearly identified in the field-subtracted CMD, yielding an age of $\sim$350 Myr.

13. KMHK 907 (Figure 3.13) is a bright, young cluster whose upper MS is prominently visible, and its age is $\sim$250 Myr. The cluster radius is r = 21", estimated from a King profile fit to the RDP. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field ($E(C - T_1) = 0.18$ mag). As seen in the cleaned cluster CMD, the lower portion of the MS is broadened, and the width increases with decreasing brightness. This feature stays even after cleaning with field regions at different annular radii. This is possibly an effect of differential reddening or the presence of equal mass binaries in the lower MS, which can be
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Figure 3.11: Single cluster candidate: HS 412. Panel description is the same as Figure 3.1 except that, no King profile over-plot to RDP is shown.
Figure 3.12: Single cluster candidate: KMHK 95. Panel description is the same as Figure 3.1.
Figure 3.13: Single cluster candidate: KMHK 907. Panel description is the same as Figure 3.1.

visually fitted by brightening the isochrones by 0.75 mag. DMG02 mention the presence of another cluster in this field, BSDL 1716, with coordinates (5° 26' 07'', -70° 59' 19'') and of similar size as KMHK 907. B08 lists BSDL 1716 as an association. We find no information about the age of BSDL1716 from PU00 or G10. Given its coordinates, it is possible that the bright clump seen in the spatial plot towards the south-west direction (at a distance of \( \sim 33'' \)) of KMHK 907 is BSDL 1716. However, we could not find any prominent cluster feature in that specific location, and hence we were unable to derive any cluster parameters for the same.
14. KMHK 975 (Figure 3.14) is a small \((r = 21\arcsec)\) cluster where the CMD of the cluster region before field-star subtraction shows a broad MS and a few RGs. The field subtracted CMD has only the upper part of the MS, as the lower part has been subtracted away, even though the limiting magnitude of this region is about \(T_1 \sim 23\) mag. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field \((E(C - T_1) = 0.10\) mag). The age estimated using the upper MS is \(\sim 200\) Myr.

15. LW 54 (Figure 3.15) is a compact and dense cluster which shows two concentrations of stars in the cluster region. The cluster radius is \(r = 18\arcsec\), estimated from a King profile fit to the RDP. The field region is very sparse as shown by the RDP. The best fit isochrones yield a lower reddening \((E(C - T_1) = 0.0\) mag) compared to the corresponding field-reddening value \((E(C - T_1) = 0.07\) mag). The cluster features are clearly seen in the CMD and are used to estimate the age \(\sim 400\) Myr.

16. SL 579 (Figure 3.16) is a rich and dense cluster. The cluster radius is \(r = 18\arcsec\) estimated from a King profile fit to the RDP. The CMD of the region is relatively shallow with a limiting magnitude of \(T_1 \sim 21\) mag. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field \((E(C - T_1) = 0.13\) mag). The cleaned CMD has a well-populated MS which is used to derive the age \(\sim 140\) Myr.

Below, we discuss the cases of some clusters for which either the RDP did not show a strong peak (BSDL 631, H88-265, H88-269, and HS 247) or where we could not obtain an RDP (BSDL 268, NGC 1793, and HS 329). Saturation effects caused by the presence of bright stars near the cluster centre have resulted in missing stars and incompleteness in the central region for these clusters. As our data could not confirm whether these clusters are genuine clusters based on spatial density enhancement, we
Figure 3.14: Single cluster candidate: KMHK 975. Panel description is the same as Figure 3.1.
Figure 3.15: Single cluster candidate: LW 54. Panel description is the same as Figure 3.1.
Figure 3.16: Single cluster candidate: SL 579. Panel description is the same as Figure 3.1.
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tried to verify the existence of these clusters by identifying density enhancement using other optical data. The OGLE III is one of the complete and relatively deep surveys of the inner region of the LMC (4°-5°) with good spatial resolution. We extracted the OGLE III fields corresponding to each of these clusters and created similar finding charts (Figure 3.24 for BSDL 631, H88-265, H88-269, and HS 247; Figure 3.25 for BSDL 268, NGC 1793 and HS 329). It is to be noted that the OGLE III spatial plots presented in this chapter and in Chapter 4, $x$ and $y$ denote the Cartesian coordinate system (units in arcminutes), with north on top and east to the left. The individual cases are discussed below.

1. BSDL 631 (Figure 3.17): A small, compact cluster with a symmetric distribution of bright stars is observed around the cluster centre. The estimated RDP shows only a weak density enhancement within a radius $\leq 15''$, mainly due to missing stars near the centre. The OGLE III field (Figure 3.24) complements the Washington field showing a small but compact clump of bright stars present within the cluster region and is devoid of saturation effects. Based on the density enhancement seen in the OGLE III field and the MS feature identified in the CMD, we conclude that BSDL 631 is a very small, compact and young cluster aged $\sim 220$ Myr. It is to be noted that, for this cluster the best fit isochrones yielded a lower reddening ($E(C - T_1) = 0.0$ mag) with respect to the corresponding field-reddening value ($E(C - T_1) = 0.12$ mag).

2. H88-265 (Figure 3.18): A small but prominent clump of stars is observed around the cluster centre in the spatial plot. A comparison of the CMD of the cluster region with the field region shows prominent MSTO and upper MS features (brighter than 19.0 mag and bluer than 0.2 mag), which could belong to the cluster. The spatial distribution of the bright stars shows significant clumping around the cluster centre within $20''$, and this value is hence adopted as the
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Figure 3.17: Single cluster candidate with weak RDP: BSDL 631. Panel description is the same as Figure 3.1.
Figure 3.18: Single cluster candidate with weak RDP: H88-265. Panel description is the same as Figure 3.1, except that no King profile over-plot to RDP is shown.

cluster radius. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field ($E(C - T_1) = 0.10$ mag). The OGLE III spatial plot (Figure 3.24) corresponding to H88-265 shows a similar small but prominent clump of bright stars around the cluster centre, thus validating the presence of this small and young cluster aged $\sim200$ Myr.

3. H88-269 (Figure 3.19): The finding chart shows a small, dense clump of stars near the central region. The observed density enhancement is caused by stars near the MSTO as well as evolved
Figure 3.19: Single cluster candidate with weak RDP: H88-269. Panel description is the same as Figure 3.1, except that no King profile over-plot to RDP is shown.
stars, as seen in the cleaned cluster profile. The cluster CMD can be visually fitted with an isochrone of age \( \log(t) = 8.90 \pm 0.10 \). Although the RDP estimated for this cluster does not show a strong peak, we find the cluster profile to prominently show up within a radius of 20\(^\circ\). In fact, the field seems to have an almost similar star formation history (SFH) as that of the cluster and suffers from differential reddening, thus making field star subtraction inefficient. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field \( (E(C - T_1) = 0.10 \text{ mag}) \). To verify the existence of this cluster, we extracted the OGLE III field (Figure 3.24) for this cluster and we were able to find a very significant density distribution of stars within the central region. We conclude that H88-269 is a small and compact cluster aged \( \sim 800 \) Myr, immersed in a dense field of almost similar age.

4. HS 247 (Figure 3.20): We observe a feeble density enhancement near the expected centre of the cluster. However, a strong upper MS (brighter than 20.0 mag and bluer than 0.4 mag) is observed when the CMDs of the cluster and the field region are compared. This prominent cluster feature is retained even after cleaning with alternate field regions. A spatial distribution of these bright stars shows significant density distribution around the cluster centre. The cluster radius (20\(^\circ\)) is selected as the radius at which the cluster profile looks well-populated. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field \( (E(C - T_1) = 0.25 \text{ mag}) \). The OGLE III spatial plot (Figure 3.24) corresponding to HS 247 shows a density enhancement within the cluster region, supporting the existence of this cluster. We suggest that HS247 is a small, young cluster aged \( \sim 350 \) Myr.

5. BSDL 268 (Figure 3.21): This is one of the youngest clusters in our sample, aged \( \sim 90 \) Myr. In the spatial plot we see a few bright stars
**Figure 3.20:** Single cluster candidate with weak RDP: HS 247. Panel description is the same as Figure 3.1, except that no King profile over-plot to RDP is shown.
Figure 3.21: Single cluster candidate with no RDP: BSDL 268. The top-right panel shows the CMD of stars within the estimated cluster size (black filled circles), while the bottom-left panel shows the CMD of the annular field (green filled circles). The top-left and bottom-right panel description is the same as Figure 3.1.
clumped near the expected cluster centre, with evidence of some missing stars. A comparison of the CMDs of the cluster and the field region shows a bright upper MS, brighter than 19.0 mag and bluer than 0.2 mag. Also, the cleaned CMD has a well-populated MS. A spatial plot of these bright MS stars shows a compact distribution within an area of about 64.8×54", and the cluster centre is chosen at the centre of this distribution. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field \((E(C - T_1) = 0.20 \text{ mag})\). The corresponding OGLE III spatial plot (Figure 3.25) for the cluster shows a strong density enhancement due to bright stars in the central region, validating that this is a young cluster candidate.

6. NGC 1793 (Figure 3.22): We considered an area of 54"×54" around the central region where the presence of a cluster is suspected. The CMD shows a strong upper MS brighter than 19.0 mag and bluer than 0.2 mag, which could belong to the cluster, and the SFH appears quite different from that of the field CMD. A radius of 25" is selected for the cluster, and the cluster feature is found to appear clearly in the cleaned CMD. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field \((E(C - T_1) = 0.21 \text{ mag})\). The corresponding OGLE III spatial plot (Figure 3.25) for the cluster is presented, which shows a strong density enhancement due to bright stars in the central region, validating this to be a cluster aged \(\sim 110 \text{ Myr}\).

7. SL 397 (Figure 3.23): the spatial plot shows a clumpy distribution of bright stars located symmetrically around the expected cluster centre and possibly some missing stars. The bright stars form a prominent upper MS (brighter than 19.0 mag and bluer than 0.2 mag) for the cluster, even after cleaning the field stars. We were unable to estimate an RDP. The cluster radius (25") is selected as the
Figure 3.22: Single cluster candidate with no RDP: NGC 1793. The top-right panel shows the CMD of stars within the estimated cluster radius (black filled circles), while the bottom-left panel shows the CMD of the annular field (green filled circles). The top-left and bottom-right panel description is the same as Figure 3.1.
Figure 3.23: Single cluster candidate with no RDP: SL 397. The top-right panel shows the CMD of stars within the estimated cluster radius (black filled circles), while the bottom-left panel shows the CMD of the annular field (green filled circles). The top-left and bottom-right panel description is the same as Figure 3.1.
Figure 3.24: OGLE III fields of clusters with weak RDPs: BSDL 631, H88-265, H88-269 and HS 247. The red dashed circles show the derived sizes for these clusters using our data.

Figure 3.25: OGLE III fields of clusters with no RDP: BSDL 268, NGC 1793 and SL 397. The red dashed circles/rectangles show the derived sizes for these clusters using our data.
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distance from the centre at which the cluster features seem to be well-populated. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field \( E(C - T_1) = 0.16 \) mag). The corresponding OGLE III spatial plot (Figure 3.25) for the cluster shows a strong density enhancement in the central region. This further confirms the object as a young \((\sim 160 \text{ Myr})\) cluster.

3.3.2 Double clusters

In this section, we discuss the cases of double clusters.

1. BSDL 341 (Figure 3.26) and H88-52 (Figure 3.27): This is a pair of clusters of different ages, with their centres separated by \( \sim 60'' \). BSDL 341 is the younger \((\sim 280 \text{ Myr})\) of the pair showing a bright upper MS. H88-52 is an intermediate age \((\sim 1.1 \text{ Gyr})\) and compact cluster showing prominent MSTO and RC stars, located in the south-west direction relative to BSDL341. The cluster radii for both BSDL 341 and H88-52 were estimated from King profile fits to the RDPs \( r = 24'' \) for BSDL 341, and \( 27'' \) for H88-52). For BSDL 341, the estimated reddening was found to be similar to the reddening of the corresponding field \( E(C - T_1) = 0.17 \) mag). However, the best fit isochrones for H88-52 had to be dereddened \( E(C - T_1) = 0.08 \) mag) with respect to the corresponding field-reddening value \( E(C - T_1) = 0.17 \) mag).

2. HS 154 (Figure 3.28) and HS 156 (Figure 3.29): These are two clusters separated by \( \sim 81'' \). HS 154 is a young \((\sim 450 \text{ Myr}, \text{i.e.} \log(t)=8.65\pm0.10)\), cluster, with a prominent upper MS. Piatti (2012b) studied this cluster and estimated an age of \( \log(t)=8.70\pm0.10 \). HS 156 is an intermediate age \((\sim 1.1 \text{ Gyr})\) cluster showing a prominent MSTO, located in the eastern direction of HS 154. Palma et al. (2013) and Piatti (2014), both found HS 156 to be an intermediate-
Figure 3.26: Double cluster candidate: BSDL 341. Panel description is the same as Figure 3.1.
Figure 3.27: Double cluster candidate: H88-52. Panel description is the same as Figure 3.1.
age cluster (aged \( \sim 1 \) Gyr). In this study we looked upon HS 154 and HS 156 from the point of view of a double cluster. Also, we find excellent agreement of our derived ages for both these clusters when compared with their respective previous studies. The cluster radii for both HS 154 and HS 156 were estimated from King profile fits to the RDPs (\( r = 24'' \) for HS 154, and \( 21'' \) for HS 156). Also, for both clusters the estimated reddening was found to be similar to the reddening of the corresponding field (\( E(C - T_1) = 0.13 \) mag).

3. KMHK 979 (Figure 3.30) and HS 329 (Figure 3.31): KMHK 979 is a young cluster aged \( \sim 80 \) Myr. We are unable to estimate an RDP for

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Figure 3.28: Double cluster candidate: HS 154. Panel description is the same as Figure 3.1.
Figure 3.29: Double cluster candidate: HS 156. Panel description is the same as Figure 3.1.
this cluster. We choose the cluster radius (20") at which the cluster profile becomes well-populated in the CMD. Due to the proximity of other clusters in the field, we choose fields of similar dimensions in different parts of the observed field, away from the cluster, to clean the cluster profile. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field ($E(C-T_i) = 0.17$ mag). The cluster may be younger than our estimated age due to missing bright stars at the centre. We have extracted the corresponding OGLE III field for this cluster (Figure 3.32). The OGLE III field shows a clear density enhancement due to bright stars near the centre of KMHK 979, thus validating the existence of a young cluster.

The second member of the pair, HS 329, is identified as a dense clump of stars distributed asymmetrically at $\sim 68$" away towards the south-east direction of KMHK 979. The CMD of this clumpy region shows the existence of an evolved population such as RC and RGB stars, along with a spread in the MSTO. An eye-estimated centre in the clumpy region is chosen as the cluster centre, and we estimate that the cluster is spread across an area of $37.8 \times 40.5$ around this centre, based on the clumpy distribution of the evolved stars. The CMD of the field region also shows the presence of evolved stars. In addition, the whole field suffers from high differential reddening owing to its location near the central region of the LMC, thus making it difficult to identify the cluster MSTO efficiently after cleaning. Due to insufficient coverage of the field region on the southern side of the cluster, we could not perform annular field subtraction. Field star subtraction using fields of similar dimensions in different parts of the observed field (away from the cluster) were hence tried out. A unique determination of age for this cluster was found to be difficult, and we suggest that the cluster might be in the age range of 800 Myr to 1 Gyr. It is to be noted that for this
Figure 3.30: Double cluster candidate: KMHK 979. The top-right panel shows the CMD of stars within the estimated cluster radius (black filled circles), while the bottom-left panel shows the CMD of the non-annular, similar sized field (green filled circles) located away from the cluster. The top-left and bottom-right panel description is the same as Figure 3.1.
Figure 3.31: Double cluster candidate: HS 329. The top-right panel shows the CMD of stars within the estimated cluster size (black filled circles), while the bottom-left panel shows the CMD of non-annular, similar sized field (green filled circles) located away from the cluster. The top-left and bottom-right panel description is the same as Figure 3.1.
cluster, the best fit isochrones indicate a lower reddening \((E(C - T_1) = 0.0 \text{ mag})\) with respect to the corresponding field-reddening value \((E(C - T_1) = 0.17 \text{ mag})\).

According to DMG02, there exists a third cluster, BSDL 1980 in this field with coordinates \((5^h 29^m 33.3^s, -70^\circ 59' 38.00'')\). The average radius suggested by them is \(\sim 11''\), smaller than KMHK 979 and HS 329. According to G10, this cluster is a young one \((\sim 20 \text{ Myr})\) and is clearly seen as a small and poorly density enhanced spot in the OGLE III spatial plot (Figure 3.32) toward the south-west direction of KMHK 979. However due to the incompleteness of bright stars in our data, we are not able to estimate the parameters of this cluster.

4. SL 230 (Figure 3.33) and SL 229 (Figure 3.34): These are two young bright clusters with prominent upper MS and MSTOs. The younger
Figure 3.33: Double cluster candidate: SL 230. The top-right panel shows the CMD of stars within the estimated cluster radius (black filled circles), while the bottom-left panel shows the CMD of the annular field (green filled circles). The top-left and bottom-right panel description is the same as Figure 3.1.
clustering, SL 230, is aged $\sim$80 Myr. Some of the bright stars near the cluster centre were saturated, and hence the photometry could not be done. It was difficult to construct an RDP for SL 230. We thus selected the cluster radius ($r = 25''$) as the one at which the cluster features were found to be well-populated. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field ($E(C - T_1) = 0.16$ mag). It is quite possible that we missed out some bright members of the cluster due to saturation, and hence SL 230 may be younger than our estimate.

Figure 3.34: Double cluster candidate: SL 229. Panel description is the same as Figure 3.1, except that the field CMD is of a non-annular, similar sized region located away from the cluster.
SL 229 is located in the south-west direction of SL 230, with its centre separated by \( \sim 66'' \), and is aged around \( \sim 320 \) Myr. The cluster radius is \( r = 21'' \), as estimated from a King profile fit to the RDP. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field \( (E(C - T_1) = 0.12 \) mag). Due to insufficient data coverage in the southern direction for SL 229, we performed field star subtraction using circular fields in different directions away from the cluster. This cluster has been studied by Piatti (2012b), and the age estimated by the author agrees with ours. We studied these clusters as a double cluster with a first time age estimation of SL 230, using deep Washington photometric data, along with a reconfirmation of the age of SL 229.

5. SL 551 (Figure 3.35) and BRHT 38b (Figure 3.36): These are two young (\( \sim 160 \) Myr) and bright clusters whose upper MS and MSTOs are prominently visible in their respective CMDs. For SL 551, it was difficult to visually fit a King profile to the RDP. We thus selected the cluster radius (\( r = 20'' \)) as the one at which the cluster features were found to be well-populated in the CMD. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field \( (E(C - T_1) = 0.18 \) mag). BRHT 38b is located towards the north-east direction of SL 551 with a separation of \( \sim 77'' \). For BRHT 38b we considered rectangular areas of different dimensions around an eye-estimated centre in the clumpy region, and the dimension for which the cluster features get well populated in the CMD was defined as the extent of the cluster (\( 27'' \times 32.''4 \)). Due to insufficient data coverage in the northern direction of BRHT 38b, the cluster CMD was cleaned using rectangular fields of the same area located in different parts of the observed field away from the cluster. The estimated reddening for this cluster is found to be similar to the reddening of the corresponding field \( (E(C - T_1) = 0.16 \) mag).
Figure 3.35: Double cluster candidate: SL 551. Panel description is the same as Figure 3.1, except that no King profile over-plot to RDP is shown.
Figure 3.36: Double cluster candidate: BRHT 38b. The top-right panel shows the CMD of stars within the estimated cluster size (black filled circles), while the bottom-left panel shows the CMD of the non-annular field (green filled circles) located away from the cluster. The top-left and bottom-right panel description is the same as Figure 3.1.
3.4 Discussion

We have presented a study of 33 unstudied/poorly studied clusters in the LMC, based on deep Washington photometry. The data is presented/analysed for the first time, with enough photometric depth to identify the turn-off of faint, poorly populated clusters. The data also cover substantial field regions around the clusters to effectively remove the field contamination even in regions with varying density and reddening. We were able to estimate the basic parameters for these 33 clusters, out of which 23 are identified as single clusters and 10 are found to be members of double clusters.

The single clusters are listed in Table 3.1, whereas the double clusters are listed in Table 3.2. In these tables we have presented the coordinates, R.A. (\(\alpha\)) and decl. (\(\delta\)), the centre of the cluster ((\(X_c, Y_c\)), to correlate with the finding chart), estimated cluster radius in arcseconds (\(r\)), reddening \(E(C - T_1)\), age in \(\log(t)\), earlier age estimate (Lit.\(^a\)) in \(\log(t)\), and cross IDs. In Table 3.2, the five double clusters are listed with members of each pair grouped together.

The 33 clusters presented in this chapter stand out either in terms of number density or features in the CMD, or both. There are clusters for which either the RDP did not show a strong peak (BSDL 631, H88-265, H88-269 and HS 247) or where we could not obtain an RDP (BSDL 268, NGC 1793 and SL 397), suggesting a poor density enhancement in the cluster region. This is likely to be due to saturation effects caused by the presence of bright stars near the cluster centres, resulting in missing stars and incompleteness in those regions. As our data could not confirm the density enhancements, we tried to identify the density enhancement using other optical data. The OGLE III is one of the complete and relatively deep surveys of the inner region of the LMC (\(4^\circ-5^\circ\)) with good spatial resolution. We extracted OGLE III fields corresponding to each of these clusters and created similar finding charts using V magnitudes. Although
Table 3.1: Estimated parameters for single clusters

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Name</th>
<th>ra (h m s)</th>
<th>dec (° m s)</th>
<th>r_E (arcmin)</th>
<th>log(t)</th>
<th>L_\text{tot} (L_\odot)</th>
<th>M_\text{tot} (M_\odot)</th>
<th>Notes</th>
</tr>
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<tr>
<td>BRHT45a</td>
<td>Cross ID</td>
<td>04 56 54</td>
<td>-68 00 08</td>
<td>1833, 3604</td>
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<td>8.10</td>
<td>(1)</td>
</tr>
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<td>HS72</td>
<td>KMHK326</td>
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<td>5421, 5679</td>
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<td>0.00</td>
<td>8.90</td>
<td></td>
</tr>
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<td></td>
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<td>-69 42 21</td>
<td>5040, 3290</td>
<td>15</td>
<td>0.00</td>
<td>8.35</td>
<td>(1)</td>
</tr>
<tr>
<td>HS116</td>
<td>KMHK286</td>
<td>05 06 34</td>
<td>-68 25 38</td>
<td>509, 3280</td>
<td>18</td>
<td>0.13</td>
<td>8.20 - 8.50</td>
<td></td>
</tr>
<tr>
<td>H88-33</td>
<td>OGLE109</td>
<td>05 06 41</td>
<td>-67 47 00</td>
<td>4791, 2141</td>
<td>24</td>
<td>0.06</td>
<td>9.00</td>
<td></td>
</tr>
<tr>
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<td></td>
<td>05 06 41</td>
<td>-68 25 38</td>
<td>509, 3280</td>
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<td>0.00</td>
<td>8.35</td>
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</tr>
<tr>
<td>H88-131</td>
<td>KMHK544</td>
<td>05 18 05</td>
<td>-69 10 18</td>
<td>1521, 3570</td>
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<td>0.10</td>
<td>8.30</td>
<td>(2)</td>
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<td>H88-265</td>
<td>OGLE323</td>
<td>05 18 41</td>
<td>-69 04 46</td>
<td>2760, 4314</td>
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<td>0.10</td>
<td>8.90</td>
<td>(2)</td>
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<td>OGLE337</td>
<td>05 41 58</td>
<td>-69 02 51</td>
<td>5595, 2411</td>
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<td>(1)</td>
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<tr>
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<td>KMHK1248</td>
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<td>-69 20 00</td>
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</tr>
<tr>
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<td>KMHK1239</td>
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<td>-68 55 02</td>
<td>4874, 8051</td>
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<td>0.25</td>
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<td>(3)</td>
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<td>-69 11 06</td>
<td>3764, 1829</td>
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<td>0.45</td>
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<td>(3)</td>
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<td>0.34</td>
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<tr>
<td>HS412</td>
<td>KMHK1347</td>
<td>05 45 56</td>
<td>-69 16 19</td>
<td>2546, 7088</td>
<td>25</td>
<td>0.34</td>
<td>8.10</td>
<td>(1)</td>
</tr>
<tr>
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<td>05 45 56</td>
<td>-69 16 19</td>
<td>2546, 7088</td>
<td>25</td>
<td>0.34</td>
<td>8.10</td>
<td>(1)</td>
</tr>
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<td>KMHK95</td>
<td></td>
<td>04 47 26</td>
<td>-67 39 35</td>
<td>809, 1705</td>
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<td>8.55</td>
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<td>05 26 12</td>
<td>-70 58 53</td>
<td>486, 3558</td>
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<td>-67 52 44</td>
<td>7467, 582</td>
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<td>0.10</td>
<td>8.30</td>
<td>(1)</td>
</tr>
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<td>-66 54 41</td>
<td>470, 7304</td>
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<td>-67 39 35</td>
<td>809, 1705</td>
<td>21</td>
<td>0.08</td>
<td>8.55</td>
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</tr>
<tr>
<td>NGC1793</td>
<td>SL163,</td>
<td>04 59 38</td>
<td>-69 33 27</td>
<td>7068, 7815</td>
<td>25</td>
<td>0.21</td>
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<td>SL397</td>
<td>ESO56SC43,</td>
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<td>-68 54 15</td>
<td>5076, 6175</td>
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<td>SL579</td>
<td>KMHK1085</td>
<td>05 34 13</td>
<td>-67 51 23</td>
<td>7723, 5989</td>
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<td>0.13</td>
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<td>(1)</td>
</tr>
<tr>
<td>KMHK975</td>
<td></td>
<td>05 29 59</td>
<td>-67 52 44</td>
<td>7467, 582</td>
<td>21</td>
<td>0.10</td>
<td>8.30</td>
<td>(1)</td>
</tr>
</tbody>
</table>

Notes:
- (1) = Reference 1
- (2) = Reference 2
- (3) = Reference 3

Please refer to the text for column descriptions and notes at the bottom of Table 3.2 for further details.
### Table 3.2: Estimated parameters for double clusters

<table>
<thead>
<tr>
<th>Cluster name</th>
<th>α (h m s)</th>
<th>δ (° ' '')</th>
<th>(Xc, Yc) (pixels)</th>
<th>r (&quot;)</th>
<th>E(C − T1) (mag)</th>
<th>log(t)</th>
<th>Lit. a</th>
<th>Cross ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSDL341</td>
<td>04 58 15</td>
<td>-68 02 57</td>
<td>(1219, 5349)</td>
<td>24</td>
<td>0.17</td>
<td>8.45</td>
<td>7.64 (3)</td>
<td>KMHK365</td>
</tr>
<tr>
<td>H88-52</td>
<td>04 58 10</td>
<td>-68 03 37</td>
<td>(1031, 5229)</td>
<td>27</td>
<td>0.08</td>
<td>9.05</td>
<td>8.73 (3)</td>
<td></td>
</tr>
<tr>
<td>HS154</td>
<td>05 10 56</td>
<td>-67 37 36</td>
<td>(5716, 6660)</td>
<td>24</td>
<td>0.13</td>
<td>8.65</td>
<td>8.70 (2)</td>
<td>H88-189, KMHK625, OGLE194</td>
</tr>
<tr>
<td>HS156</td>
<td>05 11 11</td>
<td>-67 37 37</td>
<td>(5727, 6961)</td>
<td>21</td>
<td>0.13</td>
<td>9.05</td>
<td></td>
<td>H88-190, KMHK632, OGLE199</td>
</tr>
<tr>
<td>KMHK979</td>
<td>05 29 39</td>
<td>-70 59 02</td>
<td>(387, 7390) *</td>
<td>20 **</td>
<td>0.17</td>
<td>7.90</td>
<td>7.30 (1)</td>
<td>GKK-O101</td>
</tr>
<tr>
<td>HS329</td>
<td>05 29 46</td>
<td>-71 00 02</td>
<td>(150, 7475) *</td>
<td>37.8×40.&quot;5</td>
<td>0.00</td>
<td>8.90-9.00</td>
<td>KMHK984</td>
<td></td>
</tr>
<tr>
<td>SL230</td>
<td>05 06 34</td>
<td>-68 21 47</td>
<td>(1380, 3281)*</td>
<td>25 **</td>
<td>0.16</td>
<td>7.90</td>
<td>7.40 (1)</td>
<td>BRHT29b, OGLE107</td>
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<tr>
<td>SL229</td>
<td>05 06 25</td>
<td>-68 22 30</td>
<td>(1230, 3088)*</td>
<td>21</td>
<td>0.12</td>
<td>8.50</td>
<td>8.35 (2)</td>
<td>BRHT29a, OGLE105</td>
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<tr>
<td>SL551</td>
<td>05 31 51</td>
<td>-67 59 28</td>
<td>(5956, 2989)</td>
<td>20 **</td>
<td>0.18</td>
<td>8.15</td>
<td>7.90 (1)</td>
<td>BRHT38a, KMHK1027, GKK-O202</td>
</tr>
<tr>
<td>BRHT38b</td>
<td>05 31 58</td>
<td>-67 58 18</td>
<td>(6200, 3140)*</td>
<td>27.7×32.&quot;4</td>
<td>0.16</td>
<td>8.25</td>
<td>8.00 (3)</td>
<td>KMHK1032</td>
</tr>
</tbody>
</table>

Note for Table 3.1 and 3.2: The * implies cases where we adopted either the central coordinates given by B08 or the eye-estimated centres from the densest visible cluster regions as the cluster centre. The ** are cases where either we could not over-plot King profiles to the RDPs or the RDPs could not be estimated. For these cases, the estimated radius is the one at which the cluster profile becomes prominent in the CMD. In cases where one could not define a circular area, the possible rectangular area of cluster is mentioned (dimension along X coordinate times that along Y coordinate). Lit. a: (1) Glatt, Grebel, and Koch (2010); (2) Pietrzynski and Udalski (2000); (3) Popescu, Hanson, and Elmegreen (2012).
the OGLE III data are helpful for young clusters with bright stars, the OGLE III data are not of much help for relatively older clusters.

The age distribution of the 33 clusters is shown as a histogram in Figure 3.37. The age is considered on a logarithmic scale, and the bin size is chosen to be equal to the typical age error in this study (i.e. $\Delta \log(t) = \pm 0.10$). For H88-33 and HS 329 (where we could only find out a range in age), their mean age is considered in the histogram. It is clearly seen that approximately 50% of the clusters are in the age range $\log(t) = 8.0-8.5$ (i.e. $\sim 100-300$ Myr). The rest of them are either younger or older. BSDL 268, KMHK 979 and SL 230 lie at the youngest end ($<100$ Myr) of the age distribution. These clusters could be younger than their estimated ages, as some upper MS or MSTO stars are missing from the centre of the cluster regions due to saturation effects. The clusters H88-52, HS 156, H88-131, and HS 131 are aged around 1 Gyr and lie at the oldest age end

Figure 3.37: Age distribution of 33 clusters.
3.4 Discussion

Figure 3.38: Correlation between derived and published ages by G10, PU00, and P12 for 23 out of 33 clusters. For values in G10 we have used the upper limit of the errors. For values of P12 we have used the mean of the upper and lower limit of the errors. The dashed line corresponds to the one-to-one relation.

The ages of 23 clusters are compared with the results of PU00, G10 and P12 in Figure 3.38. PU00 and G10 used CMDs to estimate ages based on the OGLE II and the MCPS data respectively. The limiting magnitude of their data did not allow them to detect older clusters and constrained them only to younger clusters. P12 used integrated photometry to estimate ages of the LMC clusters mentioned in Hunter et al. (2003). Out of 33 clusters, 13 clusters are in common with G10, whereas 6 clusters are in common with PU00. A couple of clusters in our sample (BSDL 631 and SL 230) have been studied by both G10 and PU00. For BSDL 631, PU00 estimated an age of log(t)<6.70 (with no error men-
tioned) and G10 as log(t)=7.50 (0.30 ≤ error < 0.50). In the case of SL 230, the age estimations by PU00 (log(t)=7.30±0.05) and G10 (log(t)=7.40, with error<0.30) agree very well. For both these clusters we considered the results by G10 for comparison, as it is more recent and the errors are appropriate for such poor clusters. The figure shows that the G10 clusters are primarily younger than log(t) ~ 8.50. P12 used integrated photometry to obtain the ages of LMC star clusters, and 16 out of our 33 true clusters are in common with their study. Out of these 16 clusters, G10 has mentioned ages for 8 (BRHT 45a, BSDL 268, H88-320, KMHK 975, NGC 1793, SL 397, SL 579 and SL 551), whereas PU00 has mentioned ages for 2 (H88-265 and H88-269). Integrated light provides information about the combined stellar population along the line of sight. The clusters studied here are small angular-sized objects embedded within a relatively denser field. Use of integrated photometry to estimate ages for such cases can produce poor results due to field star contamination, stochastic effects, and relatively shallower photometric depth. Thus for comparison we have adopted the age estimates given by G10 and PU00 wherever available, as their results are more reliable. We considered only 6 clusters whose ages are given by integrated photometry and find mention only in P12. The comparison suggests that the present study estimates relatively older ages for clusters younger than log(t) ~ 7.50. In the case of young clusters, there is a possibility that our data has missed out brighter stars and this might cause the above anomaly. The ages of older clusters are comparable. When we compared our age estimates with those of P12 for 16 clusters, we found that most of the common clusters are younger than log(t) = 8.00. P12 estimated relatively younger ages compared to our estimates for these clusters. We have only a few older clusters, and we find that P12 estimated significantly younger ages for these clusters.

As mentioned in Chapter 2, we have the data for 45 cluster candidates in the LMC from CTIO, out of which 33 have been presented in this chapter. The star clusters studied in this chapter are genuine clus-
ters as they have significant density enhancements in the spatial plots, as well as prominent cluster features seen in the CMDs. However, they are sparse compared to the rich clusters that have been extensively studied in the LMC. Thus, with our deep photometric data, we have been able to identify these 33 clusters to be genuine, as well as estimate their parameters successfully. The rest of the 12 cases, out of the sample of 45, have been previously mentioned as clusters by B08. However, we found that these 12 cases have poor (suspicious or missing) density enhancements with respect to their corresponding fields, and also the cluster features are either poor (only a few stars in their upper MS and MSTO) or are suspicious/missing. It will be interesting to find out in detail if it is possible to categorize such objects. If at all they are clusters, they will add to the list of LMC clusters with well-estimated parameters. In case they are not clusters, it will be useful to separate them out from the list of genuine cluster candidates in the LMC. We present a study of these 12 cases in the next chapter (Chapter 4). We will discuss the intricacies of the 33 clusters studied in this chapter combined with the 12 cases, to understand their importance in the LMC.

3.5 Summary

Below, we summarize the main results presented in this chapter.

- The study was aimed to enlarge the number of well-studied clusters in the LMC and to estimate their fundamental parameters.

- It is for the first time that the 33 clusters (studied in this chapter), have been presented/analysed using the Washington photometric system.

- All the 33 clusters are genuine cluster candidates, and with the quality of our data we were able to successfully estimate their parameters. Out of 33, 23 are single clusters (Section 3.3.1) and 10
Deep Washington photometry of star clusters in the Large Magellanic Cloud

are members of pairs (Section 3.3.2).

• The age distribution of the 33 clusters shows that about 50% fall within the age range 100-300 Myr, whereas some are older or younger. The estimated ages are compared with the previous estimations in their respective tables (Table 3.1 and 3.2). The age comparison shows some agreement with our results, with possible deviations at the young end due to missing saturated stars.
Chapter 4

Deep Washington photometry of possible clusters/asterisms in the Large Magellanic Cloud

4.1 Introduction

In Chapter 3, we explained the importance of enlarging the number of genuine star clusters in the LMC with well-estimated fundamental parameters. A study of 33 out of the 45 clusters imaged from CTIO was presented in the previous chapter. These were genuine cluster candidates and we could efficiently estimate their parameters. The rest of the 12 cases have poor (suspicious or missing) density enhancements or cluster features. These 12 cases have been previously mentioned by B08 as clusters.

Piatti (2014) worked towards disentangling the physical reality of 90 small-angular sized clusters projected towards the inner disc of the LMC. The author found that 61 out of 90 resulted to be genuine physical systems, whereas the remaining ones were classified as possible non-clusters.

The work presented in this chapter is a part of the paper published as: Choudhury, S., Subramaniam, A., & Piatti, A.E., 2015, AJ, 149, 52.
since either their CMDs and/or the distribution of stars in the respective fields do not resemble those of stellar aggregates. Also, the author statistically showed that $\sim 13 \pm 6\%$ of the catalogued clusters distributed within the inner disc (distance from the LMC $\leq 4^\circ$) could be possible non-clusters, independent of their deprojected distances. We understand that there can be clusters listed by B08 which might not be so at all. Thus, it will be a useful task to refine out possible non-clusters from the list of genuine cluster candidates in the LMC. In this chapter we carry out an analysis to understand the physical reality of the above mentioned 12 cases in our sample and make an attempt to categorize them. Combining these with the 33 clusters studied in previous chapter, we plan to increase our understanding about inconspicuous star clusters in the LMC.

In Section 4.2, we describe the data and analysis techniques used in this study. We state our results in Section 4.3 and discuss them in Section 4.4, while a summary is presented in Section 4.5.

4.2 Data and Analysis

The deep Washington system photometric data for the 12 clusters have been obtained from CTIO. The acquisition and reduction of the data is described in Section 2.2 of Chapter 2. As mentioned there, the data for each cluster consist of a running number per star, the $X$ and $Y$ coordinates (in pixels), the measured $T_1$ magnitudes and $C - T_1$ and $T_1 - T_2$ colours, the observational errors $\sigma(T_1)$, $\sigma(C - T_1)$ and $\sigma(T_1 - T_2)$. We carry out similar steps as described in Section 3.2 to estimate cluster parameters (radius, reddening, and age). The following section describes the results of our analysis.
4.3 Results

We have categorized the 12 clusters studied in this chapter as possible clusters/asterisms. They fall into this group mainly due to the inability of the present study to identify or detect any of the cluster characteristics for stars in the cluster region. This group has two types of clusters: one type could be clusters, but we could not estimate their parameters reliably, whereas the others could not even be detected or recognized reliably as clusters, which we call asterisms. We define possible cluster candidates as those with the following properties: (1) they have a marginal spatial density enhancement with respect to the field; (2) the cluster features in the CMD are very poorly defined, with only a few stars in their upper MS and MSTO; and (3) there is an identifiable difference in the evolutionary features of the CMD for the cluster and field regions. The first two properties make it difficult to clearly estimate the cluster parameters, such as radius, age and reddening, whereas the third one suggests that there may be a cluster present in the location. Asterisms are those objects with marginal or no spatial apparent density enhancement with respect to the field; the cluster features in the CMD were either suspicious or completely missing, and the CMD of the cluster and the field region appear very similar. As there is a very thin dividing line between the two types, we have put them as one group.

A detailed discussion of individual objects and their corresponding plots (similar to that of Figure 3.1, unless stated otherwise) is presented below. We provide a limit on the possible spatial extent and age of these objects, if these objects are genuine clusters at all. Given the very sparse nature of the objects under this category, the age uncertainty could be larger ($\Delta\log(t) \sim 0.20$). To avoid clutter in the CMD, we have only shown isochrones of age $\pm 0.10$ with respect to the best visually fitted isochrone. We also attempted to use OGLE III images/photometry for verification, but these objects are too poor to confirm them as clusters. As our data
Deep Washington photometry of possible clusters/asterisms in the Large Magellanic Cloud is much deeper when compared to OGLE III and other survey data, the present data should have detected the presence of such poor and faint clusters. The OGLE III spatial plots (with point size proportional to the V magnitude) were extracted and created in a similar way as described in Section 3.3.1 (for clusters with weak/no RDP). In the OGLE III spatial plots presented for a few cases, x and y denote the Cartesian coordinate system (units in arcminutes), with north on top and east to the left.

1. BSDL 677 (Figure 4.1): The centre of the cluster field (as mentioned in the B08 catalogue) is adopted for analysis. The estimated RDP shows a feeble density enhancement within a radius of 21″. The CMD of stars within this radius seems to exhibit a poor upper MS (brighter than 19.0 mag and bluer than 0.2 mag) which may belong to the cluster. The upper MS feature becomes unclear after field star subtraction, and visual fitting of isochrones to these few bright stars suggests an age of ~ 180 Myr. The estimated reddening for BSDL 677 was found to be similar to the reddening of the corresponding field ($E(C-T_1) = 0.08$ mag). Based on such a feeble density distribution and unclear upper MS, we conclude that BSDL 677 is either a very poor cluster or an asterism.

2. H88-235 (Figure 4.2): In the spatial plot, no clear density enhancement is observed near the expected centre of the cluster. We estimated the RDP, which supports the same, and shows only a very poor density enhancement within 15″. A CMD within this radius shows a few upper MS stars brighter than 20.0 mag and bluer than 0.6 mag which may belong to the cluster. We also find a good number of such stars distributed in the field, suggesting that the field and the cluster have similar MS. Hence, the field star subtraction renders a very poor cluster MS in the CMD. The estimated reddening for H88-235 is found to be similar to the reddening of the corresponding field ($E(C-T_1) = 0.12$ mag). Visual fitting of isochrones to the poor
Figure 4.1: Possible cluster/Asterism: BSDL 677. Panel description is the same as Figure 3.1.
Deep Washington photometry of possible clusters/asterisms in the Large Magellanic Cloud

Figure 4.2: Possible cluster/Asterism: H88-235. Panel description is the same as Figure 3.1.

upper MS suggests an age of $\sim 560$ Myr ($\log(t)=8.75\pm0.20$). Previous study by P12 mentions an age of $\sim 350$ Myr ($\log(t)=8.55^{+0.02}_{-0.08}$) for this cluster, which moderately agrees with our estimation within the errors. With an almost negligible density enhancement, poor cluster features, and similar SFH as the field, H88-235 is likely to be an asterism.

3. H88-244 (Figure 4.3): The spatial plot of H88-244 looks almost homogeneous, with no significant density enhancement near the expected cluster centre. The centre of the cluster field (as mentioned in the B08 catalogue) is chosen as the cluster centre, and
the CMD extracted within the estimated cluster radius (25") seems to show a very poor upper MS (brighter than 19.0 mag and bluer than 0.4 mag), which may belong to the cluster. However, the spatial distribution of the bright upper MS stars does not show any significant density enhancement at the location of the cluster and looks almost homogeneous. The feeble cluster features, a similarity between field and cluster CMDs, as well as a large amount of differential reddening, makes it inconvenient to efficiently identify the presence of the cluster. The estimated reddening for this cluster (0.25 mag) is much higher than the reddening of the corresponding field (0.10 mag). If a cluster exists at all, it is a small, poor, and young (∼ 200 Myr, i.e. log(t)=8.30±0.20) one. The previous study by PU00 mentioned an age of ∼125 Myr (log(t)=8.10±0.10), which agrees with our estimate within the errors.

4. H88-288 (Figure 4.4) and H88-289 (Figure 4.5): H88-289 is located towards the north of H88-288 at a distance of about 74". They seem to show poor density enhancements around their respective cluster centres and exhibit poor upper MS (brighter than 19.0 mag and bluer than 0.4 mag) within their estimated radii. Their size and age (∼ 250 Myr i.e. log(t)=8.40±0.20) are almost similar. However, H88-289 could be younger than our estimated age, as some bright MSTO/upper MS stars seem to be missing from the central region due to saturation effects. For both H88-288 and H88-289, the estimated reddening was found to be similar to the reddening of the corresponding field (E(C-T$_{1}$) = 0.25 mag). Using integrated photometry, P12 estimated the ages for H88-288 and H88-289 to be log(t)=8.04±0.04 and log(t)=7.80±0.43, respectively, which is younger relative to our estimate. We realized that the field region for this pair suffers from variable density and reddening. Hence decontaminating the cluster CMD from field stars was found to be difficult for this pair of clusters. We conclude that with such a poor density
Figure 4.3: Possible cluster/Asterism: H88-244. Panel description is the same as Figure 3.1, except that no King profile fit to the RDP is shown.
Figure 4.4: Possible cluster/Asterism: H88-288. Panel description is the same as Figure 3.1.
Deep Washington photometry of possible clusters/asterisms in the Large Magellanic Cloud

Figure 4.5: Possible cluster/Asterism: H88-289. The top-right panel shows the CMD of stars within the estimated cluster radius (black filled circles), while the bottom-left panel shows the CMD of the annular field (green filled circles). The top-left and bottom-right panel descriptions are the same as Figure 3.1.
enhancement and cluster features, along with issues related to variations in density and reddening within the field region, it is difficult to categorize H88-288 and H88-289 as genuine clusters.

5. H88-307 (Figure 4.6): It is difficult to observe any prominent dense clump of stars within the central region. The cluster and the field regions show similar features in the CMD, thus posing difficulty to efficiently identify the presence of a cluster and estimate its corresponding parameters. The centre of the cluster field (as mentioned in the B08 catalogue) is chosen as the cluster centre. A comparison of the cluster and field CMDs suggests a very poor upper MS (brighter than 19.0 mag and bluer than 0.4 mag). The cleaned CMD has very few MS stars. The estimated reddening for H88-307 is found to be similar to the reddening of the corresponding field ($E(C-T_1) = 0.30$ mag). If a cluster is present at all, it could be poor and young ($\sim 180$ Myr), located within an area of $54'' \times 54''$ around the cluster centre.

DMG02 mention the presence of two more clusters within the same field. These are BSDL 2768 ($5^h 40^m 39^s, -69^o 15' 29''$) and H88-306 ($5^h 40^m 24^s, -69^o 15' 10''$). B08 lists BSDL 2768 as an association. G10 estimated its age as $\sim 60$ Myr ($\log(t)=7.80$, with $0.30 \leq$ error $<0.50$). For H88-306, Piatti (2014) estimated an age of $\sim 125$ Myr ($\log(t)=8.10\pm0.10$). The coordinates of both BSDL 2768 and H88-306 suggest that they could lie within the estimated area for the central cluster H88-307. However, given the broad and marginally dense stellar distribution, coupled with a similar SFH with respect to the field, we are not able to detect, identify, and estimate the parameters for each of these clusters individually.

6. H88-316 (Figure 4.7): The spatial plot indicates an asymmetric distribution of bright stars around the expected cluster centre. The cluster and the field regions show similar features in the CMD, thus
Figure 4.6: Possible cluster/Asterism: H88-307. The top-right panel shows the CMD of stars within the estimated cluster size (black filled circles), while the bottom-left panel shows the CMD of the annular field (green filled circles). The top-left and bottom-right panel descriptions are the same as Figure 3.1.
4.3 Results

Posing difficulty to efficiently identify the presence of a cluster and estimate its corresponding parameters. The centre of the cluster field (as mentioned in the B08 catalogue) is adopted for this analysis. By comparing the CMDs of the central region with field regions at different annular radii, we conclude that there could be a cluster located within an area of 54″×54″ around the cluster centre. The estimated reddening for H88-316 is found to be similar to the reddening of the corresponding field \((E(C-T_1) = 0.30\) mag). The poor MS feature (brighter than 19.0 mag and bluer than 0.4 mag) identified in the central region is found to be \(\sim 180\) Myr \((\log(t)=8.25\pm0.20)\), suggesting that if a cluster is present at all, it is a poor and young one, located within the mentioned area. The age for this cluster has been previously estimated by G10 as \(\sim 100\) Myr \((\log(t)=8.00,\) with \(0.30\leq \text{error} <0.50)\), whereas P12 estimated the cluster to be much younger, \(\sim 18\) Myr \((\log(t)=7.27^{+0.30}_{-0.17})\). Our age estimation agrees well with that of G10, within the errors.

7. KMHK 378 (Figure 4.8): The spatial distribution shows a small and feebly enhanced stellar distribution near the central region. The CMD extracted within the estimated cluster radius \(15''\) shows a poor upper MS (brighter than 20.0 mag and bluer than 0.4 mag), which could belong to the cluster. The MS feature does not get prominent for larger radii and is retained even after field star subtraction. The bright upper MS stars are found to be compactly distributed around the cluster centre. Thus there is a possibility that KMHK 378 is a small, poor, and young \(\sim 280\) Myr i.e. \(\log(t)=8.45 \pm 0.20)\) cluster candidate. The estimated reddening for KMHK 378 was found to be similar to the reddening of the corresponding field \((E(C-T_1) = 0.14\) mag). According to DMG02, another cluster, KMHK 372 is present in the same field, with coordinates \((4^h 58^m 07^s, -69^\circ 48' 16'')\), whereas B08 lists it as an association. The age estimated by G10 for KMHK 378 is \(\sim 25\) Myr.
Figure 4.7: Possible cluster/Asterism: H88-316. The top-right panel shows the CMD of stars within the estimated cluster size (black filled circles), while the bottom left-panel shows the CMD of the annular field (green filled circles). The top-left and bottom-right panel descriptions are the same as Figure 3.1.
Figure 4.8: Possible cluster/Asterism: KMHK-378. Panel description is the same as Figure 3.1.

(log(t)=7.40, error ≤0.30) and is very similar to that estimated by P12, log(t)=7.37^{+0.12}_{-0.14}. For KMHK 372, G10 estimated an age of ~250 Myr (log(t)=8.40, with 0.30≤ error <0.50). Given its coordinate, KMHK 372 could lie within the estimated radius of KMHK 378. However, looking at the spatial plot, it is difficult to identify them individually considering the density distribution near the centre is very poor. It is probable that we are estimating the parameters for KMHK 378 and KMHK 372 put together.

8. KMHK505 (Figure 4.9): A marginal density enhancement around the cluster centre is observed in the spatial plot, which corresponds
to a peak in the RDP within a radius of 18\textquotedbl. The cluster feature extracted within this estimated radius shows a poor and broad upper MS (brighter than 20.0 mag and bluer than 1.0 mag). The feature stays even after field star subtraction. A spatial distribution of these upper MS stars shows a density enhancement at the location of the cluster. The corresponding OGLE III field does not show any significant density enhancement within the cluster region. The reason could be the age of this cluster and the absence of bright giants. Based on our analysis we infer that KMHK 505 could be a poor, small, and young (~ 560 Myr) possible cluster candidate. The estimated reddening for KMHK 505 was found to be similar to the reddening of the corresponding field ($E(C-T_1) = 0.11$ mag).

9. OGLE 298 (Figure 4.10): The spatial plot of OGLE 298 appears very homogeneous, without any significant density enhancement near the expected cluster centre. The centre of the cluster field (as mentioned in the B08 catalogue) is adopted, and the CMD extracted within the estimated cluster radius (15\textquotedbl) seems to show a very poor upper MS (brighter than 19.0 mag and bluer than 0.4 mag), which may belong to the cluster. However, the spatial distribution of the bright upper MS stars does not show any significant density enhancement at the location of the cluster and looks almost homogeneous. The feeble cluster feature, a similarity between field and cluster CMDs, as well as a large amount of differential reddening within the OGLE 298 cluster field makes it inconvenient to efficiently identify the presence of a cluster. The estimated reddening for this cluster is about 0.25 mag, much higher than the reddening of the corresponding field which is 0.10 mag. We conclude that if a cluster exists at all, it is a very small, poor, and young (~ 200 Myr i.e. log(t)=8.30±0.20) one. The cluster has been previously studied by PU00, who claimed a much younger age (~ 20 Myr i.e. log(t)=7.30±0.20). We detect only one bright MS
4.3 Results

Figure 4.9: Possible cluster/Asterism: KMHK-505. Panel description is the same as Figure 3.1.
Figure 4.10: Possible cluster/Asterism: OGLE 298. Panel description is the same as Figure 3.1.
star and could possibly derive a younger age if we consider it as a cluster member.

10. H88-279 (Figure 4.11): The spatial plot of H88-279 appears quite homogeneous, with no significant density enhancement near the expected centre of the cluster. We considered an area of $54'' \times 54''$ around the central region of the observed field. A comparison of the CMDs of the suspected cluster region and different field regions helped in identifying a poor cluster MS, brighter than 19.0 mag and bluer than 0.2 mag. For cluster areas greater than the above value, there is no change in the observed cluster MS. In order to
locate the cluster centre, we examined the spatial distribution of the bright upper MS stars and found a small compact distribution near the suspected cluster location. The cluster MS in the CMD was found to be well-populated when including stars within 20" radius. At larger radii, there is not much change observed in the extracted cluster feature. In order to cross check, we extracted the OGLE III data corresponding to this cluster, with similar area as our data. This schematic chart shows a feeble density enhancement due to bright stars around the cluster centre (Figure 4.13). We thus suggest that H88-279 is possibly a small, poor, and young (~ 125 Myr, i.e. log(t)=8.10±0.20) cluster candidate. An earlier study by PU00 using OGLE II data derived an age of ~ 100 Myr (log(t)=8.00±0.10), whereas P12 estimated a relatively younger age of ~ 74 Myr (log(t)=7.87+0.06−0.04). Our estimation is in good agreement with PU00 and in moderate agreement with P12, within the errors.

The estimated reddening for H88-279 was found to be similar to the reddening of the corresponding field (E(C − T1) = 0.16 mag).

11. SL 269 (Figure 4.12): The central region of the cluster does not look compact but instead dispersed, resulting in an uneven RDP. A clear upper MS (brighter than 20.0 mag and bluer than 0.2 mag) is observed when the CMDs of the cluster and the field region are compared. The cluster radius is selected to be the one (25") at which the upper MS becomes well-populated. It is observed that the cluster features stays and appears prominent even after field star subtraction. The spatial distribution of these upper MS stars shows a density enhancement at the location of the cluster. The cluster is a young one, and the corresponding OGLE III field (Figure 4.14) shows a marginal density enhancement within the cluster region. The estimated reddening for SL 269 is found to be similar to the reddening of the corresponding field (E(C − T1) = 0.11 mag). We conclude that SL 269 may be a poor, small, and young (~ 180 Myr)
4.3 Results

Figure 4.12: Possible cluster/Asterism: SL 269. Panel description is the same as Figure 3.1, except that no King profile fit to the RDP is shown.

possible cluster candidate.
Figure 4.13: The OGLE III schematic chart for H88-279. The red dashed circle corresponds to the derived size using our data.

Figure 4.14: The OGLE III schematic chart for SL 269. The red dashed circle correspond to the derived size using our data.
4.4 Discussion

We have presented a study of 12 poor clusters in the LMC based on deep Washington photometry data, which are analysed for the first time. Due to the difficulty in confirming the presence of an actual cluster in those fields, and getting a satisfactory estimation of their cluster parameters, they are categorized as possible clusters/asterisms. We have analysed 45 clusters in total, including 33 true (genuine) clusters mentioned in Chapter 3, and 12 cases of possible clusters/asterisms analysed in this chapter. The coverage as well as the depth of the data has helped in the identification of possible asterisms and cluster candidates from the sample of 45 clusters.

We have listed out the parameters for the possible clusters/asterisms in Table 4.1, if at all they can be considered as clusters. In the table, we have presented the coordinates, R.A. (α) and decl. (δ), the centre of the cluster ((X_c, Y_c), to correlate with the finding chart), estimated cluster radius in arcseconds (r), reddening $E(C - T_1)$, age in log(t), earlier age estimate (Lit.a) in log(t), and cross IDs. The column descriptions are same as Table 3.1 and 3.2, for single and double clusters respectively. 8 out of 12 possible clusters/asterisms have been previously studied by either PU00, G10 or by P12.

The spatial distribution of all the 45 clusters studied is shown in Figure 4.15. The 23 true single clusters are represented by colour-coded filled circles according to their ages, whereas the 5 true double clusters and the 12 cases of possible clusters/asterisms are depicted by black asterisks and black open squares, respectively. The studied clusters are seen to be located mostly in the inner LMC, with a few of them located toward the north-west side. The figure also shows the location of the bar and 30 Dor. For clusters lying in and near such crowded regions, there could be issues due to differential reddening, as well as varying field density. While performing the field star removal from the CMD, we have taken
Deep Washington photometry of possible clusters/asterisms in the Large Magellanic Cloud

Table 4.1: Estimated parameters for possible clusters and asterisms

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Note for Table 4.1: The implies cases where we adopted either the central coordinates given by B08 or the eye-estimated centres from the densest visible cluster regions as the cluster centre. The are cases where either we could not over-plot King profile to the RDP or the RDP could not be estimated. For these cases, the estimated radius is the estimated radius from the densest visible cluster region as the cluster centre. The are cases where either we could not define a circular area, the possible rectangular area of cluster is mentioned (dimension along X coordinate times that along Y coordinate). Lit.: (1) Glatt, Grebel, and Koch (2010); (2) Pietrzynski and Udalski (2000); (3) Popescu, Hanson, and Elmegreen (2012).
4.4 Discussion

Figure 4.15: Spatial distribution of 45 studied clusters in the LMC: colour-coded circles denote the 23 true single clusters. Black asterisks denote the location of 5 pairs of double clusters, and the black open boxes denote the location of 12 possible clusters/asterisms. The locations of 30 Doradus (black diamond) and the LMC bar (parallel lines) are also shown.

care to choose the field regions carefully, so as to minimize the effects of variation in density and reddening. This helped in extracting cluster features from the cluster CMD and deriving cluster parameters efficiently. The RDP method has been used to estimate the radius of most of the clusters. In the case of a few clusters, either the RDP did not show a strong peak, or we were unable to derive the RDP due to incompleteness of bright stars near the cluster centre. We thus chose radii as the ones at which the cluster features prominently show up in the CMD. We have compared the present estimation of radii for 33 true clusters with their previous estimations catalogued by B08, and we found the estimation to be comparable. B08 gives the dimension of the major and minor axis for
these objects, from which we calculated their mean radius. It is seen that the clusters analysed are typically small angular-sized objects with radii in the range of $10''$–$40''$ ($\sim 2$–10 pc). We also find similarity in size for objects under the category of single clusters and double clusters. All the clusters studied here are small in size and are similar to the sizes of open clusters in our Galaxy. Thus, this study helps to derive the parameters of open cluster like objects in the LMC.

As mentioned earlier, the reddening values for the clusters were adopted from the reddening map of the field regions (Subramanian and Subramaniam, 2010). We find that the average separation of studied clusters from the nearest field region is about 6 arcmin. Although this adopted reddening was found satisfactory for most of the clusters, for a few cases the isochrones had to be further reddened/dereddened with respect to the field-reddening values in order to get a proper visual fit of the isochrone. Figure 4.16 shows a comparison between the reddening values of 33 true clusters and their corresponding fields. The errors in the estimation of the field reddening, taken from Subramanian and Subramaniam (2010), and the error in the reddening of the cluster (photometric error and field reddening error) are shown in the X and Y axes, respectively. The range of reddening values for the clusters studied is about 0.05–0.45 mag. The cluster reddening is found to be very similar to the field reddening, except for 6 clusters (marked by open circles). Out of these 6 cases, 4 clusters have zero reddening (BSDL 77, BSDL 631, LW 54 and HS 329), and we have not indicated any error bar for them in the figure. H88-52 has less reddening compared to the corresponding field. The cluster HS 390 has the largest value of reddening in our sample and is found to be located near the 30 Dor region. The observed difference in the reddening for these 6 clusters may be due to the spatial variation in reddening and/or due to projection effects. The shift in the reddening values for these clusters with respect to the field may cause an additional error in the age estimation. We expect that the error in the age estimation for these clusters
Figure 4.16: Correlation between estimated cluster and field-reddening values for 33 true clusters. The dashed line corresponds to the one-to-one relation. The deviations are marked with open circles.

can be up to $\Delta \log(t) \sim 0.20$.

We studied the parameters of 5 double clusters listed in Table 3.2 of Chapter 3. A large number of double clusters in the LMC are identified by DMG02. These 5 pairs are also found to be mentioned in their catalogue. The sizes of the double clusters are found to be similar to the single clusters. We expect the reddening and age to be similar among the cluster members for the double clusters to be a candidate for a binary pair. For two of the cluster pairs (BSDL 341 and H88-52; KMHK 979 and HS 329), we find that the estimated reddening differs significantly. These clusters also have a fairly large difference in age. The above two differences suggest that these clusters may be pairs because of projection. Two cluster pairs (HS 154 and HS 156; SL 230 and SL 229) have similar reddening, but their
ages are not similar, suggesting that they might not be physical pairs. The cluster pair SL 551 and BRHT 38b have comparable reddening and age, within errors. Thus, these two clusters may be a candidate for a binary pair.

The clusters studied by us are up to 1 Gyr in age, and most of them are poor and inconspicuous clusters. We have also suggested that some of the clusters could be asterisms and not true clusters. The estimates of the radial extent (2–10 pc) of these clusters suggest that they are similar to the open clusters in our Galaxy. We simulated CMDs of a few rich and young clusters from our sample using Marigo et al. (2008) isochrones. Assuming a Salpeter mass function and incorporating observational errors, we simulated CMDs for the mass range 10–0.5 \( M_\odot \). The total mass simulated is adjusted to create the same number of stars within 3 mag below the turn-off, as in the observed CMD, after incorporating Poisson errors. This is expected to reduce the effect of incompleteness of fainter stars in the CMD. The estimated masses were found to be up to 1000 \( M_\odot \) for rich clusters. This is also found to be comparable to the mass estimates of P12 for the same clusters. Adopting the masses of all common clusters from P12, the relatively rich clusters in our sample are up to 1000 \( M_\odot \), whereas the poor clusters are only a few 100 \( M_\odot \). Thus, the masses also suggest that these clusters are similar to the open clusters of our Galaxy. We also find that the mass limit at which the object is unable to be identified as a cluster is a few 100 \( M_\odot \). At this mass limit, the number of stars formed are unable to create either a notable density enhancement, an identifiable cluster sequence in the CMD, or both.

Baumgardt et al. (2013) have studied the star cluster formation history of the LMC, using some recent catalogues that include PU00, G10, and P12. Their Figure 3 shows a plot between the mass and age of all the clusters. The mass of the clusters ranges from a few hundred to a few thousand \( M_\odot \) and are within the age range 10 Myr to 1 Gyr. The figure shows that the number of clusters at the higher end of the mass
distribution is relatively greater compared to the lower end, where the contribution is primarily from G10. However, the age limit for G10 clusters is constrained only to $\leq 300$ Myrs. The estimated mass range of our studied sample contributes to the lower end of the cluster mass distribution and also contains clusters beyond the age limit of G10. As mentioned earlier, a significant fraction of our clusters lie within the age range of 100-300 Myr which corresponds to the recent star formation in the last 200 Myrs. This suggests that the LMC has produced very low mass clusters, along with the massive and rich clusters in the recent past. Thus, in the context of understanding the cluster mass function in the LMC, our study had added many clusters to the lower mass limit of the distribution. The poor clusters are also of interest to understand the survival time of these clusters in the LMC. Table 4.1 suggests that the possible clusters/asterisms are in the age range of $\log(t) = 8.10-8.80$, probably suggesting their survival time. This time scale is also similar to that in our Galaxy (a few hundred Myr; Bonatto et al. (2010)).

4.5 Summary

Below, we summarize the main results presented in this chapter.

- In this chapter, the 12 poor clusters have been studied using the Washington photometric system. These could only be categorized as possible cluster/asterisms, and we list their parameters if they are clusters at all.

- Combining the clusters presented in Chapter 3 and Chapter 4, we discuss the significance of our study in the context of cluster formation and dissipation in the LMC.

- The physical sizes (radii $\sim 2 - 10$ pc) and masses ($\sim$ few 100 – 1000 $M_\odot$) of the studied clusters are found to be similar to that of open clusters in the Milky Way. Our study adds to the lower end of
cluster mass distribution in the LMC. Thus the LMC, apart from hosting rich clusters, also contains such small, less massive open clusters, particularly in the 100–300 Myr range.

- The 12 poor cases in the category of possible clusters/asterisms are also worthy of attention, in the sense that they can throw light on the survival time of such objects in the LMC. We need deeper data using DECam or LSST to identify the true nature of these clusters and also to reliably estimate their parameters.
Chapter 5

Photometric metallicity map of the Large Magellanic Cloud using OGLE III data

5.1 Introduction

In this chapter, we study the chemical enrichment of the LMC by creating a photometric metallicity map. Metallicity has an impact on star formation as well as stellar evolution. It is important to obtain an estimate of the mean metallicity gradient of a galaxy as well as its variation as a function of radius. We have used the red giant branch stars within the LMC for this study.

The stars and gas in galactic disks have a mean metallicity which depends on the luminosity of the galaxy (e.g. Tremonti et al. 2004) and often shows a radial gradient. A rich literature now exists which confirms these radial abundance trends in spirals (e.g. Simpson et al. 1995; Afflerbach, Churchwell, and Werner 1997; Mollá, Hardy, and Beauchamp 1999; Kewley et al. 2010; Sánchez-Blázquez et al. 2011 ). Observations of

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nearby spiral galaxies show that the inner disks have higher metallicities than their associated outer disk regions; at the present day, typical gradients of $\sim -0.05$ dex kpc$^{-1}$ are encountered (Pilkington et al., 2012). The presence of a fairly tightly defined radial abundance gradient in the stars and in the gas in many disk galaxies suggests that the chemical evolution of the disk is determined mainly by local chemical evolution with limited radial exchange of evolution products (van der Kruit and Freeman, 2011). A study of a large sample of SDSS galaxies by Tremonti et al. (2004) demonstrates a tight correlation between the stellar mass and the gas-phase oxygen abundance extending over 3 orders of magnitude in stellar mass and a factor of 10 in oxygen abundance. Kirby et al. (2008) show that the relation between luminosity and metallicity continues down to the faintest known dwarf spheroidal galaxies. The recognition that metals are not distributed homogeneously throughout the disk of the Milky Way (Shaver et al., 1983) has proven to be fundamental in our efforts to understand the role of interactions, mergers, accretion, migration, and gas flows in shaping the formation and evolution of galaxies. The abundance gradient for relatively young stars in the disk of the MW is nicely delineated by Cepheids (Luck, Kovtyukh, and Andrievsky, 2006). The gradient is about $-0.06$ dex kpc$^{-1}$, in good agreement with the gas-phase gradient derived by Shaver et al. (1983). Cioni (2009) used the varying ratio of C and M-type Asymptotic Giant Branch stars in the LMC and M33 to evaluate their stellar abundance gradients, finding a radial gradient in both galaxies; the shallower gradient in the LMC is possibly attributable to the existence of its prominent central bar.

Bars are a very common feature in spiral galaxies. Analytical studies and numerical simulations have shown that the presence of a bar can greatly affect the evolution of the host galaxy. Analytical calculations (Lynden-Bell 1979; Athanassoula 2003) showed that the bar produces a gravitational torque that transports angular momentum outward and matter inward. The presence of a bar appears to flatten or even erase the
abundance gradient (Alloin et al., 1981), probably due to the non-circular
motions which the bar induces in the gas of the disk. This inflow of metal-
poor gas tends to flatten the metallicity gradient. The star formation rate
(SFR) in the central regions increases, either steadily or in the form of a
star burst. This will lead eventually to an increase in central metallicity.
We would therefore expect barred galaxies to have higher central SFR,
higher central metallicities, and possibly a flatter metallicity gradient,
depending at what stage of their evolution they are being observed. This
basic scenario is indeed supported by many observations (Pagel et al.
1979; Martin and Roy 1994). The off-centre bar of the LMC is a stellar
bar, but presently there is no activity as found in HI gas. Nevertheless,

There have been many previous efforts to study the chemical enrich-
ment history (CEH) of the LMC using star clusters as well as the field star
populations, using both spectroscopic and photometric techniques. We
know that star clusters in the LMC have proven to be an excellent tool
in understanding the cluster formation history, star formation history, as
well as the chemical, and dynamical evolution of the galaxy (Pietrzynski
and Udalski 2000; Glatt, Grebel, and Koch 2010; Baumgardt et al. 2013).
There are studies that estimated the age-metallicity relation (AMR) of
LMC using star clusters (Olszewski et al. 1991; Geisler et al. 1997; Bica
et al. 1998; Dirsch et al. 2000), directed towards understanding the CEH.
Olszewski et al. (1991) used Ca II triplet (CaT) spectroscopy for RGB stars, an important metallicity indicator, to estimate the abundance for $\sim 80$ star clusters. The metallicity distribution of their cluster sample showed that the mean $[\text{Fe/H}]$ values for all clusters in the inner (radius $< 5^\circ$) and outer (radius $> 5^\circ$) LMC are almost the same. This suggested the presence of a very shallow, if any, radial metallicity gradient in the LMC disk. Later on, Grocholski et al. (2006) used CaT spectroscopy to derive updated metallicities for 28 populous LMC star clusters with a good spatial coverage of the LMC. The improved sampling in terms of the number of stars per cluster and the calibration technique led to a more accurate estimation of $[\text{Fe/H}]$. According to these authors, there was hardly any evidence for metallicity gradient in the LMC cluster system. This was in sharp contrast to what was seen in our own galaxy, the MW (Friel et al., 2002), and M33 (Tiede, Sarajedini, and Barker, 2004).

The field star population of the LMC has also been used to understand the metallicity variation. Cole et al. (2005) estimated the $[\text{Fe/H}]$ of about $\sim 400$ red giant stars in an area of about 200 arcmin sq. around the central LMC, using CaT spectroscopy. Thus, Cole et al. (2005) were able to estimate the mean metallicity and the distribution only around this small region within the bar. They found a distribution peaked at $[\text{Fe/H}] \sim -0.4$ dex with a low metallicity tail reaching $[\text{Fe/H}] \sim -2.1$ dex. Carrera et al. (2008a) studied 4 fields (each of dimension 36 $\times$ 36 arcmin sq.) towards the north of LMC bar, at galactocentric distances of $\sim 3^\circ$, $5^\circ$, $6^\circ$, and $8^\circ$. For each field, the RGB stars were selected from the CMDs, and CaT spectroscopy was carried out. They found a nearly constant metallicity $[\text{Fe/H}] \sim -0.5$ dex out to a radius of $6^\circ$, with a suggestion of a decrease at larger radii, likely driven by a change in the mean magnitude of stars selected for analysis.

A distribution peaked at a slightly lower value ($[\text{Fe/H}] = -0.75$ dex, $\sigma[\text{Fe/H}] = 0.23$ dex) was found by Pompéia et al. (2008), for a region at 1.2 kpc from the centre. Lapenna et al. (2012) estimated a $[\text{Fe/H}] =$
5.1 Introduction

-0.48 dex with a smaller dispersion ($\sigma_{[\text{Fe/H}]} = 0.13$ dex), using 91 stars in the region surrounding NGC 1786, 2° north-west from the LMC centre. The results from the above studies are compared in Figure 2 of Lapenna et al. (2012). Olsen et al. (2011) found a metallicity distribution with a peak at $[\text{Fe/H}] = -0.45$ dex, a median of $[\text{Fe/H}] = -0.56\pm0.02$ dex, and a dispersion of 0.5 dex compared to a median error of 0.15 dex, using $\sim 1000$ LMC field stars. The work of Van der Swaelmen et al. (2013) was directed towards comparing the chemical history of the LMC with that of the MW, as well as disentangling the chemical evolution of the LMC bar and disk using high-dispersion spectroscopy. Van der Swaelmen et al. (2013) performed a detailed chemical analysis of a sample of 106 and 58 LMC field red giant stars, located in the bar and the disk of the LMC respectively. The authors found the bar to be chemically enriched (primarily with $\alpha$-elements) compared to the disk, which was possibly due to the formation of a new stellar population in the central part of the LMC.

Since one can resolve individual stars in the LMC, the stellar metallicity is generally estimated using spectra of individual stars. As the LMC presents a large area in the sky, the estimation of metallicity using spectroscopy of individual stars is a laborious and time-consuming process. One can also see that all the above spectroscopic studies of star clusters and stellar populations have been carried out only in small pockets of the LMC, and have small sample sizes. Also, the spatial variation of metallicity has been estimated using studies which do not cover a substantial area of the LMC. As a result, there has been little progress or consensus in understanding the effect of the bar on the LMC metallicity or the possibility of large-scale inhomogeneities due to interactions with the SMC or MW. These require a metallicity map of the LMC with good spatial resolution and coverage.

Cioni (2009) used a photometric technique to estimate the metallicity gradient using field AGB stars as tracers. They calculated the C/M
ratio, which is an indicator of metallicity. The AGB sample was selected from the previous work of Cioni and Habing (2003), and binned in area spatially. C- and M-type AGB stars were selected using CMDs built using the DENIS IJKs data. The C/M ratio was then calculated for each area bin, and converted to [Fe/H] using a calibration relation formulated using RGB stars. The plot of [Fe/H] against galactocentric distance out to about 8 kpc showed a small metallicity gradient with a high degree of scatter. Although these authors could cover a large area of LMC and estimate the metallicity gradient of the LMC, their indicators (AGB) and calibrators (RGB) were different, and the C/M ratio is potentially susceptible to age effects. Piatti and Geisler (2013) used Washington photometry of over 5 million field stars and estimated the mean metallicity, radial variation and age-metallicity relation for the LMC; they were able to explain the differences between their inner and outer disk as due to a consistent age-metallicity relation but with an increasing concentration of star formation towards the inner disk at young ages. However, their study avoided the densely concentrated regions of the central bar.

Studies using photometric data of giants can cover a sufficiently large area and estimate the metallicity variation, suggesting that it is an efficient technique which will cover the entire LMC. In this study we have created a metallicity map of the LMC using the optical photometric data of the OGLE III survey (Udalski et al., 2008a), one of the most recent, large area surveys of the LMC. Using the red giant stars, we estimated the average metallicity of the LMC and its radial variation. This is a first of its kind map of mean metallicity up to a radius of 4°-5°. The chapter is organised as follows: in Section 5.2 we describe the data (OGLE III) and the analysis. The OGLE III metallicity maps and results are presented in Section 5.3. Section 5.4 describes the error analysis corresponding to our estimations. The discussion related to our study is presented in Section 5.5. A summary of the study is presented in Section 5.6.
5.2 Data and Analysis

In this study, we have made use of the V and I band photometric data from the OGLE III survey. This survey covered 39.7 square degrees of the central LMC, and presented the mean, calibrated VI photometry of about 35 million stars. It covers the bar region as well as the eastern and western wing of the inner LMC till a radius of ~ 4° from the LMC centre. We divided the OGLE III data into 1854 regions, each of dimension (8.88 x 8.88) sq. arcmin in RA and Dec. This was done to ensure that each area bin has a well-populated RGB, in their corresponding V, (V−I) CMD. For our analysis we only considered stars with photometric error less than 0.15 mag in V and I. The details of the OGLE III survey have been discussed in Section 2.3.

The slope of the RGB in the CMD of a small region is used as an indicator of the mean metallicity therein. In a red giant of given mass, a higher mean metallicity tends to decrease the effective temperature both due to changes in the interior structure from the increasing mean molecular weight and in the atmosphere due to increasing line-blanketing opacity (Hayashi, Hōshi, and Sugimoto 1962; Demarque and Mengel 1973). Metal-rich RGB stars are therefore redder and fainter in the visible bandpasses than their metal-poor counterparts. The redder colour at a given absolute magnitude is easily observable in principle, but as a practical matter can be obscured by differential reddening. However, a region in a galaxy with metal-rich stars is also expected to have a shallower RGB slope when compared to a relatively metal-poor region; as a differential method this is less vulnerable to obscuration by variable dust reddening. The dependence of slope of the RGB on metallicity is well known (Da Costa and Armandroff, 1990; Kuchinski et al., 1995). In the case of field stars, the stellar population is heterogeneous with respect to age and metallicity. The RGB will consist of many populations, but the dominant population dictates the shape as well as the slope of the RGB. Thus, when
we estimate the RGB slope from the CMD of a field region, the slope will correspond to the metallicity as well as age of the most dominant RGB population of the region. Here we describe the steps carried out to identify the RGB consistently in all regions and estimate the RGB slope for the OGLE III data.

5.2.1 Estimation of RGB slope

Our aim is to identify the RGB of each region similarly across the LMC and estimate its slope by using a consistent and automated method. This involves robustly identifying the RGB in the CMD of each region, independent of the reddening, as the location of the RGB varies with reddening and extinction in each region. We also need to identify a feature that can be used to fix the location of the base of the RGB and trace it in the CMDs of all the regions.

The OGLE III data for the LMC is spatially binned into 1854 small regions, the dimension of each bin being (8.88 × 8.88) sq. arcmin in RA and DEC. The CMD of each region clearly shows the presence of the MS, RGB, RC stars, as well as other evolutionary stages. We also noted that the evolved part of the CMD, along with the RGB, shifts from region to region depending on the reddening. For the metallicity of the LMC (Z=0.008), the RC stars are seen to be located close to the base of the RGB. We used the location of RC stars to trace the base close to the RGB. Subramanian and Subramaniam (2009) found that most of the LMC regions have large numbers of RC stars and their distribution can be well-identified in the CMDs. We identified the location of RC stars and assume the peak (V−I) and V of the RC distribution as the base of the RGB.

Because the RGB and RC colours are similar, they are similarly affected by reddening. That is, we do not expect any differential shift between RC and RGB stars. As the RC and RGB stars are identified together, this reduces the effect of reddening in locating the RGB simi-
larly across the LMC. Thus, we formulated a method to identify the RGB in each CMD, independent of reddening, and which identifies the RGB similarly in the CMDs of all the LMC regions. The steps involved in this method are described below.

1. Excluding the MS: As we aim to study only the RGB, we isolate the evolved part of the CMD by excluding the MS. We studied the MS in the CMDs of a few tens of regions located in different parts of the LMC, in order to decide a cut in colour and magnitude that would exclude most of the MS stars. We find that if we include only stars with $0.5 < (V-I) \leq 2.5$ mag and $12.0 \leq V < 20.0$ mag, we can isolate the evolved part of the CMD. Indu and Subramaniam (2011) used a similar cut-off to separate evolved stars and isolate the MS stars in the CMDs of LMC regions. Figure 5.1(a) shows the CMD of such a region (black filled circles), where the total number of stars in a particular region is given by N. The stars which remain after the above exclusion are shown within the rectangle.

2. Identifying the base of the RGB by constructing the density diagram: After removing the MS stars, we are left with the evolved part of the CMD. The RGB and RC are the primary contributors to this evolved portion. In order to identify the densest part of this portion of the CMD, we constructed a density diagram, where the CMD is binned in magnitude and colour with a bin width of 0.10 mag in V magnitude and 0.05 mag in $(V-I)$ colour, and count the number of stars in each bin. Figure 5.1(b) shows such a plot. The bins are colour coded based on the number of stars in each bin, as denoted in the colour bar. It is seen that the RC is the densest region for this part of the CMD, as expected. The most populated bin falls near the centre of the RC region, and is chosen as the base of the RGB. This location changes with reddening, along with the location of the RGB and is used to identify the RGB similarly in all
Figure 5.1: (a) The \( V \) versus \( (V-I) \) CMD of an OGLE III region at \((70.78^\circ, -70.07^\circ)\), of size \((8.88 \times 8.88)\) sq. arcmin, with \( N=1762 \) stars (black filled circles). The stars within the rectangle (red dashed line) belong to the evolved part of the CMD. (b) Density diagram of the evolved part of CMD, where the CMD bins are colour coded based on the number of stars contained in them, as denoted in the colour bar. (c) Density diagram after giving a colour-magnitude cut at the peak value of RC distribution. (d) Density diagram showing CMD bins that have \( \geq 3 \) stars (black). Straight line fit to these bins representing the RGB, after 3-sigma clipping, is shown as a red solid line. The estimated parameters are: \(|\text{slope}|=4.34\pm0.56, r=0.80\), and \( N_p=36 \).
the subregions. We continue the analysis with this density diagram.

3. Identifying the RGB: As we assume that the base of the RGB is the densest point of the RC, and as the location of RGB is redder and brighter with respect to this point, we remove the bluer and fainter bins with respect to the RC peak. That is, we give a cut in colour and magnitude corresponding to the densest point in the density CMD and assume that the RGB in the CMD consists of redder and brighter bins. This part of the CMD is dominated by RGB, but contaminated with some other evolutionary phases (AGBs etc.) to a lesser extent, shown in Figure 5.1(c). This method of identifying the RGB was visually inspected in the CMDs of several regions, and was found to be satisfactory. The use of the densest bin at the magnitude of the RC allows us to uniquely and consistently define a location in the RGB and identify it uniformly in the CMDs of all regions. Thus, even if this is not the actual base of the RGB, the part of RGB used for slope estimation is made uniform for all locations.

4. Estimating Slope: In order to identify the RGB unambiguously, and to reduce the scatter in the RGB, we consider only those colour-magnitude bins that contain a minimum number of stars. After inspecting the density CMD of various regions located at different parts of the LMC, we choose this minimum number to be 3. We also tried 5 stars as the minimum number, but this limits the extent of the RGB considered, as the brightest part of the RGB is, in general, poorly populated. The chosen criterion eliminates the brighter part of the RGB, typically sampling the RGB from the RC peak up to 2 magnitudes brighter in most regions. As shown in Figure 5.1(d), the selected part of the RGB thus appears to be more or less a straight line, without the curved brighter part. These bins, thus representing the RGB, are fitted with a straight line and the slope
is estimated via a least-squares fit. We carry out a $3\sigma$ clipping with a single iteration to refine our estimates. We have inspected many CMDs and the RGB fits using this method and find that the straight line fit is satisfactory in the vast majority of regions. The fit is also shown in Figure 5.1(d) and the caption lists the derived values. We define $N_p$, as the number of CMD bins (with number of stars in each bin $\geq 3$) representing the RGB, to which a straight line is fitted (after $3\sigma$ clipping) to estimate the slope. It is to be noted that we denote the estimated slope of RGB by its absolute value, as $|\text{slope}|$, and the error in slope as $\sigma_{\text{slope}}$. We also express the correlation coefficient by its absolute value, as $r$.

Thus we have calculated the number of CMD bins ($N_p$) in all regions, and calculated the slope of the fitted straight line ($|\text{slope}|$), error in slope ($\sigma_{\text{slope}}$), and the correlation coefficient ($r$) for each. While doing so we have excluded the regions that have $N_p \sim 0$, thus making estimations for 1849 regions (out of 1854). The above method is found to work consistently for most of the regions, except when there is a large variation in reddening. In some regions we identify the RGB to be very broad resulting in a poor straight-line fit. The number density of stars across the region observed by OGLE III varies significantly, with the maximum stellar density in the bar regions. If we use bins of equal area across the observed region, then the CMDs of some of the central regions are found to be very dense and broad, resulting in poor fits. This suggests that a large number of stars in the RGB might have an effect on the fit and estimation of slope. In order to probe the effect on the fit due to over-populated CMDs, Figure 5.2 shows a plot between the total number of stars in a particular region ($N$) and the number of density points ($N_p$) to which straight line is fitted to estimate the slope. The figure shows that as $N$ increases, $N_p$ also increases, suggesting that, in general, the denser areas have well-populated RGB. Now, we need to check the correlation between $N_p$ and $r$. A plot between correlation coefficient ($r$) and
$N_p$ is shown in Figure 5.3. It is seen that the regions with high $N_p$ (or correspondingly higher N) have lower correlation coefficients ($r < 0.50$) suggesting a poor fit/estimation of the slope. We identified the locations of such regions and inspected a few of them. It turns out that the CMDs of these regions show a broad RGB, likely due to small-scale variations in reddening and/or multiple dominant populations. Most of these regions are found to be located in the central regions.

A way out from this particular issue is to further sub-divide the denser OGLE regions spatially. To achieve this, we perform 8 types of area binning for OGLE III observed regions, where the binning criteria is solely based on the stellar density. We tried to keep a similar but sufficient number of density bins in the RGB, in order to get a good estimation of slope with high $r$ ($>0.50$). Table 5.1 lists the 8 division criteria adopted based on the number of stars in a region. It also lists the total number of subregions extracted under each division criteria, along with their corresponding areas. The area of the largest subregion is $8.88 \times 8.88$ sq. arcmin (128.94 $\times$ 128.94 pc$^2$) and the smallest area being $2.22 \times 2.96$ sq. arcmin (32.23 $\times$ 42.98 pc$^2$). The total number of subregions then increases to 4779. Excluding subregions with $N_p \sim 0$, the number of subregions analysed is 4777 (out of 4779). Figures 5.4 and 5.5 show the plots of $N_p$ versus N and $N_p$ vs $r$, after the above area binning is performed. It is seen that the upper limit of $N_p$ is now confined to a lower value, and remains similar for almost all the 8 cases of sub-divisions. Also, the number of regions with higher $r$ values is found to increase, as compared to the previous case. Thus, we find that the sub-division has improved the fit to the RGB for a large number of regions. On the other hand, we still have some regions with low values of $r$. These regions were found to have either a poorly defined RGB due to scattered RGB stars, or a very broad RGB. In both cases, the fit is found to be poor. The spread in the RGB might be due to variations in reddening within the region or multiple dominant population.
Photometric metallicity map of the Large Magellanic Cloud using OGLE III data

Figure 5.2: Plot of number of bins in RGB to be fitted with a straight line ($N_p$) versus the total number of stars ($N$) for OGLE III subregions, after initial area binning.

Figure 5.3: Plot of number of bins in RGB to be fitted with a straight line ($N_p$) versus correlation coefficient ($r$) for OGLE III subregions, after initial area binning.
Table 5.1: Subdivision of OGLE III regions

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>No. of stars (a)</th>
<th>No. of regions</th>
<th>No. of divisions along RA (b)</th>
<th>No. of divisions along Dec (c)</th>
<th>No. of sub-divisions (d=b×c)</th>
<th>Area of a sub-division (arcmin sq.)</th>
<th>Number of subregions (a×d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 &lt; N ≤ 2000</td>
<td>637</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>(8.88×8.88)</td>
<td>637 (black)</td>
</tr>
<tr>
<td>2</td>
<td>2000 &lt; N ≤ 5500</td>
<td>628</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>(4.44×8.88)</td>
<td>1256 (brown)</td>
</tr>
<tr>
<td>3</td>
<td>5500 &lt; N ≤ 8000</td>
<td>245</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>(2.96×8.88)</td>
<td>735 (red)</td>
</tr>
<tr>
<td>4</td>
<td>8000 &lt; N ≤ 11000</td>
<td>141</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>(4.44×4.44)</td>
<td>564 (orange)</td>
</tr>
<tr>
<td>5</td>
<td>11000 &lt; N ≤ 14000</td>
<td>74</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>(2.96×4.44)</td>
<td>444 (yellow)</td>
</tr>
<tr>
<td>6</td>
<td>14000 &lt; N ≤ 18000</td>
<td>60</td>
<td>4</td>
<td>2</td>
<td>8</td>
<td>(2.22×4.44)</td>
<td>480 (dark green)</td>
</tr>
<tr>
<td>7</td>
<td>18000 &lt; N ≤ 22000</td>
<td>35</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>(2.96×2.96)</td>
<td>315 (blue)</td>
</tr>
<tr>
<td>8</td>
<td>N &gt; 22000</td>
<td>29</td>
<td>4</td>
<td>3</td>
<td>12</td>
<td>(2.22×2.96)</td>
<td>348 (cyan)</td>
</tr>
</tbody>
</table>

Note for Table 5.1: The table describes the 8 binning criteria used to sub-divide OGLE III regions. For each criteria, the second column denotes the limit on total number of stars (N) within a region. The third column gives the number of regions, having N, within that specified limit. Column four and five specify the number times a region is binned along RA and Dec respectively. Column six thus gives the total number of subregions, a single region is binned into. Whereas, the seventh column gives the area of each such subregion. The last (eighth) column denotes the total number of subregions corresponding to each of the 8 sub-division criteria. The colours adjacent to the numbers are used to denote them in Figure 5.4 and 5.5.
**Figure 5.4:** Plot of $N_p$ versus $N$ for OGLE III subregions, after finer area binning. The colours correspond to the eight different bin areas, as mentioned in the eighth column of Table 5.1.

**Figure 5.5:** Plot of $N_p$ versus correlation coefficient ($r$) for OGLE III subregions, after finer area binning. The colours correspond to the eight different bin areas, as mentioned in the eighth column of Table 5.1.
To carry forward our analysis, we need to remove regions that have a poor slope estimation. Although the goodness-of-fit is best described by the correlation coefficient \( r \), a few more parameters may also be considered. Figure 5.6 shows a plot between \( N_p \) and estimated RGB slope (\(|\text{slope}|\)). It is seen from the plot that for regions with \( N_p < 10 \), there is a large range in slope value, along with a few regions estimated with a very large value for \(|\text{slope}|\). A low value of \( N_p \) signifies a sparsely populated RGB, hence the large slope value may be an artefact. To exclude regions with poorly-populated RGBs, we select only those regions that have \( N_p \geq 10 \), implying that the fitted RGB should at least have 30 stars. We need to decide the optimal cut-off for \( r \), to remove regions with poor fits to the RGB slope. It is also necessary to exclude regions that have large error in \(|\text{slope}|\), i.e. \( \sigma_{\text{slope}} \). Figure 5.7 shows a plot between \( \sigma_{\text{slope}} \) versus \( r \). The figure shows that most of the regions have \( r \) in the range 0.4–0.95, and \( \sigma_{\text{slope}} \) in the range 0.5–2.0. Large scatter is observed for regions with \( \sigma_{\text{slope}} > 2.0 \) and \( r < 0.4 \). It is also seen that the densest part of the diagram is found for \( \sigma_{\text{slope}} < 1.5 \) and \( r > 0.5 \). Thus, to remove regions with poor fit from our analysis, we have considered four different cases based on the cut-off for \( r \) and error in \( \sigma_{\text{slope}} \) (with \( N_p \geq 10 \) for all cases). They are as follows:

- criteria (I): \( r \geq 0.4 \) and \( \sigma_{\text{slope}} \leq 2.0 \).
- criteria (II): \( r \geq 0.4 \) and \( \sigma_{\text{slope}} \leq 1.5 \).
- criteria (III): \( r \geq 0.5 \) and \( \sigma_{\text{slope}} \leq 2.0 \).
- criteria (IV): \( r \geq 0.5 \) and \( \sigma_{\text{slope}} \leq 1.5 \).

Figure 5.8 shows the histogram of the RGB slope, estimated using OGLE III data. The slope distributions for all the 4 cut-off cases mentioned above are plotted with respect to the original distribution. It is observed from the plot that most of the regions with slopes less than 2.0 get removed after the cut-off criteria are implemented. A decrease in \( \sigma_{\text{slope}} \) for
Figure 5.6: Plot of $N_p$ versus $|\text{slope}|$ for OGLE III subregions. The red line at $N_p = 10$ denotes the cut-off decided to exclude regions with poorly populated RGBs.

Figure 5.7: Plot of $\sigma_{\text{slope}}$ versus $r$ for OGLE III subregions. The blue dashed and solid lines corresponds to the cut-off criteria on $\sigma_{\text{slope}}$ at 2.0 and 1.5, respectively. The red dashed and solid lines denote the cut-off corresponding to $r$ at 0.4 and 0.5, respectively.
the same value of $r$ does not produce a significant change in the width of the distribution. However, with increasing value of the cut-off in $r$, the width of the distribution reduces mostly for the lower values of slope. Thus, out of these 4 cut-off criteria listed above, the last one is the most strict for selecting the regions with best fits and the first one is the most relaxed.

5.2.2 Calibration of slope to metallicity

After estimating the RGB slope of subregions within the LMC, the next task is to convert the slope to metallicity. The slope derived here is only a proxy to the metallicity and we need to build a relation between the slope of the RGB and metallicity. As the slope of the RGB is a mea-
sure of the average metallicity of the region, we use the spectroscopically estimated average metallicity of red giants in that region to build the required relation. In order to build this relation, we need to estimate the mean spectroscopically-determined metallicity for several regions, in the inner LMC. As there is no such single study, we identified three studies which cover the inner to outer regions. We used spectroscopically derived metallicities of field red giants (Cole et al., 2005), star clusters (Grocholski et al., 2006) and field red giants around these clusters (Cole et al., in preparation). We have chosen the above three studies for the following reasons: (1) These studies derive metallicities for the same population as our study, the RGs. (2) Our slope map covers a fairly large range in slope and hence metallicity. As the map also covers a large area of the LMC, the slope to metallicity relation should be built from a range in metallicity as well as location in the LMC. The combination of these three studies provide a broad range in metallicity as well as location in the LMC. (3) All three studies have used the Ca II triplet lines to derive the metallicity from the spectra, including the calibration of CaT strength to [Fe/H]. Thus, there is no inconsistency or systematic offsets between these studies.

Cole et al. (2005) calculated the abundance of 373 field RGs within a 200 arcmin$^2$ area at the optical centre of the LMC bar. According to their study, the [Fe/H] distribution peaks at $-0.40$ dex. The metallicity histogram of the RGs in their Figure 7 is described by a sum of two Gaussians with a major component (with 89% of the stars) that peaks at $[\text{Fe}/\text{H}] = -0.37$ dex ($\sigma_{[\text{Fe}/\text{H}]} = 0.15$) and a minor component (with 11% of the stars) that peaks at $[\text{Fe}/\text{H}] = -1.08$ dex ($\sigma_{[\text{Fe}/\text{H}]} = 0.46$). We calculate the mean metallicity for a subregion by averaging over the Cole et al. metallicities within its area. While doing so, we consider stars lying within twice the standard deviation about the mean metallicity. To ensure a good calibration, we consider those subregions that have $r \geq 0.7$, $\sigma_{\text{slope}} \leq 1$, and contain a spectroscopic metallicity estimate of at
least 5 RGs. Using these criteria, we identified 12 subregions which can
be used for calibrating the RGB slope-metallicity relation. It is found
that the range of slope value covered by all these sub regions, except for
one, lies mostly within a range of $|\text{slope}| \sim 3.2\text{--}3.8$. One point is found
near $|\text{slope}| \sim 4.4$. We are unable to find any subregion overlapping with
the Cole et al. (2005) sample that has higher mean metallicity than that
corresponding to $|\text{slope}| \sim 3.2$. The slope histogram of the full LMC
shows that the majority of regions have $|\text{slope}| > 3.2$, but there are also
some regions with $|\text{slope}| < 3.2$.

To cover a larger range in slope, so as to formulate a good calibra-
tion relation, we used Grocholski et al. (2006). The authors studied the
abundance of 28 LMC clusters, and the metallicity range covered in their
study is: $-0.3 \geq [\text{Fe/H}] \geq -2.0$. Out of these 28 clusters, only 12 are
located within the OGLE III area. Using the central co-ordinates and
radii of these clusters, we extracted their corresponding OGLE III data
to construct their V, (V–I) CMDs. We tried to estimate the slope of the
RGB for all these clusters using the same technique as in Section 5.2.1,
for field stars. For most of the clusters, the RGB was either sparsely
populated or had significant scatter about the mean RGB (either due to
crowding or intermingling of cluster and field stars in the OGLE III data
or, less likely, differential reddening). Therefore, we could only make a
good estimate of the cluster RGB slope for NGC 2121. Examination of
the remaining clusters showed that by manually cleaning the OGLE III
sample in the subregion we could additionally make a good estimate of the
RGB slope for NGC 1651, in which the cluster RGB was not very dense.
The estimated slope values for these two clusters increased the range of
slopes in our calibration relation. These are the two points which are at
the slope value corresponding to the lower value of metallicity. From the
slope histogram, it can be seen that only a small number of regions have
$|\text{slope}| > 4.6$.

The third set of data used for calibration is from Cole et al. (in prepa-
The authors have estimated the mean metallicity of field regions around the 28 clusters that were studied by Grocholski et al. (2006). The dimension of each field region is similar to that mentioned in Cole et al. (2005). As mentioned above, only 12 of such fields lie within the OGLE III survey. We repeated a similar process as described above to extract the OGLE III data corresponding to each such field, with the cluster area excluded. The CMD of the resultant field was then used to estimate the RGB slope. For most of these fields our usual method did not work either due to scatter in RGB or due to differential reddening. The fields around NGC 2121 and NGC 1751 suffered least from these issues but had sparse RGBs. For these two cases, we adopted a similar technique as for the cluster NGC 1651 to estimate the slope. The metallicity of these fields were found to be similar to that of the clusters, with $|\text{slope}| \sim 4.2$.

In Figure 5.9 the final 16 subregions used for the slope-metallicity calibration are plotted. These values are also tabulated in Table 5.2. The trend shows that metallicity decreases with increasing value of $|\text{slope}|$. We estimate a linear relation between them by fitting a straight line using least square fit. The slope-metallicity relation estimated is given by:

$$[\text{Fe/H}] = (-0.137 \pm 0.024) \times |\text{slope}| + (0.092 \pm 0.091); \quad (5.1)$$

with $r=0.83$. We need to extrapolate this relation to the whole range of slopes estimated for different subregions within the LMC and obtain the value of corresponding metallicity. Although the range of slope covered by the 16 calibration points ($3.2 \leq |\text{slope}| \leq 4.6$) is small compared to the range in slope we obtained ($1.5 - 6.0$), nearly all regions have $3 \leq |\text{slope}| \leq 5$. Thus, we have used the above relation for the entire range of the slope to estimate metallicity.
Figure 5.9: Plot of metallicity ([Fe/H]) versus |slope|. Blue points denote our subregions whose mean [Fe/H] has been found using RGs from Cole et al. (2005), red points denote clusters (NGC 1651 and NGC 2121) from Grocholski et al. (2006), and the dark green points correspond to field around clusters (NGC 2121 and NGC 1751) from Cole et al. (in preparation). The straight line fit to all the calibrators is shown as a black solid line. The error bar (black dashed line) shown for each point is the standard error of the mean [Fe/H].
Photometric metallicity map of the Large Magellanic Cloud using OGLE III data

Table 5.2: Calibrators for OGLE III slope-metallicity relation

| Name               | (RA°, Dec°)      | |slope| ± σ_{slope} | r    | Mean [Fe/H] (dex) | Standard error of mean [Fe/H] (dex) |
|--------------------|------------------|-----|-------------|------|------------------|-----------------------------------|
| Subregion 1        | (81.48, −69.72)  | 3.27±0.32 | 0.87       | −0.29| 0.05             |
| Subregion 2        | (81.48, −69.66)  | 3.79±0.49  | 0.80       | −0.37| 0.05             |
| Subregion 3        | (81.48, −69.62)  | 3.33±0.40  | 0.83       | −0.38| 0.05             |
| Subregion 4        | (80.63, −69.62)  | 3.22±0.49  | 0.74       | −0.36| 0.05             |
| Subregion 5        | (80.62, −69.77)  | 3.38±0.40  | 0.83       | −0.45| 0.06             |
| Subregion 6        | (80.73, −69.77)  | 3.72±0.49  | 0.78       | −0.39| 0.04             |
| Subregion 7        | (81.16, −69.82)  | 3.62±0.38  | 0.89       | −0.38| 0.06             |
| Subregion 8        | (81.16, −69.77)  | 3.71±0.46  | 0.84       | −0.36| 0.06             |
| Subregion 9        | (81.37, −69.97)  | 4.47±0.75  | 0.79       | −0.53| 0.06             |
| Subregion 10       | (80.78, −69.92)  | 3.51±0.52  | 0.76       | −0.45| 0.05             |
| Subregion 11       | (81.21, −70.02)  | 3.46±0.50  | 0.75       | −0.39| 0.04             |
| Subregion 12       | (81.36, −70.02)  | 3.28±0.44  | 0.75       | −0.34| 0.05             |
| NGC 1651           | (69.39, −70.58)  | 4.59±0.37  | 0.84       | −0.53| 0.03             |
| NGC 2121           | (87.05, −71.48)  | 4.52±0.35  | 0.96       | −0.50| 0.03             |
| NGC 1751 Field     | (73.56, −69.83)  | 4.24±0.20  | 0.82       | −0.52| 0.03             |
| NGC 2121 Field     | (87.04, −71.50)  | 4.15±0.22  | 0.83       | −0.53| 0.03             |

Note for Table 5.2: The table lists out the 16 calibrators used to construct the slope-metallicity relation for OGLE III data. The first 12 entries in column number one corresponds to subregions lying near the central LMC, followed by two clusters (NGC 1651 and NGC 2121), and field around two clusters (NGC 1751 and NGC 2121). The central (RA, Dec) corresponding to each calibrator is listed down in second column. The third column gives the estimated slope and its associated error for each calibrator, whereas the correlation coefficient (r) for each case is specified in the fourth column. The fifth column denotes the mean [Fe/H] estimated for each calibrator using spectroscopic results of Cole et al. (2005) (for 12 subregions), Grocholski et al. (2006) (for two clusters), and Cole et al. (in preparation) (for field around two clusters). The standard error of mean [Fe/H] is mentioned in the sixth column. It is calculated as 0.15/√n, where n is the number of RGs located within the area of the calibrator.
5.3 Results

5.3.1 The metallicity map

After converting the OGLE III slopes to metallicities using Equation 5.1, we can now make the average metallicity map for the inner LMC derived from photometry. This is the first such average metallicity map of the LMC estimated using red giant photometry with both high spatial resolution and complete spatial coverage of the bar and disk. This map can be used to estimate the average metallicity of the inner bar region, outer region, and the radial variation of metallicity. To understand the variation of metallicity in the projected sky plane we convert the RA-Dec ($\alpha$, $\delta$) to the Cartesian coordinates X-Y. The conversion equation used for the purpose is given by van der Marel and Cioni (2001) as:

$$
X(\alpha, \delta) = \rho \cos(\phi), Y(\alpha, \delta) = \rho \sin(\phi), \quad (5.2)
$$

where $\rho$ and $\phi$ are the angular coordinates of a point defined by the coordinates ($\alpha$, $\delta$) on the celestial sphere. $\rho$ is the angular distance between the points ($\alpha$, $\delta$) and ($\alpha_0$, $\delta_0$) which is defined to be the centre of the LMC, and $\phi$ is the position angle of the point ($\alpha$, $\delta$) with respect to ($\alpha_0$, $\delta_0$). We have used the value of ($\alpha_0$, $\delta_0$), as RA = $5^h 19^m 38^s$; Dec = $-69^\circ 27^m 5.2^s$ (J2000.0 de Vaucouleurs and Freeman 1972). It is to be noted that X, Y and $\rho$ are expressed in degrees.

We created a metallicity map in the (X,Y) plane using all the 4 cut-off criteria described in Section 5.2.1 (Figures 5.10, 5.11, 5.12, and 5.13). The maps primarily reveals the metallicity trend in the central, eastern and western regions of the LMC. The four maps look more or less similar, with the last two being almost identical. All the maps show a gradient in the metallicity from the centre to the outer regions. The bar region is found to be more metal rich, with a small scale variation in metallicity. We detect a drop in the metallicity beyond a radial distance of $2^\circ$–$2.5^\circ$. The maps also suggest that most of the regions with metallicity below
**Figure 5.10:** OGLE III metallicity map with cut-off criteria (I): $N_p \geq 10$, $r \geq 0.4$ and $\sigma_{\text{slope}} \leq 2.0$.

**Figure 5.11:** OGLE III metallicity map with cut-off criteria (II): $N_p \geq 10$, $r \geq 0.4$ and $\sigma_{\text{slope}} \leq 1.5$. 
5.3 Results

Figure 5.12: OGLE III metallicity map with cut-off criteria (III): \( N_p \geq 10, \) \( r \geq 0.5 \) and \( \sigma_{slope} \leq 2.0. \)

Figure 5.13: OGLE III metallicity map with cut-off criteria (IV): \( N_p \geq 10, \) \( r \geq 0.5 \) and \( \sigma_{slope} \leq 1.5. \)
Photometric metallicity map of the Large Magellanic Cloud using OGLE III data

-0.6 dex are located in the outer regions, with a few of them located in the middle of the metal rich bar region. The OGLE III data covers mostly the east and west of the outer LMC. The eastern and the western LMC are found to be metal poor compared to the bar region. Due to our cut-off criteria, several regions get removed from our analysis due to poor estimation of slope and thus metallicity. Most of the regions which are excluded due to poor slope estimation are located close to the 30 Dor star forming region, with a few in the bar region. These regions are likely to suffer from large reddening or variation in reddening within the small subregion.

5.3.2 Mean metallicity for different regions in the LMC

The average values of metallicity of the complete LMC, the bar region and the outer region of the LMC are calculated and tabulated in Table 5.3 for all the cut-off criteria. By complete LMC, we mean all the regions for which metallicity has been estimated. The bar region is defined according to the region shown in Figure 2 of Subramanian and Subramaniam (2010). By outer LMC, we mean the regions that lie beyond a radial distance of 2.5° away from the LMC optical centre. It can be seen that the estimated average metallicity values do not change significantly between the criteria, though the number of regions considered change. Also, the difference between the average metallicity and the number of regions are not significantly different between criteria (III) and (IV). Nevertheless, we use criteria (IV) and the last row in Table 5.3 as final values and discuss these. The errors shown in the table, along with the average metallicity values, are the standard deviation about the mean and do not reflect errors in the individual metallicity estimations. It can be seen that there is a metallicity difference between the bar region and the outer regions, though it is not very high. The average metallicity value
### Table 5.3: Mean metallicity for different regions of the LMC using OGLE III data

<table>
<thead>
<tr>
<th>Cut-off criteria</th>
<th>$r$</th>
<th>$\sigma_{\text{slope}}$</th>
<th>Region of LMC</th>
<th>Number of subregions</th>
<th>Mean [Fe/H] (dex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>≥ 0.40</td>
<td>≤ 2.0</td>
<td>COMPLETE</td>
<td>4259</td>
<td>−0.39±0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>BAR</td>
<td>1284</td>
<td>−0.34±0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OUTER</td>
<td>1248</td>
<td>−0.46±0.11</td>
</tr>
<tr>
<td>II</td>
<td>≥ 0.40</td>
<td>≤ 1.5</td>
<td>COMPLETE</td>
<td>4202</td>
<td>−0.39±0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>BAR</td>
<td>1278</td>
<td>−0.34±0.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OUTER</td>
<td>1210</td>
<td>−0.46±0.11</td>
</tr>
<tr>
<td>III</td>
<td>≥ 0.50</td>
<td>≤ 2.0</td>
<td>COMPLETE</td>
<td>4014</td>
<td>−0.40±0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>BAR</td>
<td>1191</td>
<td>−0.35±0.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OUTER</td>
<td>1212</td>
<td>−0.47±0.11</td>
</tr>
<tr>
<td>IV</td>
<td>≥ 0.50</td>
<td>≤ 1.5</td>
<td>COMPLETE</td>
<td>3969</td>
<td>−0.40±0.10</td>
</tr>
<tr>
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<td></td>
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<td>BAR</td>
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<td></td>
<td></td>
<td>OUTER</td>
<td>1180</td>
<td>−0.47±0.11</td>
</tr>
</tbody>
</table>

Note for Table 5.3: The first column denotes the four different cut-off criteria considered to filter out LMC subregions. It is to be noted that we considered $N_p \geq 10$ for all four cut-off criteria. The second and third column specify the constraint on correlation coefficient ($r$) and $\sigma_{\text{slope}}$ respectively, corresponding to each cut-off criteria. The fourth column mentions three specific regions of LMC: the complete coverage, bar region, and outer region (as defined in the text). The number of subregions that satisfy the cut-off for each of these three specific regions are mentioned in the fifth column. The mean metallicity and standard deviation for these three specific LMC regions are mentioned in the last (sixth) column.
Photometric metallicity map of the Large Magellanic Cloud using OGLE III data

of [Fe/H] = −0.40±0.10 suggests that the part of the LMC studied here does not have much of variation in metallicity as suggested by the relatively low standard deviation. The last row in the table also suggests that the number of subregions in the bar region and the outer region are similar and hence, are similarly sampled. Also, the outer regions sampled here are mainly the eastern and the western regions and have an average metallicity of [Fe/H] = −0.47±0.11.

5.3.3 Metallicity distribution and radial metallicity gradient

The metallicity distribution is presented in Figure 5.14 for all the 4 cut-off criteria. The distribution is binned to 0.15 dex, which is of the order of 1σ error. The distribution contains a smaller number of regions with high metallicity as we progressively tighten the selection criteria from (I) to (IV). On the other hand, the difference in distribution between criteria (III) and (IV) is marginal, suggesting that all estimates in the distribution are likely to be more or less reliable. The peak of the distribution is found be in the bin spanning −0.30 to −0.45 dex, which is consistent with the values listed in Table 5.3. Almost no regions are found to have metallicity lower than −0.75 dex and higher than −0.15 dex.

Figure 5.15 shows a plot of the radial metallicity gradient for all 4 cut-off criteria. To construct the radial gradient, we binned the metallicity map into annular bins 0.25° in width, and estimated their mean metallicity. It is seen from the figure that the mean metallicity is almost constant in the bar region, i.e. within a region of ∼2° around the optical centre. Also, the radial metallicity gradient is shallow. As mentioned above, the OGLE III region covers the bar and the eastern and western part of the bar. Thus, the radial profile basically shows the variation across the bar and off the bar, as the northern and the southern regions are not covered in OGLE III. The profile thus suggests a homogeneous and metal-rich bar.
5.3 Results

Figure 5.14: Histogram of metallicity ([Fe/H]) for OGLE III data, estimated for all the four cut-off criteria ((I) in cyan, (II) in orange, (III) in blue, and (IV) in red). \( N_p \geq 10 \) for all these four cases.

Figure 5.15: Radial variation of metallicity ([Fe/H]) for OGLE III data, estimated for all the four cut-off criteria ((I) in cyan, (II) in orange, (III) in blue, and (IV) in red). \( N_p \geq 10 \) for all these four cases.
region with a relatively metal-poor eastern and western disk.

5.4 Error analysis

We now discuss the estimation of error in slope and metallicity. The factors that can contribute to the error in slope estimation are the photometric error associated with individual points in the CMD (error in V and I magnitude are $\leq 0.15$), and errors due to fine binning of the CMD (dimension of each bin is 0.05 in colour, and 0.10 in magnitude), thus contributing to error in the slope as well. As the error associated with a star is more than or equal to the bin size, it means that there can be a possibility that the star may very well belong to the neighbouring bin. Thus, just counting the number of stars in a bin might not be the best idea for knowing the population strength of a colour-mag bin. In that sense, one can calculate the probability of a star lying within a particular CMD bin, and normalize by the area of each bin to create a density plot to as the best representation of the RGB. However, as mentioned earlier we are interested only in the mean metallicity of a region, of which the slope is an indicator. Under this scenario, we are not looking into the strength of individual CMD bins, and concentrating only on the overall feature of the RGB. After we identify the most populated bins as a part of RGB, the spread in the distribution of RGB bins is such that it more or less makes a good representation of the RGB. These bins are then fitted with the standard least-squares technique, to estimate the slope and its corresponding error. Figure 5.7 shows that for most of the regions, $\sigma_{\text{slope}}$ shows a clumpy distribution below 2. The values of $\sigma_{\text{slope}}$ estimated in our study are relatively larger. This is caused by the natural spread of the populated RGB bins. Thus, in this study we have not considered the contribution of errors associated with individual stars and colour-magnitude binning while estimating error in slope. We expect these contributions to be negligible.
We have used three spectroscopic studies to formulate a slope-metallicity relation, given in Equation 5.1. The error associated with the metallicity estimation of individual RGs in all of these are of the order of 0.15 dex. We can express this Equation 5.1 as:

\[
[Fe/H] = (b \pm \sigma_b) \times |slope| + (a \pm \sigma_a); \tag{5.3}
\]

where |slope| denotes the absolute value of the RGB slope, \( b \) is the slope of the calibration relation (−0.137), \( \sigma_b \) is its error (0.024), \( a \) is the y-intercept (0.092), and \( \sigma_a \) is its error (0.091). The error associated with metallicity (\( \text{error}_{[Fe/H]} \)) for each subregion can be calculated by propagation of error. By applying the additive rules of propagation of error to Equation 5.3, we find that \( \text{error}_{[Fe/H]} \) can be expressed as:

\[
\text{error}_{[Fe/H]} = \sqrt{\sigma_{(b \times |slope|)|}^2 + \sigma_a^2}; \tag{5.4}
\]

The second term inside the square root is already known, while the first term \( \sigma_{(b \times |slope|)|} \) is the error associated with the quantity \((b \times |slope|)|\). This can be calculated using the multiplicative rule of propagation of errors as:

\[
\sigma_{(b \times |slope|)} = |(b \times |slope|)| \times \sqrt{\left(\frac{\sigma_b}{b}\right)^2 + \left(\frac{\sigma_{slope}}{|slope|}\right)^2}; \tag{5.5}
\]

Thus using Equation 5.4 and 5.5, we can estimate the error in metallicity. Thus, the slope (|slope|) of a region, its error (\( \sigma_{\text{slope}} \)), along with parameters of calibration relation (\( a \) and \( b \)), and their associated errors (\( \sigma_a \) and \( \sigma_b \)), contribute to the error in metallicity. It is to be noted that while calculating \( \text{error}_{[Fe/H]} \), we have not considered the error associated with individual calibration points.

Figure 5.16 shows a plot between \( \text{error}_{[Fe/H]} \) and [Fe/H], estimated for the most stringent cut-off criteria (IV). It is very well seen that \( \text{error}_{[Fe/H]} \) falls primarily in the range of 0.10–0.25 dex. Thus the values of \( \text{error}_{[Fe/H]} \) are of the similar order as the error in spectroscopic values of metallicity of RGs (∼ 0.15 dex as mentioned earlier), that were used for calibration. A slight trend is observed in the figure, where the error
Figure 5.16: Plot of error$[\text{Fe/H}]$ versus $[\text{Fe/H}]$ for OGLE III data, for cut-off criteria (IV): $N_p \geq 10$, $r \geq 0.5$, and $\sigma_{\text{slope}} \leq 1.5$.

Figure 5.17: Plot of histogram for error$[\text{Fe/H}]$ for OGLE III data, for cut-off criteria (IV): $N_p \geq 10$, $r \geq 0.5$, and $\sigma_{\text{slope}} \leq 1.5$. 
in abundance is seen to increase with decrease in metallicity. Figure 5.17 shows the histogram of error[Fe/H] for OGLE III data. The distribution also confirms that most of the regions have error[Fe/H] between 0.10–0.20 dex. The peak of the distribution is in the range 0.10–0.15 dex.

5.5 Discussion

We have estimated the photometric metallicity map of the LMC using OGLE III data. We estimated the slope of the RGB of several subregions in the LMC using a method which takes care of reddening and density variation between regions. The slope is converted to metallicity using spectroscopic measures which cover nearly the full range. The method used in this study is tailored to estimate the average slope of the RGB in a given region, which is a proxy to the average metallicity of the region. The following points are summarized to bring out the results presented in this chapter to the right perspective.

- The aim of this study is to map the average metallicity distribution of the LMC. The method traces the densest part of the RGB and the slope is estimated using a straight line fit. We thus estimate only the metallicity of the population which has the largest number of stars in the RGB phase. The analysis does not bring out any information regarding the contribution from the less dominant populations.

- If there are multiple populations with similar number of stars, then the RGB tends to be broad and the slope may be poorly estimated. If there are small scale variations in the reddening, then also the RGB tends to be broad resulting in a poor estimation of the slope. These regions will not get considered in our analysis, due the removal of regions with poor estimation of slope.

- A metallicity estimation based on photometry can cover a large area of the LMC, unlike the spectroscopic method, which can over
only relatively small areas. The photometric method, though, might have large errors and hence may not be ideal to perform detailed and comprehensive studies of metallicity. Nevertheless, it is quite useful, especially when the area to be covered is large. It can bring out the overall distribution, variation and global average of metallicity. It also can identify regions which might show large deviations with respect to the mean value. These regions can then be earmarked for further detailed studies. Thus, a photometric metallicity map, though not very accurate, has its own advantages.

- The calibration used to estimate the metallicity is based on spectroscopic data. We have used the average value of metallicity for selected subregions, estimated from spectroscopic data. The calibration rests on the assumption that the spectroscopic targets are drawn from the dominant population of the subregion. The assumption is fair enough, as the spectroscopic targets are also chosen from the RGB and are likely to be picked from the population with the largest number of stars. The tail of metal-poor stars that is observed in spectroscopic studies is not detected in our sample because it does not strongly influence the mean metallicity of regions.

- Across the inner 4° of the LMC, the RGB slope has a relatively large range; the calibration relation between slope and metallicity should hold good for the full range. We combined results from three different spectroscopic studies to achieve this calibration. All three studies have used similar spectral lines and techniques to estimate metallicity, thus we expect no systematic differences between them. We have used field giants and two star clusters for the calibration. Thus, the metallicity values presented in this study are tied to this choice of metallicity calibration.

We have estimated the metallicity distribution for various regions within the LMC (complete, bar region, and outer LMC) for the most
stringent cut-off criteria (IV). We fit Gaussians to these distributions in order to estimate the peak and the width of the distribution for each of these cases. In Figure 5.18 we show the metallicity distribution of the complete LMC fitted with a Gaussian. The peak of the distribution is estimated to be at $[\text{Fe/H}] = -0.395 \pm 0.002$ dex and the width of the distribution to be $\sigma[\text{Fe/H}] = 0.103 \pm 0.001$ dex. In Figure 5.19, we have shown the distribution of metallicity for the bar region. The distribution clearly shows that the OGLE III data has a large number of data points within the $-0.3$ to $-0.4$ dex bin. The peak of the distribution is estimated to be at $[\text{Fe/H}] = -0.353 \pm 0.002$ dex and the width of the distribution to be $\sigma[\text{Fe/H}] = 0.087 \pm 0.002$ dex. Thus, the bar region is found to be metal rich and the distribution has a relatively less $\sigma[\text{Fe/H}]$ value, suggesting that the range of $[\text{Fe/H}]$ is relatively narrow in the bar region. The metallicity distribution for the outer LMC is shown in Figure 5.20. The distribution has the peak at $-0.45$ to $-0.60$ dex, though one can in general consider a broad peak from $-0.30$ to $-0.60$ dex. By fitting a Gaussian distribution we estimated a peak at $[\text{Fe/H}] = -0.465 \pm 0.003$ dex and the width of the distribution to be $\sigma[\text{Fe/H}] = 0.113 \pm 0.002$ dex. Thus, we find that there is a statistically significant difference between the metallicity of the bar region and the outer region.

To understand the variation of metallicity with radius in the de-projected plane of the galaxy, we carry out a coordinate transformation from the sky plane to the plane of the LMC. This radial gradient of metallicity is presented in Figure 5.21. The LMC plane is inclined with respect to the sky plane by an angle $i$, and the position angle of the line of nodes (measured counter-clockwise from the north) is given by $\Theta$. If we know the mean distance to the LMC centre $D_0$, we can apply the correction for the position angle and $i$, using the conversion equations from van der Marel (2001):

$$X' = \frac{D_0 \cos(i) \sin(p) \cos(\phi - \Theta_{far})}{\cos(i) \cos(p) - \sin(i) \sin(p) \sin(\phi - \Theta_{far})}, \quad (5.6)$$
Figure 5.18: Histogram of metallicity (dashed line) for complete LMC fitted with a Gaussian function (solid line), for OGLE III data.

Figure 5.19: Histogram of metallicity (dashed line) for LMC bar fitted with a Gaussian function (solid line), for OGLE III data.
5.5 Discussion

![Histogram of metallicity for the outer LMC](image1)

**Figure 5.20:** Histogram of metallicity (dashed line) for the outer LMC fitted with a Gaussian function (solid line), for OGLE III data.

![Variation of metallicity with radius](image2)

**Figure 5.21:** Variation of metallicity with radius in the de-projected plane of the LMC, for OGLE III (red solid line) data. The gradients estimated till a radius of about 4 kpc are shown as black solid lines.
Photometric metallicity map of the Large Magellanic Cloud using OGLE III data

\[ Y' = \frac{D_0 \sin(\rho) \sin(\phi - \Theta_{far})}{\cos(i) \cos(\rho) - \sin(i) \sin(\rho) \sin(\phi - \Theta_{far})}. \]

(5.7)

For our purpose we have used the value of \( i \) to be 37°.4, and \( \Theta \) to be 141°.2, from Subramanian and Subramaniam (2010). The authors had estimated the values of \( i \) and \( \Theta \), in their study of structural parameters of the LMC using RC stars, using the OGLE III and MCPS data. We used the values derived using MCPS data, since it has wider coverage. Thus the sky-plane \((X,Y)\) is de-projected to the LMC plane \((X',Y')\) using Equations 5.6 and 5.7 and assuming \( D_0 = 50 \) kpc. It should be noted that the new co-ordinate system \((X',Y')\) is in kpc. We constructed a radial metallicity gradient by assuming a bin width of 0.25 kpc. This is done only for the cut-off criteria \( (IV) \). We have quantified the variation of metallicity with the de-projected radius from the LMC centre \((\rho'\) in kpc), by fitting a straight line using least square fit as shown in the Figure 5.21. We have estimated the slope for the central region that contains the bar, where the metallicity seems to remain almost constant (up to \( \rho' \sim 2.5 \) kpc). This is found to be \([\text{Fe/H}] = (-0.027 \pm 0.003) \times \rho' + (-0.333 \pm 0.004)\); with \( r = 0.96 \). For outside the central LMC \((\rho' \sim 2.5 \) to 4 kpc), the variation of metallicity is found to be \([\text{Fe/H}] = (-0.066 \pm 0.006) \times \rho' + (-0.259 \pm 0.020)\); with \( r = 0.98 \). The unit for the slope is dex kpc\(^{-1}\). This variation in metallicity gradient from the central to the outer region is a due to the presence of a homogeneous and metal rich bar, and the relatively metal-poor eastern and western regions.

From our analysis of the OGLE III data we could estimate and understand the metallicity trend of the LMC bar as well as the eastern and western regions. However, a more complete analysis of the disk metallicity requires the northern and the southern regions to be included. Thus, in order to sample more of the disk, we analyse the MCPS data and create a metallicity map using the same in Chapter 6.
5.6 Summary

- We present a metallicity map of the LMC derived from OGLE III photometric data and calibrated using spectroscopic data.

- We developed a robust and automated technique to estimate the slope of the RGB in CMDs of small subregions within the galaxy. The technique is independent of reddening and extinction. We also derived a calibration relation to transform RGB slope to metallicity, using a consistent set of calibrators from spectroscopic studies of giants in the field as well as clusters.

- The OGLE III metallicity map unravels the metallicity trend primarily within the bar region, and the eastern and western disk of the LMC.

- The average metallicity of the LMC is estimated to be $-0.39$ dex ($\sigma{[\text{Fe/H}]} = 0.10$), within a radius of 4 degrees.

- The bar region of the LMC is found to have an average metallicity of $-0.35$ dex ($\sigma{[\text{Fe/H}]} = 0.9$), and a shallow gradient in metallicity ($-0.027\pm0.003$ dex kpc$^{-1}$).

- The outer regions have an average metallicity of $-0.46$ dex ($\sigma{[\text{Fe/H}]} = 0.11$). The radial metallicity gradient for the outer LMC disk ($\sim$ 2.5 to 4 kpc) is found to be $-0.066 \pm 0.006$ dex kpc$^{-1}$.
Photometric metallicity map of the Large Magellanic Cloud using OGLE III data
Chapter 6

Photometric metallicity map
of the Large Magellanic Cloud
using MCPS data

6.1 Introduction

In Chapter 5 we presented a high-resolution metallicity map for the LMC using the OGLE III photometric survey. The metallicity maps exhibited the metallicity trend primarily within the bar and the eastern and western wing of the LMC. To understand the metallicity variation across the complete LMC disk, the northern and southern regions of the LMC also needs to be covered.

In this chapter, we create a metallicity map using the Magellanic Cloud Photometric Survey (MCPS, Zaritsky et al. 2004) data. The MCPS survey not only covers the northern and southern LMC but also has more areal coverage compared to OGLE III. We also present a comparison of the results derived from the OGLE III and MCPS analyses. The chapter is organised in the following way: in Section 6.2 we describe the data="Choudhury S., Subramaniam A., and Cole A.A., 2016, MNRAS, 455, 1855."
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(MCPS) and the analysis. The MCPS metallicity maps and results are presented in Section 6.3. Section 6.4 describes the error analysis corresponding to our estimations. The discussion related to our study, as well as comparison with the OGLE III results, is presented in Section 6.5. A summary of the study is presented in Section 6.6.

6.2 Data and Analysis

In this study we have made use of the V and I band photometric data from the MCPS survey. The MCPS survey covered an area of about 64 square degrees of the central LMC, and provided the optical photometric data of about 24 million stars in the U, B, V, and I pass bands. Thus, the MCPS survey covers a comparatively larger area than the OGLE III survey (39.7 square degrees) in the optical bands. The survey is of comparatively lower resolution (0′.70 pixel$^{-1}$) than the OGLE III (0′.26 pixel$^{-1}$) survey. We divided the whole MCPS survey region into 1512 regions of equal areas, (10.53 x 15) sq. arcmin in RA and Dec, so as to have a well populated RGB in the V, (V−I) CMD. For our analysis we only consider stars with photometric errors less than 0.15 mag in the V and I pass bands. The details of the MCPS survey have been discussed in Section 2.4.

6.2.1 Estimation of RGB slope

For the MCPS data, we used similar steps to estimate the slope of the RGB as in Section 5.2.1, starting from isolating the RGB, locating the densest point of the RC and estimating the density distribution of stars on the RGB. Thus we estimated the number of CMD bins to which straight line is fitted ($N_p$) in all regions, the slope of the fitted straight line (|slope|), error in slope ($\sigma_{slope}$), and the correlation coefficient ($r$) for each. These estimated parameters ($N_p$, |slope|, $\sigma_{slope}$, and $r$) are defined in a similar way as was done for the OGLE III data in Section 5.2.1. We
have excluded regions that have $N_p \sim 0$, thus making estimations for 1355 regions (out of 1512). We present the plot for $N_p$ versus $N$ in Figure 6.1 for these regions of the MCPS, which is similar to Figure 5.2 for OGLE III. The plot suggests that with increasing number of stars within a region ($N$), the number of bins in RGB ($N_p$) to which a straight line is fitted also increases. The plot for $N_p$ versus $r$ shown in Figure 6.2 resembles Figure 5.3 created for OGLE III, and suggests that as $N_p$ increases, $r$ decreases. As mentioned in Section 5.2.1, the inner regions of the LMC had issues due to multiple populations and large variations in reddening. Similar to OGLE III, we performed 7 types of area binning of the MCPS regions in order to achieve similar number of density points on RGB ($N_p$) and a good correlation coefficient ($r$). The division criteria adopted based on the number of stars in a region are presented in Table 6.1. The total number of MCPS subregions increases to 4750. Excluding subregions with $N_p \sim 0$, the number of subregions analysed is 4742. The area of largest bin being $10.53 \times 15.00$ sq. arcmin ($152.9 \times 217.8$ pc$^2$), whereas the area of smallest bin is $3.51 \times 5.00$ sq. arcmin ($50.96 \times 72.6$ pc$^2$). The slopes for each of these subregions are then re-estimated.

Figures 6.3 and 6.4 show the plots of $N_p$ versus $N$, and $N_p$ versus $r$ respectively, after the revised area binning is performed. It is seen that the upper limit of $N_p$ is now confined to a lower value, and remains almost same for all the 7 cases of division. Also, there are more regions with relatively high $r$ values. The regions with lower values of $r$ are likely to be those that suffer either from issues of multiple dominant population and/or small scale variations in reddening. As already mentioned in Chapter 5, such regions lie mostly in the central and the star-forming regions of LMC.

After the RGB slopes have been estimated for MCPS subregions, the next step is to calibrate slope to metallicity. We proceeded to estimate a slope–metallicity relation for MCPS, as was done for OGLE III i.e. using spectroscopic studies of RGs within field and clusters (Cole et al.
Figure 6.1: Plot of number of bins in RGB to be fitted with a straight line ($N_p$) versus the total number of stars ($N$) for MCPS subregions, after initial area binning.

Figure 6.2: Plot of number of bins on RGB to be fitted with a straight line ($N_p$) versus correlation coefficient ($r$) for MCPS subregions, after initial area binning.
### Table 6.1: Subdivision of MCPS regions

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>No. of stars</th>
<th>No. of regions division (a)</th>
<th>No. of division along RA (b)</th>
<th>No. of division along Dec (c)</th>
<th>No. of sub-divisions (d×b×c)</th>
<th>Area of a sub-division (arcmin sq.)</th>
<th>Number of subregions (a×d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 &lt; N ≤ 4000</td>
<td>192</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>(10.53×15.00)</td>
<td>192 (black)</td>
</tr>
<tr>
<td>2</td>
<td>4000 &lt; N ≤ 7500</td>
<td>353</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>(5.26×15.00)</td>
<td>706 (brown)</td>
</tr>
<tr>
<td>3</td>
<td>7500 &lt; N ≤ 11000</td>
<td>293</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>(3.51×15.00)</td>
<td>879 (red)</td>
</tr>
<tr>
<td>4</td>
<td>11000 &lt; N ≤ 13800</td>
<td>233</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>(5.26×7.50)</td>
<td>932 (orange)</td>
</tr>
<tr>
<td>5</td>
<td>13800 &lt; N ≤ 16400</td>
<td>143</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>(3.51×7.50)</td>
<td>858 (yellow)</td>
</tr>
<tr>
<td>6</td>
<td>16400 &lt; N ≤ 19100</td>
<td>86</td>
<td>4</td>
<td>2</td>
<td>8</td>
<td>(2.63×7.50)</td>
<td>688 (dark green)</td>
</tr>
<tr>
<td>7</td>
<td>N &gt; 19100</td>
<td>55</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>(3.51×5.00)</td>
<td>495 (blue)</td>
</tr>
</tbody>
</table>

Note for Table 6.1: The table describes the 7 binning criteria used to sub-divide MCPS regions. For each criteria, the second column denotes the limit on total number of stars (N) within a region. The third column gives the number of regions, having N within that specified limit. Column four and five specify the number times a region is binned along RA and Dec respectively. Column six thus gives the total number of subregions a single region is binned into. The seventh column gives the area of each such subregion. The last (eighth) column denotes the total number of subregions corresponding to each of the 7 sub-division criteria. The colours adjacent to the numbers are used to denote Figures 6.3 and 6.4.
**Figure 6.3:** Plot of $N_p$ versus $N$ for MCPS subregions, after finer area binning. The seven different colours correspond to the seven different binning criteria, as mentioned in the eighth column of Table 6.1.

**Figure 6.4:** Plot of $N_p$ versus correlation coefficient ($r$) for MCPS subregions, after finer area binning. The seven different colours correspond to the seven different binning criteria, as mentioned in the eighth column of Table 6.1.
2005; Grocholski et al. 2006; Cole et al. in preparation). We could not get a good estimation of the slope for most of the subregions lying near the central LMC due to scatter in RGB, which is probably caused by differential reddening and/or multiple populations. Thus, for the central subregions whose mean metallicity could be calculated from RGs of Cole et al. (2005), we could not consider their corresponding slopes due to bad fits ($r < 0.5$). In addition, due to the relatively poor resolution of MCPS data, the CMDs of clusters (Grocholski et al., 2006) and field (Cole et al., in preparation) around them were sparse compared to the OGLE III case, resulting in poorly populated or scattered RGB. Due to these reasons we could not formulate an independent slope–metallicity relation for MCPS, similar to OGLE III. An alternate way for calibration is to use the slope–metallicity relation derived for OGLE III (Equation 5.1), since both the data sets use V and I passband filters. Before doing that we must explore if there exists any difference in the slope estimations from the two data sets.

To carry forward our analysis, we need to remove MCPS regions that have a poor estimation of slope. We consider the most stringent criteria, similar to that adopted for the OGLE III slope values, ($N_p \geq 10$, $r \geq 0.5$, and $\sigma_{slope} \leq 1.5$) that filters out the best estimated slope. The slope distribution is compared with that of OGLE III, as shown in Figure 6.5. It is seen that that peak of the MCPS as well as the overall slope distribution for MCPS is shifted towards a lower value with respect to the OGLE III distribution. This shift could be a genuine shift or due to some other effect. One possibility is that the slope would depend on the V magnitude and $(V-I)$ colour calibration. If there is any difference between the filter systems of OGLE III and MCPS, it might appear as a shift in slope. Thus, it is important to compare the two data base to detect any systematic difference. In the following section we try to address this issue.
Figure 6.5: Histogram for MCPS and OGLE III $|\text{slope}|$ values with cut-off criteria (IV): $N_p \geq 10$, $r \geq 0.5$ and $\sigma_{\text{slope}} \leq 1.5$.

6.2.2 Comparison of OGLE III and MCPS data

In order to find systematics, if any, between the OGLE III and MCPS data, we compared the V magnitude and (V−I) colour derived by both the catalogues and checked for systematic variations. We selected a few MCPS subregions for this purpose. The regions are selected based on the criteria that they have sufficient number of RGB stars ($N_p \geq 10$), are located away from the central region to have relatively less crowding effect ($\rho \geq 2.5^\circ$, where $\rho$ is defined in Equation 5.2), and have well-estimated slope suggesting relatively less differential reddening ($r \geq 0.85$ and $\sigma_{\text{slope}} \leq 0.50$). These criteria ensure that the regions do not lie in the outskirts of the LMC where the stellar density is sparse or close to the central regions where there are problems due to crowding and differential reddening. Because the colour differences are small, if there exists a difference in the filter system, it is unlikely to be dependent on the metallicity or RGB slope of a region. However, to remain unbiased we selected four regions.
Table 6.2: Subregions to cross-correlate MCPS and OGLE III filter systems:

| Serial no. | (RA°, Dec°) | Data       | No. of stars in evolved part of CMD | |slope| ± σslope | r  | Np |
|------------|-------------|------------|-------------------------------------|-----------------|------------------|--------|----|
| i          | (90.12, −70.62) | MCPS       | 714                                 | 3.14±0.38       | 0.89             | 19     | |
|            |             | OGLE       | 749                                 | 4.06±0.64       | 0.81             | 23     | |
| ii         | (71.59, −70.12) | MCPS       | 759                                 | 3.53±0.33       | 0.92             | 22     | |
|            |             | OGLE       | 850                                 | 3.96±0.40       | 0.89             | 28     | |
| iii        | (70.12, −70.12) | MCPS       | 823                                 | 4.01±0.41       | 0.91             | 22     | |
|            |             | OGLE       | 940                                 | 4.53±0.45       | 0.89             | 26     | |
| iv         | (70.12, −69.87) | MCPS       | 781                                 | 4.68±0.48       | 0.91             | 20     | |
|            |             | OGLE       | 817                                 | 4.44±0.92       | 0.73             | 22     | |

Note for Table 6.2: The table lists out four subregions used to estimate cross-correlation between the MCPS and OGLE III filter systems. The central (RA, Dec) for each subregion is mentioned in column number two. The survey data used for each subregion is mentioned in the third column, and the corresponding number of stars in evolved part of the CMD (0.5 < (V−I) ≤ 2.5 mag and 12.0 ≤ V < 20.0 mag), is specified in the fourth column. In fifth column the estimated slope along with its associated error, for each data set is listed. The corresponding correlation coefficient (r) and number of density bins on RGB fitted with straight line (Np), for each case, are mentioned in column number six and seven, respectively.

with different values of slope. Then, for each of these MCPS subregions a region of similar dimension is extracted from the OGLE III data.

Table 6.2 lists the coordinates, number of stars in the evolved part of the CMD, value of slopes, r and Np corresponding to MCPS and OGLE III for each of these subregions. To derive a cross correlation between the filters in the two different surveys, we began by taking a star from MCPS data and identified its closest counterpart in the OGLE III data. For each star we then calculated the difference in V mag between OGLE III and MCPS (Δ(V)= VOGLE−VMCPS) and plotted it with respect to the V mag of OGLE III, in Figure 6.6. The plot looks symmetric with respect to the zero value of Δ(V). We can conclude that there is no significant difference in V magnitude between the two filter systems. Figure 6.7 shows a similar plot for Δ(I) (i.e. IOGLE−IMGPS) versus I mag of OGLE III. The figure clearly shows a mild negative slope. It seems as one goes fainter (higher magnitude) in I band, Δ(I) becomes more and more negative.
This suggests that there exists a systematic trend in ΔI as a function of I magnitude, which can cause a mild change in the slope of the RGB. Any such shift is not found in the case of V magnitude. We also checked if there exists any dependence of Δ(V) and Δ(I) on colour. To do so we plot Δ(V) and Δ(I) against (V–I) mag of OGLE III in Figures 6.8 and 6.9 respectively. These plots look symmetric with respect to zero values of Δ(V) and Δ(I), thus conveying that both Δ(V) and Δ(I) are invariant with respect to colour: any systematic variation is seen to be below 0.03 mag for Δ(V) and 0.01 mag for Δ(I) over (V–I)$_{OGLE}$ ranging from 0.5 to 2.5 mag.

Having found a systematic shift in I magnitude, we make a plot of I$_{OGLE}$ versus I$_{MCPS}$ and fit a relation, which is found to be linear. We fit a straight line (Figure 6.10) with a 3σ cut. We consider only those stars that are brighter than 18 mag as the RGB for both OGLE III and MCPS data, and exclude fainter stars. We find that the relation followed by the two photometric systems can be then described as a function:

$$I_{OGLE} = (0.990 \pm 0.001) \times I_{MCPS} + (0.124 \pm 0.028);$$

with \( r=0.99 \). We can now transform the I magnitudes of stars in MCPS system to their corresponding I magnitudes in OGLE III system using Equation 6.1, whereas the V magnitude in both the data sets remains the same. This transformation is carried out for all the stars in the MCPS data and the slopes are re-estimated for all the MCPS subregions. Thus, we converted the MCPS data to the OGLE III system and estimated the slope of the RGB. Now, these slope values can be directly compared with the slopes estimated from the OGLE III data.

We considered 4 cut-off criteria, similar to OGLE III (Section 5.2.1) to select regions with reliable slope values. In Figure 6.11 we have plotted \( N_p \) against the re-estimated slopes for the MCPS subregions. The plot of \( \sigma_{slope} \) versus \( r \) is shown in Figure 6.12. We chose cut-offs similar to OGLE III, and show them in these figures. The slope distribution for the
Figure 6.6: Plot of $\Delta(V)$ versus $V_{OGLE}$ for stars belonging to the four cross-correlated LMC subregions mentioned in Table 6.2.

Figure 6.7: Plot of $\Delta(I)$ versus $I_{OGLE}$ for stars belonging to the four cross-correlated LMC subregions mentioned in Table 6.2.
Figure 6.8: Plot of $\Delta(V)$ versus $(V-I)_{OGLE}$ for stars belonging to the four cross-correlated LMC subregions mentioned in Table 6.2.

Figure 6.9: Plot of $\Delta(I)$ versus $(V-I)_{OGLE}$ for stars belonging to the four cross-correlated LMC subregions mentioned in Table 6.2.
4 cut-off criteria are shown in Figure 6.13. The distribution without any cut-off is also plotted in black. The figure shows that as the correlation coefficient cut-off becomes more stringent, the width of the histogram reduces such that the lower slope values are removed. The effect of $\sigma_{\text{slope}}$ is insignificant on the distribution for same cut-off in r. The strictest cut-off, $N_p \geq 10$, $r \geq 0.5$, and $\sigma_{\text{slope}} \leq 1.5$ shows that the slope values ranges primarily from 2 to 6 for the regions studied here.

Now, we need to check whether the process of removing the systematics in the I magnitude has changed the slope distribution in the case of MCPS data. For this, we plot the slopes of the MCPS data estimated in the MCPS system, the slope estimated after changing to the OGLE III system and the slope estimated using the OGLE III data (Figure 6.14). It can be seen that the change of photometric system has not changed the slope distribution significantly, as there is hardly any shift in the peak value. Thus, even though we identified a systematic shift in the I magni-
Figure 6.11: Plot of $N_p$ versus $|\text{slope}|$ after I magnitude transformation for MCPS subregions. The red line at $N_p = 10$ denotes the cut-off decided to exclude regions with poorly populated RGB.

Figure 6.12: Plot of $\sigma_{\text{slope}}$ versus $r$ after I magnitude transformation for MCPS subregions. The blue dashed and solid lines correspond to the cut-off criteria on $\sigma_{\text{slope}}$ at 2.0 and 1.5 respectively. The red dashed and solid lines denote the cut-off corresponding to $r$ at 0.4 and 0.5 respectively.
6.2 Data and Analysis

Figure 6.13: Histogram of MCPS $|\text{slope}|$ values after I magnitude transformation, estimated for all the four cut-off criteria ($I$) in cyan, ($II$) in orange, ($III$) in blue, and ($IV$) in red). $N_p \geq 10$ for all these four cases. The black solid line shows the distribution of $|\text{slope}|$ with no cut-offs, for all subregions.

Figure 6.14: Comparison of histogram for MCPS $|\text{slope}|$ values before (black) and after (blue) I magnitude transformation with respect to the OGLE III $|\text{slope}|$ values (red), where all estimations are with cut-off criteria ($IV$): $N_p \geq 10$, $r \geq 0.5$ and $\sigma_{\text{slope}} \leq 1.5$. 
tude of the MCPS system when compared to the OGLE III system and corrected it, the slope estimation does not seem to be affected by this difference. Therefore, the observed shift in the slope distribution is not due to the photometric system. Thus, we consider the shift to be possibly a genuine one, likely to be arising due to difference in the area covered by these two data sets. We shall discuss this point in the Section 6.5.

6.2.3 Calibration of slope to metallicity

The slopes estimated from the MCPS data also need to be converted to metallicity. We discussed in Section 6.2.1 that it was not possible to derive a slope–metallicity relation for MCPS, similar to OGLE III. Also, it is not justified to transform the MCPS slopes directly to metallicity using the OGLE III slope–metallicity relation due to systematic difference between the filter systems (Section 6.2.2). However, now that the photometric system of MCPS is converted to the OGLE III system, we can use the same transformation used to convert the OGLE III slopes to metallicity. Thus, the slopes estimated in the previous section are converted to metallicities using Equation 5.1.

6.3 Results

6.3.1 The MCPS metallicity map

To understand the variation of metallicity in the projected sky plane we convert the RA-Dec ($\alpha$, $\delta$) to the Cartesian coordinates $X$-$Y$. The conversion equation used is same as was used for OGLE III, Equation 5.2. Figures 6.15, 6.16, 6.17 and 6.18 show the metallicity map derived using MCPS data created using the 4 cut-off criteria. It can be seen that, similar to the OGLE III data, there is not much difference between the maps created using 4 different criteria. Similar to the OGLE III analysis, we shall use the most stringent criteria, with the minimum number of
subregions for further analysis. The metallicity maps presented in these figures are the first of their kind and give a high-resolution map of average metallicity in the inner LMC. These maps are very helpful in identifying the range and variation in metallicity between various parts of the inner LMC.

The gaps in the map are due to regions with poorly estimated slopes. The regions which get missed out due to this effect are those located near 30 Dor (similar to OGLE III map, Figures 5.10, 5.11, 5.12, and 5.13), along with some regions to the north-east and north of the LMC centre. More gaps appear around these regions, as well as within the bar region, when the selection criteria become more stringent. As most of these regions are near regions of star formation, the poor estimate of slopes might be due to the presence of small-scale variation in reddenings. We notice that the central region has a more or less uniform metallicity distribution, which is relatively high when compared to the outer regions. Even though we notice a radial variation of metallicity, the maps also suggest that the variation is likely to be very small. We also notice that regions with metallicity below $-0.60$ are located mostly in the outer regions, with a few in the metal rich central region. In the MCPS map, a large number of regions in the bar region get removed due to poor slope estimation; due to this, the appearance of the bar as a homogeneous metal rich region is not present in the map. We also estimate the metallicity distribution of the northern and southern regions. These regions are not as metal poor as the eastern and western disks, but rather moderately metal rich. That is, we do see a change in the metallicity as we move from the bar to the north or south. Even though we can visually identify these variations, quantitatively these may not be very significant.
Photometric metallicity map of the Large Magellanic Cloud using MCPS data

Figure 6.15: MCPS metallicity map with cut-off criteria (I): \( N_p \geq 10, r \geq 0.4 \) and \( \sigma_{\text{slope}} \leq 2.0 \).

Figure 6.16: MCPS metallicity map with cut-off criteria (II): \( N_p \geq 10, r \geq 0.4 \) and \( \sigma_{\text{slope}} \leq 1.5 \).
6.3 Results

Figure 6.17: MCPS metallicity map with cut-off criteria (III): $N_p \geq 10$, $r \geq 0.5$ and $\sigma_{slope} \leq 2.0$.

Figure 6.18: MCPS metallicity map with cut-off criteria (IV): $N_p \geq 10$, $r \geq 0.5$ and $\sigma_{slope} \leq 1.5$. 
6.3.2 Mean metallicity for different regions in the LMC

As the MCPS data cover a larger area of the LMC, the MCPS metallicity distribution can be used to estimate the average metallicity in the bar region with respect to the outer regions of the LMC, as well the radial variation of the metallicity (estimated in the next section). The average values of metallicity of the complete LMC, the bar region and the outer region of LMC are listed in Table 6.3. By complete LMC, we mean all the regions for which metallicity has been estimated. The bar region is defined according to the region shown in Figure 2 of Subramanian and Subramaniam (2010). By outer LMC, we mean the regions that lie beyond a radial distance of 2.5° away from the LMC optical centre. We estimated the averages for these various regions using all the four cut-off criteria. The table also shows the number of regions used to estimate the average. The estimated average value, listed in the last column, has an error which reflects the standard deviation of the average and does not include the error in the metallicity estimation of each region. The table shows that the bar region is relatively metal rich when compared to the outer regions, but the variation is quite small. This trend is observed for all the 4 cases of slope selection. As we consider the fourth criteria, the averages shown in the last row are used for further discussion. The bar region is found to have an average metallicity of \(-0.28\pm0.10\) dex whereas the outer LMC has an average metallicity of \(-0.41\pm0.10\) dex. The average metallicity of the LMC is found to be \(-0.37\pm0.11\) dex. The average value of metallicity estimated from OGLE III, as given in Table 5.3, is very similar to the value estimated here, whereas the metallicity estimate for the bar region and the outer region are slightly different. The OGLE III estimate of average metallicity for the outer LMC is relatively lower, probably due to the fact that the OGLE III covers more of the eastern and western regions which are found to be metal poor. Since, the OGLE III data has more regions...
6.3 Results

Table 6.3: Mean metallicity for different regions of the LMC using MCPS data

<table>
<thead>
<tr>
<th>Cut-off criteria</th>
<th>$r$</th>
<th>$\sigma_{\text{slope}}$</th>
<th>Region of LMC</th>
<th>Number of subregions</th>
<th>Mean [Fe/H] (dex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$\geq 0.40$</td>
<td>$\leq 2.0$</td>
<td>COMPLETE</td>
<td>3724</td>
<td>$-0.35\pm0.12$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>BAR</td>
<td>544</td>
<td>$-0.26\pm0.10$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OUTER</td>
<td>1792</td>
<td>$-0.40\pm0.12$</td>
</tr>
<tr>
<td>II</td>
<td>$\geq 0.40$</td>
<td>$\leq 1.5$</td>
<td>COMPLETE</td>
<td>3587</td>
<td>$-0.35\pm0.12$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>BAR</td>
<td>544</td>
<td>$-0.26\pm0.10$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OUTER</td>
<td>1694</td>
<td>$-0.40\pm0.11$</td>
</tr>
<tr>
<td>III</td>
<td>$\geq 0.50$</td>
<td>$\leq 2.0$</td>
<td>COMPLETE</td>
<td>3235</td>
<td>$-0.37\pm0.12$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>BAR</td>
<td>420</td>
<td>$-0.28\pm0.10$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OUTER</td>
<td>1637</td>
<td>$-0.42\pm0.11$</td>
</tr>
<tr>
<td>IV</td>
<td>$\geq 0.50$</td>
<td>$\leq 1.5$</td>
<td>COMPLETE</td>
<td>3144</td>
<td>$-0.37\pm0.11$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>BAR</td>
<td>420</td>
<td>$-0.28\pm0.10$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OUTER</td>
<td>1569</td>
<td>$-0.41\pm0.10$</td>
</tr>
</tbody>
</table>

Note for Table 6.3: The first column denotes the four different cut-off criteria considered to filter out LMC subregions. It is to be noted that we considered $N_p \geq 10$ for all four cut-off criteria. The second and third column specify the constraint on correlation coefficient ($r$) and $\sigma_{\text{slope}}$ respectively, corresponding to each cut-off criteria. The fourth column mentions three specific regions of LMC: the complete coverage, bar region, and outer region (as defined in the text). The number of subregions that satisfy the cut-off for each of these three specific regions, are mentioned in the fifth column. The mean metallicity and standard deviation for these three specific LMC regions, are mentioned in the last (sixth) column.

(1189) in the bar, when compared to the MCPS data (420 regions), the difference in metallicity may be because of this effect. The metallicity maps in fact show that though the bar region is relatively metal rich, there is a lot of small-scale variation.

6.3.3 Metallicity distribution and radial metallicity gradient

The metallicity distribution of the LMC covered by the MCPS data is shown in Figure 6.19, for all the 4 cut-off criteria. The data is binned at 0.15 dex, which is similar to the error in the average metallicity. The histogram suggests that the peak of the distribution lies in the $-0.30$ to $-0.45$ dex bin. There is not much difference between the four criteria
Photometric metallicity map of the Large Magellanic Cloud using MCPS data

used, though the fourth criteria has the smallest number of regions and fewer regions with high metallicity values. Also, there are almost no regions with metallicity below $-0.75$ dex. The range in metallicity is thus found to be from $-0.15$ to $-0.75$ dex. The histogram is very similar to the OGLE III distribution (Figure 5.14), the striking difference being that this distribution has a reduced peak height and is skewed to positive values unlike OGLE III distribution. This difference may be due to the inclusion of more northern and southern regions and fewer eastern and western regions, and the exclusion of the relatively metal-rich bar due to crowding.

The metallicity gradient estimated using the MCPS data is presented in Figure 6.20. The radial average is estimated for $0.25^\circ$ annuli. The radial variation for all selection criteria are shown and the error bar indicates the standard deviation about the average for the radial bin. There are a good number of regions within a radial distance of 4 degrees, beyond which the number of regions decrease and hence the metallicity values may be biased. The radial profile shows a peak near the central region, which was absent in the plot derived from OGLE III data (Figure 5.15). As discussed in the previous section, the higher value obtained here is based on a smaller number of regions which are relatively metal rich. As the peak is basically due to the higher metallicity of the inner-most bin, which originates from a smaller number of regions, the peak may be an artefact. The profile from the second bin, up to a radial distance of $4^\circ$, shows a smooth variation from the inner to the outer region. Thus, this once again confirms the smooth and gradual decrease in metallicity as a function of radius. Also, the radial gradient does not show the bar effect, similar to the metallicity map. The profile shows a rather gradual gradient, which is probably the effect of inclusion of the northern and southern regions. As the MCPS data covers more of the disk of the LMC and less of the bar, the profile could be suggestive of the metallicity distribution of the LMC disk.
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Figure 6.19: Histogram of metallicity ([Fe/H]) for MCPS data, estimated for all the four cut-off criteria ((I) in cyan, (II) in orange, (III) in blue, and (IV) in red). $N_p \geq 10$ for all these four cases.

Figure 6.20: Radial variation of metallicity ([Fe/H]) for MCPS data, estimated for all the four cut-off criteria ((I) in cyan, (II) in orange, (III) in blue, and (IV) in red). $N_p \geq 10$ for all these four cases.
6.4 Error analysis

We discuss the estimation in error in slope and metallicity for MCPS data. We have corrected for the systematic difference in I bands between the OGLE III and MCPS filter systems that is given by Equation 6.1, derived from Figure 6.10 using the standard least-squares fit. The errors in the slope and y-intercept of Equation 6.1 are smaller than the photometric error for individual stars, as well as the error associated with the fine binning of the CMD. After transforming the I magnitudes for all MCPS subregions, their slopes and corresponding error in slope were estimated by a technique similar to OGLE III (i.e., standard least-squares fit). The value of \( \sigma_{\text{slope}} \) is found to be relatively high, similar to those derived from OGLE III data (Figure 5.7). The \( \sigma_{\text{slope}} \) distribution is primarily below a value of 2 (Figure 6.12). The MCPS slopes after transformation have been calibrated to metallicity using Equation 5.1. We have made similar assumptions as OGLE III (Section 5.4) while estimating the associated error in metallicity \( \text{error}_{[\text{Fe/H}]} \), and used Equation 5.4 and 5.5 for that purpose.

We have compared the error in metallicity derived for OGLE III and MCPS data. Figure 6.21 shows a plot between \( \text{error}_{[\text{Fe/H}]} \) and \([\text{Fe/H}]\), estimated for the most stringent cut-off criteria (IV), for both OGLE III and MCPS. It is very well seen that \( \text{error}_{[\text{Fe/H}]} \) falls primarily in the range of 0.10–0.25 dex for MCPS, similar to OGLE III. As mentioned already in Section 5.4, these values of \( \text{error}_{[\text{Fe/H}]} \) are of the similar order as the error in the spectroscopic values of metallicity of RGs (\( \sim 0.15 \) dex), that were used for calibration. A slight trend is observed in the figure, where the error in abundance is seen to increase with decrease in metallicity. Figure 6.22 shows a comparison of histograms of \( \text{error}_{[\text{Fe/H}]} \) for OGLE III and MCPS. The distribution also confirms that most of the regions have \( \text{error}_{[\text{Fe/H}]} \) between 0.10–0.20 dex. The OGLE III data has more regions with error in the range 0.10–0.15 dex, whereas, the MCPS data
Figure 6.21: Plot of $error_{[Fe/H]}$ versus $[Fe/H]$ for OGLE III (red filled circles) and MCPS (blue filled circles), for cut-off criteria (IV): $N_p \geq 10$, $r \geq 0.5$, and $\sigma_{slope} \leq 1.5$.

Figure 6.22: Plot of histogram for $error_{[Fe/H]}$ for OGLE III (red) and MCPS (blue), for cut-off criteria (IV): $N_p \geq 10$, $r \geq 0.5$, and $\sigma_{slope} \leq 1.5$. 

has more regions with error in the range 0.15–0.20 dex. Both data sets have similar number of regions within the error range 0.20–0.25 dex. We conclude that the error associated with [Fe/H] estimation is similar in both the data sets.

6.5 Discussion

In this chapter we have estimated a metallicity map for the LMC using MCPS data. We calculated the average value of metallicity for different regions within the galaxy, and also estimated its radial metallicity gradient. In this section, we discuss the assumptions and their impact on our study using both MCPS and OGLE III data. We discuss the implications of the MCPS results and compare them with the OGLE III results. We also present a map of metallicity outliers and discuss its significance.

6.5.1 Assumptions and their impact

In Chapters 5 and 6, we have used two large photometric datasets (OGLE III and MCPS, respectively) to create a metallicity map of the LMC. The steps adopted in this process might have affected the outcome of the study. We discuss below each step and its impact on the estimated value of the RGB slope and the corresponding metallicity.

6.5.1.1 Effect of sub-division

The two data sets were sub-divided to create regions with smaller areas. We have also considered different sizes for sub-division in the outer and inner LMC part of the LMC for both data sets. We also argued that the estimation of RGB slope improves if there is a moderate number of stars in the RGB. As the depth and resolution of MCPS and OGLE III are different, we were unable to make subregions of the same area for both data sets. The MCPS sub regions are larger than the OGLE III subregions in all parts of the LMC. Due to this, even though we eventually
6.5 Discussion

converted the MCPS data to the OGLE III system, we are unable to make a one-to-one correlation between the metallicity estimated using each data set. As the area changes, we notice that the estimated slope changes mildly, though within the errors. Thus, the estimated value of slope mildly depends on the area considered, but the change is found to be within the uncertainty in slope estimation. This may be due to the fact that the dominant population as well as differential reddening can change with area. We note that the important result of our study is not the average metallicity of each region, but the global average and its variation across the LMC.

6.5.1.2 Effect of reddening and differential reddening

The LMC is known to have variations in reddening with respect to populations (Zaritsky et al., 2004). The reddening variation can shift the location of the RGB in the CMD. This effect is taken care in the analysis by anchoring the RGB to the densest part of the RC. Nevertheless, the effect of differential reddening will remain and broaden the RGB. In the structure maps presented by Subramanian and Subramaniam (2010), they found that many regions were left out, probably due to large differential reddening. Large-scale variations in reddening can broaden the RGB, resulting in a poorly estimated slope. These regions are eliminated from the analysis. Most of the regions which get eliminated are found to be located near star forming regions. It is possible that we still have such regions left out in our final set of regions, although they are likely to be small in number. As we are interested in the statistical average estimated using a large number of regions, their impact is likely to be negligible.

6.5.1.3 Systematic effects

There can be two systematic effects in our study. The first one is due to the photometric systems of the two data sets used and the second one arises in the conversion of slope to metallicity. We have tried to
minimise the first one by converting the MCPS system to the OGLE III system. We found the I magnitude to have a small systematic shift which was corrected, while the V magnitude was found to be the same in both systems. Even though we performed the transformation, we did not find any change in the slope distribution before and after the conversion. The conversion of slope to metallicity was done by correlating the OGLE III slope of some regions with the average metallicity estimated using spectroscopic data. The population used to estimate the slope as well as the metallicity is the same: RGB stars. We used field red giants as well as giants in star clusters for calibration. We used three references from the same group and hence there is minimal systematic shift among the calibrations. Thus, we have tried to minimize the systematics as much as possible. On the other hand, we would like to comment on the impact of any uncorrected systematics on the result. If the photometric shift was not corrected completely, then the shift in metallicity between the MCPS and OGLE III could remain and lead to an artificially higher metallicity in the MCPS regions. On the other hand, the radial variation as well as the global averages are less impacted by this.

### 6.5.2 Comparison of metallicity distribution

After we have addressed the impact of various assumptions on the estimates, we now compare the results obtained from the two data sets. We notice similarities as well as discrepancies between the two data sets, discussed below. Using the OGLE III data in Chapter 5, we found the bar region to be a more or less homogeneous metal-rich region. We noticed some small-scale variation in [Fe/H] within the errors. The eastern and the western disks were found to be relatively metal poor. The MCPS map presented in this chapter shows a gradual gradient from near the central region to the outer regions. The northern and the southern regions are only marginally metal poor. If the OGLE III data is considered to describe the bar (as the central region has a reduced contribution from
the disk) and the MCPS data to describe the disk (as the central region
has a minimal contribution from the bar), then our analysis suggests that
the LMC has a metal rich bar and a disk with a very shallow metallicity
gradient. The analysis is also indicative of the east and the west regions
of the LMC disk being metal poor compared to the north and south areas
- although this needs to be verified with additional spectroscopic data.

Next, we compare the metallicity distributions for different regions
within the LMC, estimated with the most stringent cut-off criteria (IV),
and fit Gaussian functions to them. In Figure 6.23, we compare the distri-
bution of metallicity for the complete LMC as estimated from these two
data sets. It can be seen that in general the distributions are similar. The
peaks of the distributions are almost identical but the two surveys differ in
their secondary peaks, as OGLE III data shows a metal-poor second peak,
whereas the MCPS data shows a metal-rich second peak. This is likely
to be due to the difference in the area coverage. We fitted a Gaussian to
the OGLE III distribution (Section 5.5) and estimated its peak to be at
$[\text{Fe/H}] = -0.395 \pm 0.002$ dex with a width of $\sigma[\text{Fe/H}] = 0.103 \pm 0.001$ dex.
In the case of MCPS data, the peak has $[\text{Fe/H}] = -0.369 \pm 0.002$ dex and
its width is $\sigma[\text{Fe/H}] = 0.117 \pm 0.001$ dex. Thus, both data sets yield the
same mean value of $[\text{Fe/H}]$ and comparable widths.

In Figure 6.24, we have compared the distribution of metallicity for
the bar region as estimated for OGLE III and MCPS data. The distribu-
tion clearly shows that the OGLE III data have a large number of data
points peaking in the $-0.3$ to $-0.4$ dex bin, whereas the MCPS data has
a relatively lower number of points which peak in the $-0.15$ to $-0.30$ dex
bin. The distributions of the two sets of data for the bar region are thus
different. As mentioned above, the OGLE III data have many more sub-
regions and thus can be considered as having smaller (random) errors. In
Section 5.5, the peak for the OGLE III distribution was estimated to be at
$[\text{Fe/H}] = -0.353 \pm 0.002$ dex with a width of $\sigma[\text{Fe/H}] = 0.087 \pm 0.002$ dex.
On the other hand, the distribution using the MCPS data was estimated
Figure 6.23: Histogram of metallicity (dashed line) for the complete LMC fitted with a Gaussian function (solid line), compared between OGLE III (red colour) and MCPS data (blue colour).

Figure 6.24: Histogram of metallicity (dashed line) for the LMC bar fitted with a Gaussian function (solid line), compared between OGLE III (red colour) and MCPS data (blue colour).
to be centred at $[\text{Fe/H}] = -0.269\pm0.004$ dex with a width of $\sigma[\text{Fe/H}] = 0.091\pm0.004$ dex. Thus, the bar region is found to be metal rich by both OGLE III and MCPS data. We also notice that the MCPS distribution has a relatively smaller value of $\sigma[\text{Fe/H}]$, similar to OGLE III, suggesting that the range of $[\text{Fe/H}]$ is relatively narrow in the bar region.

In Figure 6.25, we have shown the distribution of $[\text{Fe/H}]$ for the outer LMC estimated for both data sets. The MCPS distribution shows a peak at $-0.3$ to $-0.45$ dex bin, whereas the OGLE III distribution has a peak at $-0.45$ to $-0.60$ dex, though one can in general consider a broad peak from $-0.30$ to $-0.60$ dex. The MCPS distribution has a relatively larger amount of metal-rich regions while OGLE III has marginally more metal-poor regions. The peak of the MCPS data is also marginally metal rich. These differences, as indicated above, are likely to be due to the difference in area coverage. The MCPS distribution has a peak at $[\text{Fe/H}] = -0.414\pm0.003$ dex with a width of $\sigma[\text{Fe/H}] = 0.110\pm0.002$ dex, while the OGLE III distribution has a peak at $[\text{Fe/H}] = -0.465\pm0.003$ dex with a width of $\sigma[\text{Fe/H}] = 0.113\pm0.002$ dex (Section 5.5). Thus, we find that there is a statistically significant difference between the metallicity of the bar region and the outer region. We also suggest that the northern and southern regions of the LMC could be marginally more metal rich than the eastern and western regions. We note that the mean $[\text{Fe/H}]$ and the peak of the distribution estimated using a Gaussian fit are similar. The standard deviation and the estimated $\sigma[\text{Fe/H}]$ are also found to be similar.

To estimate the variation of metallicity with radius in the de-projected plane of LMC using MCPS data, we follow similar steps as those described in Section 5.5 for the OGLE III data (Equations 5.6 and 5.7). In Figure 6.26, we compare the radial gradient of metallicity from the two data sets, estimated only for the cut-off criteria ($IV$). For MCPS data, to avoid issues due to sampling, we exclude the region nearest to the LMC centre and limit our estimation from $\rho' \sim 0.5$ to 4 kpc. The metallic-
Photometric metallicity map of the Large Magellanic Cloud using MCPS data

**Figure 6.25:** Histogram of metallicity (dashed line) for the outer LMC fitted with a Gaussian function (solid line), compared between OGLE III (red colour) and MCPS data (blue colour).

**Figure 6.26:** Variation of metallicity with radius in the de-projected plane of the LMC for OGLE III (red solid line) and MCPS (blue solid line) data. The gradients estimated till a radius of about 4 kpc are shown as black solid lines for both OGLE III and MCPS.
ity is found to decrease with increase in $\rho'$ as $[\text{Fe/H}]=(-0.049\pm0.002) \times \rho' + (-0.250\pm0.005)$ with a correlation coefficient of $r = 0.99$. In Section 5.5 for OGLE III data, we estimated the metallicity variation for the bar region (up to $\rho' \sim 2.5$ kpc) to be $[\text{Fe/H}]=(-0.027\pm0.003) \times \rho' + (-0.333\pm0.004)$ with $r = 0.96$, while outside the central LMC ($\rho' \sim 2.5$ to 4 kpc) it was found to be $[\text{Fe/H}]=(-0.066\pm0.006) \times \rho' + (-0.259\pm0.020)$ with $r = 0.98$. The comparison of these estimated slopes suggests that the metallicity variation in MCPS is steeper as compared OGLE III till a distance of $\rho' \sim 2.5$ kpc. Beyond this distance, the metallicity decreases more rapidly for OGLE III regions than for the MCPS regions. Thus, it is suggestive of a marginally different radial gradient for the northern and southern LMC when compared to the eastern and western regions.

Cioni (2009), using the C/M ratio of the field AGB population as an indicator of metallicity, found that the $[\text{Fe/H}]$ of the LMC decreases linearly with distance from the centre up to a distance of 8 kpc, following the relation: $[\text{Fe/H}]=-0.047\pm0.003 \times \rho' - 1.04\pm0.01$. This variation is shown in their Figure 2. In this figure they also plotted the metallicity of RR Lyrae stars within a radius of about 3 kpc (from Borissova et al. (2006)), which have a steeper metallicity gradient $-0.078\pm0.007$ dex kpc$^{-1}$. There is no requirement that the two populations share a common distribution, as the RR Lyrae stars are older than 10 Gyr while the AGB stars are strongly biased towards ages of $\approx 1-2$ Gyr. Their Figure 2 also showed the radial variation of metallicity of field RGBs (from Cole et al. 2005; Pompéia et al. 2008; Carrera et al. 2008a) and star clusters (from Grocholski et al. 2006, 2007), which is almost constant within the inner LMC. We note that the metallicity gradient estimated in this study using the MCPS data matches very well with that estimated by Cioni (2009), though the $y$-intercept, which is the metallicity at the centre, are very different. The origin of this discrepancy requires further investigation, and may be due to the difference in mean age between the general RGB field discussed here and AGB stars previously studied. The results derived in this sec-
Photometric metallicity map of the Large Magellanic Cloud using MCPS data

Table 6.4: Summary of average [Fe/H] and gradient for different regions of the LMC

<table>
<thead>
<tr>
<th>Data</th>
<th>LMC region</th>
<th>[Fe/H] (dex)</th>
<th>σ[Fe/H] (dex)</th>
<th>Gradient (dex kpc⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGLE III COMPLETE</td>
<td>-0.39</td>
<td>0.10</td>
<td></td>
<td>-0.027±0.003</td>
</tr>
<tr>
<td>OGLE III BAR</td>
<td>-0.35</td>
<td>0.09</td>
<td>0.027</td>
<td>0.003</td>
</tr>
<tr>
<td>OGLE III OUTER</td>
<td>-0.46</td>
<td>0.11</td>
<td>0.066</td>
<td>0.006</td>
</tr>
<tr>
<td>MCPS COMPLETE</td>
<td>-0.37</td>
<td>0.12</td>
<td>-0.049</td>
<td>0.002</td>
</tr>
<tr>
<td>MCPS BAR</td>
<td>-0.27</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCPS OUTER</td>
<td>-0.41</td>
<td>0.11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note for Table 6.4: The table presents a summary of results derived from OGLE III and MCPS data. The mean [Fe/H] and the corresponding σ[Fe/H], estimated using these two data sets, for different regions within the LMC (as defined in the text), are listed in the third and fourth columns. The fifth column gives the radial metallicity gradient derived corresponding to each case.

The mean [Fe/H] and the shallow gradient in the bar region suggest that the bar of the LMC could be considered to show the expected enhancement seen in barred galaxies. While many observations support the basic scenario of bar and galaxy evolution, several recent studies of barred galaxies using large samples reveal a dependence on galaxy mass. A study of 294 galaxies with strong bars from the Sloan Digital Sky Survey (SDSS) by Ellison et al. (2011) showed that barred galaxies with stellar masses M < 10^{10} M_☉ show an increase in central metallicity but without a corresponding increase in central SFR. One possible explanation is that star formation in the centre of low-mass barred galaxies, which is presumably responsible for the observed higher metallicities, has now ceased, while stars are still forming in the centre of high-mass galaxies (Martel, Kawata, and Ellison, 2013). Thus, LMC might also belong to this class of objects,
where we detect higher metallicity but no enhanced star formation.

6.5.3 Map of metallicity outliers

One of the aims of this study was to identify regions which have metallicity significantly deviating from the mean value, or with respect to the surrounding regions. As we have the average metallicity as $-0.40$ dex, we considered regions with metallicity less than $-0.65$ dex and more than $-0.15$ dex as deviations, which corresponds to deviations beyond $2.5\sigma$ about the mean. In Figure 6.27, we show the combined OGLE III and the MCPS data for cut-off criteria ($IV$). All regions with metallicity between $-0.65$ dex to $-0.15$ dex are shown as small dots, which covers most of the galaxy. Regions with metallicity above $-0.15$ dex are shown as red filled circles (OGLE III data) and red open circles (MCPS data). It can be seen from the figure that the red points, both from OGLE III and MCPS, are mostly located in the central region coincident with the bar. We stress that co-location of points from both the data sets is seen here and re-emphasises that the bar is indeed the most metal-rich part of the LMC. We also find a location to the north of the bar (RA $\sim 82^\circ$ and Dec $\sim -68.5^\circ$) to be metal rich, as identified by both data sets. A few additional regions in the north of the LMC are seen as metal-rich by the MCPS data. The southern and eastern LMC are not found to have any metal rich regions, apart from a couple of regions close to the bar.

Regions with metallicity below $-0.65$ dex are shown as filled green circles (OGLE III data) and open green circles (MCPS data). Most of the metal-poor regions are in the outer LMC, with a few points in the bar region as well. The eastern and western disk of the LMC have a large number of metal-poor regions from both the data sets. The northern disk has such regions identified from the MCPS data. In general, the southern LMC does not show either metal rich or metal poor regions. Thus, there is a clear demarcation between the bar and the outer regions of the LMC. We also identify a few locations which are either metal rich
Photometric metallicity map of the Large Magellanic Cloud using MCPS data

Figure 6.27: A combined metallicity map for OGLE III and MCPS data displaying subregions with large deviation from the mean metallicity. The significantly metal rich regions ([Fe/H] ≥ −0.15 dex) are shown in red colour (filled circles for OGLE III and open circles for MCPS), whereas the significantly metal poor regions ([Fe/H] ≤ −0.65 dex) are shown in green colour (filled circles for OGLE III and open circles for MCPS).
or poor with respect to their surroundings. These regions are candidates for a detailed spectroscopic study to understand the source of deviation. There does not seem to be any correlation between the regions identified as metal-poor and the locations in which Olsen et al. (2011) discovered a population of kinematically distinct, metal-poor giants which they attributed to an accreted SMC population. This suggests that at no location in the inner LMC is the kinematically distinct population strong enough to significantly draw down the metallicity of the field in general, relative to neighbouring fields; either the total accreted population is very small, or well-mixed into the disk as a whole.

6.6 Summary

1. We present a metallicity map of the LMC derived from MCPS photometric data and calibrated using spectroscopic data. This, along with the OGLE III metallicity map, is the first of its kind map derived using RGB stars.

2. The MCPS metallicity map unravels the metallicity trend primarily in the LMC disk outside the bar region, more of northern and southern LMC and less of eastern and western regions. Thus the MCPS map complements its OGLE III counterpart.

3. The average metallicity of the LMC is found to be $-0.37 \text{ dex} \ (\sigma[\text{Fe/H}] = 0.12)$ from MCPS data within a radius of 4°. This agrees well with the value derived from OGLE III.

4. The bar region of the LMC is found to be metal rich as was found using OGLE III data.

5. The outer regions have an average metallicity of $-0.41 \text{ dex} \ (\sigma[\text{Fe/H}] = 0.11)$ estimated from the MCPS data, slightly metal rich compared to what was found from OGLE III. This is probably due to the inclusion of the northern and southern LMC.
6. The MCPS data sets suggest a shallow radial metallicity gradient of $-0.049 \pm 0.002$ dex kpc$^{-1}$ for the LMC disk, up to a radius of 4 kpc, in agreement with Cioni (2009).

7. We present a map of metallicity outliers using both OGLE III and MCPS data, and identify a few areas where the metallicity is found to be significantly different from the surrounding regions. These should be studied in detail using spectroscopic data.
Chapter 7

Conclusions

7.1 Summary

In this thesis we aimed to study the evolved stellar populations in the LMC to understand its evolution history. The study was primarily divided into two parts.

In the first part we studied sparse star clusters in the LMC to increase our understanding of such stellar systems and their significance within the galaxy. A systematic study was performed to analyse 45 previously unstudied/poorly studied cluster candidates, using deep Washington photometric data for the first time. The basic parameters (radius, reddening, and age) were estimated by using the MSTO, as well as the evolved portion of the CMDs. The study was presented as two parts in Chapters 3 and 4, for genuine and possible clusters/asterisms respectively. The important results of this study can be summarised as follows:

1. The study of 45 clusters was aimed at enlarging the number of objects confirmed as genuine star clusters and estimating their fundamental parameters.

2. Out of 45 clusters, 33 were found to be true (genuine) cluster candidates whereas the remaining 12 clusters could only be categorized as possible cluster/asterism. We successfully estimated the param-
eters of the true clusters and at the same time list the parameters of the other category, if at all they are clusters. The age distribution of the true clusters shows that about 50% fall within the age range of 100–300 Myr, whereas some are older or younger.

3. The physical sizes (radii \( \sim 2 - 10 \) pc) and masses (\( \sim \) few 100 – 1000 M\( \odot \)) of the studied clusters were found to be similar to that of open clusters in the Milky Way. Our study adds to the lower end of cluster mass distribution in the LMC. Thus the LMC, apart from hosting rich clusters, also contains such small, less massive open clusters particularly in the (100–300) Myr range.

4. The 12 poor cases in the category of possible clusters/asterism are also worthy of attention, in the sense that they can throw light on the survival time of such objects in the LMC.

In the second part of our study we estimated a photometric metallicity map of the LMC to understand the chemical evolution history of the galaxy, using the OGLE III and MCPS data. The RGB was identified in the \( V,(V-I) \) CMD of small subregions of varying sizes in both data sets. The slope of the RGB was used as an indicator of the average metallicity of a subregion, and this slope was calibrated to metallicity using spectroscopic data for field and cluster RGs in selected subregions. This work presents an estimate of the average and radial variation of metallicity ([Fe/H]) in the LMC in Chapters 5 and 6, using OGLE III and MCPS data respectively. The important results of this study can be summarised as follows:

1. We present a metallicity map of the LMC derived from photometric data and calibrated using spectroscopic data. This is a first of its kind map derived using RGB stars from the OGLE III and MCPS data sets.

2. We estimate the RGB slope of several subregions in the LMC and
7.1 Summary

convert the slope to metallicity using spectroscopic data of field and cluster giants.

3. The average metallicity of the LMC is found to be $-0.37$ dex ($\sigma[\text{Fe/H}] = 0.12$) from MCPS data and $-0.39$ dex ($\sigma[\text{Fe/H}] = 0.10$) from OGLE III data, within a radius of 4°.

4. The bar region of the LMC is found to have an average metallicity of $-0.35$ dex ($\sigma[\text{Fe/H}] = 0.9$), and a shallow gradient in metallicity ($-0.027\pm0.003$ dex kpc$^{-1}$).

5. The outer regions have metallicity ranging from $-0.41$ dex ($\sigma[\text{Fe/H}] = 0.11$) from the MCPS data to $-0.46$ dex ($\sigma[\text{Fe/H}] = 0.11$) from OGLE III data.

6. Both data sets suggest a shallow radial metallicity gradient for the LMC disk, up to a radius of $\approx 4$ kpc (from $-0.049\pm0.002$ dex kpc$^{-1}$ for MCPS to $-0.066\pm0.006$ dex kpc$^{-1}$ for OGLE III), in agreement with Cioni (2009).

7. We identify a few areas where the metallicity is found to be significantly different from the surrounding regions, which should be studied in detail using spectroscopic data.

A standard method which is popularly employed to estimate the metallicity in galaxies that are not as close as the MCs, is using spectroscopic data for infrared (IR) fine-structure transitions within their HII regions. There are studies based on IR fine-structure transitions that were carried out in the HII regions of our Galaxy (Afflerbach, Churchwell, and Werner, 1997; Martín-Hernández et al., 2002a), as well as in the LMC (Martín-Hernández et al., 2002b; Vermeij and van der Hulst, 2002). These studies estimate the present day elemental abundance (e.g. S, Ne) in the gas within the HII regions. The number of such regions and their spatial coverage in the LMC are statistically small to derive a global variation of metallicity within the galaxy. In this thesis, we used the RGB in the
Conclusions

CMDs of a few thousand subregions spread across the inner 4° of the LMC to map the variation of mean metallicity ([Fe/H]) across the galaxy. The metallicity map corresponds to an epoch of a few Gyr, similar to the age of the tracers and calibrators, and does not provide estimates of elemental abundances. Thus, it is difficult to derive a one-to-one relation between the mean metallicity of the LMC estimated using RGBs and the present day elemental abundance in the gas.

7.2 Conclusion

As mentioned in Chapter 1, the populous clusters in the MCs have attracted a lot of attention and the well-studied clusters fall in the massive end of the mass spectrum. Therefore, studies which focus on the cluster formation history and survival of cluster systems are biased towards massive clusters. Some of the recent studies have attempted to increase our understanding of the open cluster like systems in the LMC (e.g., Piatti 2012b, 2014; Palma et al. 2013). It is important that we locate, identify and study clusters even at the low mass limit of the cluster mass spectrum.

In this context, this study has not only contributed to estimating parameters of poor clusters, but also in separating true clusters from asterisms. From our study of sparse star clusters in the LMC, we conclude that the LMC has open cluster like star cluster systems. It is important to include them to understand the CFH and the survival time scale of clusters. In this connection, our estimates of the mass of possible clusters suggest that a mass of few hundred M☉ is possibly the lower limit of the cluster mass spectrum. This is the limit where the system fails to get itself identified as a star cluster. Our attempt to identify these systems at different ages is a step towards understanding the lifetimes of these systems as groups in the disk of the LMC.

The metallicity map of the LMC is first of its kind and we have suc-
cessfully demonstrated that our method of combining photometry with spectroscopy is very efficient in obtaining a high spatial resolution metallicity map. We point out that this is the first such attempt even in this nearby and well-studied galaxy. In this thesis, we have developed an efficient technique where large area photometry is combined with spectroscopy of selected regions. This technique can be applied to nearby galaxies in the Local Group to obtain their mean metallicity maps, which are unavailable for all of them.

The metallicity map identifies the bar of the LMC to be a chemically distinct and its most metal-rich component. The bar, at least chemically, fits the general definition of bars, with uniform and high metallicity. The above facts lead us to define the LMC, in the galaxy classification scheme. We find that the chemical distinction of the bar and lack of recent star formation puts the LMC in the class of low-mass galaxies (Ellison et al., 2011). In the context of the role of bar in the LMC, we find that the bar of the LMC must have been active in the past, which is necessary to explain the uniform and high metallicity.

The LMC metallicity gradient of the disk, though shallow, resembles the gradient seen in spiral galaxies (Pilkington et al., 2012). The value of the gradient is also similar to that found in our Galaxy (Luck, Kovtyukh, and Andrievsky, 2006). Thus, chemically, the LMC disk resembles spiral galaxies. The disk of the LMC is a prominent entity which chemically resembles disks of our Galaxy, even though the LMC is much less massive than our Galaxy.

\section*{7.3 Future Work}

In continuation to the study done during the thesis, we plan to follow up on the following lines:

We plan to increase the number of low-mass star clusters by identifying them and estimating their parameters. One of the challenges in
studying large number of poor clusters is in the consistent estimation of cluster parameters. Also, it is not possible to visually inspect large samples of clusters and estimate parameters manually. We plan to create a framework for a systematic and consistent estimation of cluster parameters. The initial implementation of this method is planned using the OGLE III data and the clusters listed in Bica et al. (2008), which will be identified and studied. This method, once tested and executed can be used for all upcoming major data sets, such as, OGLE IV, DECAM survey, VISTA survey and LSST.

The LMC disk suffers from differential reddening, primarily near the central bar and star forming regions. Such regions give poor estimations of slope, and thus were left out in the photometric metallicity maps presented using V and I passbands of OGLE III and MCPS data. The effect of reddening will be less in the near-infrared (NIR) passbands. The NIR photometric data from the Infrared Survey Facility (IRSF)–Magellanic Clouds Point Source Catalogue of the LMC (Kato et al., 2007), can be used to construct a metallicity map. The data has a resolution of 0.45 arcsecond per pixel, and a sky coverage of 40.0 square degrees that almost overlaps with the MCPS survey region. The high resolution NIR metallicity map will thus complement its optical counterpart. The metallicity maps based on optical and NIR data will be compared in future to understand the effect of differential reddening.

A similar study will be initiated to estimate a metallicity map for the SMC, using the OGLE III (Udalski et al., 2008b) and MCPS (Zaritsky et al., 2002) photometric data in V and I passbands. We plan to develop a technique similar to the LMC to first estimate the RGB slopes and then calibrate the same to metallicity using spectroscopic results. There have been some recent as well as previous efforts to understand the chemical enrichment of the SMC using field giants, e.g. Carrera et al. (2008b); Parisi et al. (2010); Dobbie et al. (2014a,b); Cioni (2009), as mentioned in Subsection 1.2.2 of Chapter 1. However, a high spatial resolution metallicity
map showing the trend across the complete SMC is still unavailable. The LMC and the SMC map will be compared to understand the chemical evolution history and the interaction history of the Clouds.

We also propose a detailed spectroscopic study of a few regions in the LMC metallicity map of the outliers, since they are found to be significantly different from the surrounding regions. We plan to use the AAOmega spectrograph at the AAT for these observations, which can obtain up to 300 spectra in these selected regions. This proposal will be developed in collaboration.
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