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Stellar populations in the Magellanic Clouds

Smitha Subramanian* and Annapurni Subramaniam
Indian Institute of Astrophysics, Bengaluru 560 034, India

Abstract. The structural parameters of the Large Magellanic Cloud and the Small Magellanic Cloud are derived from the study of different stellar populations, such as, Cepheids (age ∼ 100 Myr), Red Clump stars (age ∼ 2-9 Gyr) and RR Lyrae stars (age ∼ > 9 Gyr). The structural changes of these galaxies as a function of time are identified and the processes which are responsible for these changes are discussed. The formation and early evolution of these two galaxies are found to be different.

Keywords : (galaxies:) Magellanic Clouds, stars: distances, stars: horizontal branch, (stars: variables:) Cepheids

1. Introduction

The Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC), together known as Magellanic Clouds (MCs), are two nearby dwarf galaxies located at a distance of around 50 kpc and 60 kpc respectively. They are considered to have had interactions with each other as well as with our Galaxy (Westerlund 1997). The Magellanic Bridge and the Magellanic Stream, neutral H I gas, between the MCs and trailing the MCs respectively, are considered as signatures of these interactions. It is also believed that the tidal forces due to these interactions have caused structural changes in these galaxies. However the recent proper motion estimates by Kallivayalil et al. (2013), and Besla et.al. (2007) indicate that the MCs may be approaching our Galaxy for the first time. These authors also claim that the MCs might not have always been a binary system. Therefore, it is not clear whether the modifications in the structure of the MCs are due to their mutual interactions, interactions with our Galaxy or something else, like minor mergers. In this thesis, Cepheids (age ∼ 100 Myr), Red Clump (RC) stars (age ∼ 2-9 Gyr) and RR Lyrae stars (RRLS) (age > 9 Gyr) in the MCs are studied to understand the structure and evolution of the MCs due to processes like interactions as well as mergers at different epochs.

*email: smitha@iiap.res.in

2. Data and analysis

The *VI* bands data of the MCs from the Optical Gravitational Lensing Experiment (OGLE) survey and Magellanic Cloud Photometric Survey (MCPS) are used to identify and study the RC stars. The *JH* data from the Infrared Survey Facility Magellanic Cloud point source catalog (IRSF MCPSC) are also used for the study of the RC stars in the LMC. For the study of Cepheids and RRLS, the catalogues from the OGLE III survey are used.

All the tracers used are standard candles. For the analysis of the RC stars and RRLS, the observed region is divided into several sub-regions. Their mean dereddened magnitude is a measure of the distance to the sub-region with respect to the mean distance to the galaxy and the dispersion (after correcting for internal extinction, intrinsic dispersion and photometric errors) is an estimate of line of sight depth. The RA, Dec and relative distance of different regions are used to locate these regions in a Cartesian like coordinate system. In the case of Cepheids, period-luminosity (PL) relation is used to estimate the relative distance of each Cepheid with respect to the mean distance of each galaxy. The structural parameters of different components of the MCs are obtained by applying appropriate methods, such as plane fitting procedure and inertia tensor analysis.

3. Results

Large Magellanic Cloud :
Disk: The disk of the LMC is studied using the photometric data of RC stars in the *V,I,J* and **H** bands. The structural parameters of the disk, such as the inclination *i* and the position angle of the line of nodes, PA_{lon} are obtained (Subramanian & Subramaniam 2010 ; Subramanian & Subramaniam 2013). We also identify a symmetric but off-centered warp in the inner LMC. The structure of the LMC disk inside the 3 degree radius is found to be different from the outside disk such that the inner disk has relatively less inclination and relatively large PA_{lon}. We found that the variation in the estimated planar parameters of the LMC disk is caused by the differences in coverage and the complicated inner structure of the disk. A large line of sight depth is found for the LMC disk, 3.44 ± 1.16 kpc and 2.88 ± 1.78 kpc from OGLE III and MCPS data sets respectively (Subramanian & Subramaniam 2009). The northern disk is found to have larger depth compared to other regions.
Bar: From the study of the RC stars we found that the bar is coplanar with the disk within ∼ 460 pc (Subramaniam & Subramanian 2009a). An average line of sight depth 3.95 ± 1.42 kpc is estimated from the study of optical data. Also, the ends of the bar are found to be flared.
Halo: We studied the RRLS to identify the halo (Subramaniam & Subramanian 2009b). The distribution of RRLS in the inner LMC is found to have a major axis (= $125^o \pm 17^o$) and inclination (= $31^o.3 \pm 3^o.5$) similar to that of the disk. These suggest that the RRLS do not form a spheroidal system, but lie on an equatorial plane,

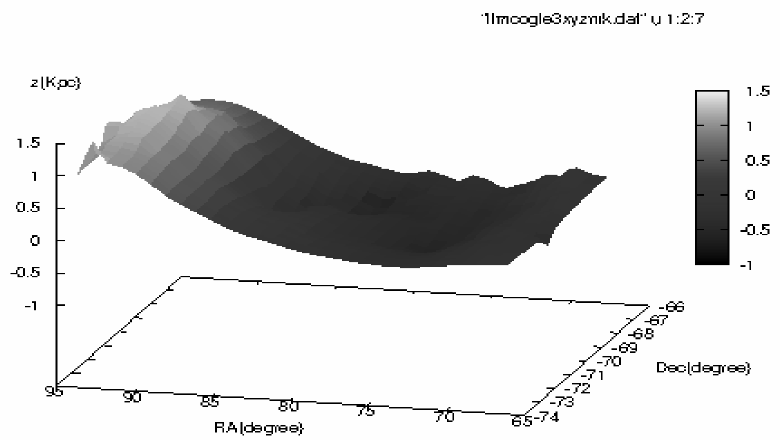

Figure 1. A three dimensional picture of the LMC.

Table 1. Structural Parameters of the MCs as a function of time.

Galaxy	RRLS (> 9 Gyr)	RC stars (~ 2–9 Gyr)	Cepheids (~ 100 Myr)
LMC	Majority are in disk i = 31^o.3 ± 3^o.5 Major axis = 125 ^{o} ± 17^o	Disk i = 37°.4 ± 2°.3 PA_{lon} = 141°.2 ± 3°.7	Disk i = 30^o.7 ± 1^o.1 PA_{lon} = 151 ^{o} ± 2^o.4 Nikolaev et al. (2004)
SMC	Spheroid Axes ratio:1:1.33:1.61 i(of longest axis) = 2°.6 ϕ = 70^o.2	Spheroid Axes ratio 1:1.33:1.61 i(of longest axis) = 2°.6 ϕ = 70^o.2	Disk i= 61^o.35± 3^0.5 PA_{lon} 132^o.5 ± 10^o.5

similar to that of the disk. From scale height analysis we found that 43% of stars in the sample follow a distribution with a scale height like that of the disk. There is another fraction (47%) of RRLS which has a puffed up distribution which probably traces the inner halo. Only a small fraction (10%) is likely to be tracing the extended halo of the LMC.

Small Magellanic Cloud :

Spheroidal component: The properties of the RC stars and RRLS are studied and compared to understand the spheroidal component. The depth profiles of both the populations are found to be similar indicating that these two populations occupy the same region within the SMC. The line of sight depth estimated is ~ 14 kpc. The surface density distribution and the radial density profile of the RC stars suggest that they are distributed in a nearly spheroidal system. The tidal radius estimated for the SMC system is ~ 7-12 kpc. An elongation from NE -SW is also seen in the surface density map of the RC stars in the SMC. Our estimates for the tidal radius and various observational studies of the outer regions suggest that the full extent of the SMC in the XY plane is similar to the front to back distance estimated along the line of sight.

These results suggest that the actual structure of the SMC is spheroidal or slightly ellipsoidal (Subramanian & Subramaniam 2012).
Disk: From the study of Cepheids, we found an inclination, $i = 61°.35±3°.5$ and $PA_{lon} = 132°.5±10°.5$ for the disk. The Cepheids with period P < 2.5 days and with period P > 2.5 days are found to be two different populations.

4. Summary and Conclusions

- We did not find a prominent stellar halo for the LMC. The structural parameters of the disk as a function of time suggest that the disk of the LMC has not evolved much through its lifetime. To explain the disk-like distribution of the major fraction of the RRLS we suggest that a major star formation event happened 10-12 Gyr ago in the LMC, probably due to a gas rich merger . The highly structured disk and warps in the disk also suggest that the LMC has experienced heating due to minor mergers and interactions with the SMC and/or the Milky Way.
- The SMC is a dwarf galaxy without a prominent stellar halo. We propose that the SMC experienced a merger with another dwarf galaxy, about 4−5 Gyr ago, and the merger process was completed in another 2-3 Gyr. This resulted in a spheroidal distribution comprising of stars older than 2 Gyr and the formation of a highly inclined disk.
- The formation and early evolution of the LMC and the SMC are found to be different. The LMC and the SMC seem to have experienced major mergers individually at different epochs. Thus it is quite possible that the LMC and the SMC came closer after the major event experienced by the SMC. It is possible that the LMC and the SMC formed and evolved separately and have been interacting with each other only in the last 4 Gyr or less.

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