Structure of the Large Magellanic Cloud from Near Infrared magnitudes of Red clump stars

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ABSTRACT

Context. The structural parameters of the disk of the Large Magellanic Cloud (LMC) are estimated.

Aims. We used the JH photometric data of red clump stars from the Magellanic Cloud Point Source Catalog (MCPSC) obtained from the InfraRed Survey Facility (IRSF) to estimate the structural parameters of the LMC disk, like the inclination, $i$ and the position angle of the line of nodes (PA$_{\text{lin}}$), $\phi$.

Methods. The observed LMC region is divided into several sub-regions and stars in each region are cross identified with the optically identified red clump stars to obtain the near infrared magnitudes. The peak values of H magnitude and (J−H) colour of the observed red clump distribution are obtained by fitting a profile to the distributions and also by taking the average value of magnitude and colour of the red clump stars in the bin with largest number. Then the dereddened peak H$_{\text{der}}$ magnitude of the red clump stars in each sub-region is obtained from the peak values of H magnitude and (J−H) colour of the observed red clump distribution. The RA, Dec and relative distance from the center of each sub-region are converted into x, y & z Cartesian coordinates. A weighted least square plane fitting method is applied to this x,y,z data to estimate the structural parameters of the LMC disk.

Results. An intrinsic (J−H)$_{0}$ colour of 0.40 ± 0.03 mag in the IRSF SIRIUS filter system is estimated for the RC stars in the LMC and a reddening map based on (J−H) colour of the RC stars is presented. When the peaks of the red clump distribution were identified by averaging, an inclination of 25°.7 ± 1°.6 and PA$_{\text{lin}}$ = 141°.5 ± 4°.5 were obtained. We estimate a distance modulus, $\mu$=18.47±0.1 mag to the LMC. Extra-planar features which are in front as well as behind the fitted plane are identified which match with the optically identified extra-planar features. The bar of the LMC is found to be part of the disk within 500 pc.

Conclusions. The estimates of the structural parameters are found to be independent of the photometric bands used for the analysis. The radial variation of the structural parameters are also studied. We find that the inner disk, within ~ 3°.0, is less inclined and has larger value of PA$_{\text{lin}}$ when compared to the outer disk. Our estimates are compared with the literature values and the possible reasons for the small discrepancies found are discussed.

Key words. (galaxies:) Magellanic Clouds; galaxies: structure; stars: horizontal-branch

1. Introduction

The Large Magellanic Cloud (LMC) is a disk galaxy with planar geometry and the orientation measurements of the LMC disk plane have been estimated previously by various authors (de Vaucouleurs & Freeman 1972, van der Marel & Cioni 2001, Olsen & Salyk 2002 and Subramanian & Subramaniam 2010) using optical data of different tracers. Reddening plays an important role in the estimation of the structural parameters of a galaxy. As the effect of reddening is less in longer wavelengths, the LMC structure estimated using near infrared (NIR) data is likely to have reduced effect due to reddening. Koerwer (2009) (hereafter K09) derived an inclination, $i$ of 23°.5 ± 0°.4 and a postion angle of line of nodes (PA$_{\text{lin}}$), $\phi$ of 154°.6 ± 1°.2, using the JH photometric data of red clump (RC) stars from the Infrared Survey Facility Magellanic Cloud Point Source Catalog (IRSF MCPSC). This study was unable to identify the warps in the south western end of the disk, which is evident in the optical studies (Olsen & Salyk 2002 and Subramanian & Subramaniam 2010) of the structure of the LMC using the RC stars.

The sample of RC stars used in the study by K09 have contamination from stars in the other evolutionary phases like the AGB stars. The details of the method applied for the reddening correction is not clearly mentioned in the paper by K09. The intrinsic (J−H)$_{0}$ colour of the RC stars estimated by K09 is in the Johnson Cousins Glass filter system. This has to be transformed to the SIRIUS IRSF filter system for the accurate reddening estimation. The extinction maps of the LMC estimated from the RC stars data in optical bands, given in the lower panels of Fig. 5 and Fig. 6 of Subramanian & Subramaniam (2010) and in Fig. 3 of Haschke et al (2011) show variation in extinction across the galaxy. Especially a large reddening in the south-western disk is seen in the reddening maps where warps are identified. Hence reddening correction is a important factor in the estimation of the structural parameters and the extra-planar features of the LMC. In the analysis done by K09, there is also an overlap of sub-regions in the peripheral regions of the disk which can cause some structural information to be averaged out. The above mentioned points motivated us to re-estimate the LMC structure using the same NIR data of the RC stars used by K09. In this paper we use the photometric data of the RC stars in the J and H pass bands from IRSF MCPSC (Kato et al. 2007). The K$_{s}$ band...
The RC stars are core helium burning stars which are metal rich and massive counter parts of the horizontal branch stars. They have a constant magnitude which make them standard candles for distance estimation (Stanek et al. 1998). Their constant characteristic colour make them good tracers for reddening estimation (Subramaniam 2005). Here we use the JH magnitudes of RC stars to understand the structure of the LMC disk. The RC stars occupy a compact region in the optical colour magnitude diagram (CMD) which makes them easily identifiable. Even though they occupy a compact region in the infrared CMD, their location is blended with the location of stars in the other evolutionary phases. In this study, we identify the RC stars in the NIR by cross identifying with the optically identified RC stars to minimize the contamination of stars in other evolutionary phases, especially the AGB stars.

The structure of the paper is as follows. In section 2 the data and the selection of the RC sample are explained. The analysis is described in section 3 and the results are given in section 4. The variation of structural parameters as a function of radius is described in section 5. The effects of reddening and population effects of RC stars in the estimation of the structure are discussed in section 6. As this work is motivated by the study of K09 and we use the same data set and the tracer that used in the study, in section 7 we compare our results with the study of K09 in detail. The differences seen are also explained in this section. The conclusions of our study are given in section 8.

2. Data

The IRSF Magellanic Cloud Point Source Catalog (IRSF-MCPSC) (Kato et al. 2007) is an outcome of an imaging survey of the Magellanic Clouds (MCs) in the NIR bands J (1.25 μm), H (1.63 μm) and K_s (2.14 μm) during the period October 2001 to March 2006. The observations were made with the SIRIUS camera (Simultaneous three colour InfraRed Imager for Unbiased Survey) on the InfraRed Survey Facility (IRSF) 1.4 m telescope at Sutherland, the South African Astronomical Observatory. The SIRIUS camera is equipped with three 1024 x 1024 HAWAII arrays to enable simultaneous observations in the three bands (Nagashima et al. 1999, Nagayama et al. 2003).
The IRSF/SIRIUS pixel scale is 0.45 arcsec/pixel, yielding a field of view of 7.7 x 7.7 arcmin$^2$. The photometric catalog (Kato et al., 2007) includes 14811185 point sources for a 40 deg$^2$ area of the LMC and 2769682 sources for an 11 deg$^2$ area of the SMC. In our present study, the LMC catalog is used to estimate the structural parameters of the LMC using the RC stars.

We divided the IRSF MCPSC region of the LMC into 928 regions with a bin size of approximately 10.53 x 15 arcmin$^2$. The average photometric error (magnitude range 15 - 20 in J and H bands) is around 0.1 mag. Photometric data with error less than 0.3 mag are considered for the analysis. A sample (J - H) vs H CMD is shown in Fig. 1. To isolate the approximate RC location in the infrared CMD, we used the optical CMD of the corresponding sub-region. The RC stars are easily identifiable in the optical CMD as a separate component.

The Magellanic Cloud Photometric Survey (MCPS) (Zaritsky et al., 1997) obtained the UBVI photometry of virtually all stars brighter than V = 21 mag in the MCs. The five year survey was conducted at the Las Campanas Observatory's 1 m Swope telescope and the images were obtained using the Great Circle Camera (GCC, Zaritsky et al., 1996). The thinned 2048 x 2048 CCD has 0.7 arcsec/pixel scale. The survey scanned 64 deg$^2$ of the LMC and 16 deg$^2$ of the SMC. The IRSF observed region of the LMC comes within the MCPS observed region of the LMC. Zaritsky et al., (2004) presented the data of the LMC MCPS survey. The MCPS observed region of the LMC is also sub-divided into 1512 regions (each with an area of 10.53 x 15 arcmin$^2$). For each sub-region (V - I) vs I CMD is plotted and the RC stars are identified. A sample optical CMD of the LMC is shown in Fig. 2. For all the regions, the RC stars are found to be located well within the box shown in the CMD, with boundaries 0.65 - 1.35 mag in (V - I) colour and 17.5 - 19.5 mag in I magnitude. The average photometric error of stars in the RC magnitude range is 0.05 mag in the V and I bands. We considered only stars with error less than 0.15 mag for the identification of the RC stars.

We cross-identified the optical and infrared data and obtained the infrared (J,H) magnitudes of the RC stars identified within the box of the optical CMD (Fig. 2). Those are shown as red points in Fig. 3. Most of the RC stars are well within the box of infrared CMD, with boundaries 0.2 - 0.8 mag in (J - H) colour and 15.9 - 17.8 mag in H magnitude. Stars outside the box are not considered for the analysis. There are a few stars outside the box, especially fainter than 17.8 mag. As the H band limiting magnitude of the survey is 17.8 mag, it is justifiable to exclude those stars from the analysis. Again, from Fig. 3 we can see that the peak of the RC stars in H band is brighter than 17.8. As our method needs to identify the peak of the RC distribution, the box is used. The RC stars within the box are optically identified for all the 928 sub-regions. Out of 928 regions only 926 regions have reasonable number (100-3000) of RC stars to do the analysis.

3. Analysis

3.1. Identification of the peak magnitude and colour of the RC distribution

3.1.1. Method 1

The number distribution of the RC stars in H magnitude and (J - H) colour are obtained with a bin size of 0.05 mag and 0.04 mag respectively. The obtained distributions in colour and magnitude are fitted with a) a Gaussian function, b) Gaussian + quadratic polynomial and c) Combination of two Gaussian functions. A non linear least square method is used for fitting and the parameters are obtained. The parameters obtained are the coefficients of each term in the function used to fit the profile, error
in the estimation of each parameter and reduced $\chi^2$ value. The errors in the estimated parameters are calculated using the covariance matrix. By comparing the reduced $\chi^2$ values of different profile fits we found that combination of two Gaussian profiles, one narrow component and one broad component, fits well for the H magnitude distribution. The $(J-H)$ colour distribution in majority of the (~60%) sub-regions fits better with a single Gaussian. The colour distributions in the remaining sub-regions are best fitted with a double Gaussian distribution or a Gaussian + quadratic polynomial. By comparing the reduced $\chi^2$ values, the best profile fit is used for further analysis. The H magnitude and $(J-H)$ colour distributions are shown in Fig. 4 and Fig. 5 respectively. The best fit profiles are also shown in the figures. From Fig. 4 we can see that the H magnitude distribution is well represented by two Gaussian functions. Each Gaussian profile is separately shown as blue and red lines and the combined profile is shown as black line. The peak of the narrow component coincides with the the bin with maximum number of stars. Thus this value is taken as the RC peak magnitude for our analysis. The peak shift between the broad and narrow component ranges from 0.05 mag to 0.1 mag. The broad component peak is fainter than the narrow component peak in some sub-regions and in some other sub-regions it is brighter. The broad component may be representing the thick disk RC population and/or can be due to stars in other evolutionary phases which are the contaminants in the sample. The NIR sample are optically selected and in optical magnitude distribution such a double peak feature is not seen by Subramanian & Subramaniam [2010]. Hence we cannot conclusively say anything about the broad component peak and dispersion. In Fig. 5, the RC colour distribution which is best fitted by a single Gaussian is shown. In 20% of the sub-regions, the RC colour distribution shows double peak with broad and narrow components. The peak shift between the broad and narrow components is not always in one direction. The broad component peak is bluer than the narrow component peak in some sub-regions and in some other sub-regions it is redder. The narrow component peak is taken as the RC peak colour. Note that the RC colour distribution in majority of sub-regions has only one peak. The parameters that are needed to estimate the structure of the LMC are the peak H mag, peak $(J-H)$ mag, and the associated errors and the reduced $\chi^2$ values. Regions with peak errors greater than 0.1 mag and those with reduced $\chi^2$ value greater than 3.0 are omitted from the analysis. Thus the regions used for final analysis reduced to 775 from 926. Around 85% of the sub-regions are available for the final analysis.

3.1.2. Method 2

In the method 1, 15% of the sub-regions of the LMC are omitted from the final analysis due to poor fit of the RC distribution. Many sub-regions in the central region (within a radius of 2.5 degrees) are part of the omitted data points. Some of the outer regions are also omitted. The structural parameters of the LMC are very much dependent on the coverage and hence these inner regions which are omitted can make a vast difference in the estimates by Subramanian & Subramaniam [2010]. The location of the bar with respect to the disk and the structural parameters of the inner region (within the radius of ~2.5-3 degrees) are some of the interesting aspects related to the structure of the LMC. Thus to understand the structure of the LMC in more detail, it is important to increase the available regions in the inner region. Though the most appropriate method for the estimation of the accurate peak of the RC distribution in a sub-region is by fitting a profile by numerical analysis (method 1), we can also estimate the peak of the distribution as the average of the magnitudes of stars in the bin with largest number of stars. This allows us to estimate the peak mag of RC stars in all the sub-regions including the central regions.

The RC stars identified are binned in both H mag and $(J-H)$ colour with a bin size of 0.04 and 0.03 mag respectively. The bin with largest number of RC stars is identified in both the magnitude and colour distribution. The average H mag, $(J-H)$ colour of the stars in that particular bin and the associated standard deviation are estimated. In order to reduce the effect of binning in the estimation of average H mag and $(J-H)$ colour, we identified the number of RC stars in each bin on either sides of the bin with largest number of RC stars. If the number of RC stars in those bins is greater than the number, $(N - \sqrt{N})$ where N is the largest number of RC stars identified, those stars are also included in the estimation of average values.

3.2. Estimation of $E(J-H)$ reddening

To estimate the structural parameters of the LMC disk from the RC magnitude we need to correct for extinction. The RC peak $(J-H)$ mag at each location is used to estimate the $E(J-H)$ reddening and hence the extinction in H band. The reddening is calculated using the relation,

$$E(J-H) = (J-H)_{obs} - (J-H)_{intrinsic}$$

To obtain the absolute J and H band RC magnitudes and hence the $(J-H)_{intrinsic}$ colour of RC stars in the LMC, we used the method 1 described in Girardi & Salaris [2001]. The mean RC properties as a function of time and metallicity based on Girardi et al. [2000] isochrones are available in table format in http://pleiadi.pd.astro.it. We used the star formation rate from Harris & Zaritsky [2009] and the age-metallicity relation given by Pagel & Tautvaisiene [1998] to obtain the absolute mean absolute J and H magnitudes of RC stars in the LMC. The RC stars in the LMC has an age range. They are older than 1 Gyr and younger than 10 Gyr. We used 1-10 Gyr age range and also 1.5-9.5 Gyr age range and obtained the mean magnitudes. The mean and the standard deviation of the values obtained in the above mentioned two age ranges are used as the final value. The $(J-H)_{intrinsic}$ value is obtained as 0.47 ± 0.02 mag. K09 did a similar analysis to estimate the intrinsic colour of RC stars, assuming a constant star formation rate and a slightly different age range. The value obtained by K09 for $(J-H)_{intrinsic}$ is also 0.47 ± 0.06 mag which matches with our estimate.

But the Girardi isochrones estimate the absolute magnitudes in Bessell & Brett [1988] filters. The IRSF SIRIUS observations are done in MKO filter system. Thus it is important to do the necessary transformations to obtain the $(J-H)_{intrinsic}$ value in MKO system. The $(J-H)_{intrinsic}$ value in the MKO system has to be used for the reddening correction. We did the necessary transformations [Carpenter [2001]] and obtained the $(J-H)_{intrinsic}$ colour in MKO system as 0.40 ± 0.03 mag. The errors in the transformation co-efficients are also considered while estimating the final error associated with the $(J-H)_{intrinsic}$ colour in MKO system. In the process, the absolute mean H and J magnitudes of RC stars in the LMC are also estimated. The mean values are $M_J = -1.13 ± 0.02$ mag and $M_H = -1.53 ± 0.02$ mag. The reddening,

$$E(J-H) = J - H_{observed peak} = 0.40 ± 0.03$$ mag
towards each sub-region is estimated. The interstellar extinction towards each sub-region is estimated using the relation,

\[ A_H = 1.65 \pm 0.16 \times E(J - H) \] (K09).

3.3. Estimation of the relative distance of sub-regions from the center

The dereddened H\(_0\) magnitude of the RC stars for each sub-region is estimated using H\(_0\) = H - A\(_H\).

The difference in H\(_0\) mag between regions is assumed only due to their difference in the relative distance, \(\Delta D\) in kpc, calculated using the distance modulus formula given below.

\[ \Delta D = 50 \times 10^{(H_{\text{region}} - H_{\text{mean}})/5}, \]

where 50 is the distance to the center of the LMC in kpc.

3.4. Plane fitting procedure

The R.A, Dec and relative distance of a sub-region from the center are used to create a cartesian coordinate system using the transformation equations given below (van der Marel & Cioni 2001). Subramanian & Subramaniam 2010 see also Appendix A of Weinberg & Nikolaev 2001).

\[ x = -D \sin(\alpha - \alpha_0) \cos \delta, \]
\[ y = D \sin \delta \cos \delta_0 - D \sin \delta \cos(\alpha - \alpha_0) \cos \delta, \]
\[ z = D_0 - D \sin \delta \sin \delta_0 - D \cos \delta \cos(\alpha - \alpha_0) \cos \delta, \]

where D\(_0\) is the distance to the center of the LMC and D, the distance to each sub-region is given by D = D\(_0\) + \(\Delta D\). The (\(\alpha, \delta\)) and (\(\alpha_0, \delta_0\)) represents the R.A and Dec of the region and the center of the LMC respectively. In our analysis, the optical center of the LMC, 05\(^{h}\)19\(^{m}\)38\(^{s}\).0 -69\(^{\circ}\)27\(^{\prime}\)5\(^{\prime\prime}\).2 (J2000) (de Vaucouleurs & Freeman 1972) is taken as the center of the LMC. According to van der Marel & Cioni 2001, the adopted center does not affect the derived parameters for the LMC disk plane (inclination, PA\(_{\text{lon}}\)). The distance, D\(_0\) to the center of the LMC is taken as 50 kpc.

Once we have the x, y, and z coordinates we can apply a weighted least square plane fit to obtain the structural parameters of the LMC disk. The equation of the plane used for the plane fit is given by

\[ z = Ax + By + C \]

From the coefficients of the plane A, B & C, i and \(\phi\) can be calculated using the formula given below.

Inclination, i = \arccos(C/\sqrt{A^2 + B^2 + 1})

PA\(_{\text{lon}}\), \(\phi\) = arctan(-A/B) + sign(B)\(\pi/2\).

We calculated the deviations of the LMC disk from the plane with estimated coefficients. The expected \(\Delta D\) for a plane is calculated from the equation of a plane. The difference in the expected and calculated \(\Delta D\) values is taken as the deviation of the LMC disk from the plane. Thus the extra-planar features of the LMC disk are identified and quantified. Once the deviations are estimated, the regions with deviations above the error in \(\Delta D\) are omitted and the plane-fitting procedure is applied to the remaining regions to re-estimate the structural parameters of the LMC disk plane.

The uncertainty in the H and (\(J - H\)) peak values, uncertainty in the intrinsic colour of the RC stars, uncertainty in the reddening law are all propagated properly to estimate the error in relative distance. The error in the \(\Delta D\) values are used in the weighted least square plane fitting procedure to obtain the error in the estimated disk parameters. Thus the error in the estimate of the LMC disk parameters is calculated by propagating the systematic errors associated with all the quantities involved in the estimation.
4. Results

4.1. NIR Reddening Map towards the LMC

One of the by products of this study is the NIR reddening map towards the LMC. The shift in the peak of the \((J-H)\) colour distribution with respect to the characteristic \((J-H)\) colour of RC stars is a measure of reddening. The peak \((J-H)\) colour of the RC stars in each sub-region is estimated based on method 1 and also based on method 2. The intrinsic value of the \(E(J-H)\) colour of the RC stars in the LMC is chosen as \(0.40 \pm 0.03\) mag. Using this value, the \(E(J-H)\) value of each sub-region is estimated as described in section 3.2. A colour coded two dimensional reddening map obtained based on method 1 is shown in Fig 6. The \(E(J-H)\) value has a range from 0.04 mag to 0.13 mag with an average of 0.08\(\pm\)0.03 mag. A similar plot obtained based on method 2 is shown in Fig 7. The \(E(J-H)\) value has a range from 0.05 mag to 0.15 mag with an average of 0.08\(\pm\)0.03 mag. From the figures, Fig 6 and Fig 7 we can see that there are slight variations in the reddening estimates when region to region is considered. But the locations where large/less reddening are seen coincide well. Also, the range of reddening values (0.04-0.13 mag and 0.05-0.15 mag) and the average reddening (0.08 \(\pm\)0.03 mag) estimated from both the methods match well. In order to get a quantitative estimate of the variations, the difference in the reddening estimates obtained for each region using two methods is calculated. The difference has a range from a minimum value of 0.0002 mag to a maximum value of 0.05 mag. In most of the regions, the difference is \(\leq 0.009\) mag , which is much less than the average error (0.03 mag) associated with the estimation of reddening in both the methods. Only for a few regions (less than 6%) the difference is more than 0.03. From these maps we can see that reddening varies across the LMC. The reddening is more in the south western regions of the LMC disk as well on the eastern side. The reddening variations obtained here are similar to those obtained in the optical studies [Haschke et al 2011] & [Subramanian & Subramaniam 2010].

4.2. Structural parameters of the LMC disk

4.2.1. Method 1

The structural parameters of the LMC disk are estimated using the dereddened mean \(H_0\) magnitude of the RC stars in 775 regions. This method gives an inclination of \(i=26^o.6 \pm 1^o.2\) & \(PA_{alon}=146^o.5 \pm 3^o.5\) for the LMC disk. The deviation of the LMC disk regions from the estimated plane are calculated as explained in section 3.3. Deviations above 1.5 kpc are considered as significant deviations from the fitted plane. The lower left and upper left panels of Fig 8 show the deviation of the LMC regions from the plane. In the lower left panel, all the regions used for the analysis are plotted. The black points are those which are on the fitted plane, red points are disk regions which are behind the plane and blue points are the disk regions which are in front of the plane. In the upper left panel only the regions with deviations above 1.5 kpc are plotted and the size of the points are proportional to the amplitude of the deviation. Here also, red points are regions behind the fitted plane and blue are in front of the fitted plane. The magenta points are the regions where wars are identified by Olsen & Salyk [2002]. The blue and red crosses are the regions where infront of the plane and behind the plane features are identified in the study of Subramanian & Subramaniam [2010] using MCPS data. From the plots we can see that there are some regions which are deviated from the planar structure of the LMC disk. Even though the coverage of MCPS is larger than that of the IRSF MCs survey and that there are large number of regions omitted in the IR analysis, we can see that most of the locations of deviations identified in the present study match with the locations of deviations identified from the previous optical analysis [Subramanian & Subramaniam 2010]. In the south western LMC, there are regions which are closer to us and also away from us.

The presence of extra-planar features would affect our estimation of the structural parameters of the disk. Out of 775 regions, 91 regions show deviations greater than 1.5 kpc and are considered as real deviations. We removed these regions and re-estimated the structural parameters of the disk using the remaining 684 regions. We obtained an inclination of \(i=26^o.6 \pm 1^o.3\) & \(PA_{alon}=148^o.3 \pm 3^o.8\). The dereddened RC magnitude is plotted against the axis perpendicular to the line of nodes which is the axis of maximum gradient and it is shown in the lower panel of Fig 9. The plot clearly shows the effect of inclination from NE to SW of the LMC disk. The black points are those on the plane of the disk and the red are the extra-planar regions. The slope and y-intercept of the line fitted to the data, excluding the extra-planar regions are 0.019 \(\pm\)0.001 mag/kpc and 16.94 \(\pm\)0.1 mag. The slope is the measure of the inclination and the inclination estimated from the slope is \(25^o.4 \pm 1^o.4\).

4.2.2. Method 2

Using this method we obtained an inclination of \(i=26^o.6 \pm 1^o.4\) & \(PA_{alon}=138^o.7 \pm 3^o.5\) for the LMC disk from the analysis of 919 sub-regions. The standard deviations estimated for the peak H mag and \((J-H)\) colour are used to estimate the error in the estimation of distance. The regions which show deviation larger than 1.5 kpc are considered as real deviation. The lower right and upper right panels of Fig 8 show the deviation of the LMC regions from the plane. The optically identified deviations are also plotted. The symbols are the same as shown in the lower left and upper left panels of Fig. 8. Most of the deviations identified are similar to that obtained based on method 1. As there are more regions in the analysis based on method 2, there are some more extra-planar features identified. These deviations more or less match with the optically identified deviations. The structures in the south western region are better revealed in this analysis. As seen earlier, in the south western region along with the regions which are closer to us (which matches with the regions where wars are identified by Olsen & Salyk [2002]), there are regions which are away from us as well. Based on the amplitude of the deviations in the south western region, the deviations closer to us are significant than those away from us. Out of 919 regions, 215 regions show deviations. These regions are removed and the structural parameters are re-estimated. An inclination of \(i=25^o.7 \pm 1^o.6\) and \(PA_{alon}=141^o.5 \pm 4^o.1\) are obtained. The inclination obtained matches well within errors with the inclination obtained based on method 1. The \(PA_{alon}\) is slightly different. As the estimated parameters very much depend on the coverage of the data set, the variation in these values can be attributed to more number of inner and outer regions included in the analysis based on method 2 as compared to method 1. The dereddened H magnitude is plotted against the axis of maximum gradient and is shown in the upper panel of Fig 9. The colour scheme is the same as that of the plot in the lower panel of Fig 9. From the slope and intercept of the line fitted to the data points, the inclination of the LMC disk and the distance modulus to the LMC center are estimated. We estimated an inclination of \(25^o.0 \pm 1^o.5\) for the LMC disk.
Fig. 8. The IRSF MCPSC regions which are fitted on the plane and those which are deviated are shown. The lower left and upper left panels are the plots which are obtained from the analysis using method 1. The lower right and upper right panels are the plots obtained from the analysis using method 2. In the lower panels, black dots represent regions on the fitted LMC plane, red dots represent regions behind the fitted plane and the blue dots represent regions which are in front of the fitted plane. The upper panels show only regions with deviations, greater than 1.5 kpc out of the plane and the size of the points are proportional to the amplitude of the deviations. The blue and red crosses are regions which are in front of the plane and behind the plane respectively, identified in the optical study using MCPS data (Subramanian & Subramaniam 2010). Magenta dots are regions which are suggested as warps by Olsen & Salyk (2002). The green hexagon in both the panels represents the optical center of the LMC.

The significant result of this analysis, based on method 2, is that the structure of the central region is revealed. Most of the regions in the bar are on the plane and there are only a few regions which show deviations from the plane. This suggests that the bar is co-planar with the disk. This result is very similar to the result obtained by Subramanian & Subramaniam (2009) regarding the location of the bar with respect to the disk. Even though most of the regions in the bar are on the plane of the LMC disk, there are some localized regions which are brighter than the nearby regions. There is also one region near the center which is away from us. These suggest that the bar region of the LMC is structured.
The red points are regions which show deviation larger than \( \sigma \).
The y-intercepts obtained from the Fig 9 and Fig 11 are the mean H band magnitude to the LMC, \( M_H(\text{LMC}) \).

### 4.3. Distance Modulus

The y-intercepts obtained from the Fig 9 and Fig 11 are the mean \( H_0 \) value of the RC stars in the LMC. The mean distance modulus to the LMC can be obtained using the formula:

\[
\mu_0 = H_{0,\text{mean}} - M_{H(\text{LMC})}.
\]

In the above equation, \( M_H \) is the absolute H band magnitude of the RC stars in the LMC. \( M_{H(\text{LMC})} \) is taken as \( -1.53 \pm 0.02 \) which is calculated in section 3.2. The \( H_{0,\text{mean}} \) obtained from the lower panel of Fig 9 (method 1) is 16.94\pm0.1 mag and from the upper panel of Fig 9 (method 2) is 16.95\pm0.1 mag. Then the mean distance modulus to the LMC, \( \mu_0 \), is 18.47\pm0.1 mag (from method 1) and 18.48\pm0.1 mag (from method 2). These values match with in errors with the previous estimates of 18.54\pm0.06 mag (K09), 18.55\pm0.01 mag & 18.5\pm0.01 mag (from MCPS and OGLE III data sets, Subramanian & Subramaniam [2010], 18.5 \pm 0.02 (Alves [2004]) and 18.53 \pm 0.07 (Salaris & Girardi [2002]) towards the LMC.

### 5. Dependence of structural parameters on the photometric band

In the present study to estimate the structural parameters of the LMC disk, we assume that the variation in the extinction corrected H band magnitude of the RC stars between various sub-regions is solely due to the distance effect induced by the structure of disk. Then the variations should be independent of the chosen photometric bands. Thus, it is useful to compare the results obtained from the magnitude distribution of RC stars in H band with that of J band analysis. The analysis in J band described below is done similar to method 2 given in section 3.1.2 for H band analysis. The optically identified RC stars are over plotted in the J vs \((J - H)\) CMD and is shown in Fig 10. From the CMD we can see that most of the RC stars are well within the box of infrared CMD, with boundaries 0.2 - 0.8 mag in \((J - H)\) colour and 16.4 - 18.4 mag in J magnitude. For all the 926 sub-regions, the RC stars are identified with in this box. The RC stars identified are binned in J magnitude with a bin size of 0.04 mag. The bin with largest number of RC stars is identified in J magnitude distribution. The average J mag in that particular bin and the associated standard deviation are estimated. In order to reduce the effect of binning in the estimation of average J mag, we identified the number of RC stars in each bin on either sides of the bin with largest number of RC stars. If the number of RC stars in those bins are greater than the number, \((N \quad \pm \quad \sqrt{N})\) where \(N\) is the largest number of RC stars identified, those stars are also included in the estimation of average values. The \( E(J-H) \) value estimated for each sub-region in section 4.1 is used to find the extinction in J band for that region. The formula used is

\[
A_J = 2.63 \pm 0.23 * E(J-H) \quad \text{[Indebetouw et al. [2005]]}
\]

The extinction corrected J band magnitude for all the sub-regions are estimated. From the extinction corrected J band magnitudes the relative distance between regions and hence the \( z \) co-ordinates are obtained. A weighted least square plane fitting procedure is applied to estimate the structural parameters of the LMC disk. The deviations from the plane are also estimated. The structural parameters are re-estimated after removing the regions which show deviations larger than 1.5 kpc from the plane. An inclination of \( i = 24^\circ.4\pm2^\circ.5 \) and \( PA_{\text{lon}} = 146^\circ.3\pm6^\circ.5 \) are obtained. The parameters match well with in errors with the estimates from the analysis of H band data. The deviations from the plane are shown in Fig 11. The black points are those on the plane. The red and blue are points are regions which are behind and in front of the plane respectively. The size of the red and black points is proportional to the amplitude of deviations. The deviations obtained also match well with the deviations (shown in Fig 8) obtained from the analysis of H band data. The distance modulus towards the LMC is also calculated using the J band data and is found to be 18.47 \pm 0.1 mag. The results for the analysis of J band data match well with the results obtained from the analysis of H band data.

### 6. Radial Variation of the structural parameters

In this section, the variation of the structural parameters of the LMC disk as a function of radius is studied. As the data points are more in the analysis based on method 2, we make use of that data to find the variation of the parameters as a function of the radius. We estimated the parameters using the data within different radii, starting from 1.5 degrees to 4.5 degrees with an increment of 0.1 degree. The estimates obtained are plotted in Fig. 12 as function of radius. The lower panel shows the variation of \( PA_{\text{lon}} \) and the upper panel shows the variation of inclination. The parameters are more or less similar above the radius of 3 degrees. From the plot we can also see that the inner LMC, (within the radius of 3 degrees) is disturbed. Inclination of the disk increases gradually from inner to outer region till a radius of \( \sim 3.25 \) degrees. The \( PA_{\text{lon}} \) varies much within a radius of 2.8 degrees and then remains almost constant outwards. Variations in the inclination and position angle of line of nodes are seen with in \( \sim 3 \) degree radius. Variations with in the inner region suggest that the inner LMC, where the bar is also located, is structured/disturbed. This could be due to the effect of tidal
interactions and/or mergers experienced by the LMC. After 3.25 degrees, both the parameters of the disk remain almost constant ($i \sim 26^\circ.0$ and $PA_{lon} \sim 143^\circ.0$). Subramanian & Subramaniam (2010) estimated the parameters of the outer disk (regions which have radius greater than $3^\circ$) and that of the inner disk (data within in the radius of $3^\circ$). They found the inner disk to have lower inclination and larger $PA_{lon}$ and vice versa for the outer disk. As they had only a few regions in the inner 3 degree radius they could not see the continuous trend from inner to outer region. Here from this analysis, we confirm that the inner structure of the LMC is different from the outer structure and the inner disk is less inclined with large $PA_{lon}$ and the outer disk is highly inclined with less $PA_{lon}$. The increase in the inclination of the outer disk, which makes the north eastern part of the LMC more closer to us, could be due to the tidal interaction with the our Galaxy.

7. Effect of reddening and population effects in the detection of extra-planar features

The extra-planar features identified in the disk of the LMC are important as they give clues to the interaction of the LMC with the external systems. The effects of the population differences of the RC stars and reddening in the detection of the extra-planar features have to be looked at carefully to understand whether the structures identified are real or not. In this section we discuss in detail the above mentioned effects.

7.1. Heterogeneous population

The RC stars in the LMC disk are a heterogeneous population, and therefore they would have a range in mass, age, and metallicity. The density of stars in various locations will also vary with the local star-formation rate as a function of time. These factors result in a range of magnitude and color of the net population of RC stars in any given location and would contribute to the observed peaks in magnitude and color distributions. Therefore, the deviations found in some regions may also be due to these population differences of RC stars. But previous studies by Olsen & Salyk (2002), van der Marel & Cioni (2001), Subramaniam & Anupama (2002), Grocholski et al. (2006) and Piatti et al. (2013) suggest that the population effects in the magnitude and colour of the RC stars in the central regions of the LMC are likely to be negligible.

The contamination of the RC sample by stars in the other evolutionary phases, like the AGB stars, is less in our analysis as the stars in our sample are optically identified RC stars, as described in Section 2.

7.2. Effect of Reddening

The extra-planar features which are found to be located both behind the disk and in front of the disk, could be in the plane of the LMC disk itself if there were an over-estimate or under-estimate of the reddening respectively. It has been demonstrated by Zaritsky et al. (1997) that the extinction property of the LMC varies both spatially and as a function of stellar population. In our study, the dereddening of RC stars is done using the reddening values estimated from the RC stars itself. In order to understand the effect of reddening, we plotted a two dimensional plot of reddening as well as the deviations. The deviations and the reddening values obtained by applying method 1 as well as method 2 are given in Fig 13. The lower left and lower right
8. Comparison with previous estimates

Previously many studies have been done to obtain the planar parameters of the LMC disk using various tracers. The values obtained from those studies along with our estimates are summarised in Table 1. Tracers used in those studies are also mentioned in the table. From Table 1 we can see that the structural parameters have a range of values. The inclination varies from 122° ± 0°.8 to 37°.4 ± 2°.3 and PA$_{lon}$ varies from 122°.5 ± 8°.3 to 170° ± 5°. Our estimates are found to be with in this range. Subramanian & Subramaniam (2010) suggested that the complicated structure of the inner LMC causes variation in the estimated planar parameters depending on the area covered for each study. In the present study also, in section 5 we showed that the inner structure of the LMC is disturbed with structural variations. Various studies of the LMC disk and bar regions (Fig.6 given in Koerwer (2009), Fig.2 in Subramanian & Subramaniam (2009) and Fig.4 in Subramaniam (2003)) have shown that it is a highly structured galaxy. Thus the variations in the estimate of the planar parameters are likely to be due to these structures.

8.1. Comparison with the study of K09

In our present study we used the same data set and tracer used by K09 to understand the structure of the LMC disk. In this section we compare the results of their study with ours in detail. K09 obtained an inclination of 23°.5 ± 0°.4 and PA$_{lon}$ to be 154°.6 ± 1°.2 for the LMC disk. Our estimates of the inclination is slightly higher than the value obtained by K09 and we estimate a lower value for PA$_{lon}$. The variation in the values of PA$_{lon}$ and inclination may be due the differences in the methodologies adopted in both the analysis. There is an overlap of sub-regions in the edges of the data set in the analysis of K09. In our analysis there is no overlap of sub-regions. The contamination of the RC sample by the stars in other evolutionary phases is less in our study compared to the study of K09. Also, the reddening correction adopted by K09 is not very clear. If K09 adopted a reddening correction on a star-by-star basis, the intrinsic colour chosen by K09 is for the RC stars. The reddening correction on a star-by-star basis is applicable only if all the stars in the sample are RC stars. The sample of K09 has AGB stars and also stars in other evolutionary phases. A method less susceptible to contamination on a star-by-star basis, the intrinsic colour chosen by K09 is for the RC stars. The reddening correction on a star-by-star basis is applicable only if all the stars in the sample are RC stars. The sample of K09 has AGB stars and also stars in other evolutionary phases. A method less susceptible to contamination is to deredden the observed peak colour corresponding to the RC stars. The reddening correction on a star by star basis is applicable only if all the stars in the sample are RC stars. The sample of K09 has AGB stars and also stars in other evolutionary phases. A method less susceptible to contamination is to deredden the observed peak colour corresponding to the RC stars.
Table 1. Summary of orientation measurements of LMC disk plane

| Reference | Inclination, \(i\) | PA\(_{\text{lan}}, \phi\) | Tracer used for the estimate |
|-----------|-----------------|-----------------|-------------------------------|
| de Vaucouleurs & Freeman (1972) | 27°±2° | 170°±5° | Isophotes |
| Feitzinger et al. (1977) | 33°.0±3° | 168°±4° | HI |
| Caldwell & Coulson (1986) | 28°.0±5°.9 | 142°.4±7°.7 | Cepheids |
| Luks & Robits (1992) | – | 162°.0 | HI |
| Kim et al. (1998) | 22°.0±6° | 168°.0 | HI |
| van der Marel & Cioni (2001) | 34°.7±6°.2 | 122°.5±8°.3 | AGB stars |
| Olsen & Salvyk (2002) | 35°.8±2°.4 | 145°±4° | Red clump stars |
| Nikolaev et al. (2004) | 30°.7±1°.1 | 151°±2°.4 | Cepheids |
| Persson et al. (2004) | 27°.0±6°.0 | 127°±10°.0 | Cepheids |
| Koerwer (2009) | 23°.5±0°.4 | 154°.6±1°.2 | Red clump stars |
| Subramanian & Subramaniam (2010) (OGLE III data) | 23°±0°.8 | 163°.7±1°.5 | Red clump stars |
| Subramanian & Subramaniam (2010) (MCPS data) | 37°.4±2°.3 | 141°.2±3°.7 | Red clump stars |

Our estimates

- Method1 (H band magnitudes) | 26°.6±1°.3 | 148°.3±3°.8 | Red Clump stars |
- Method2 (H band magnitudes) | 25°.7±1°.6 | 141°.5±4°.5 | Red Clump stars |
- Method2 (J band magnitudes) | 24°.4±2°.5 | 146°.3±6°.5 | Red Clump stars |

Fig. 14. The regions in the bar of the LMC. The size of the red and blue points is proportional to the amplitude of the deviation.

colour chosen by K09). Though we expect a spread in the colour (RC stars which are slightly bluer and slightly redder than the intrinsic colour) of the RC distribution due to population effects, internal reddening and photometric errors, the colour selection range used by K09 is very large and includes stars from other evolutionary phases. If K09 has adopted star by star reddening correction, then it is not clear how they did correction for those stars which are bluer than 0.47 mag. The above mentioned differences could have resulted in the variation of the estimated parameters in the two studies.

Fig. 15. The regions used in the analysis based on method 1 are shown. The black points are regions on the fitted plane. The blue and red points are the regions which are in front of the plane and behind the plane respectively. The green points are the locations of super giant shells given by Book et al. (2008). The cyan points are the location of major star forming regions 30 Dor and N11. The magenta lines are the approximate location of the bar. The magenta hexagon is the optical center of the LMC.
K09 found that the bar floats above the disk by 1 kpc and is closer to us. The bar regions are included in our analysis based on method 2. In our study most of the bar regions are on the plane of the LMC disk. As the error associated in the estimation of the distance is ~ 1.4 kpc, regions which show deviations less than 1.5 kpc (1 sigma) are not considered as the real deviations in our analysis. In that case if the bar is brighter than the disk by only 1 kpc then it is not identified as a feature closer to us. In order to clarify this, we plotted the regions in the bar which show deviation greater than 0.5 kpc along with those which are on the plane. The plot is shown in the lower left panel of Fig. 14. The upper left and upper right panels show regions which deviate greater than 1 kpc and 1.5 kpc respectively along with the regions on the plane. In all the panels, the blue points are those which are in front of the plane, the red points are those which are behind the plane and the black points are those which are on the plane. From the comparison of our results with the study of K09 may be due to two factors. One may be the lack of appropriate reddening correction by K09 for the RC stars in the south western region. From Fig. 6 and Fig. 7 we can see that the reddening is relatively high in the south western regions. A large reddening was also found in the south western region by Olsen & Salyk [2002]. The second factor which may have contributed is the overlapping of sub-regions. In the analysis of K09 there is an overlapping of sub-regions in the south western end. From Fig 8 (upper panels) we can see that there are both in front of the plane feature as well as the behind the plane feature which may get averaged out if the regions are overlapped.

9. Conclusions

• The structure of the LMC disk is studied using the J and H magnitudes (near IR magnitudes) of the RC stars. We find an inclination of $26^\circ.6 \pm 1^\circ.3$ & $PA_{lon} = 148^\circ.3 \pm 3^\circ.8$ for the disk when the peaks were identified by profile fitting. When the peaks of the red clump distribution were identified by averaging, an inclination of $25^\circ.7 \pm 1^\circ.6$ and $PA_{lon} = 141^\circ.5 \pm 4^\circ.5$ were obtained.

• A reddening map based on $(J-H)$ colour of RC stars is presented.

• We estimate a distance modulus, $\mu=18.48 \pm 0.1$ mag to the LMC.

• The bar is found to be part of the disk, within 500 pc.

• The inner ($r< 3^\circ.0$) and outer ($r> 3^\circ$) disk structures of the LMC are found to be different.

• We identified extra-planar features in the disk similar to those identified from the optical analysis of the RC stars.

• From the comparison of our results with the study of K09, who used the same data set and tracer, we found that the selection of the RC sample from optical identification helps to reduce the contamination of the sample by stars in other evolutionary phases.

References

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