

HST observations of the field star population in the Large Magellanic Cloud

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ABSTRACT

We present V and I photometry, obtained with the *Hubble Space Telescope*, for $\sim 15\,800$ stars in a field in the inner disc of the Large Magellanic Cloud. We confirm previous results indicating that an intense star formation event, probably corresponding to the formation of the LMC disc, occurred a few times 10^9 yr ago. We find a small but real difference between our field and one further out in the disc observed by Gallagher et al.: either star formation in the inner disc commenced slightly earlier, or the stars are slightly more metal-rich. We also find evidence for a later burst, around 1 Gyr ago, which may correspond to the formation of the LMC bar. About 5 per cent of the stars in our field are substantially older than either burst, and are probably members of an old disc or halo population with age ~ 12 Gyr.

Key words: galaxies: evolution – Magellanic Clouds – galaxies: stellar content.

1 INTRODUCTION

Deep surveys of faint galaxies have revealed an ‘excess’ of faint blue objects, and it has been suggested that these may be dwarf galaxies at redshifts $z \lesssim 0.5$ (lookback times of $\lesssim 7$ Gyr) undergoing intense bursts of star formation (cf. Cowie, Songalia & Hu 1991; Babul & Ferguson 1996). We have in our vicinity a number of dwarf galaxies known to have undergone bursts of star formation (see Hodge 1989 for a review). Detailed studies of their star formation history and field star populations can contribute to our understanding of the evolution of such galaxies, of the mechanisms provoking bursts, of the time-scales and mass functions involved, and of what such galaxies look like prior to the onset of bursts. The time-scales and mass functions are particularly important as input for population synthesis models which attempt to interpret the integrated light of galaxies too distant to resolve into stars.

Among our neighbours, the closest and best studied is the Large Magellanic Cloud (LMC), believed to have undergone a global burst of star formation a few Gyr ago, possibly provoked by a close encounter with the Milky Way. The LMC is still experiencing a significant amount of star forma-

tion, which gives it a patchy, irregular appearance, but its underlying light is well represented by an exponential disc with scalelength $\alpha = 0.65 \text{ deg}^{-1}$ ($= 0.74 \text{ kpc}^{-1}$) (cf. de Vaucouleurs 1960; Elson, Fall & Freeman 1987). The inner $\sim 5^\circ$ of the disc, imaged in the Hodge–Wright Atlas (Hodge & Wright 1967), is relatively well studied. The disc extends to at least $\sim 9^\circ$, and its rotation curve appears to be constant out to this distance, and possibly to $\sim 15^\circ$, suggesting the presence of a dark matter halo (cf. Schommer et al. 1992).

Until recently, the rich star clusters in the LMC have provided the primary tracers of its star formation history (cf. Girardi et al. 1995). The clusters range from a few million years old to objects as old as the globular clusters in the halo of our own Galaxy. There appears to be a gap in the age distribution: a thorough investigation of the richest clusters has so far yielded no examples with age between about 4 and 10 Gyr (cf. Da Costa, King & Mould 1987; Jensen, Mold & Reid 1988). Clusters with age less than ~ 4 Gyr share the kinematics of the young disc. The oldest clusters also appear to have disc-like, rather than halo-like kinematics, although the sample is small ($N \sim 10$) and so the properties of this disc are poorly determined (Freeman, Illingworth & Oemler 1983; Schommer et al. 1992).

Field stars provide a more direct and detailed probe of the star formation history of the LMC. Recent ground-based studies of the field star population have been carried

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out by Bertelli et al. (1992), Westerlund, Linde & Lyngå (1995) and Vallenari et al. (1996a,b). Bertelli et al. examined three regions $\sim 5^\circ$ from the centre of the LMC, with photometry to $V_0 \lesssim 23$. Their data suggest a global burst of star formation 2–4 Gyr ago, with the exact timing depending on the choice of stellar evolution models. Vallenari et al. use the same method and similar data to investigate the stellar population in six fields, and reach a similar conclusion. They also suggest that the time of onset of the burst varies with location. Westerlund et al. study regions in the NW and SW of the LMC, and find a strong component with age 1–3 Gyr, and a very weak component with age 7–10 Gyr in each region. Gallagher et al. (1996) use the data from the *Hubble Space Telescope* (*HST*) in the V and I bands to construct a colour–magnitude diagram (CMD) to $V \sim 25$ for 2000 stars in a field $\sim 4^\circ$ from the centre of the LMC. They conclude that a peak in the star formation rate occurred ~ 2 Gyr ago, and that there was little star formation activity prior to ~ 8 Gyr ago.

While these studies have focused on the intermediate-age population, others have addressed the question of what the LMC looked like prior to the onset of the burst, and whether it has an extended stellar halo. The oldest globular clusters, as already mentioned, have kinematics which are not consistent with a pressure-supported halo. Old long-period variables have kinematics consistent with a thick disc or flattened spheroid, with velocity dispersion $\sim 33 \text{ km s}^{-1}$ and scaleheight $\sim 0.8 \text{ kpc}$ (Hughes, Wood & Reid 1991). Other tracers of a Population II component in the LMC are giants which are too blue to be of intermediate age, and RR Lyraes (Kinman et al. 1991). Giants too blue to belong to an intermediate-age population are present in many CMDs of field stars used to subtract the background in studies of star clusters. Their numbers are generally small, and they have rarely been commented on, although occasionally they have been cited as evidence of an older population (cf. Da Costa et al. 1987; Westerlund et al. 1995). Field RR Lyraes have been studied by Kinman et al., who concluded from a sample of 80 objects that the LMC has a Population II halo or thick disc extending to $\sim 17^\circ$ and containing about 2 per cent of the mass of the LMC, a fraction similar to that in the stellar halo of our Galaxy. For a review of the intermediate and older populations in the LMC, see Olszewski, Suntzeff & Mateo (1996).

Finally, the third important component of the stellar population in the LMC is the bar, which is $\sim 2^\circ$ long, and is offset from the centre of the disc. Ground-based observations of the bar are severely limited by crowding, so little is known of when it formed or how long it took to do so. Hardy et al. (1984) studied a field near the NW end of the bar with photometry to $V \sim 21$, and found that the bulk of star formation there began earlier than ~ 1 Gyr ago. Bica, Claria & Dottori (1992) have used the star clusters in the bar to attempt to trace its evolution. They report an absence of clusters with ages 2–6 Gyr, suggesting that the bar formed $\lesssim 2$ Gyr ago; however, their results are uncertain because of the relatively small number of clusters, and because of the possibility that some of the clusters are merely seen superposed against the bar, and are not actually associated with it.

To summarize, a picture is emerging of this ‘irregular’ galaxy as composed of a Population II halo or thick disc, an

intermediate-age disc that formed quite quickly 2–4 Gyr ago, and a bar which formed a few Gyr after that. In this paper we use data from the *HST* to attempt to place further limits on the properties of these three components. In Section 2 we present *HST* observations in V and I of a field ~ 1.3 from the centre of the LMC, acquired as part of the Medium Deep Survey. Our photometry extends to $V_0 \sim 25$, well below the main-sequence turn-off of a $\sim 10^{10}$ -yr-old population. The contribution to our sample of an old and intermediate-age population is analysed in Section 3. Our results are summarized and discussed in Section 4.

2 OBSERVATIONS

Our field is located at RA = $05^{\text{h}}35^{\text{m}}36^{\text{s}}$, Dec. = $-69^\circ 25' 36''$ (J2000), near the SE end of the LMC bar, 0.7 off the major axis of the bar, and 1.3 from the kinematic centre of the LMC. It lies just 2 arcmin west of the association NGC 2050. It was observed with WFPC2 on board *HST* on 1996 January 30. The F814W ($\sim I$) and F606W ($\sim V$) filters were used. Two exposures of 500 s were taken with each of the filters. The field size is 4.56 arcmin^2 (excluding the unexposed borders of each chip). The FWHM is ~ 1.5 pixel, and the image scale is $0.1 \text{ arcsec pixel}^{-1}$. To ensure uniform star selection and photometry, we did not use the smaller Planetary Camera image, which would not increase our sample size significantly.

The images were reduced using the standard pipeline procedure, and co-added. In order to remove cosmic ray events, the smaller of the two pixel values at each position in each chip was adopted. We used the DAOPHOT task DAOFIND to identify all sources in the images to a threshold of 5σ in the F814W image. We constructed a point-spread function (PSF) from isolated stars in each chip, and fitted this to all the sources detected. In addition to stars, DAOFIND identifies a significant number of spurious detections, particularly along diffraction spikes and surrounding saturated stars. To eliminate these from our sample, we used the parameters ‘sharpness’ and χ^2 , which characterize the goodness of fit to the PSF to each object. We plotted each against magnitude, and eliminated outlying objects. (General details of this approach are presented in the context of a study of the globular cluster ω Cen by Elson et al. 1995.)

Aperture photometry in the undersampled WFC images can give more accurate magnitudes than PSF fitting, as judged by the width of the resulting main sequence; this is particularly true in fields where isolated, well-exposed stars for constructing a PSF are difficult to find. We constructed CMDs from the PSF magnitudes and from magnitudes derived from aperture photometry with an aperture with radius 2 pixel. Indeed, the main sequence was ~ 25 per cent narrower in the CMD constructed from aperture photometry. We therefore adopted magnitudes from aperture photometry rather than from PSF fitting.

We applied the following corrections to our 2-pixel aperture magnitudes, following Holtzman et al. (1995a,b). (1) A small correction for geometric distortion; this was always less than 0.04 mag, and independent of filter. (2) Aperture corrections to a 10-pixel radius which contains 100 per cent of the light. These were 0.26 mag in V_{606} and 0.28 mag in I_{814} , from table 2b of Holtzman (1995a); uncertainties are ± 0.05 mag. (3) Synthetic zero-points from table 9 of

Holtzman et al. (1995b). (4) A reddening correction of $E(B-V) = 0.20 \pm 0.04$ from Hill, Madore & Freedman (1994), which was determined from *UBV* photometry of 72 stars in the association NGC 2050, just 2 arcmin east of our field. This corresponds to $E(V-I) = 0.27$ and $A_V = 0.63$ (Taylor 1986). We note that any variations in the reddening in this area of the LMC on a scale $\lesssim 2$ arcmin will contribute to the uncertainties in our results. However, the agreement with the results of Gallagher et al. (1996), discussed in Section 3.1 below, gives us confidence in our adopted value of reddening. Finally, we adopted a distance modulus for the LMC of 18.5 ± 0.1 mag, derived by Panagia et al. (1991) from SN 1987A. This corresponds to a distance to the LMC of 50.1 ± 3.1 kpc. At this distance, $1^\circ \equiv 0.875$ kpc.

A dereddened instrumental CMD for the $\sim 15\,800$ stars in our sample is shown in Fig. 1. We converted the instrumental magnitudes to the Johnson–Cousins system using synthetic calibrations taken from table 10 of Holtzman et al. (1995b). CMDs in the Johnson–Cousins system are shown in Figs 2(a)–(c). Stars brighter than $V_0 \sim 18.6$ are saturated. Representative Poisson error bars are shown, and the additional systematic uncertainties from sources mentioned above are $\delta V_0 = \delta I_0 = \pm 0.16$, and $\delta(V-I)_0 = 0.213$. Tables with photometry are available electronically from R. Elson.

3 STELLAR POPULATIONS

To facilitate analysis of our CMD, we constructed $(V-I)_0$ histograms in 0.5-mag bins to define the loci of the main

sequence and giant branch. The histograms are shown in Figs 3(a)–(l). The colours of the peaks were estimated by eye. Fitting Gaussians gives similar results in some cases, but in many cases (e.g., the blue edge of the upper main sequence with its tail redwards) a Gaussian function is not appropriate. The peak value(s) of $(V-I)_0$ for each bin are plotted as filled circles in Figs 2(a)–(c). We have checked that the positions of these peaks are not sensitive to the choice of binning.

Superposed on the CMDs are Yale isochrones (Green, Demarque & King 1987) with $Y=0.3$ and a range of metallicities and ages. We based our choice of metallicities on the results of Olszewski et al. (1991), who plot $[\text{Fe}/\text{H}]$ versus age for 29 LMC clusters with metallicities determined from spectra of a total of 80 individual stars. The value $Z=0.01$ is appropriate for populations with age $\lesssim 1$ Gyr, while the values $Z=0.01$ and 0.004 bracket the likely metallicities of populations with age 1–5 Gyr. For a population with age $\gtrsim 5$ Gyr the range $0.004 < Z < 0.0001$ is appropriate.

The main features of our CMD are as follows.

(i) The upper main sequence is well represented by the $Z=0.01$ ZAMS. Its redward extension indicates a range of stellar ages, but because our image is saturated at $V_0 \approx 18.6$, we are unable to say anything quantitative about recent star formation in this field.

(ii) There are two peaks in the colour distribution of intermediate-age stars with $20 < V_0 < 23$; these peaks are clearly visible in the histograms in Figs 3(c)–(g), and are suggestive of two distinct main-sequence turn-offs in the CMD, and hence of two distinct bursts of star formation.

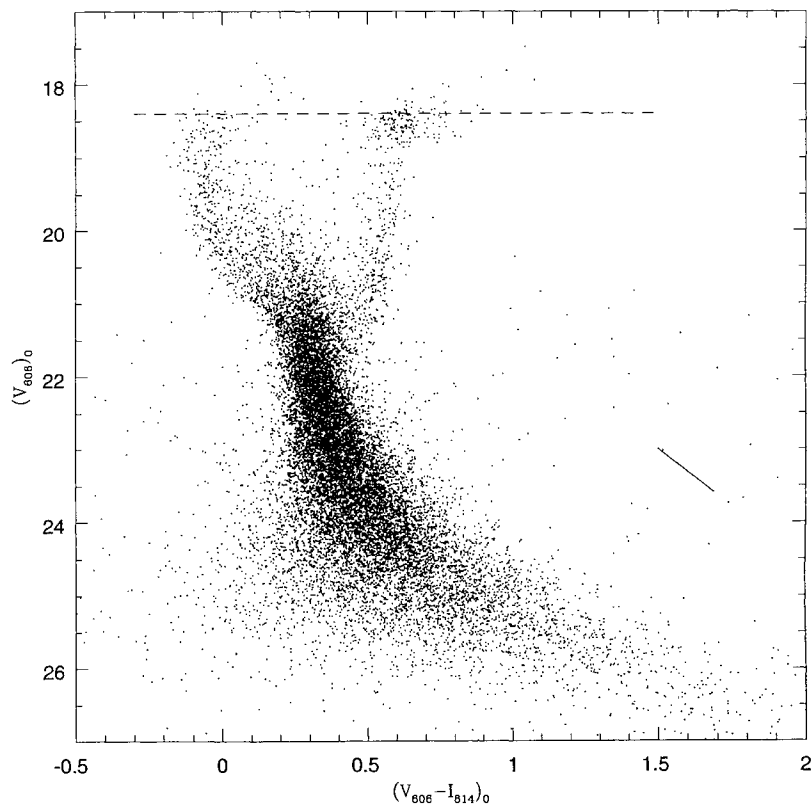


Figure 1. Dereddened instrumental CMD for $\sim 15\,800$ stars in a field in the inner disc of the LMC. The diagonal dash indicates the reddening correction applied. The horizontal dashed line indicates the saturation limit.

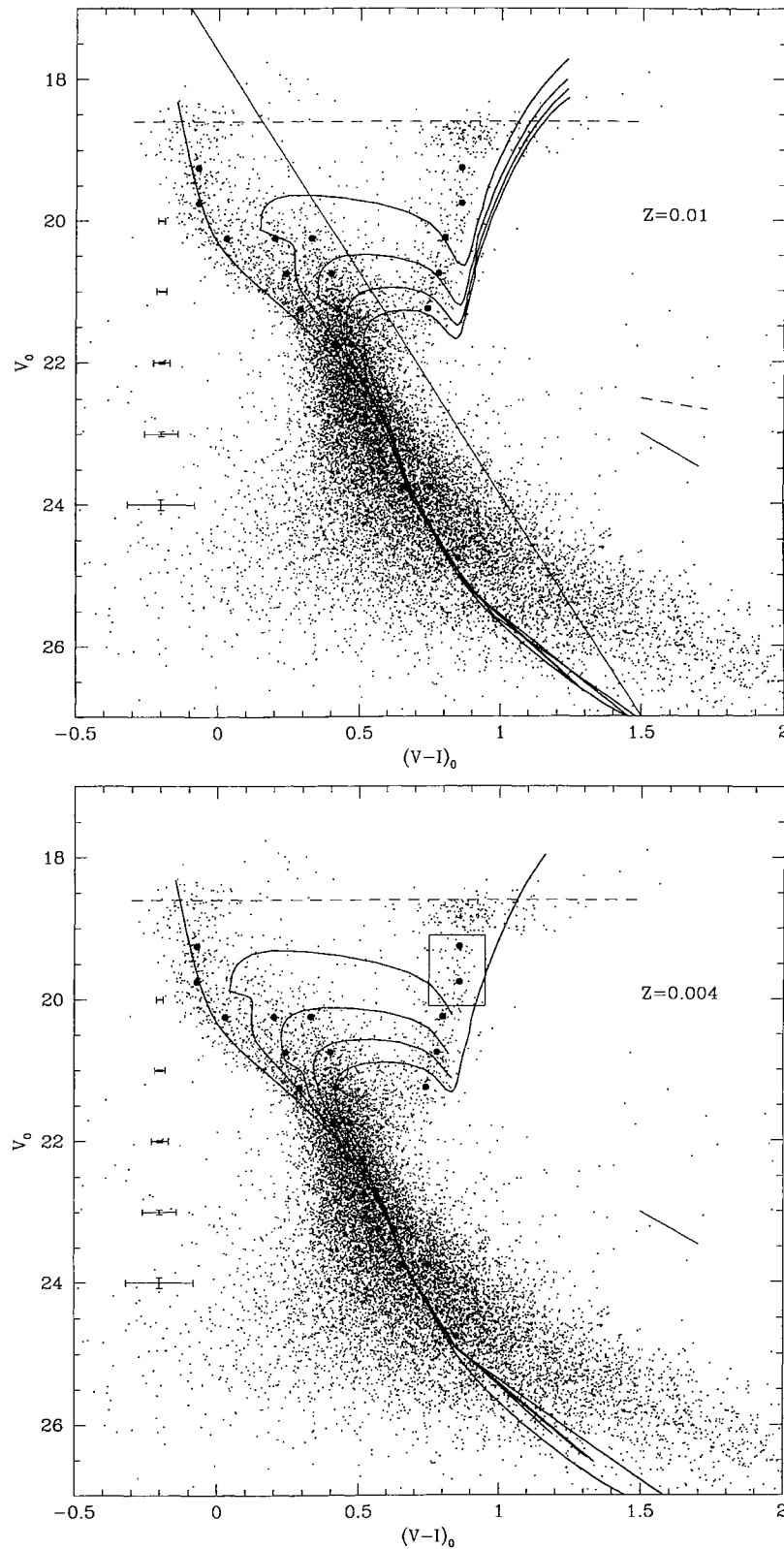


Figure 2. CMDs in the Johnson–Cousins system for $\sim 15\,800$ stars in our field. Representative Poisson error bars are shown. The dashes indicate the reddening correction applied (solid) and the systematic uncertainty (dotted), as discussed in the text. The horizontal dashed line indicates the saturation limit. The filled circles are the loci of the distribution derived from Figs 3(a)–(l). Superposed are the following isochrones: (a) A zero-age main-sequence with $Z=0.01$ and 1-, 2-, 3- and 4-Gyr isochrones, also with $Z=0.01$; the diagonal line illustrates our selection criterion for main-sequence stars. (b) A zero-age main-sequence with $Z=0.01$ and 1-, 2-, 3- and 4-Gyr isochrones with $Z=0.004$; the box indicates the selected sample of Population II giants discussed in the text. (c) A zero-age main-sequence with $Z=0.01$, a 7-Gyr isochrone with $Z=0.001$ (dotted), and 12- and 15-Gyr isochrones with $Z=0.0001$. The dashed curves are the loci of the observed giant branches of the old LMC clusters NGC 1841 and 2210.

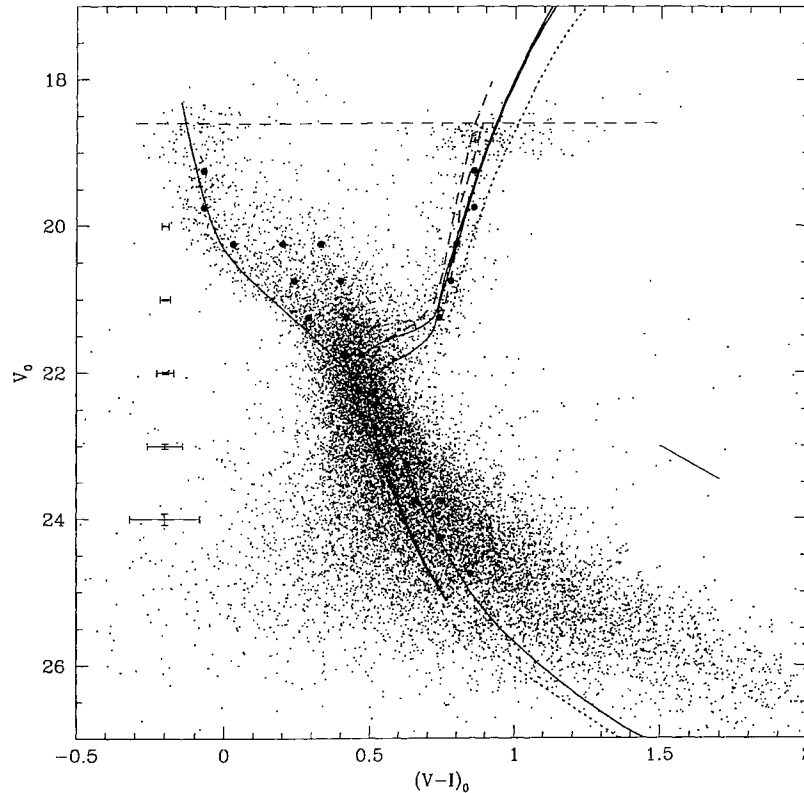


Figure 2 – continued

(iii) The lower main sequence at $V_0 > 23$ is best represented by the isochrones with $Z = 0.004$, although at $V_0 \sim 23$ the loci of the data are slightly bluer than these isochrones. This may indicate the presence of a more metal-poor population, as suggested by the isochrones with $Z < 0.001$ in Fig. 2(c).

(iv) The bulk of stars on the giant branch are significantly bluer than the intermediate-age isochrones, regardless of metallicity, but are well represented by the oldest isochrones. There is a small but significant number of redder giants, well represented by the intermediate isochrones.

(v) There is a prominent red horizontal branch ‘clump’ of giants just below our saturation limit, at $V_0 \sim 19$. Studies show that the magnitude and colour of this clump are essentially independent of the age of the population for stars with ages $\gtrsim 0.5$ Gyr (Hardy et al. 1984; Hatzidimitriou 1991).

The overall features of this comparison between our CMD and the isochrones are not dependent on the choice of isochrones; for example, the Bertelli et al. (1994) isochrones give the same general results. We now discuss in detail the different populations represented in our sample.

3.1 The intermediate-age populations: formation of the disc and bar?

The $(V-I)_0$ histograms in Figs 3(c)–(g) show two clear peaks [not including the reddest one corresponding to the giant branch, and in (c) the bluest one, which reflects the

most recent star formation]. These must correspond to two populations with distinct ages. Comparison of the loci of the stellar distribution with the isochrones in Figs 2(a) and (b) suggests an age for the younger population of slightly less than 1 Gyr, or of ~ 2 Gyr, depending on the adopted metallicity. The redder peak corresponds to a population with age ~ 2 –4 Gyr, again depending on metallicity.

Given the proximity of our field to the bar, we tentatively identify the younger component with the bar population. Our age estimate agrees well with those of Hardy et al. (1984) and Bica et al. (1992) discussed above. The age of the older component corresponds well with age estimates for the widely studied burst of star formation at 2–4 Gyr. We identify this global burst with the formation of the disc of the LMC. A more precise dating of the onset and duration of the burst is difficult, because such estimates are sensitive to the adopted (range of) metallicity, and to the choice of stellar isochrones, and because the number of stars belonging unambiguously to any one age range is small.

While absolute measurements are difficult, relative measurements are more straightforward. If, for instance, we are correct in identifying the two intermediate populations with the disc and bar, then whatever the absolute ages, the bar formed ~ 1 –2 Gyr after the disc. It would be interesting to determine from models whether an instability in a disc with the observed properties of the LMC disc would produce such a bar on this time-scale. In this context it is important to determine the age of the LMC bar more precisely, as it is the only such structure close enough to be resolved into stars, and therefore for which the star formation history and mass function can be studied in detail.

Relative measurements can also reveal whether there are spatial variations in the age and/or metallicity of the intermediate-age disc population as claimed, for example, by Vallenari et al. (1996b). Strong variations, particularly with position angle, are unlikely: at a radius of $\sim 4^\circ$ the orbital velocity in the LMC is $\sim 60 \text{ km s}^{-1}$ (Hughes et al. 1991; Schommer et al. 1992), and a typical intermediate-age star will have orbited the LMC about four times. With a velocity dispersion in the disc of $\sim 5\text{--}10 \text{ km s}^{-1}$ (Hughes et al. 1991), a star 2 Gyr old will have travelled 10–20 kpc in a random direction. The intermediate population should therefore be well mixed, and a sample drawn from any one position will contain stars that formed at random positions in the disc.

To explore whether our data contain any evidence for age or metallicity gradients in the disc, we compare our CMD with that of Gallagher et al. (1996), which was obtained with the same instrument, filters and calibrations as ours, for a field $\sim 4^\circ$ from the centre of the LMC, near the cluster NGC 1866. Figs 4(a)–(f) show a comparison between the $(V-I)_0$ histograms that Gallagher et al. derive for their sample, and those for our sample, for five different magnitude bins. In the two brightest bins there are small differ-

ences reflecting the variations in recent star formation between the two locations. The absence in the Gallagher et al. sample of the red peak from the giant branch in Fig. 4(a) is due simply to the smaller size of their sample (~ 2000 stars compared to our $\sim 15\,800$ stars). In the intermediate bins at $V_0 \approx 21.1$ and ≈ 21.7 in Figs 4(c) and (d), our histograms are significantly redder than those of Gallagher et al. The peaks are plotted in the CMDs in Figs 5(a)–(c), with isochrones with two different metallicities superposed. Either our (inner) field is slightly more metal-rich (Fig. 5a), or star formation in our field commenced slightly earlier than in the outer disc (Figs 5b and c), or both. Olszewski et al. (1991) find evidence of a slight metallicity difference, in this same sense, between clusters closer and further than 5° from the centre of the LMC.

The histograms for the faintest magnitude bin, shown in Fig. 4(e), are in excellent agreement, the only difference being that, with the longer exposure times of Gallagher et al., their errors are smaller and their colour distribution is therefore narrower. There is no offset in colour between the two samples. This further justifies our adopted value of reddening. If, for example, we had adopted a smaller red-

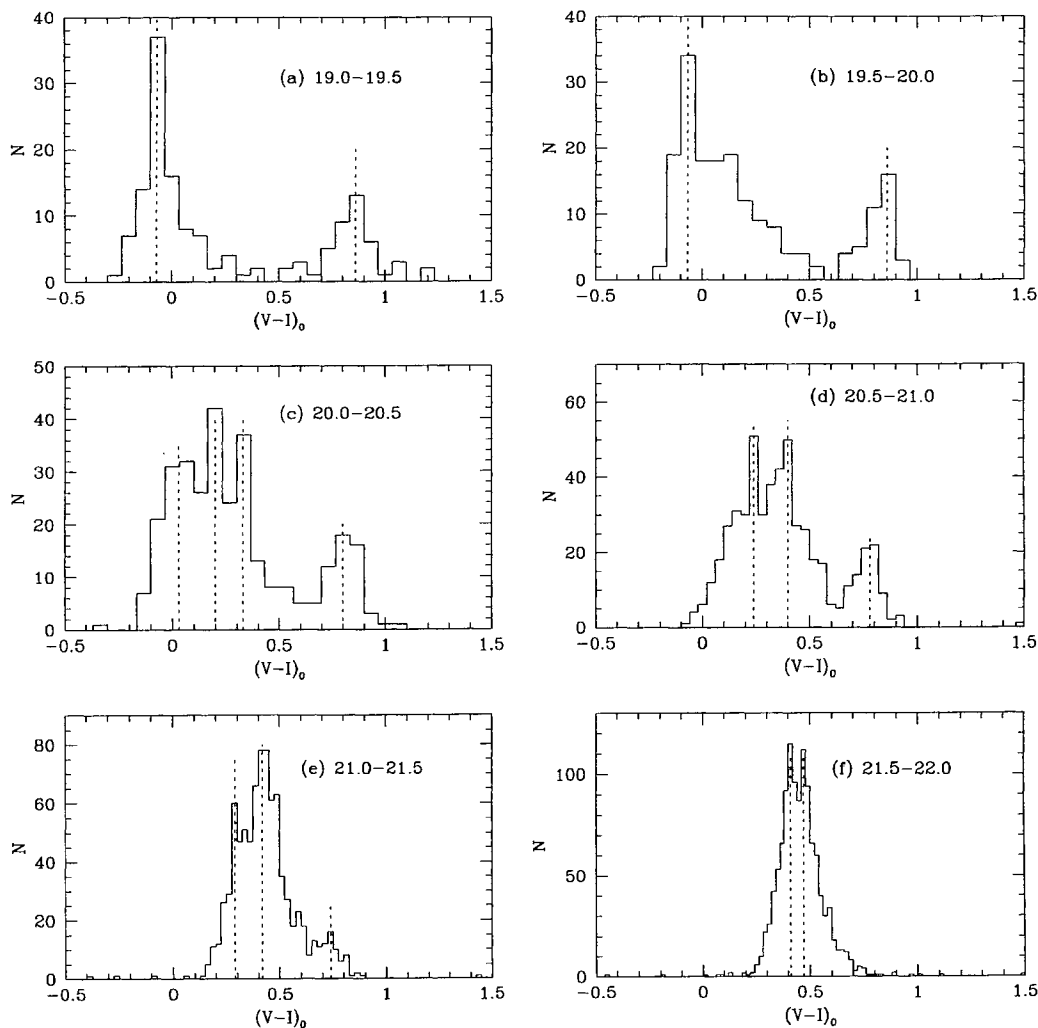


Figure 3. Histograms of $(V-I)_0$ colour constructed in 0.5-mag bins in V_0 , as indicated. The adopted peaks (plotted as filled circles in Figs 2a–c) are indicated with dotted lines.

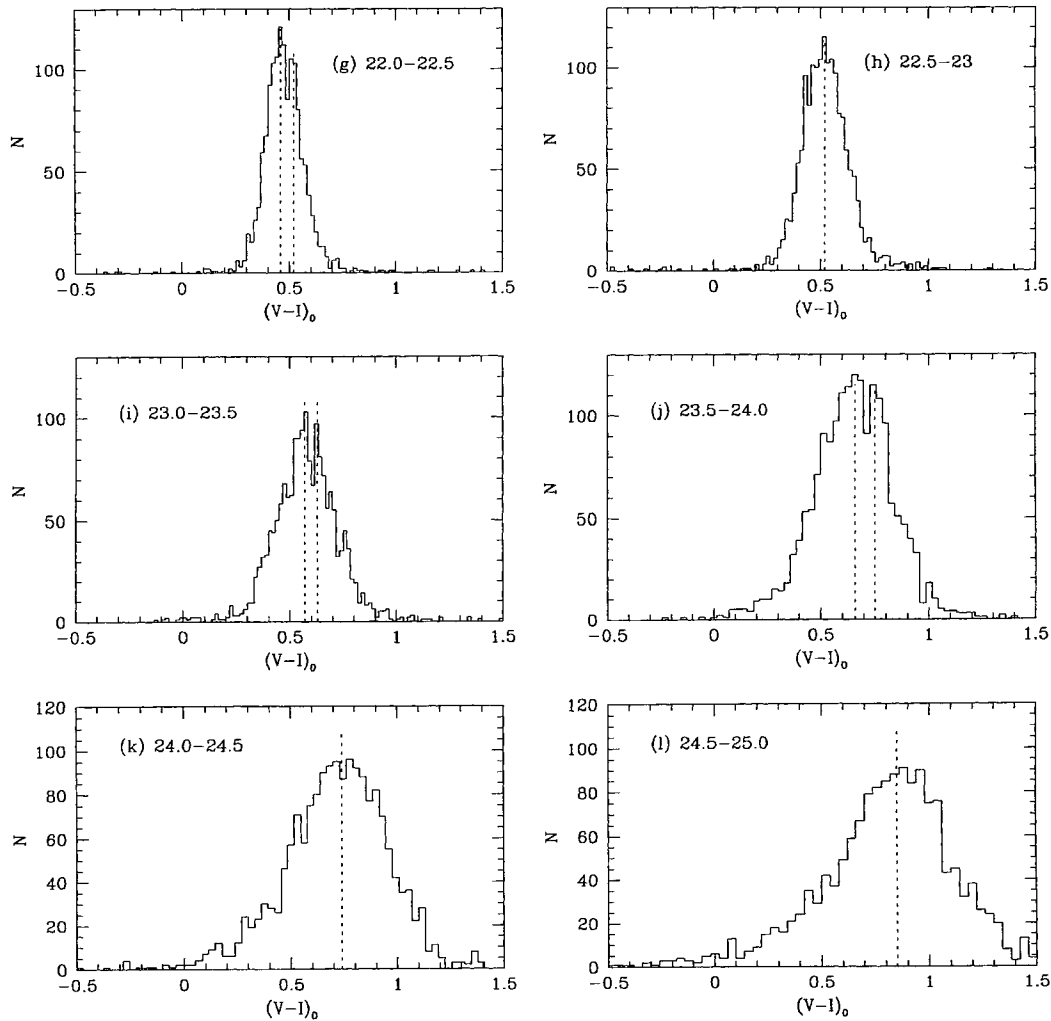


Figure 3 – continued

dening of $E(B-V)=0.1$, the giant branches of the isochrones in Figs 2(a) and (b) would pass closer to the bulk of the giants, and the main sequence would still fit adequately (although it would be too blue at the faintest end). However, there would be an offset in intrinsic colour between our sample and that of Gallagher et al. in the faintest bin, as illustrated in Fig. 4(f), while the difference in the intermediate-magnitude bins would essentially vanish. It would be difficult to explain such a large difference in intrinsic colour of main-sequence stars at faint magnitudes without a corresponding difference at slightly brighter magnitudes (Figs 4c and d).

Finally, we compare the main-sequence stellar luminosity function in our field with those in other parts of the LMC disc. Fig. 6 shows main-sequence luminosity functions for our field, and for those from Bertelli et al. (1992) and Valenari et al. (1996a,b) corrected for incompleteness. In our field, stars blueward of the dashed line in Fig. 2(a) were selected as main-sequence stars. No completeness corrections are required for our data at $M_V < 4$. We have normalized the luminosity functions to coincide at $M_V=3$ ($V_0=21.5$), below the turn-off of the intermediate-age population. Brighter than $M_V \sim 3$ there are differences

among the luminosity functions, which reflect variations in the recent star formation history across the LMC disc. Fainter than $M_V \sim 3$ the slopes of the luminosity functions appear to be quite similar, suggesting that there are no large differences in initial mass function among the different fields, although deeper observations are required to confirm this (cf. Santiago et al., in preparation).

3.2 A Population II halo or thick disc?

A picture is now emerging of the LMC in which an exponential disc formed $\sim 2-4$ Gyr ago, followed by a bar which formed perhaps $\sim 1-2$ Gyr after that. But what did the LMC look like before the formation of the disc and bar? The rotation curve suggests the presence of a halo of dark matter (Schommer et al. 1992), and studies of about a dozen old globular clusters, ~ 80 RR Lyrae stars and 63 old long-period variables provide some evidence for a Population II component. A few studies of normal field stars have also hinted at the presence of such a population (cf. Da Costa et al. 1987; Elson, Forbes & Gilmore 1994). Neither the clusters nor the variables have the kinematics of an isothermal halo, but instead appear to form a thick disc, although in the

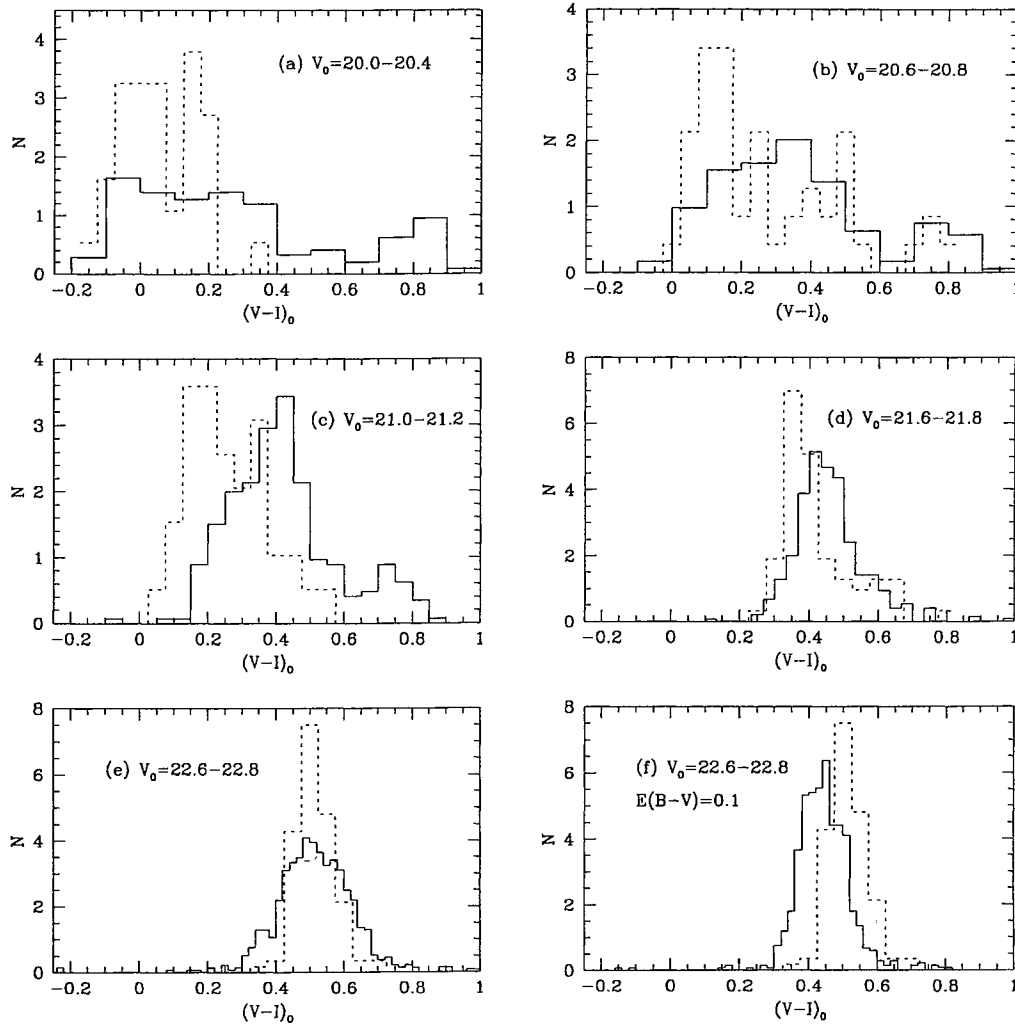


Figure 4. Histograms in $(V-I)_0$ in five different magnitude bins, as indicated. The solid histograms are for our sample, and the dotted histograms are for a field at radius $\sim 4^\circ$ in the outer disc of the LMC studied by Gallagher et al. (1996). The agreement in colour is excellent in (e), while in (c) and (d) a significant offset is present. (f) shows the comparison for the faintest magnitude bin if we had adopted $E(B-V)=0.1$ instead of 0.2.

case of the clusters, the number is so small that their systemic properties are uncertain. Kinman et al. (1991) explore the distribution of the RR Lyraes, and conclude that they are distributed either as a King model with tidal radius $r_t \sim 15$ kpc, or in a disc with exponential scalelength $\alpha \sim 0.39$ kpc^{-1} (compared to 0.74 kpc^{-1} for the young/intermediate disc).

An old stellar component is clearly visible in our CMD (Fig. 2c), in the giants just below the clump. These giants are too blue to be of intermediate age, and are well represented by 12–15 Gyr isochrones with $Z=0.0001$. (As illustrated, even a 7-Gyr isochrone has a giant branch too red to represent this population.) For comparison, the giant branches of two old globular clusters in the LMC (NGC 1841 and 2210) are also shown (Brocato et al. 1996). These clusters have ages determined from deep CMDs to be as old as the globular clusters in the halo of our Galaxy.

To quantify the spatial distribution of this old stellar population, we focus on the giant branch stars in a bin just below the bottom edge of the clump, illustrated by the box

in Fig. 2(b). These stars have $19.1 < V_0 < 20.1$ and $0.75 < (V-I)_0 < 0.95$. The numbers of stars in this box in our CMD and in that of Gallagher et al. are 60 and 12 respectively (in a field with area 4.56 arcmin^2). These surface densities are plotted against distance (R) from the centre of the LMC in Figs 7(a) and (b). The adopted centre of the LMC is at $\text{RA} = 5^{\text{h}}35^{\text{m}}48^{\text{s}}.41$, $\text{Dec.} = -69^\circ 25' 16'' 12$ (J1975). The results of Kinman et al. (1991) for RR Lyrae stars, normalized to overlap with the *HST* data, are also plotted. Fig. 7(a) shows the King models which best fit the two *HST* points, and the one derived by Kinman et al. for the RR Lyraes. The King model preferred by Kinman et al. is clearly inconsistent with our data, which indicates a higher central surface density, if the giants and RR Lyraes are indeed members of the same population. Fig. 7(b) shows the same data plotted such that a straight line represents an exponential disc. Again, our data and those of Kinman et al. suggest different scalelengths. Our results imply a central surface density of 15–20 stars per arcmin^2 in the colour and magnitude range defined by the box in Fig. 2(b).

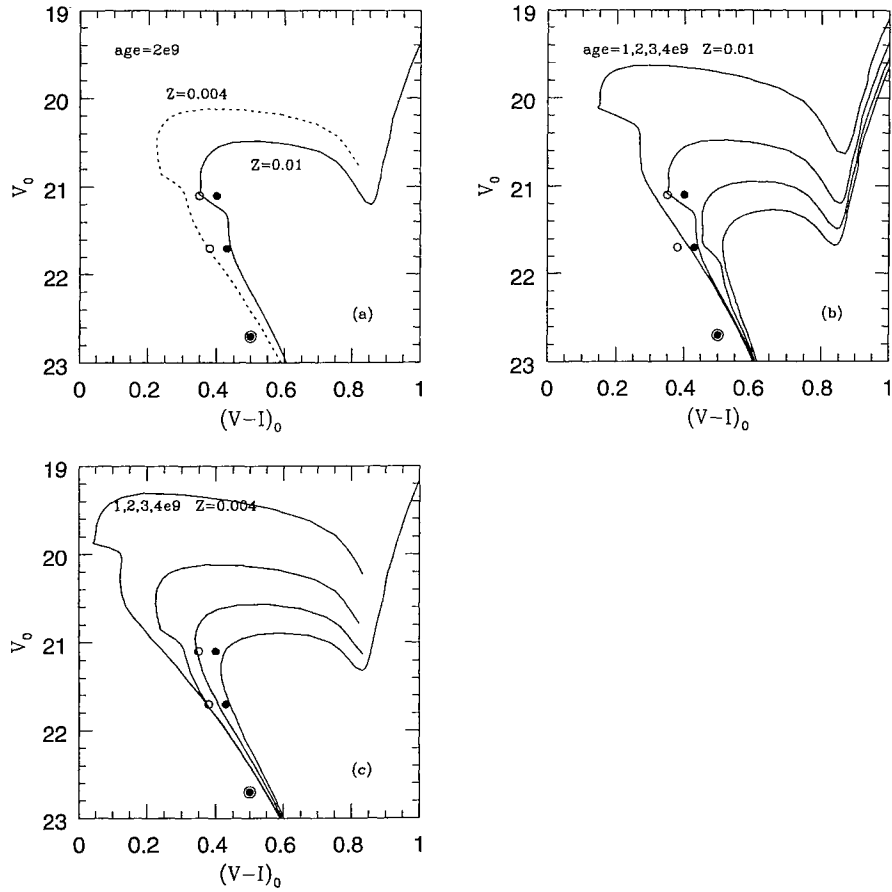


Figure 5. The positions of the peaks in Figs 4(c) and (d) compared with Yale isochrones of different metallicities and ages, as indicated. Filled circles are from our data and open circles are from Gallagher et al. (1996).

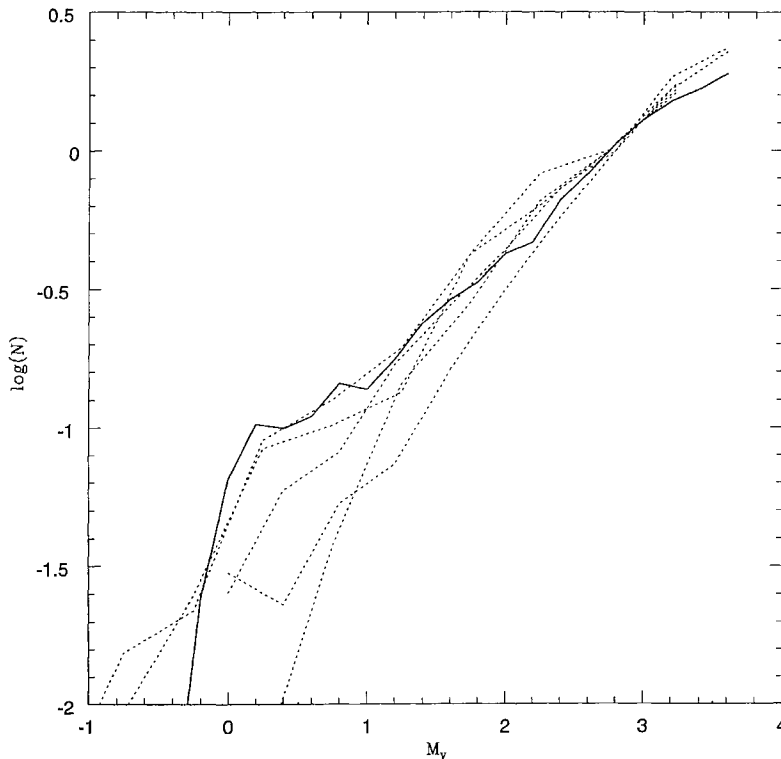


Figure 6. Luminosity functions for main-sequence stars in our field (solid curve), and for five other fields in the LMC from Bertelli et al. (1992) and Vallenari et al. (1996a,b) (dotted curves). The luminosity functions have been normalized to coincide at $M_V=3.0$ ($V_0=21.5$).

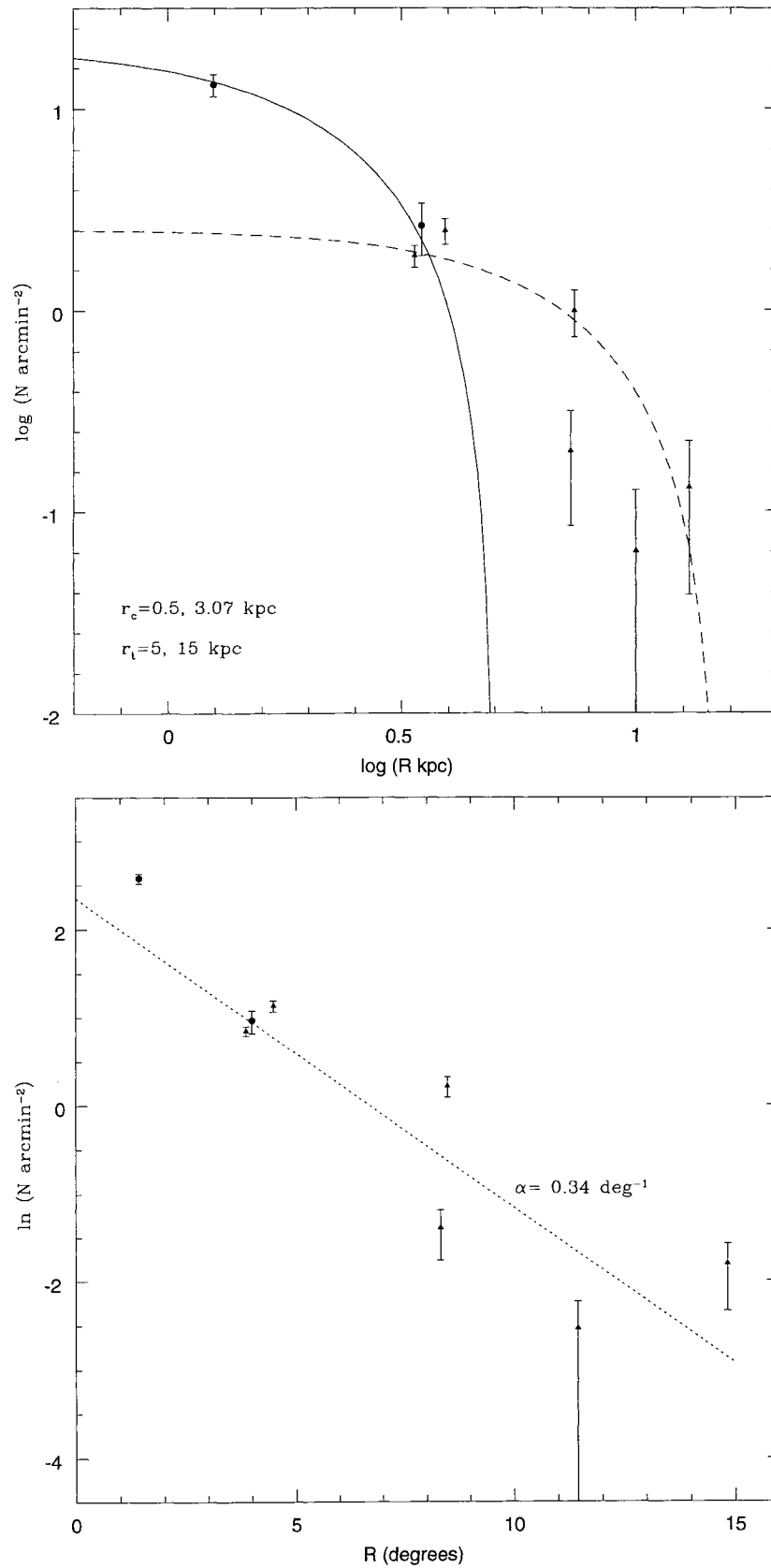


Figure 7. Surface density of Population II giants in the two fields studied with *HST* (circles), and of RR Lyraes from Kinman et al. (1991) (triangles). The RR Lyrae data have been normalized to overlap the stellar data. \sqrt{N} error bars are shown. (a) Two King models have core and tidal radii as indicated. The solid curve is fitted to the two *HST* points, and the dashed curve is as adopted by Kinman et al. (b) The same data are plotted so that a straight line corresponds to an exponential disc. The dotted line is the fit adopted by Kinman et al. for the RR Lyrae data and has exponential scalelength $\alpha \sim 0.39 \text{ kpc}^{-1} = 0.34 \text{ deg}^{-1}$.

The two *HST* points are clearly insufficient for further quantification of the structure of a Population II component of the LMC, and we note only that the old, metal-poor component of the LMC includes a significant population of ordinary field giants as well as RR Lyraes and globular clusters. In our CMD, the total number of Population II giants is ~ 250 . Assuming that there is about the same number of stars in this population at the turn-off, and assuming a Salpeter mass function below the turn-off, we estimate that a total of ~ 800 stars in our CMD, or ~ 5 per cent of our sample, are members of a population that substantially predates the formation of the LMC disc.

Further quantification of the structure of this Population II halo/disc must await the results of more deep imaging with *HST*, and analysis of the field star variables discovered by the microlensing surveys. For example, Alard (1996) uses a stack of ~ 60 Schmidt plates to isolate a sample of $\sim 10\,000$ variable stars in the LMC, most of them RR Lyraes. The sample shows a strong central concentration and appears to have a line-of-sight depth of 2–3 kpc. A similar study of the RR Lyraes in the outer parts of the LMC would be valuable.

4 SUMMARY

We have presented a CMD for $\sim 15\,800$ stars in a field ~ 1.3 from the centre of the LMC. The following features are apparent in our sample.

- (1) Ongoing star formation.
- (2) A population with age $\lesssim 1$ or ~ 2 Gyr, depending on the adopted metallicity, which we tentatively identify with the LMC bar.
- (3) A burst of star formation ~ 2 – 4 Gyr ago, which we identify with the formation of the disc. Star formation either began slightly earlier in the inner disc, or the gas in the inner disc was slightly enriched compared to another field at a radius of $\sim 4^\circ$.
- (4) A population of stars (~ 5 per cent of our sample) that substantially predates the formation of the disc.

The star formation history in local dwarf galaxies is very varied, as illustrated by Hodge (1989). For example, recent studies of the Carina dwarf galaxy by Smecker-Hane et al. (1996) show that it has a history of episodic bursts and periods of quiescence, qualitatively similar to that of the LMC. On the other hand, galaxies such as the Fornax dwarf elliptical appear to have consumed (or discarded) all their gas early in their evolution, and are almost exclusively made of old stars. The explanation of the variation in star formation histories remains elusive. A common feature appears to be that all Galactic satellites have survived very early star formation, with most retaining, or acquiring later, sufficient gas to sustain later star formation.

Are these properties of the local dwarf galaxies relevant to understanding the ‘excess’ faint blue galaxies observed in deep surveys? Cowie et al. (1991) determined redshifts for a small but complete sample of galaxies with $B = 23$ – 24 , and found the sample to be dominated by objects with $z \sim 0.25$. At this redshift, assuming $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, these galaxies have $-17 \lesssim M_V \lesssim -19$, comparable to the present absolute magnitudes of the Large and Small Magellanic Clouds ($M_V = -18.4$ and -17.0). The LMC underwent a

burst of star formation at ~ 2 – 4 Gyr ago, Carina at ~ 3 – 6 Gyr ago and ~ 2 Gyr ago. As lookback times these correspond to redshifts of $z \sim 0.1$ – 0.4 . Thus a distant observer of the Milky Way would observe its satellites flaring at these redshifts, after which they would fade quite rapidly. The disappearance of such satellites would be due to quiescence in their star formation, and not to merging.

The initial burst $\gtrsim 12$ Gyr ago in which the Population II component of such dwarf galaxies was formed would correspond to a redshift of $z \gtrsim 2$. Since the number of stars involved in the initial bursts is small, these objects would be of low surface brightness, and prior to $z \sim 0.5$ they would not be visible. For example, the Fornax dwarf galaxy has $M_V \sim -13$. At $z = 0.5$ it would have $V \sim 28$, which is near the limit of objects detected in the Hubble Deep Field (cf. Mobasher et al. 1996).

An additional constraint on the evolution of the Galactic satellites was derived by Unavane, Wyse & Gilmore (1996), who compared the stellar populations of the Galactic field halo and the dwarf spheroidal satellites to show that at most a few large dwarf spheroidal satellites can have merged into the Galactic halo in the last ~ 10 Gyr. We may combine this constraint with the results of this paper, which strengthens the evidence that dwarf satellites can survive several periods of active star formation. The combined evidence supports models of faint blue galaxies in which galaxy number is approximately conserved, but both total luminosity and, particularly, surface brightness evolve considerably.

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