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Abundance Patterns of the Large Magellanic Cloud Disk and Bar

A. A. COLE[1], T. A. SMECKER-HANE[2], E. TOLSTOY[1], and J. S. GALLAGHER[3]
(1) Kapteyn Astronomical Institute, Groningen, The Netherlands
(2) University of California, Irvine, CA, USA
(3) University of Wisconsin-Madison, Madison, WI, USA

Abstract

We give a progress report on our program to measure the metallicity distribution function, age-metallicity relation, and star-formation history of the Large Magellanic Cloud (LMC). Our main observational drivers are deep optical color-magnitude diagrams for $>10^5$ stars and medium-resolution far-red spectra for $\approx$700 red giants at several locations in the LMC. In this report, we present the first measurement of the metallicity distribution function (MDF) of red giants in the central bar of the LMC, and compare the preliminary results to the MDF of the inner disk (radius = 2° $\approx$ 1 disk scale length). In the first 15% of our bar sample to be analyzed, we have already discovered red giants as metal-poor as [Fe/H] ≈ -1.8, although the fraction of stars more metal-poor than [Fe/H] $\lesssim -1$ appears to be significantly smaller than that of the inner disk.

1.1 Introduction

The Large Magellanic Cloud (LMC) was thought for many years to have lain dormant for a large fraction of a Hubble time (e.g., Olszewski, Suntzeff & Mateo 1996), but since the advent of the *Hubble Space Telescope* and the proliferation of high-quality color-magnitude diagrams (CMDs) including stars as small as $\approx$0.6 $M_\odot$ on the main sequence, this conventional wisdom has become increasingly unfashionable (e.g., Smecker-Hane et al. 2002). While it has always been clear that intermediate-age (3–10 Gyr) and old ($>$10 Gyr) populations are present in the LMC, the relative size of these populations compared to the dominant, younger population is an open question. The existence of multiple, possibly dynamically segregated structures in the Cloud (e.g., bar, high-surface brightness central disk, low-surface brightness outer disk/flattened spheroid— see Westerlund 1998) presents an additional complication.

We have therefore undertaken an intensive study of several fields in the LMC disk and bar, obtaining deep CMDs with the WFPC2 aboard *HST* for $\sim10^5$ stars down to V $\approx$ 26 in each. Our long-term goal is an accurate and precise derivation of the star-formation and chemical evolution history of the LMC.

Results comparing the first two fields to be analyzed are presented in Smecker-Hane et al. (2002): it was found that the bar experienced an epoch of increased star-formation from $\approx$2–6 Gyr ago, for which little evidence was seen in the inner disk (see Figure 1.1). Like all CMD-based results for complex stellar populations, these conclusions are systematically uncertain due to the effects of age-metallicity degeneracy on broadband stellar colors.

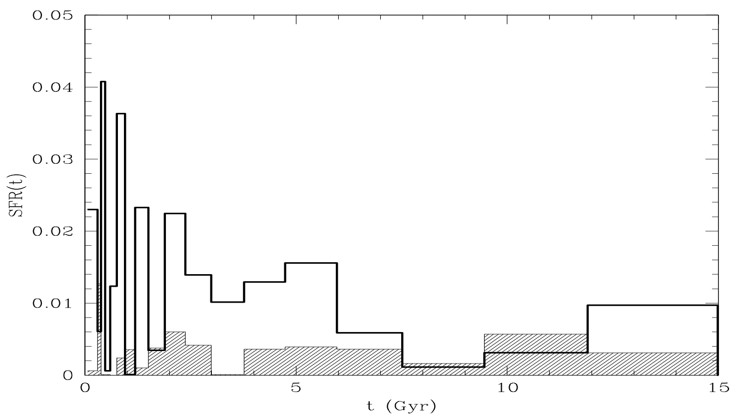

Fig. 1.1. Relative Star-formation rates as a function of age in the LMC bar (heavy line) and inner disk (hatched histogram), derived by Smecker-Hane et al. (2002). Based on WFPC2 photometry for $\sim 10^5$ stars in each field, there is strong evidence for a higher fraction of 2–6 Gyr old stars in the bar than in the disk.

The only practical way to break the degeneracy is to determine the metallicity distribution function (MDF) independently, by spectroscopic means. Therefore our photometry is supplemented by medium-resolution spectroscopy of several hundred red giants in each CMD field. We are using the far-red ($\lambda \approx$ 8500 Å) Ca II spectrophotometric index to provide abundance estimates [Fe/H] accurate to ≈ 0.15 dex per star, as well as radial velocities accurate to $\lesssim$10 km sec^{-1}. In our initial exploration of the technique, we identified a deficit of metal-poor stars compared to the predictions of simple chemical evolution models (i.e., a "G-dwarf problem"), and determined the mean metallicity of the inner disk at radius = 2° (Cole, Smecker-Hane & Gallagher 2000). Here, we recapitulate in brief our disk results to date (Smecker-Hane et al. 2004), and compare the inner disk MDF to the preliminary indications from our most recent observations: multi-object spectroscopy for ≈390 red giants in the central LMC bar.

1.2 Observations

Two disk fields at projected radius ≈ 2° were observed using the Hydra multi-fiber spectrograph at the CTIO Blanco 4-m telescope. 114 stars in a field south of the LMC center, and 150 in a western field were observed over 3 nights in December 2000. The bar field could not be observed with Hydra because of the extremely high crowding, the difficulty of placing sky fibers, and the breadth of the fibers ($2''$). Therefore we observed the bar field using the FORS2 multi-slit spectrograph at UT4 (Yepun) of the VLT. FORS2 has a $6.8'$ field of view; we observed 390 red giants in 21 instrumental setups over 3 nights in December 2002. A CMD of the bar is shown in Figure 1.2, with our targets identified. With exposure times of 2×600 sec in each setup, we reached signal-to-noise >80 per resolution element in the continuum. During periods of poor seeing, we observed a low-density field in the transitional

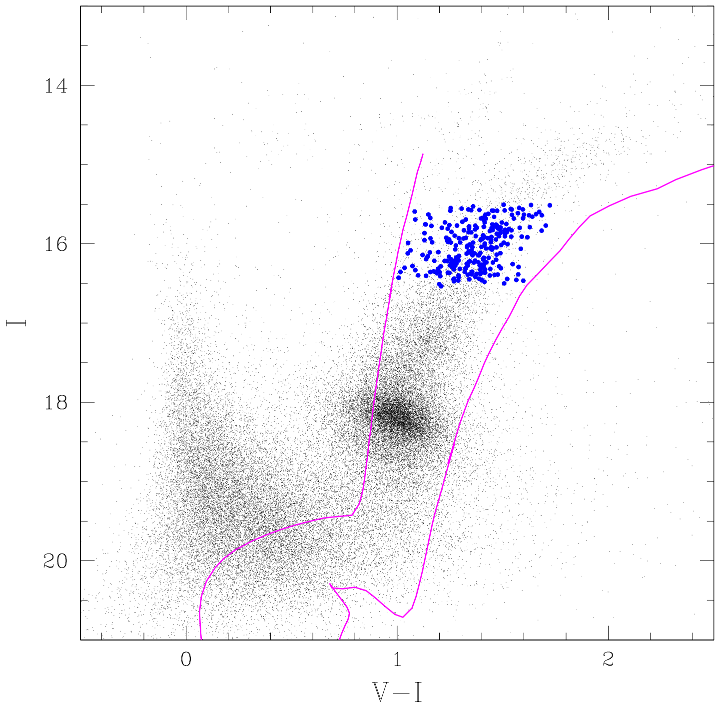

Fig. 1.2. Color-magnitude diagram of the bar field based on CTIO 1.5-meter imaging. The VLT/FORS2 targets are plotted in blue. The selection region is bounded on the red (blue) by an isochrone with age = 3 Gyr, Z = 0.019 (0.0001).

disk field near the cluster NGC 1866, at radius r = 4°. This field has WFPC2 photometry from Gallagher et al. (1996), but no abundance measurements to date– we observed 90 RGB stars in 8 FORS2 setups in the transitional disk field. A sample of stars in globular and open clusters was also observed in order to calibrate the relation between calcium line strength and [Fe/H] to a standard system (Rutledge et al. 1997).

1.3 Results

1.3.1 Disk

The disk results of Cole et al. (2000) and Smecker-Hane et al. (2004) do not need to be repeated in detail here. One of the puzzling facts discovered by Smecker-Hane et al. (2004) is that the two disk fields, at the same radius but separated by ≈90° in azimuth, have different mean abundances, by 0.15 dex: [Fe/H] = −0.61 on the minor axis, and −0.46 on the major axis. Student's *t*-test shows this difference is significant at the 99% level. The reason for the difference is unknown, but it is tempting to associate the higher abundance of the second disk field to its location near the western end of the bar. Comparing the inner disk to the outer disk/spheroid (Olszewski 1993), a difference of ≈0.3 dex in mean abundance is found, which corresponds to a metallicity gradient of ≈ −0.05 dex kpc^{-1}.

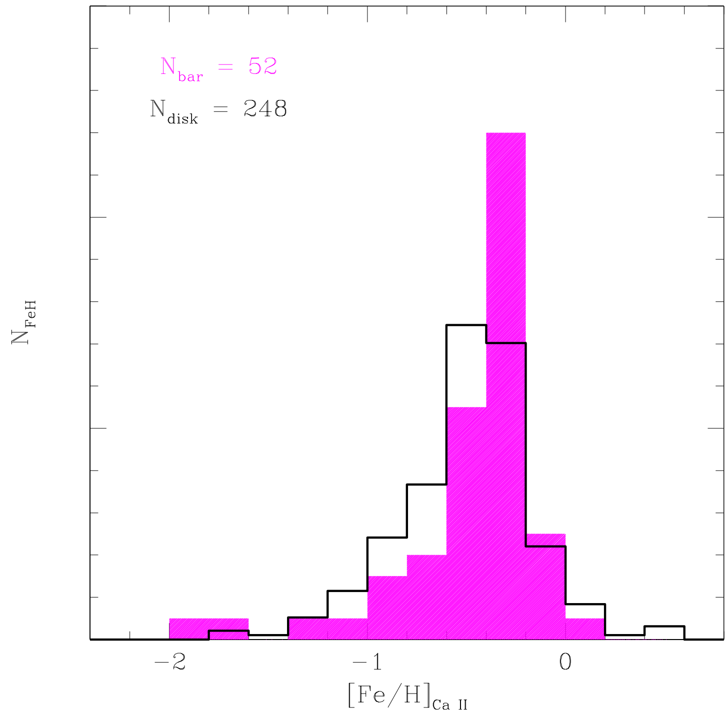

Fig. 1.3. Preliminary metallicity histogram of the LMC bar. The histogram, for 52 stars (15% of our sample), is similar in shape and peak value to the inner disk fields of Smecker-Hane et al. (2004– also shown), but has a higher fraction of stars with [Fe/H] ≈ -0.3 and a smaller fraction with $-1.1 \leq$ [Fe/H] ≤ -0.5. The outliers at -1.88 and -1.71 have radial velocities of 265 and 297 km/sec, respectively, so they are definite members of the LMC. The single bar point at [Fe/H] = +0.15 has a radial velocity of 246 km/sec. Based on its location in the CMD, it could be an AGB star or supergiant that has been differentially reddened by E(B−V) $\approx$ 0.4 mag.

1.3.2 Bar

Because of low instrumental overheads and superb observing conditions, we were able to observe 60% more stars in the bar than we had originally anticipated, bringing our total bar sample to 390 stars. The reduction and analysis of this large sample is still in progress at the Kapteyn Institute. Here we present our preliminary results for the first 52 spectra reduced. All 52 stars are located in a single co-spatial $6.8'$ square region. They are a random sampling of roughly a quarter of the available stars in our CMD selection region in this small field (Figure 1.2). Our preliminary metallicity histogram is shown in Figure 1.3. The inner disk results (both fields of Smecker-Hane et al. 2004) are shown for comparison, scaled down to the same sample size. While metal-poor stars exist in the bar, there is an apparently significant lack of stars at metallicities between -1.1 and -0.5 compared to the inner disk fields. Overall, the disk and bar MDF's have similar shapes, and the peak of the bar MDF is not *strongly* shifted to higher abundances, particularly in comparison to the major axis "disk 2" field of Smecker-Hane et al. (2004). Only one star out of 52 in the bar was found to have super-Solar metallicity according to the current calibration– it is our suspicion that this anomalously high measurement is in error, possibly due to differential reddening in the amount of E(B−V) $\approx$ 0.4 mag. Consideration of near-infrared photometry will address this issue.

1.3.3 Improved Calibration

The calibration of calcium line strength to [Fe/H] is defined by a sample of globular clusters spanning the metallicity range $-2.5 \leq$ [Fe/H] ≤ -0.5 (Rutledge et al. 1997). Therefore the possibilities of age-dependence and variable calcium:iron ratios are a concern for the interpretation (Cole et al. 2000). Available evidence supports the robustness of the Ca II triplet index (e.g., V. Hill, these proceedings), but it is still of interest to extend the range of calibration objects for this important metallicity index. During our VLT observing run, we measured the Ca triplet in red giants of 5 old open clusters with reliable metallicities (M67, NGC 2141, Melotte 66, Berkeley 20, & Berkeley 39), in order to derive a modified calibration that accounts for age-dependence (the topic of calcium:iron ratio must await a larger sample of open clusters with measured Ca abundances). This issue will become critical to the interpretation of Ca II lines in, e.g., the M31 disk and halo.

1.4 Summary

We report our progress in measuring the metallicity distribution function of LMC red giants, with emphasis on its spatial variations. We have made the first measurement of the MDF in the bar, and find it to be more metal-rich than the inner disk fields. Our results are consistent with two recent hypotheses: 1) the bar is dominated by younger and more metal-rich stars than the inner disk; and 2) azimuthal variations in the inner disk MDF are in part due to differing mixtures of bar and disk populations. Further analysis of our data will strongly constrain the places and times of chemical enrichment, and subsequent dispersal of heavy elements, throughout the LMC.

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