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Breaking the age–metallicity degeneracy: The metallicity distribution and star formation history of the Large Magellanic Cloud

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Abstract. We have obtained metallicities from near-infrared calcium triplet spectroscopy for nearly a thousand red giants in 28 fields spanning a range of radial distances from the center of the bar to near the tidal radius. We have used these data to investigate the radius-metallicity and age-metallicity relations. A powerful application of these data is in conjunction with the analysis of deep *HST* color–magnitude diagrams (CMDs). Most of the power in determining a robust star-formation history from a CMD comes from the main-sequence turnoff and subgiant branches. The age-metallicity degeneracy that results is largely broken by the red giant branch color, but theoretical model RGB colors remain uncertain. By incorporating the observed metallicity distribution function into the modelling process, a star-formation history with massively increased precision and accuracy can be derived. We incorporate the observed metallicity distribution of the LMC bar into a maximum-likelihood analysis of the bar CMD, and present a new star formation history and age–metallicity relation for the bar. The bar is certainly younger than the disk as a whole, and the most reliable estimates of its age are in the 5−6 Gyr range, when the mean gas abundance of the LMC had already increased to $[\mathrm{Fe/H}] \gtrsim -0.6$. There is no obvious metallicity gradient among the old stars in the LMC disk out to a distance of 8−10 kpc, but the bar is more metal-rich than the disk by $\approx 0.1-0.2$ dex. This is likely to be the result of the bar's younger average age. In both disk and bar, 95% of the red giants are more metal-rich than $[\mathrm{Fe/H}] = -1.2$.

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In the decade since the last IAU Symposium on the Magellanic Clouds, study of the star-formation history and chemical evolution of the field stars has become a major path toward understanding the history of the clouds. This has become important because of the growing realization that the field stars and the clusters have experienced significantly different star-formation histories (e.g., Holtzman *et al.* 1999; Smecker-Hane *et al.* 2002). Great progress has come about due to the enormously successful synergy between extremely deep *Hubble Space Telescope* imaging and wide-field photometric surveys spanning most of the central regions of both clouds. A concomitant explosion of data has occurred on the spectroscopic front, owing to the emergence of the 8-meter class telescopes and massively multiplexed spectrographs. Between the pioneering abundance survey of LMC clusters by Olszewski *et al.* (1991) and the field red giant spectroscopy of 39 disk stars in Cole, Smecker-Hane & Gallagher (2000) just one spectroscopic study of the *old* field star population appeared, the conference paper on the LMC outer disk/halo by Olszewski (1993). Since then, the amount of data has multiplied literally a hundredfold, with studies including Cole *et al.* (2005) and Carrera *et al.* (2008) using the calcium triplet, and higher-dispersion ground being broken by Smith *et al.* (2002) and Pompéia *et al.* (2008).

Our group has commenced measuring the chemical abundances of field stars in the LMC disk and bar to fill in the parameter space spanning the cluster age gap, to measure the variation of metallicity with position across the LMC, and to attempt to discern the nature of the bar as a subpopulation of the disk or a distinct entity. This requires the measurement of old stars, spanning the entire ≈ 13 Gyr history of the LMC. The most common bright stars with this range of ages are red giants, which top out in the LMC at a magnitude I ≈ 14.8. At these levels, the most reliable easy way to obtain large spectroscopic samples in a moderate amount of time is to use the near-infrared Ca II triplet at $\lambda \approx 8600$ Å. This method was calibrated with an extensive set of globular cluster data by Rutledge *et al.* (1997), and the calibration extended into the open cluster regime by Cole *et al.* (2004). The Ca triplet had previously been applied to Magellanic Cloud clusters by Olszewski *et al.* (1991) and Da Costa & Hatzidimitriou (1998). In addition to the immediate significance of metallicity information, and the radial velocity data that comes along with the spectra, this effort pays an enormous dividend in giving added value to very deep photometric studies.

The evolutionary history of a galaxy is encoded in the distributions of age and metallicity of its long-lived stellar populations. The most powerful way to recover the information from these populations is by obtaining deep color–magnitude diagrams of the galaxy and using them to derive the variation in star-formation rate as a function of time. An example of the variations that star-formation history imposes on the color-magnitude diagram is the progressive fading of the brightest main-sequence turnoff stars with population age. This can create very obvious features in a differential comparison of luminosity functions (e.g., Butcher 1977) or color–magnitude diagrams (e.g., Smecker-Hane *et al.* 2002) when the fields compared differ in mean age. Comparisons between LMC bar and disk fields in Holtzman *et al.* (1999) and in Smecker-Hane *et al.* (2002) have consistently shown an excess of stars in the bar corresponding to the main-sequence turnoff of a dominant stellar population that is much younger than a Hubble time. However, the inferred age, metallicity, and mass fraction in the younger population are model dependent — for a vivid example of the systematic effects introduced by these dependencies, see the excellent writeup of the 2001 Coimbra experiment on *HST* data taken at the center of the LMC bar, by Skillman & Gallart (2002).

Age-metallicity degeneracy is the chief source of non-uniqueness in obtaining the star formation rate as a function of time (star formation history, SFH) from deep color–magnitude diagrams (CMDs). The age–metallicity degeneracy of a simple stellar population is explicitly illustrated in Figure 1, where a tripling of the age of an isochrone is countered by a halving of the metallicity in order to create a nearly identical red giant branch (RGB). The isochrones have been chosen to be representative of the upper envelope of LMC metallicities, and have been shifted by a distance modulus $(m-M)_0 = 18.5$ mag for ease of comparison to real LMC data. In the presence of any realistic photometric error, the two giant branches in the left panel of Fig. 1 will be indistinguishable. However, CMDs that reach the subgiant branch and main sequence turnoff (shaded area) can break the degeneracy — the age and metallicity tradeoff is different for stars that are core

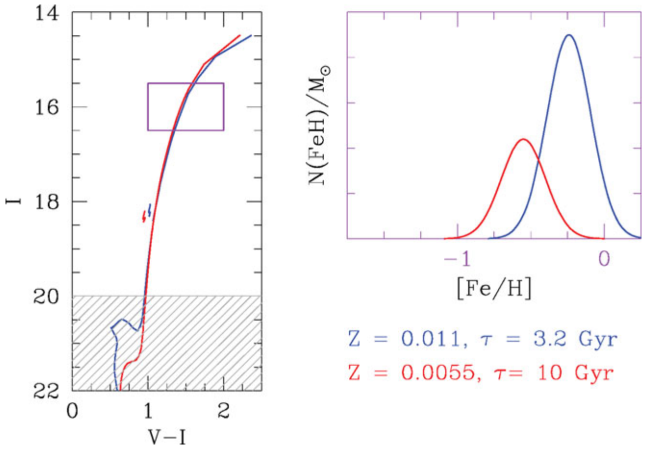

Figure 1. Illustration showing how spectroscopic metallicity measurements can break the age-metallicity degeneracy. *Left panel:* Isochrones from the Padua group (Girardi, private communication) showing how two red giant branches can have the same color if a factor of three in age is compensated by a simultaneous factor of one-half in metallicity. In this simplified example, the degeneracy is broken by observations that reach the main-sequence turnoff (shaded area), but this can be ambiguous in real, complex stellar populations. *Right panel:* The metallicity distribution functions that would be obtained from spectra of red giants selected at random from within the box in the left panel. The isochrone metallicities have been converted to [Fe/H], and convolved with the observational errors reported in Cole *et al.* (2005). Knowledge of the metallicity distribution function prevents an over-reliance on RGB colors that are notoriously difficult to compute accurately. When the photometry is deep enough, the metallicity distribution allows a more precise disentangling of age, metallicity, and reddening in complex stellar populations than provided by the CMD alone.

hydrogen-burning and not fully convective (e.g., Worthey 1999). In this case, sufficiently deep observations can break the age–metallicity degeneracy without ambiguity.

However, for a complex stellar population such as the LMC, this is not as easily done. The deep CMDs show a continuous distribution of stars corresponding to an extremely wide range of possible combinations of age and metallicity. Smearing by photometric error and differential reddening further complicate the picture, such that even with observations as deep as shown in Fig. 1, the interpretation of CMDs is challenging. Comparison of the CMDs to suites of synthetic models via χ^2 minimization or maximum likelihood techniques can find the statistically *most likely* resolution of the degeneracy, but in effect all such comparisons rely on the RGB color to supply the additional information necessary to break the degeneracy. When the ages are older than a few Gyr and the metallicities are low this is likely to be reasonable (e.g., Gallart, Zoccali & Aparicio 2005), but this is often not the case, and is certainly untrue for the Magellanic Clouds. Such an approach necessarily introduces a large degree of systematic uncertainty that will not be reflected in the reported errorbars on the solution, because of the inherent uncertainty in modelling the RGB color (e.g., Salaris 2002). Reliance on the RGB color to break the age-metallicity degeneracy may provide a satisfactory statistical fit to the CMD, but it necessarily imprecise, and incorporates a high degree of model dependence into the solution.

The right panel of Fig. 1 shows an alternative based on incorporating spectroscopic information directly into the maximum-likelihood fits to the CMD data. If a box is drawn around an area of the CMD that is accessible to spectroscopic observations (in Fig. 1a, the box corresponds to the selection area from Cole *et al.* 2005), and the metallicities of

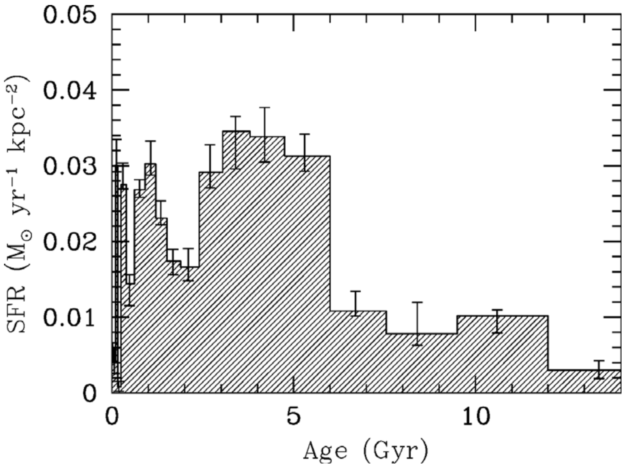

Figure 2. Star formation history of a field at the center of the LMC bar. The epoch of bar formation can be reliably dated to ≈ 6 Gyr ago, when the metallicity of the gas had already risen to [Fe/H] $\gtrsim -0.6$. The star-formation history shown here, combined with the metallicity distribution function of Cole *et al.* (2005), closely tracks the "bursting" chemical evolution model presented in Pagel & Tautvaišienė (1998), but with the burst epoch pushed back to ≈ 6 Gyr ago.

the two overlapping isochrones are plotted, the degeneracy is clearly broken: even with the metallicities convolved with the ±0.15 dex errorbar typical of modern calcium triplet studies, there is an obvious difference in the resulting metallicity distribution functions (MDF). In the extremely simple case shown, two distinct stellar populations with very different properties can be identified in a vanishingly narrow RGB even without recourse to main-sequence photometry.

Note that the total number of red giants sampled per unit *created mass* of the stellar population decreases with increasing age and decreasing metallicity — there are fewer old, metal-poor stars in the MDF of Fig. 1, even though the 3.2 Gyr and 10 Gyr populations were born in equal numbers. This bias arises because of the observational selection: the number of stars sampled is effectively proportional to the integral over the initial mass function (IMF) from the bottom to the top of the selection box along the RGB. The higher the age of the population, the smaller the mass range sampled by the selection box, and for stellar masses below ≈ 1.3 $M_\odot$, the IMF is not weighted strongly enough to lower mass stars (older red giants) to compensate.

This raises the possibility that the MDF and the CMD can be *simultaneously* fit in order to derive the SFH and age–metallicity relation without the necessity of assuming a chemical evolution model or relying on uncertain RGB colors. The LMC is an ideal test case for this method, because both very deep CMDs that reach far below the oldest main-sequence turnoffs and large numbers of spectroscopic metallicities for stars spanning a wide range of ages are available.

New results: SFH of the bar, metallicity of the disk

Cole *et al.* (2004, 2005) measured [Fe/H] for 373 red giants in the LMC bar, at the location of the field analyzed in Smecker-Hane *et al.* (2002) and examined in Skillman & Gallart (2002). They found a mean metallicity [Fe/H] = −0.45 that was well-fit by a Gaussian with a 10% tail down to [Fe/H] < −2. They noted the very wide range in RGB color at given metallicity and concluded that the age-metallicity relation must have been

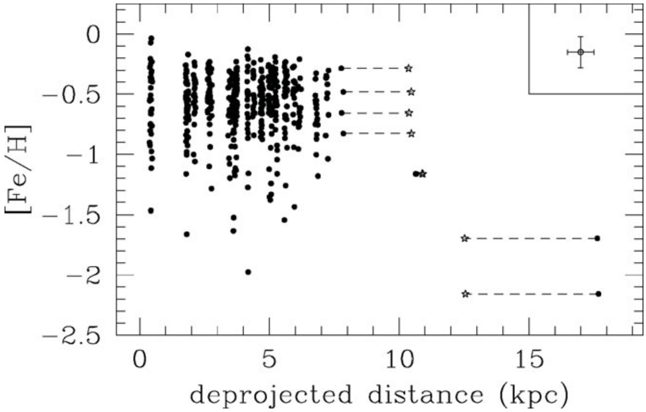

Figure 3. Metallicities of 511 red giants in the LMC disk and bar. The locations of the fields are given in Grocholski *et al.* (2006); radial distances are found assuming the fields lie in the plane of the LMC disk as described in van der Marel (2001). The errorbar shows a representative average 1σ error of ± 0.13 dex and ± 1 kpc in distance. For stars near globular clusters projected beyond 7.5°, a second point is plotted for each star, showing the effect on the derived radius if these *field* stars are assumed to lie at the same location along the line of sight as the nearby clusters (open stars).

extremely flat over most of the LMC history. Confirming the earlier result of Cole *et al.* (2000), they found no sign of the cluster metallicity/age gap. By finding the model star-formation + chemical evolution history that simultaneously reproduces both the *HST* CMD and the MDF from Cole *et al.* (2005), we derive the SFH anew, shown in Fig. 2. We also derive the age-metallicity relation, and find excellent agreement with the results in Cole *et al.* (2005) and with the bursting models of Pagel & Tautvaišienė (1998), if the models are modified to cause the burst to occur at 6 Gyr instead of at 3 Gyr. The large star formation rate at an age of 1 Gyr is reflected in the large number of carbon stars observed in the LMC bar.

We have also obtained several hundred new spectra in and around clusters scattered across the face of the LMC (Grocholski *et al.* 2006). There are 511 field red giants in this sample, which probes 27 regions from the bar to 15° away. The shapes of the disk and bar MDFs are broadly similar: both distributions cut off sharply on the high-metallicity end, and both contain an identical 5% fraction of stars with [Fe/H] $\leqslant -1.2$. However, the disk shows a far higher fraction of stars between $-1.2 \leqslant$ [Fe/H] $\leqslant -0.7$: this range contains 20% of the disk stars, but just 5% of those in the bar. Detailed modelling in conjunction with the disk CMDs will be necessary to confirm this, but it seems likely that this is due to the higher number of young stars in the bar field: the CMD analysis requires a younger bar, and Figure 1 shows that an observationally “unbiased” sample will tend to be dominated by young, metal-rich RGB stars.

Figure 3 shows the metallicities of every field star in our *disk* sample, along with its deprojected radius (according to the disk model of van der Marel 2001). There is no clear radial gradient in metallicity out to at least 8–10 kpc deprojected distance. Virtually all of the stars at larger radii turned out to be Milky Way foreground dwarfs or cluster members (by radial velocity), so the details of the metallicity gradient beyond this point are not well constrained in this data. The small number of stars at radii of 10−18 kpc in this sample mean that the significance of any inferred gradient is strongly tied to the field/cluster discrimination. Only one of our disk fields has a similar metallicity distribution to the bar: the innermost field is projected against the bar, and is the highest metallicity field observed; combined with the field from Cole *et al.* (2005), this begins to suggest that the disk-bar metallicity difference is real and not just a statistical artifact. It is important to note that we see no difference in mean metallicity between fields that lie within the $\approx 4°$ limit of active current star formation and those that lie beyond; this may be related to the fact that the RGB stars are older than 1 Gyr, and dynamically well-mixed, but in that case the difference with respect to the bar becomes more puzzling.

Several new questions are raised by these data: how has the bar maintained its apparently separate identity for several Gyr when it is apparently so kinematically unimportant? Can the epoch of bar formation identified in the deep *HST*+abundance data be reconciled with the new, longer-period Magellanic Clouds orbits implied by the recent proper motion data (Kallivayalil *et al.* 2006; Kallivayalil, van der Marel & Alcock 2006)? Although the SFH, chemical evolution and dynamical history of the LMC since the time corresponding to redshift $z = 1$ is becoming well-constrained by data, putting the pieces together into a coherent understanding is proving to be a challenge. At the other end of time, the earliest 1–2 Gyr of LMC history remain very poorly constrained. This is a critical time for galaxy evolution. Comparing the state of our knowledge at the last Clouds meeting (IAU 190) to our understanding today, it is possible to optimistically look forward another decade to a complete description of the halo SFH and metallicity and the detailed chemical abundances of dozens of stars with $[\mathrm{Fe/H}] \lesssim -3$ (another factor of five below the most metal-poor LMC stars currently known).

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