Ca II TRIPLET SPECTROSCOPY OF GIANTS IN SMALL MAGELLANIC CLOUD STAR CLUSTERS: ABUNDANCES, VELOCITIES, AND THE AGE-METALLICITY RELATION

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ABSTRACT

We have obtained spectra at the Ca II triplet of individual red giants in seven Small Magellanic Cloud (SMC) star clusters whose ages range from ~4 to 12 Gyr. The spectra have been used to determine mean abundances for six of the star clusters to a typical precision of 0.12 dex. When combined with existing data for other objects, the resulting SMC age-metallicity relation is generally consistent with that for a simple model of chemical evolution, scaled to the present-day SMC mean abundance and gas mass fraction. Two of the clusters (Lindsay 113 and NGC 339), however, have abundances that are ~0.5 dex lower than that expected from the mean age-metallicity relation. It is suggested that the formation of these clusters, which have ages of ~5 Gyr, may have involved the inflow of unenriched gas, perhaps from the Magellanic Stream. The spectra also yield radial velocities for the seven clusters. The resulting velocity dispersion is 16 ± 4 km s⁻¹, consistent with those of the SMC planetary nebula and carbon star populations.

Key words: galaxies: abundances — galaxies: individual (Small Magellanic Cloud) — galaxies: kinematics and dynamics — galaxies: star clusters — Magellanic Clouds

1. INTRODUCTION

The age-metallicity relation of a stellar system is one of the fundamental diagnostics through which we can learn about the chemical enrichment processes that occur during the system’s evolution. Within the solar neighborhood, for example, it is possible to determine the age-metallicity relation for the Galactic disk from the ages and metallicities of field stars (see, e.g., Edvardsson et al. 1993), and modeling of this relation and its scatter suggests a complex evolution involving gas inflow and the radial diffusion of orbits in the presence of a radial abundance gradient (see, e.g., Pagel & Tautvaisiene 1995). However, for more distant systems, we can no longer use individual F- and G-type dwarfs to determine ages and abundances. Instead, we must use star clusters since, at least in principle, it is relatively straightforward to determine a cluster’s age and abundance. In particular, for our nearest galactic neighbors it is possible to constrain cluster ages via main-sequence turnoff luminosities even if the clusters are as old as the Galactic halo globular clusters. Thus, provided clusters of all ages can be found (which is, of course, a function of formation and destruction processes), the age-metallicity relations of these nearby systems can be fully outlined.

It is with this proviso, however, that a major difficulty often arises. For example, in the Large Magellanic Cloud (LMC) there is a well-established population of old metal-poor star clusters whose properties are comparable to the Galactic halo globular clusters (see, e.g., Suntzeff et al. 1992). There is also a large population of intermediate-age clusters, but the ages of these clusters are 3–4 Gyr (see, e.g., Da Costa 1991; Olszewski, Suntzeff, & Mateo 1996; Geisler et al. 1997) and only a single cluster, ESO 121-SC03 (Mateo, Hodge, & Schommer 1986), is known to fall in the “age gap” between the old and intermediate-age objects. As emphasized by Olszewski et al. (1996), for example, this gap in the LMC cluster age distribution also represents an “abundance gap,” in that the old clusters are all metal-poor while the intermediate-age clusters are all relatively metal-rich (Olszewski et al. 1991), approaching even the present-day abundance in the LMC. Yet, because of the lack of clusters older than ~3 Gyr, we have essentially no constraints on the timescale for what was the major enrichment event in the LMC’s history. The Small Magellanic Cloud (SMC), on the other hand, is known to have a different distribution of cluster ages from the LMC (e.g., Da Costa 1991). In particular, while the number of clusters with ages determined from main-sequence turnoff photometry is smaller than for the LMC, there is no sign in these data of any substantial “age gap.” Thus, in principle, the SMC age-metallicity relation defined by the star clusters can cover from the present day back almost to the age of the oldest Galactic halo globular clusters.¹

¹ NGC 121, the oldest SMC star cluster for which age information exists, is perhaps 2–3 Gyr younger than the Galactic halo globular clusters (see, e.g., Stryker, Da Costa, & Mould 1985).
the newly synthesized metals were lost in a strong galactic wind (or a combination of these processes). The second component could result from the cessation of these processes, or from an increased star formation rate (perhaps as a result of an interaction with the LMC). However, it must be emphasized that the majority of the cluster abundances used to define this age-metallicity relation are rather uncertain: most are derived from the color of the cluster red giant branch in the color-magnitude diagram (CMD). This technique depends on the reddening of the cluster and on the zero point of the photometry, and it also contains the uncertainty inherent in the calibration of a parameter that is sensitive to both age and abundance.

It is obvious, then, that to verify the chemical history of the SMC implied by this age-metallicity relation, it needs to be redetermined using a consistent, accurate, and reddening-independent method. Spectroscopy at the Ca II triplet of globular cluster red giants analyzed in terms of the magnitude difference from the horizontal branch is such a method (see, e.g., Da Costa & Armandroff 1995; Rutledge, Hesser, & Stetson 1997; references therein), and as Olszewski et al. (1991) have shown, it can be extended to red giants in intermediate-age star clusters, since the higher gravity of the younger stars has little effect, at least for ages in excess of perhaps 2 Gyr. The purpose of this paper, therefore, is to present Ca II triplet spectroscopy for red giants in a number of SMC star clusters and to discuss the implications of these new results for the SMC age-metallicity relation and the SMC chemical history. Spectroscopy of individual stars has the added bonus that we can also determine the cluster radial velocities. The kinematics of the LMC cluster system has produced some intriguing results (e.g., Schommer et al. 1992), and while the sample of clusters observed here is small, the velocity results can nevertheless be compared with the kinematics of other SMC populations.

The outline of the remainder of the paper is as follows. In the following section the sample of SMC clusters observed, the data reduction procedure, and the line-strength and radial velocity analysis techniques are described. Section 3 discusses in some detail the derivation of abundances from the observed line strengths. Then, in the first part of § 4, the kinematics implied by the cluster radial velocities is derived and compared with those of other SMC populations with similar ages. In the second part of this section (§ 4.2) the full SMC age-metallicity relation is constructed. The implications of this relation for the chemical evolution of the SMC are discussed in the final section.

2. OBSERVATIONS AND REDUCTIONS

2.1. SMC Cluster Sample

Compared with the LMC, there are fewer well-studied star clusters in the SMC, though, as noted above, the SMC clusters do not show the large “age gap” exhibited by the LMC cluster population. For this reason, we initially selected only those clusters with both good-quality CMDs and ages (as determined from main-sequence turnoff photometry) greater than ~2 Gyr. There are six such clusters: Lindsay 1 (Olszewski, Schommer, & Aaronson 1987), Kron 3 (Rich, Da Costa, & Mould 1984), Lindsay 11 (Mould, Jensen, & Da Costa 1992), NGC 121 (Stryker et al. 1985), NGC 339 (E. W. Olszewski 1994, private communication), and Lindsay 113 (Mould, Da Costa, & Crawford 1984). For each cluster, the brighter half-dozen or so candidate cluster red giants were selected for spectroscopic observation at the Ca II triplet. In this selection process we were careful to ensure that none of the stars chosen had been previously identified via IR photometry and/or low-resolution spectroscopy as upper-asymptotic giant branch (AGB) stars (whether of C, M, or S spectral type). Then, in order to increase the sample, we constructed a second list of SMC clusters for which main-sequence turnoff CMDs were not available, but for which independent data suggested an age in the 2–12 Gyr range. The only cluster from this second list for which stars were actually observed was NGC 361. Arp (1958) gives a photographic CMD for this cluster, but it does not reach as faint as even the expected magnitude for the core helium burning stars and, therefore, yields little age information. However, when corrected for the effects of a superposed bright star (see van den Bergh 1981), the integrated UBV colors of NGC 361 are similar to those of the six clusters in the first list. Thus it is likely that NGC 361 is of intermediate age, and the brighter red giants from the CMD of Arp (1958) were added to the sample for spectroscopic study.

2.2. Observations

The program stars were observed with the Anglo-Australian Telescope using the RGO spectrograph with the 25 cm camera and a Tektronix 1K CCD, during runs in 1992 September (second halves of five nights) and 1994 August (second halves of two nights). The instrumental setup was identical to that discussed in Da Costa & Armandroff (1995, hereafter DA95), which can be consulted for a more detailed description. In brief, the spectra cover the wavelength interval ~7700–9300 Å at a resolution of ~3 Å. Total exposure times for the SMC cluster stars ranged from 800 s to 2 hr for the faintest stars. Wherever possible, two stars were observed simultaneously by rotating the spectrograph slit to an appropriate position angle. Standard IRAF procedures were used to generate sky-subtracted, wavelength-calibrated spectra from the raw data. Some examples of the final spectra are shown in Figure 1. Spectra of Galactic globular cluster red giants obtained during these observing runs are discussed by DA95, who have demonstrated that the data from the two observing runs have no systematic differences and can be used interchangeably. At this point, it is also worth mentioning that Lindsay 11 star 1 from Mould & Aaronson (1982) was also observed during the 1994 August run. This star has the infrared colors of an upper-AGB carbon star (see Mould & Aaronson 1982), and the presence of strong CN bands at λ ≈ 7850 and 8050 Å in the spectrum confirm this classification. Such bands were not seen in the spectrum of any other star observed. There were also no indications in these spectra of TiO bands, whose presence can affect the measurement of the Ca II triplet line strength (see, e.g., Olszewski et al. 1991).

2.3. Line-Strength Measurements

The (pseudo-) equivalent widths of the two stronger lines of the Ca II triplet, λ8542 and λ8662, were measured from

2 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
the red giant spectra by applying the Gaussian fitting technique of DA95 (see also Armandroff & Da Costa 1991). The sum of these line-strength measures, \( W_{8542} + W_{8862} \), was then computed for each observation. Final values for 33 stars in the fields of the seven SMC clusters are given in Table 1. In this table, the errors accompanying the \( W_{8542} + W_{8862} \) values are those resulting from the uncertainties in the parameters that define the Gaussian line profile fits. Comparison of these errors with the mean single-observation error in \( W_{8542} + W_{8862} \) derived from the 31 repeat observations of 15 stars shows that these Gaussian line profile fit uncertainties probably overestimate the true errors by perhaps 25% (0.32 vs. 0.40 Å). Nevertheless, we have been conservative and have retained the individual Gaussian line profile fit uncertainties.

For four of the seven clusters, the available photometry is in the \( B \) and \( R \) bandpasses, whereas the abundance calibration procedure (see DA95) requires \( V \) magnitudes for both the individual stars and the horizontal-branch luminosity. To overcome this situation, we have made use of the empirical transformation

\[
B - V = (0.685 \pm 0.005) (B - R) - 0.06 \pm 0.01 . \tag{1}
\]

This transformation is based on high-quality photoelectric \( BVR \) photometry of red giants in the Galactic globular clusters 47 Tuc and NGC 288, 362, 6397, and 6752 (E. M. Green 1987, private communication) and is appropriate for the reddening \( E(B - V) = 0.04 \) mag assumed for the SMC clusters. The rms deviation about the fitted line is only 0.010 mag, and the equation is valid between \( B - R \approx 1.1 \) (\( B - V \approx 0.7 \)) and \( B - R \approx 2.5 \) (\( B - V \approx 1.65 \)). The \( V \) magnitude for each program star then follows from the observed \( B \) magnitude and the computed \( B - V \) color. The same process has also been used to fix the \( V_{HB} \) values for these clusters: the median \( B - R \) color of the red clump of core helium burning stars (which constitutes the horizontal branch in these clusters) was converted to \( B - V \) via equation (1) and combined with \( B_{HB} \), taken as \( R_{HB} \) plus the median \( B - R \) color, to generate \( V_{HB} \). This process can be verified for two of the four clusters involved, since independent \( BV \) photometry is available. For Kron 3, the CMD of Gascoigne (1980) suggests \( V_{HB} \approx 19.3 \) while Alcaino et al. (1996) list \( V_{HB} = 19.50 \pm 0.05 \). Both these values are in agreement with our adopted value of 19.44 derived from the \( (R, B - R) \) photometry of Rich et al. (1984). We also note that the Lindsay 1 CMD in Gascoigne (1980) gives \( V_{HB} \approx 19.3 \), again in good accord with our value \( V_{HB} = 19.20 \) adopted from the \( (V, B - V) \) photometry of Olszewski et al. (1987). For NGC 121, the photometry of Tifft (1963) for zones 2 and 3, which should be free of photographic background effects (see Stryker et al. 1985), gives \( V_{HB} \approx 19.6 \). This agrees well with the value \( V_{HB} = 19.60 \) derived from the \( (R, B - R) \) photometry of Stryker et al. (1985). The adopted \( V_{HB} \) values for all the sample clusters (except NGC 361, for which no suitable photometry exists) are given in Table 2.

In Figure 2, the line-strength measures are plotted against the \( V \) magnitude difference from the horizontal branch, \( V - V_{HB} \), for all stars observed in the fields of six of the seven clusters in the sample. The lack of a CMD reaching faint enough to reveal the magnitude of the horizontal branch (or red clump) in NGC 361 precludes analysis of the
Since there is no reason to suspect that any of these clusters contain a substantial internal abundance range, we can assume that any star whose Ca II triplet line strength lies significantly away from those of the majority is not likely to be a member of that cluster. Inspection of Figure 2 shows that the star MJD 240 in the field of Lindsay 11 has such a discrepant line strength, while all other stars appear, on this basis at least, to be members of their respective clusters. An additional, and independent, means to investigate cluster membership status is provided by the comparatively large heliocentric velocity of the SMC. The measurement of radial velocities from the observed spectra will be discussed in § 2.4, but for the moment we note that all stars except Lindsay 11 MJD 240 and NGC 121 SDM 029 have radial velocities consistent with not only SMC membership, but also membership in their respective clusters. Lindsay 11 MJD 240 is apparently an SMC field star, while the low radial velocity of NGC 121 SDM 029 indicates that this star is probably a foreground Galactic star. This star, and Lindsay 11 MJD 240, will not be considered further.

As shown by a number of authors (e.g., DA95; Rutledge et al. 1997; references therein), the slope of the relation between the Ca II line-strength index $W_{8542} + W_{8662}$ and $V - V_{\text{HB}}$ is independent of abundance, at least for $V - V_{\text{HB}} \lesssim -0.5$ mag. Thus the individual line-strength measures for the stars observed in a cluster can be combined into a single quantity, the reduced equivalent width, denoted by $W'$. $W'$ can then be calibrated in terms of metal abundance. On the system of DA95, which we follow here, $W'$ is defined as the mean value of the quantity $W_{8542} + W_{8662} + 0.62(V - V_{\text{HB}})$ for the stars observed in a particular cluster. Since we have now established the cluster membership status of the program stars, we can compute $W'$ for each cluster. The resulting values are listed in Table 2. We note that for the clusters Lindsay 1, Kron 3, and NGC 339, the cluster $W'$-value is simply the mean of the stellar values, since the individual $W_{8542} + W_{8662}$ errors are all similar. For the other three clusters, however, this is not the case, and the value of $W'$ is computed as a weighted average, with the weights taken as the inverse square of the $W_{8542} + W_{8662}$ errors given by the Gaussian line profile fit uncertainties for each individual star. We note also that the error listed with the $W'$-values in Table 2 contains not only the error, as expressed by the standard error in the mean, from the scatter of the individual values but also includes the effect of an assumed $+0.10$ mag uncertainty in the value of $V_{\text{HB}}$ for each cluster.

For the three clusters where the value of $W'$ was computed as a weighted average, it is of interest to see whether the values change significantly if different weighting schemes are adopted. Consequently, we have computed values of $W'$ for these clusters for the case of no weighting and for a weighting scheme in which the observed mean single-observation error in $W_{8542} + W_{8662} (0.32 \AA)$ together with the number of observations per star was used to compute the weights. We find that in each of these cases, the values of $W'$ computed for the three clusters agree with those given in Table 2 to well within the uncertainties listed in the table. The uncertainties in the alternate $W'$-values are also comparable to those given in Table 2, except for the case of Lindsay 113 and no weighting. Here the outliers (see Fig. 2), whose larger errors are ignored in this particular calculation, generate an uncertainty that is a factor of 2 larger than that listed in Table 2. We believe, however, that

\begin{table}[h]
\centering
\caption{SMC Cluster Observed Data}
\begin{tabular}{lcccc}
Cluster & Age (Gyr) & $V_{\text{HB}}$ & $W'$ & $V_c$ & $N$ \\
\hline
Lindsay 1 & 10 & 2 & 19.20 & 4.22 & 0.11 & 126 & 3 & 4 \\
Kron 3 & 9 & 3 & 19.44 & 4.29 & 0.14 & 123 & 3 & 4 \\
Lindsay 11 & 3.5 & 3 & 19.50 & 4.81 & 0.18 & 132 & 5 & 4 \\
NGC 121 & 12 & 4 & 19.60 & 3.74 & 0.18 & 134 & 8 & 4 \\
NGC 339 & 4 & 15 & 19.36 & 3.91 & 0.07 & 117 & 8 & 6 \\
NGC 361 & 6 & 1 & 19.13 & 3.91 & 0.19 & 162 & 6 & 4 \\
Lindsay 113 & 6 & 1 & 19.13 & 3.91 & 0.19 & 162 & 6 & 4 \\
\end{tabular}
\end{table}
Fig. 2.—Plots of the Ca II line-strength index $W_{8542} + W_{8662}$ in angstroms vs. magnitude difference from the horizontal branch, $V - V_{HB}$, for individual stars in the fields of six SMC star clusters. Probable cluster members are plotted as circles, while probable nonmembers are shown as crosses. The lines in the panels are taken from Da Costa & Armandroff (1995) and represent the Ca II line strength vs. magnitude relations for Galactic globular clusters. In order of increasing Ca II line strength, the clusters are M15, NGC 4590 (M68), NGC 6397, NGC 6752, M5, M4, 47 Tuc, and NGC 5927. These clusters have abundances [Fe/H] on the Zinn & West (1984) scale of $-2.17, -2.09, -1.91, -1.54, -1.40, -1.28, -0.71$, and $-0.31$ dex, respectively.
the values listed in Table 2 are the appropriate ones to adopt. The relation between these $W$-values and abundance will be discussed in § 3.

2.4. Radial Velocities

The determination of radial velocities from the spectra obtained in these observing runs has been discussed in detail in DA95. Briefly, the program star spectra were cross-correlated with high signal-to-noise ratio spectra of bright G- and K-type giant radial velocity standards. The velocity zero point for each run was set by minimizing, after applying heliocentric corrections, the difference between the observed and standard velocities for both the radial velocity and $V$-values and abundances. Consequently, for a given abundance calibration (see below), we will tabulate two abundances for each cluster, based on the observed value of $W$ and a second derived from a corrected value of $W'$. The correction to $W'$ comes from using the adopted cluster ages given in Table 2 with Bertelli et al. (1994) isochrones of appropriate abundance to estimate the change in $V_{\text{hel}}$. An independent calculation of this effect using the models of Seidel, Demarque, & Weinberg (1987b) in conjunction with the Revised Yale Isochrones (Green, Demarque, & King 1987), as described in Hatzidimitriou (1991), yields essentially identical results.

The second issue involves the fact that $W'$ is a calcium line-strength index, whereas the calibration is to $[\text{Fe/H}]^*$ values. As long as there is no difference in $[\text{Ca/Fe}]$ from the program and calibration objects, this is not a matter for concern. However, calcium, being an s-element, has its origin primarily in Type II supernovae (SNe II) and is enhanced, relative to the solar ratio, in both globular cluster and metal-poor Galactic halo stars (see, e.g., Wheeler, Sneden, & Truran 1989). Iron enrichment, on the other hand, is thought to occur primarily from SNe Ia, which have a longer evolutionary time than SNe II. Thus the $[\text{Ca/Fe}]^*$ ratio is quite likely to be a function of star formation and enrichment history. In particular, a star in an SMC cluster with an age half that, or less, of the Galactic globular clusters is not likely to have the same $[\text{Ca/Fe}]$ value as a Galactic globular cluster star, even though they may have the same $[\text{Fe/H}]$. At the present time we can do little about this issue other than to note, first, that investigation of elemental abundance ratios in SMC and LMC intermediate-age and old cluster and field stars is likely to be a prime science project for the coming 8 m-class telescopes in the Southern Hemisphere and, second, that in young SMC field stars the $[\alpha/\text{Fe}]$ ratio is approximately solar despite the moderate overall Fe depletion (see, e.g., Hill 1997; Luck & Lambert 1992). As regards our own data, two points can be made. First, interpreting $W'$ with a Galactic globular cluster–based relation (i.e., $[\text{Fe/H}] \approx +0.3$) will lead to an underestimate of the true $[\text{Fe/H}]$ if $[\text{Ca/Fe}] < -0.3$ in the program stars. In such a case the derived $[\text{Fe/H}]$ values will represent lower limits on the actual abundance value. Second, it would seem unlikely that clusters with comparable ages could have substantially different $[\text{Ca/Fe}]$ ratios. Thus, the difference in $W'$ between Lindsay 11 and NGC 339, for example, is likely to reflect a significant difference in overall abundance.

The final issue is that of the calibration relation itself. As noted above, in DA95 the $W'$ calibration is tied to the globular cluster abundance scale of Zinn & West (1984). In a recent paper, however, Carretta & Gratton (1997) have compiled a consistent set of $[\text{Fe/H}]$ values derived from high-dispersion spectroscopy for Galactic globular clusters. These authors find that their $[\text{Fe/H}]$ values do not scale linearly with those of Zinn & West (1984). While there is reasonable agreement for both the metal-poor ($[\text{Fe/H}] \approx -2.0$) and the metal-rich ($[\text{Fe/H}] \approx -0.7$) clusters, at intermediate abundances there are substantial
which abundance scale is correct, though the high-dispersion studies of Sneden, Kraft, and coworkers (e.g., Kraft et al. 1995 and references therein), for example, do support the Carretta & Gratton (1997) results for the clusters in common.

With the exception of Lindsay 11, all the observed SMC cluster \( W' \)-values fall in the range where the \((W', [\text{Fe/H}]_{\text{ZW84}})\) and \((W', [\text{Fe/H}]_{\text{CG97}})\) calibrations differ significantly. Thus we will interpret our results using both calibration relations. In Table 3, then, we list four abundances for each SMC cluster. These are abundances with and without the correction for the brightening of the horizontal branch with decreasing age, and for both the \([\text{Fe/H}]_{\text{ZW84}}\) calibration of DA95 and the \([\text{Fe/H}]_{\text{CG97}}\) derived above. The errors listed include both the uncertainty in the \( W' \)-value from Table 2 and the uncertainty in the particular calibration. These uncertainties are comparable in size for clusters such as Lindsay 113, but for clusters with smaller errors in \( W' \), such as NGC 393, the calibration error dominates. In general, the results in Table 3 reveal no major surprises: the abundances are not very different (though of higher precision) from existing estimates based on integrated spectroscopy and photometry and/or red giant branch colors. For example, Zinn & West (1984) list \([\text{Fe/H}] = -1.51 \pm 0.15\) for NGC 121, in excellent agreement with our value of \([\text{Fe/H}]_{\text{ZW84}} = -1.46 \pm 0.10\) dex.

4. RESULTS

4.1. Kinematics of the Cluster Sample

Analysis of the kinematics of the cluster system of the LMC has revealed generally ordered motion. For example, the majority of the clusters form a disk system whose parameters agree with those of the optical isophotes and the H I rotation curve (Schommer et al. 1992). Further, unlike (the at most) slowly rotating, pressure-supported, Galactic halo globular cluster system, even the oldest LMC star clusters have the kinematics of a disk system: the rotation amplitude is comparable to that of the younger clusters and the velocity dispersion is relatively small (Schommer et al. 1992). For the SMC, however, the situation is apparently quite different. Kinematic studies of both planetary nebula (Dopita et al. 1985) and carbon star (Hardy, Suntzeff, & Azzopardi 1989; Hatzidimitriou et al. 1997) samples have not revealed any indications of systematic rotation, while the recent high-resolution study of the H I in the SMC reveals a complex structure dominated by the effects of expanding H I shells, rather than a rotating disklike structure (Staveley-Smith et al. 1997). The ongoing interaction with the LMC (and with the Galaxy) undoubtedly also influences the kinematics of SMC populations, particularly

| SMC CLUSTER ABUNDANCE RESULTS |
| --- |
| \([\text{Fe/H}]_{\text{ZW84}}\) | \([\text{Fe/H}]_{\text{CG97}}\) |
| **CLUSTER** | Raw | \(V_{\text{sub}}(\text{age})\) corrected | Raw | \(V_{\text{sub}}(\text{age})\) corrected |
| Lindsay 1 | -1.14 ± 0.10 | -1.17 ± 0.10 | -0.99 ± 0.11 | 1.01 ± 0.11 |
| Lindsay 11 | -0.70 ± 0.14 | -0.80 ± 0.14 | -0.75 ± 0.13 | 0.81 ± 0.13 |
| NGC 121 | -1.46 ± 0.10 | -1.46 ± 0.10 | -1.19 ± 0.12 | -1.19 ± 0.12 |
| NGC 339 | -1.36 ± 0.10 | -1.46 ± 0.10 | -1.12 ± 0.10 | -1.19 ± 0.10 |
| Lindsay 113 | -1.37 ± 0.16 | -1.44 ± 0.16 | -1.12 ± 0.12 | -1.17 ± 0.12 |

**Fig. 3.** Reduced equivalent width \( W' \) in angstroms plotted against iron abundance \([\text{Fe/H}]\) from Carretta & Gratton (1997), if available, for the abundance calibration clusters of Da Costa & Armandro (1995). These \([\text{Fe/H}]\) values all have their basis in high-dispersion spectroscopy. The solid line is a least-squares fit to the data. The dotted line is the two-linear-segment fit of to \([\text{Fe/H}]\) values on the scale of DA95 Zinn (1984). The ongoing interaction with the LMC (and with the Galaxy) undoubtedly also influences the kinematics of SMC populations, particularly...
in the outer regions to the northeast of the SMC center and in the wing (see, e.g., Hatzidimitriou, Cannon, & Hawkins 1993).

While our sample of intermediate-age and old SMC star clusters is small, it is nevertheless distributed over the entire spatial extent of the SMC. Thus, it is worthwhile to investigate the kinematics implied by the cluster radial velocities. Moreover, the ages of the star clusters studied range from \( \sim 4 \) to \( \sim 12 \) Gyr, and thus, it is sensible to compare the cluster results with those from the planetary nebula (Dopita et al. 1985) and carbon star (Hardy et al. 1989; Hatzidimitriou et al. 1997) samples. Both these populations have progenitors whose ages are comparable to those of the star clusters. Also available for comparison is the study of the kinematics of SMC red clump stars (Hatzidimitriou et al. 1993) and that for SMC field red giants (Suntzeff et al. 1986). These studies are restricted to particular areas; a region near NGC 121 in the latter case and a region approximately 3.5 northeast of the SMC center in the former.

As mentioned above, both the planetary nebula and the carbon star samples show no evidence for any systematic rotation of the SMC, and our cluster velocities support this conclusion. In particular, the seven clusters fall within the scatter shown by the carbon stars in the \( V_{GSR} \) versus position angle diagram of Hardy et al. (1989). Similarly, in the diagram of \( V_{LSR} \) versus projected distance from the centroid along the SMC major axis of Dopita et al. (1985), the clusters are indistinguishable from the planetary nebulae. We have then used a maximum likelihood code kindly provided by C. P. Pryor to calculate the mean velocity \( \langle V \rangle \) and velocity dispersion \( \sigma \) for the cluster sample. The results are, using heliocentric values, \( \langle V \rangle = 138 \pm 6 \) km s\(^{-1} \) and \( \sigma = 16 \pm 4 \) km s\(^{-1} \). The results are summarized and compared with other samples in Table 4. The mean velocity of the cluster sample is in good accord with those for the other samples. The dispersion, though, is somewhat lower: \( 16 \pm 4 \) km s\(^{-1} \), versus 21–27 km s\(^{-1} \) for the other large-area surveys. Given the small number of clusters in our sample, we ascribe no significance to this difference. It is interesting to note, though, that the dispersion of the old and intermediate-age populations in the SMC is, at \( \sim 24 \) km s\(^{-1} \), very comparable to the dispersion seen for the LMC clusters of similar age (Schommer et al. 1992). The major kinematic difference, though, lies in the substantial rotation of the LMC cluster system \( (V_{circ} \geq 50 \) km s\(^{-1} \)), which is apparently completely lacking in the SMC. It is of further interest to note that Staveley-Smith et al. (1997) also find a similar dispersion (25 \pm 6 km s\(^{-1} \)) from their SMC H I observations. When combined with, for example, the Cepheid observations of Mathewson, Ford, & Visvanathan (1988), for which \( \sigma = 22 \pm 3 \) km s\(^{-1} \), it is evident that the kinematics of the various SMC populations studied are all similar. As a result, it appears that kinematics is independent of age in the SMC. This result contrasts rather strongly with the situation in our Galaxy and in the LMC, but whether it is a result of the interaction history of the SMC remains unclear.

### 4.2. SMC Age-Metallicity Relation

In Table 2, we list our adopted ages for the six clusters in our sample for which we have determined metallicities. These ages have been largely taken from the original CMD references (see § 2.1) and are appropriate for our assumed SMC distance modulus of \( (m - M)_0 = 18.8 \). For Kron 3, however, we have taken account of the results of Alcaino et al. (1996), who found a somewhat older age than did Rich et al. (1984). Similarly, for Lindsay 113, we follow Seidel, Da Costa, & Demarque (1987a), who noted that the apparent magnitude of the red clump in this cluster, which lies at the extreme eastern edge of the SMC, suggests that it is \( \sim 0.2–0.3 \) mag closer than the standard SMC modulus. Consequently, we have adopted the Seidel et al. (1987a) value of \( 6 \pm 1 \) Gyr for the age of this cluster, rather than the somewhat younger value given by Mould et al. (1984). In all cases we have assigned relatively generous error bars to the adopted ages. Figure 4 plots our spectroscopic abundance determinations for these six clusters against the adopted ages. The top panel shows the abundances on the Zinn & West (1984) scale, while the bottom panel employs the Carretta & Gratton (1997) abundance scale. In both panels the abundance plotted is that corrected for the variation with age of the horizontal-branch luminosity (see Table 3).

In Figure 4 we have also plotted additional data relevant to defining the age-metallicity relation of the SMC. We now briefly discuss these data. First, in Figure 4 points are plotted for five additional clusters: NGC 152, 330, 411, 419,
and 458. For NGC 152, the abundance ([Fe/H] = -0.8 ± 0.3) is from Hodge (1981a) and is based on the giant branch color. The adopted age of 1.9 ± 0.5 Gyr comes from considering the magnitude difference between the main-sequence turnoff and the red clump in the CMD of Hodge (1981b; see Mould & Da Costa 1988 for details). For NGC 411, we adopted the age (1.8 ± 0.3 Gyr) given by Da Costa & Mould (1986) for our adopted SMC modulus. The abundance for this cluster ([Fe/H] = -0.84 ± 0.3 dex) also comes from the giant branch color: Da Costa & Mould (1986) determine an abundance of -0.6 ± 0.3 dex relative to the Galactic cluster NGC 7789, for which Friel (1995) lists [Fe/H] = -0.24 dex. The age (1.2 ± 0.5 Gyr) and abundance ([Fe/H] = -0.7 ± 0.3) adopted for NGC 419 follow from the CMD isochrone fits of Durand, Hardy, & Melnick (1984), who also indicate that integrated Washington-system photometry of this cluster requires [Fe/H] ≳ -1.0 dex. These results are consistent with those of Rabin (1983), who showed from integrated spectra that NGC 419 and NGC 411 occupy essentially identical locations in a diagram of hydrogen line strength versus calcium K line strength. For NGC 458, Papenhausen & Schommer (1988) list an age of 0.3 Gyr, based on fitting a log(Z/Z_⊙) = -0.23 isochrone from VandenBerg (1985). Given the uncertainty of abundance determination via isochrone fits, we have in this case adopted a larger error for the abundance. In particular, the adopted error covers the comment of Stothers & Chin (1992) that NGC 458 is likely to have an abundance similar to that of the average SMC young population. Our adopted age error of ±0.2 Gyr also encompasses the Stothers & Chin (1992) age estimate of ~0.1 Gyr for this cluster. Finally, we adopt an abundance of [Fe/H] = -0.82 ± 0.10 for the young (25 ± 15 Myr; Choisi et al. 1995) cluster NGC 330. This abundance is from the high-dispersion spectroscopic study of Hill & Spite (1998; see also Meliani, Barbuy, & Perrin 1995 and references therein).

Figure 4 also includes relevant data for SMC field objects. In particular, we have plotted, at an adopted age of 13 ± 1 Gyr, the mean abundance found by Butler, Demarque, & Smith (1982) for seven SMC RR Lyrae stars in a field near NGC 121. Further, Suntzeff et al. (1986) have studied both spectroscopically and photometrically a proper-motion-selected sample of ~30 SMC red giants, again in a field near NGC 121. The mean abundance of these stars is [Fe/H] = -1.56 ± 0.06, and a real abundance spread is apparently present in these data. Figure 9 of Suntzeff et al. (1986) suggests a total abundance range from perhaps [Fe/H] ≳ -2.1 to [Fe/H] ≲ -1.2. Here it is relevant to note that the Suntzeff et al. (1986) results are on the Zinn & West (1984) scale, and that both the upper limit on the abundance distribution and the mean abundance would be raised if the Carretta & Gratton (1997) scale were used instead. However, of all the additional results presented in Figure 4, these are the only ones affected by the abundance scale difference. As for the likely ages of the stars in the Suntzeff et al. (1986) sample, individual determinations are, of course, not possible, but we can turn to the field region results of Stryker et al. (1985). These authors find that the field population near NGC 121 is dominated by old stars (unlike the LMC), and they suggest that an age range from perhaps 8 to 14 Gyr is present. The actual age distribution, however, is unknown.

Finally, we also show in Figure 4 representative values of the present-day abundance in the SMC. These determinations are from the high-dispersion spectroscopic studies of Russell & Bessell (1989), [Fe/H] = -0.65 ± 0.06 from eight F-type supergiants; Luck & Lambert (1992), [Fe/H] = -0.53 ± 0.05 from seven Cepheids and supergiants; and Hill (1997), [Fe/H] = -0.69 ± 0.05 from six K-type supergiants. These studies are consistent with each other, and none provide any compelling evidence for the existence of any substantial abundance range among the youngest populations in the SMC. Russell & Dopita (1990) also find no significant metallicity spread among the H II regions of the SMC, in agreement with the earlier result of Pagel et al. (1978).

5. DISCUSSION

The appearance of the SMC age-metallicity relation in Figure 4 is somewhat different from previous depictions of
the cluster and field star data (e.g., Stryker et al. 1985; Da Costa 1991; Olszewski et al. 1996), principally as a result of the increased precision of our spectroscopic abundance determinations. Leaving aside for the moment the two clusters (Lindsay 113 and NGC 339) with anomalously low abundances, the enrichment history for the SMC indicated by Figure 4 suggests a relatively rapid ($\tau \lesssim 3$ Gyr) initial abundance increase followed by a more modest rise starting at $\sim 10$ Gyr and continuing until the present day. In particular, the previous requirement (e.g., Da Costa 1991) for an increased rate of enrichment to bring the abundance from $[\text{Fe/H}] \approx -1.3$ at approximately 3 Gyr to the present-day value of $[\text{Fe/H}] \approx -0.6$ is alleviated. Indeed, the data of Figure 4, again excepting Lindsay 113 and NGC 339, are now quite consistent with the predictions of the simple “closed box” model of chemical evolution. Thus it is also no longer necessary to postulate the significant gas infall or strong galactic winds that were invoked (e.g., Dopita 1991) to explain the apparent lack of enrichment from $\sim 10$–12 Gyr to approximately 3 Gyr. Of course, such processes may, however, still take place.

The SMC, with its likely past interactions with the LMC and the Galaxy, may well be an “open” rather than a closed box, but nevertheless simple models scaled to a present-day abundance, the current SMC gas mass fraction (taken as 0.36; Lequeux 1984) and a formation epoch, assumed to be at 15 Gyr, yield reasonable representations of the data. This is especially the case in the top panel of Figure 4, where we show simple models with present-day abundances of $\log (Z/Z_{\odot}) = -0.6$ and $\log (Z/Z_{\odot}) = -0.5$ dex. The scatter about the model curves is entirely consistent with the uncertainties in the data. In the bottom panel of Figure 4 the same simple model curves are shown. Here the fit is somewhat less satisfactory, the rate of enrichment from $\sim 10$ Gyr to the present suggested by the observations being generally somewhat lower than the model predictions. Conversely, the rate of enrichment prior to $\sim 10$ Gyr may have been more rapid than the simple model predicts. The model fits to the data in the bottom panel of Figure 4 could no doubt be improved by invoking infall, for example, but tighter constraints on the age-metallicity relation are required before such additional calculations would be meaningful.

We now turn to the “anomalous” clusters Lindsay 113 and NGC 339. These clusters have abundances approximately 0.5 and 0.65 dex lower, respectively, than the simple model curves predict for their ages on the Zinn & West (1984) abundance scale, or 0.25 and 0.4 dex lower, respectively, using the Carretta & Gratton (1997) scale. These clusters are considered anomalous since in dwarf galaxies like the SMC (provided the star formation rate is relatively constant and the infall of external material is insignificant) the expanding gas shells driven by evolving massive stars should througfly mix the interstellar medium over galaxy-wide scales on timescales that are considerably less than a Hubble time (see, e.g., Roy & Kunth 1995; Kobulnicky & Skillman 1997). At the present epoch it does appear that the SMC is chemically homogeneous. The studies listed above indicate that for both the young field stars and the H II regions the maximum abundance dispersion permitted by the observations is $\lesssim 0.1$ dex. Further, while there has been considerable controversy in the past regarding the abundance of the young massive star cluster NGC 339, recent work (e.g., Hill & Spite 1998) suggests that this cluster is only $\sim 0.1$ dex more metal-poor than field objects of comparable age, a minor offset. As regards the LMC, where there is a large population of intermediate-age star clusters, we can draw on the results of Olszewski et al. (1991), who also used Ca II triplet spectroscopy to determine abundances for a large number of LMC star clusters. Olszewski et al. (1991, p. 534) indicate that for the clusters in the age range 0.5–3 Gyr, the inner ($r < 5^\circ$, or $\sim 4$ kpc) and outer clusters have “approximately the same abundance spread, both of which are consistent with the measurement errors [in] our metallicities.” Thus there is no compelling case for a significant abundance spread among the LMC intermediate-age clusters. However, in the Olszewski et al. (1991) sample, one can find relatively well observed clusters such as Hodge 14 (five observations of three stars, $[\text{Fe/H}] = -0.66$) and NGC 1777 (three observations of three stars, $[\text{Fe/H}] = -0.35$), for which the results do suggest the existence of an intrinsic abundance range among the intermediate-age LMC clusters of size perhaps $\lesssim 0.3$ dex. But this abundance range is considerably less than that between the SMC clusters NGC 339 and Lindsay 11 (Delta [Fe/H] = 0.66 $\pm$ 0.17 on the Zinn & West 1984 abundance scale, which is that used by Olszewski et al. 1991; $\Delta[\text{Fe/H}] = 0.38 \pm 0.16$ on the Carretta & Gratton 1997 scale), again pointing to the unusual nature of the two SMC low-abundance clusters. Indeed, these abundance differences are comparable in size to the full range in abundance seen in the Galactic disk age-metallicity relation at comparable age (Edvardsson et al. 1993).

Can we then offer an explanation for their anomalously low abundances? We note first that Lindsay 113 lies in the extreme eastern part of the SMC, 4:2 ($\sim 4.2$ kpc in projection) from the center, while NGC 339 lies 1:5 to the south. This might suggest an abundance gradient, but in fact all the other clusters in our abundance sample are further from the SMC center, at least in projection, than NGC 339. In particular, Lindsay 1 lies 3:4 to the west and does not appear anomalous. We can also use the age-compensated horizontal-branch magnitudes to investigate any possible line-of-sight distance variations. These data suggest that Kron 3, Lindsay 11, NGC 121, and NGC 339 are at approximately the same distance, while Lindsay 1 and Lindsay 113 are perhaps $\sim 0.3$ mag closer. Again it seems that a simple abundance gradient is not the answer.

As for other explanations, a number of possibilities exist. Roy & Kunth (1995), for example, suggest that large abundance discontinuities might arise in dwarf galaxies lacking significant differential rotation if there are long dormant phases between successive star-forming episodes. This might appear an attractive possibility given the SMC’s apparent lack of rotation, but the existence of a relatively
uniform age distribution for the SMC star clusters with main-sequence turnoff age determinations (see Fig. 4) argues against the required long dormant phases.

The remaining possibility is that the formation of these clusters involves the infall of unenriched, or at least less enriched, gas. Given the extensive H i halo surrounding both Magellanic Clouds (see, e.g., Mathewson & Ford 1984) and the existence of the Magellanic Stream, this possibility seems plausible. We note, however, that Lu, Savage, & Sembach (1994) have used absorption-line spectroscopy of a background source to argue that the Magellanic Stream gas is certainly not of primordial \( \log (Z/Z_{\odot}) \lesssim -2 \) composition. Indeed, the abundance limits are consistent with present-day Magellanic Cloud abundances (Lu et al. 1994). If these abundances are generally applicable to the Magellanic Stream gas, then it seems to rule out the Magellanic Stream as the source of the low-abundance gas involved in the formation of these clusters. However, Lu et al. (1994) caution that the greatest uncertainty in abundance studies of this type is the sampling differences that can result from the narrow pencil beam of the absorption-line data versus the large beam of the 21 cm data. Since the H i column density can vary substantially on small scales (cf. the high-resolution SMC H i map of Staveley-Smith et al. 1997 vs. the earlier Parkes data of, e.g., Mathewson & Ford 1984), the true abundances could differ substantially from the derived values. We note also that postulating a Magellanic Stream origin for the low-abundance gas involved in the formation of these clusters requires that the Stream have an age of at least 4 Gyr. This conflicts with at least some models for the Stream’s origin (e.g., Gardiner & Naguchi 1996).

A further, speculative possibility is that the gas from which Lindsay 113 and NGC 339 formed (presumably separately, since the clusters have different ages) contained a low-abundance component that had been expelled in galactic wind at an early epoch, but which remained bound to the SMC and subsequently cooled and fell back (see Tenorio-Tagle 1996; Burkert & Ruiz-Lapuente 1997). A second speculative possibility is that the SMC acquired these clusters in a past interaction much in the same way that the Galaxy is now acquiring clusters from the Sagittarius dwarf galaxy (see, e.g., DA95). However, we note that among the dwarf galaxies of the Local Group, the only system known to contain star clusters of age similar to Lindsay 113 and NGC 339 (i.e., \( \sim 4–6 \) Gyr) is the SMC itself!

We conclude by noting that the chemical evolution of the SMC, as exhibited by the data described here for old and intermediate-age clusters, is obviously quite complex. If we are to provide further constraints on the processes involved, then it will be necessary to determine abundances (and ages) for additional SMC star clusters. There are a number of candidate clusters (e.g., NGC 361) whose ages are likely to lie between 1–2 Gyr and \( \sim 10 \) Gyr. The results for such clusters would help enormously in clarifying whether the low abundances exhibited by Lindsay 113 and NGC 339 are common, or are restricted to only a small fraction of the SMC cluster population. There are no technical difficulties preventing the collection of such data.

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